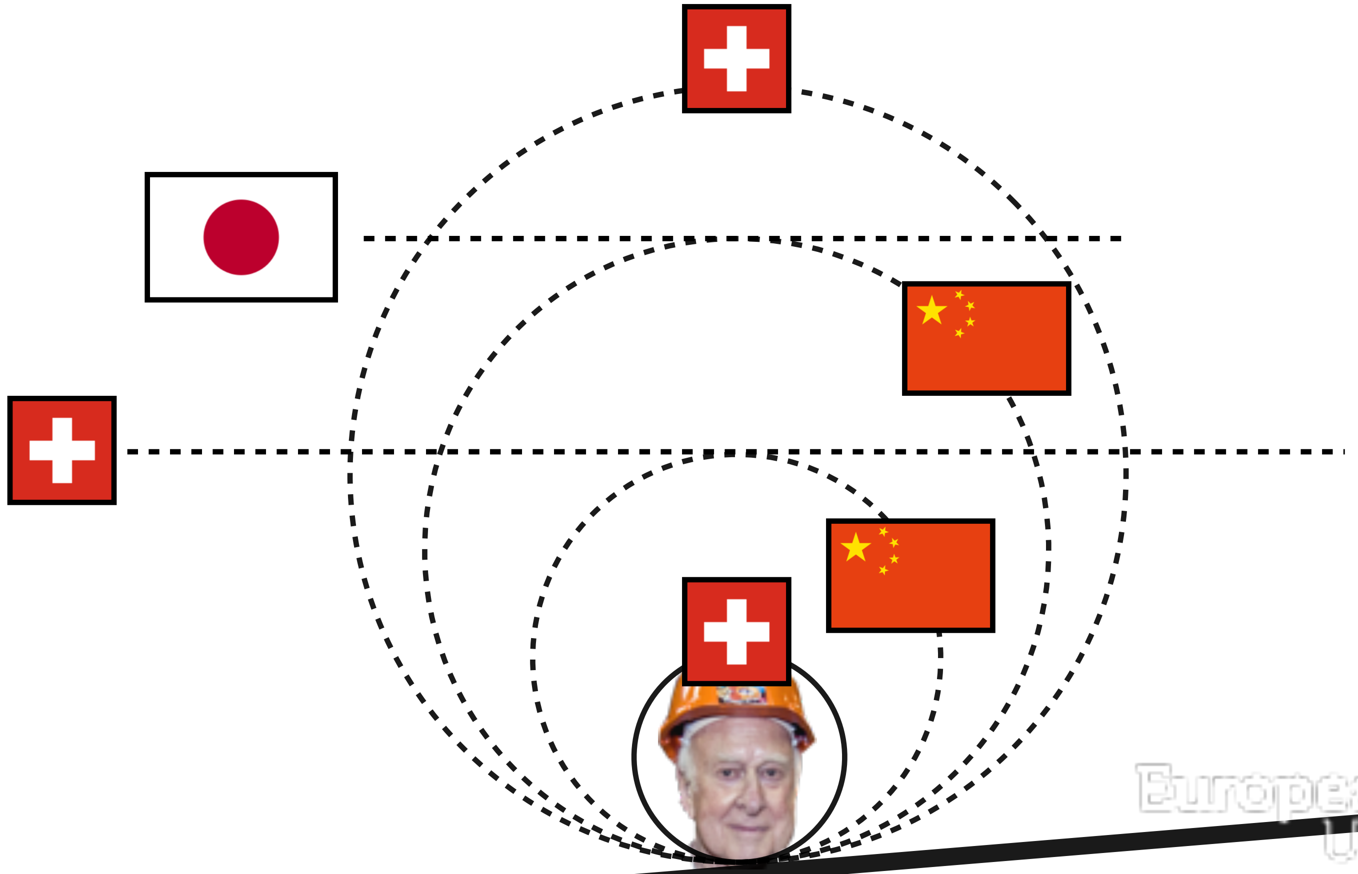
Strategies in pursuing HEP
once and the future

Phenomenology Virtual Symposium 2020
"Pittsburgh on Zoom", May 6, 2020

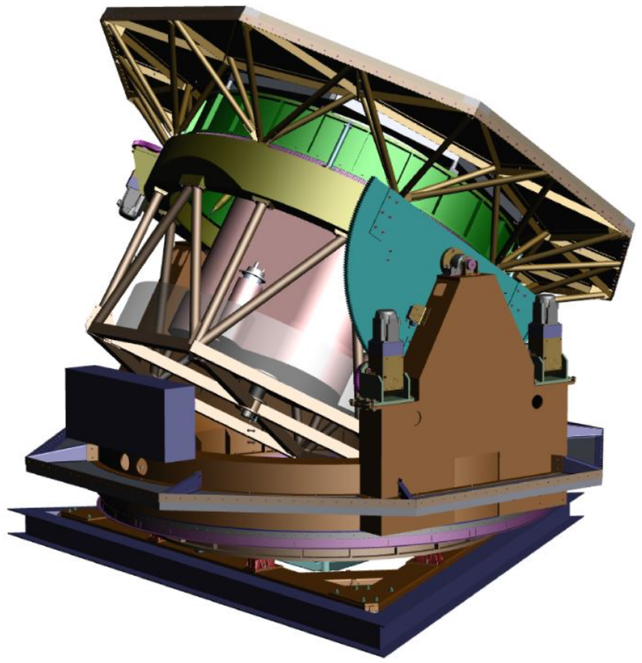


Christophe Grojean
DESY (Hamburg)
Humboldt University (Berlin)
(christophe.grojean@desy.de)

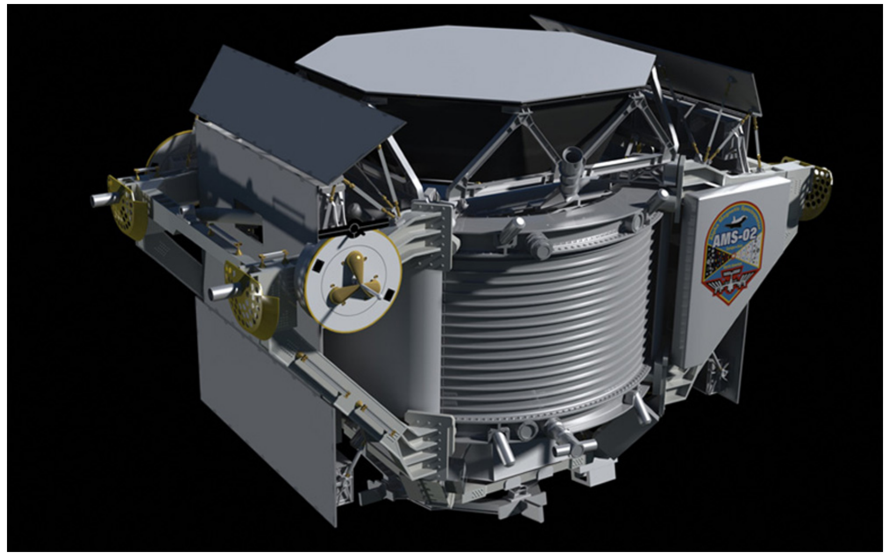
Tools to Answer the Big Questions

As the last speaker of this superb conference,
I don't have to list the big questions in the field that keep all of us awake at night…
(no, I'm not talking about how to find the "share screen" button on Zoom)
Instead, Tao asked me to talk about the tools we should use/build to answer them.

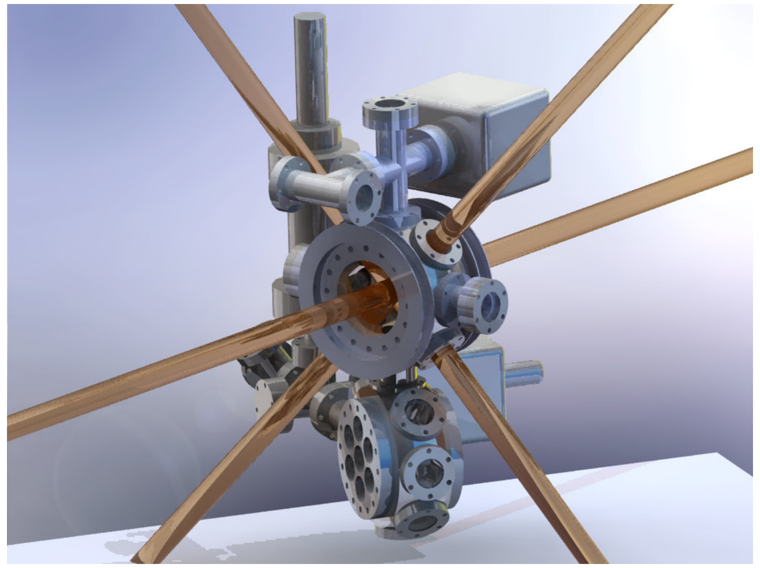
The physics world according to Snowmass



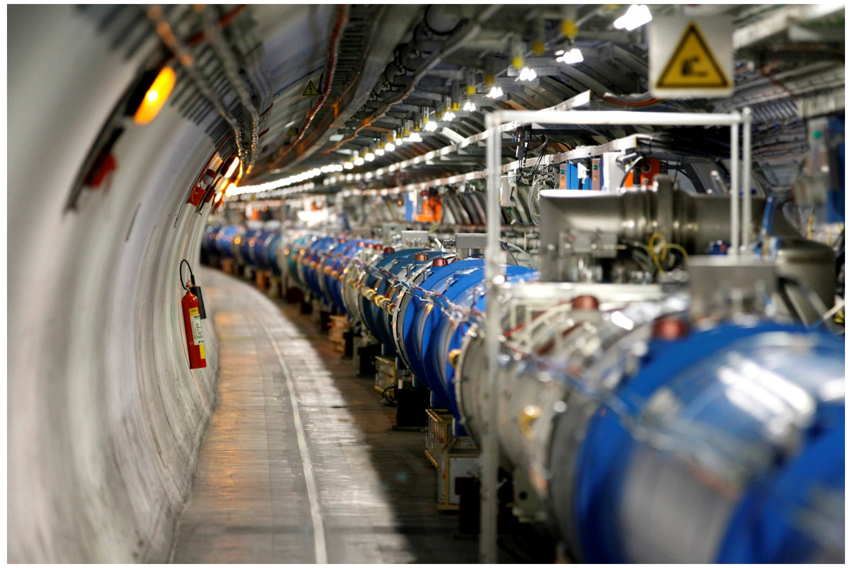
Cosmology frontier



Astroparticle frontier



Intensity frontier



Energy frontier

These days, the best tool that would ensure big progress in science is 

Chirality and the Mass Conundrum

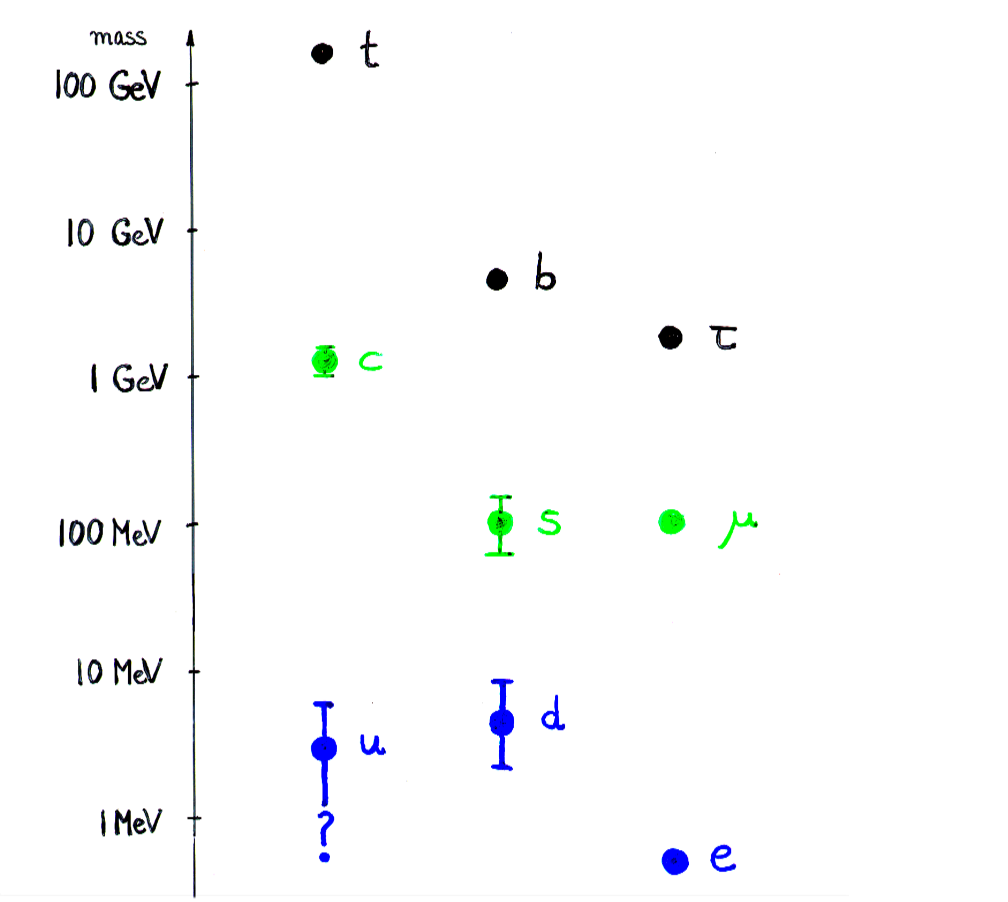
SM = S(R+Q)M
triumph of Quantum Mechanics + Special Relativity

particles = representations of Poincaré group, labelled by (according to Coleman-Mandula)

(spin, mass) ⊗ internal quantum numbers

- spin: quantised
- mass: continuous
- internal quantum numbers: at least SU(3)xSU(2)xU(1)

A priori in agreement with data



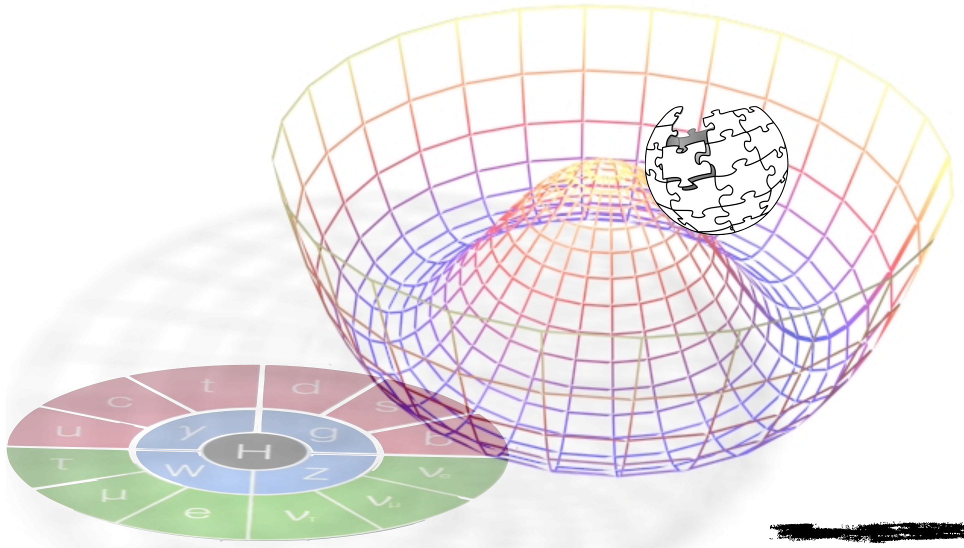
(picture: courtesy of A. Weiler)

BUT
spectrum is incompatible with **chiral** nature of gauge symmetries
chiral fermion ⇏ m=0 only
gauge boson ⇏ m=0 only

In **molecular biology**, chirality seems an **emergent** property.
Are the chiral nature of the **weak** interactions **emergent** too?

Solution: Spontaneous Symmetry Breaking

Short-distance interactions ≠ Long-distance interactions
The masses are emergent due to a non-trivial structure of the vacuum

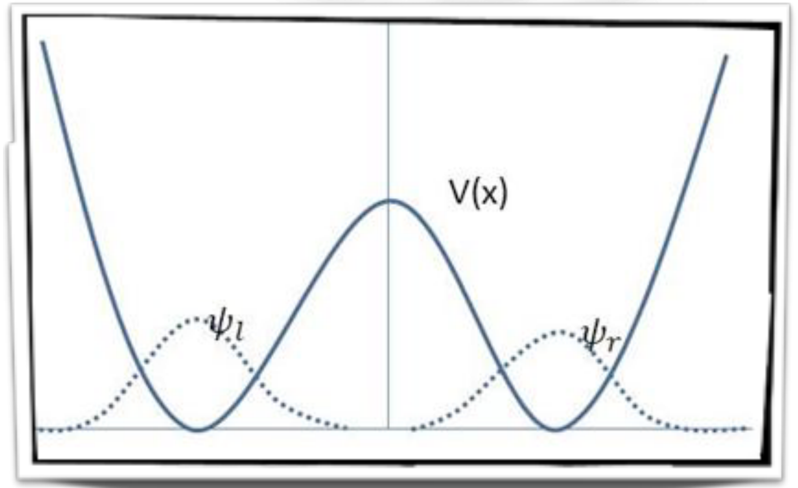


vacuum = a space entirely devoid of matter
Oxford English

vacuum = a space filled with Higgs substance
Physics English

QM vs QFT

(courtesy of J. Lykken@Aspen2014)



Ground state of QM double well potential
is a superposition of two states localised on one minimum,
and this superposition preserves the Z_2 symmetry of the potential

In QFT, it is more difficult to transition between degenerate vacua
and spontaneous symmetry breaking can occur
(or more correctly, the symmetry is non-linearly realised in Hilbert space)

The vacuum of the SM breaks SU(2)xU(1) to $U(1)_{em}$ via the dynamics of an elementary scalar field
The Higgs Boson

The Higgs Boson is Special

The Higgs discovery in 2012 has been an important milestone for HEP.
And many of us are still excited about it.
And others, especially in other fields of science, should be excited too.

Higgs = **new forces** of different nature than the gauge interactions known so far

- No underlying local symmetry
- No quantised charges
- Deeply connected to the space-time vacuum structure

The knowledge of the values of the **Higgs couplings**
is essential to our understanding of the deep structure of matter

- Up- and Down-quark Yukawa's decide if $m_{proton} < m_{neutron}$ i.e. stability of nuclei
- Electron Yukawa controls the size of the atoms
- Top quark Yukawa decides (in part) of the stability of the EW vacuum
- The Higgs self-coupling controls the (thermo)dynamics of the EW phase transition ($t \sim 10^{-10}$s)

(and therefore might be responsible of the dominance of matter over antimatter in the Universe)

Which Machine(s) to Measure the Higgs?

Hadrons

- o large mass reach ⇛ exploration?
- ▹ S/B ~ 10^{-10} (w/o trigger)
- o S/B ~ 0.1 (w/ trigger)
- o requires multiple detectors
  (w/ optimized design)
- ▹ only pdf access to $\sqrt{\hat{s}}$
- o ⇛ couplings to quarks and gluons

Leptons

- o S/B ~ 1 ⇛ measurement?
- o polarized beams
  (handle to chose the dominant process)
- o limited (direct) mass reach
- o identifiable final states
- o ⇛ EW couplings

Circular

- o higher luminosity
- o several interaction points
- o precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)
- ▹ $\sqrt{s}$ limited by synchroton radiation

Linear

- o easier to upgrade in energy
- o easier to polarize beams
- o "greener": less power consumption*
- ▹ large beamsthralung
- ▹ one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

Which Machine(s) to Measure the Higgs?

Hadrons

- large mass reach ⇒ exploration?

Leptons

- S/B ~ 1 ⇒ measurement?

Exploration machines are at the heart of HEP

Current consensus towards European Strategy Update:

the best way to go to energy frontier is to start with **e^+e^- Higgs factory**

Linear or Circular?

- Can be extended in energy
- Polarised beams

- Higher luminosity
- Z-pole run

Three relevant questions to address to help taking a decision:

1) Impact of Z pole measurements?

2) Benefit of beam polarisation?

3) Is low energy a limitation?

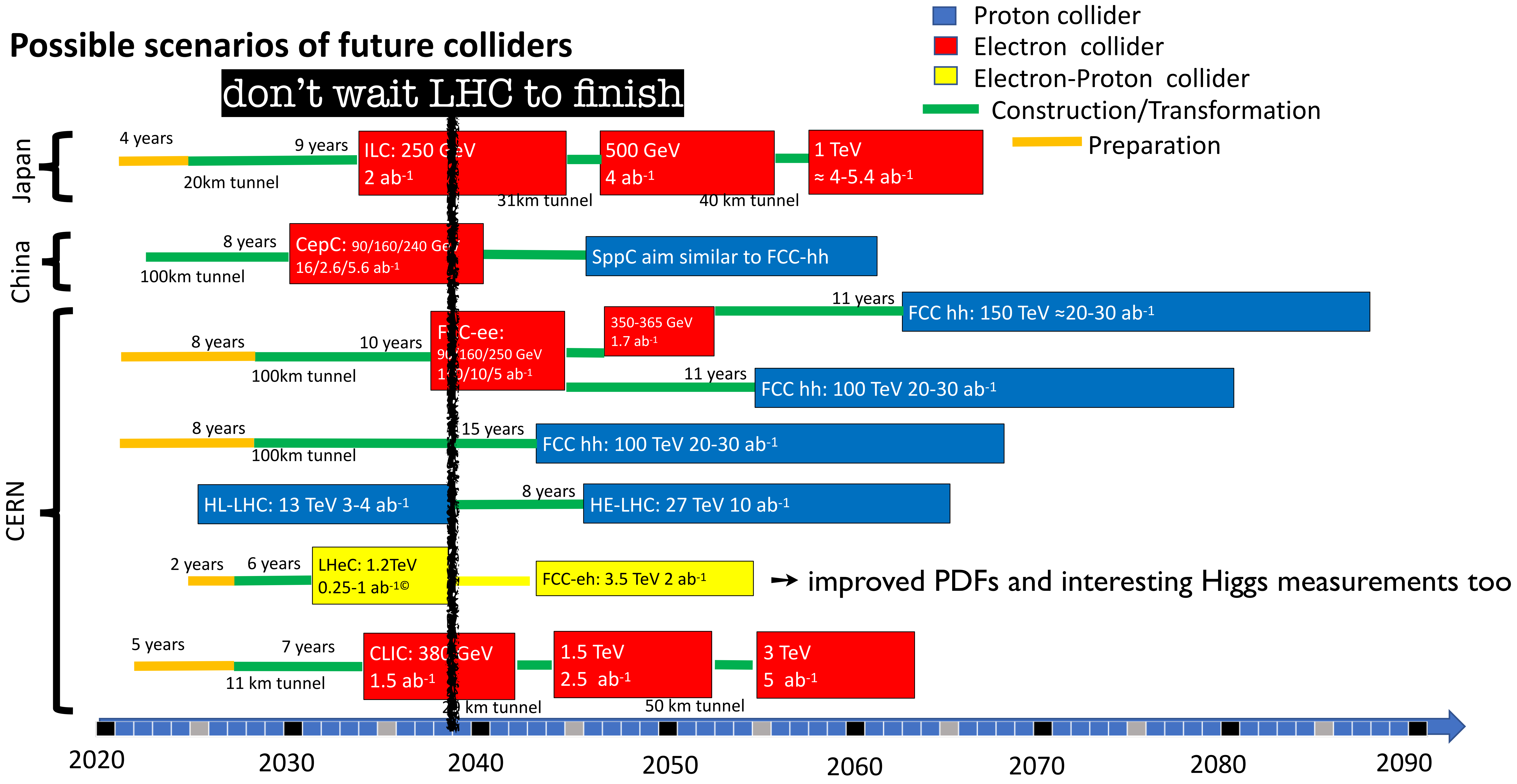
- precise E-b…
(O(0.1MeV) via…
- √s limited …

…nsumption*

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

Future of HEP: Flagship Projects

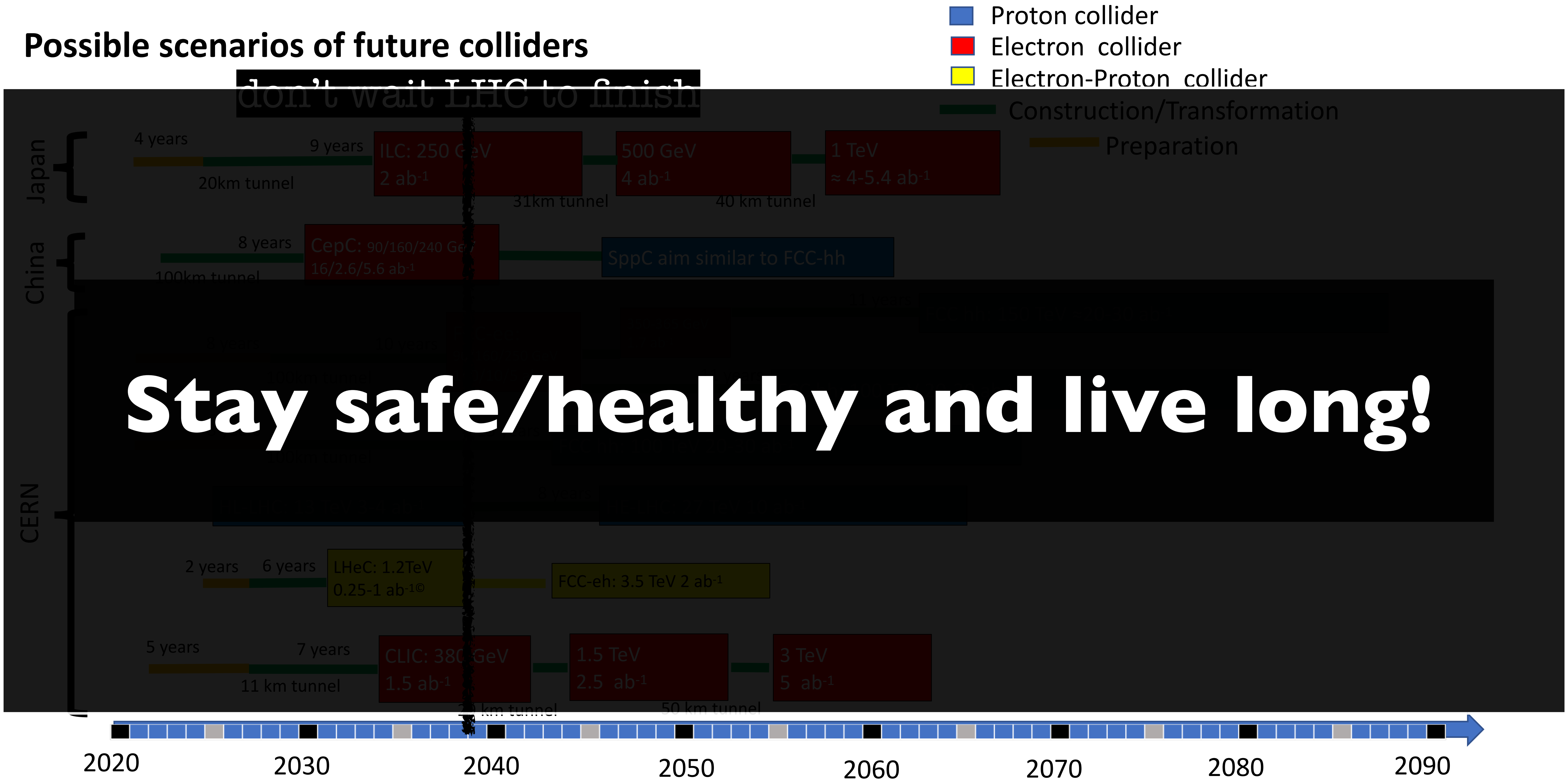
Possible scenarios of future colliders



Ursula Baesler, Granada 13.05.2019

Future of HEP: Flagship Projects

Possible scenarios of future colliders



Stay safe/healthy and live long!

Ursula Baesler, Granada 13.05.2019

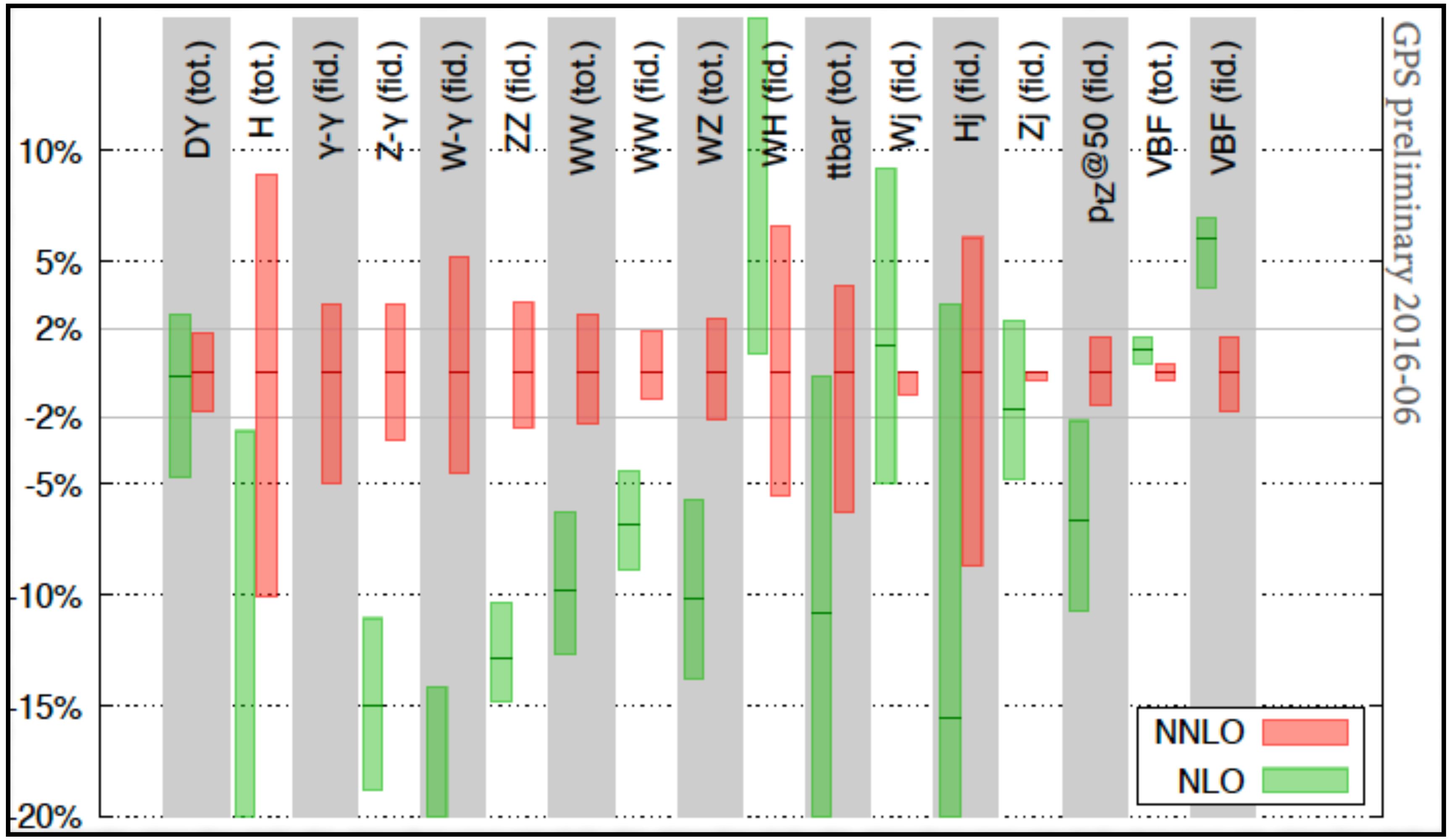
The SM Challenges

Early LHC days: fast progress followed from increased statistics

Statistics will become less and less important ↔ Systematics will become dominant

— Therefore progress requires —

- Better control of parametric uncertainties, e.g. PDFs, α_s, m_t, m_H
- Higher order theoretical computations, e.g. N…NLO
- Understand correlations among different bins in diff. distributions

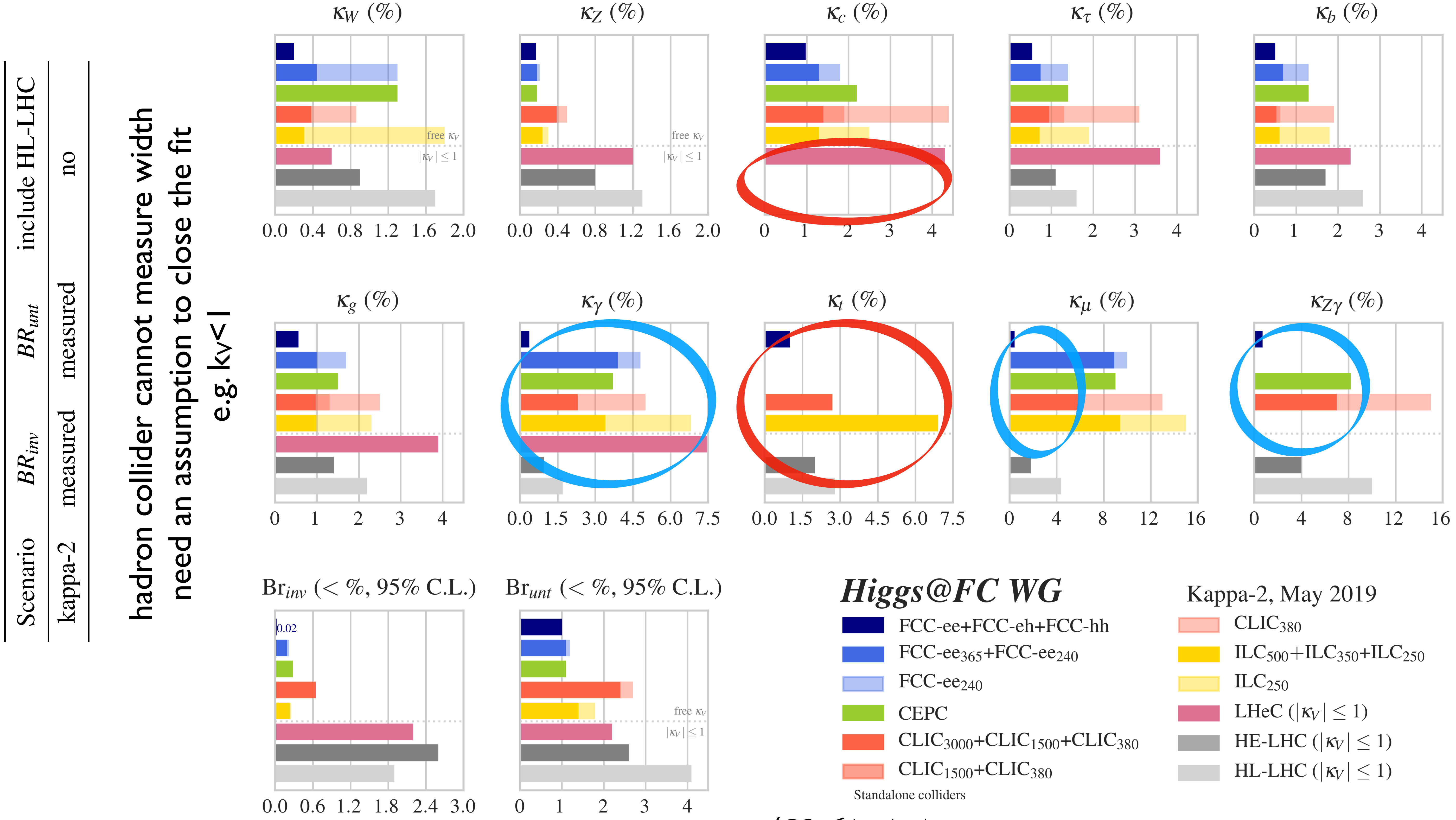


NNLO needed
to reach O(1%) precision

Don't think future HEP is only EXP-business. Theorists have to work harder too!

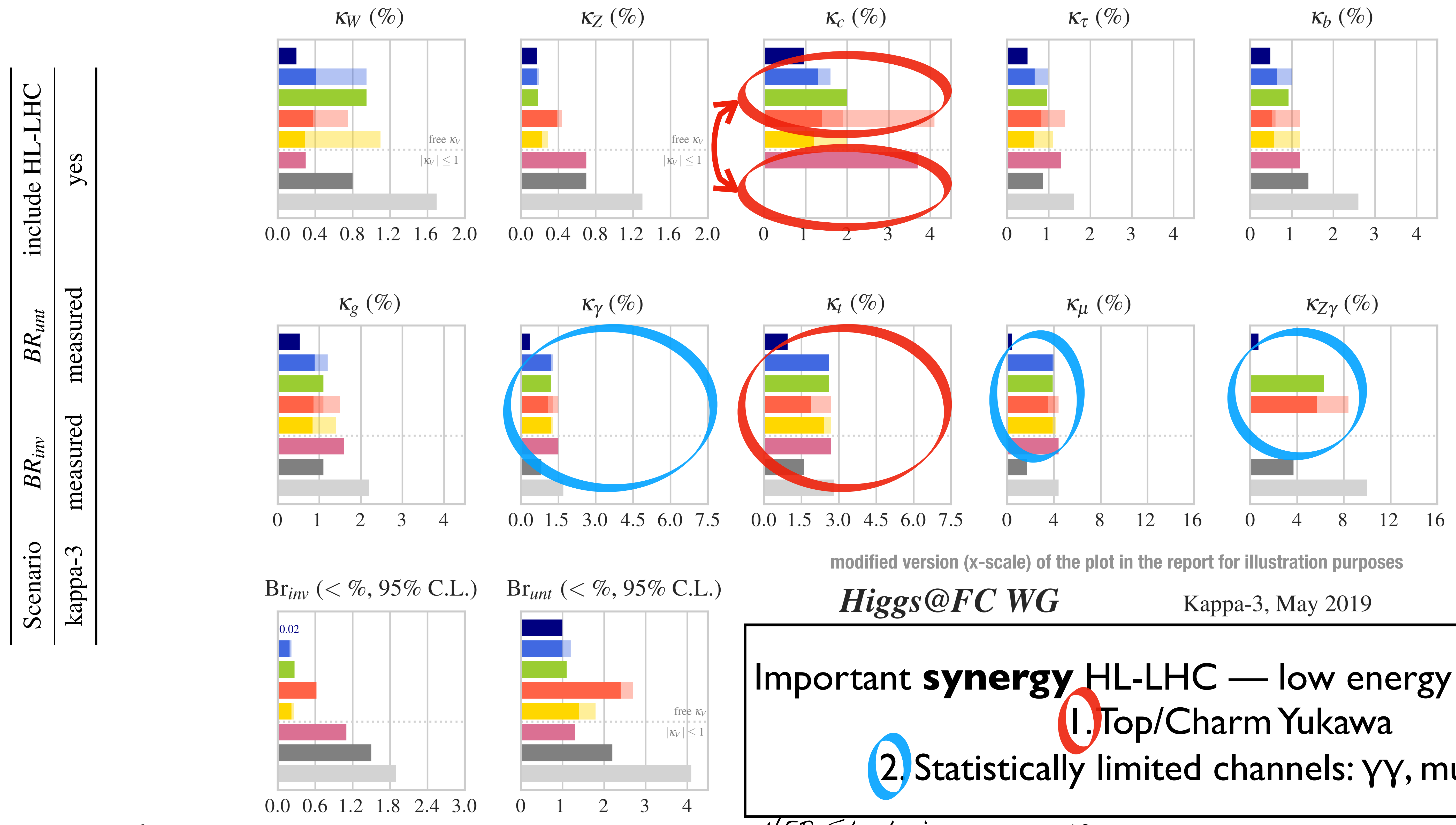
Higgs Coupling Fit (Future Collider Standalone)

ECFA Higgs study group '19



Higgs Coupling Fit (HL-LHC+Future Collider)

ECFA Higgs study group '19



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

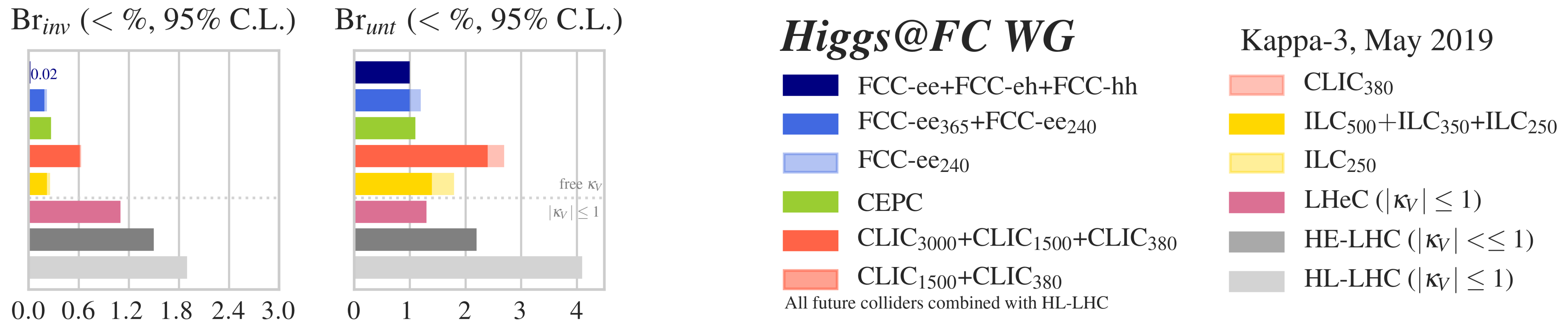
Higgs@FC WG Kappa-3, May 2019

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

1. Top/Charm Yukawa

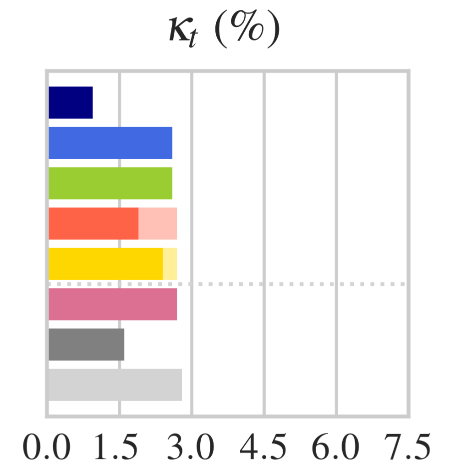
2. Statistically limited channels: γγ, mumu, Zγ

Synergy ee-hh

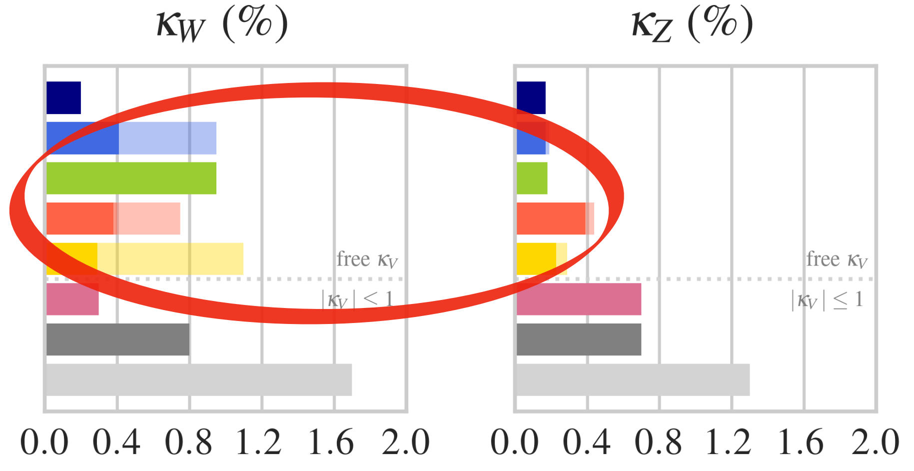


FCC-hh without ee could still bound BR_{inv}

but it could say nothing about BR_{unt}



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

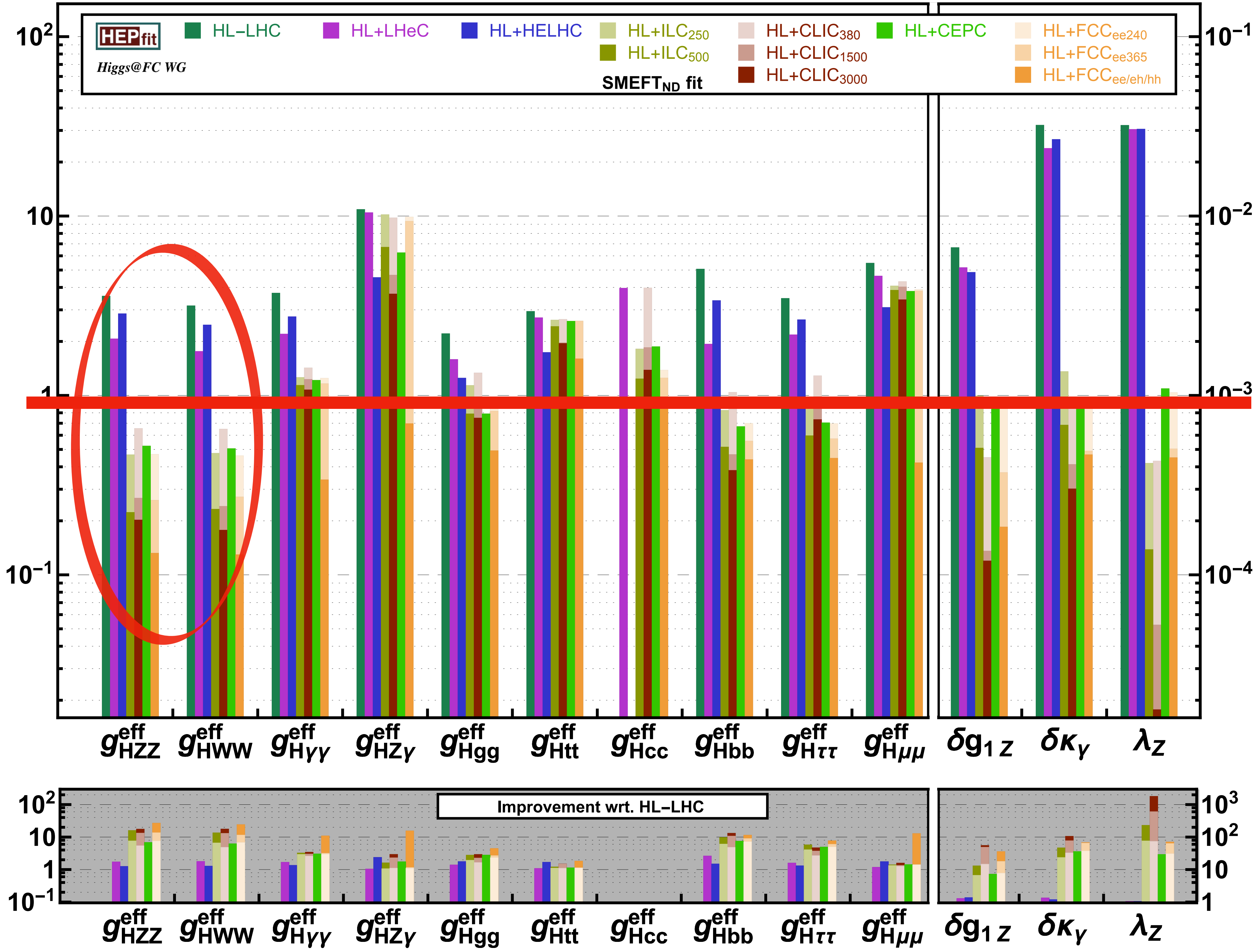


k_W improves significantly with energy increase

But it also benefits a lot from a synergy with EW measurements.
This cannot be captured by the kappa's and requires a full EFT analysis

Global EFT fit

ECFA Higgs study group '19



hZZ & HWW
are now
very much the same thanks
custodial symmetry emerging
from EW measurements

1%
magic
threshold

There is life
beyond HL-LHC

Going Beyond Inclusive Measurements

European Strategy Studies focused on inclusive measurements
They don't do justice to richness of kinematical distributions accessible
at either leptonic machines (thanks to their clean environment) or high-energy hadronic machines

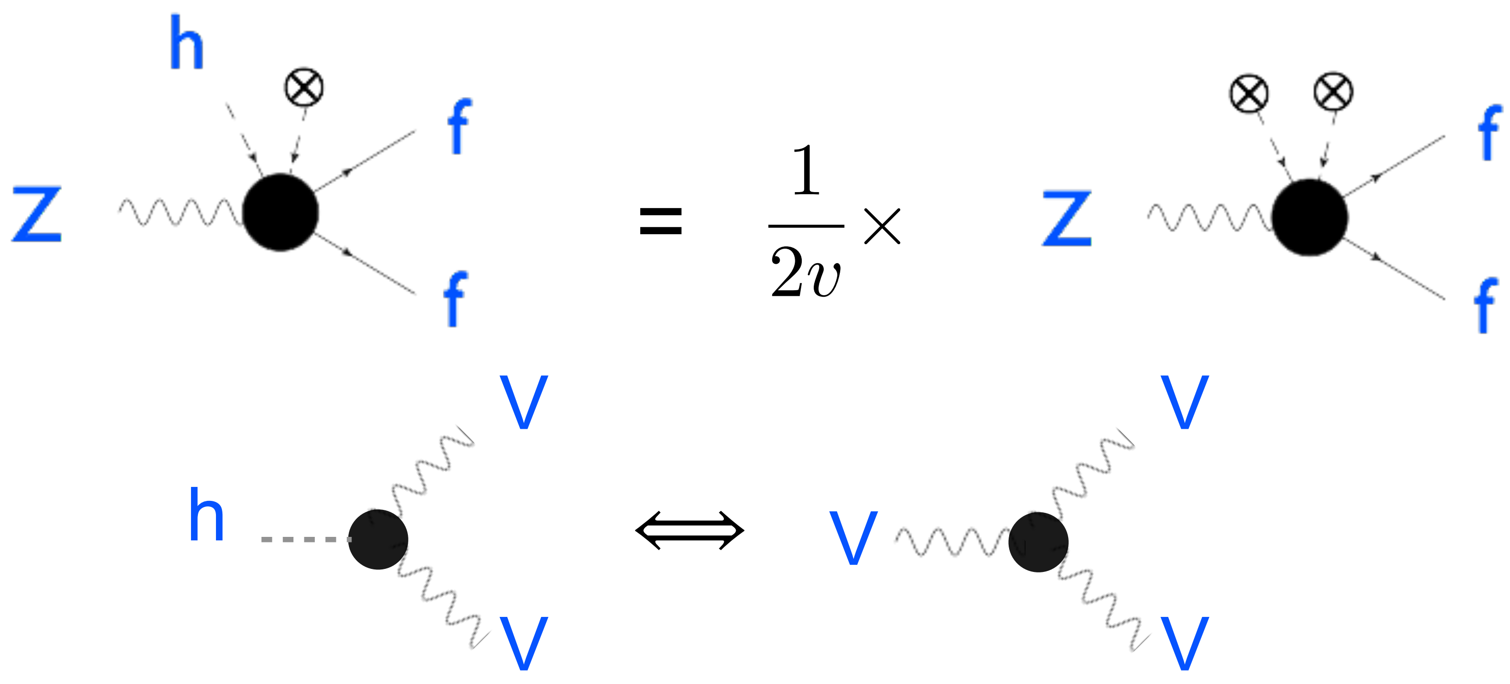
- Higgs couplings at high-energy:
  1. off-shell $gg \to h^* \to ZZ \to 4l$
  2. boosted Higgs: Higgs + high-p_T jet

- High pT distribution: "energy helps accuracy"
  1. BSM effects often grow with energy
  2. study of poorly populated phase space regions with smaller systematics

Higgs & EW interplay

Gupta, Pomarol, Riva '14

Assuming h is part of a SU(2) doublet



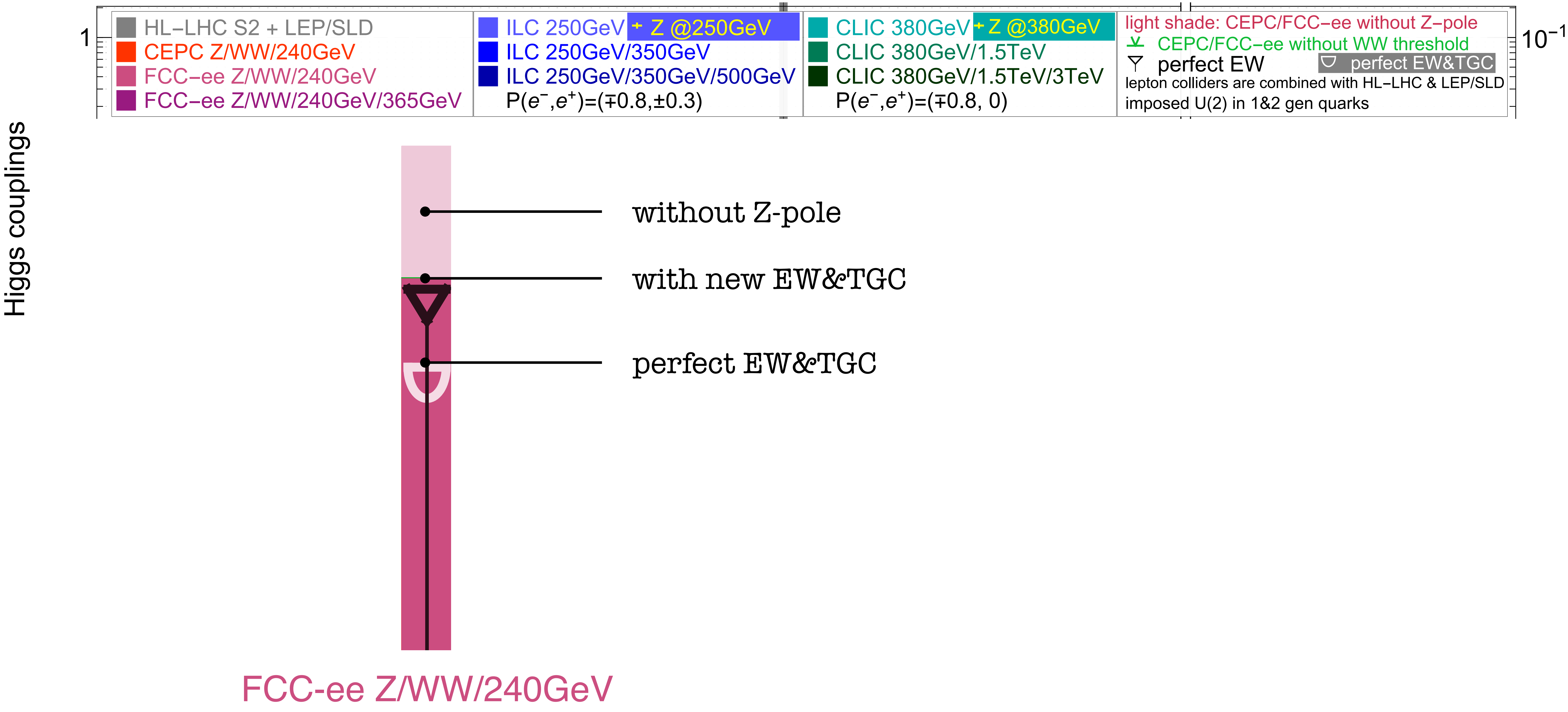
At LHC: EW/VV precision strong enough not to interfere with Higgs measurements
8 Higgs primaries (SM deformations that are not constrained, at LO, outside Higgs physics)

Not true at future colliders ⇒ need a more global strategy and a full EFT fit of Higgs+EW data

Impact of Z-pole measurements

J. De Blas et al. 1907.04311

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



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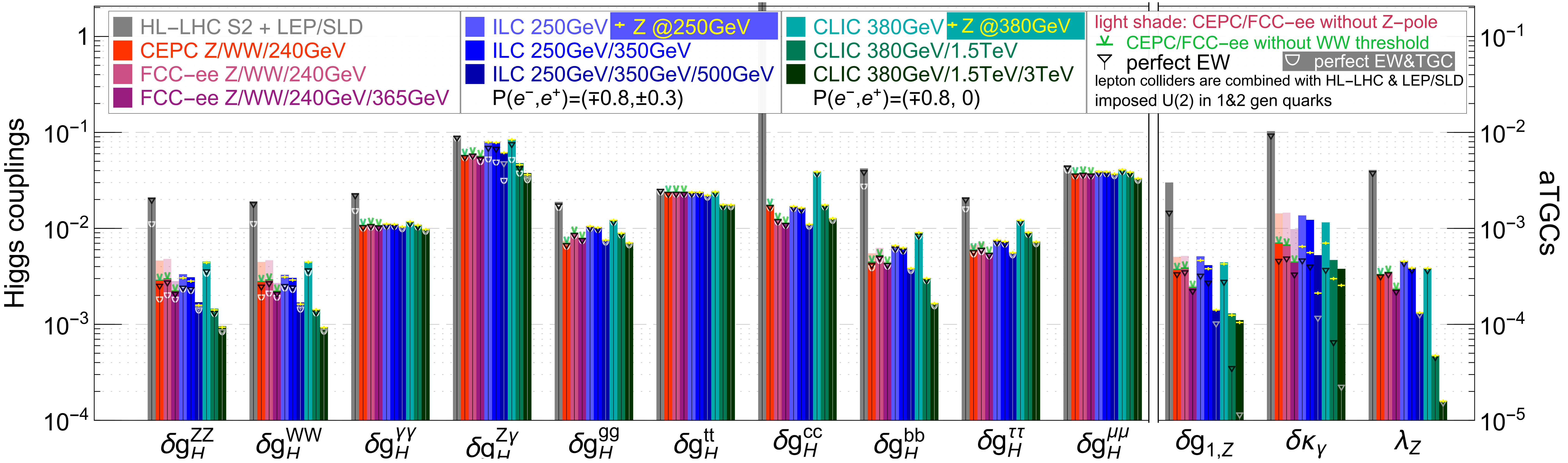

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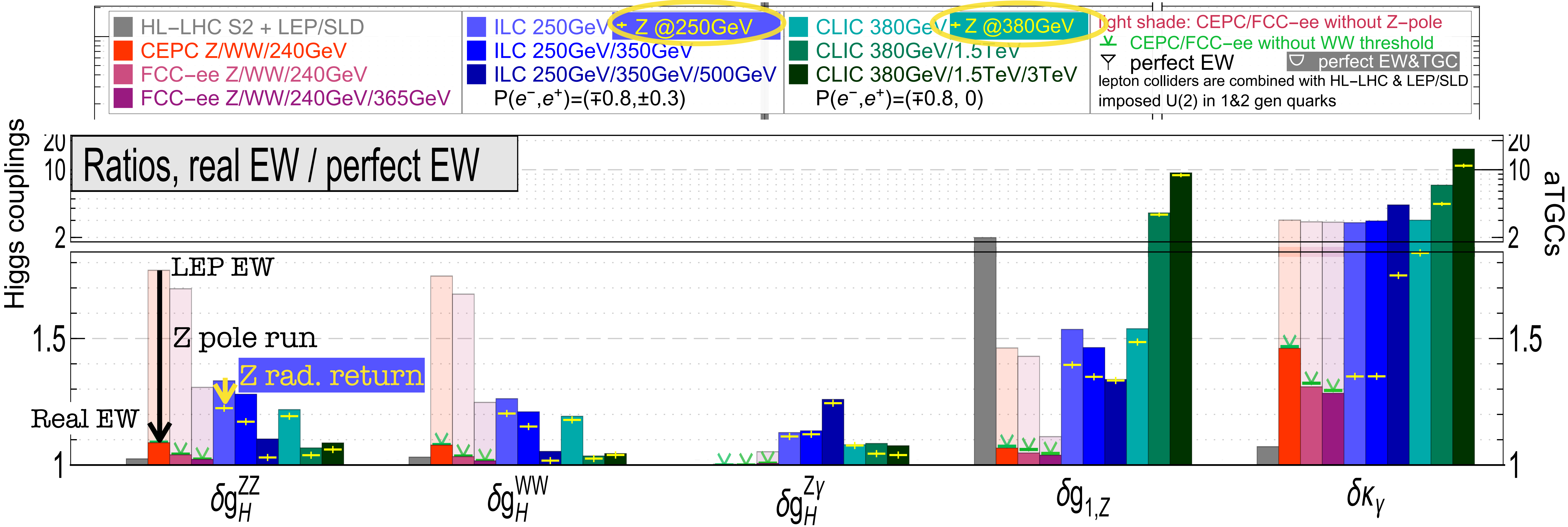
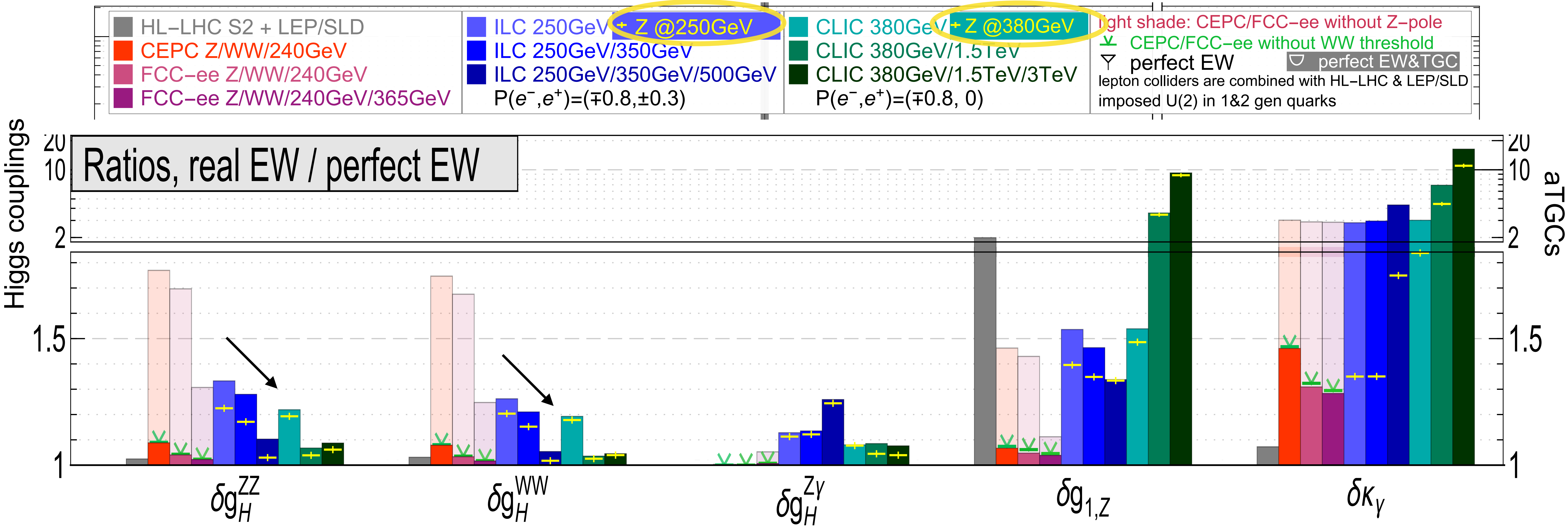


- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics (<10%).
- LEP EW measurements are a limiting factor (~30%) to Higgs precision at ILC, especially for the first runs But EW measurements at high energy (via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

Impact of Z-pole measurements

J. De Blas et al. 1907.04311

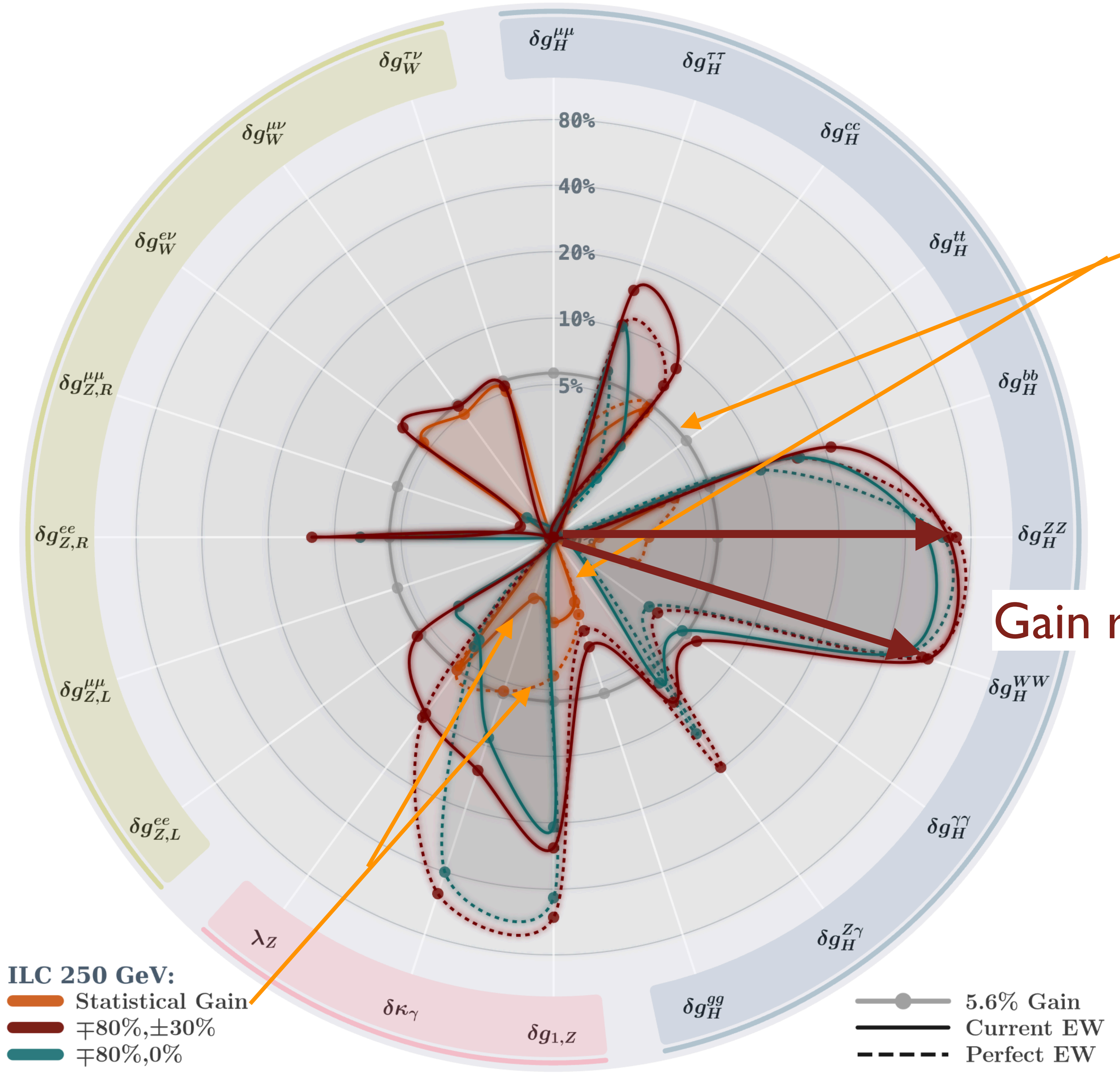
Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements



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

Impact of Beam Polarisation (@250GeV)

J. De Blas et al. 1907.04311



increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

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

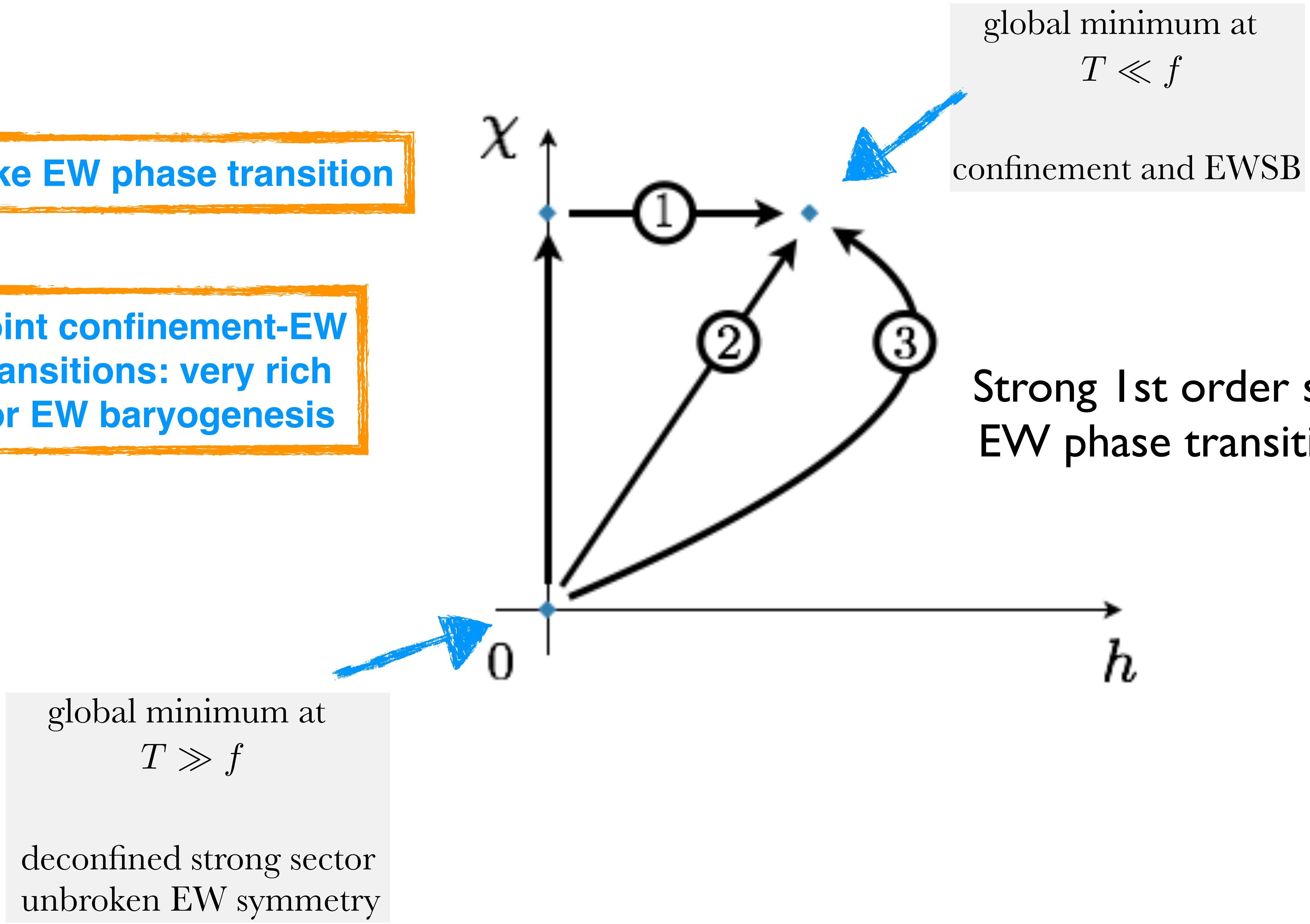
Polarisation benefit diminishes when other runs at higher energies are added and basically left only with statistical gain

How Did We End Up in the EW Vacuum?

G. Servant @ ESU-Granada '19

(1) SM-like EW phase transition

(2)-(3) Joint confinement-EW phase transitions: very rich pheno for EW baryogenesis



Strong 1st order supercooled EW phase transition possible

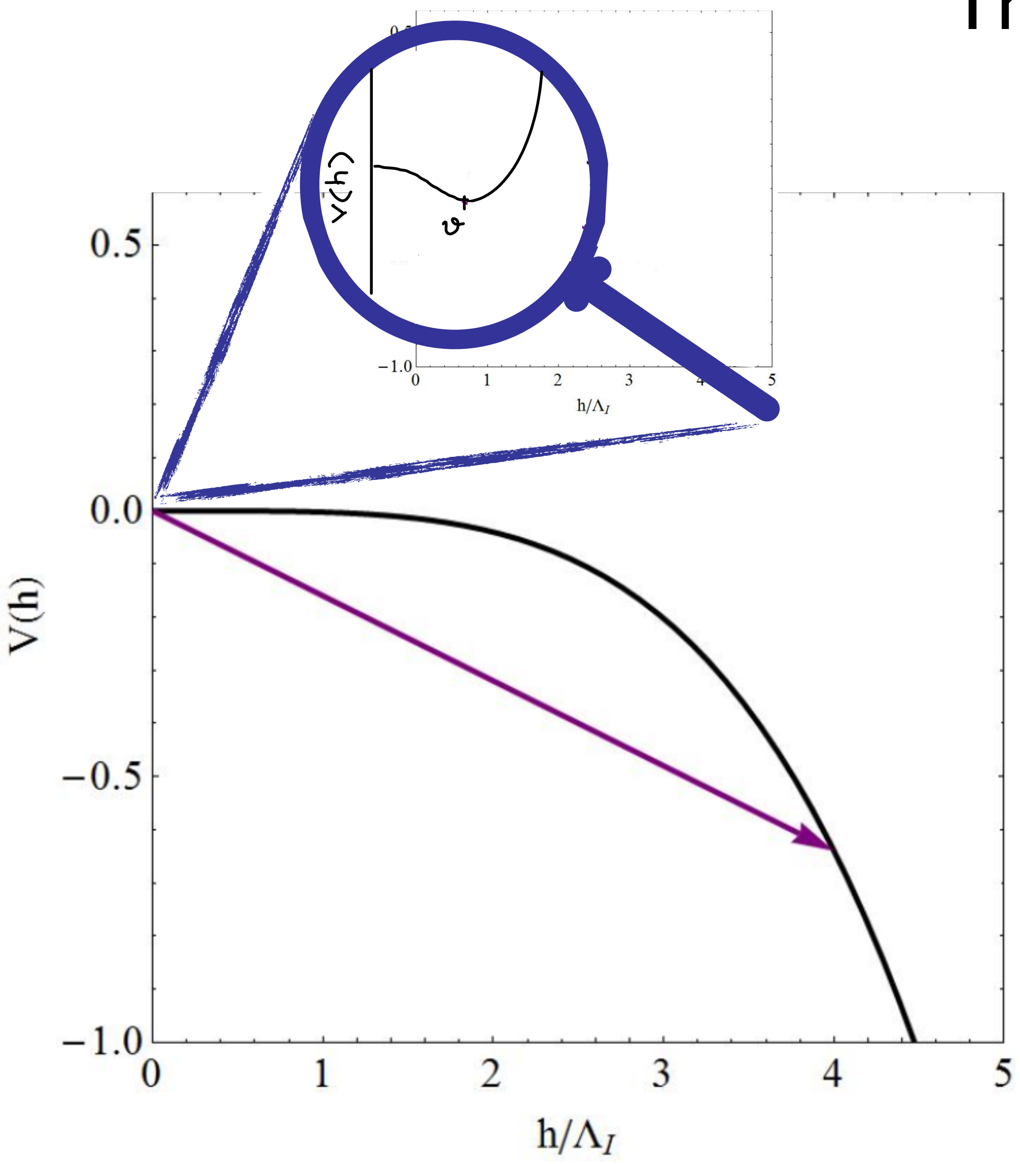
Structure of the Vacuum?

The EW vacuum breaks SU(2)xU(1) to $U(1)_{em}$: is this vacuum a local or a global minimum?

Within the SM, quantum corrections induce a deeper minimum of the Higgs potential

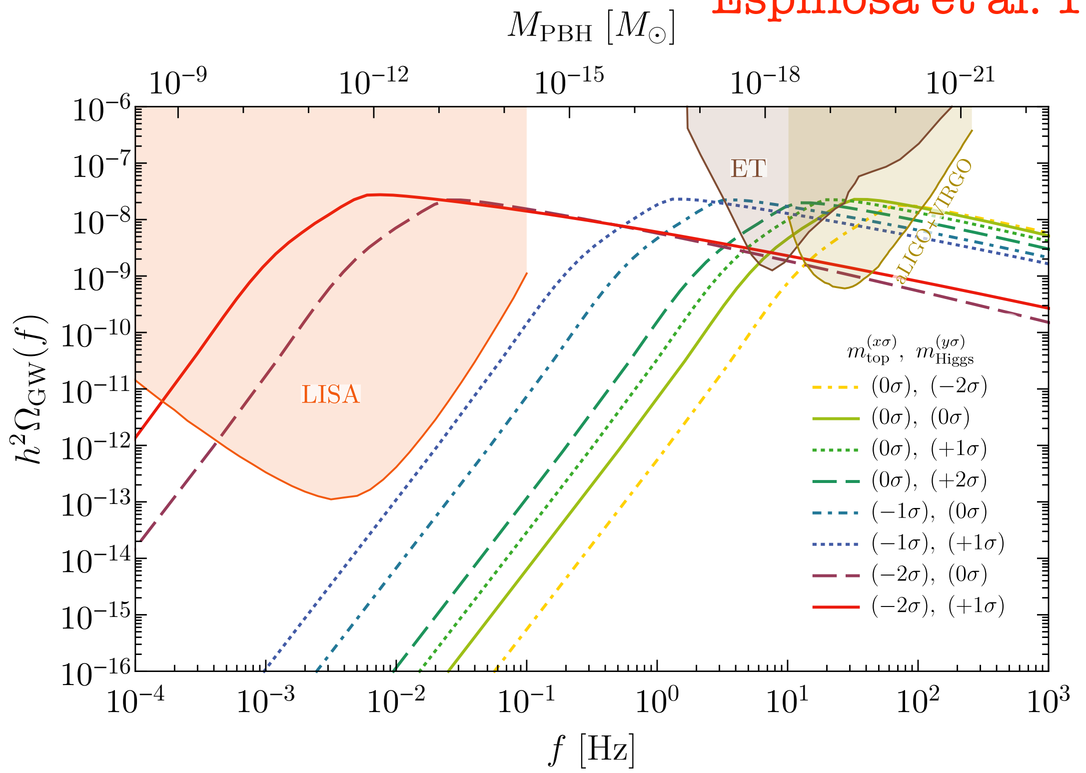
The transition rate is super tiny: $\tau_{EW} \approx 10^{161}$ y

Andreassen et al. 1707.08124
see also Chigusa et al 1707.09301



But such a vacuum structure
could have interesting **cosmological implications**:
Higgs inflation, GW and PBH sourced by Higgs fluctuations@inflation

Espinosa et al. 1710.11196 and 1804.07732



Hierarchy Problem

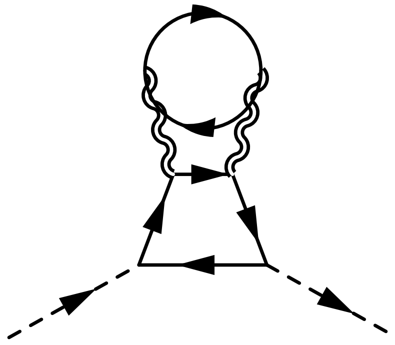
The potential of an elementary scalar field is highly sensitive to UV physics:
Is the EW vacuum compatible with new physics at higher energy (aka **hierarchy/naturalness** problem)?

M. Reece @ Pheno 2020 N. Arkani-Hamed @ Pheno 2020

Conspiracy/intelligent design

Arrange high-scale physics,
including quantum gravity,
to give small enough corrections
to Higgs potential

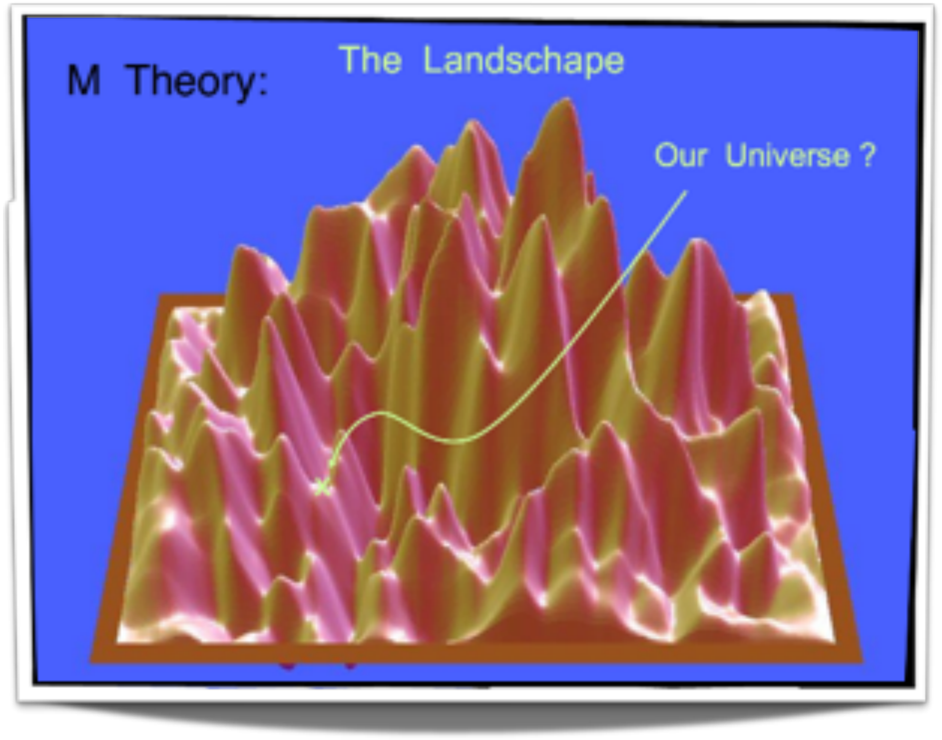
— Challenge —



$$\delta m_H^2 \sim \frac{6y_t^2}{(16\pi^2)^3}\frac{m_\Psi^6}{M_{Pl}^4}$$

Even new physics
only gravitationally coupled to SM
can generate large corrections
because off-shell couplings to gravitons

Anthropic selection in multiverse



Particles and fields are not
the building block of matter.
Strings and D-branes are.
Non-trivial fluxes generate multiverse

Dynamical screening

More conservative approach

Add new physics
to stabilise the EW vacuum

- New spacetime symmetry (supersymmetry)
- New forces/new particles (composite Higgs)
- New vacua

Structure of the Vacuum?

Dynamical screening of the UV corrections to Higgs potential

Single vacuum

New particles
with couplings related to SM ones by
symmetry cancel the large corrections

1. a symmetry (Susy, PQ)
2. a form factor (composite Higgs)

Low scale of quantum gravity

1. Large extra dimensions (ADD)
2. Gravitational sequestering (RS)

Combination of the above

TeV scale new physics

Multiple vacua

many metastable vacua with a vast range of values for m_H
Dynamical selection of $m_H \ll \Lambda$

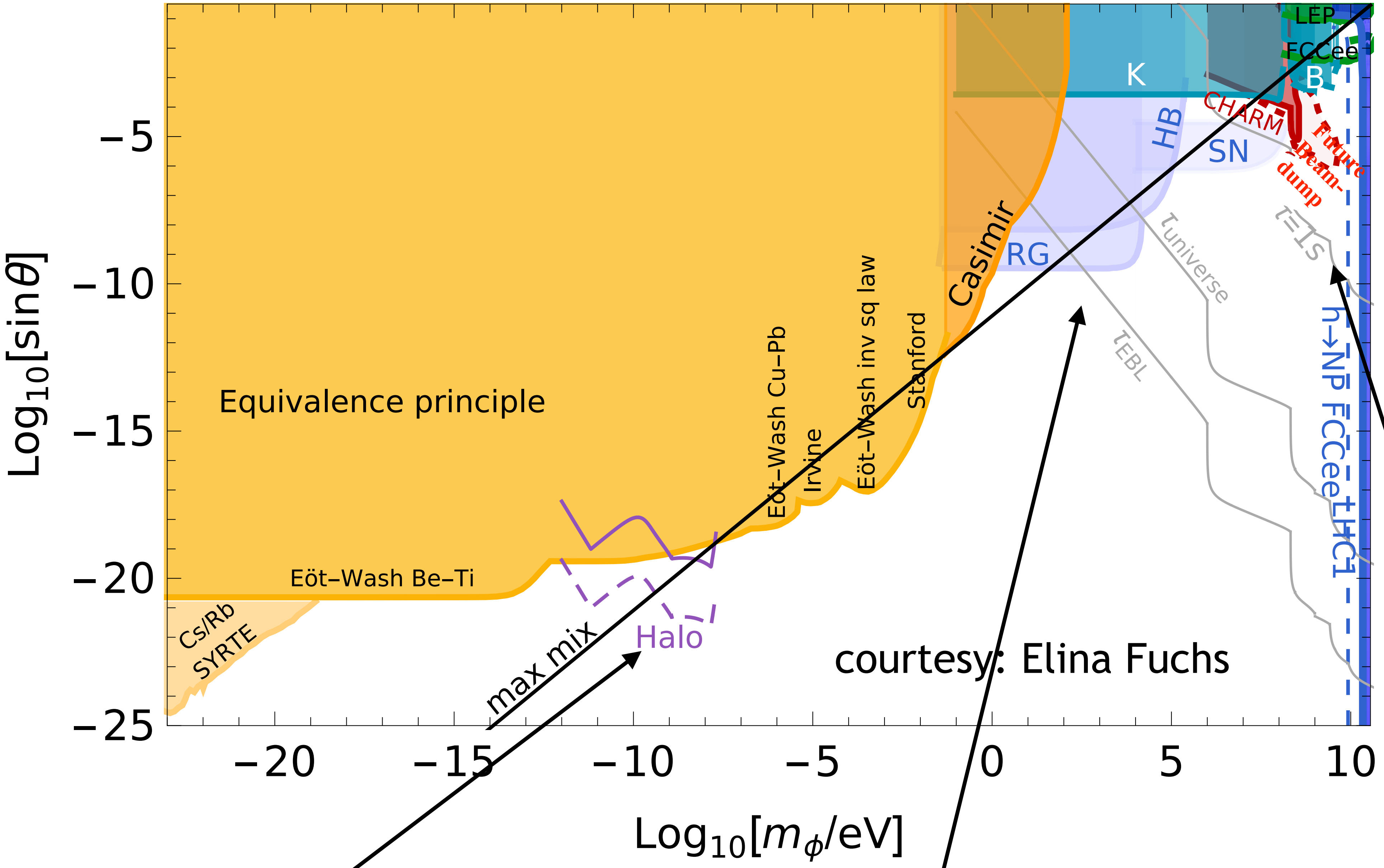
1. The patches with different Higgs VEVs expand differently: either they shrink to nothing and they expand too fast and no particle reheating possible. The patch with the right EW vacuum is selected.
2. Relaxion and cosmological scanning with non-trivial back reaction that stops the exploration of the vacuum manifold at the right place

Light new physics expected

The *log* Crisis of the Higgs

G. Perez et al '17-'19

Overview plot: the relaxion 30-decade-open parameter space



Rich opportunities at different scales

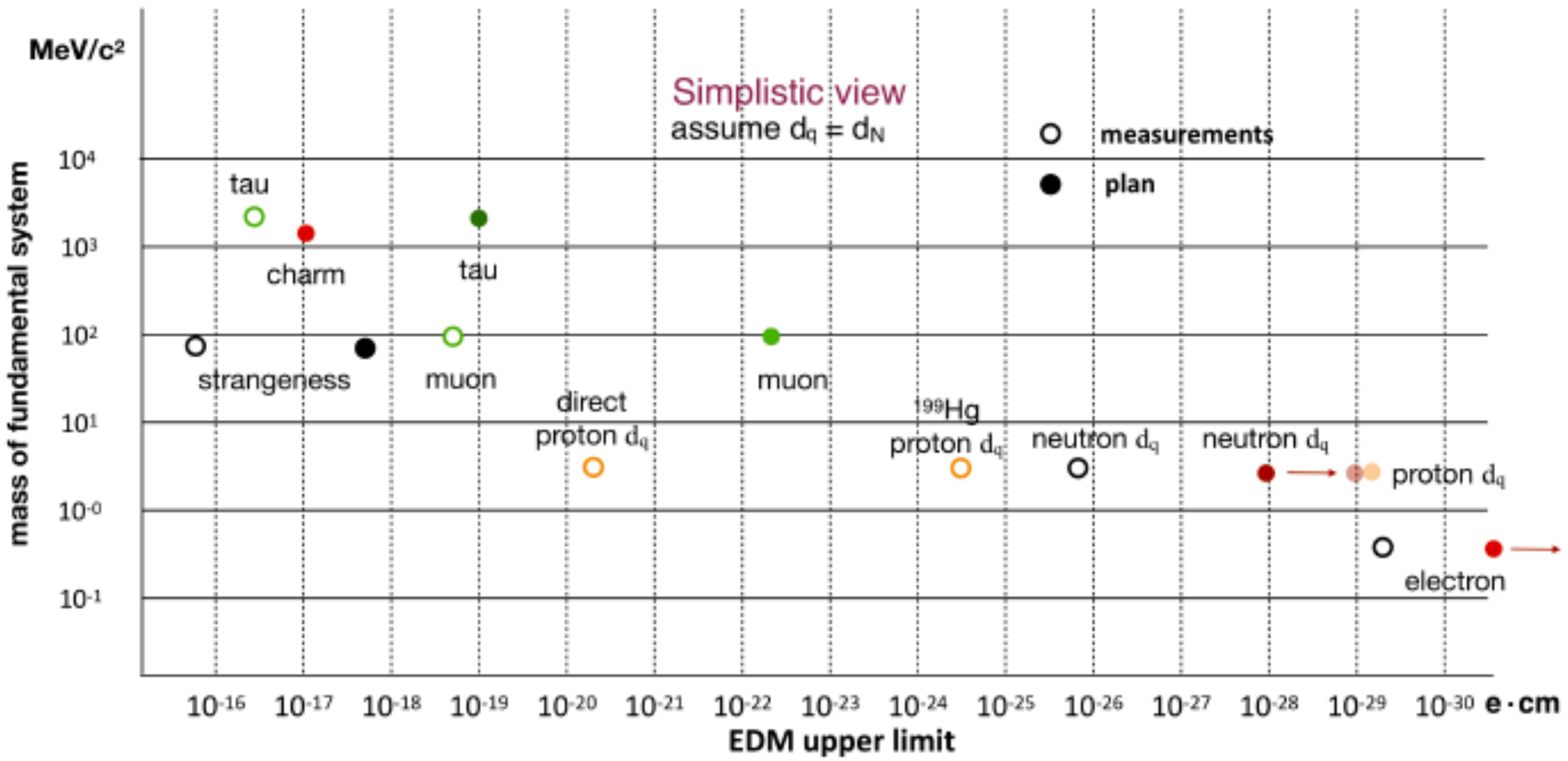
"fun signatures"

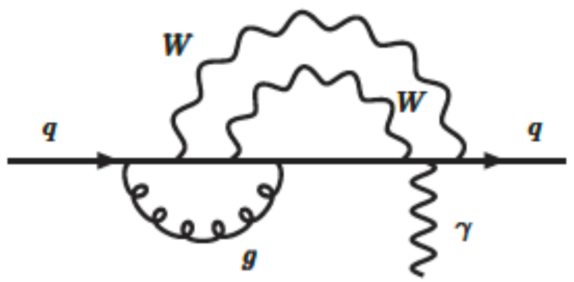
Z. Liu @ Pheno 2020

Precision frontier	Astro frontier	Collider frontier
Higgs vev oscillates	DM halo, super radiance	Invisible Higgs decays

Precision Probes BSM

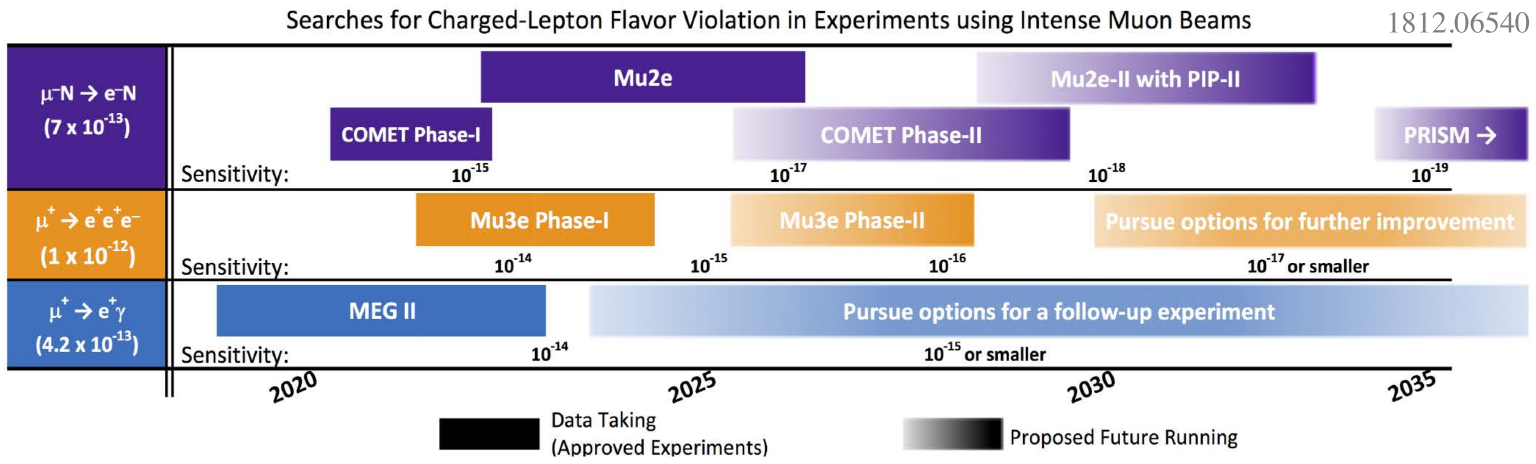
EDM

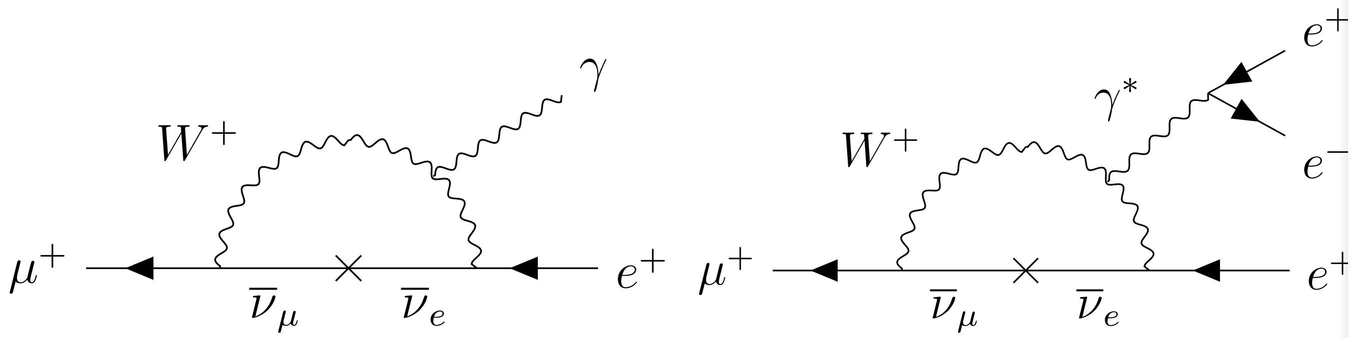




M. Reece @ Pheno 2020

LFV

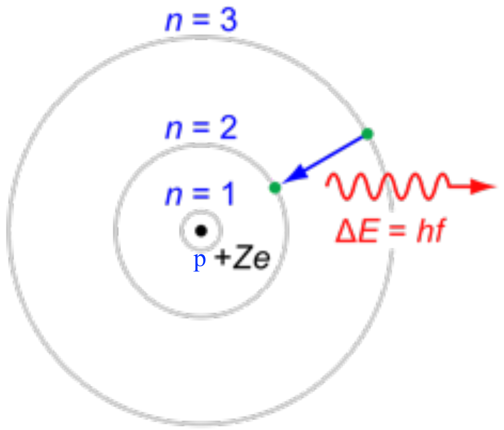


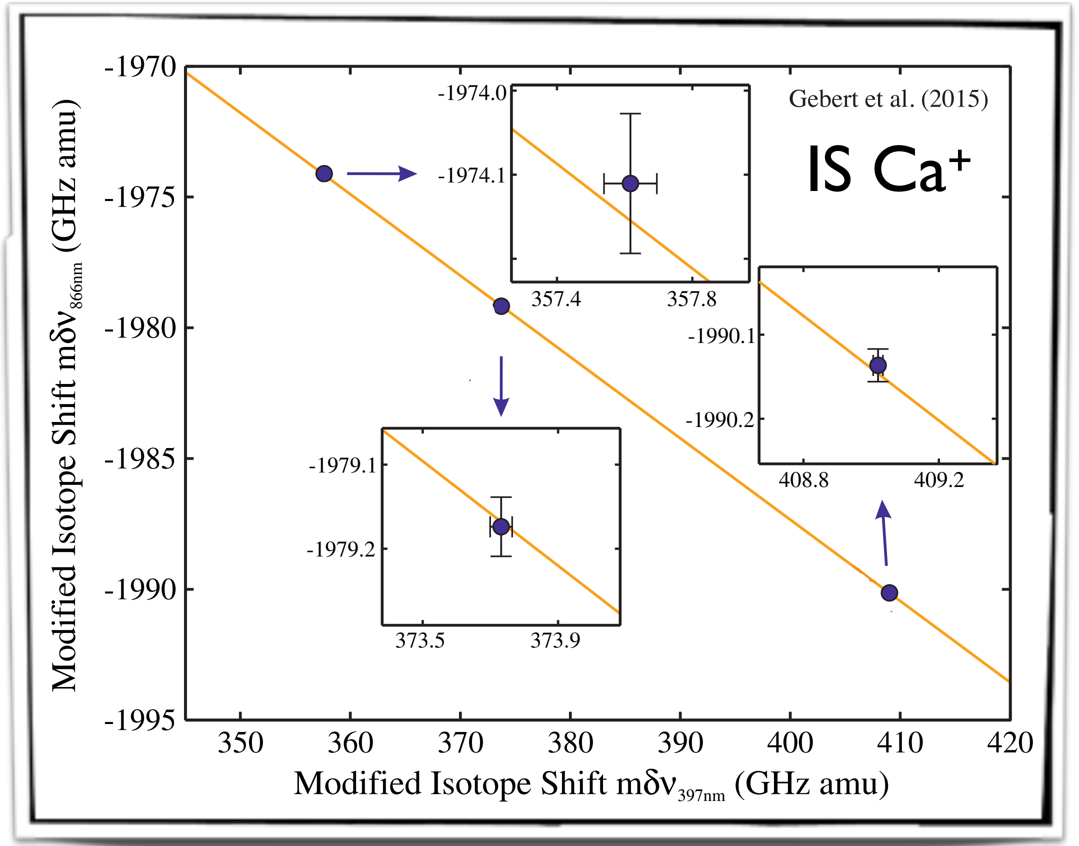


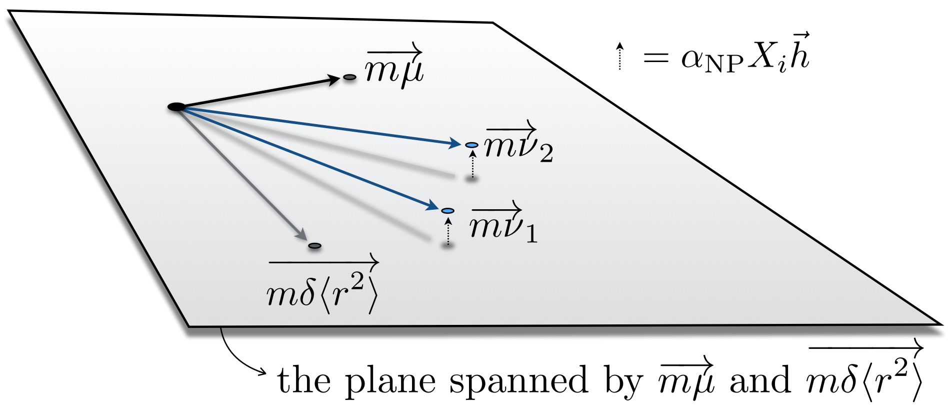
(a) μ → eγ via neutrino mixing. (b) μ → eee via neutrino mixing.

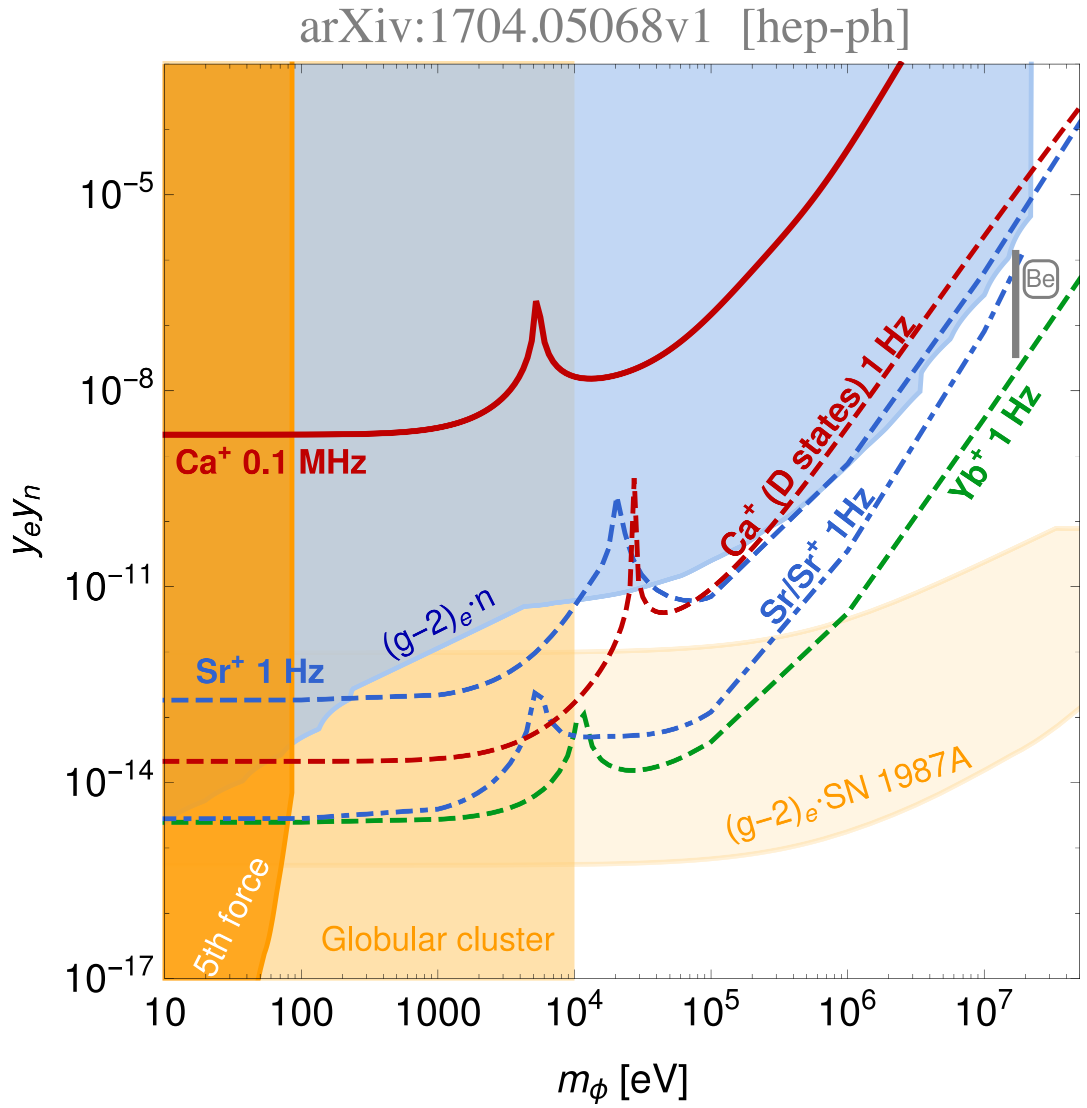
HEP Meets AMO

O(10^{-18}) sensitivity in atomic clock measurements can be used to detect new (long range) forces









can only probe long-range force

(no bound on e- Yukawa, unfortunately)

Spectacular experimental progress very recently

2004.11383

Yb+ King plot (300 Hz)

2005.00529

Ca+ King plot (20 Hz)

Conclusions

The Higgs discovery revealed a non-trivial and rich **vacuum**.
The true vacuum of our world might have an even richer structure than the SM one.
Exciting promises for great discoveries at different scales.

All projects of **Higgs factories** have a rich potential to outperform (HL-)LHC:
* Legacy measurements that will go into textbook
* Reach in BSM discoveries
* Refinements in our understanding of Nature (EW phase transition, naturalness…)

But there is also a complementary and vibrant **diversity** program worldwide

- Beam Dump Facility (SHiP, TauFV)
- eSPS (LDMX)
- CPEDM (Julich), ESSvSB (ESS), PERLE(Saclay), LFV(PSI), ...
- COMPASS/AMBER as QCD facility, MUonE, KLEVER, nuSTORM, MATHUSLA, FASER, CODEX-b, milliQan, LHCSpin, REDTOP, DIRAC, ...

BONUS PLOTS

High Energy Physics with a Higgs

The Higgs boson hasn't taught us much about **Beyond the Standard Model physics** yet.
Bottom-up **rigidity** of the SM: given the low-energy spectrum, all the Higgs couplings are uniquely fixed (G_F, m_W, m_Z, m_{quark}, m_{lepton})

New physics can alter this structure and induce a deformation of the Higgs couplings:

$$\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2\, v^2}{\Lambda_{\rm BSM}^2}$$

current (and future) LHC sensitivity
O(10-20)% ⇔ Λ_{BSM} > 500(g_*/g_{SM}) GeV

not doing better than direct searches unless in the case of strongly coupled new physics
(notable exceptions: New Physics breaks some structural features of the SM
e.g. flavour number violation as in $h\to\mu\tau$)

Higgs precision program is very much wanted to probe BSM physics

1% is also a magic number to probe naturalness of EW sector

EFT and Higgs couplings

EFT fits can be performed in different bases (difficult to compare results among different analyses) and seldom the meaning on the sensitivity on the various Wilson coefficients is transparent

— Practical approach —

perform the fit in any basis you like and project the results on **effective/pseudo couplings**

(need a special care for top coupling and self-coupling)

$$g_{HX}^{\text{eff }2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\text{SM}}}$$

Effective Higgs couplings

Similar definition as κ modifiers, but different interpretation, e.g.

$$\frac{\Gamma_{ZZ^*}}{\Gamma_{ZZ^*}^{\text{SM}}} \simeq 1 + 2\,\delta c_Z - 0.15\,c_{ZZ} + 0.41\,c_{Z\Box} + \ldots \text{ (EW } Vff,\ hVff)$$

Only these are described in κ-framework

Not enough to match EFT d.o.f : Add also aTGC

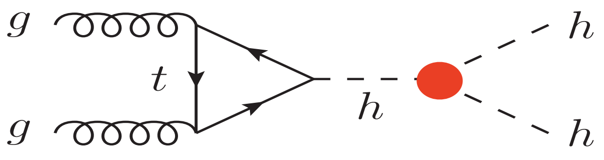
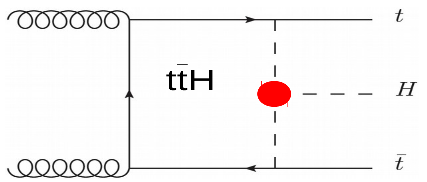
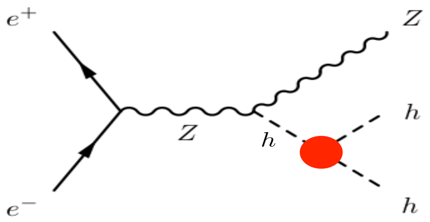
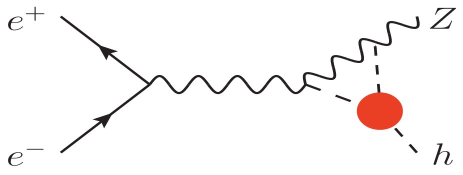
Similarly, for EW interactions, **project results into effective *Zff* couplings** defined from EWPO, e.g.

$$\Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w \cos^2\theta_w}\left(|g_L^e|^2 + |g_R^e|^2\right), \qquad A_e = \frac{|g_L^e|^2 - |g_R^e|^2}{|g_L^e|^2 + |g_R^e|^2}$$

Higgs Self-Coupling

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

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

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

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	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

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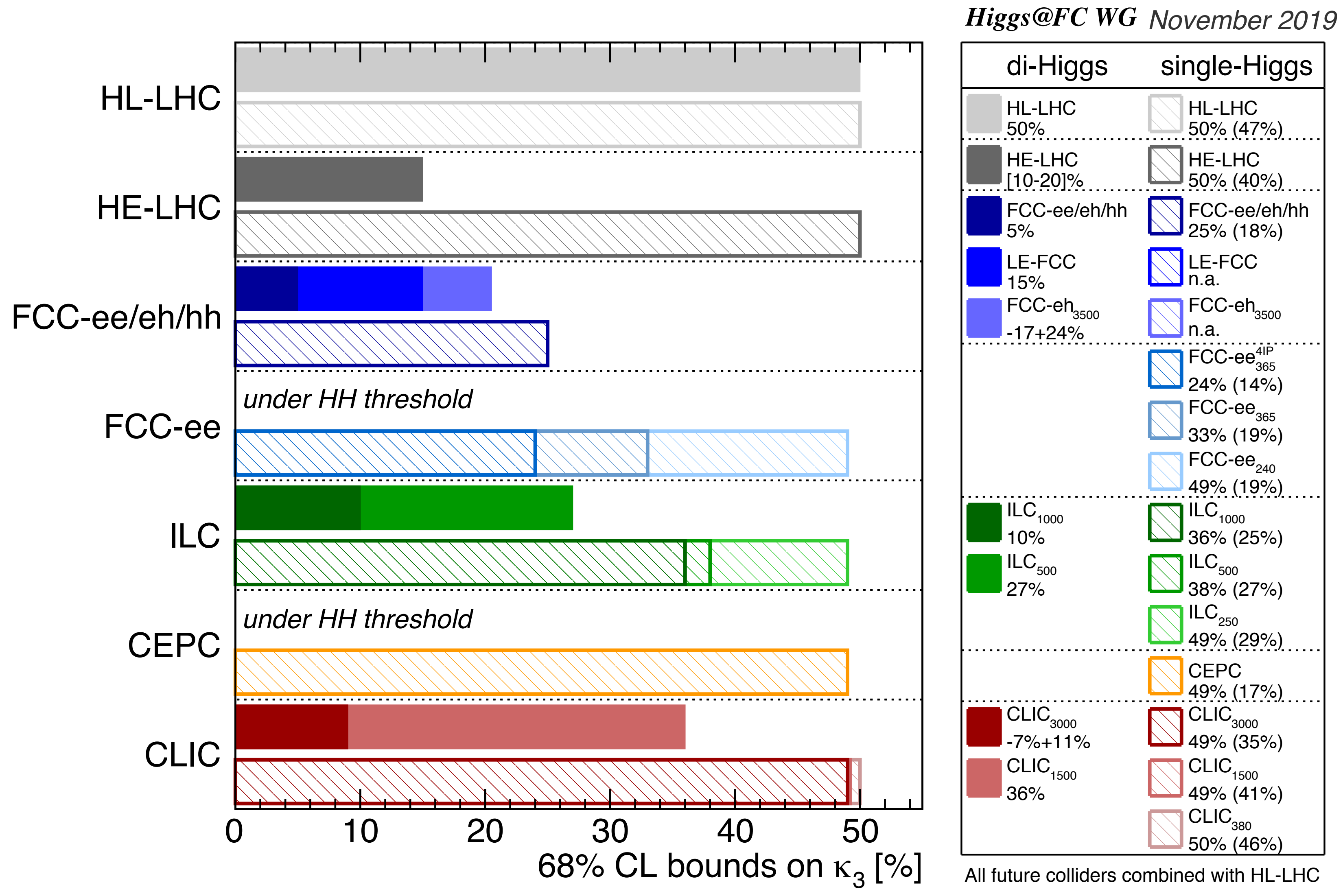

1

Don't need to reach HH threshold to have access to h3. 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

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	-

Theoretical Uncertainties

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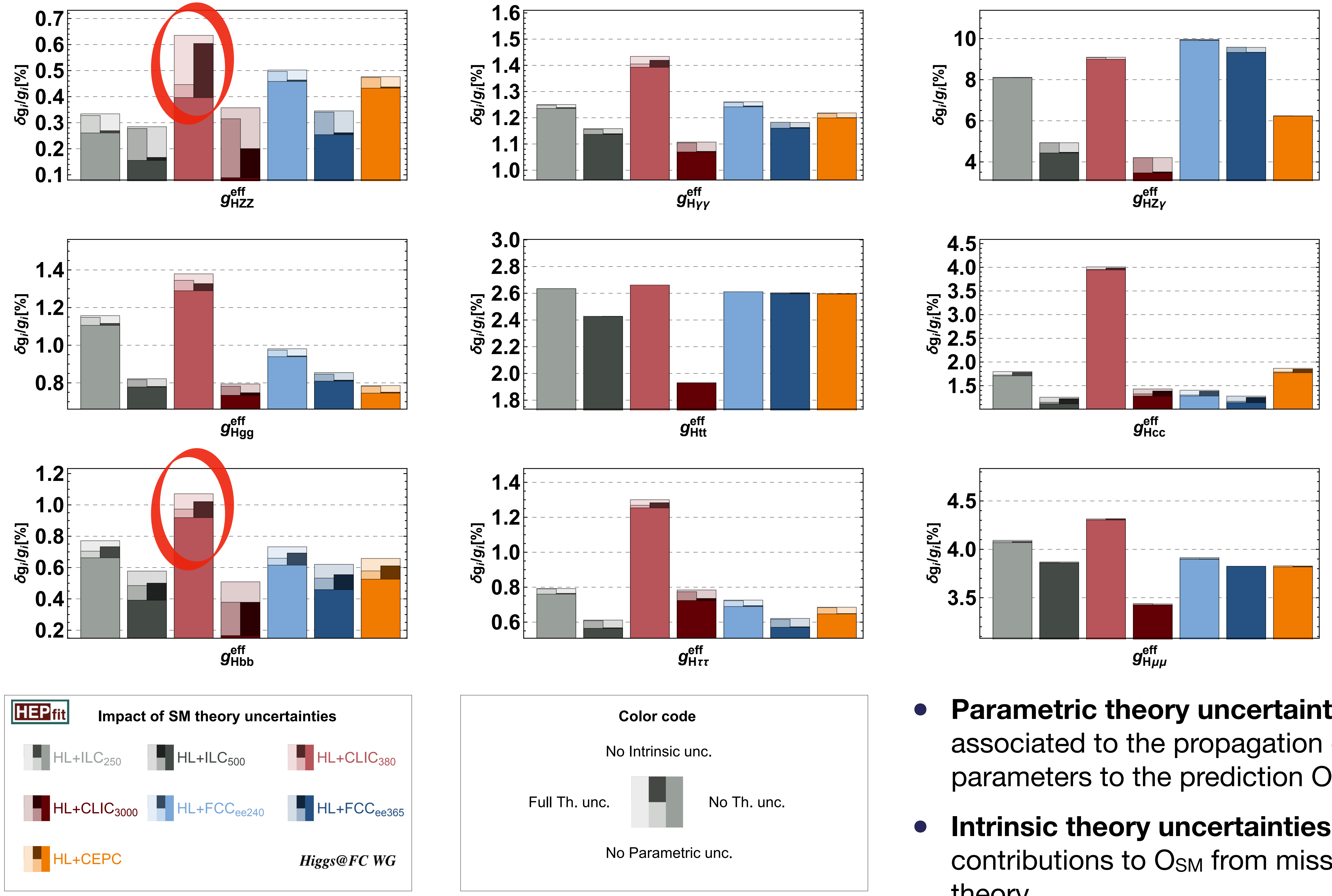

Theorists can do better in few channels (hZZ, hbb…)

- **Parametric theory uncertainties:** For an observable O, this is the error associated to the propagation of the experimental error of the SM input parameters to the prediction O_{SM} .
- **Intrinsic theory uncertainties:** Estimate of the net size associated with the contributions to O_{SM} from missing higher-order corrections in perturbation theory.

Theoretical Uncertainties

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More theory work needed to match EXP uncertainties

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
ΔM_Z[MeV]	2.1	–	0.1			
$\Delta \Gamma_Z$[MeV]	2.3	1	0.1	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta \sin^2\theta_{\rm eff}^\ell [10^{-5}]$	23	1.3	0.6	4.5	$\alpha^3, \alpha^2\alpha_s$	1.5
$\Delta R_b [10^{-5}]$	66	14	6	11	$\alpha^3, \alpha^2\alpha_s$	5
$\Delta R_\ell [10^{-3}]$	25	3	1	6	$\alpha^3, \alpha^2\alpha_s$	1.5

Need TH results to fully exploit Tera-Z

Improvements of EW measurements

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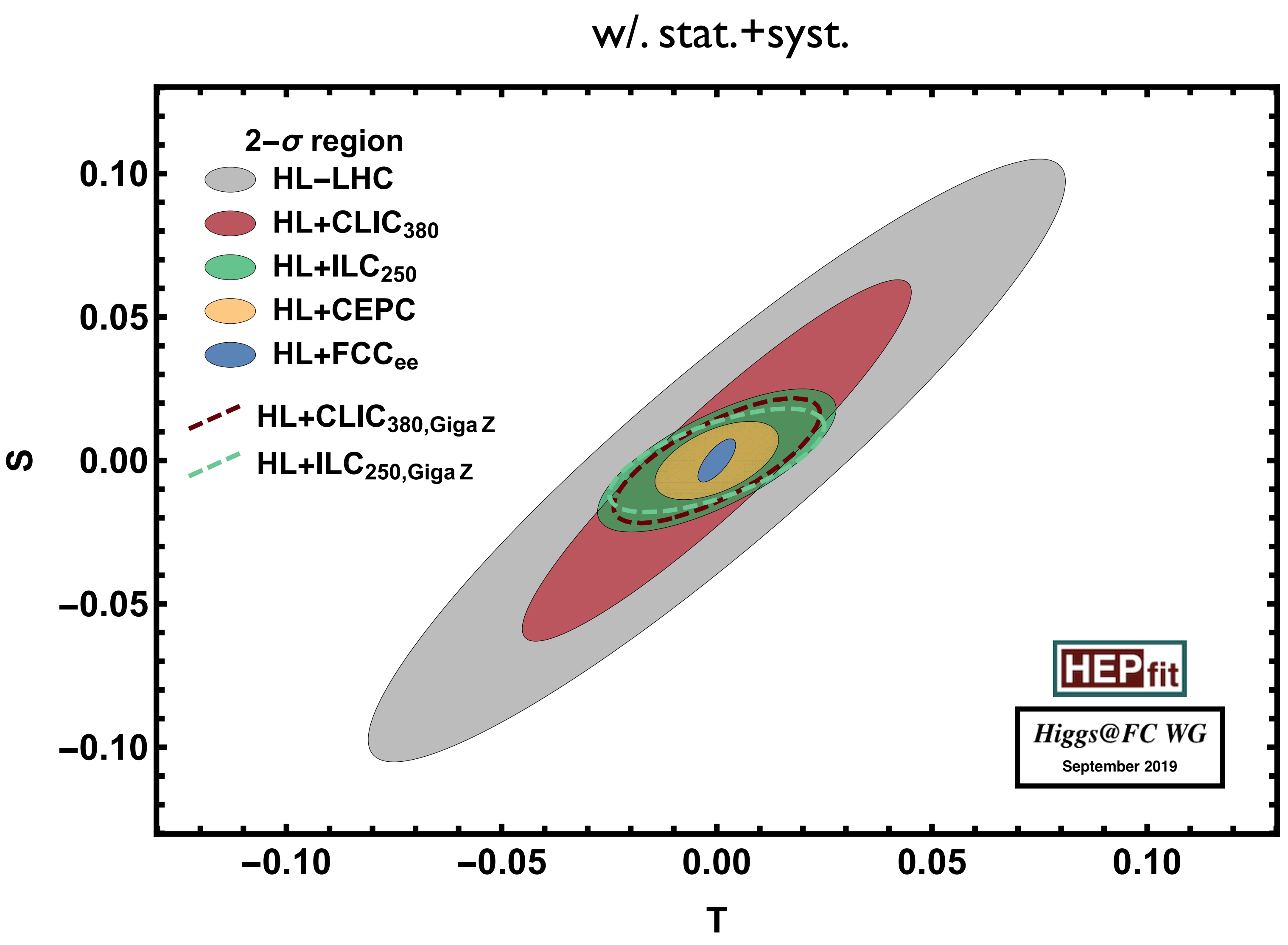

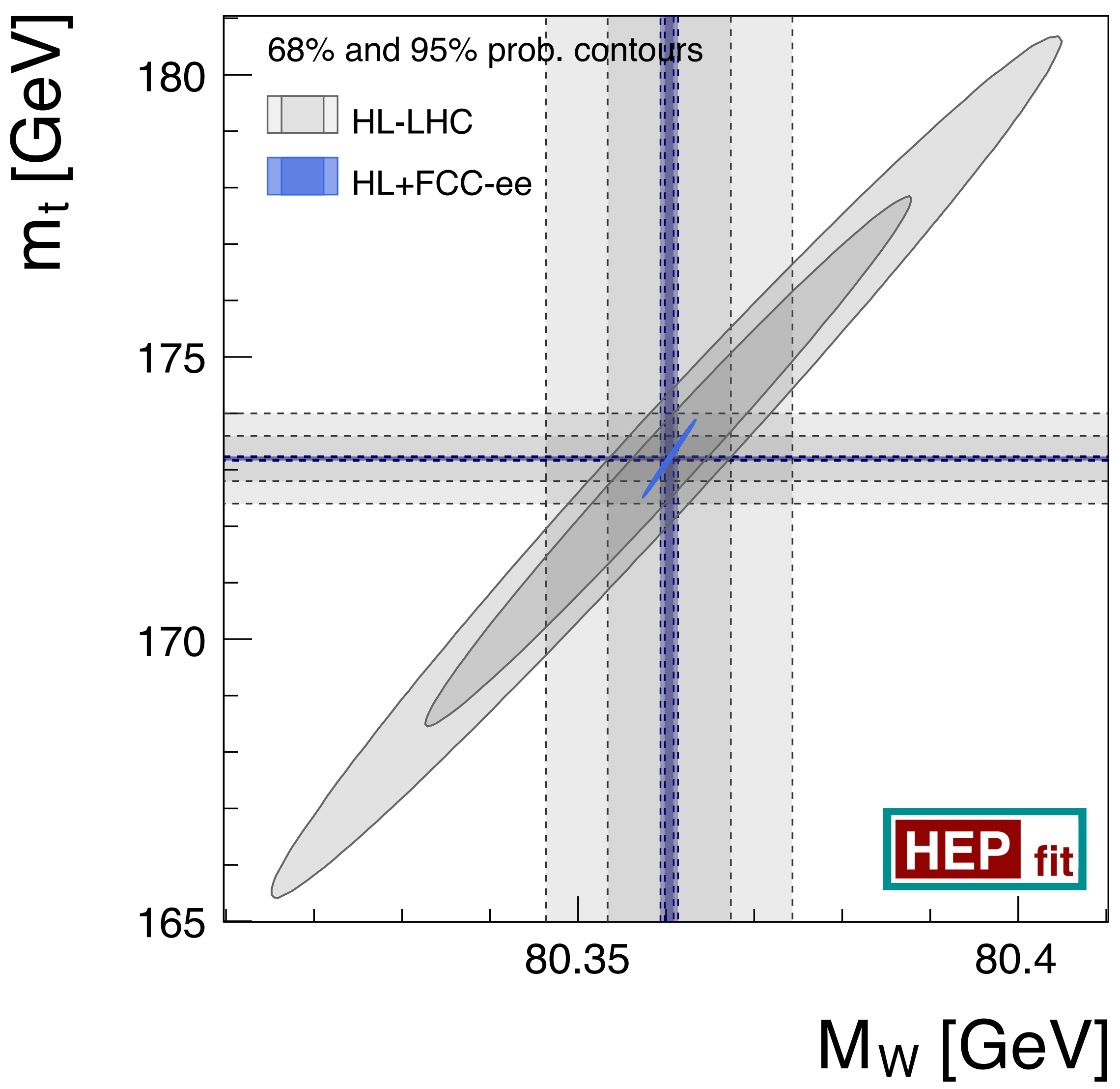

The importance of improved EW measurements is twofold:
1) reduced parametric uncertainties
2) reduced degeneracies in a global fit for Higgs couplings

Improvements of EW measurements

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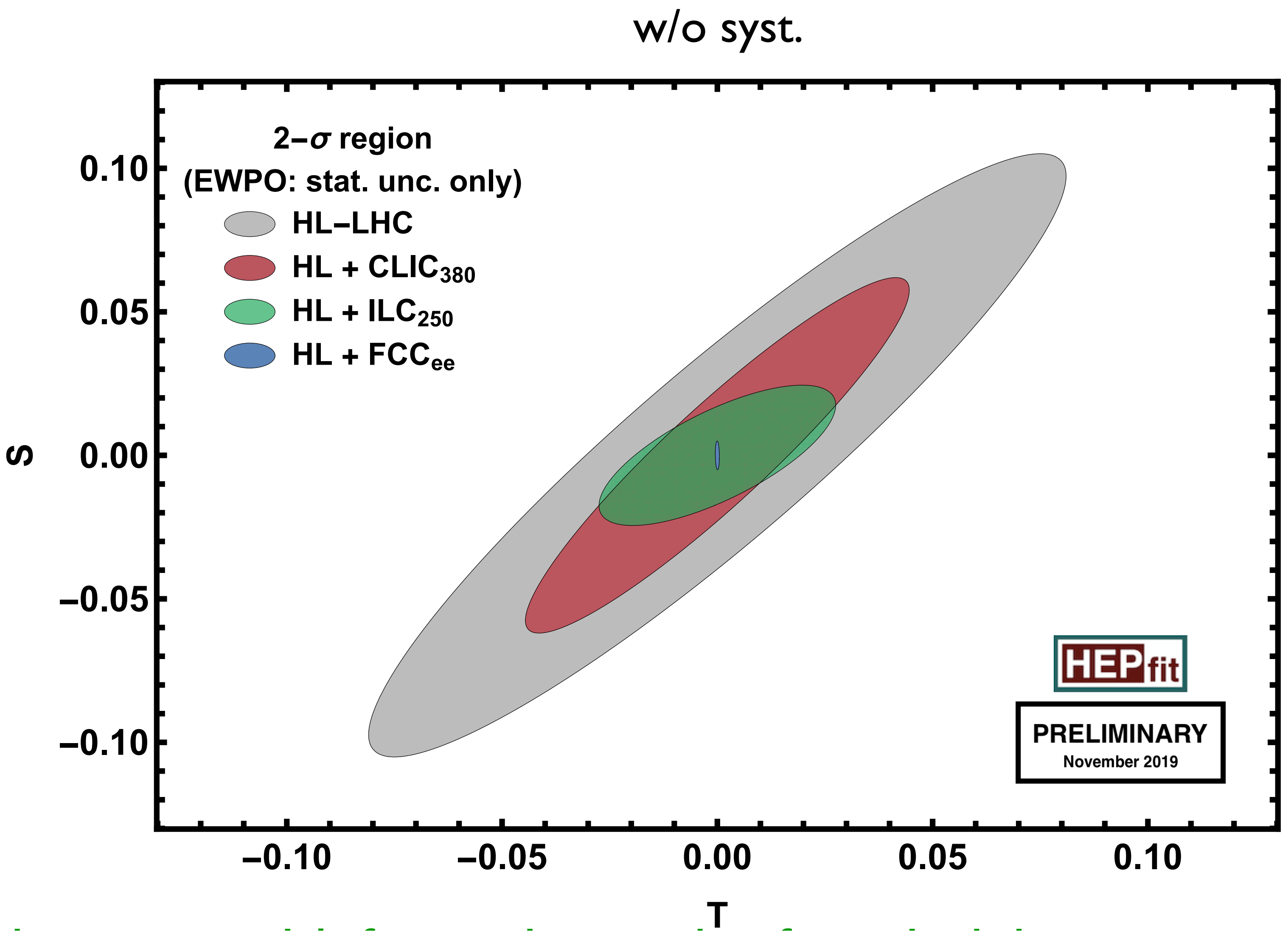

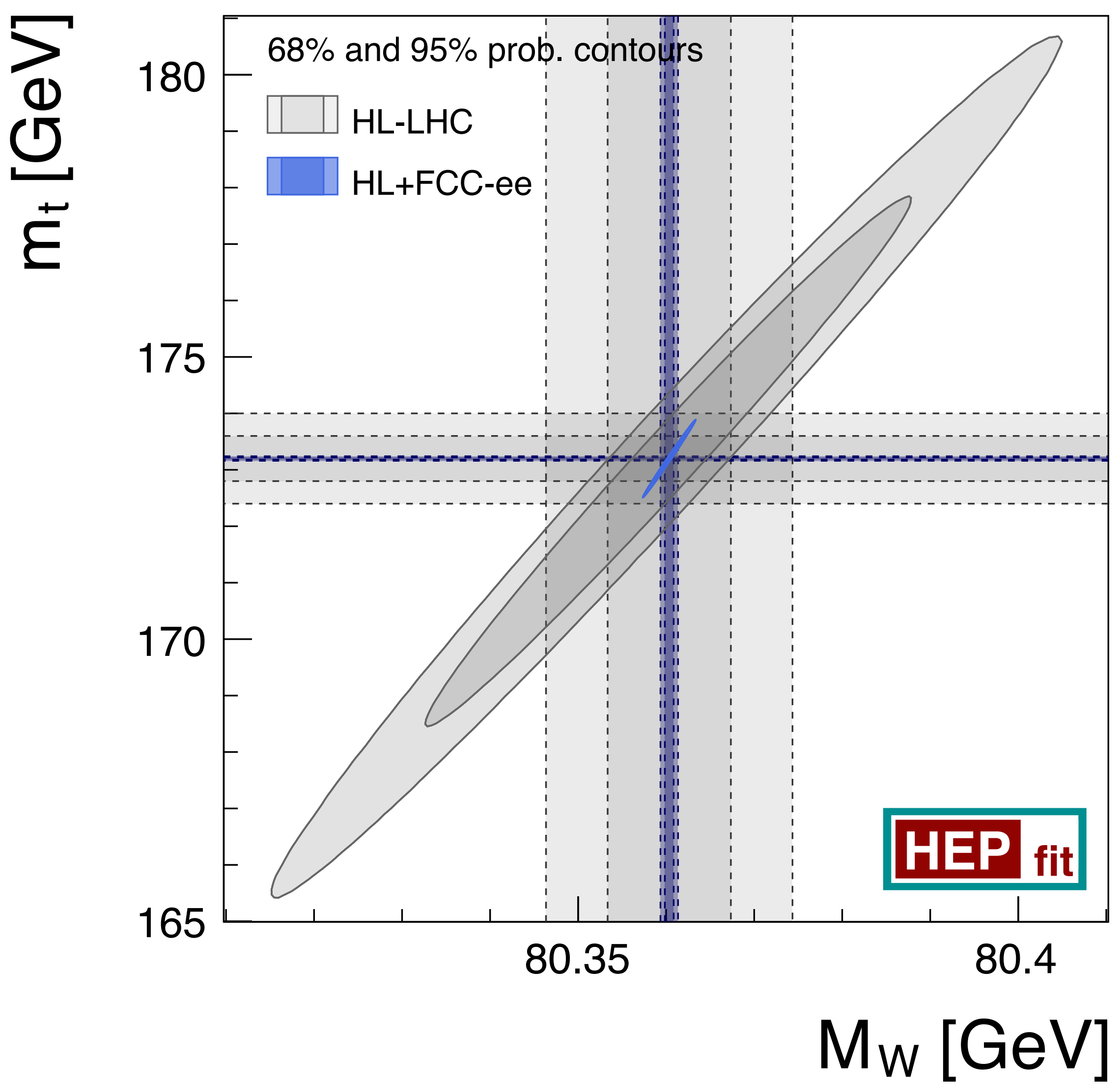

The importance of improved EW measurements is twofold:

1) reduced parametric uncertainties

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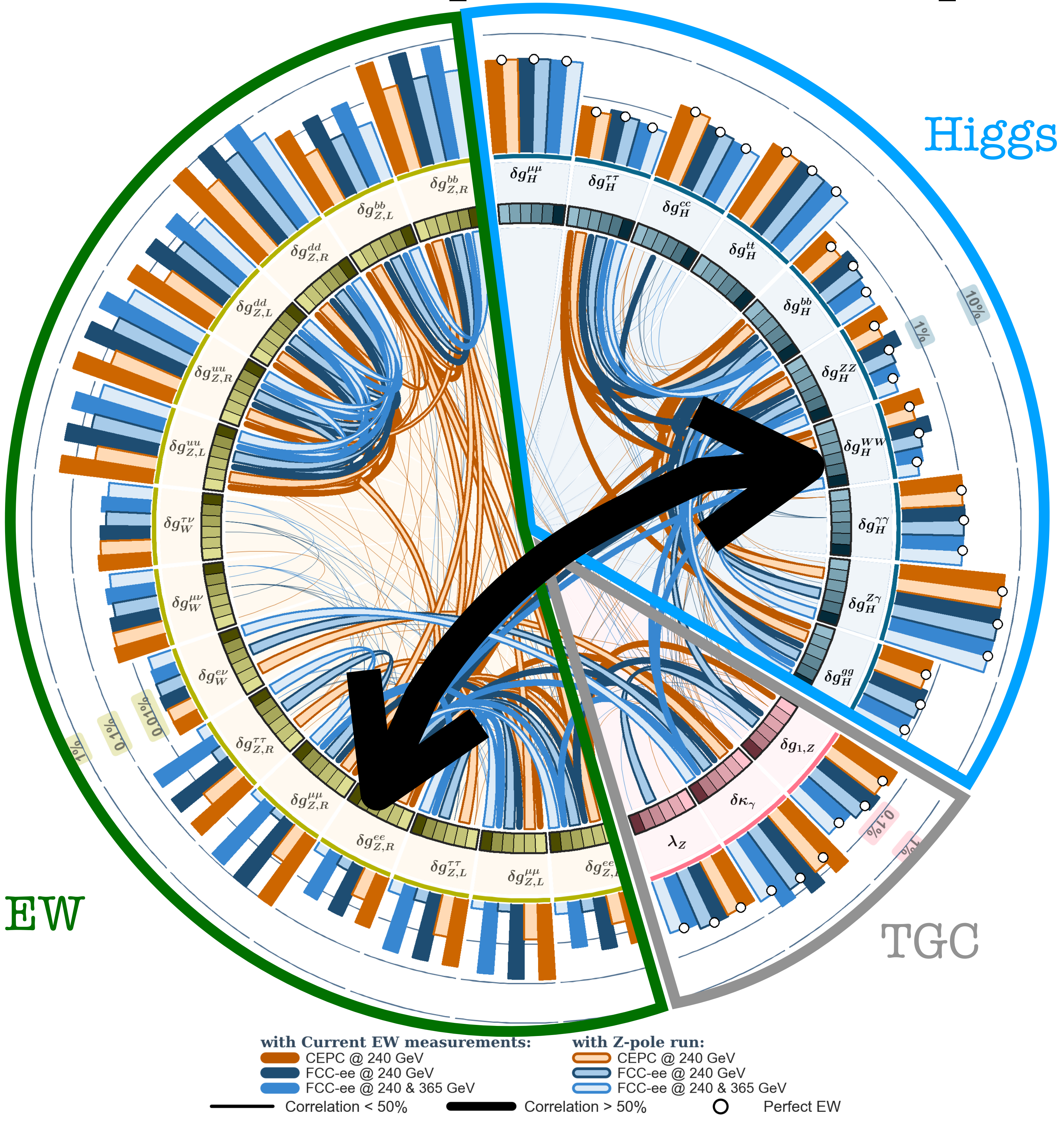
Impact of Z-pole measurements

J. De Blas et al. 1907.04311



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

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

Impact of Z-pole measurements

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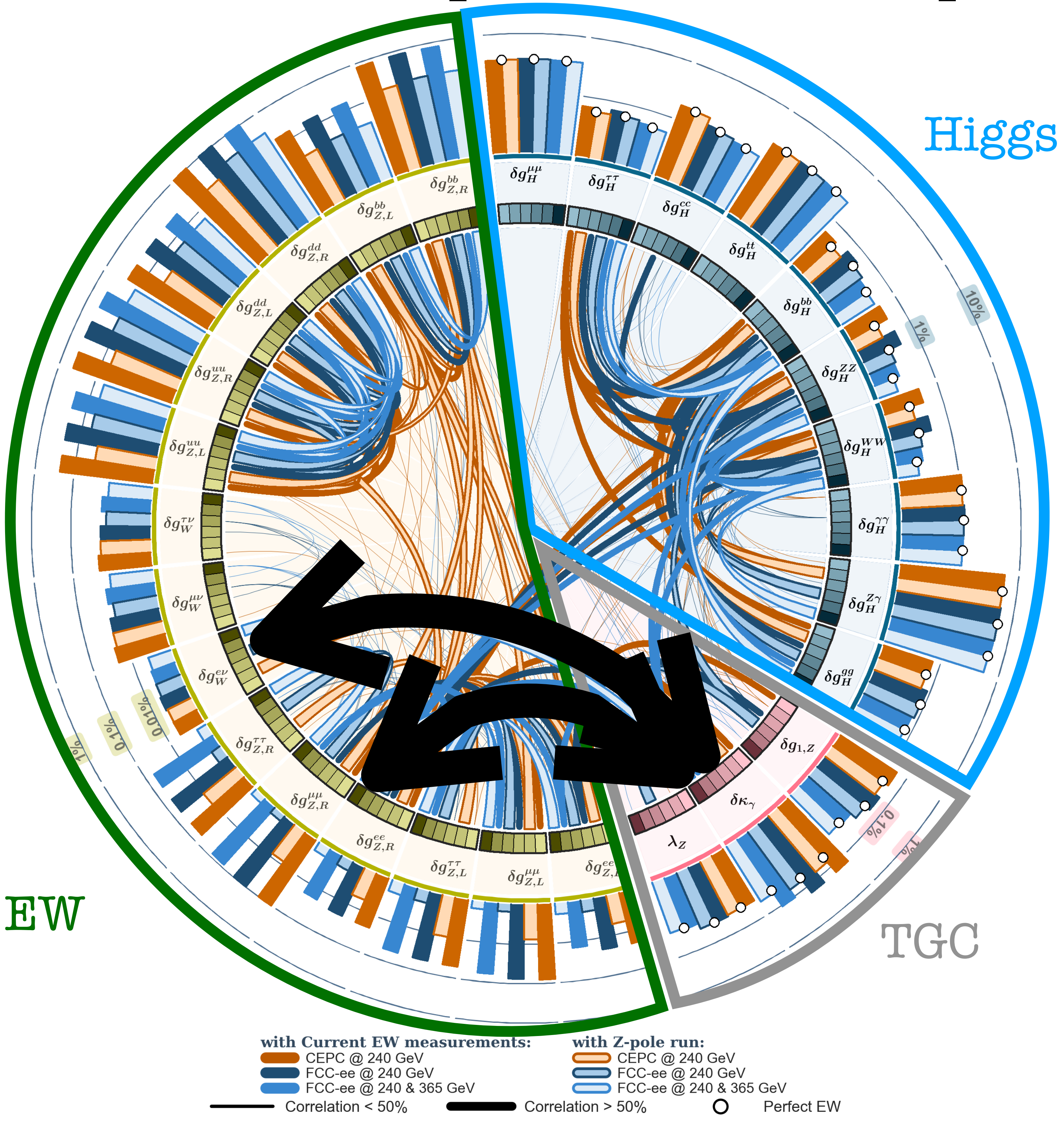

Contamination EW/TGC/Higgs can be understood by looking at correlations

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

Impact of Z-pole measurements

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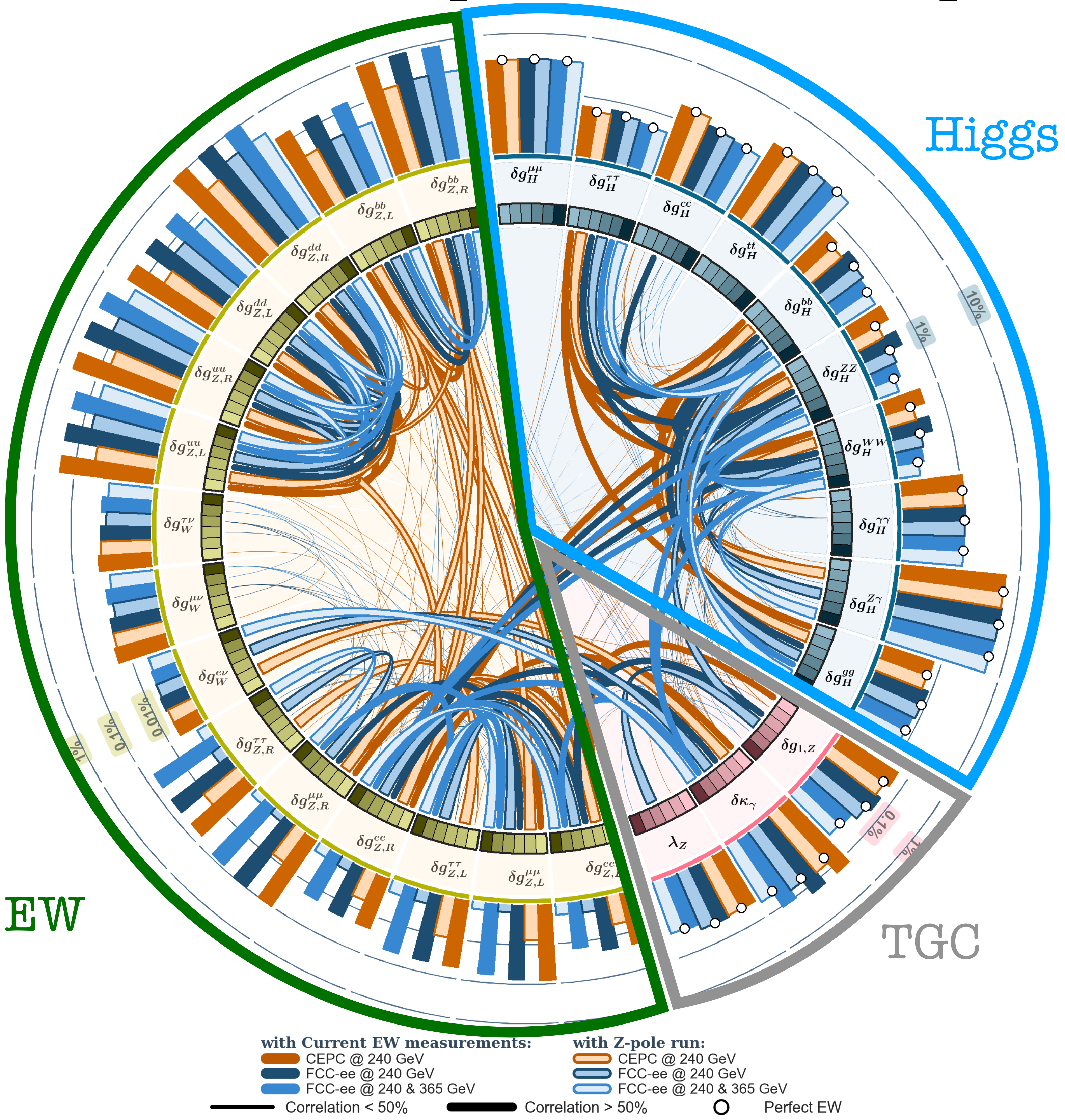
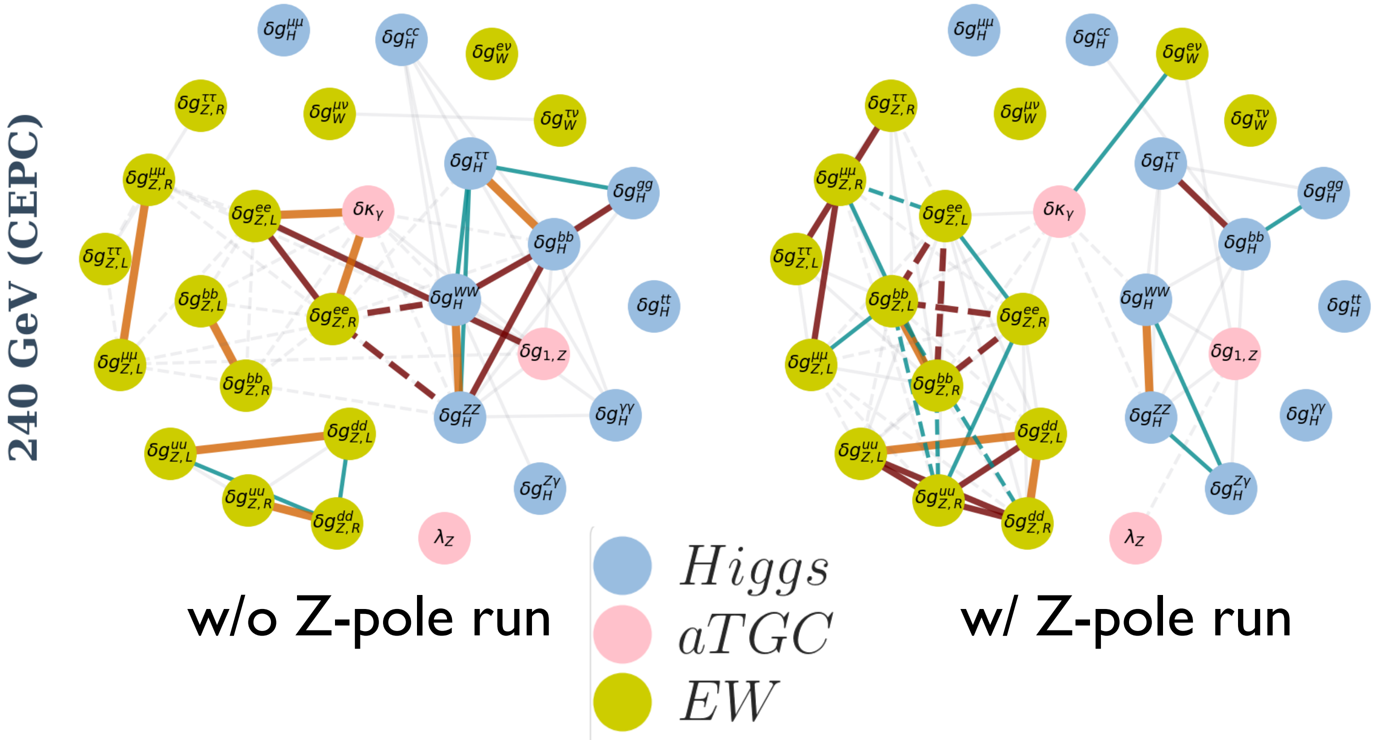


Contamination EW/TGC/Higgs can be understood by looking at correlations

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



Sensitivity on EW couplings

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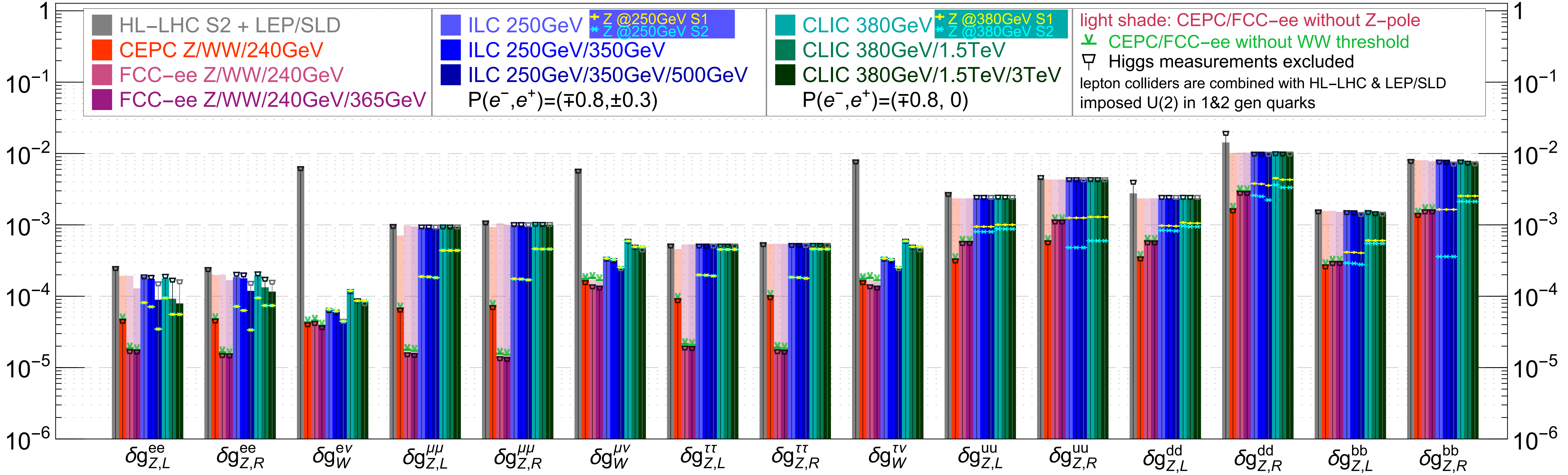

Sensitivity on EW couplings

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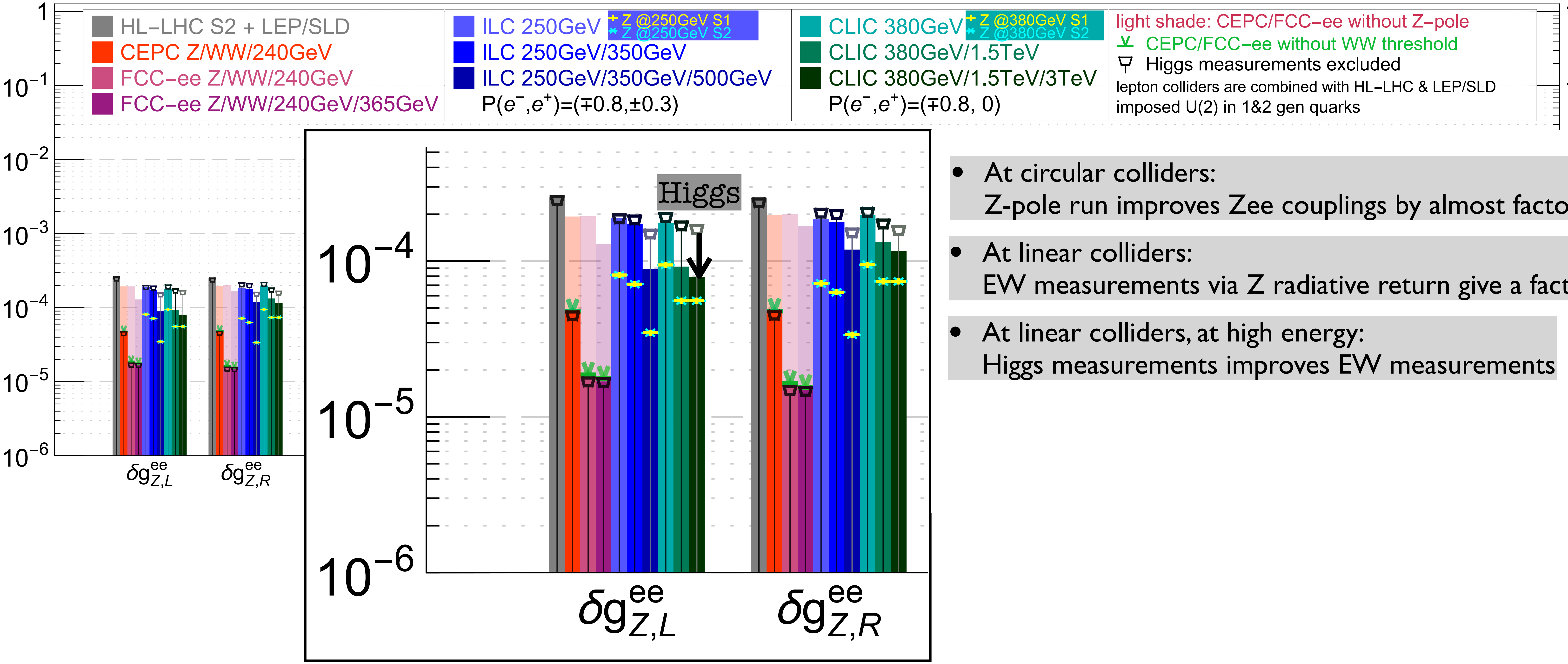

- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10
- At linear colliders:
  EW measurements via Z radiative return give a factor 3
- At linear colliders, at high energy:
  Higgs measurements improves EW measurements

Sensitivity on EW couplings

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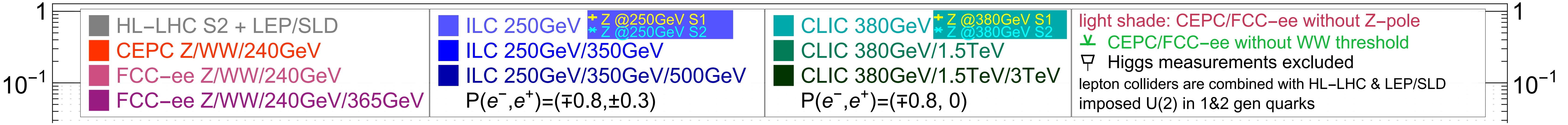
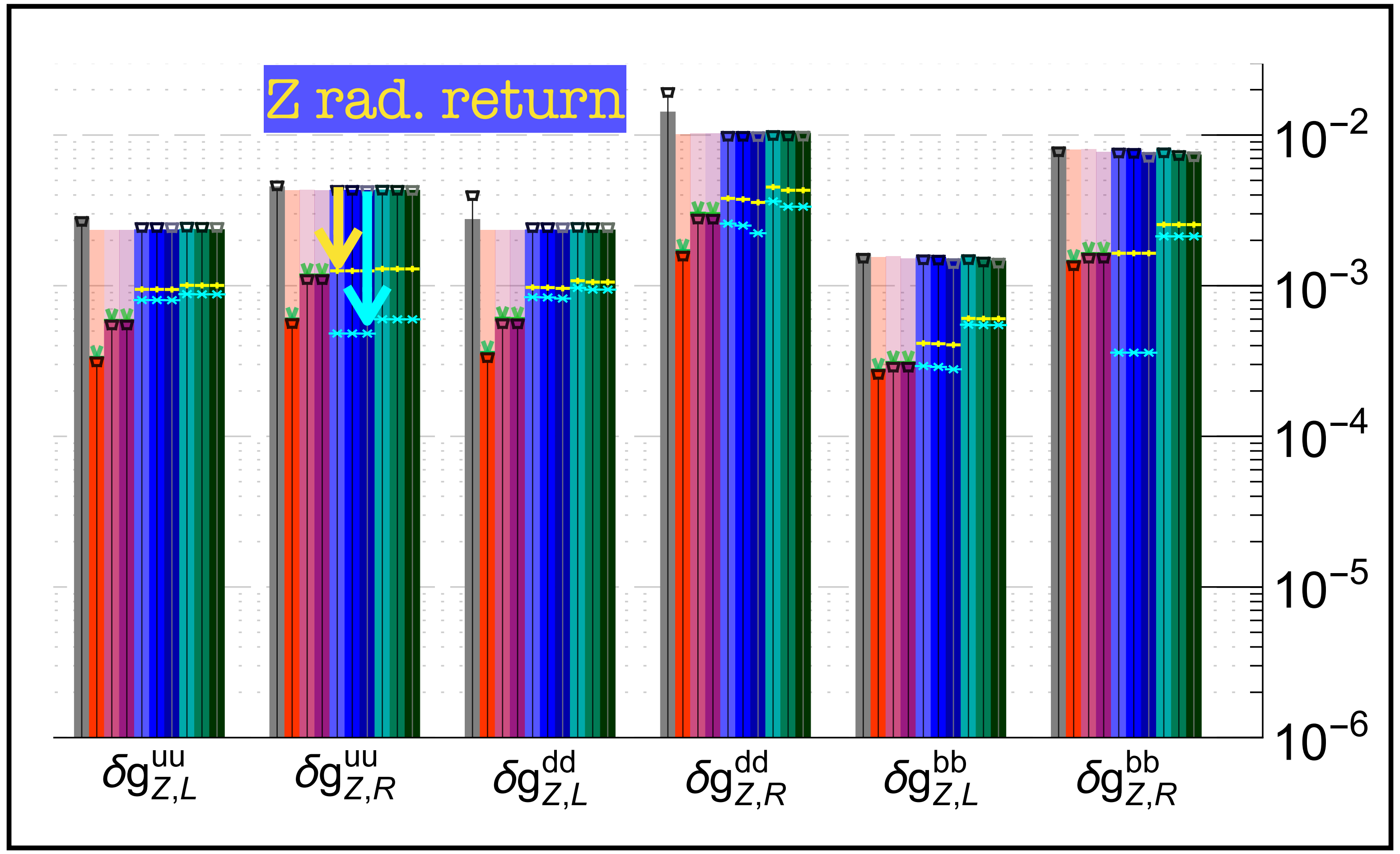


- At linear colliders, at high energy:
  EW measurements via Z-radiative return has a large impact on Zqq couplings
- Improvements depend a lot on hypothesis on systematic uncertainties
  Yellow: LEP/SLD systematics / 2
  Blue: small EXP and TH systematics



Impact of Diboson Systematics

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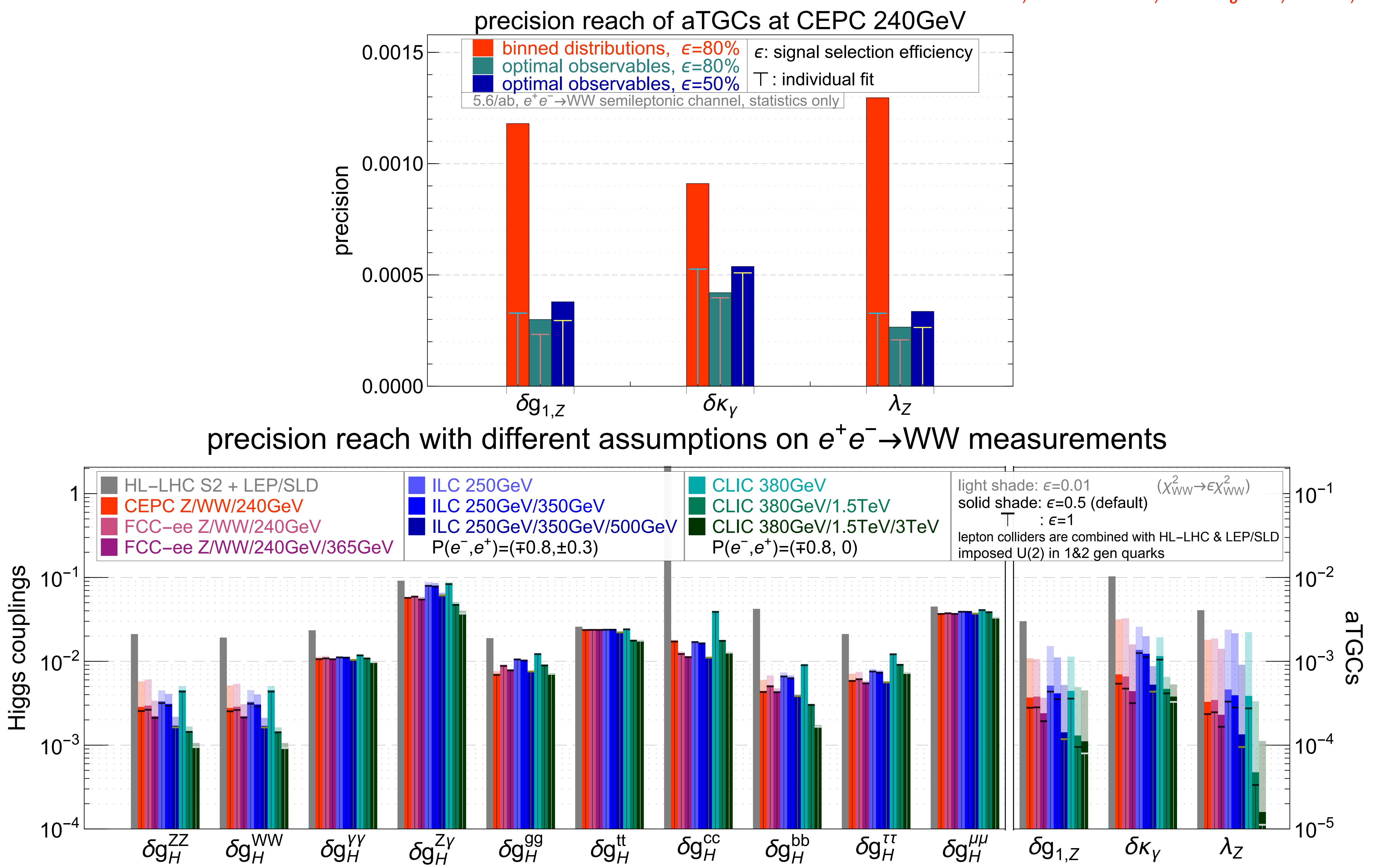

Impact of Beam Polarisation

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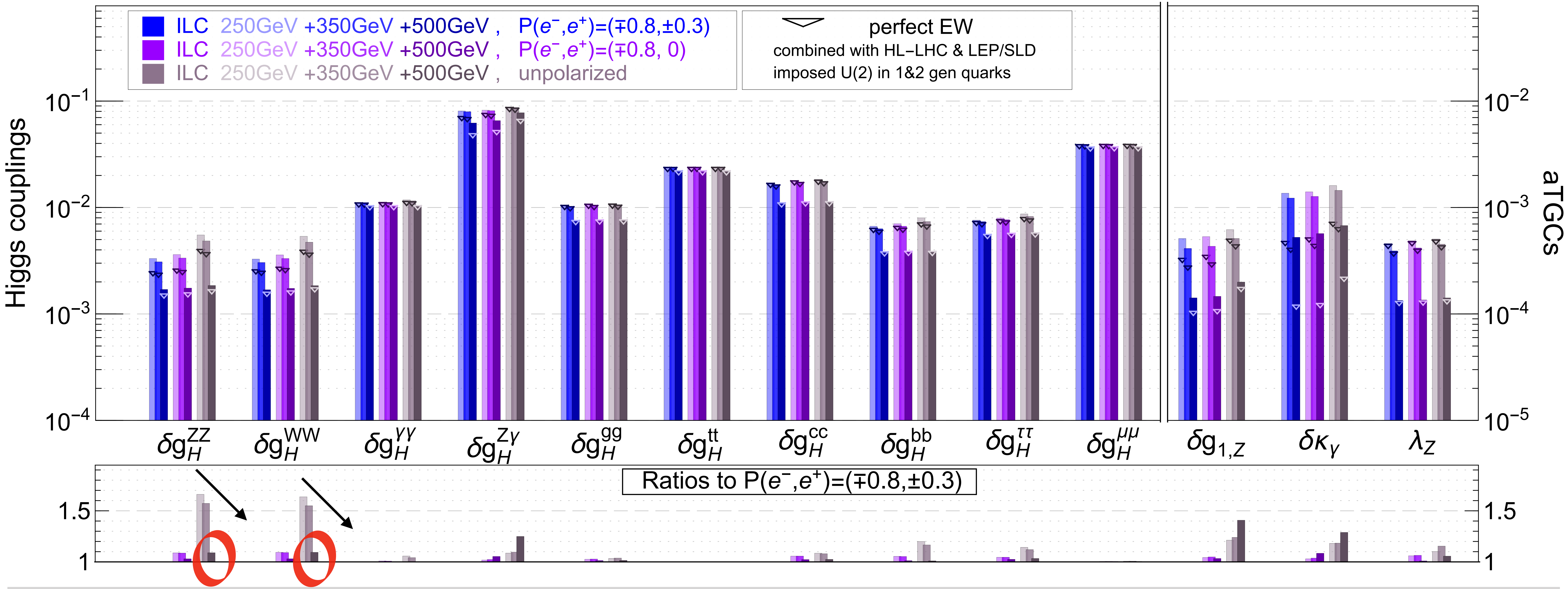

- Positron polarisation doesn't play a big role (for Higgs couplings determination)
- If 250GeV run only: electron polarisation improves significantly (>50%) hVV determination
- Polarisation-benefit diminishes (in relative and absolute terms) when other runs at higher energies are added