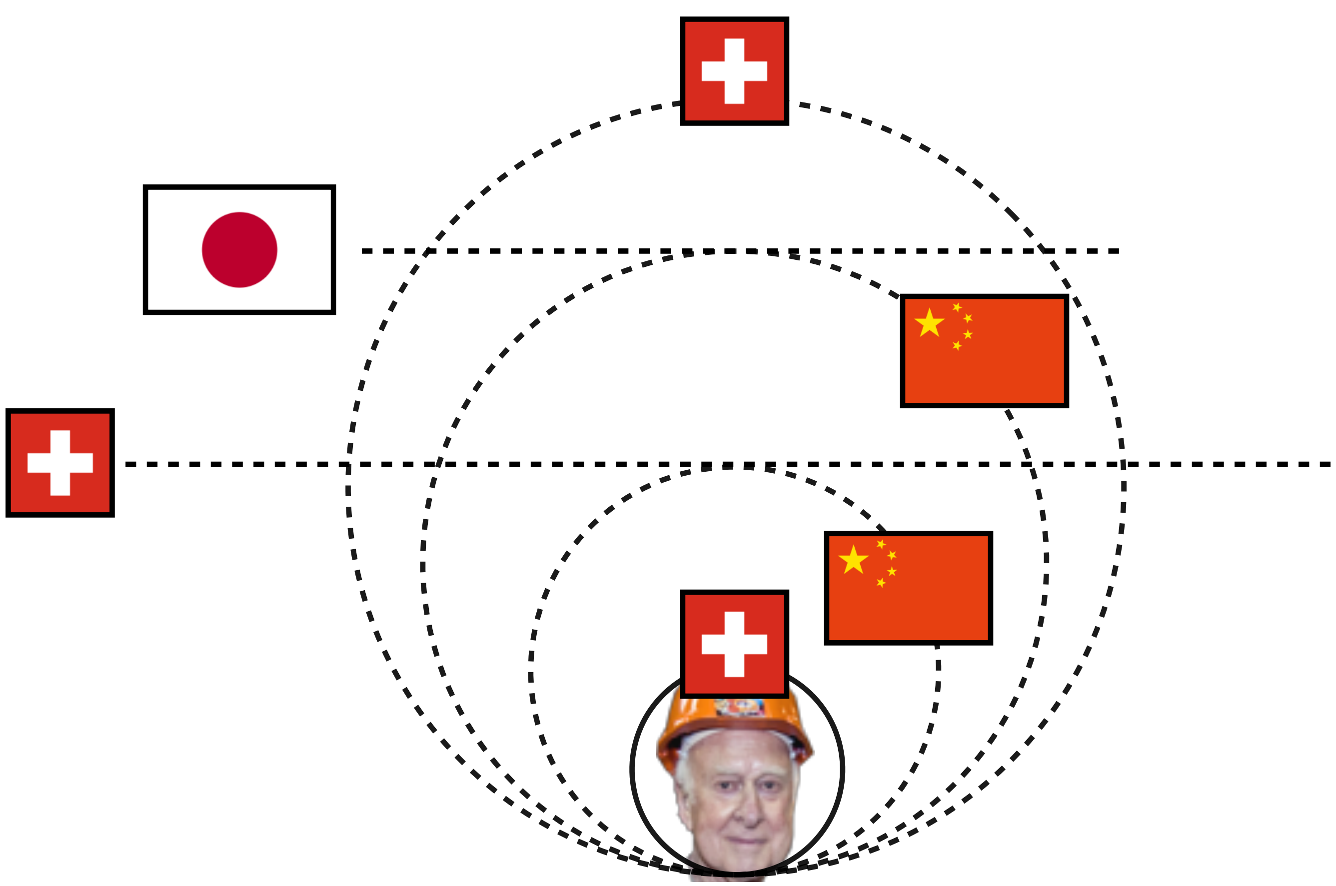
Higgs couplings discussion

(with a special focus on the impact of EW, diboson, polarisation)

— Preparation for ESPP —

FCC-ee physics Vidyo meeting

April 29, 2019



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HEP with a Higgs boson

The Higgs discovery has been an important milestone for HEP
but it hasn't taught us much about **BSM** yet

typical Higgs coupling deformation: $$\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2\, v^2}{\Lambda_{\rm BSM}^2}$$

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. flavor number violation as in $h\to\mu\tau$)

Higgs precision program is very much wanted
to probe BSM physics

The SM challenges to further progress

Parametric uncertainties (m_b,m_c, α_s…) are under control till 0.1% in Higgs couplings

Statistical uncertainty will become less and less important.

Systematics wall will be faced.

	Benchmark SMEFT$_1$	ILC$_{250}$	ILC	CLIC$_{380}$	HL-LHC + CLIC	CEPC	FCC-ee$_{240}$	FCC-ee
g_{HZZ}^{eff}	Exp$_{\text{Stat}}$	0.24	0.16	0.33	0.088	0.31	0.33	0.24
	Exp$_{\text{Stat}}$ + Th$_{\text{Par}}$	0.25	0.17	0.34	0.11	0.31	0.34	0.24
	Exp$_{\text{Stat}}$ + Th$_{\text{Intr}}$	0.3	0.28	0.38	0.29	0.35	0.37	0.31
	Exp$_{\text{Stat}}$ + Th	0.31	0.29	0.38	0.3	0.36	0.38	0.32

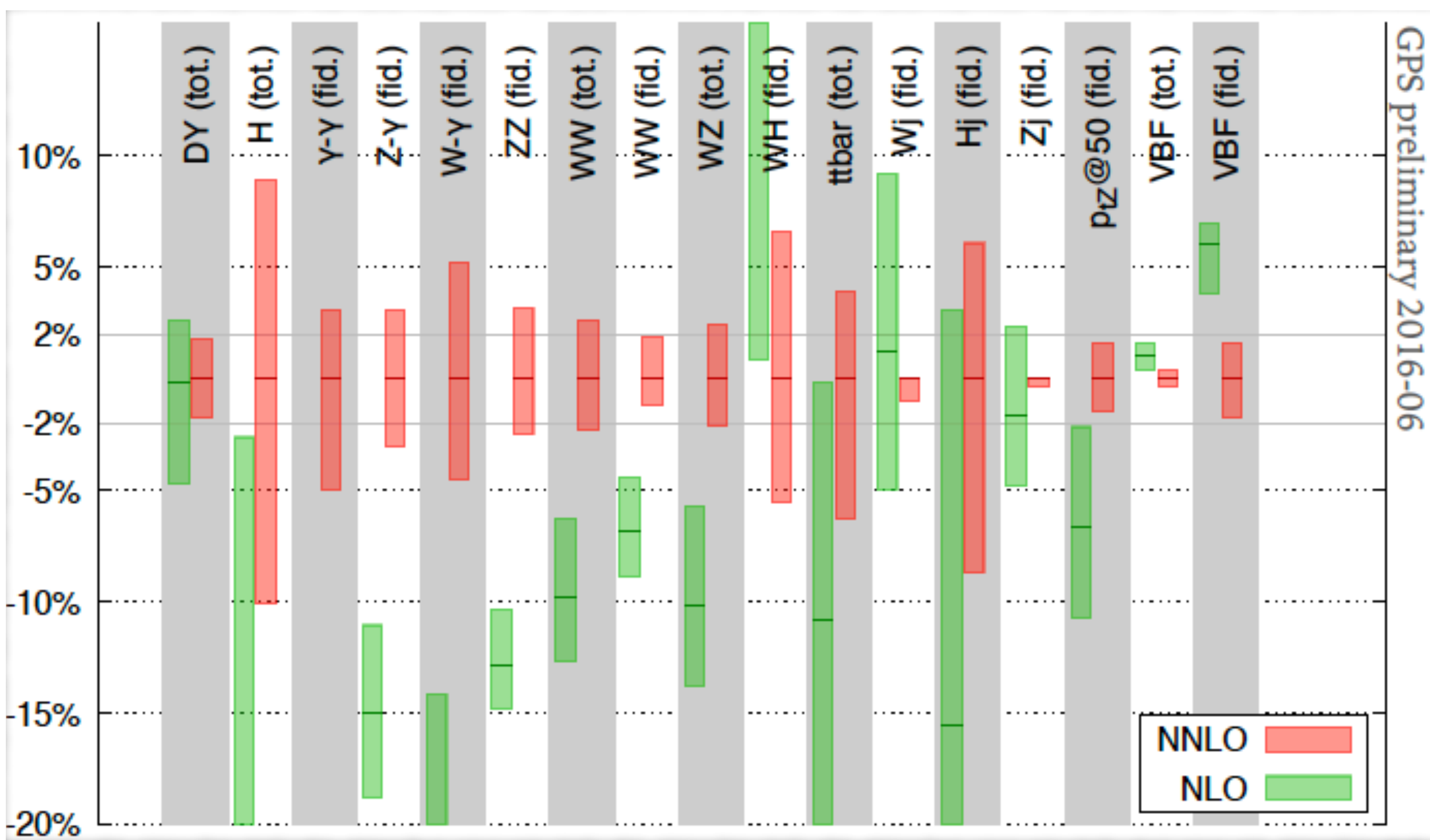
ECFA Higgs study group '19

The SM challenges to further progress

Parametric uncertainties (m_b,m_c, α_s…) are under control till 0.1% in Higgs couplings
Statistical uncertainty will become less and less important.
Systematics wall will be faced.

Progress requires a combination of

- Better control of parametric uncertainties, e.g. PDFs
- Higher order theoretical computations, e.g. N…NLO
- Access to phase-space limited regions
- Understand correlations among different bins in diff. distributions



Which Machine(s)?

Hadrons

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

Leptons

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

Circular

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

Linear

- easier to upgrade in energy
- easier to polarize beams
- large beamsthralung
- “greener”: less power consumption*

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

Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration?
- S/B ~ 10^{-10} (w/o trigger)
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Leptons

- S/B ~ 1 ⇛ measurement?
- polarized beams
  (handle to chose the dominant process)

Exploration machines are at the heart of HEP
Current consensus:
the best way to go there is to start with a Higgs factory
Linear or Circular?

- Can be extended in energy
- Polarised beams

- Higher luminosity
- Z-pole run

- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)

- "greener": less power consumption*

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

Higgs couplings: kappa vs EFT

Complementarity between the two approaches

— Kappa:

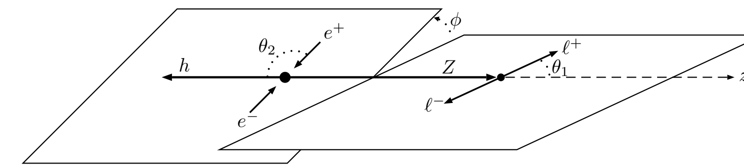
- Close connection to exp measurements
- Widely used
- Exploration tool (very much like epsilons for LEP)
- Could still valid even with light new physics
- Captures leading effects of UV motivated scenarios (SUSY, composite Higgs)
- Doesn’t require BSM theoretical computations

— EFT:

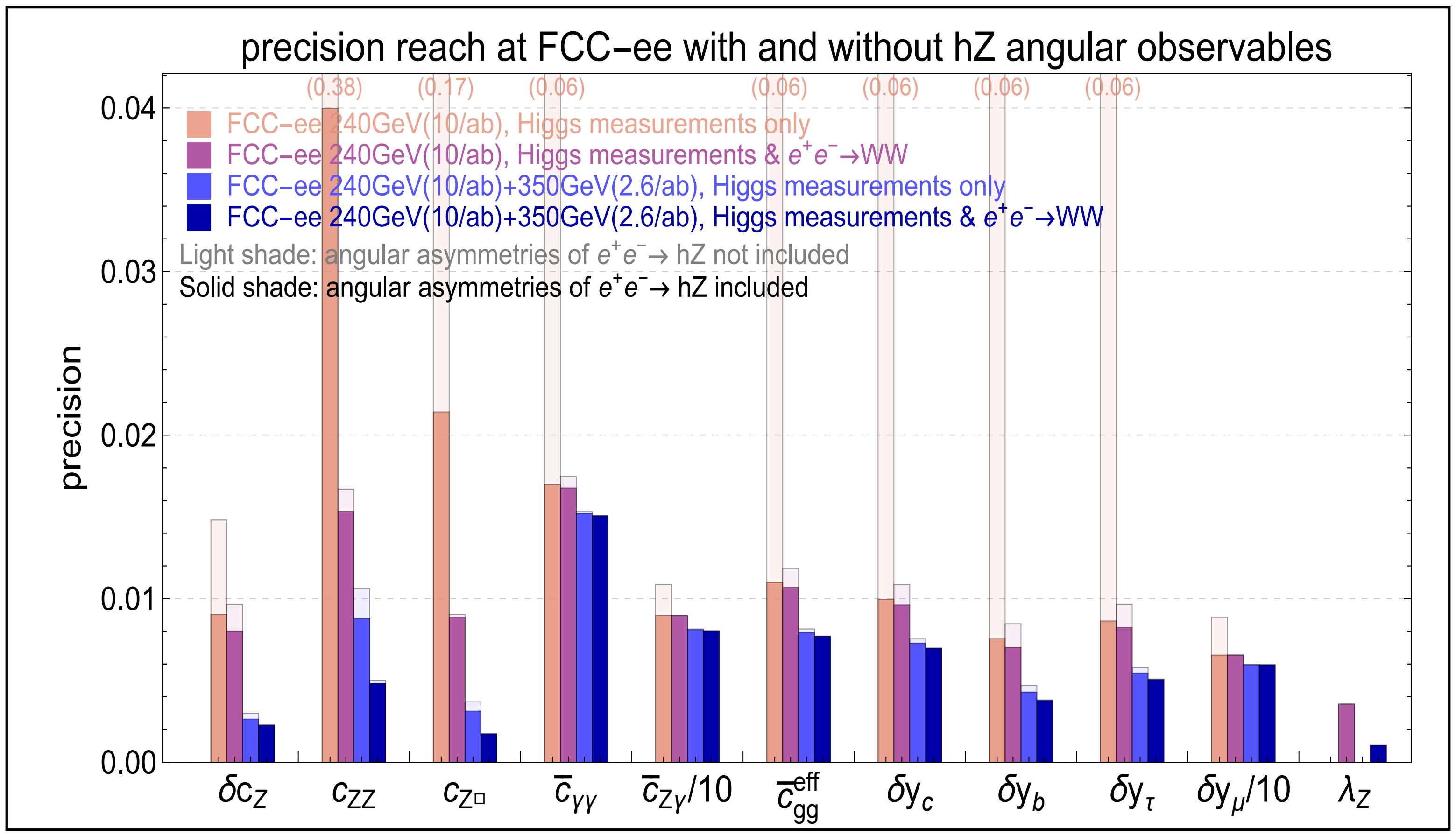
- Allows to put Higgs measurements in perspective with other measurements (EW, diboson, flavour…)
- Connects measurements at different scales (particularly relevant for high-energy colliders CLIC, FCC-hh)
- Fully exploits more exclusive observables (polarisation, angular distributions…)
- Can accommodate subleading effects (loops, dim-8…)
- Fully QFT consistent framework
- Assumptions about symmetries more transparent
- Challenged if there is no mass gap between weak scale and new physics
- Should we include the option of new exotic decays? Not inconsistent but more model-dependent

Which measurements are needed?

Higgs coupling measurement is not relying on Higgs data alone
Need a machine that is complete and efficient at different energies



Durieux, Grojean, Gu, Wang '17



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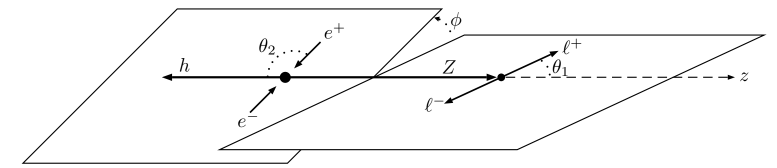

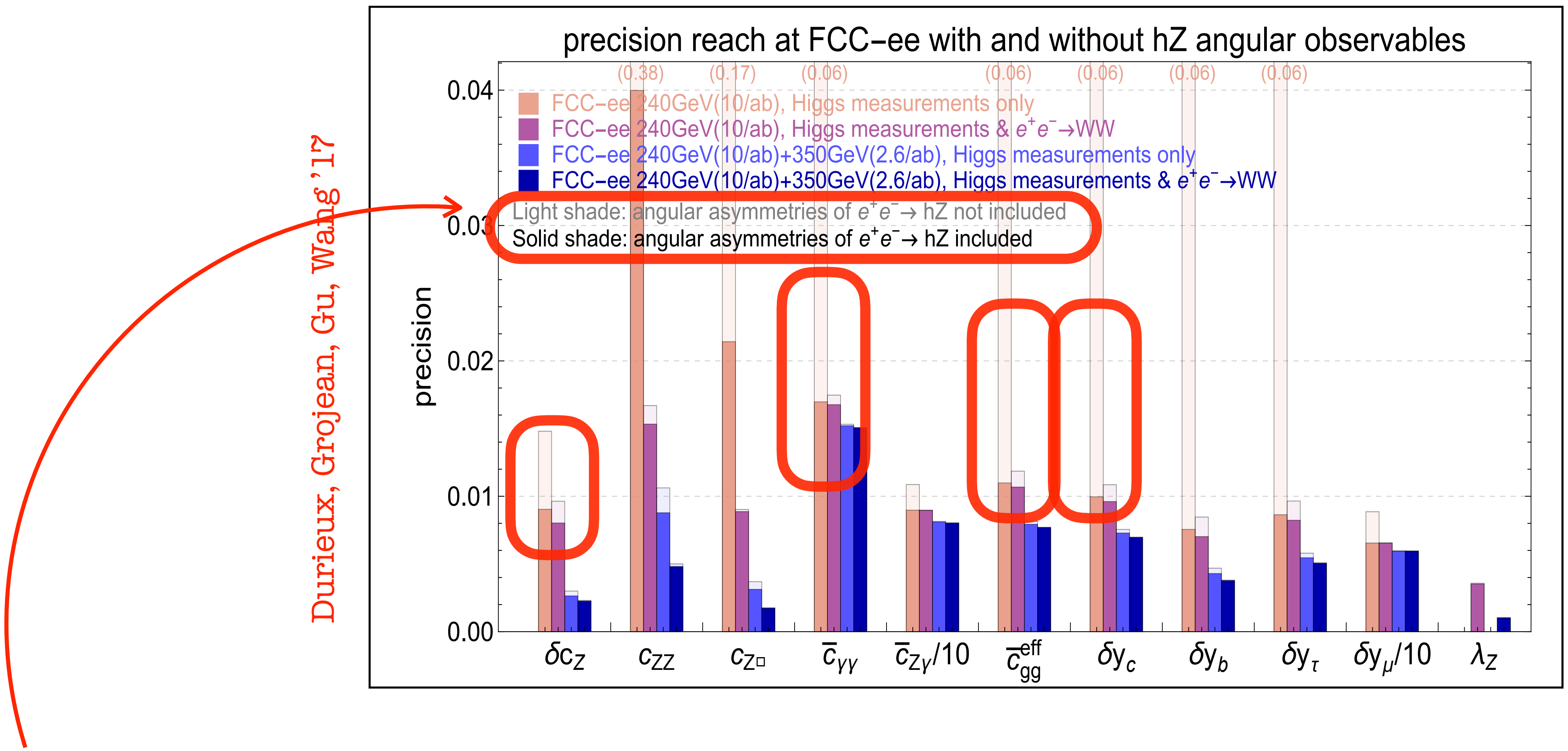

1) with a run at 240/250 GeV alone, it is crucial to have access to angular distributions to break degeneracies (e.g. 20%-50% for hZZ)

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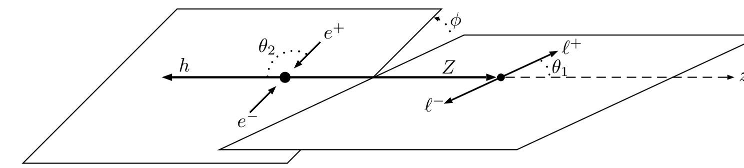

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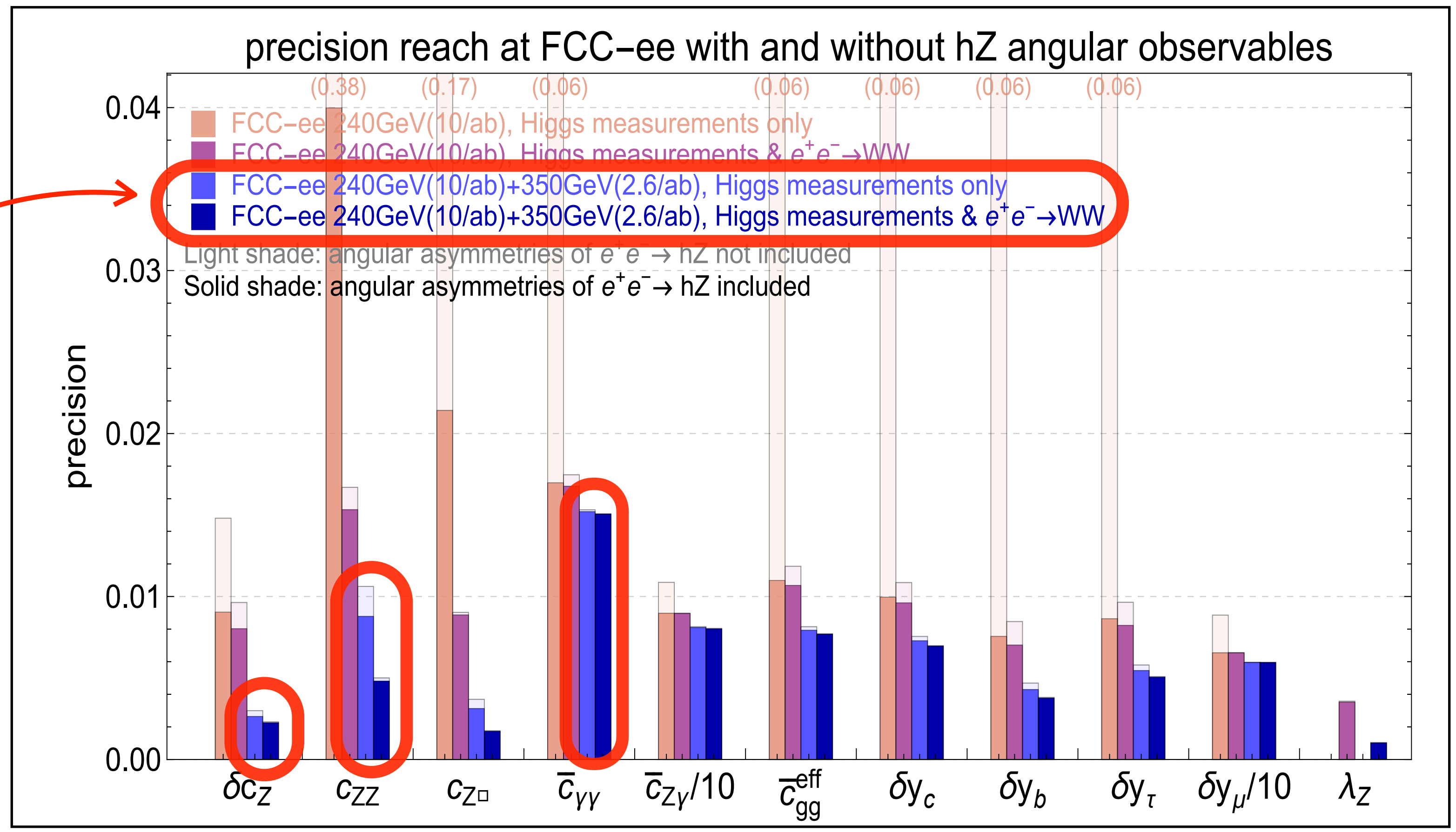


1) with a run at 240/250 GeV alone, it is crucial to have access to angular distributions to break degeneracies (e.g. 20%-50% for hZZ)

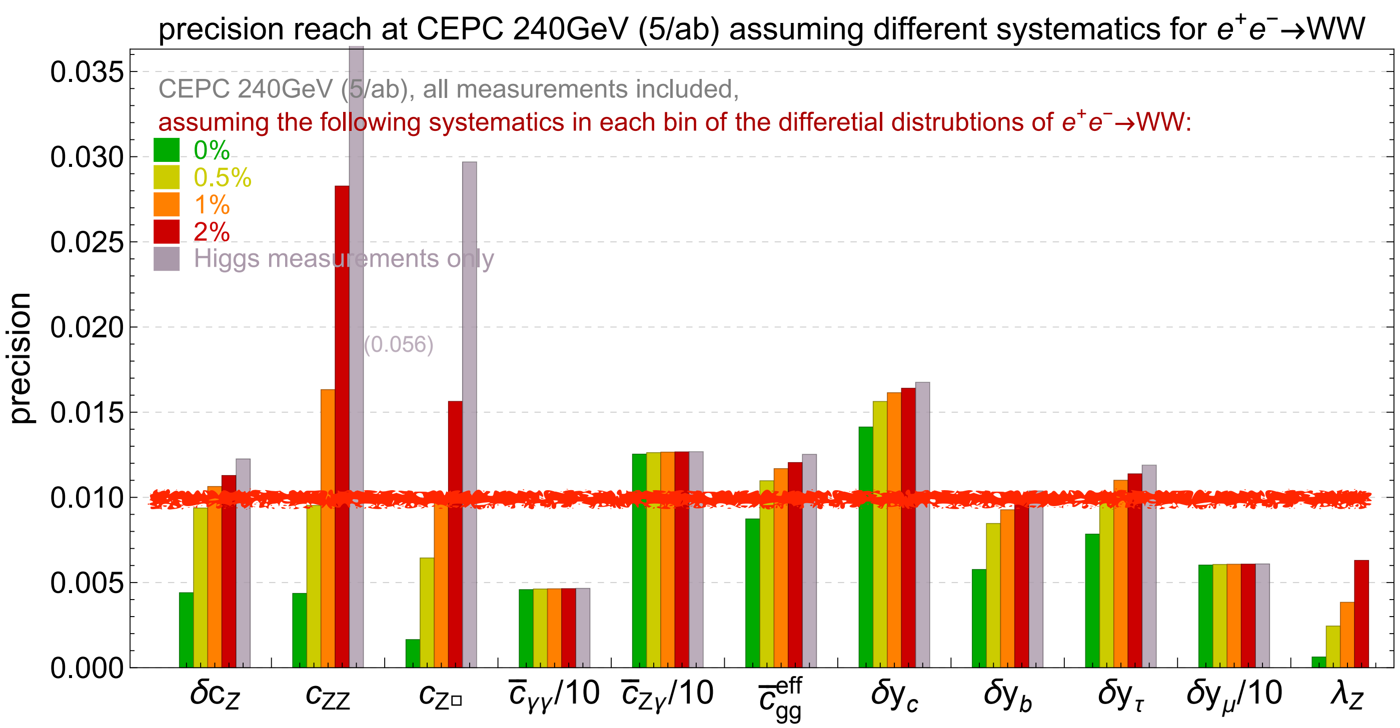
2) with a second run at higher energy makes it less important to look at distributions

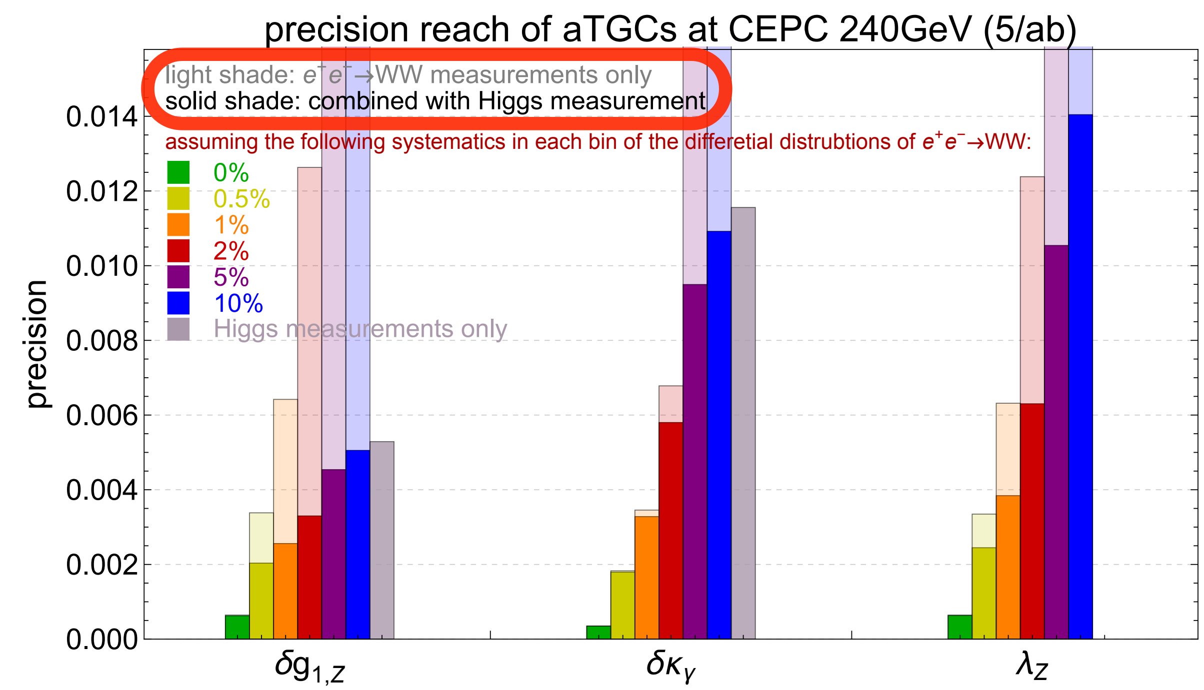
Importance of WW run

(TGC+Higgs)>(TGC)∪(Higgs)

Don’t do a WW analysis in terms of TGC only

Full EFT analysis away from TGC dominance assumption needed





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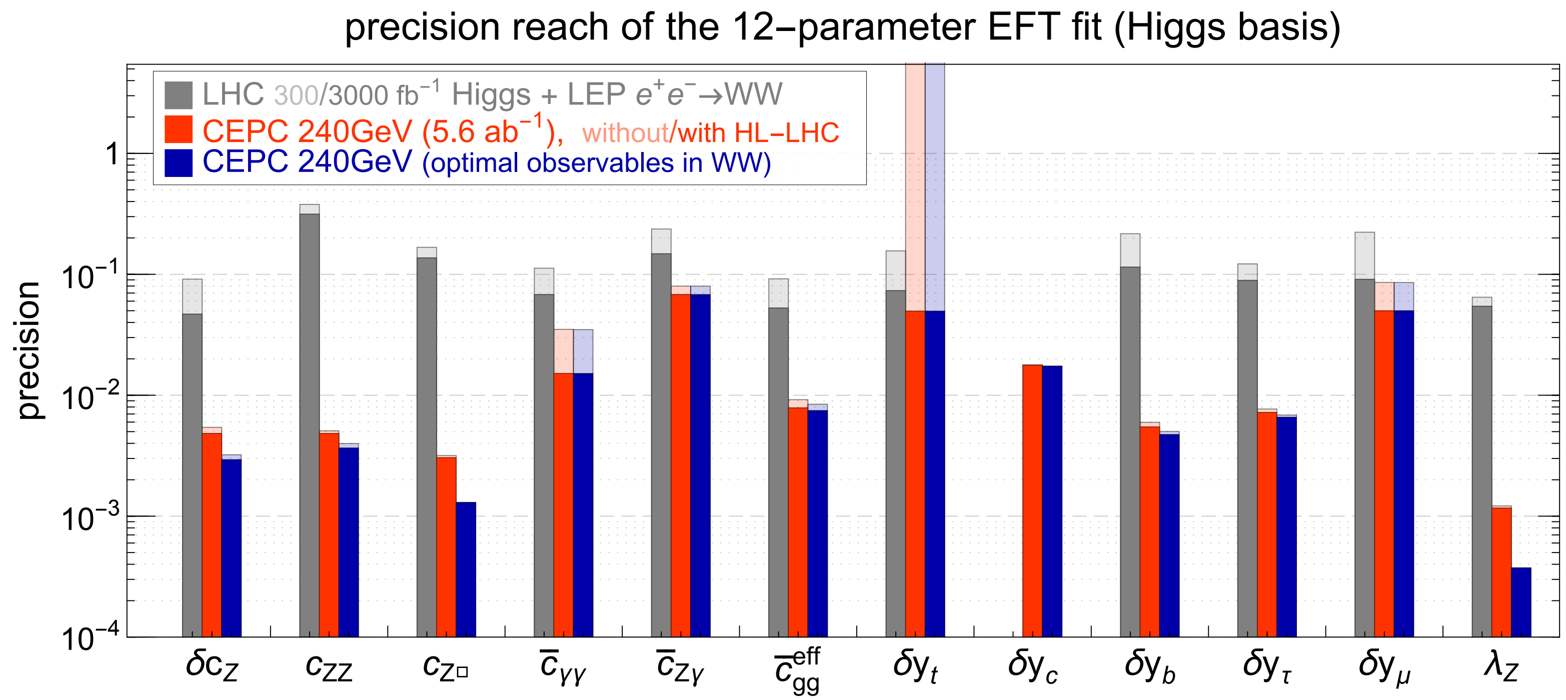
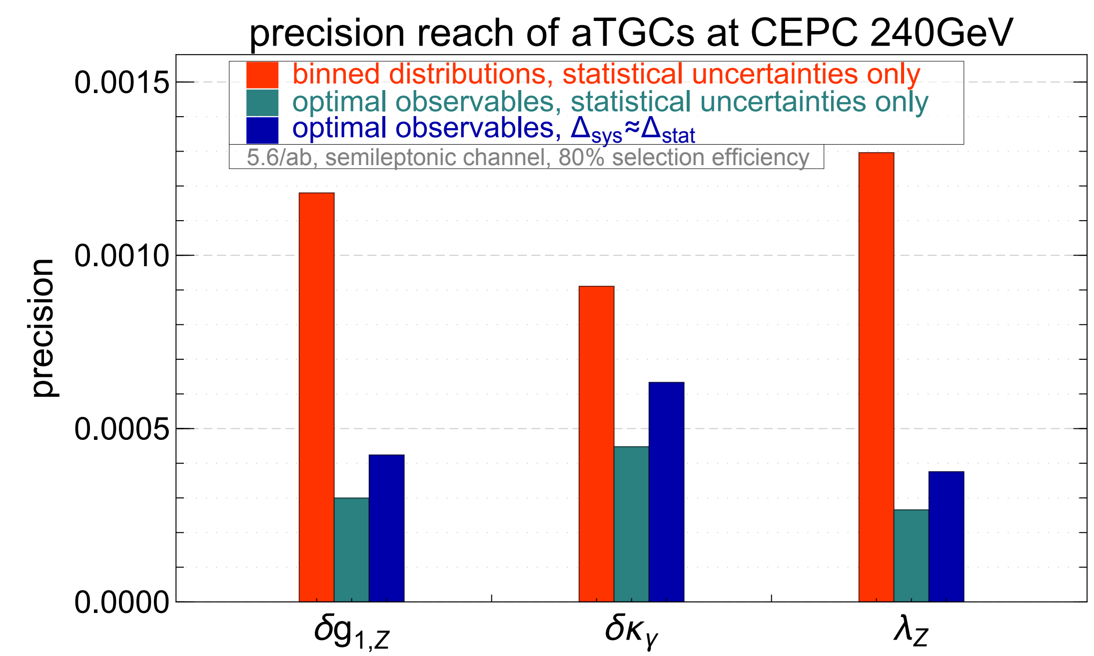
Keep WW systematics below 1% in order to reach 0.1% HZZ coupling sensitivity

Importance of WW run

(TGC+Higgs)>(TGC)∪(Higgs)

Diboson analysis can still be improved, e.g., using optimised observables





De Blas, Durieux, Grojean, Gu, Paul 'in progress

Keep WW systematics below 1% in order to reach 0.1% HZZ coupling sensitivity

EW measurement's impact on Higgs

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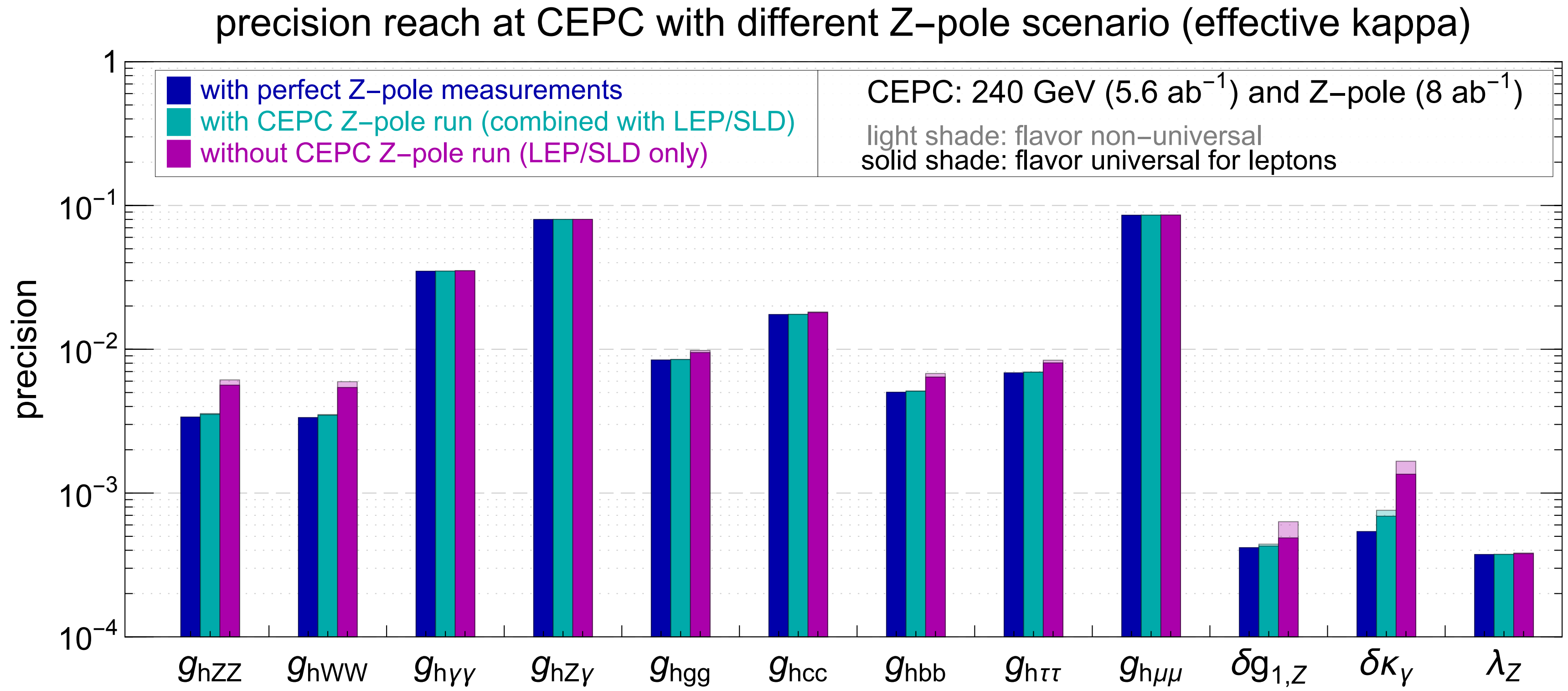
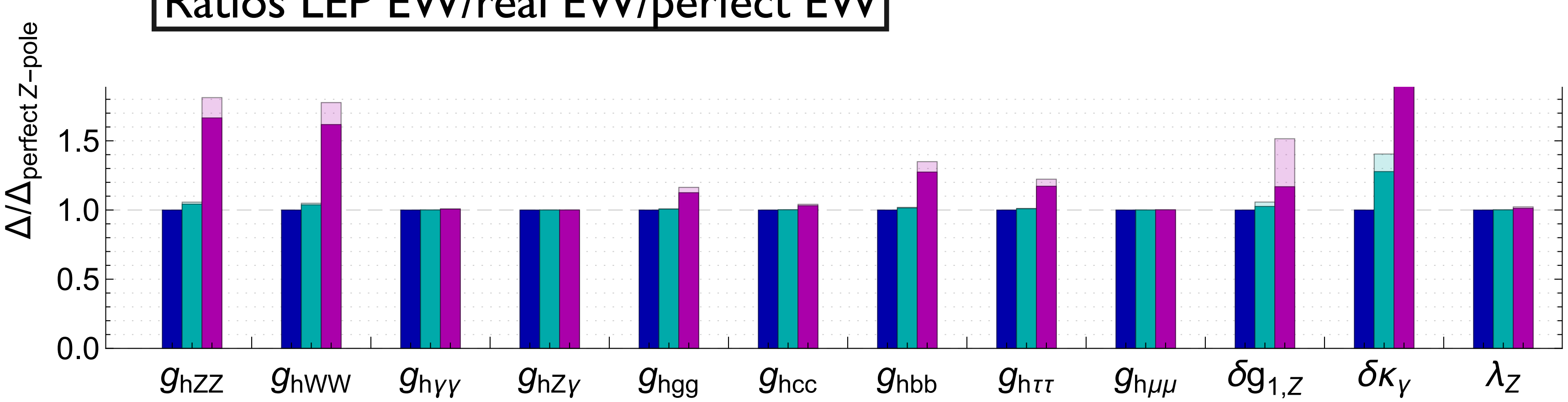


EFT fit translated into

postdicted Higgs couplings

($e.g.$ $g_{hZZ} \propto \sqrt{\Gamma_{h\to ZZ}}$)

Ratios LEP EW/real EW/perfect EW



✗ CEPC alone

EW measurement's impact on Higgs

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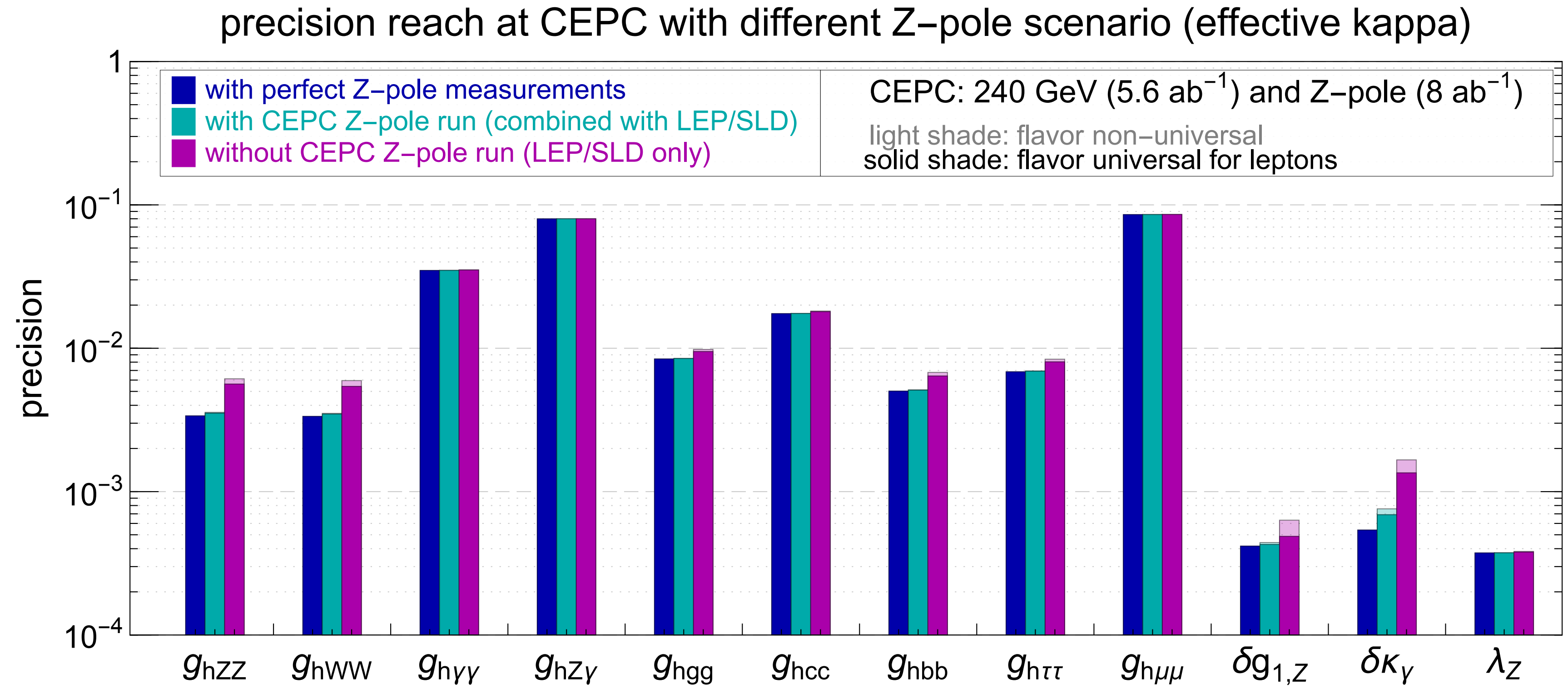

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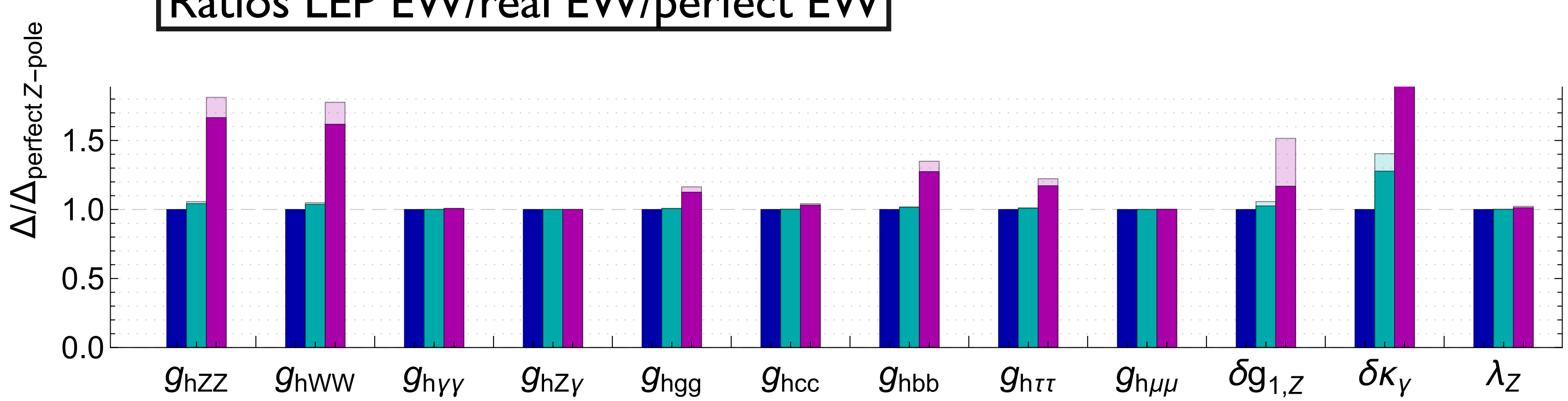


✗ CEPC alone

Z-pole run needed
LEP/SLD is not enough
Issue for ILC?

Linear: L ↗ w/ E

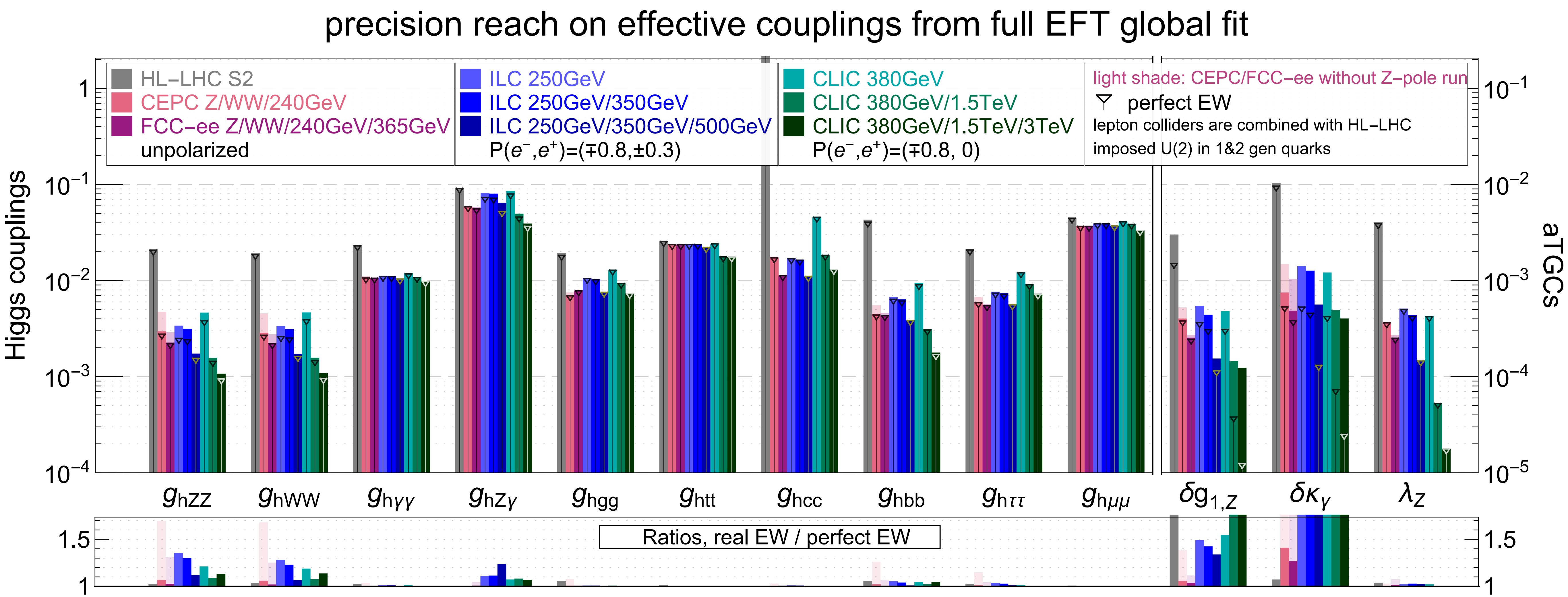
Circular: L ↘ w/E

How many Z are needed?
Giga-Z enough?

350GeV run & polarisation could help alleviating the need for Z-pole run

EW measurement's impact on Higgs

De Blas, Durieux, Grojean, Gu, Paul 'in progress



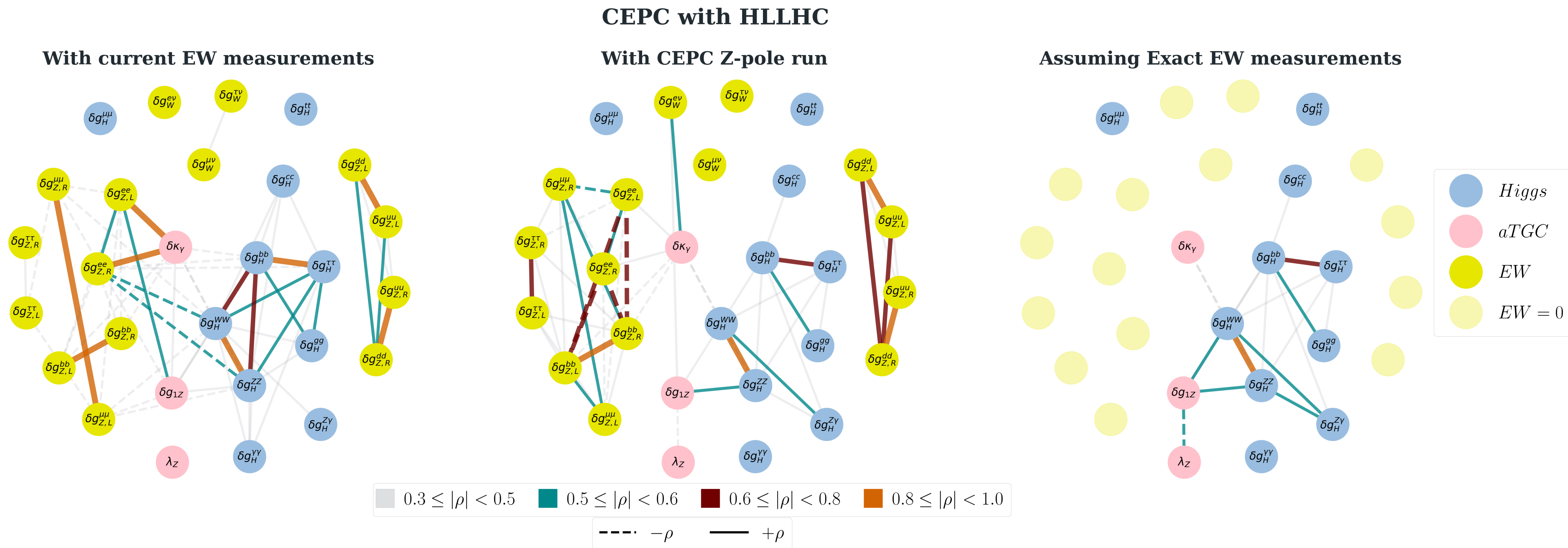
- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics
- LEP EW measurements are a limiting factor to Higgs precision at ILC, especially for the first runs

EW measurement's impact on Higgs

Z pole runs remove some correlations among SM deformations

Decouple Higgs data from EW data

De Blas, Durieux, Grojean, Gu, Paul 'in progress



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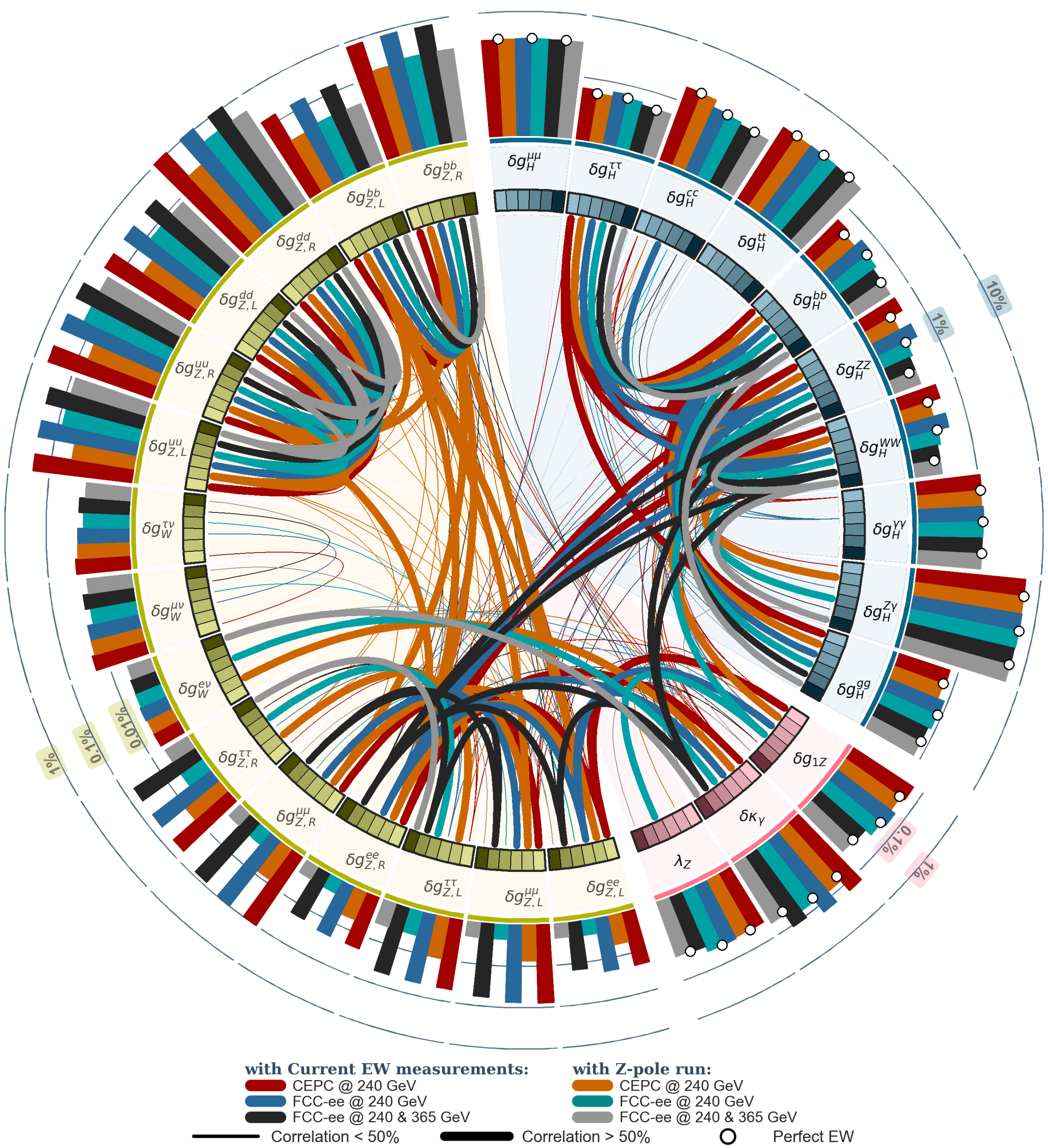

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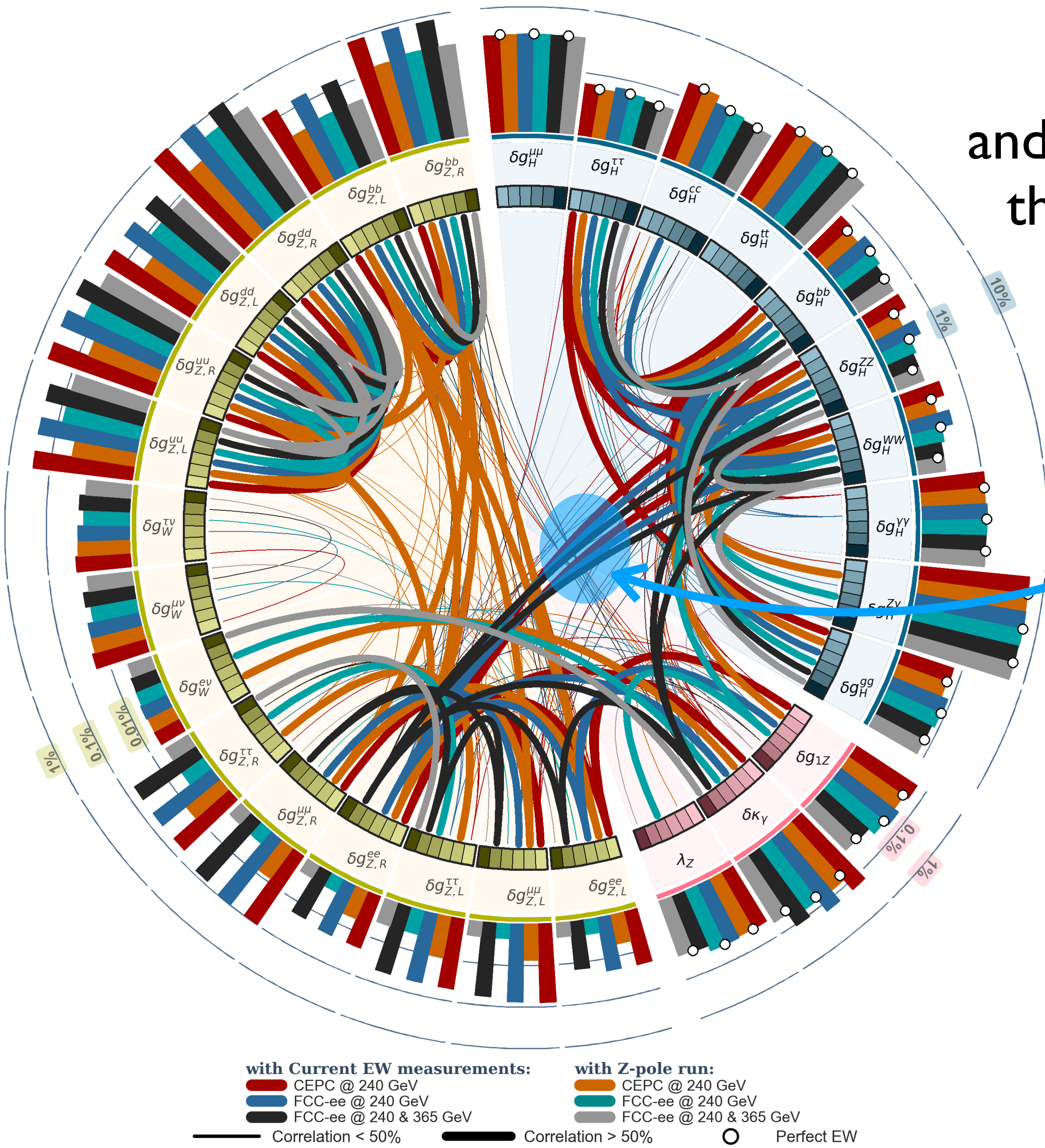

Look carefully at the plot
and you'll see that, with a dedicated Z-pole,
the correlations between Higgs and EW
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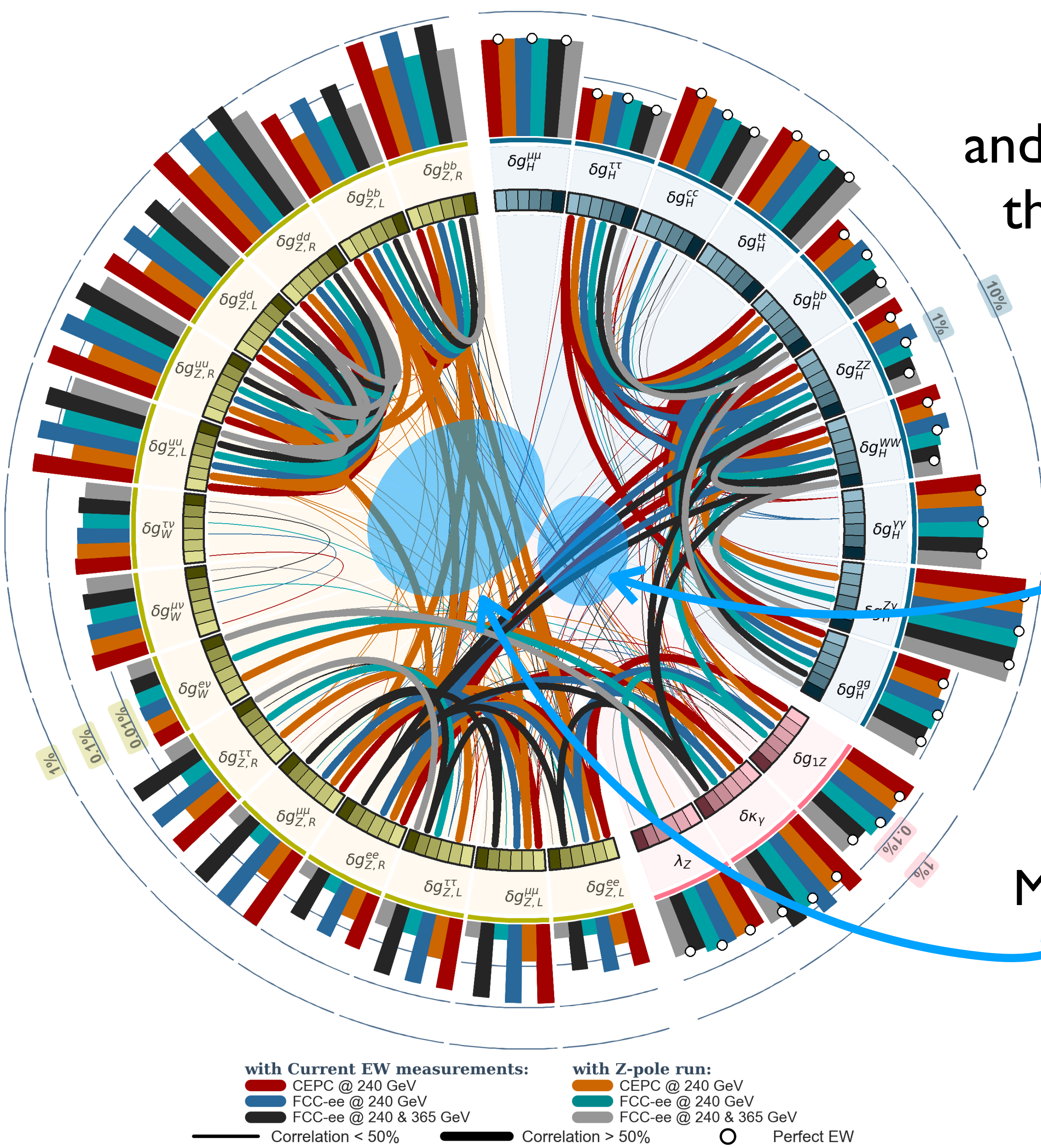

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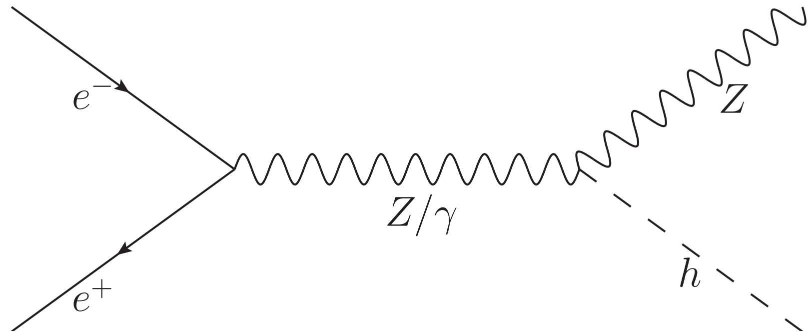
More correlations among EW observables at CEPC240 than at FCC240. Why?

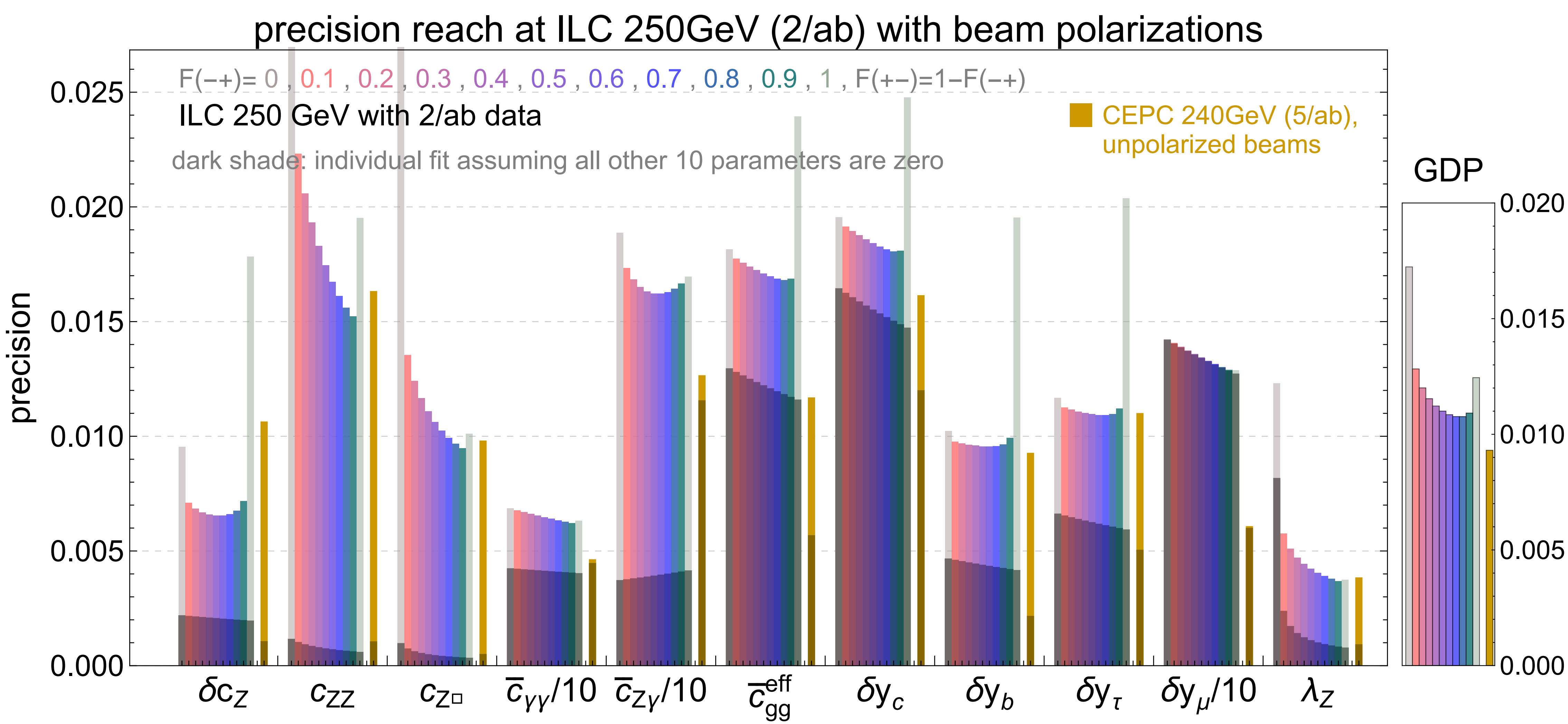
Polarisation Impact



$$\frac{\sigma_{hZ}}{\sigma_{hZ}^{\rm SM}}\Bigg|^{P=\begin{pmatrix}(0,0)\\(-0.8,+0.3)\\(+0.8,-0.3)\end{pmatrix}}_{250\,\rm GeV} \simeq 1+2\,\delta c_Z+1.6\,c_{ZZ}+3.5\,c_{Z\Box}+\begin{pmatrix}0.060\\0.82\\-0.89\end{pmatrix}c_{Z\gamma}+\begin{pmatrix}0.16\\2.2\\-2.3\end{pmatrix}c_{\gamma\Box}\,.$$

The un-polarised xs is accidentally almost insensitive to hZA

Durieux, Grojean, Gu, Wang '17



Polarisation Impact

ILC study: how much luminosity does polarisation buy you?

v0: 25.02.2019

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.66	0.35	0.51	0.36
HWW	0.65	0.35	0.52	0.37
Hbb	1.1	0.58	0.78	0.63
$H\tau\tau$	1.2	0.75	0.86	0.72
Hgg	1.7	0.95	1.2	0.97
Hcc	1.9	1.2	1.3	1.1
$H\gamma\gamma$	1.2	1.0	1.1	1.0
$H\gamma Z$	5.7	2.6	9.0	6.8
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.5	1.6	1.7	1.4
Γ_{inv}	0.36	0.32	0.34	0.30

TABLE XVIII: Projected uncertainties in the Higgs boson couplings computed using the same methodology as in Tab. XVII but including projected improvements in precision electroweak measurements. At this moment (as I understand it - MEP) the uncertainties on precision electroweak results described in the FCC-ee CDR [278] are used in all columns. It would be interesting to add 2 columns with ILC + Gigaz.

Polarisation Impact

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$\text{ILC}_{80/30}$ vs $\text{ILC}_{0/0}$

1st column vs 3rd column of table XVIII?

2/ab polarised ~ 8/ab unpolarised

Factor 4

Polarisation Impact

ILC study: how much luminosity does polarisation buy you?

v0: 25.02.2019

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v3: 05.04.2019

Standard ILC EW

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol	2/ab-350 e^- pol.
HZZ	0.57	0.38	0.69	0.40	0.51
HWW	0.55	0.37	0.67	0.40	0.50
Hbb	1.0	0.60	0.88	0.65	1.0
$H\tau\tau$	1.2	0.77	0.96	0.74	1.3
Hgg	1.6	0.96	1.2	0.98	1.6
Hcc	1.8	1.2	1.4	1.1	2.2
$H\gamma\gamma$	1.1	1.0	1.2	1.0	1.1
$H\gamma Z$	9.1	6.6	9.6	9.1	8.9
$H\mu\mu$	4.0	3.8	3.8	3.7	4.0
Htt	-	6.3	-	-	-
HHH	-	27	-	-	-
Γ_{tot}	2.4	1.6	1.9	1.5	2.4
Γ_{inv}	0.36	0.32	0.34	0.30	0.58
Γ_{other}	1.6	1.2	1.1	0.95	1.6

TABLE XVIII: Projected uncertainties in the Higgs boson couplings computed using the EFT method, with ILC uncertainties per unit of luminosity and assuming a run with the quoted integrated luminosity and energy. The notation is that of Tab. XVI. The first two columns are identical to the ILC values from Tab. XVI. In the last column, we assume ± 80% electron polarisation and zero positron polarisation.

Improved ILC EW

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
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Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

TABLE XIX: Projected uncertainties in the Higgs boson couplings computed using the same methodology as in Tab. XVIII but including projected improvements in precision electroweak measurements. In the first two columns, the polarised collider projections from Tab. XVIII are modified to include an improvement by a factor 10 in A_ℓ, as discussed in Sec. 8.4. In the second two columns, the unpolarised collider projections from from Tab. XVIII are modified to include the improvement of the uncertainties on precision electroweak observables described in the FCC-ee CDR [284].

Polarisation Impact

ILC study: how much luminosity does polarisation buy you?

v0: 25.02.2019

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
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$ILC_{80/30}$ vs $ILC_{0/0}$

1st column vs 3rd column of table XVIII?

Polarisation gain: 73% for HZZ

v3: 05.04.2019

Standard ILC EW

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol	2/ab-350 e^- pol.
HZZ	0.57	0.38	0.69	0.40	0.51
HWW	0.55	0.37	0.67	0.40	0.50
Hbb	1.0	0.60	0.88	0.65	1.0
$H\tau\tau$	1.2	0.77	0.96	0.74	1.3
Hgg	1.6	0.96	1.2	0.98	1.6
Hcc	1.8	1.2	1.4	1.1	2.2
$H\gamma\gamma$	1.1	1.0	1.2	1.0	1.1
$H\gamma Z$	9.1	6.6	9.6	9.1	8.9
$H\mu\mu$	4.0	3.8	3.8	3.7	4.0
Htt	-	6.3	-	-	-
HHH	-	27	-	-	-
Γ_{tot}	2.4	1.6	1.9	1.5	2.4
Γ_{inv}	0.36	0.32	0.34	0.30	0.58
Γ_{other}	1.6	1.2	1.1	0.95	1.6

TABLE XVIII: Projected uncertainties in the Higgs boson couplings computed using the EFT method, with ILC uncertainties per unit of luminosity and assuming a run with the quoted integrated luminosity and energy. The notation is that of Tab. XVI. The first two columns are identical to the ILC values from Tab. XVI. In the last column, we assume ± 80% electron polarisation and zero positron polarisation.

Improved ILC EW

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

TABLE XIX: Projected uncertainties in the Higgs boson couplings computed using the same methodology as in Tab. XVIII but including projected improvements in precision electroweak measurements. In the first two columns, the polarised collider projections from Tab. XVIII are modified to include an improvement by a factor 10 in A_ℓ, as discussed in Sec. 8.4. In the second two columns, the unpolarised collider projections from from Tab. XVIII are modified to include the improvement of the uncertainties on precision electroweak observables described in the FCC-ee CDR [284].

Polarisation Impact

ILC study: how much luminosity does polarisation buy you?

v0: 25.02.2019

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.66	0.35	0.51	0.36
HWW	0.65	0.35	0.52	0.37
Hbb	1.1	0.58	0.78	0.63
$H\tau\tau$	1.2	0.75	0.86	0.72
Hgg	1.7	0.95	1.2	0.97
Hcc	1.9	1.2	1.3	1.1
$H\gamma\gamma$	1.2	1.0	1.1	1.0
$H\gamma Z$	5.7	2.6	9.0	6.8
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.5	1.6	1.7	1.4
Γ_{inv}	0.36	0.32	0.34	0.30

TABLE XVIII: Projected uncertainties in the Higgs boson couplings computed using the same methodology as in Tab. XVII but including projected improvements in precision electroweak measurements. At this moment (as I understand it - MEP) the uncertainties on precision electroweak results described in the FCC-ee CDR [278] are used in all columns. It would be interesting to add 2 columns with ILC + Gigaz.

v3: 05.04.2019

Standard ILC EW

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol	2/ab-350 e^- pol.
HZZ	0.57	0.38	0.69	0.40	0.51
HWW	0.55	0.37	0.67	0.40	0.50
Hbb	1.0	0.60	0.88	0.65	1.0
$H\tau\tau$	1.2	0.77	0.96	0.74	1.3
Hgg	1.6	0.96	1.2	0.98	1.6
Hcc	1.8	1.2	1.4	1.1	2.2
$H\gamma\gamma$	1.1	1.0	1.2	1.0	1.1
$H\gamma Z$	9.1	6.6	9.6	9.1	8.9
$H\mu\mu$	4.0	3.8	3.8	3.7	4.0
Htt	-	6.3	-	-	-
HHH	-	27	-	-	-
Γ_{tot}	2.4	1.6	1.9	1.5	2.4
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Improved ILC EW

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
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$ILC_{80/30}$ vs $ILC_{0/0}$

1st column vs 3rd column of table XVIII?

Polarisation gain: 73% for HZZ

1st column vs 3rd column of table XIX?

Polarisation gain: 40% for HZZ

i.e. 2/ab polarised ~ 3.4/ab for unpolarised

Polarisation Impact

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v0: 25.02.2019

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.66	0.35	0.51	0.36
HWW	0.65	0.35	0.52	0.37
Hbb	1.1	0.58	0.78	0.63
$H\tau\tau$	1.2	0.75	0.86	0.72
Hgg	1.7	0.95	1.2	0.97
Hcc	1.9	1.2	1.3	1.1
$H\gamma\gamma$	1.2	1.0	1.1	1.0
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$H\tau\tau$	1.2	0.77	0.96	0.74	1.3
Hgg	1.6	0.96	1.2	0.98	1.6
Hcc	1.8	1.2	1.4	1.1	2.2
$H\gamma\gamma$	1.1	1.0	1.2	1.0	1.1
$H\gamma Z$	9.1	6.6	9.6	9.1	8.9
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$ILC_{80/30}$ vs $ILC_{0/0}$

1st column vs 3rd column of table XVIII?

Polarisation gain: 73% for HZZ

1st column vs 3rd column of table XIX?

Polarisation gain: 40% for HZZ

i.e. 2/ab polarised ~ 3.4/ab for unpolarised

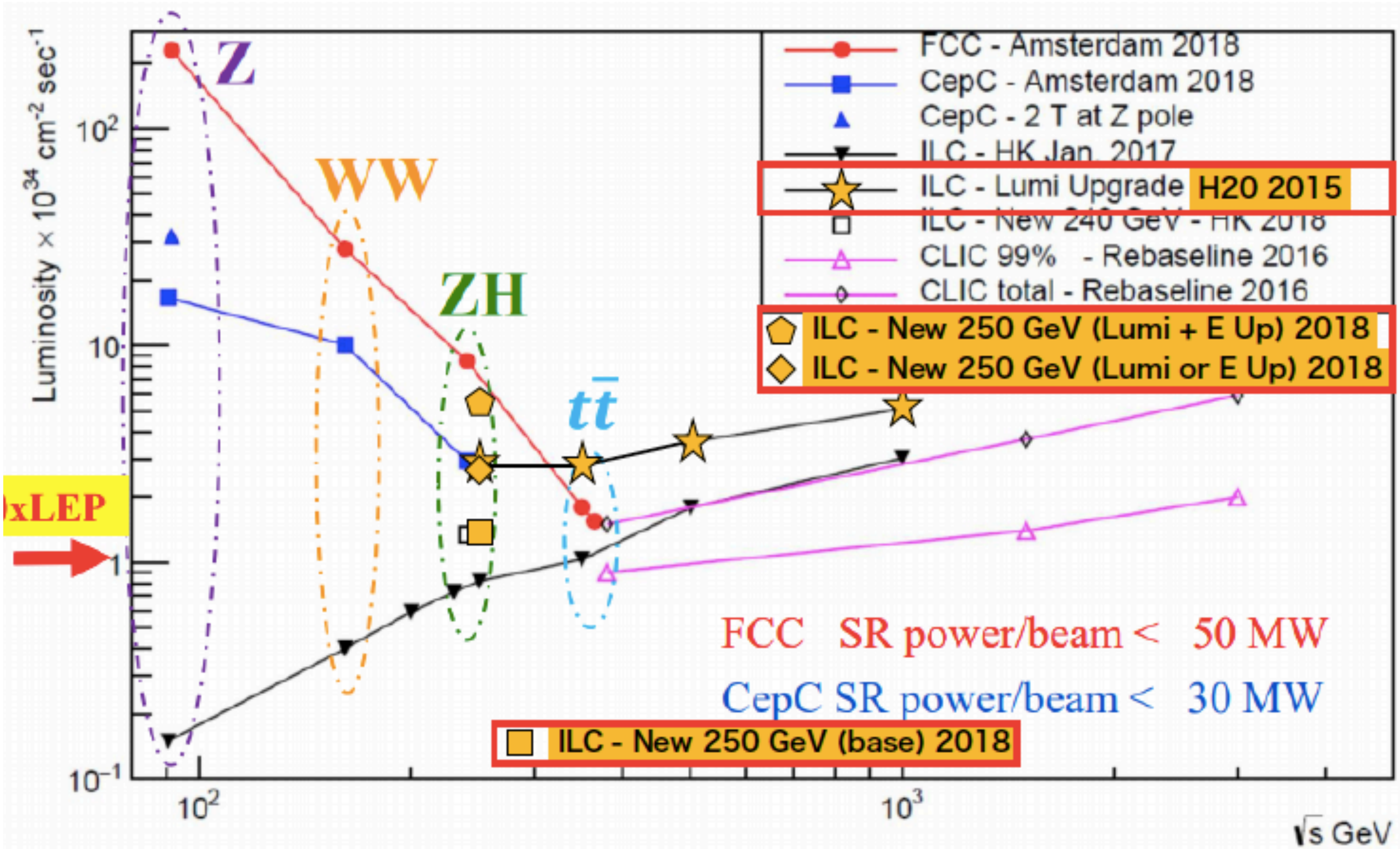
ILC vs. FCC-ee?

1st column of table XVIII vs 4th column of table XIX?

Polarisation gain: 33% for HZZ

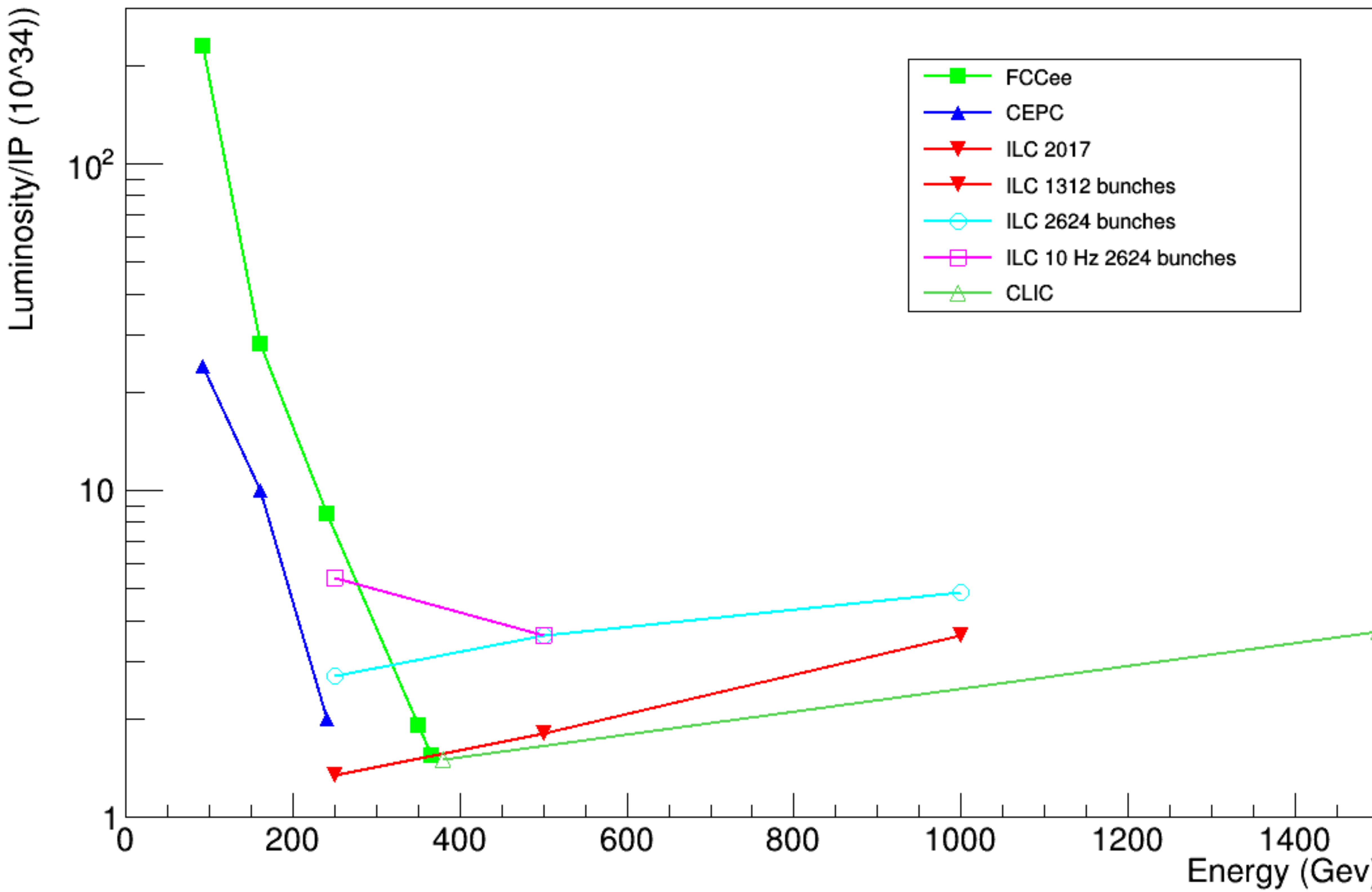
Luminosity Plots

Taylor, HK 2019



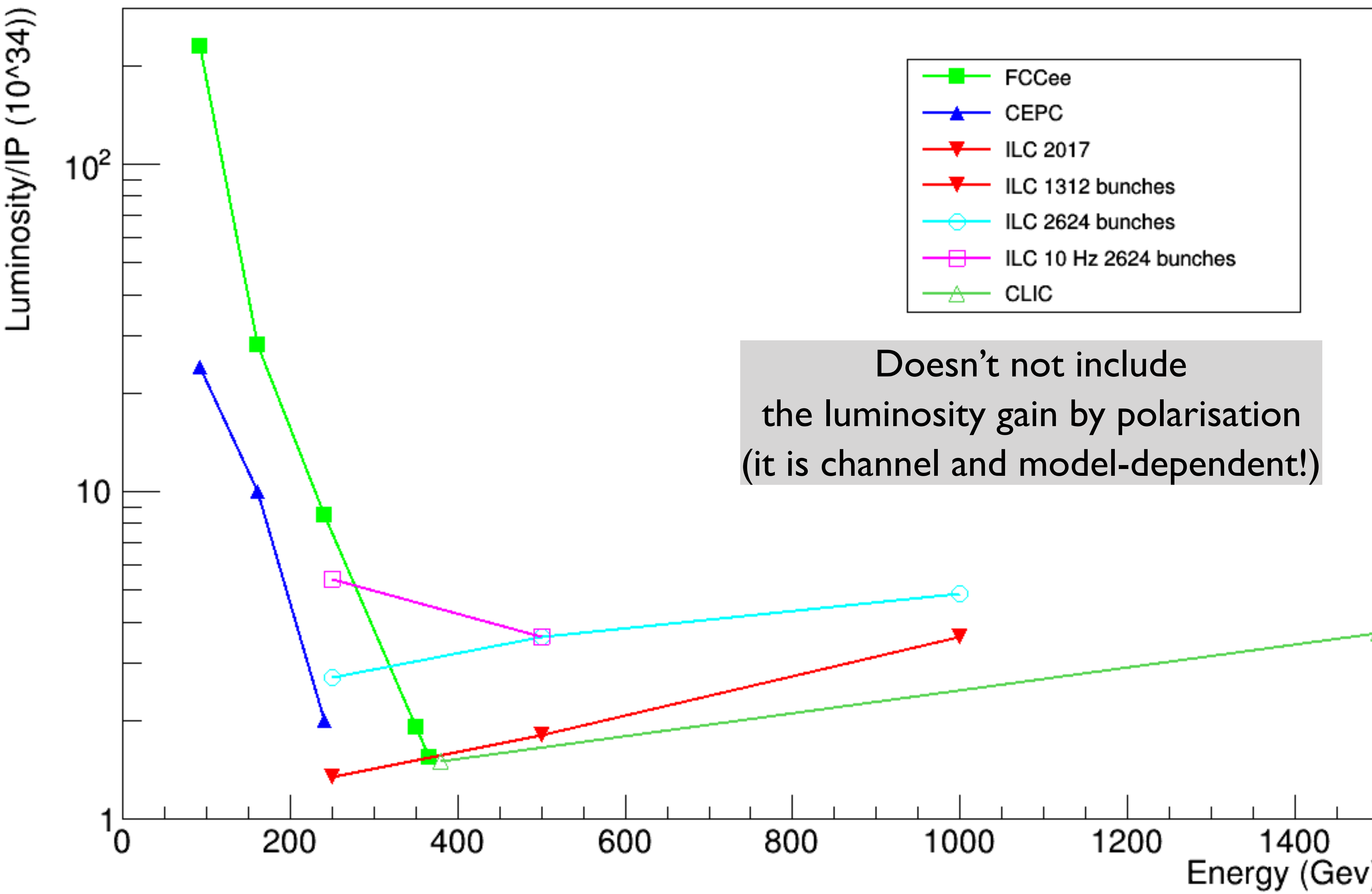
Luminosity Plots

Stanitzki, CEPC Oxford 2019



Luminosity Plots

Stanitzki, CEPC Oxford 2019

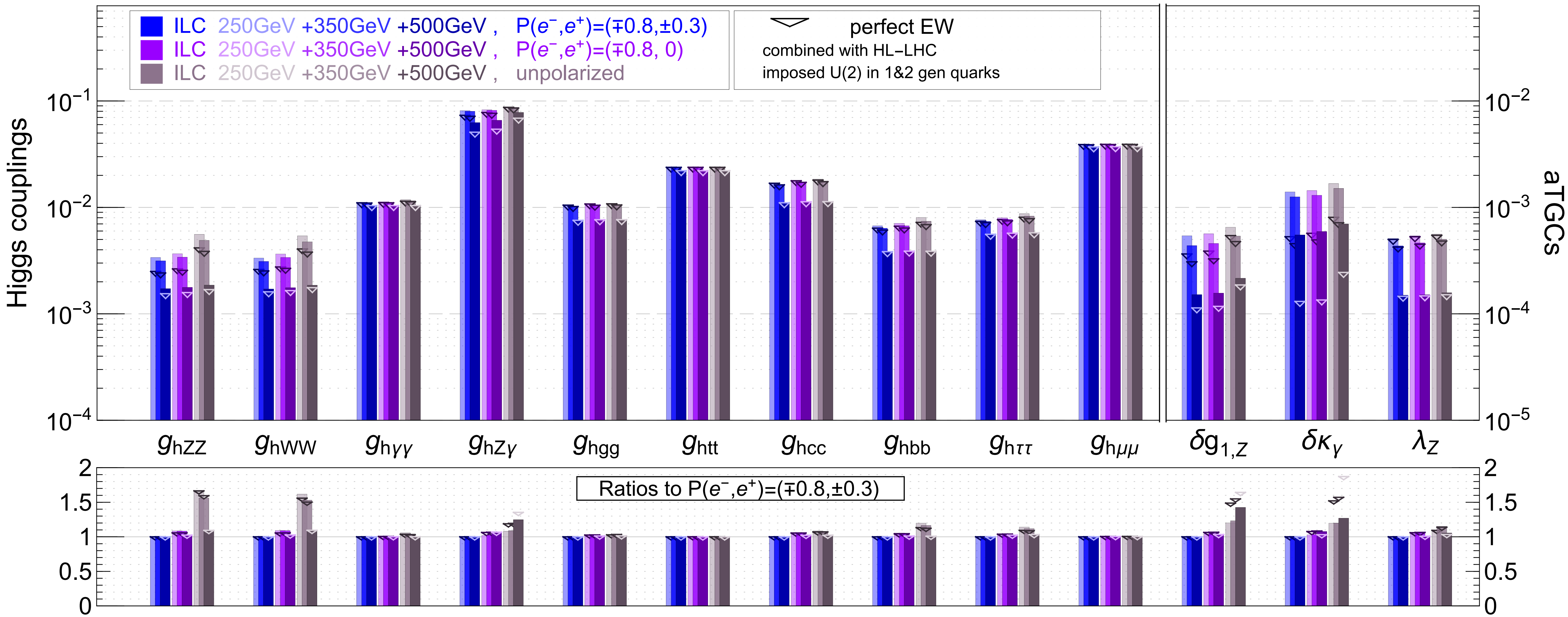


Doesn't not include
the luminosity gain by polarisation
(it is channel and model-dependent!)

Polarisation Impact

De Blas, Durieux, Grojean, Gu, Paul 'in progress

precision reach on effective couplings from full EFT global fit



(assuming the total luminosity is equally divided in +- and -+)

Polarisation does matter because it helps lifting some degeneracies among operators
Other runs at higher energies does the same.
That's why polarisation benefit fades away for 250+350+500 runs.
Question: can other kin. distribution at 250 GeV compensate for the absence of polarisation?

The missing beast: Higgs self-coupling

The Higgs self-coupling plays important roles

1) controls the quantum corrections to m_H (hierarchy problem)

2) dictates the dynamics of EW phase transition and potentially conditions the generation of a matter-antimatter asymmetry via EW baryogenesis

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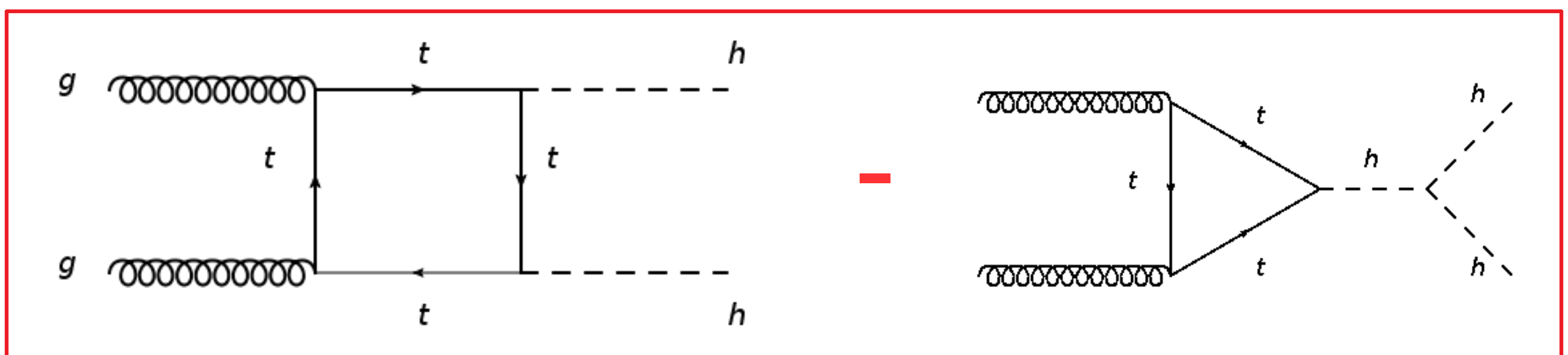
Does it need to be measured with high accuracy?

difficult to design new physics scenarios that dominantly affect the Higgs self-couplings and leave the other Higgs coupling deviations undetectable



$$\frac{\sigma(pp \to hh)}{\sigma(pp \to h)} \sim 10^{-3}$$

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Under the assumption of heavy/decoupling new physics (i.e. analytic EFT Lagrangian)

deviation of Higgs cubic self-coupling can be a priori large

Perturbativity: $\kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} - 1 < 600\,\xi$ where ξ is the typical deviation in single Higgs couplings

Stability of EW vacuum: $\kappa_3 < 70\,\xi$

O(1) sensitivity in Higgs self-coupling is competitive to **5%** sensitivity in single Higgs couplings

Relevant for particular models, e.g. Higgs DM-portal models, not for composite/susy

DiVita et al,: 1704.01953

Falkowski, Rattazzi: 1902.05936

The missing beast: Higgs self-coupling

The Higgs self-coupling plays important roles

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Does it need to be measured with high accuracy?

difficult to design new physics scenarios that dominantly affect the Higgs self-couplings and leave the other Higgs coupling deviations undetectable

What sort of precision should we aim for?

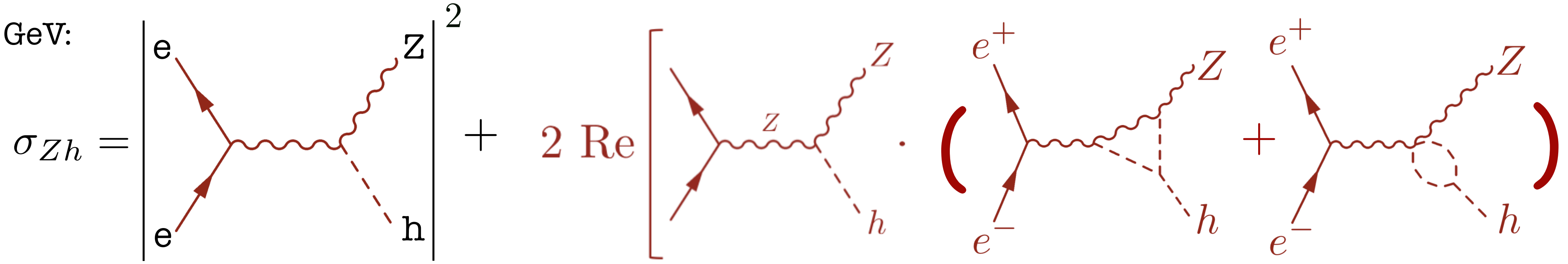
- 95% confidence it exists: Around 50% accuracy
- 5σ discovery: Around 20 % accuracy.
- Quantum structure: Around 5% accuracy.

M. McCullough, DESY'18

h³ from h@NLO

M. McCullough '14

At 240 GeV:



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

h³ from h@NLO

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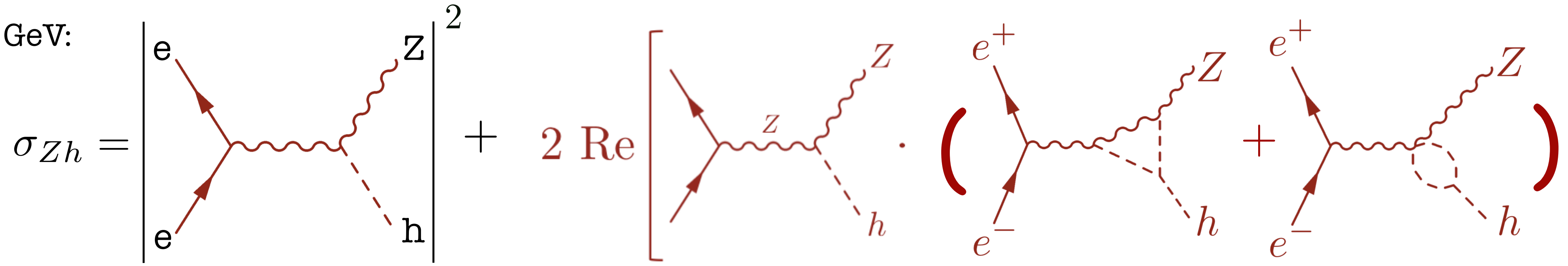

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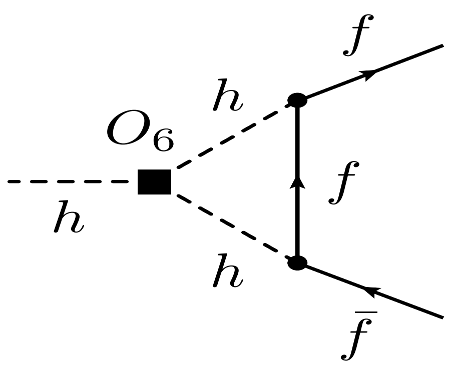
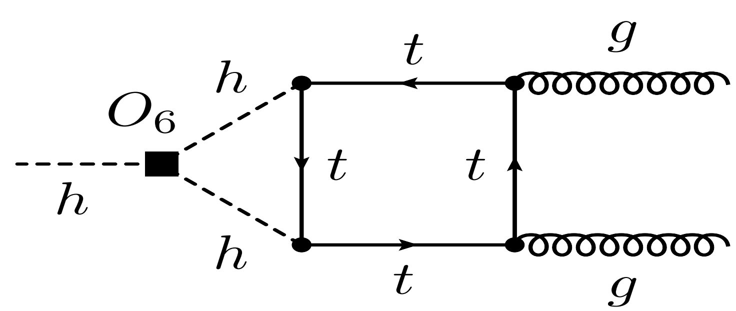
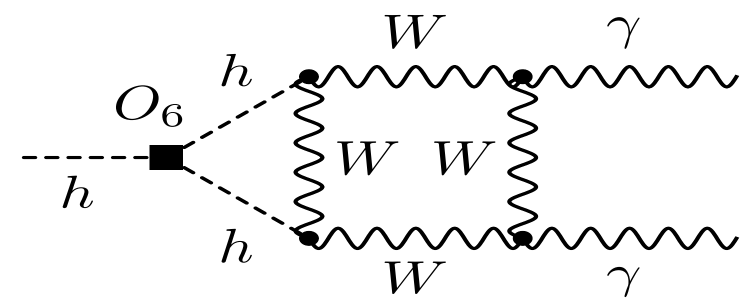
Gorbahn et al '16

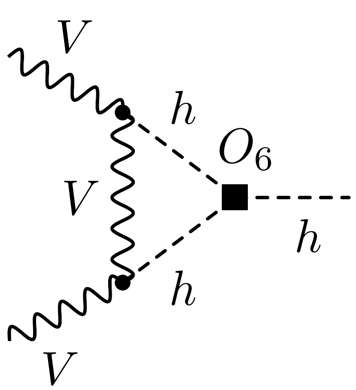
Degrassi et al '16

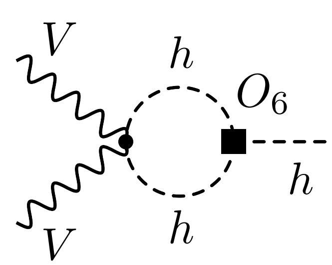
Bizon et al '16

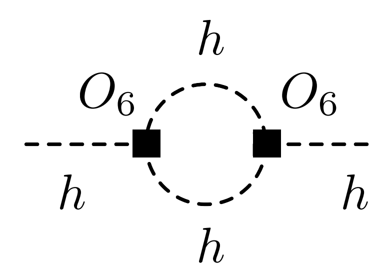




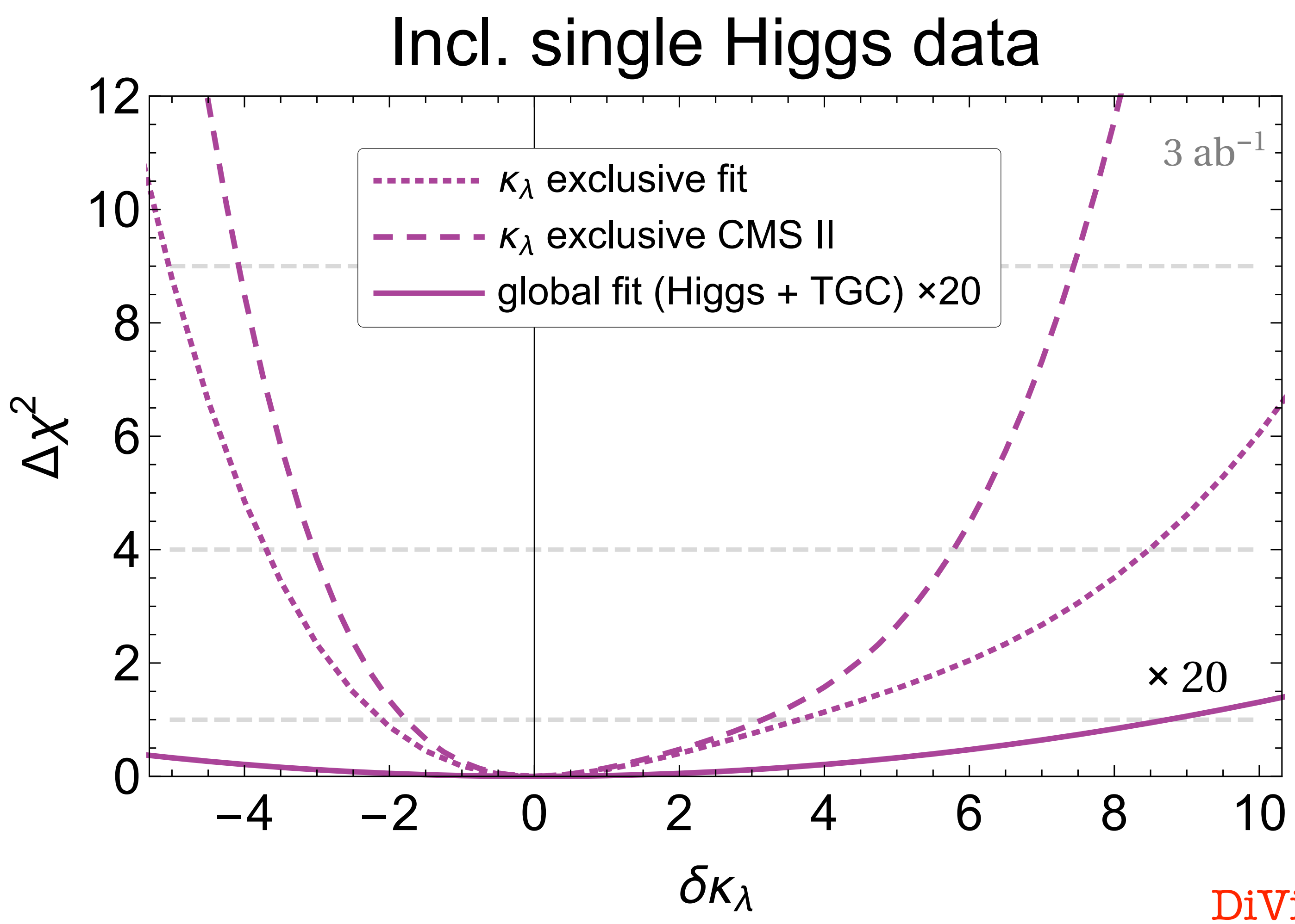








h^3 from h@NLO



DiVita et al '17

At hadron colliders, deviation of h^3 cannot be separated from deviations of other Higgs couplings!

flat direction!

Low energy e^+e^- colliders?

1 main production mode (ZH) & 1 subdominant production (VBF)
+ access to full angular distributions (4) and/or beam polarizations (2)
7 (+2) accessible decay modes: ZZ, WW, $\gamma\gamma$, Zγ, $\tau\tau$, bb, gg, (cc, μμ)

no flat direction is expected!

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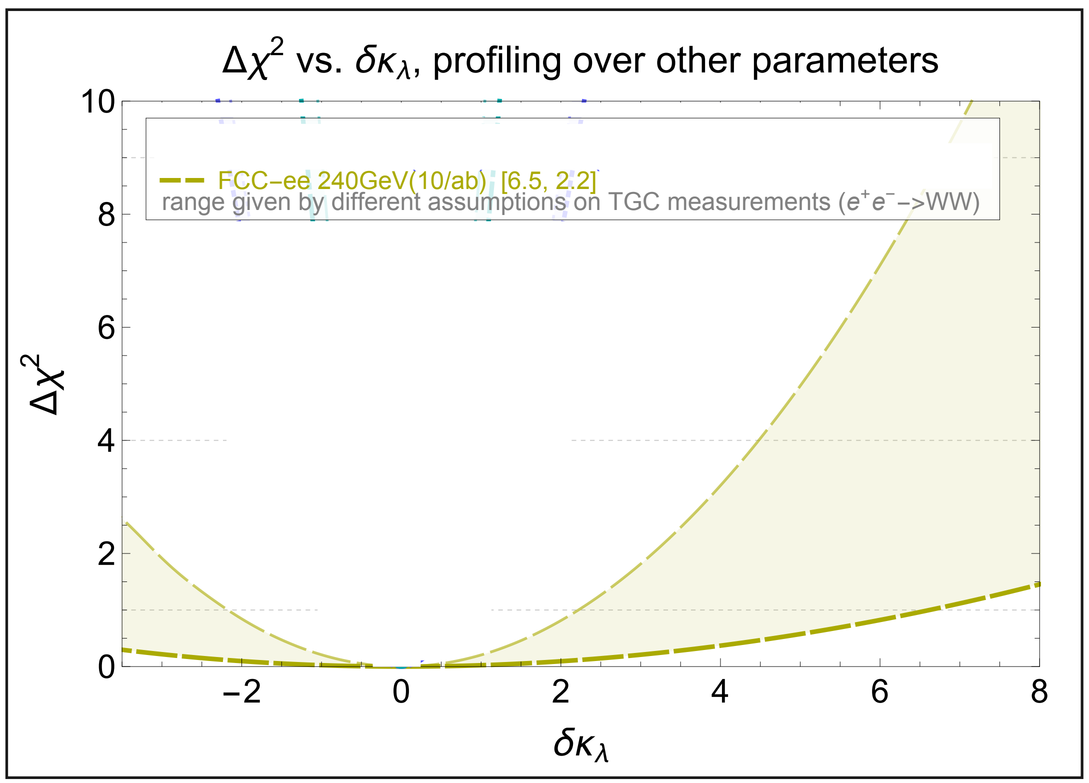

S. Di Vita +, '17

See also F. Maltoni +. '18

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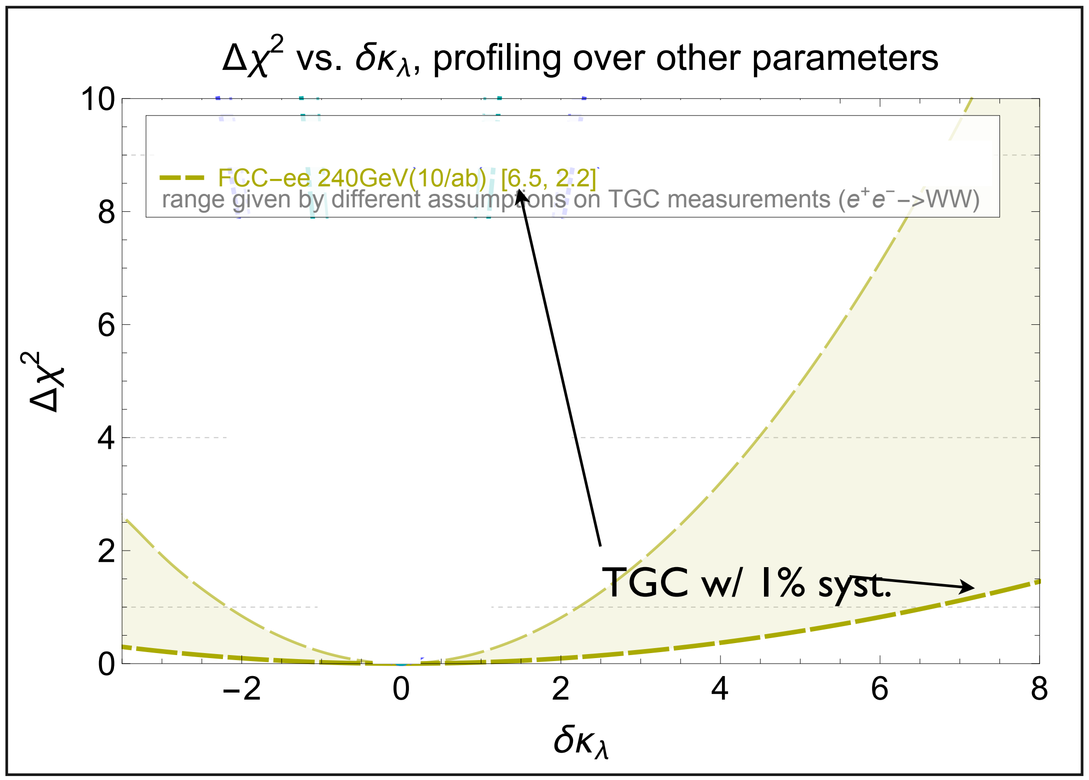

1) with a run at 240 GeV only, bound starts to become meaningful only if perfect control of di-boson

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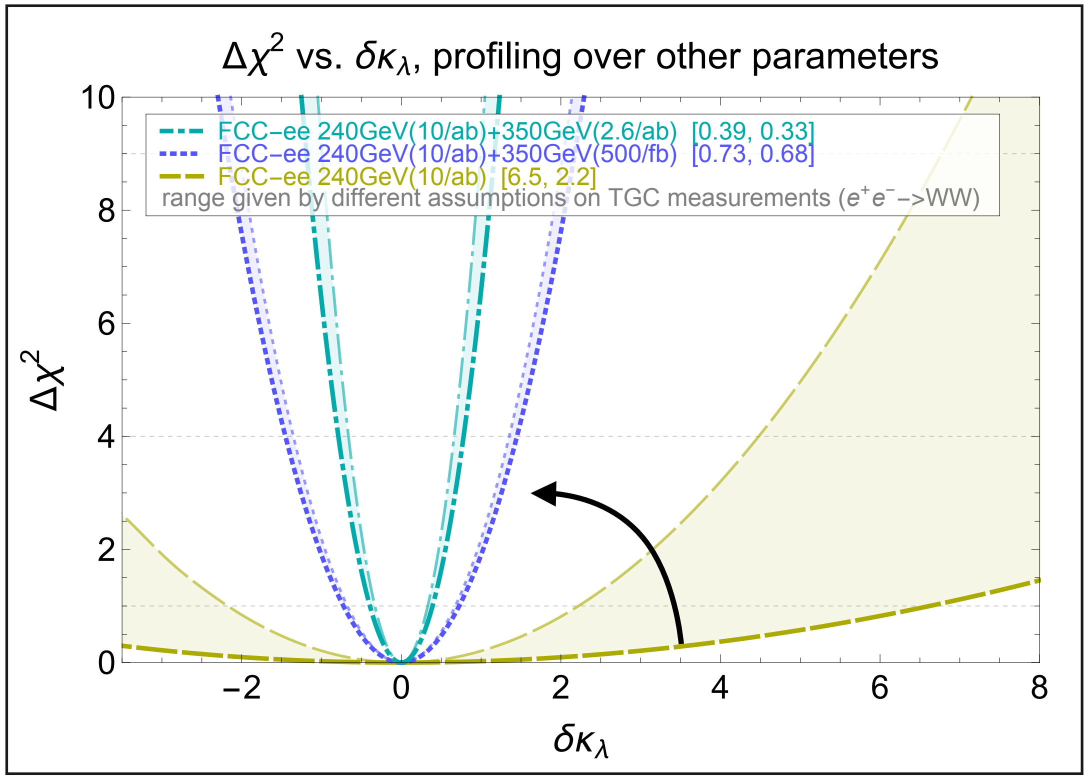

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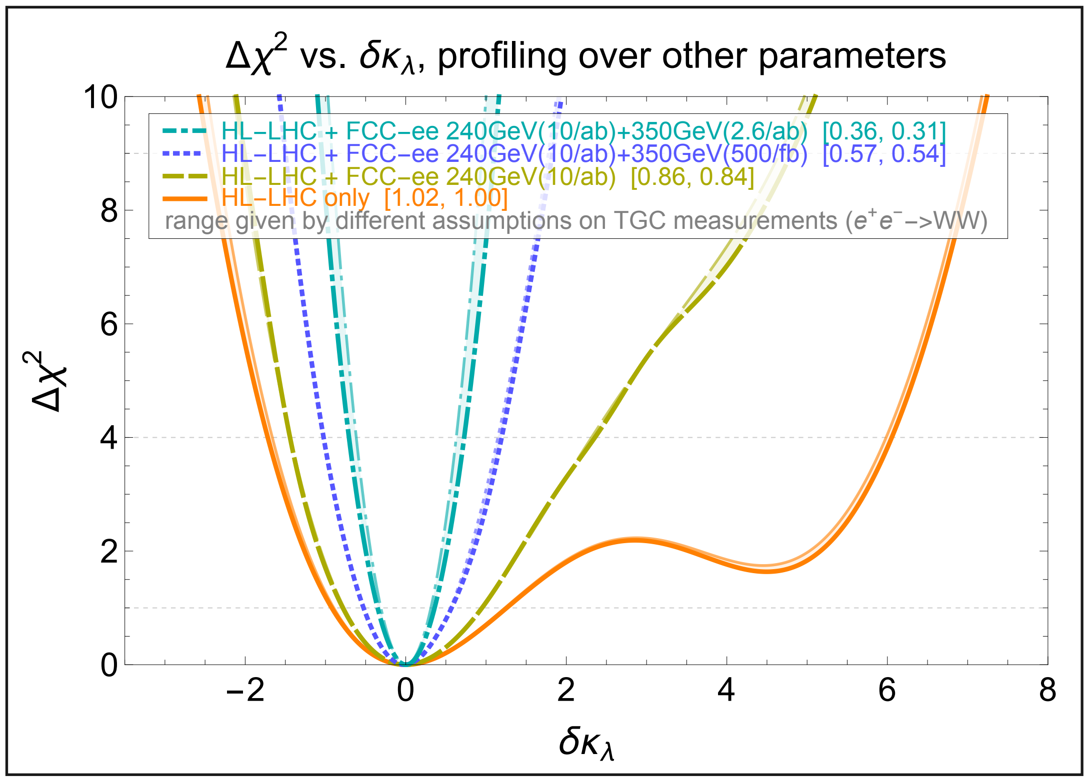

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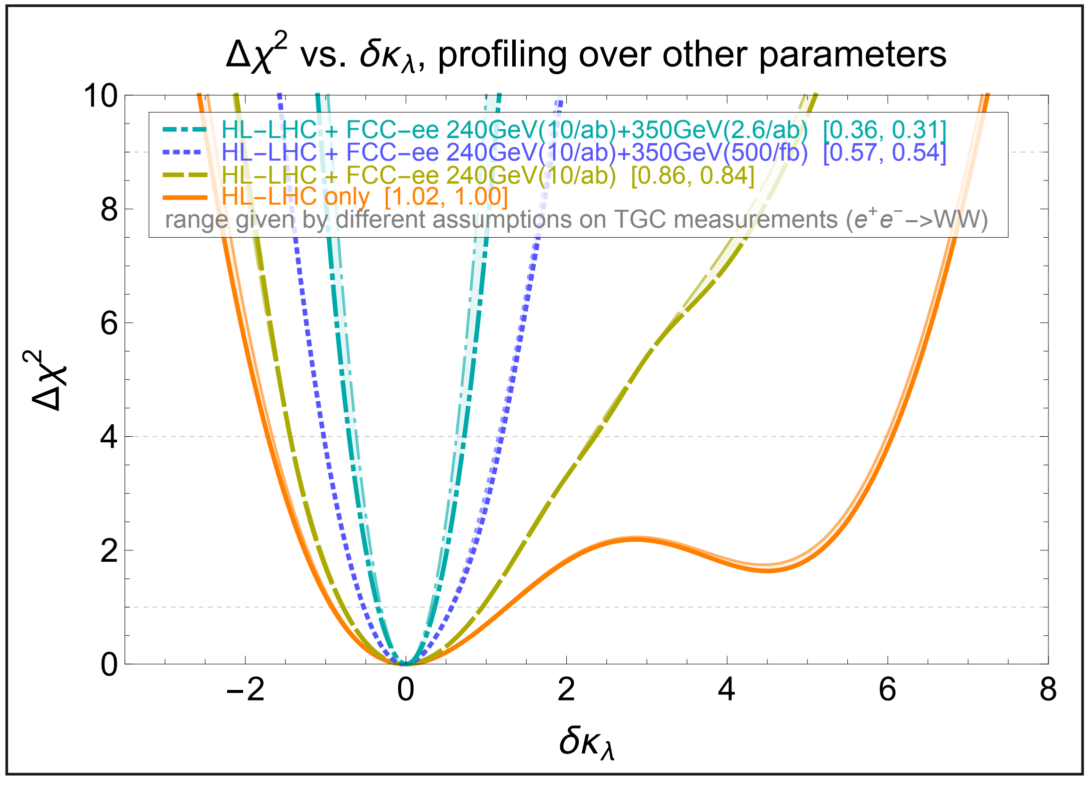

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Don't need HE ee to measure h^3

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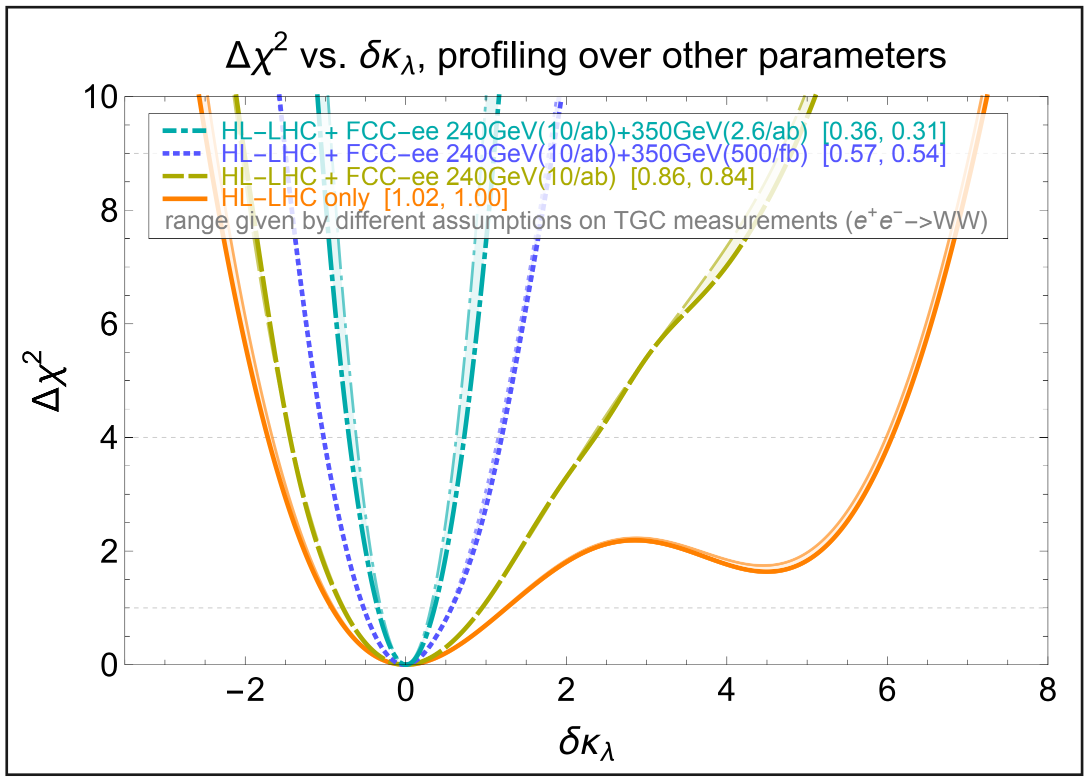

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But a run @ 240 GeV alone is not enough

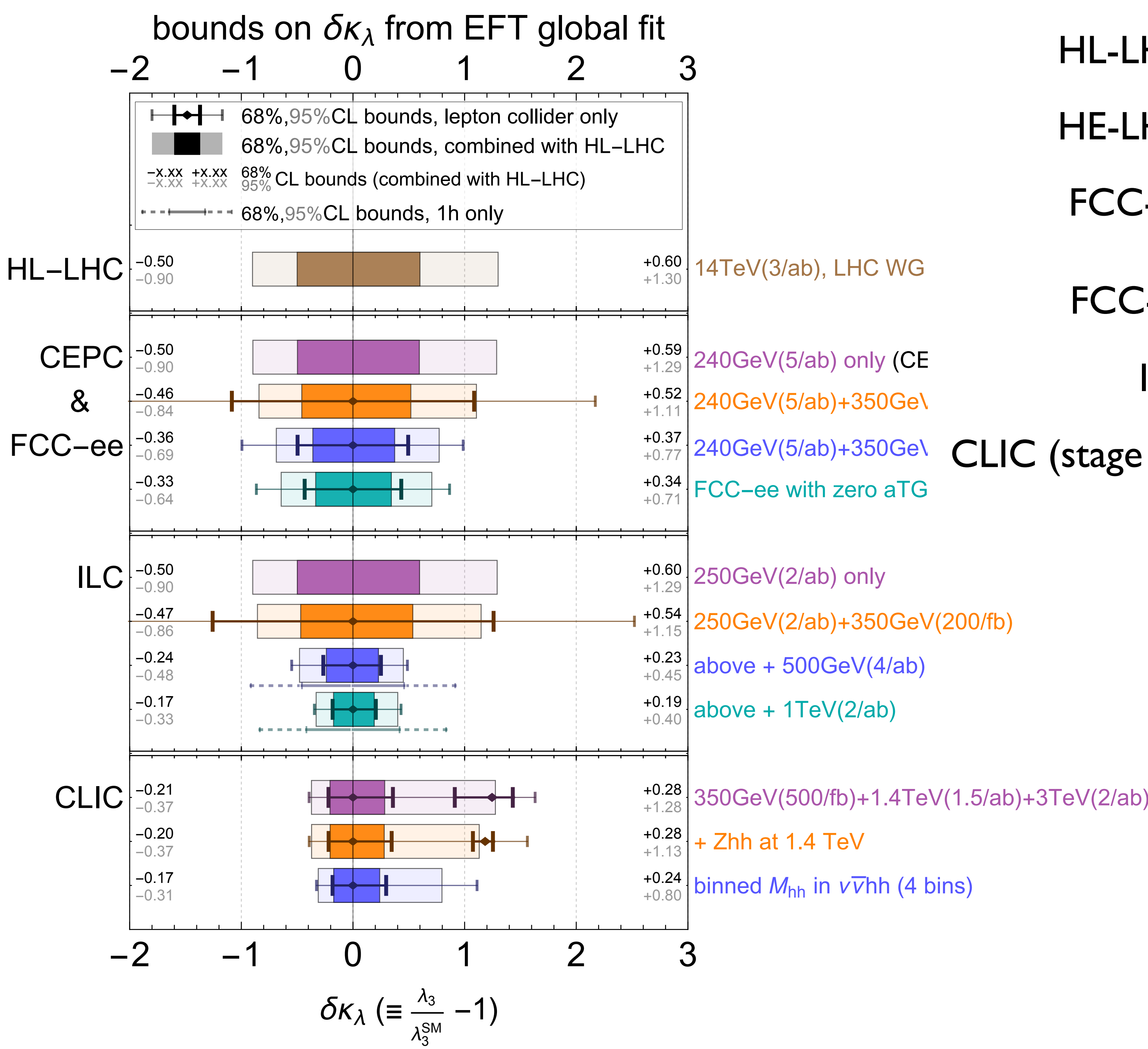
Stress that sensitivity on Higgs cubic self-couplings is often obtained in many different ways:

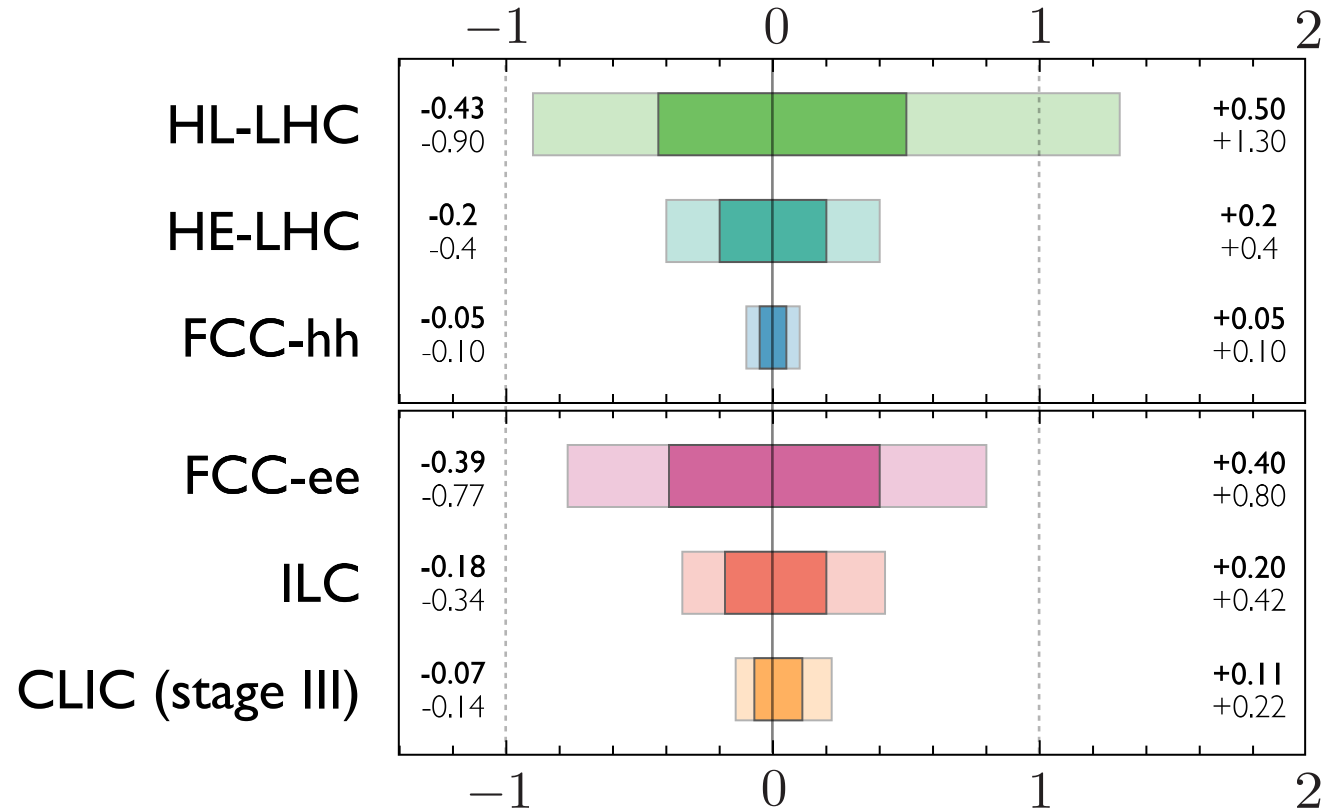
1. an exclusive analysis of HH production, i.e., a fit of the double Higgs cross section considering only deformation of the Higgs cubic coupling;
2. a global analysis of HH production, i.e., a fit of of the double Higgs cross section considering also all possible deformations of the single Higgs couplings that are already constrained by single Higgs processes;
   (a) the global fit does not consider the effects at higher order of the modified Higgs cubic coupling to single Higgs production and to Higgs decays;
   (b) these higher order effects are included;
3. an exclusive analysis of single Higgs processes at higher order, i.e., considering only deformation of the Higgs cubic coupling;
4. a global analysis of single Higgs processes at higher order, i.e., considering also all possible deformations of the single Higgs couplings.

collider	method 1	method 2.a	method 3	method 4
HL-LHC	50%	being evaluated	150%	270%
HE-LHC	10-20%		46%	50%
FCC-hh	5%		tba	25%♦
ILC_{250}	–		tba	47%♦
ILC_{350}	–		tba	44%♦
ILC_{500}	23%		tba	36%♦
$CLIC_{380}$	–		tba	49%♦
$CLIC_{1500}$	36%		tba	48%♦
$CLIC_{3000}$	$^{+11}_{-7}\%$		tba	47% ♦
$FCC\text{-}ee_{240}$	–		50%♦	46%♦
$FCC\text{-}ee_{365}$	–		12%♦	32%♦
CEPC	–		tba	46%♦

h^3 prospects

DiVita et al, arXiv: 1711.03978
(updated with latest HL-LHC) projections





Dark: 68%CL, Light: 95%CL

ee colliders
will establish at 95%CL that
the Higgs self-coupling exists
ILC will establish it at 5σ
FCC-hh will probe
the quantum corrections
of the Higgs potential