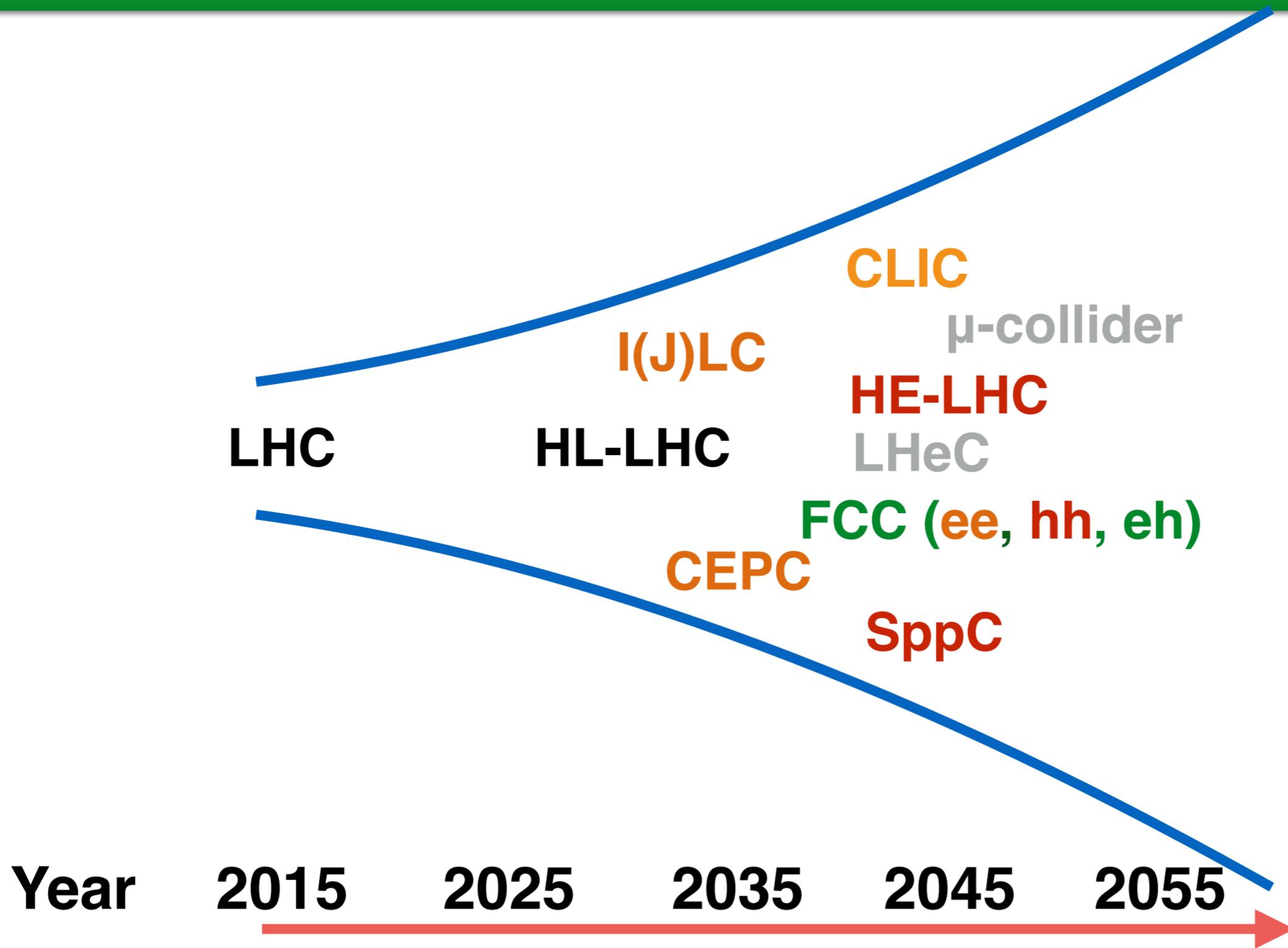




Work in progress!



Future Collider Landscape



How will our understanding of Higgs boson couplings evolve?

The Inputs



➔LHC and HL-LHC

- Using arXiv:1307.7135
- Several updates are available but not in a coherent form
- ATLAS and CMS are working on updates for the HL(HE) - LHC Yellow report
- Following the discussions closely

➔FCC-ee

- Work in progress
- Using scaled results from arXiv:1308.6176

➔FCC-ep

- Looking at talk at 2nd FCC physics workshop in Jan '18
 - https://indico.cern.ch/event/618254/contributions/2833243/attachments/1583310/2502817/FCC_CERN_16.01.2018.pdf

➔FCC-pp

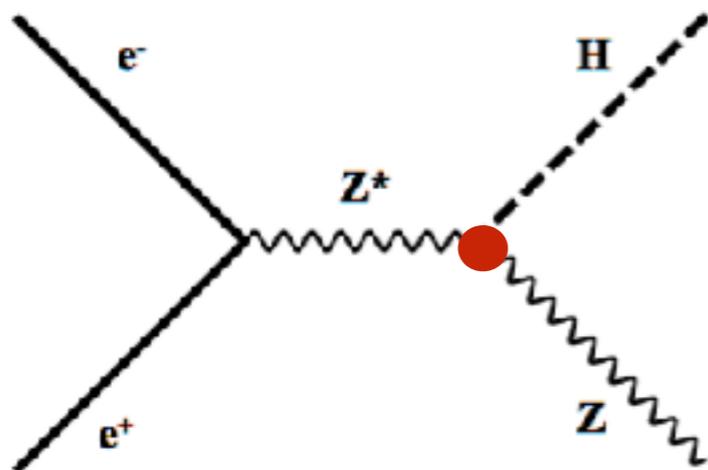
- Looking at talk at 2nd FCC physics workshop in Jan '18 and FCC-pp Higgs report
 - https://indico.cern.ch/event/618254/contributions/2833244/attachments/1583341/2502519/higgs_2ndFCCWS.pdf

Higgs coupling to Z bosons

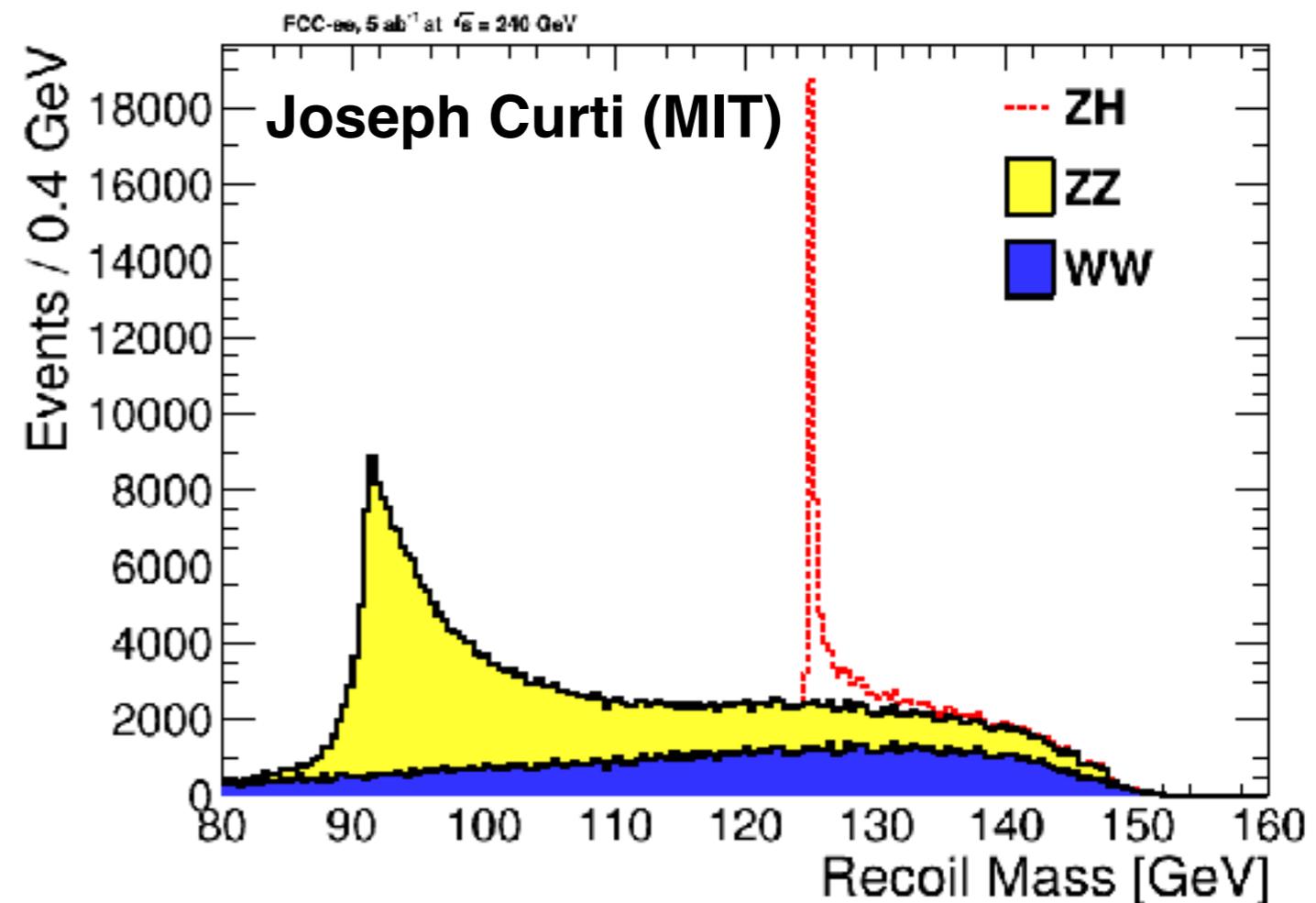
➔ Recoil method provides unique opportunity for model independent measurement of HZ coupling

- ⦿ Higgs events are tagged Higgs decay mode independent
- ⦿ Expected precision **~0.5%** on ZH cross section
- ⦿ Using only leptonic Z decays and only measurement at 240 GeV so far

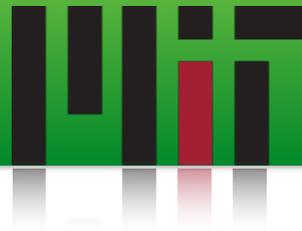
$$\sigma(ee \rightarrow ZH) \propto g_{HZ}^2$$



$$m_R^2 = (\sqrt{s} - E_H)^2 - |\vec{p}_H|^2$$



Total Higgs Boson Width



➔ Total Higgs boson width can be extracted from a combination of measurements in a model independent way

⊙ 1) tagging Higgs final states

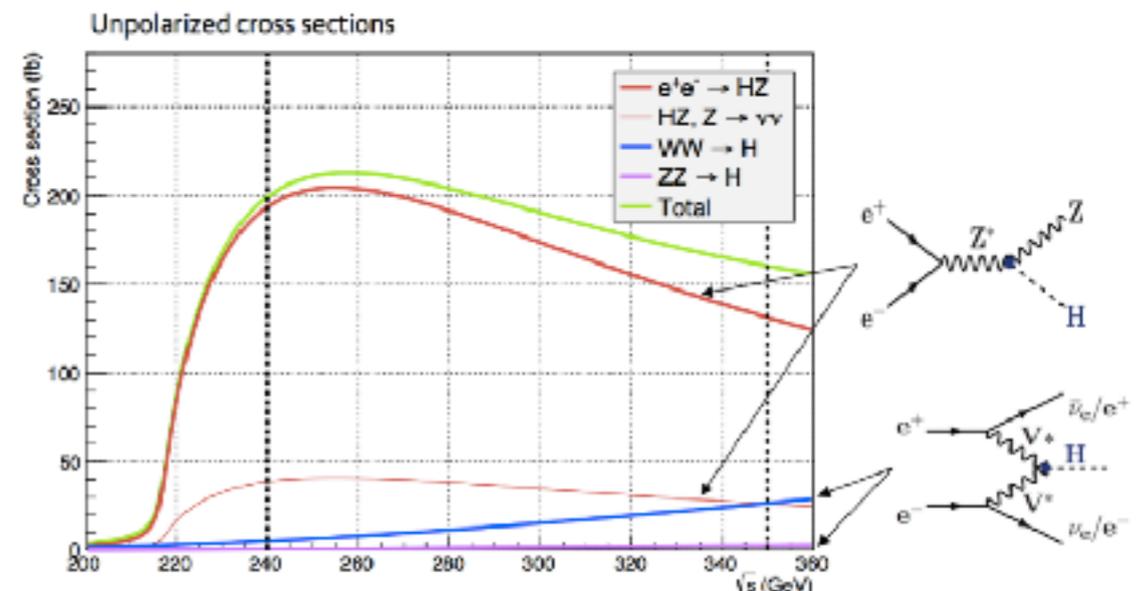
$$\sigma(ee \rightarrow ZH) \cdot \text{BR}(H \rightarrow ZZ) \propto \frac{g_{HZ}^4}{\Gamma}$$

⊙ 2) measurements of vector boson fusion production at 350 GeV

$$\frac{\sigma(ee \rightarrow ZH) \cdot \text{BR}(H \rightarrow WW) \cdot \sigma(ee \rightarrow ZH) \cdot \text{BR}(H \rightarrow bb)}{\sigma(ee \rightarrow \nu\nu H) \cdot \text{BR}(H \rightarrow bb)}$$

$$\propto \frac{g_{HZ}^2 \cdot g_{HW}^2}{\Gamma} \cdot \frac{g_{HZ}^2 \cdot g_{Hb}^2}{\cancel{\Gamma}} \cdot \frac{\cancel{\Gamma}}{g_{HW}^2 \cdot g_{Hb}^2} = \frac{g_{HZ}^4}{\Gamma}$$

⊙ 3) combination of all measurements

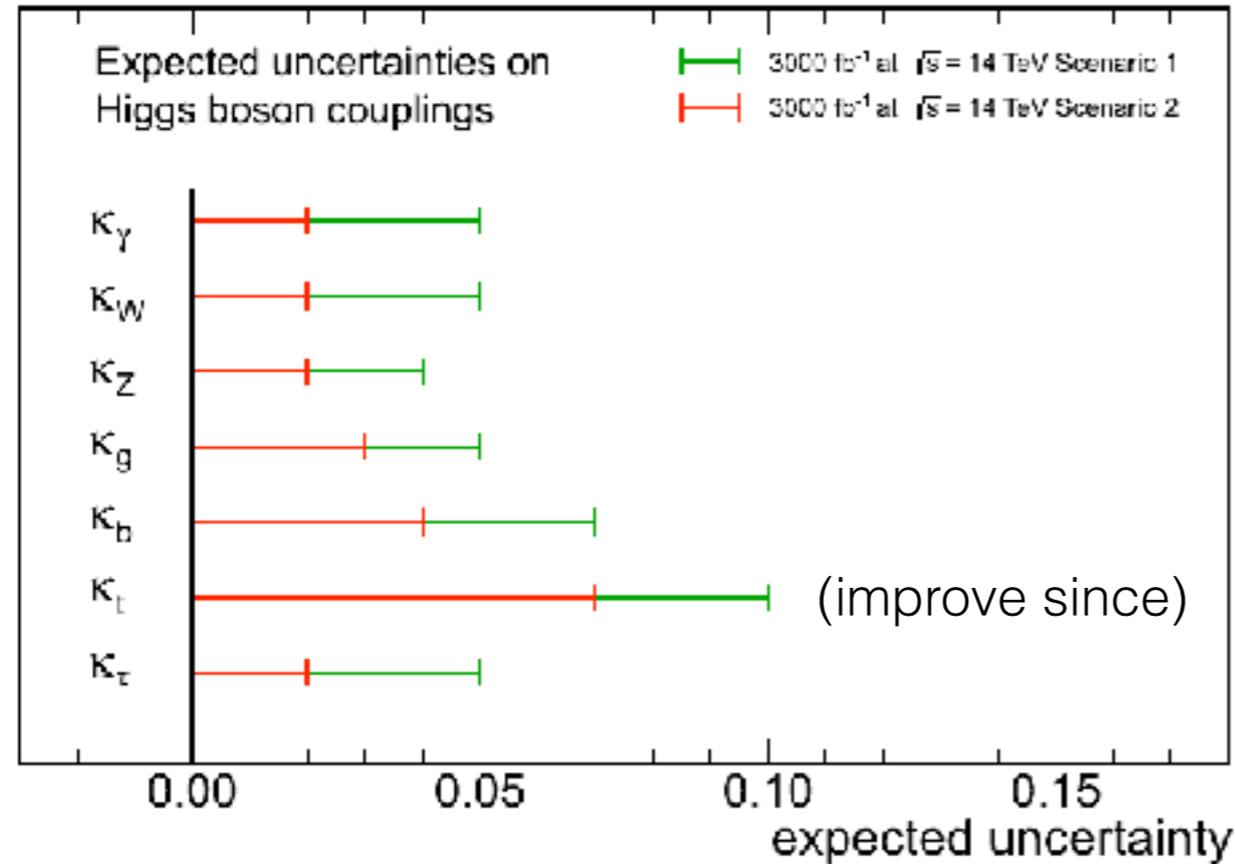


HL-LHC Results



➔ LHC and HL-LHC: extrapolation using Run I results

CMS Projection



Coupling Fits rely on assumption on total Higgs width

Key question is the evolution systematic uncertainty

Assumptions made on cross section uncertainties already superseded

Assuming Scenario 2 or better can be achieved

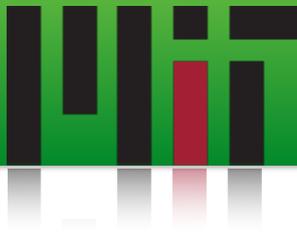
L (fb ⁻¹)	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z,\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

(improves to 5%)



➔ LHC and HL-LHC

- Hadron Collider Higgs coupling measurement rely on assumption on the total Higgs width
- When adding FCC-ee (lepton collider) Higgs measurement, the assumption on the total Higgs width are not longer necessary
 - This turns Higgs coupling results into coupling measurements
 - In addition, the uncertainties on the total Higgs width through the correlation of the measurements is not longer relevant



➔ Hadron collider couplings fits

- Correlation of uncertainties in measurements due to total width
- Γ_b is most prominent
- Noteworthy that statistical uncertainties in measurements are significantly smaller than quoted results
- Tuned ratio measurements can explore statistical power
- These results can be enabled with FCC-ee measurements
 - Updates to HL-LHC studies should consider this
 - Studies for the Higgs boson at FCC-ep and FCC-pp should be aware

L (fb ⁻¹)	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR _{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

L (fb ⁻¹)	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ / κ_Z	κ_W / κ_Z	κ_b / κ_Z	κ_τ / κ_Z	κ_Z / κ_g	κ_t / κ_g	κ_μ / κ_Z	$\kappa_{Z\gamma} / \kappa_Z$
300	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

HE-LHC



➔ Simple extrapolation for Higgs Physics

- ⦿ 4 times larger dataset, better detectors, more difficult environment
- ⦿ 2.5 times larger cross section for single Higgs production
- ⦿ 5 times larger cross section for double Higgs production

➔ Effective statistical gain in Higgs measurements w.r.t HL-LHC

- ⦿ Factor 3 for single Higgs
- ⦿ Factor 5 for double Higgs

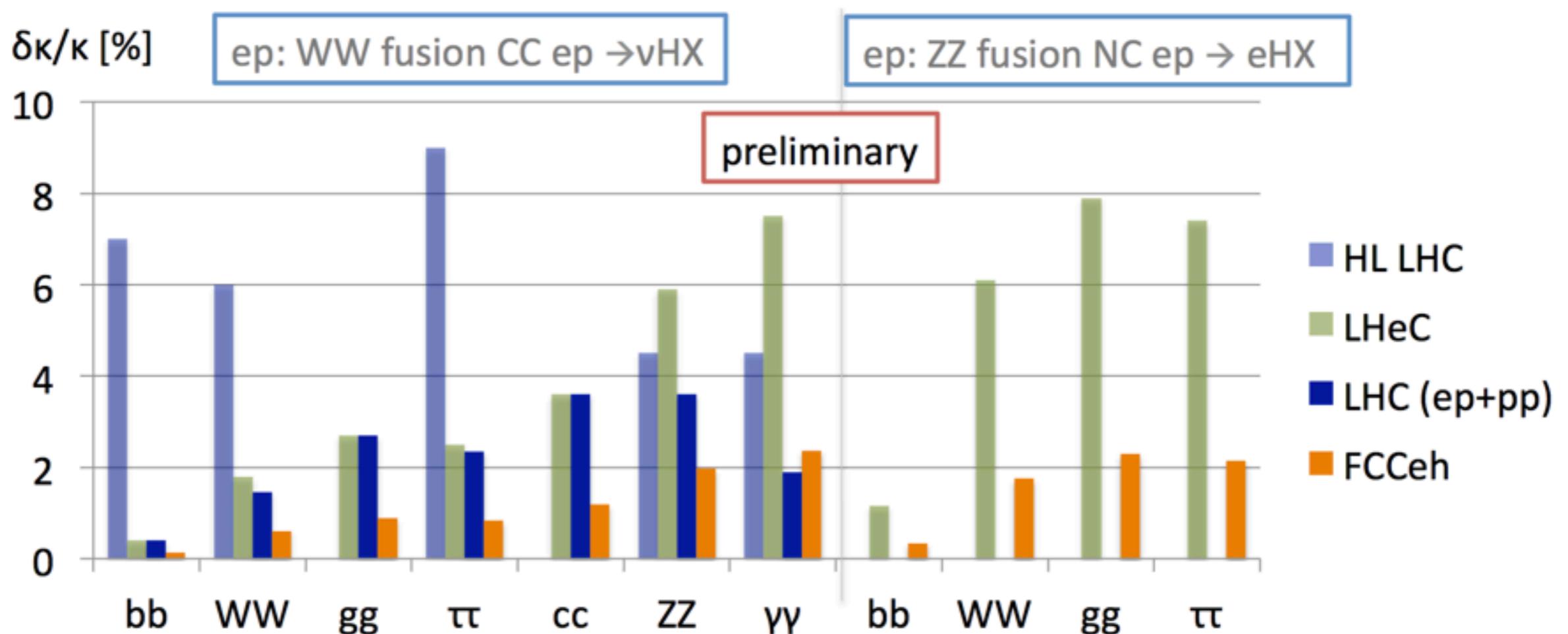
➔ Studies are an interpolation between HL-LHC and FCC-hh

parameter	HE-LHC
collision energy cms [TeV]	27
dipole field [T]	16
circumference [km]	27
straight section length [m]	528
# IP	2 & 2
beam current [A]	1.12
bunch intensity [10^{11}]	2.2 (0.44)
bunch spacing [ns]	25 (5)
rms bunch length [cm]	7.55
peak luminosity [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	25
events/bunch crossing	~800 (160)
stored energy/beam [GJ]	1.3
beta* [m]	0.25
norm. emittance [μm]	2.5 (0.5)

FCC-ep

➔ Relatively clean sample for Higgs event but ...

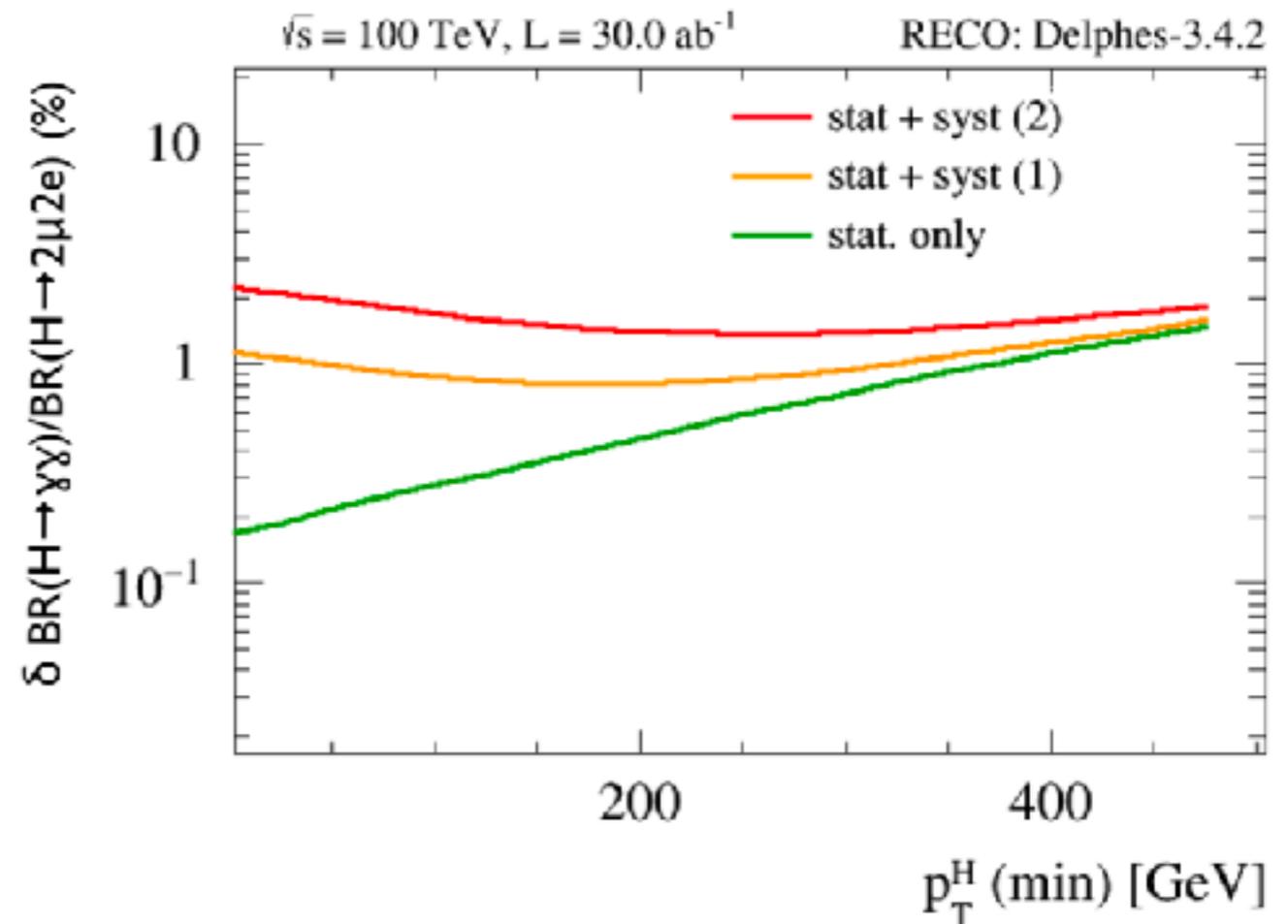
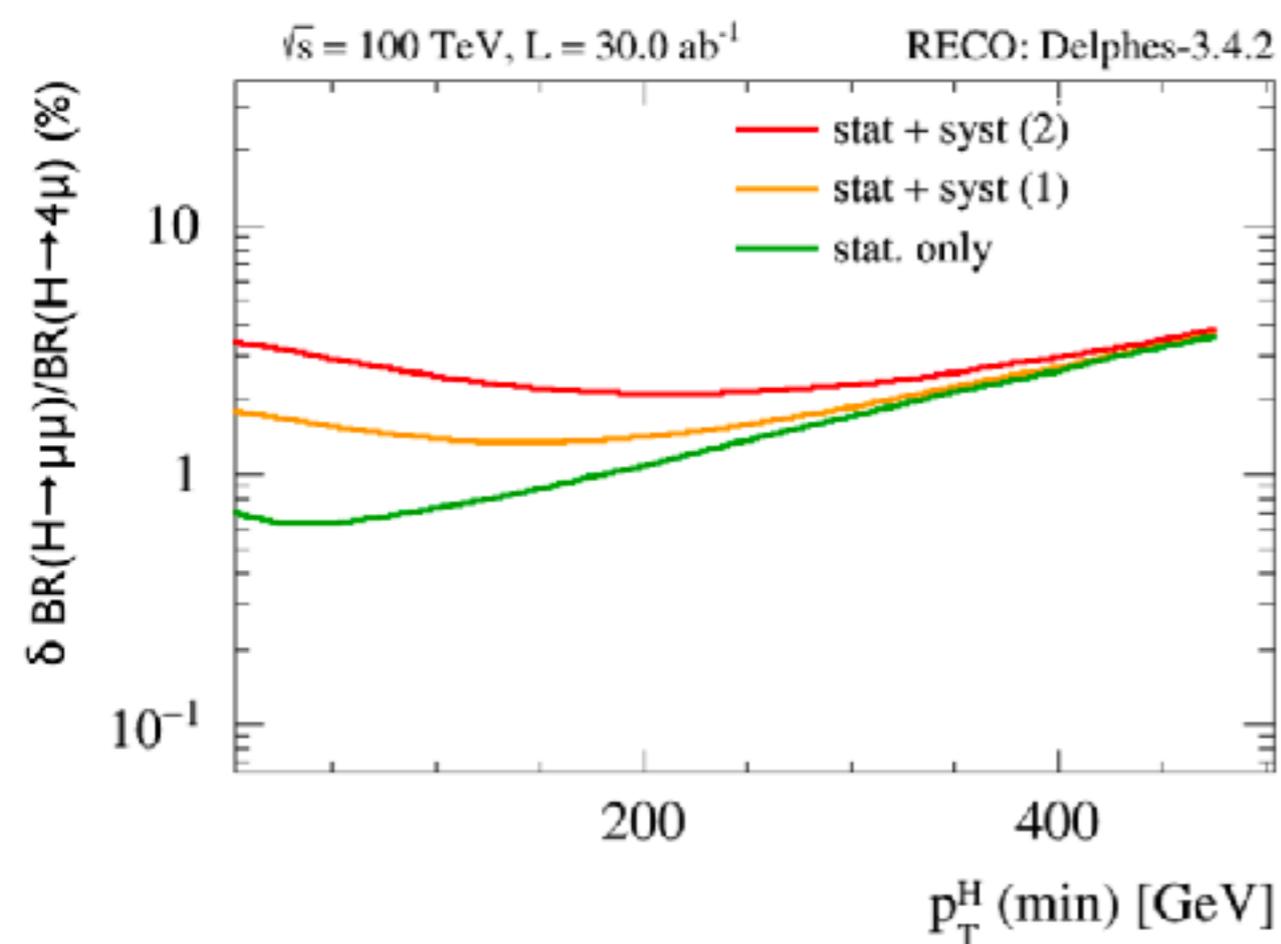
- Results shown with statistical uncertainties only
- Experimental and theoretical uncertainties do not allow cross section measurements of $O(0.1\%)$
- HL-LHC results are misrepresented



FCC-pp



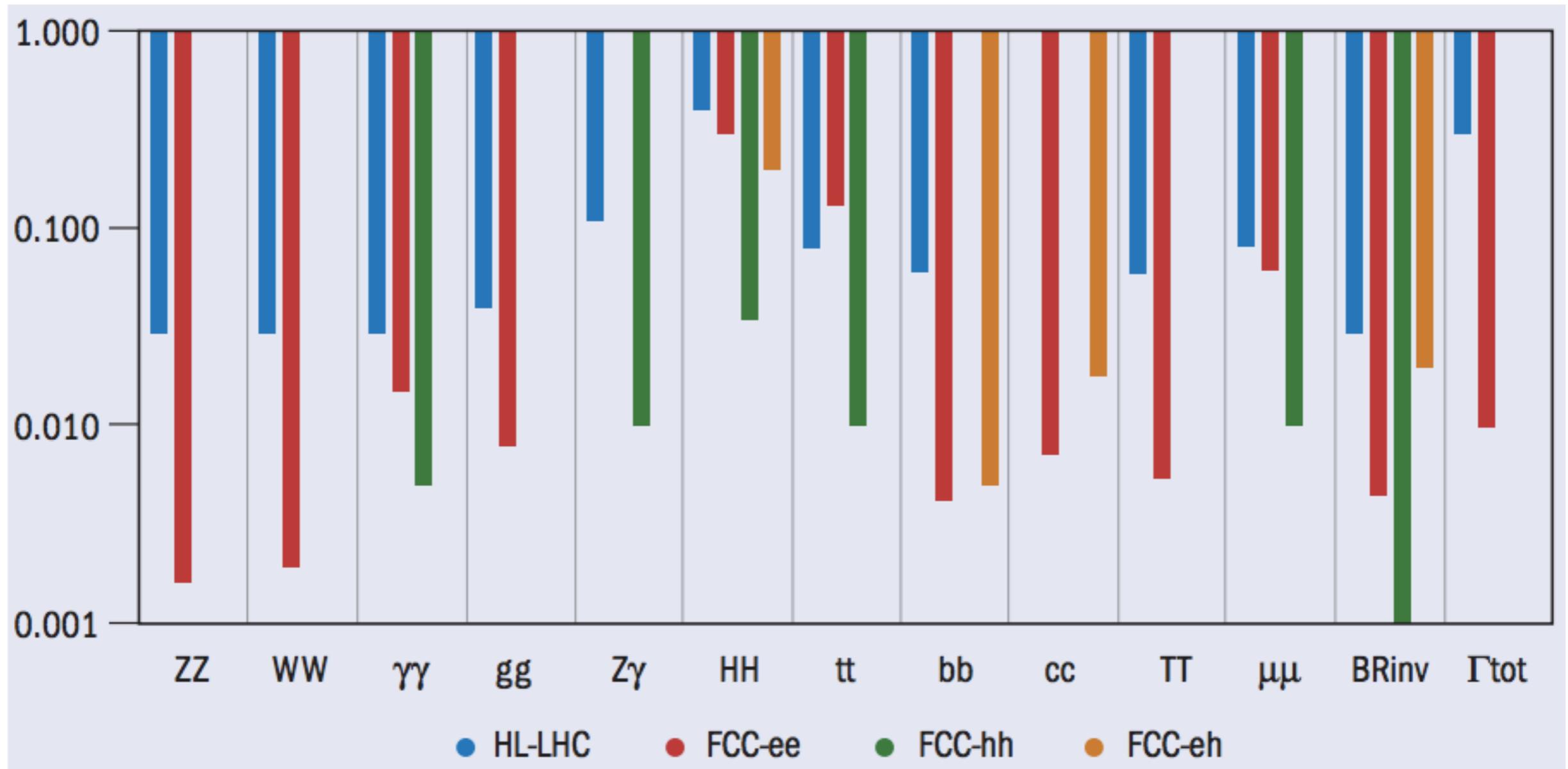
- ➔ Enormously rich Higgs dataset
- ➔ Significant progress on top-Yukawa coupling and Higgs self couplings
- ➔ Questions of systematic uncertainties as or even more relevant as in the HL-LHC case
- ➔ Ratio measurements are key. They will be enabled as coupling measurements through FCC-ee results



Higgs Boson Couplings

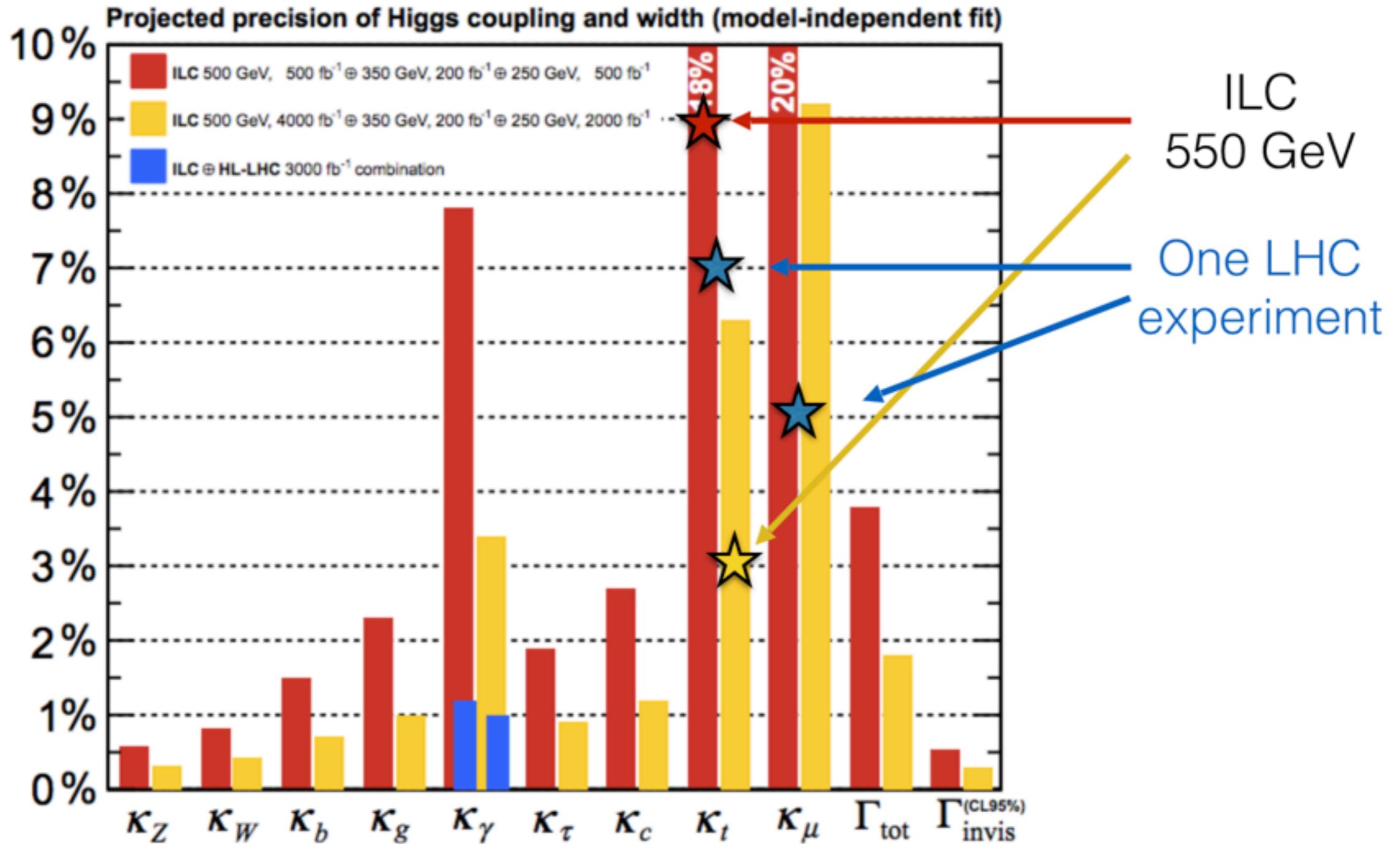


Summary from CERN Courier



Not a combination of results and comparing apples with oranges

Higgs Boson Couplings



Combination of results but not exploring the full potential

Global Higgs Couplings



- ➔ **This study is work in progress**
- ➔ **We have the technology to perform global fits, but**
 - Some open questions on inputs
- ➔ **It is Key to correctly tell the story of complementarity and synergy of future Higgs program**
- ➔ **FCC-ee in a position to enable HL-LHC and FCC-pp Higgs program**