Higgs Factories

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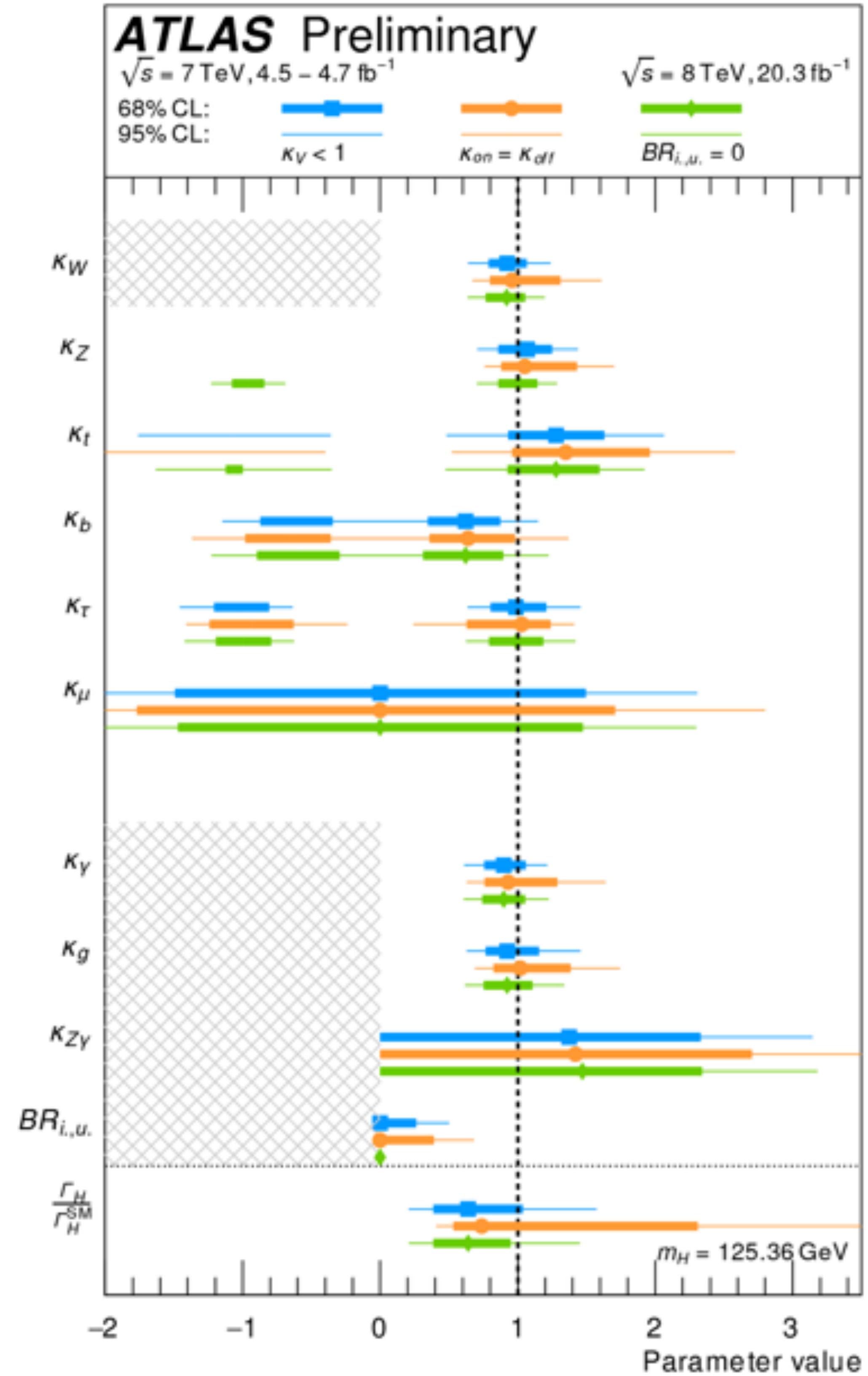
Status of Higgs studies at the LHC

- ➡ **Fantastic progress in last 3 years**
  - ◉ Observation in three boson channels
  - ◉ Evidence for fermion couplings
  - ◉ Precision mass measurements: 125.09 ± 0.24 GeV (ATLAS+CMS)
  - ◉ Spin/parity determined
  - ◉ Higgs total width from off-shell production
  - ◉ First results on differential cross sections
- ➡ **New particle looks more and more like the SM Higgs boson**
  - ◉ No evidence for non-SM decays
  - ◉ No evidence for additional Higgs bosons



Case for precision Higgs physics

➡ **How large are potential deviations from BSM physics?**

➡ **How well do we need to measure Higgs couplings?**

- **To be sensitive to a deviation δ, the measurement needs a precision of at least δ/3, better δ/5**
- **Implications of new physics scale on couplings from heavy states or through mixing**

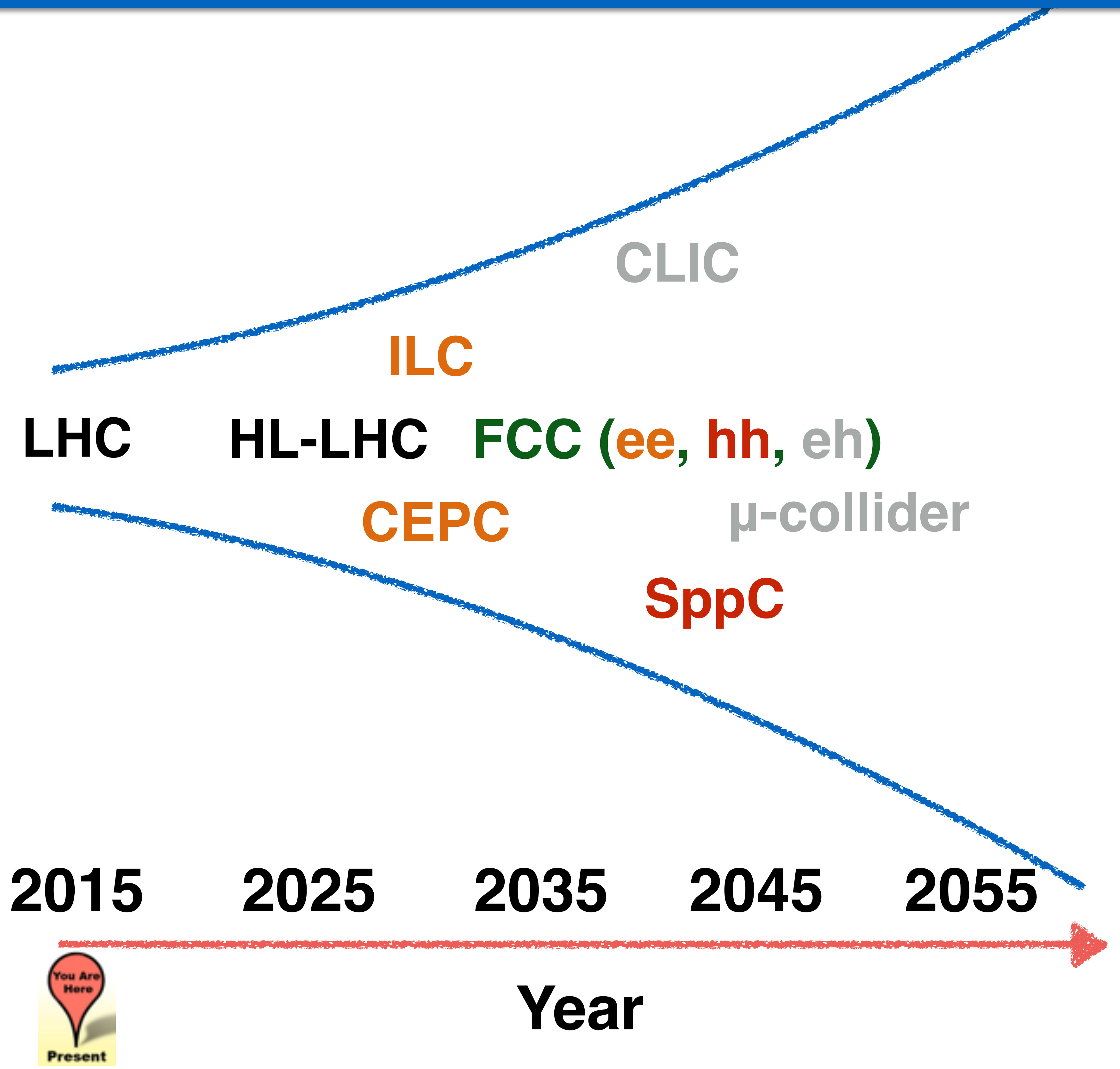
$$g = g_{\rm SM}\,[1+\Delta] \quad : \quad \Delta = \mathcal{O}(v^2/\Lambda^2)$$

$\frac{\Gamma_{\rm 2HDM}[h^0 \to X]}{\Gamma_{\rm SM}[h \to X]}$	type I	type II	lepton-spec.	flipped
VV^*	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$
$\bar{u}u$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$
$\bar{d}d$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$
$\ell^+\ell^-$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$

➡ **Percent-level precision needed to test TeV scale**

➡ **There is no strict limit to the precision needed!**

Collider of the 21st century



Linear vs. circular

- no synchrotron radiation
- no bending magnets
- currents and focusing are limiting L
- gradients are limiting E
- limited to one experiment

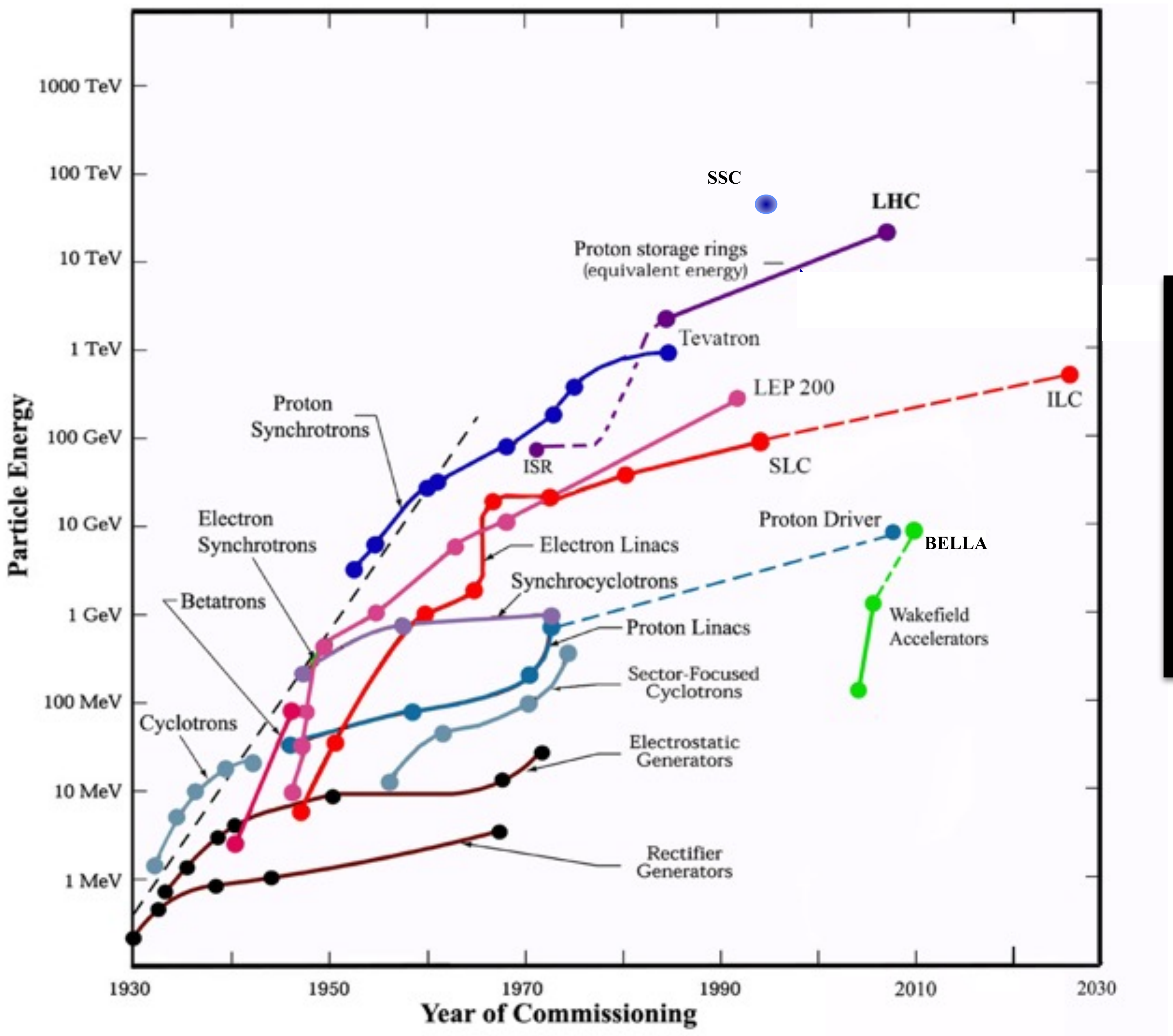
- accelerate over long distance by repetition
- recycle particles not used in collisions
- in principle, this leads to larger L and E

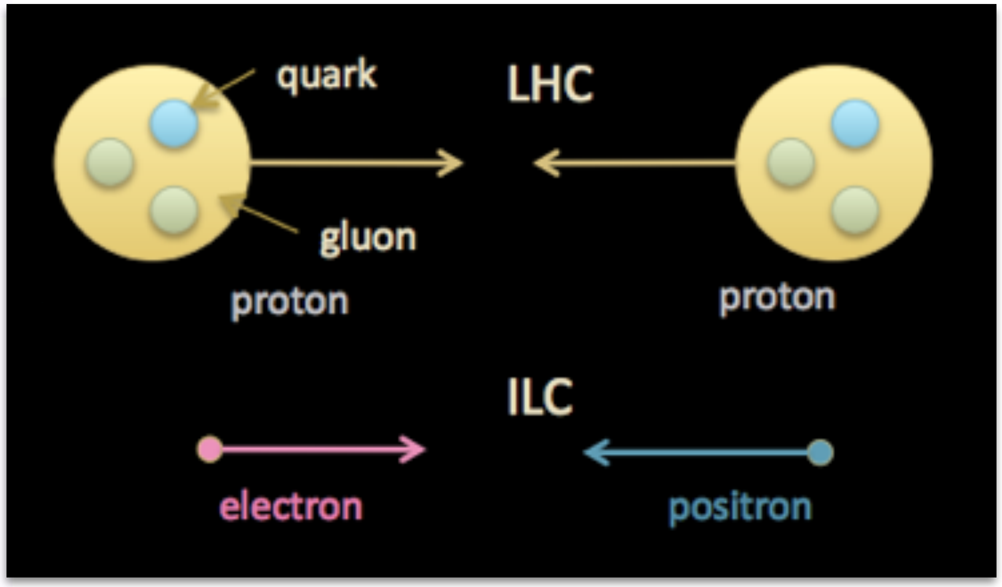
$$P_{\text{radiation}} = \frac{c}{6\pi\varepsilon_0} N \frac{q^2}{\rho^2} \gamma^4 \quad \Downarrow$$

Energy needed to compensate
Radiation becomes too large

$$\rho = \frac{p}{qB} \quad \Rightarrow$$ The rings become too long

Lepton vs. hadron



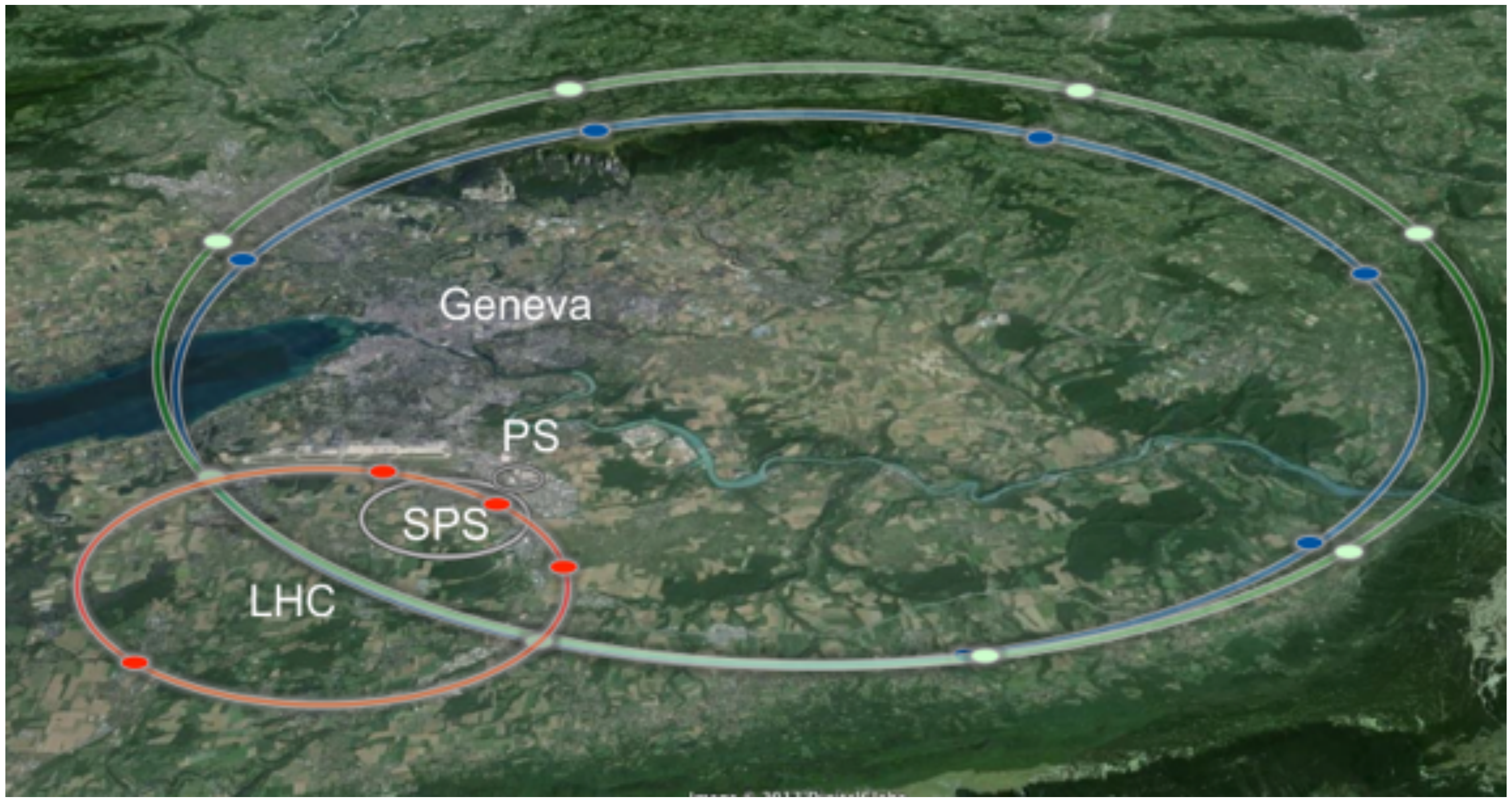


Lepton vs. hadron

"Every event at a lepton collider
is physics, every event at a
hadron collider is background."
- Sam Ting.

"All events (background)
are equal but some events
are more equal than others."
- George Orwell (Klute-fied)

Future hadron collider



LHC
27 km, 8.33T
14 TeV

HE-LHC
27 km, 20T
33 TeV

FCC-hh
80 km, 20T
100 TeV

FCC-hh
100 km, 16T
100 TeV

SppC
50-70 km,20T
50-70 TeV

Higgs prospects for the HL-LHC

Rare-decays

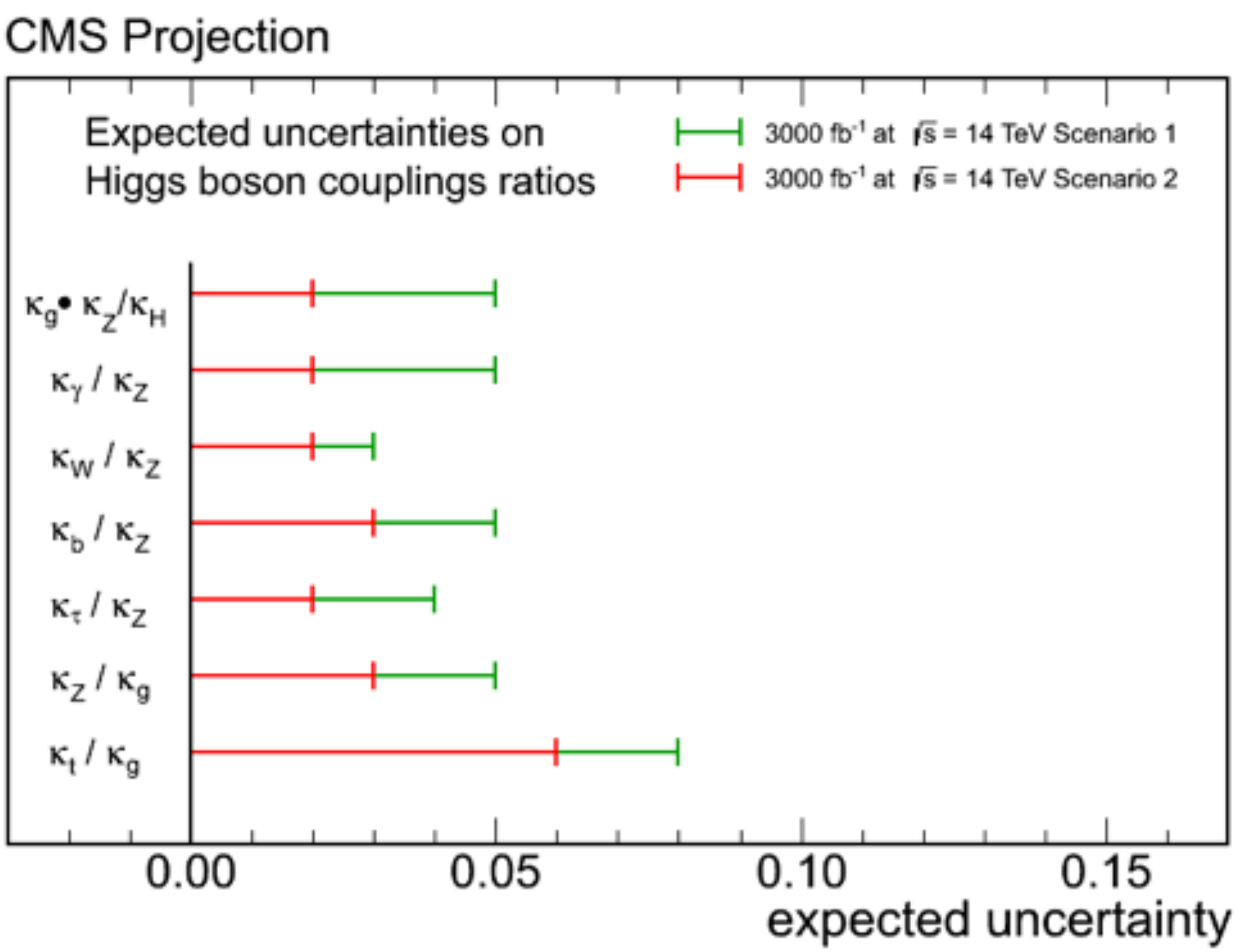
CMS Projection for precision of Higgs coupling measurement

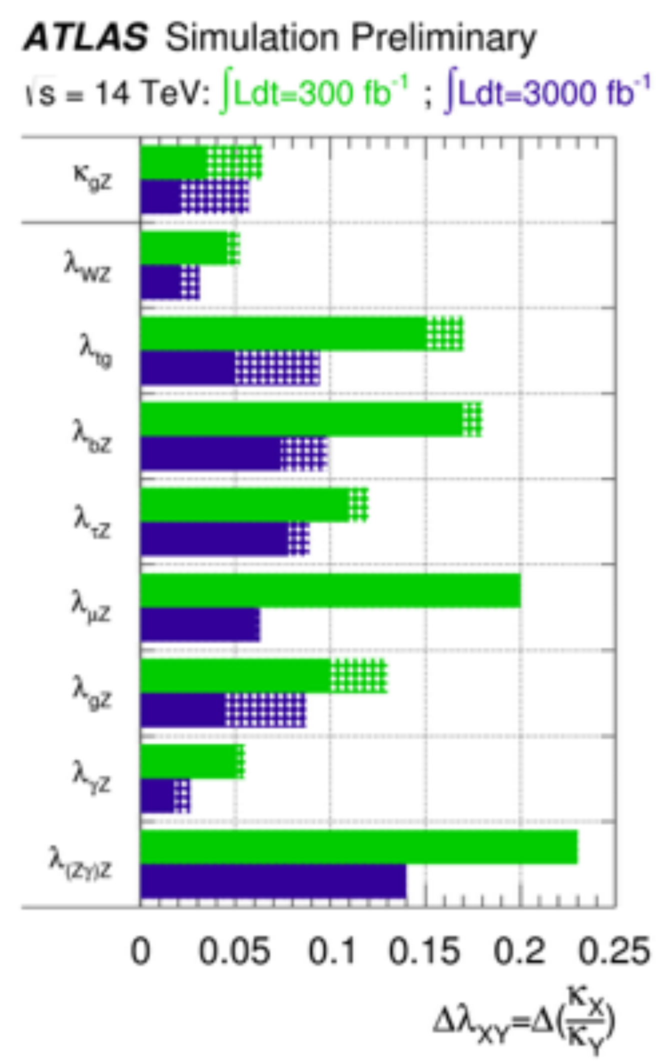
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

Coupling precision 2-10 %
factor 2-3 improvement from HL-LHC

Key question is the
evolution systematic uncertainty

Snowmass Whitepaper for CMS - http://arxiv.org/abs/1307.7135





Higgs prospects for the HL-LHC

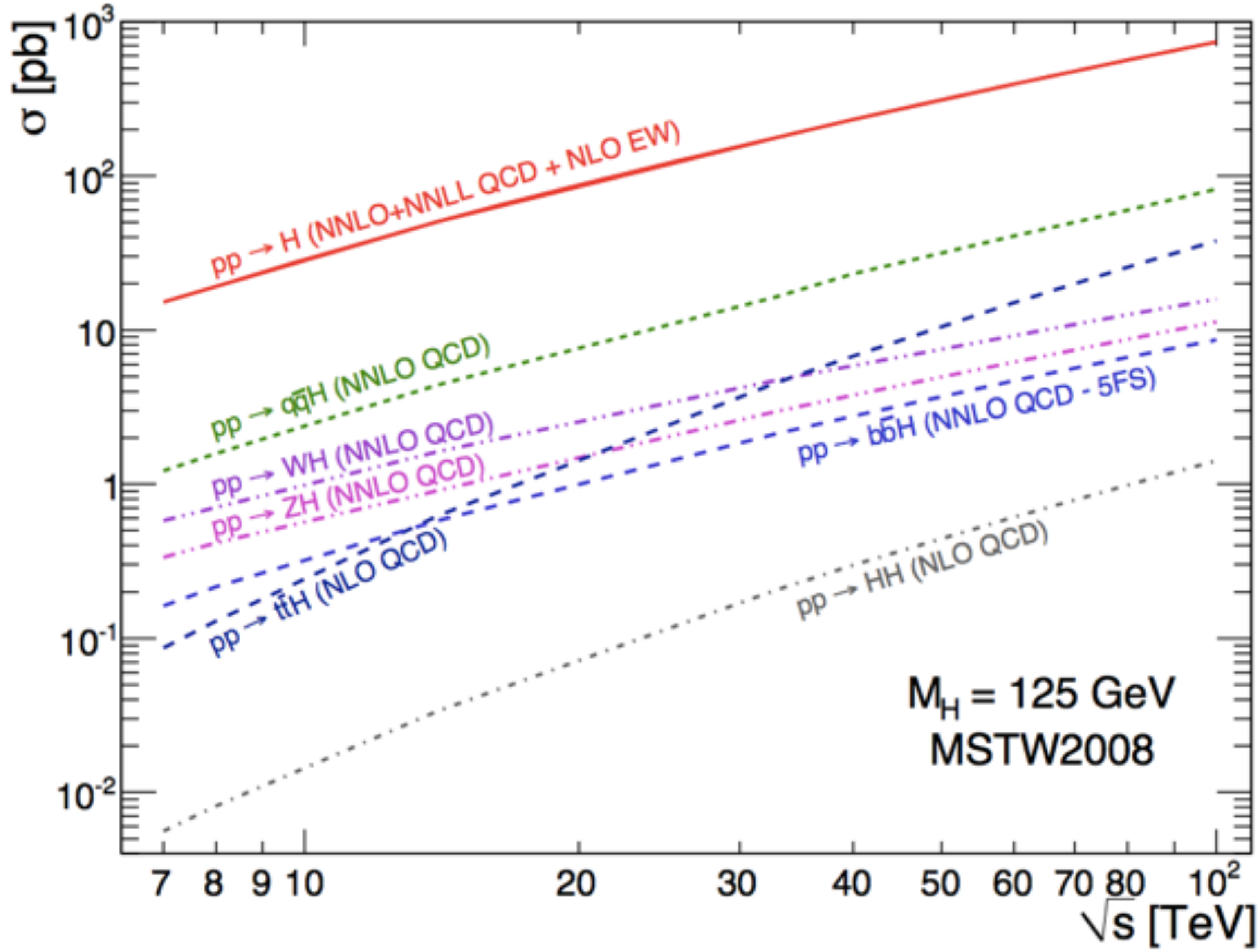
ATLAS Scenario	Status	Deduced size of uncertainty to increase total uncertainty							
	2014	by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j $\to$ 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j $\to$ 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j $\to$ VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j $\to$ VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

Key question is the
evolution systematic uncertainty

FCC-hh analyses can explore the size of the dataset to limit systematic uncertainties and require theoretical improvements

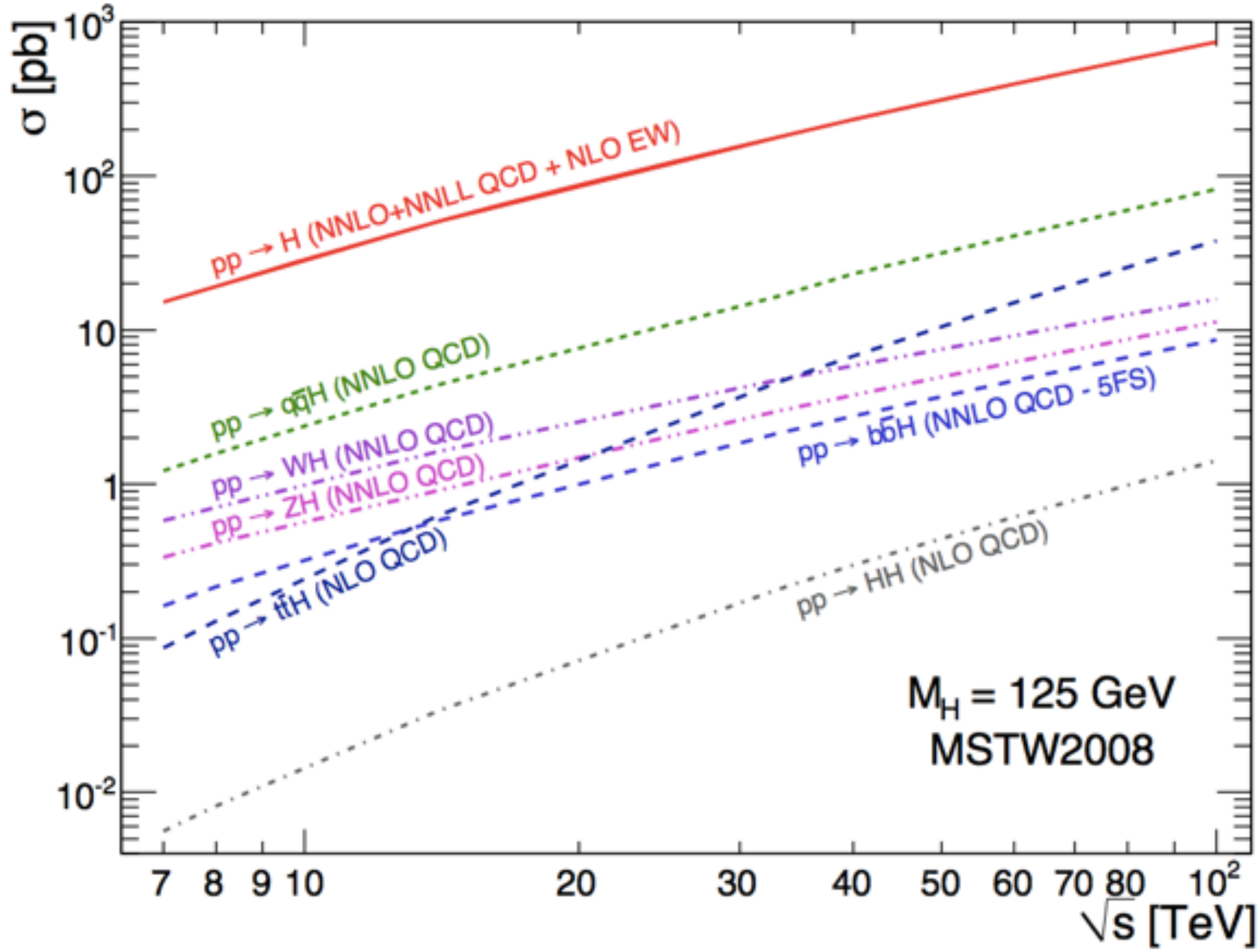
Higgs production: FCC-pp

Process	8 TeV	14 TeV	100 TeV
gF	19.3 pb	50.35 pb	740.3 pb
VBF	1.58 pb	4.40 pb	82.0 pb
WH	0.70 pb	1.63 pb	15.9 pb
ZH	0.42 pb	0.90 pb	11.3 pb
ttH	0.13 pb	0.62 pb	37.9 pb
bbH	0.20 pb	0.58 pb	8.64 pb
gF to HH	8.15 fb	33.8 fb	1.42 fb



Higgs production: FCC-pp

Process	8 TeV	14 TeV	100 TeV
gF	0.38	1	14.7
VBF	0.38	1	18.6
WH	0.43	1	9.7
ZH	0.47	1	12.5
ttH	0.21	1	61
bbH	0.34	1	15
gF to HH	0.24	1	42



Proton-proton Higgs datasets | **LHC Run I** → x300-600 → **HL LHC** → x10-400 → **FCC pp**

Higgs physics program: FCC-pp

➡ Rare SM and non-SM decays

- $\delta\kappa_\mu \cong 2\%$ (extrapolated from LHC)

➡ Higgs self coupling

➡ BSM (heavy) Higgs boson production

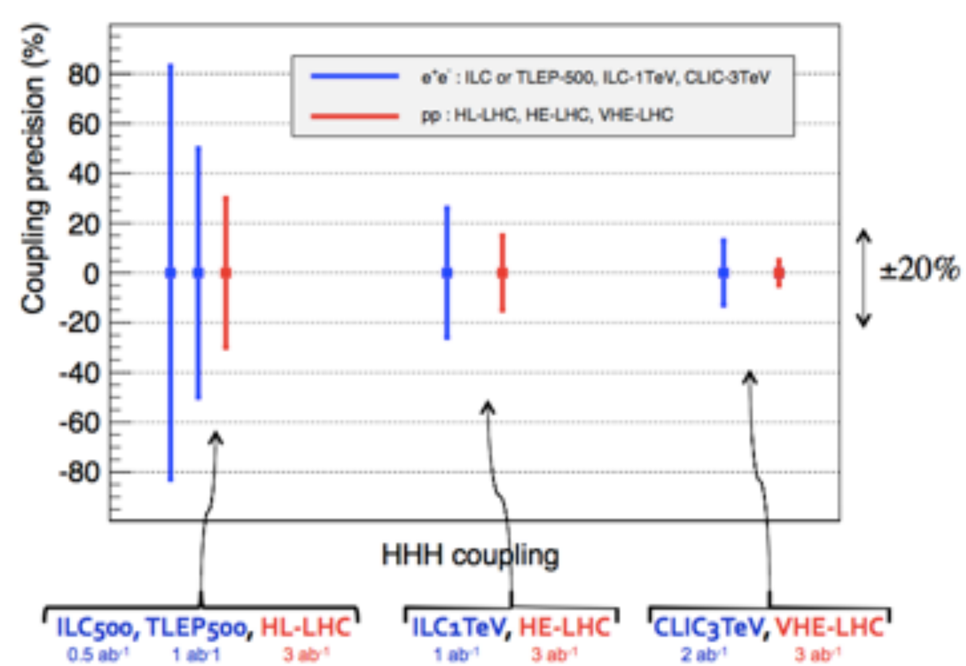
➡ Cascade decays including Higgs bosons

➡ Differential cross section measurements

➡ … and in general a continuation of the LHC/HL-LHC program

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

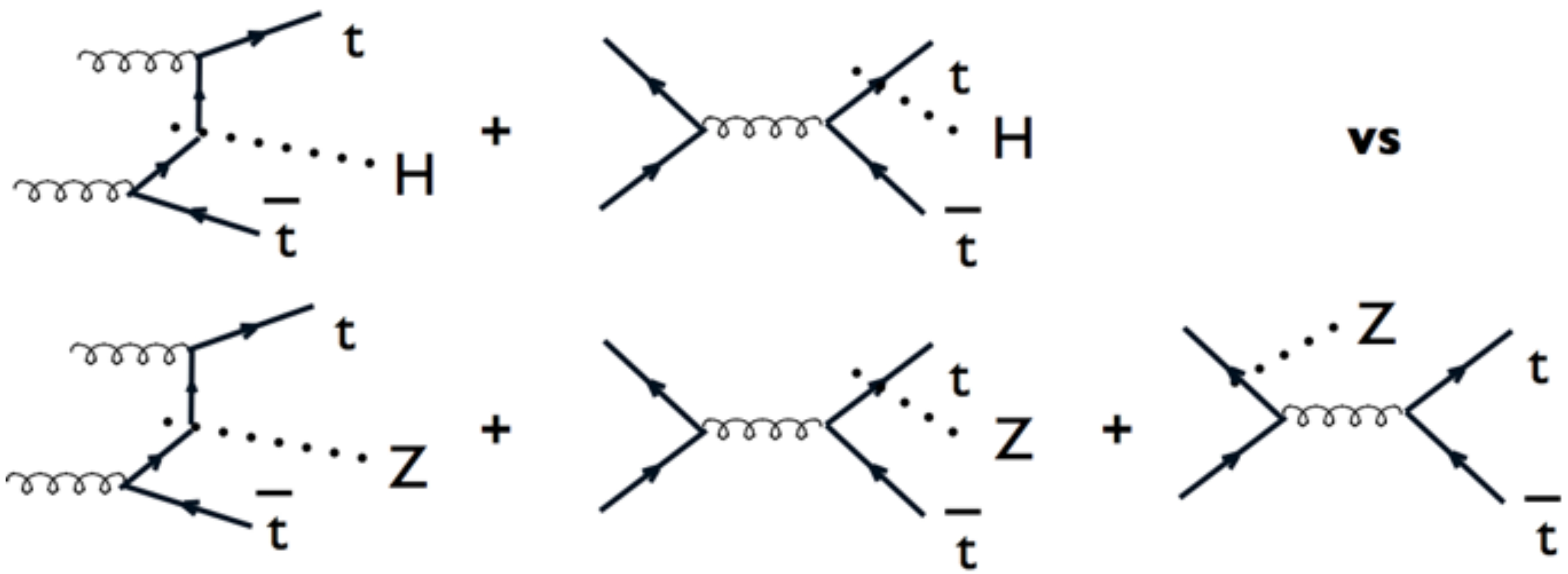
arXiv:1310.8361



Higgs physics program: FCC-pp

➡ … but also new measurements not possible at the LHC/HL-LHC

ttH / ttZ



➡ Theoretical uncertainties cancel mostly

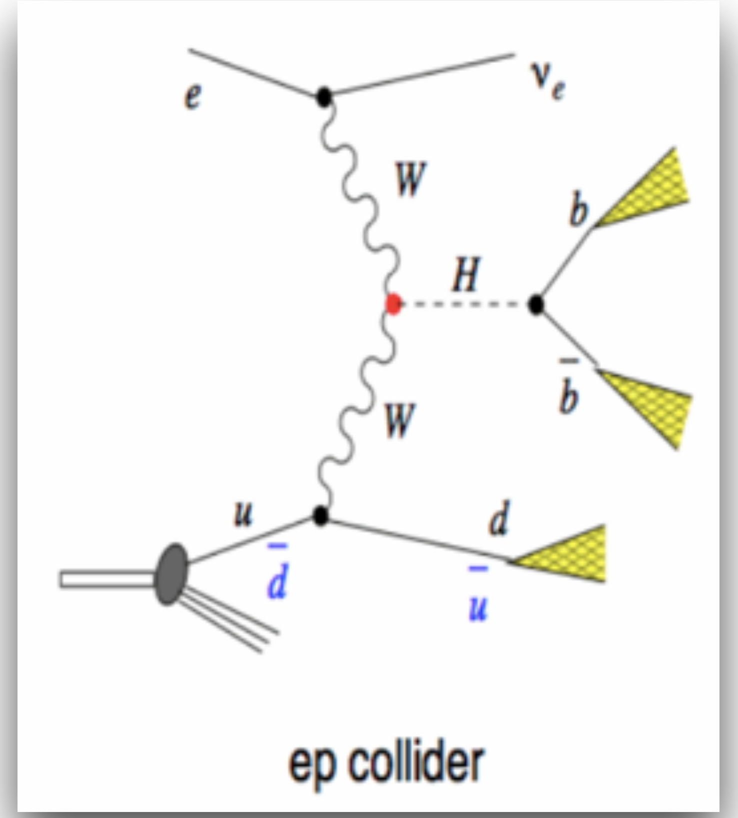
- PDF (CTEQ 6.6) ± 0.5%
- Missing higher orders ± 1.2%

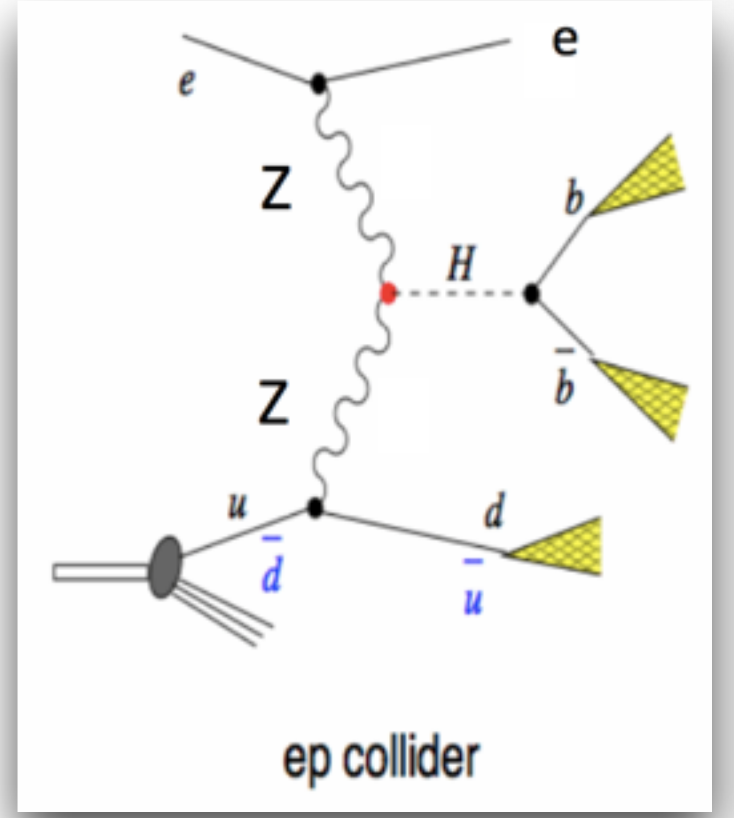
➡ One can not conclude that one can measure the cross section ratio with ~2% ($\delta\lambda_{top} \cong$ 1%) precision. **More detailed studies are ongoing.**

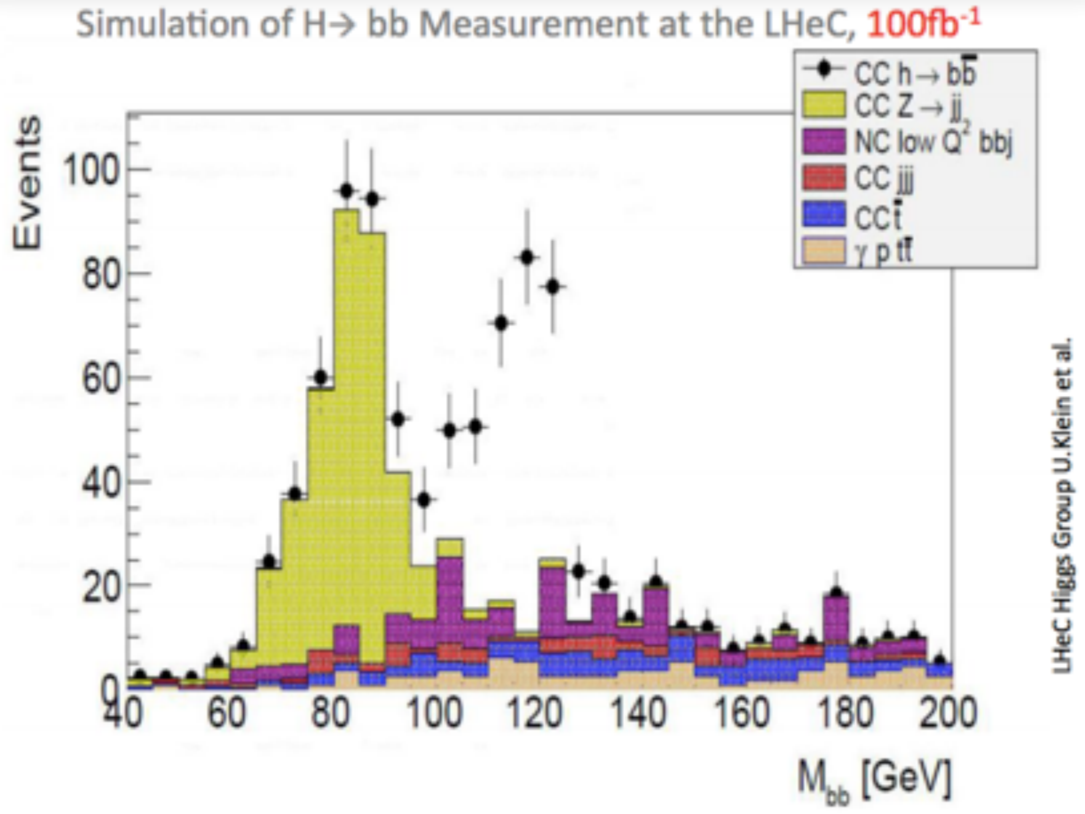
Higgs production: FCC-ep

- ➡ FCC-ep can deliver PDFs for FCC-pp (Higgs) program
- ➡ Higgs studies in relatively clean environment
- ➡ Higgs precision κ_b measurement, < 1%
- ➡ Investigation potential of κ_c measurement using charm tagging

Higgs in e^-p		CC - LHeC	NC - LHeC	CC - FHeC
Polarisation		-0.8	-0.8	-0.8
Luminosity [ab^{-1}]		1	1	5
Cross Section [fb]		196	25	850
Decay	BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$	0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$	0.029	5 700	700	123 000
$H \to \tau^+\tau^-$	0.063	12 350	1 600	270 000
$H \to \mu\mu$	0.00022	50	5	1 000
$H \to 4l$	0.00013	30	3	550
$H \to 2l2\nu$	0.0106	2 080	250	45 000
$H \to gg$	0.086	16 850	2 050	365 000
$H \to WW$	0.215	42 100	5 150	915 000
$H \to ZZ$	0.0264	5 200	600	110 000
$H \to \gamma\gamma$	0.00228	450	60	10 000
$H \to Z\gamma$	0.00154	300	40	6 500

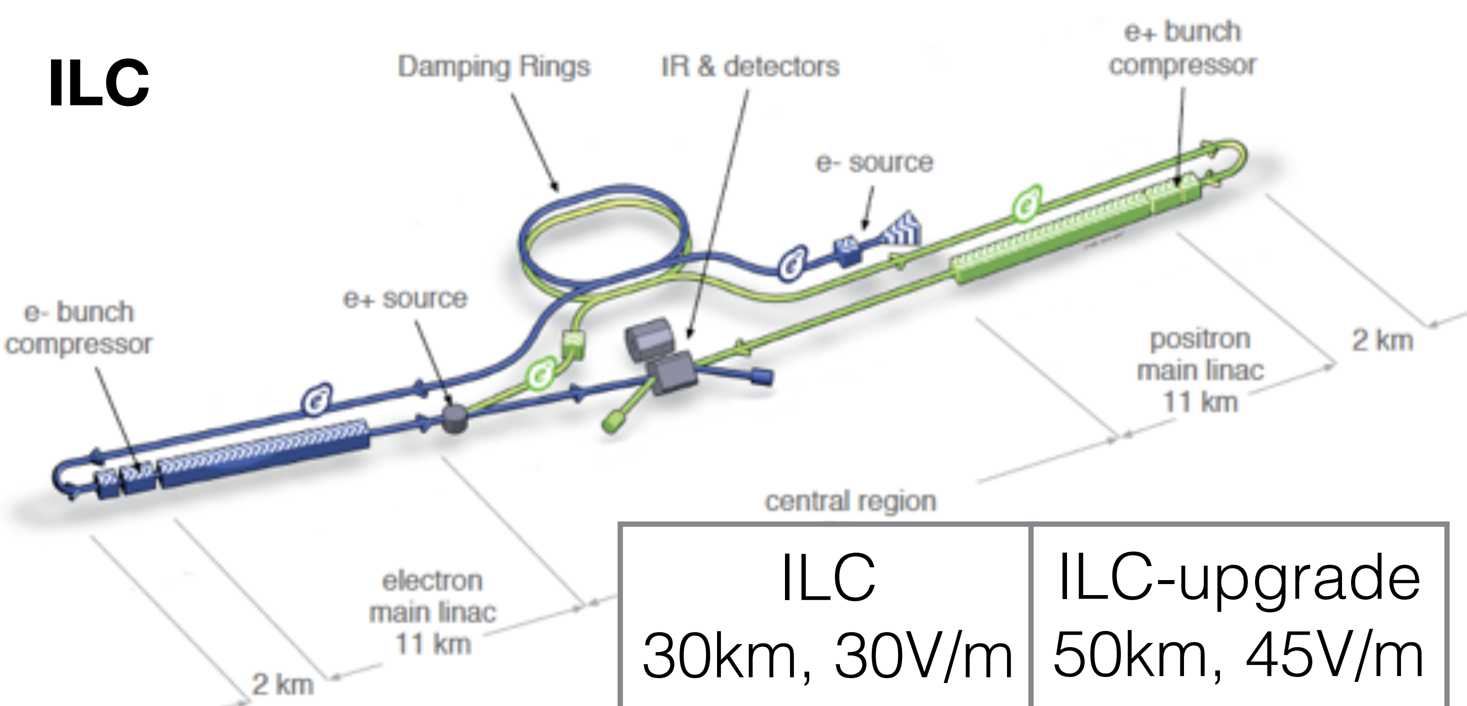




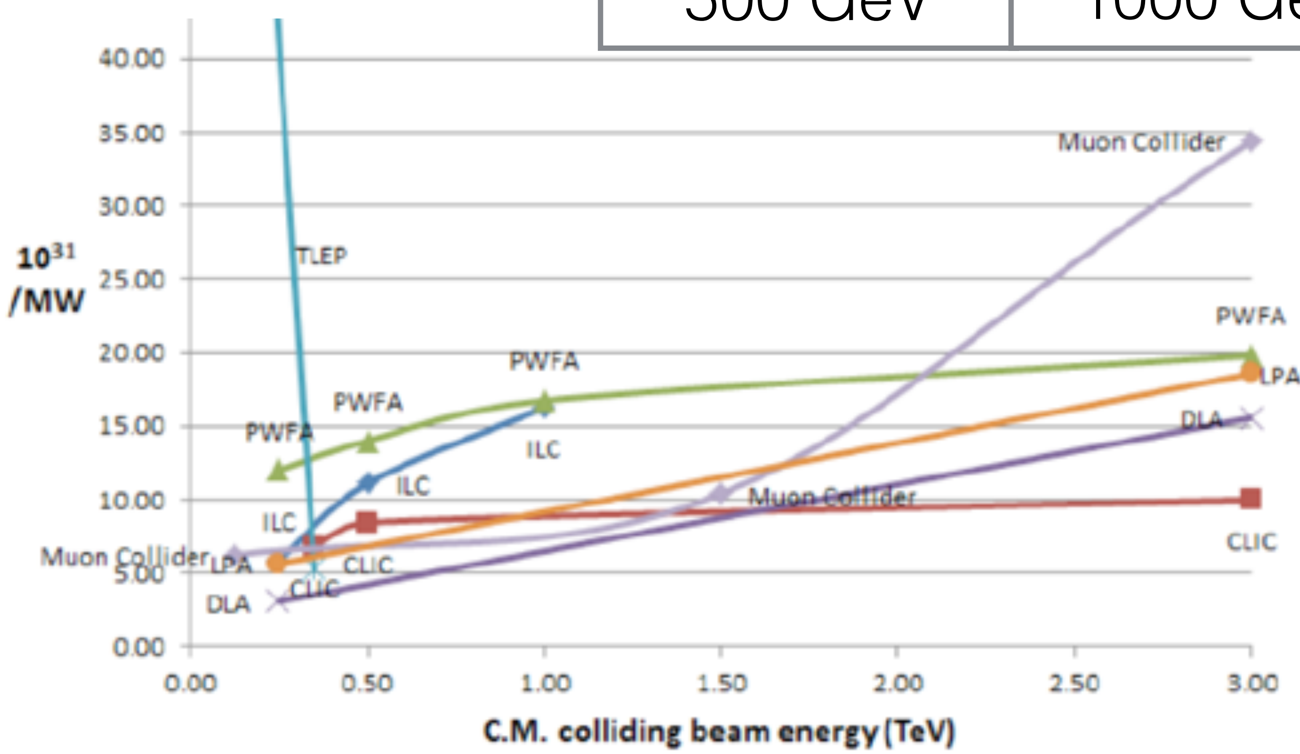


Future lepton collider

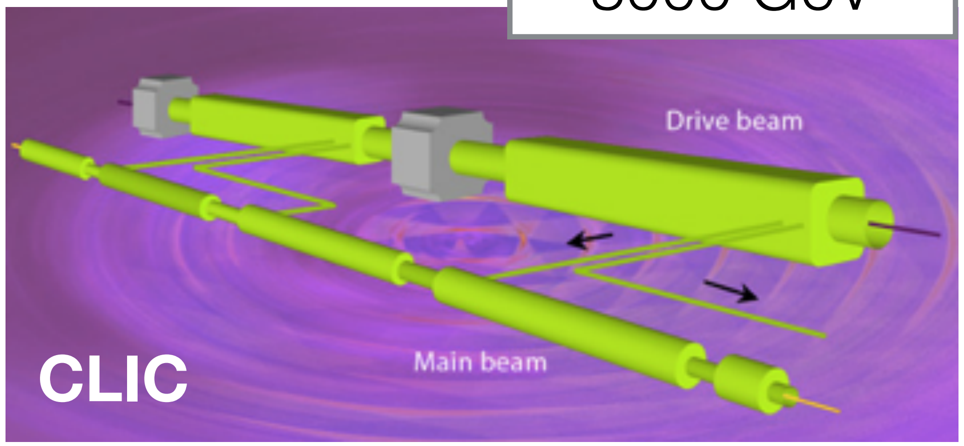
ILC



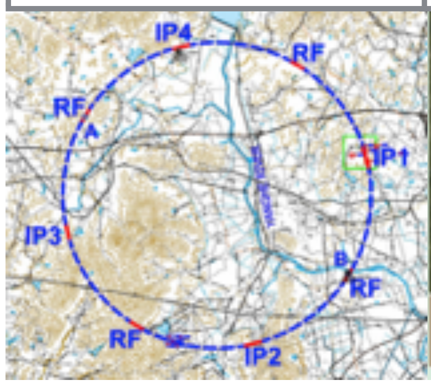
ILC	ILC-upgrade
30km, 30V/m	50km, 45V/m
500 GeV	1000 GeV



CLIC
50km, 100V/m
3000 GeV



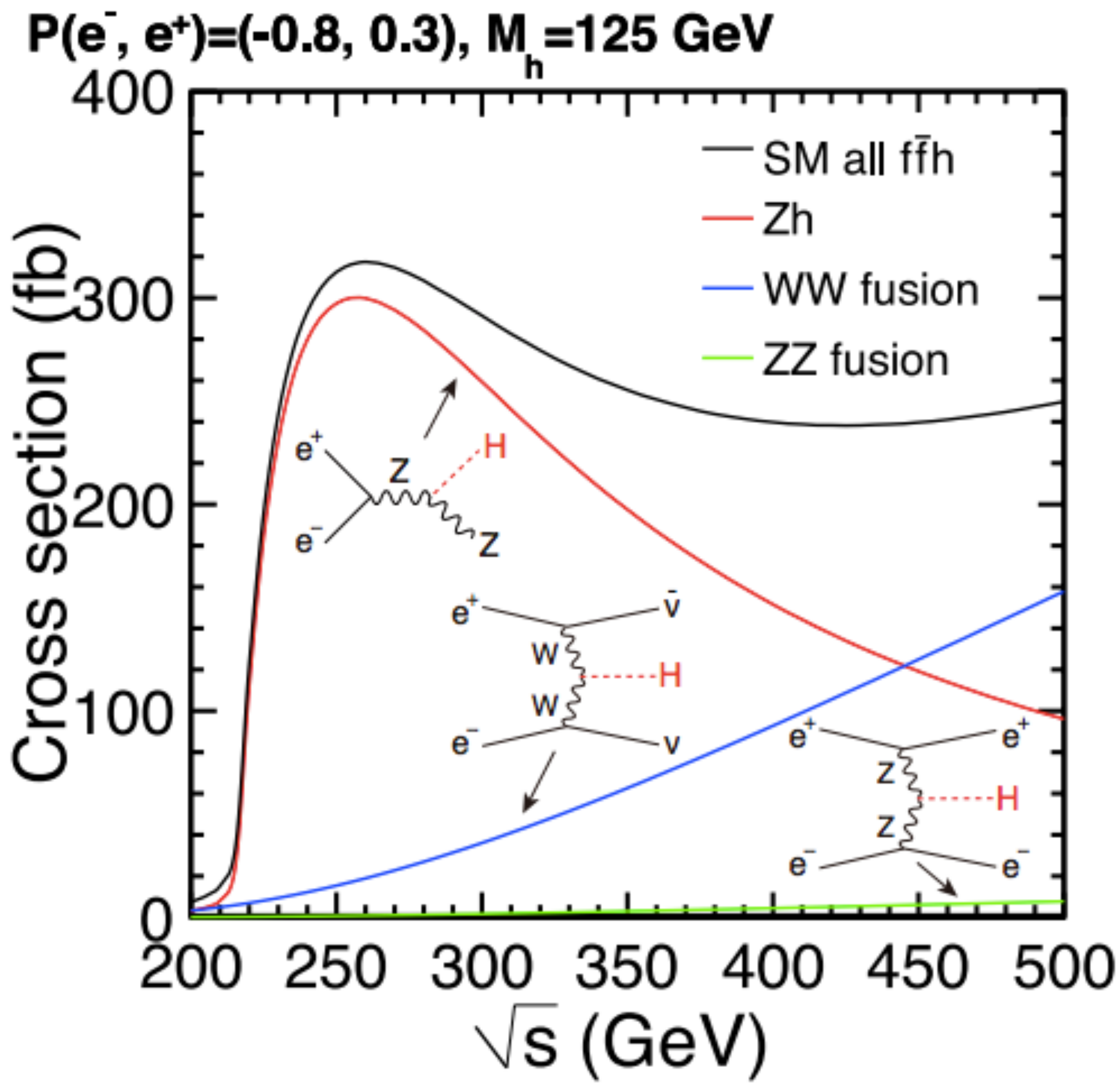
CEPC	FCC-ee
50km	100km, 200MV
240 GeV	350 GeV



Future Circular Collider (FCC-ee)

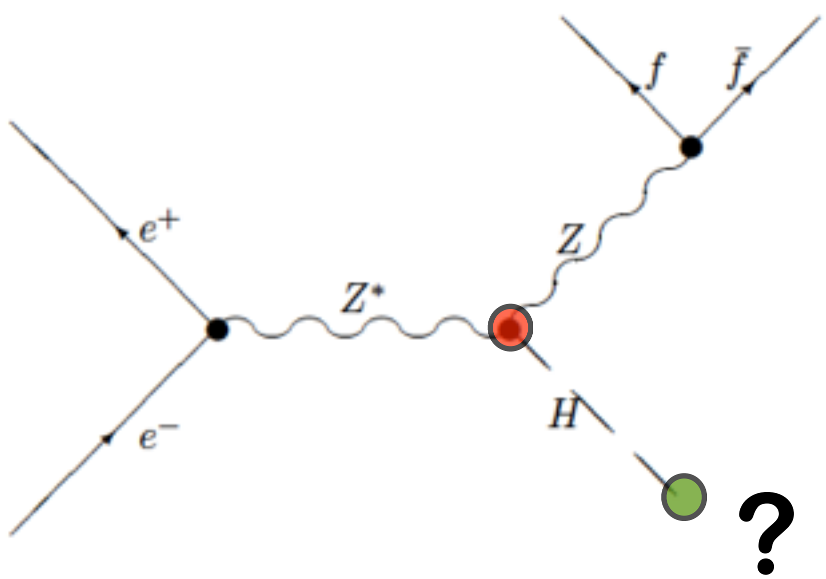
Circular Electron Position Collider (CEPC)

Higgs production

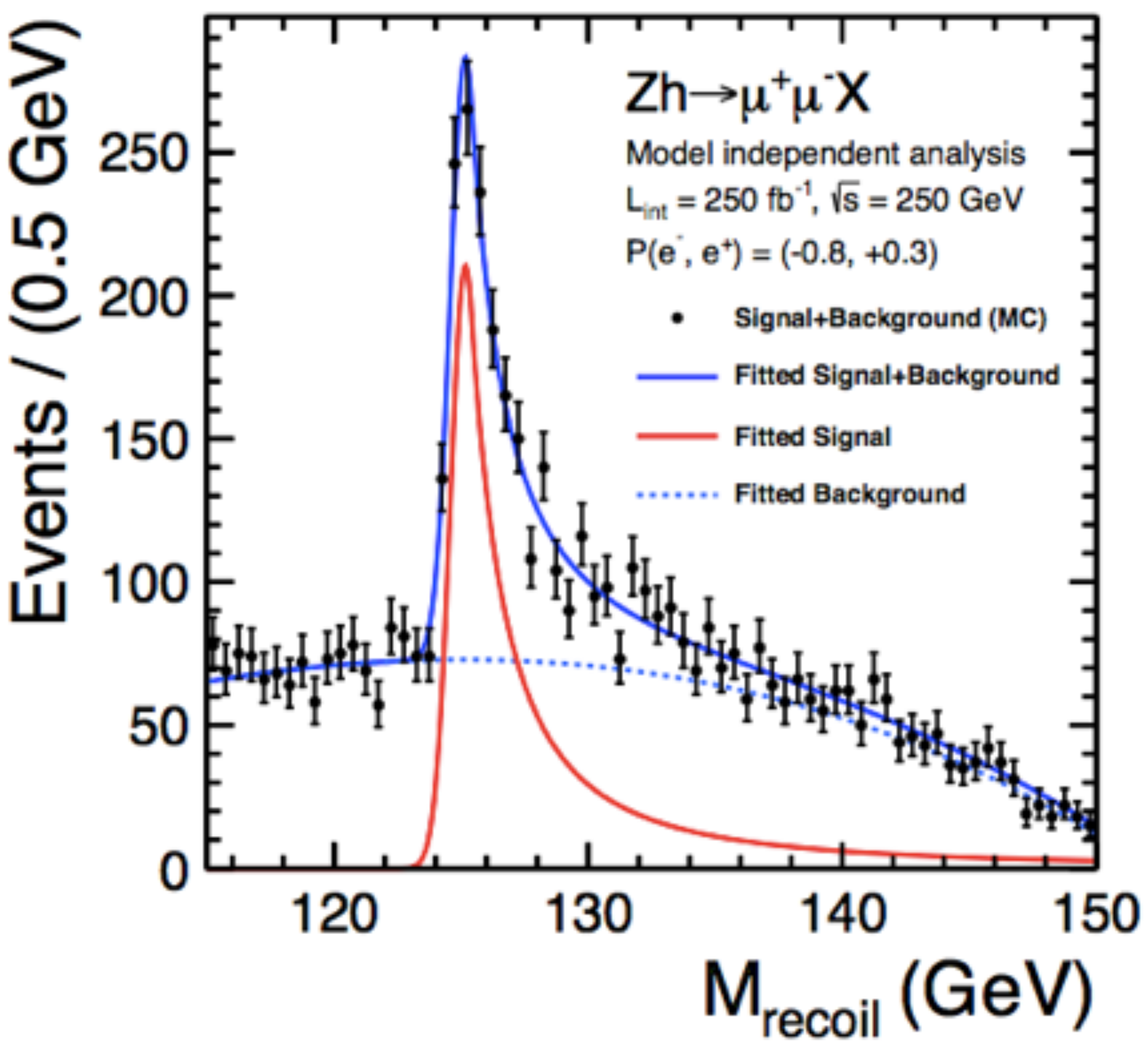


Precision Higgs couplings

- ➡ Recoil method unique to lepton collider
- ➡ Tag Higgs event independent of decay mode
- ➡ Provide precision measurement of σ(ee→ZH)



$$m^2_{\rm recoil} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

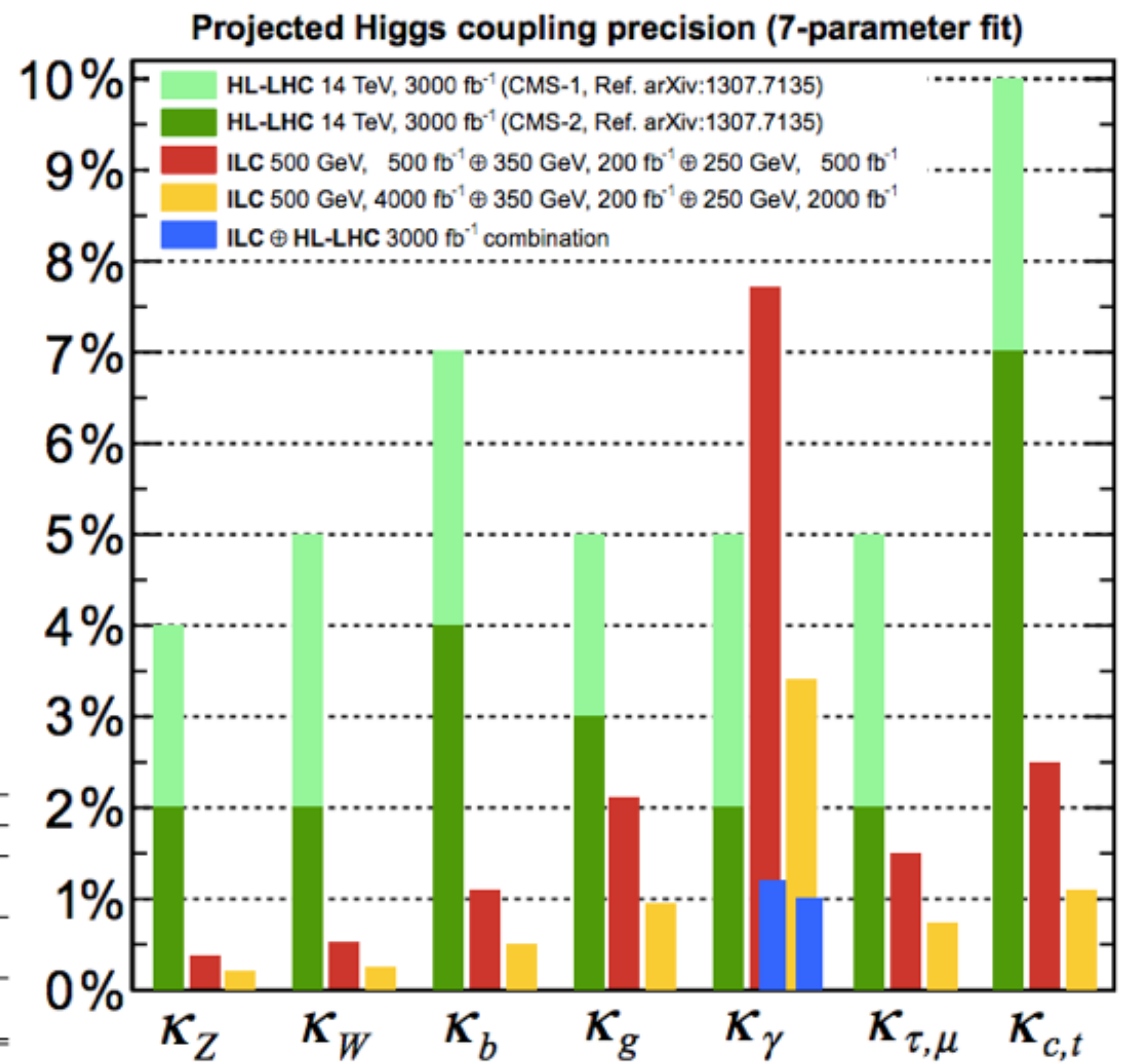


Precision Higgs couplings

- ➡ Measure σ(ee→ZH) * BR (H→X) by identifying X
- ➡ Total width from combination of measurements or fit
- ➡ Hadronic and invisible Z decays increase precision
- ➡ Example: ~20y operating time for ILC

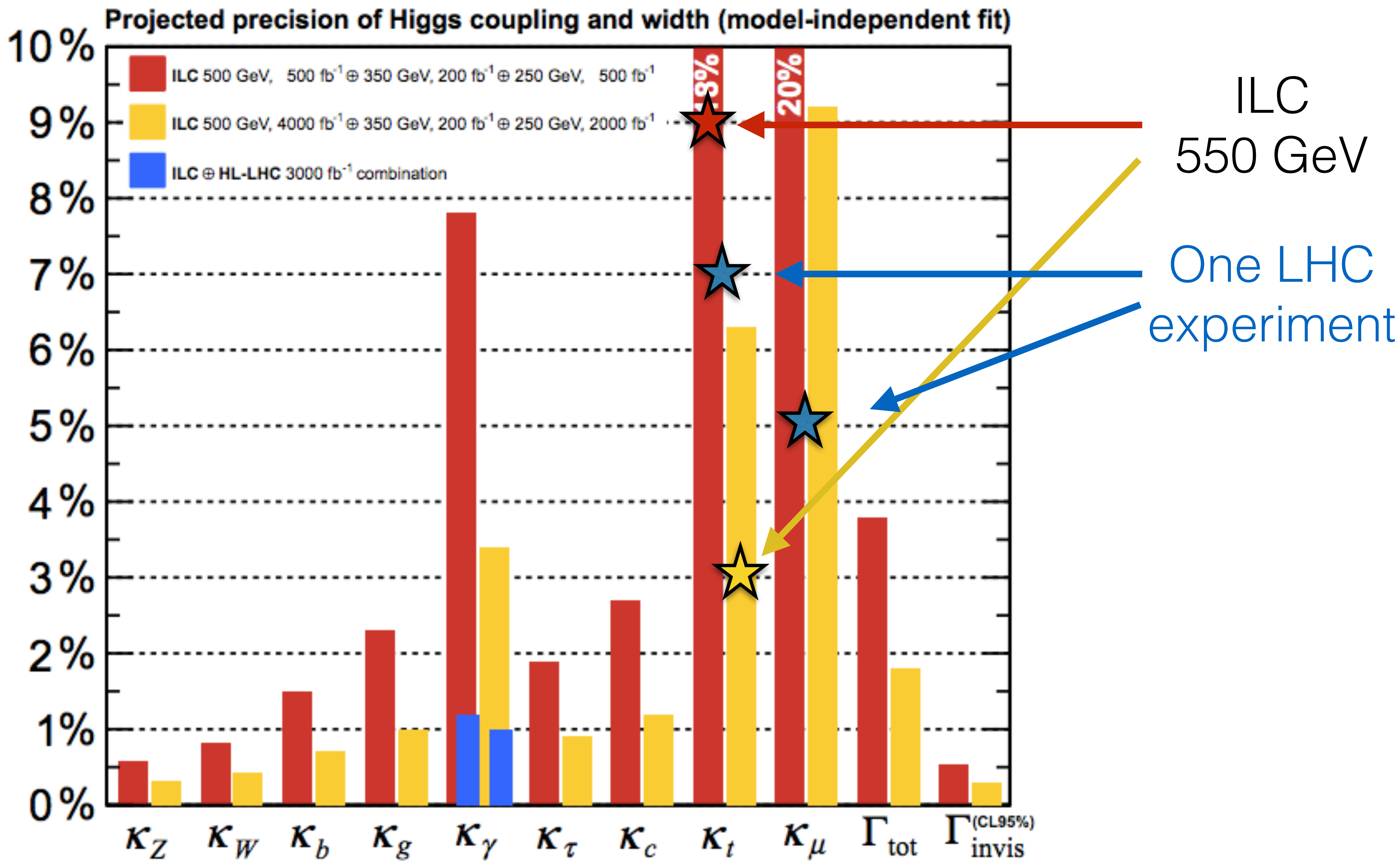
Scenario	Stage	500			500 LumiUP		
	$\sqrt{s}$ [GeV]	500	350	250	500	350	250
G-20	$\int \mathscr{L}dt$ [fb^{-1}]	1000	200	500	4000	-	-
	time [years]	5.5	1.3	3.1	8.3	-	-
H-20	$\int \mathscr{L}dt$ [fb^{-1}]	500	200	500	3500	-	1500
	time [years]	3.7	1.3	3.1	7.5	-	3.1
I-20	$\int \mathscr{L}dt$ [fb^{-1}]	500	200	500	3500	1500	-
	time [years]	3.7	1.3	3.1	7.5	3.4	-

Scenario	Stage	500			500 LumiUP		
	$\sqrt{s}$ [GeV]	250	500	350	250	350	500
Snow	$\int \mathscr{L}dt$ [fb^{-1}]	250	500	200	900	-	1100
	time [years]	4.1	1.8	1.3	3.3	-	1.9



arXiv:1506.07830
arXiv:1506.05992

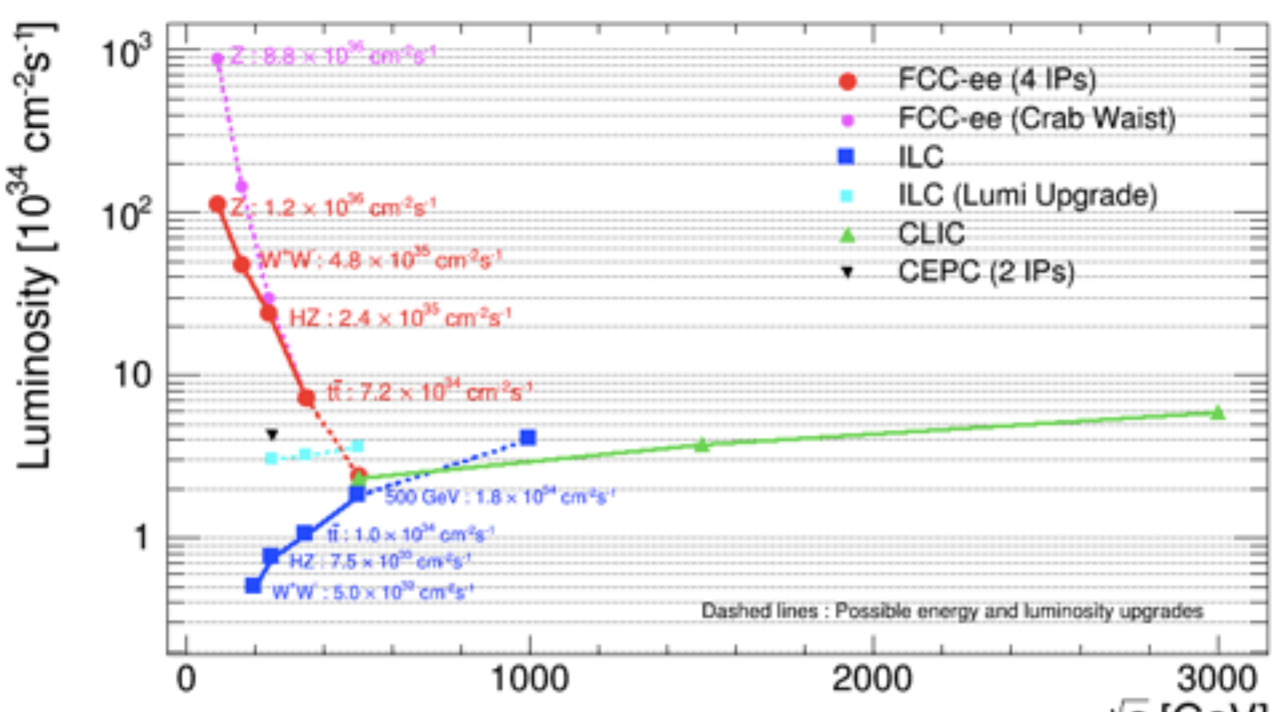
Precision Higgs couplings



Higgs physics at the FCC

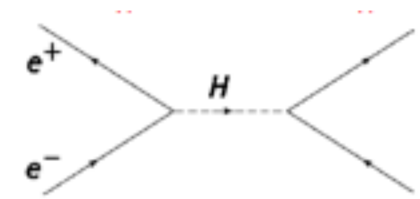
➡ Circular machine outperforming linear machine as Higgs factory

	FCC-ee Z	FCC-ee W	FCC-ee H	FCC-ee TOP	FCC-hh	FCC-ep
√s [GeV]	90	160	240	350	100.000	3.464 (Ee=60/Ep=50.000)
Inst. luminosity [$10^{34} cm^{-2} s^{-1}$/IP]	28	12	6	1.8	5-30	6.2
L_{int} [ab^{-1}/year/IP]	2.8	1.2	0.6	0.18	0.3-1.8	0.4
Beam current [mA]	1450	152	30	6.6	500-3000	480 / 500

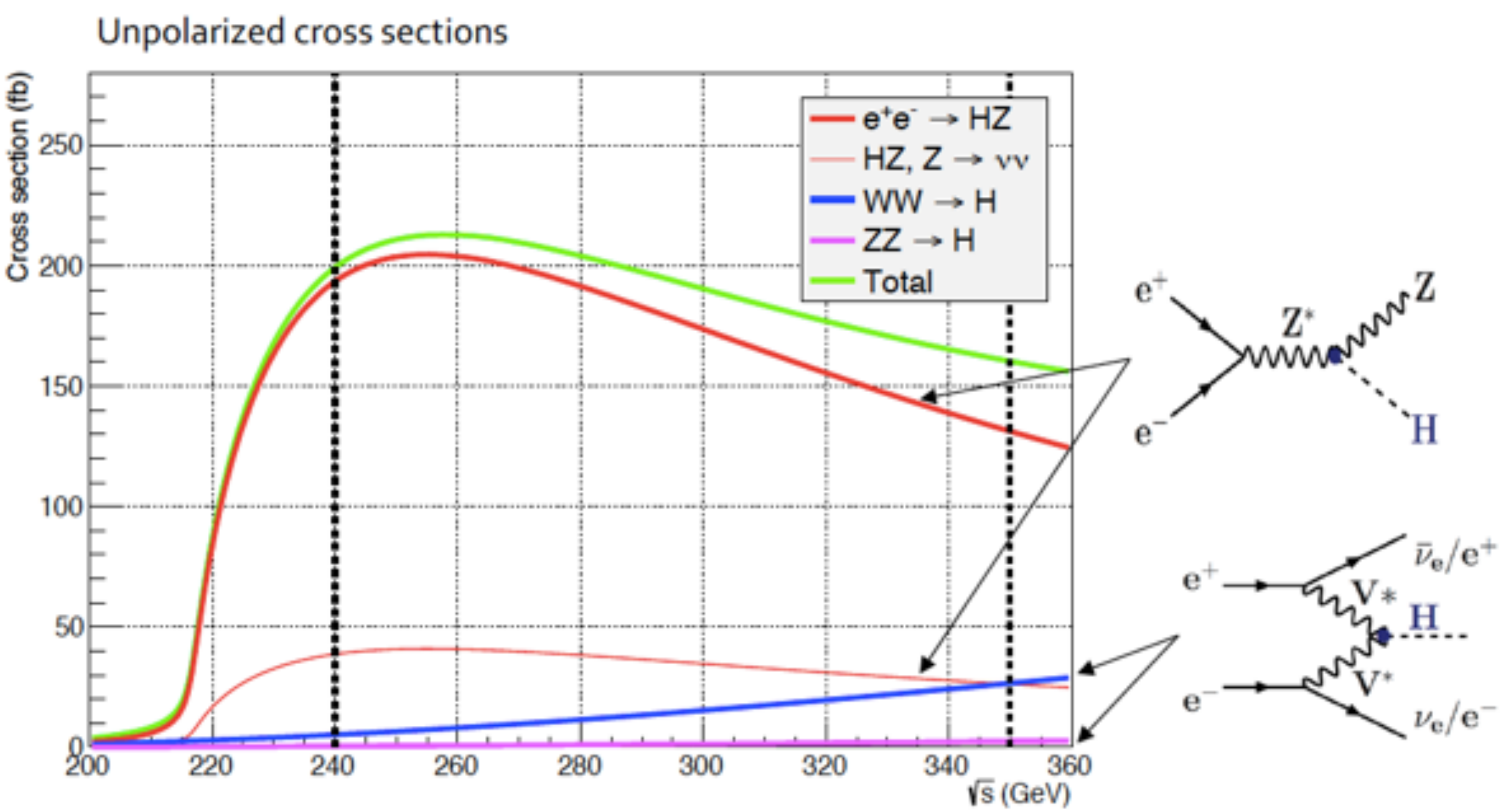


Higgs Physics at the FCC-ee

- ➡ Precision Higgs coupling studies and total width
- ➡ Higgs self coupling through loop corrections
- ➡ 1st and 2nd fermion generation couplings
- ➡ Rare and exotic decays (e.g. DM decays)
- ➡ Extra Higgs bosons
- ➡ Tensor structure
- ➡ …



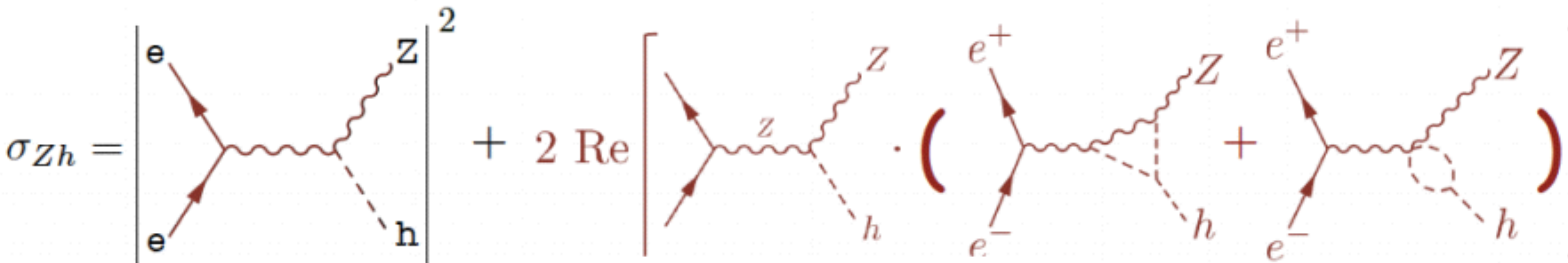
	TLEP 240
Total Integrated Luminosity (ab^{-1})	**10**
Number of Higgs bosons from $e^+e^- \to HZ$	**2,000,000**
Number of Higgs bosons from boson fusion	**50,000**



	TLEP 240
σ_{HZ}	**0.4%**
$\sigma_{HZ} \times BR(H \to bb)$	**0.2%**
$\sigma_{HZ} \times BR(H \to c\bar{c})$	**1.2%**
$\sigma_{HZ} \times BR(H \to gg)$	**1.4%**
$\sigma_{HZ} \times BR(H \to WW)$	**0.9%**
$\sigma_{HZ} \times BR(H \to \tau\tau)$	**0.7%**
$\sigma_{HZ} \times BR(H \to ZZ)$	**3.1%**
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	**3.0%**
$\sigma_{HZ} \times BR(H \to \mu\mu)$	**13%**

stat. uncertainties

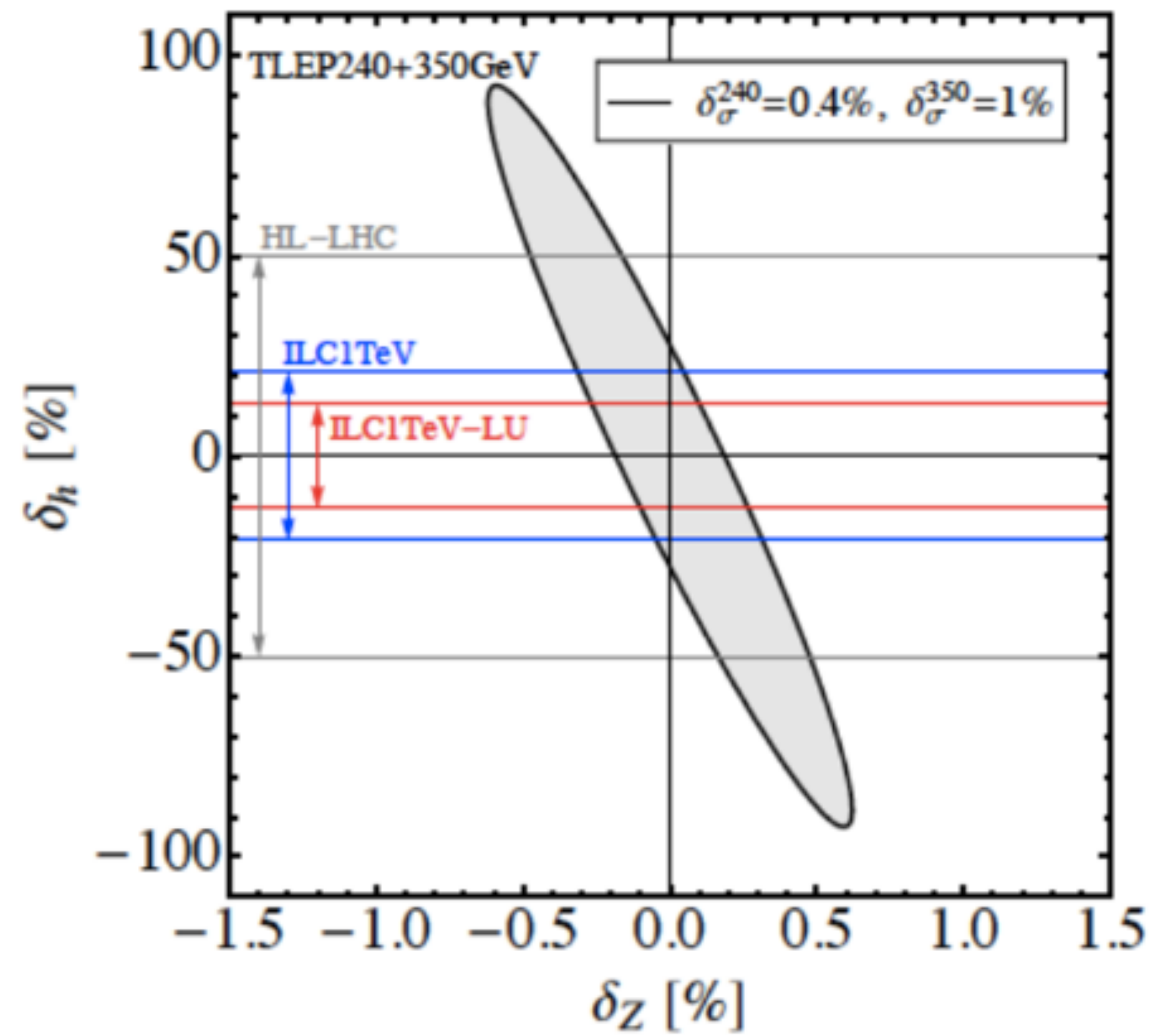
Higgs self-coupling through loop corrections



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

arxiv:1312.3322

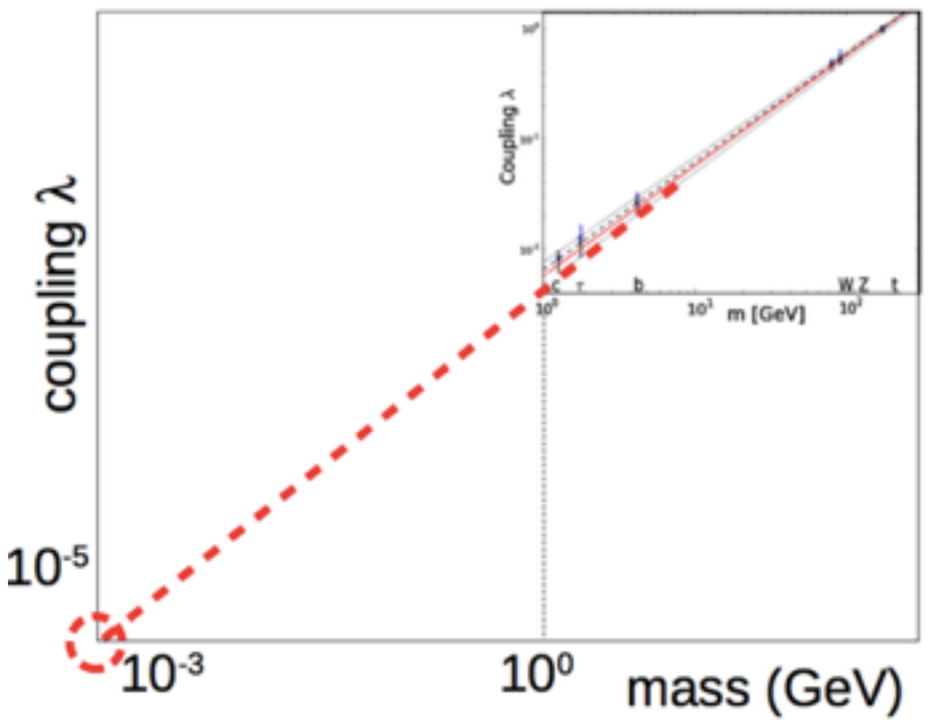
- ➡ Very large datasets at high energy allow extreme precision g_{ZH} measurements
- ➡ Indirect and model-dependent probe of Higgs self-coupling
- ➡ Note, the time axis is missing from the plot

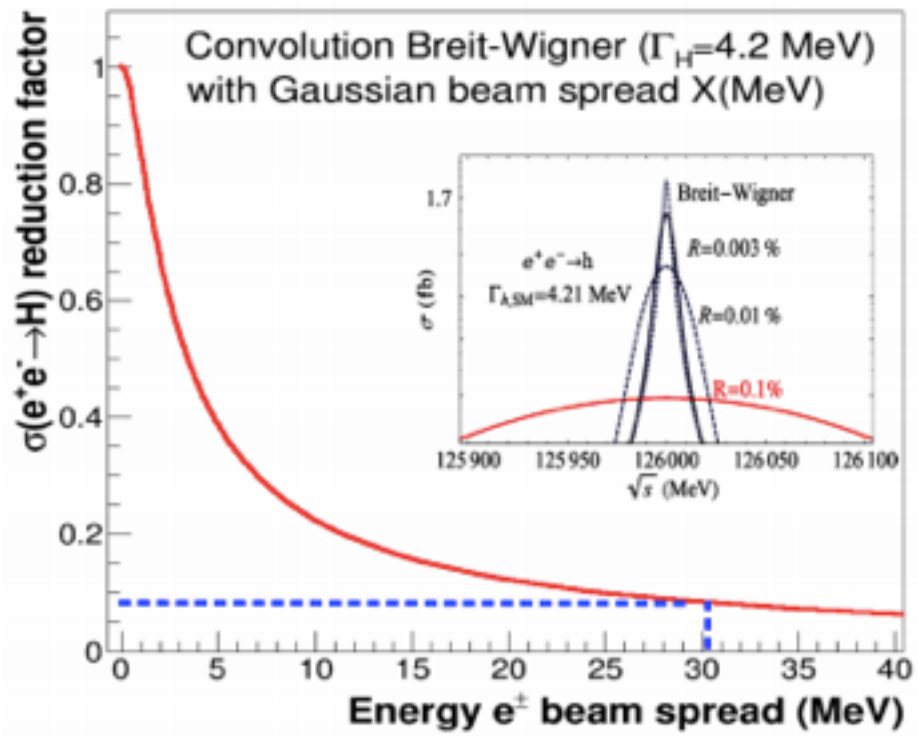


First generation couplings

➡ **s-channel Higgs production**

- Unique opportunity for measurement close to SM sensitivity
- Highly challenging; σ(ee→H) = 1.6fb; 7 Higgs decay channels studied





Preliminary Results

L = 10 ab^{-1}

κ_e < 2.2 at 3σ

➡ **Work in progress**

- How large are loop induced corrections? How large are BSM effects?
- Do we need an energy scan to find the Higgs?
- How much luminosity will be available for this measurement? By how much is the luminosity reduced by monochromators?
- Can polarization increase sensitivity?

Conclusion

- ➡ Very strong motivation to study the Higgs sector thoroughly
- ➡ Exploration of the Higgs sector at the LHC on its way
  - So far all results SM-like
- ➡ LHC & HL-LHC will set a high bar for Higgs precision measurements
  - Large discovery potential for Higgs and beyond
- ➡ Sub-per-cent precision Higgs factory will be critical
- ➡ Strong complementarity between lepton and hadron collider
- ➡ Combination of lepton and hadron collider in one facility offers a long term strategy
- ➡ Need significant theoretical improvements to exploit full potential

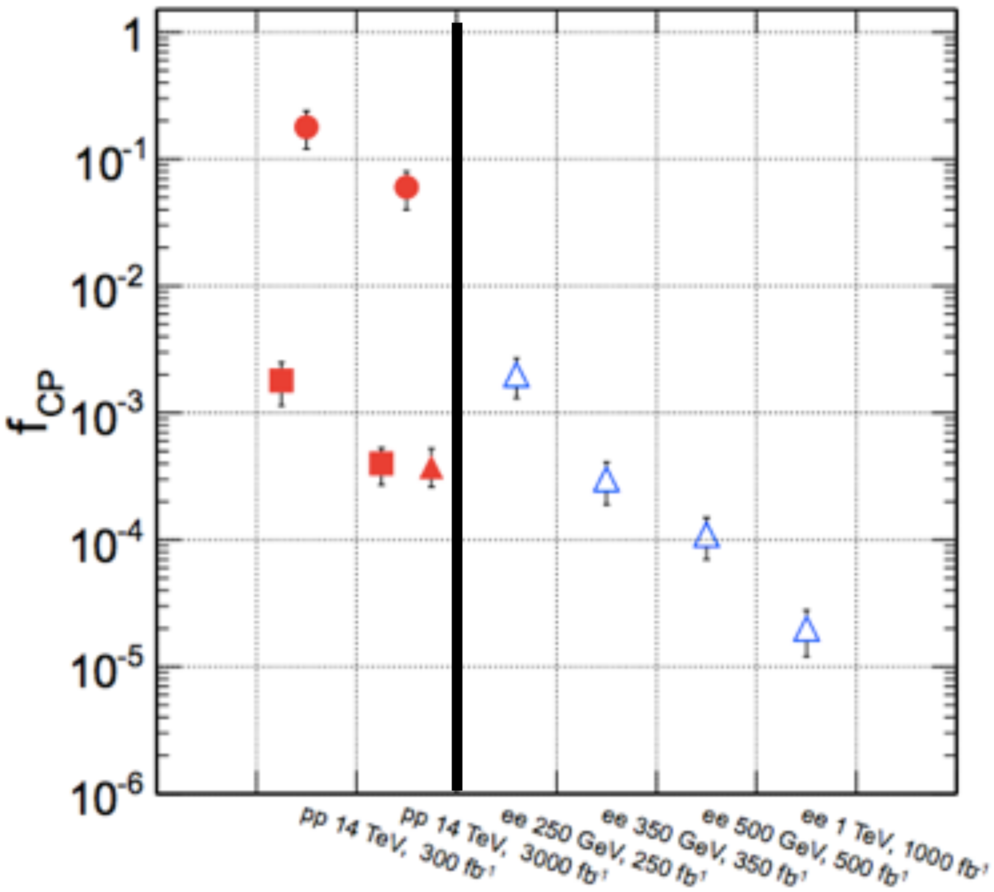
References / Input from

- s-channel Higgs production: D.d'Enterria, R.Aleksan, G.Wojcik
- recent ILC paper: arXiv:1506.07830 (parameter report), arXiv:1506.05992 (physics report)
- FCC-ep: M.Klein
- CMS: Snowmass report, ECFA report
- ATLAS: ATL-CONF-15-007, ATL-PHYS-PUB-2014-016, 019
- TLEP/FCC-ee: TLEP Case Study
- CP measurement: http://arxiv.org/abs/1308.1094, Felix Xu's meeting in the meeting
- Implications of new physics scales: http://arxiv.org/abs/1403.7191
- Luminosity needs for FCC-hh: M.Mangano
- ILC Physics arXiv:1506.05992
- ILC Parameter arXiv:1506.07830
- …

CP measurements

- ➡ CP violation can be studied by searching for CP-odd contributions; CP-even already established
- ➡ Snowmass Higgs paper http://arxiv.org/abs/1310.8361
- ➡ Higgs to Tau decays of interest
- ➡ More detailed presentation by Felix Yu http://arxiv.org/abs/1308.1094

for HVV couplings



$$\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5 \sin\Delta)f$$

Colliders	LHC	HL-LHC	FCCee (1 ab^{-1})	FCCee (5 ab^{-1})	FCCee (10 ab^{-1})
Accuracy(1σ)	25°	8.0°	5.5°	2.5°	1.7°

Rare and Exotics Higgs Bosons

- ➡ 2,000,000 ZH events allow for detailed studies of rare and exotic decays
  - requires hadronic and invisible Z decays
  - set requirements for FCC-ee detector
- ➡ Coupling measurements have sensitivity to BSM decays
- ➡ Dedicated studies using specific final states improve sensitivity
- ➡ Example: Higgs to invisible, flavor violating Higgs, and many more
- ➡ Potential at the LHC (and HL-LHC) currently not fully explored
- ➡ Modes with of limited LHC sensitivity are of particular importance to FCC-ee program
  - currently under study
- ➡ FCC-ee might allow precision measurement of exotic Higgs decays
- ➡ Detailed discussion of exotic Higgs decays at Phys. Rev. D 90, 075004 (2014)

$h \to \not{E}_T$

$h \to 4b$

$h \to 2b2\tau$

$h \to 2b2\mu$

$h \to 4\tau, 2\tau 2\mu$

$h \to 4j$

$h \to 2\gamma 2j$

$h \to 4\gamma$

$h \to ZZ_D, Za \to 4\ell$

$h \to Z_D Z_D \to 4\ell$

$h \to \gamma + \not{E}_T$

$h \to 2\gamma + \not{E}_T$

$h \to$ 4 ISOLATED LEPTONS $+ \not{E}_T$

$h \to 2\ell + \not{E}_T$

$h \to$ ONE LEPTON-JET $+ X$

$h \to$ TWO LEPTON-JETS $+ X$

$h \to b\bar{b} + \not{E}_T$

$h \to \tau^+\tau^- + \not{E}_T$

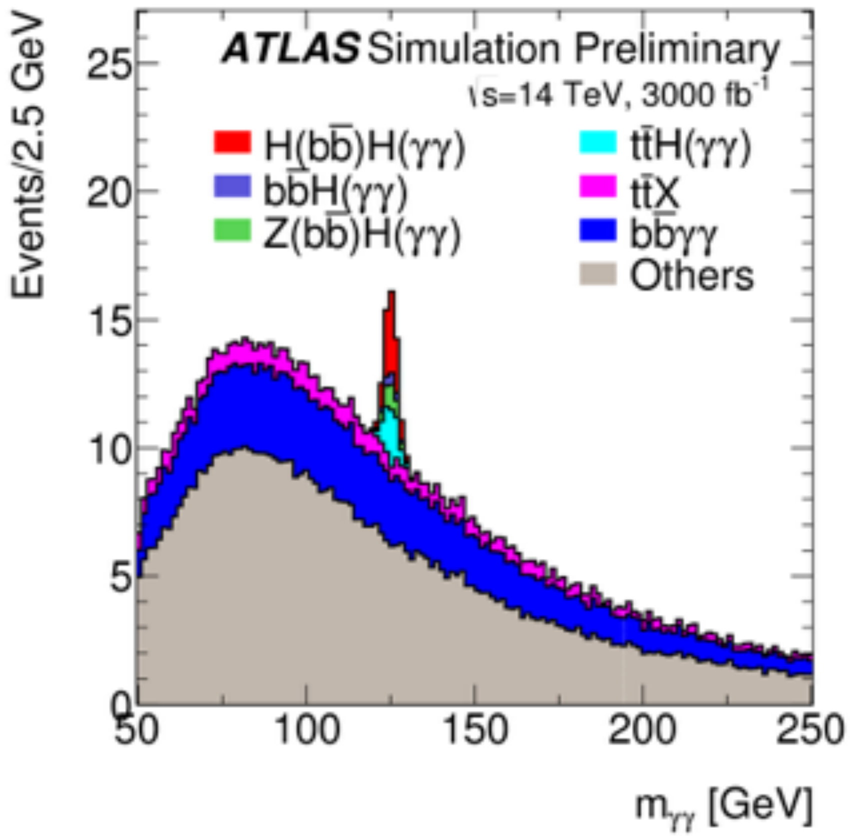
Higgs prospects for the HL-LHC

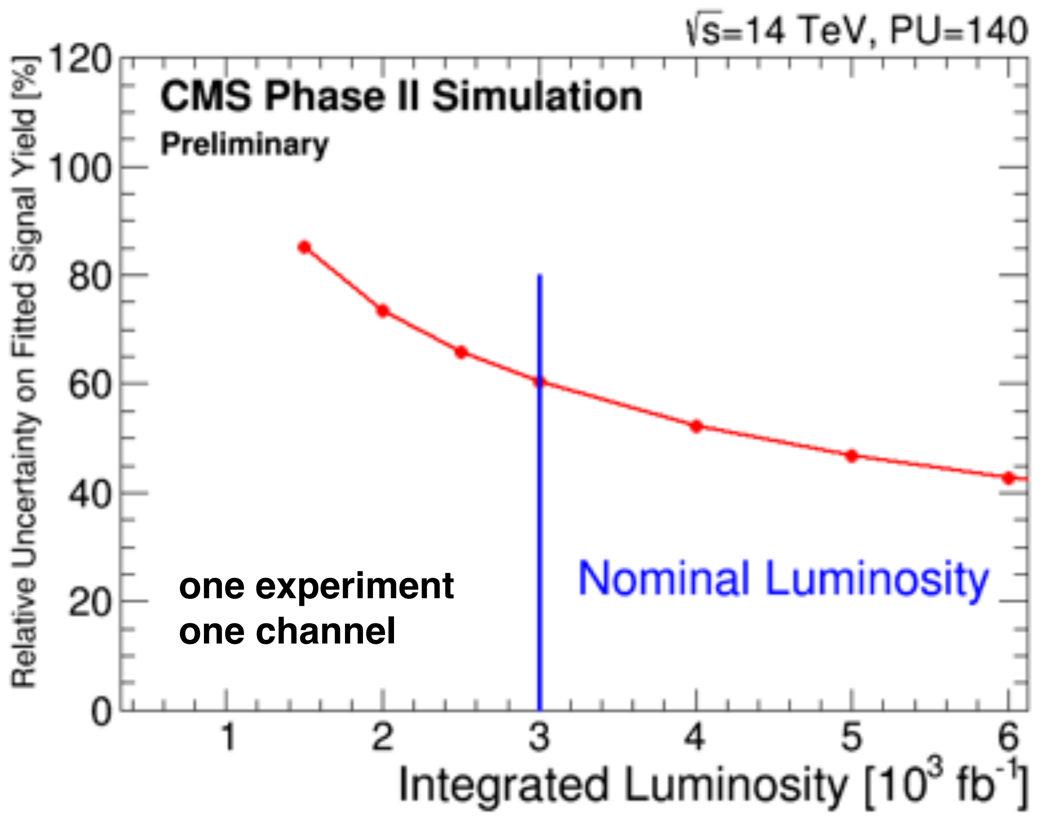
ATLAS Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty							
		by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j → 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j → 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j → VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j → VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

Key question is the
evolution systematic uncertainty

Higgs prospects for the HL-LHC

- ➡ **Di-Higgs production: exciting prospects of the HL-LHC**
  - ◉ Gluon fusion cross section is only **40.2fb** [NNLO] at 14 TeV
  - ◉ Vector boson fusion cross section is 2fb
- ➡ **Most interesting final states**
  - ◉ bb**γγ** [320 expected events in 3ab-1]
  - ◉ bb$\tau\tau$ [9000 expected]
  - ◉ bbbb [40k expected (2k in VBF)]
  - ◉ bbWW [30000 exp. events]
- ➡ **Goal is to reach minimum sensitivity of 3σ for SM production and with that to BSM scenarios**





Process / Selection Stage	HH	ZH	$t\bar{t}H$	$b\bar{b}H$	$\gamma\gamma$+jets	γ+jets	jets	$t\bar{t}$
Object Selection & Fit Mass Window	22.8	29.6	178	6.3	2891	1616	292	113
Kinematic Selection	14.6	14.6	3.3	2.0	128	96.9	20	20
Mass Windows	9.9	3.3	1.5	0.8	8.5	6.3	1.1	1.1

CMS - central photon yield

Exclusive Higgs boson decays

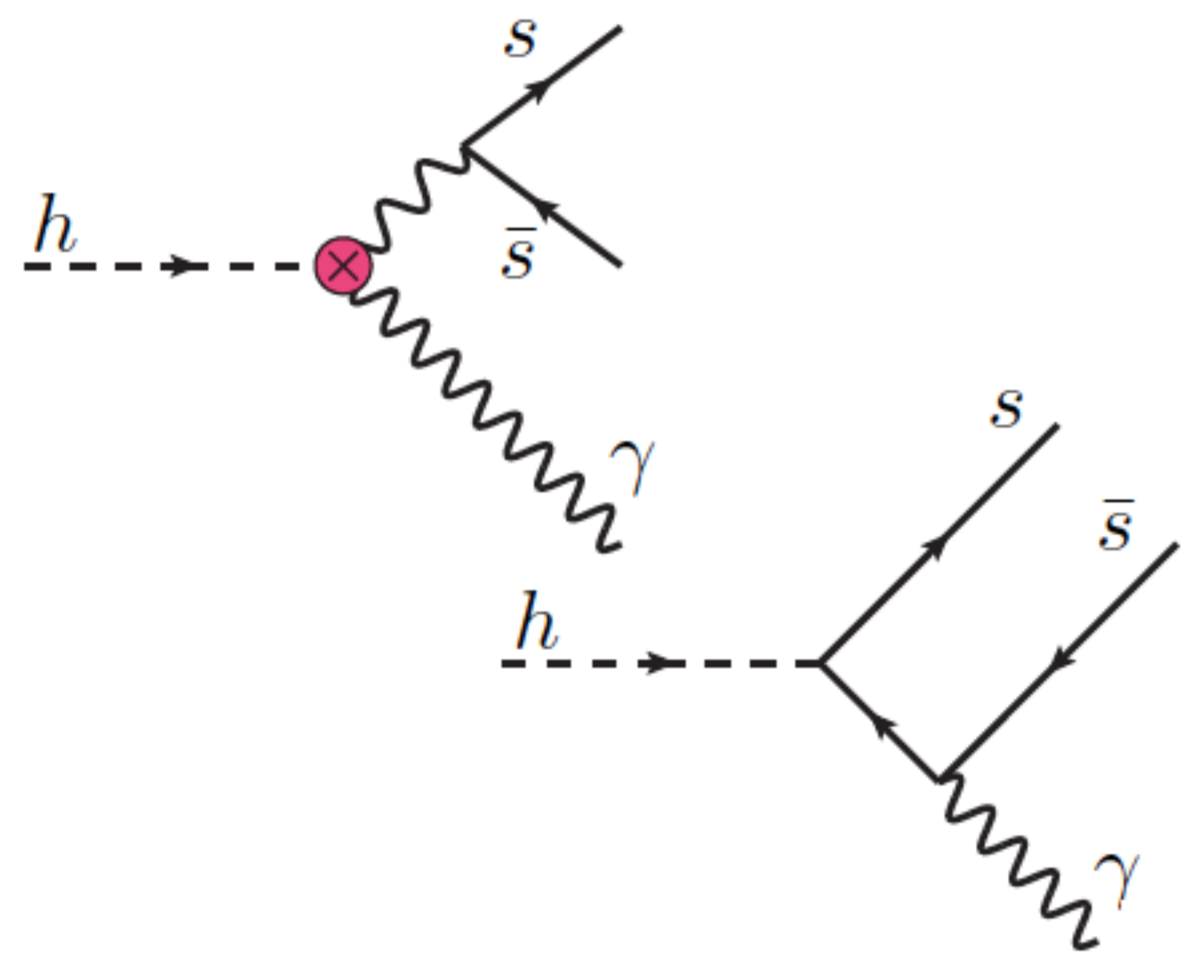
➡ First and second generation couplings accessible

- Study of **ργ** channel most promising; expect ~50 evts.
- Sensitivity to u/d quark Yukawa coupling
- Sensitivity due to interference

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2} \times 10^{-5}$$

➡ Also interesting to FCC-hh program

➡ Alternative H→MV decays should be studied (V= γ, W, and Z)



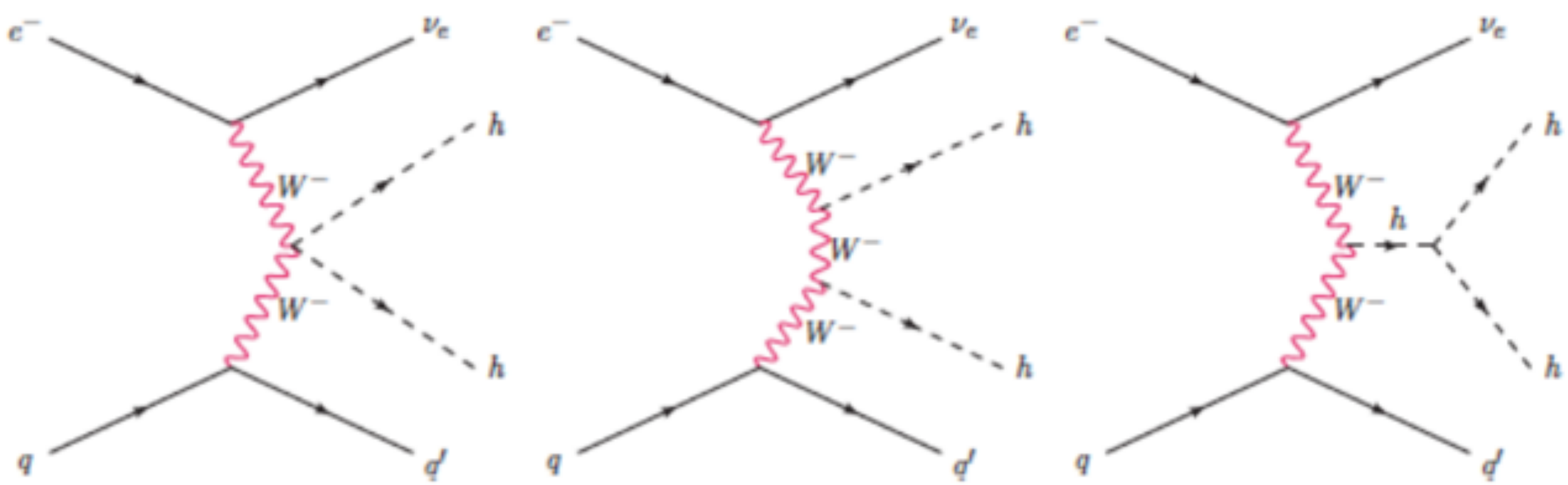
H → J/Ψ γ → y_c

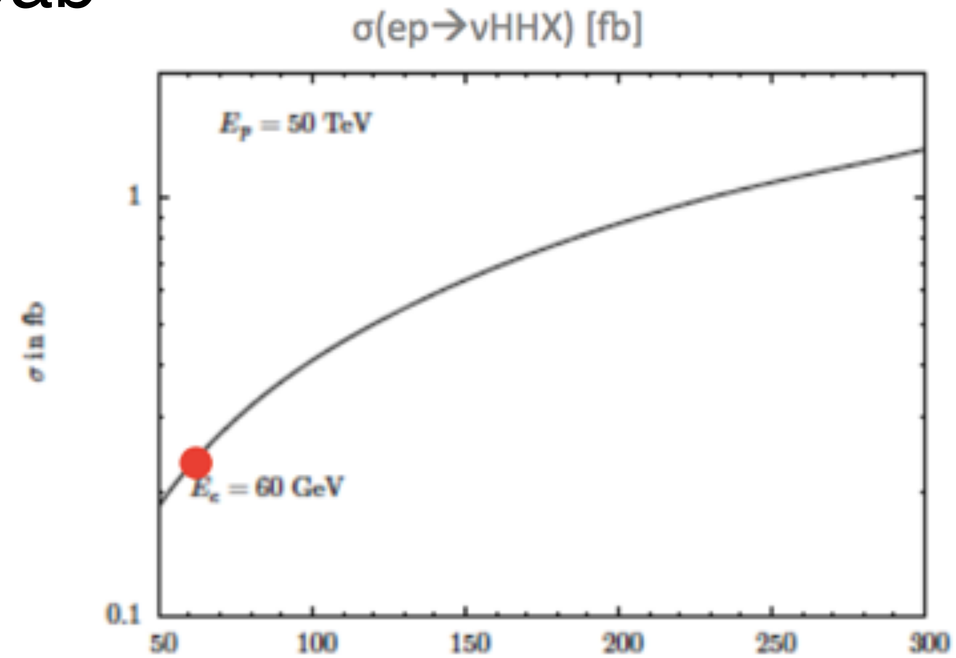
H → ϕ γ → y_s

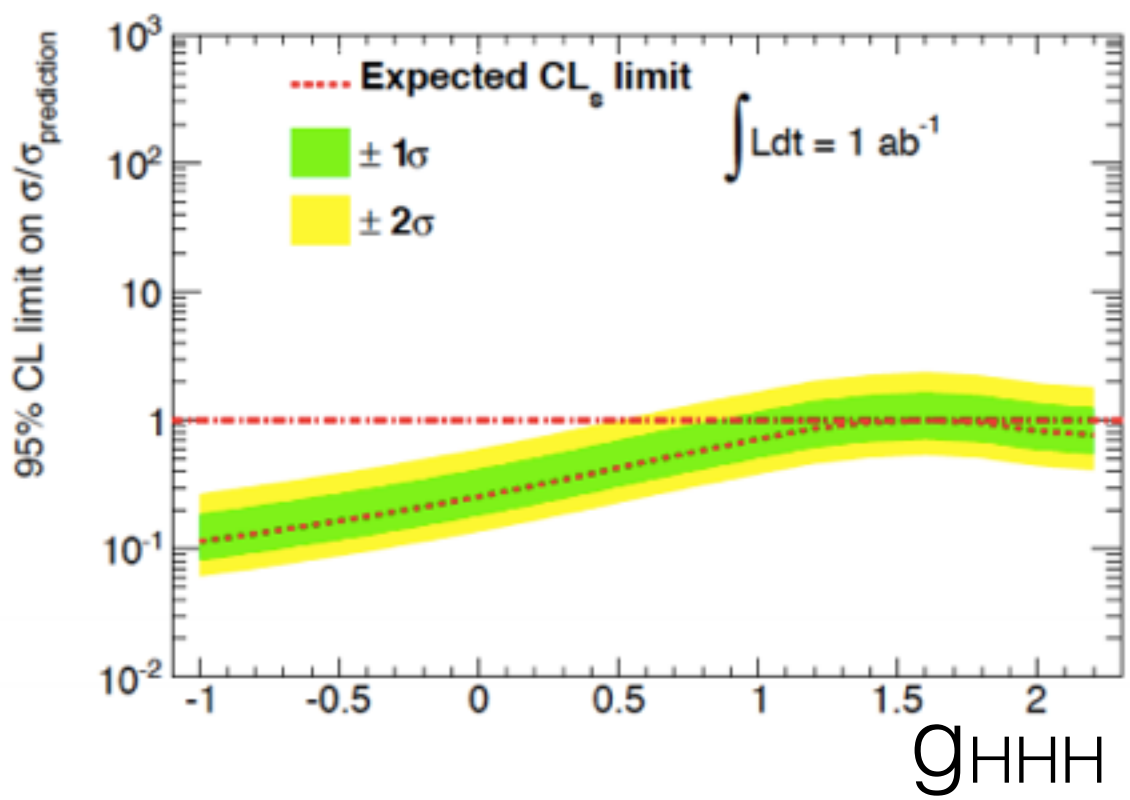
H → **ρ** γ, H → ω γ → y_u, y_d

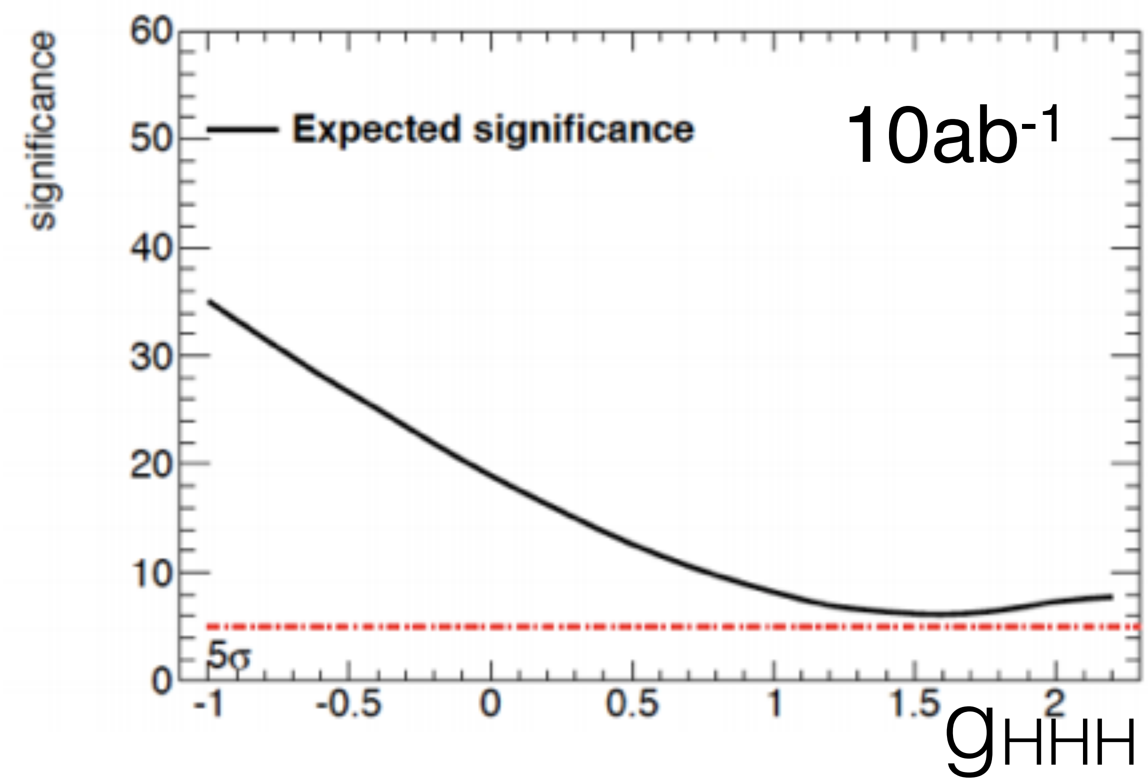
Higgs Production: FCC-ep

- ➡ Study of di-H production possible in bbbb final state
- ➡ O(15%) precision on di-H cross section in $10ab^{-1}$









ILC Timeline

Delivered TDR

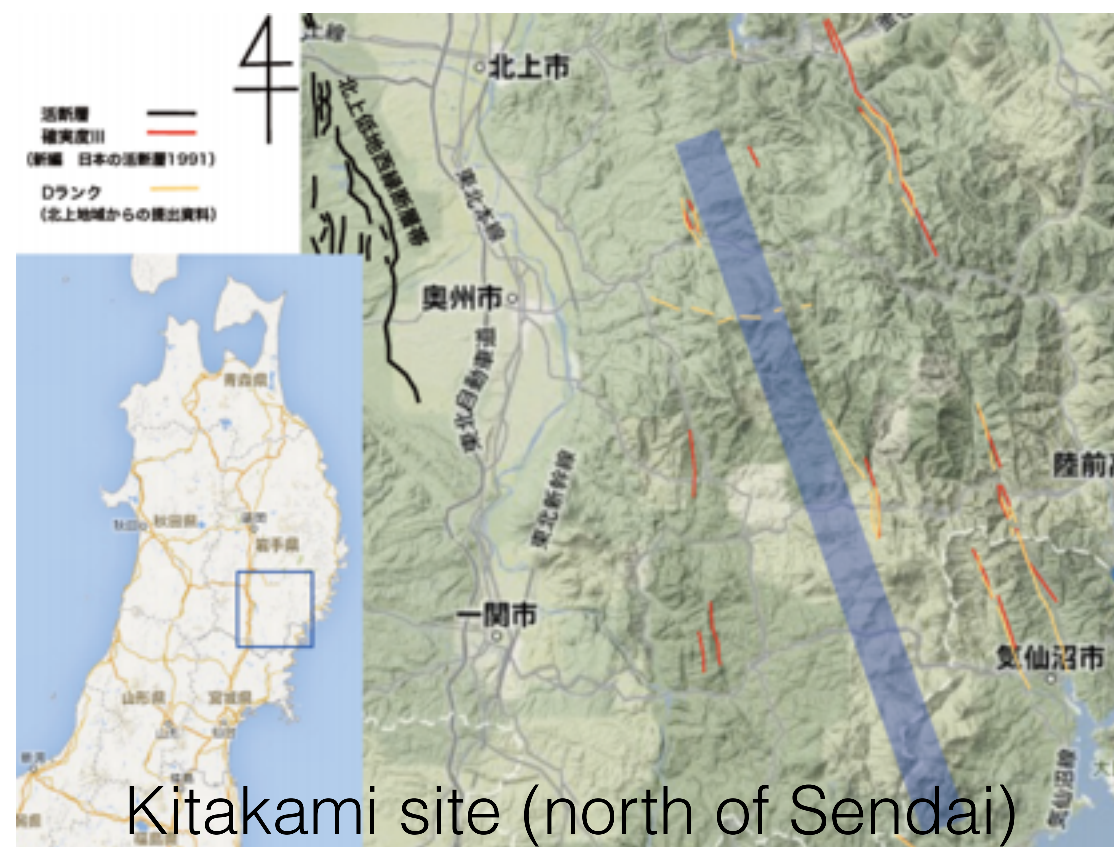
Machine commissioning starts

Present

2013	2016	2018
Negotiations among governments **Prepare for international lab** **Accelerator detailed design** **R&D for cost-effective production** **Site studies**	**International agreement** **"Green-light" for construction** **Preparation for bidding**	**Construction**

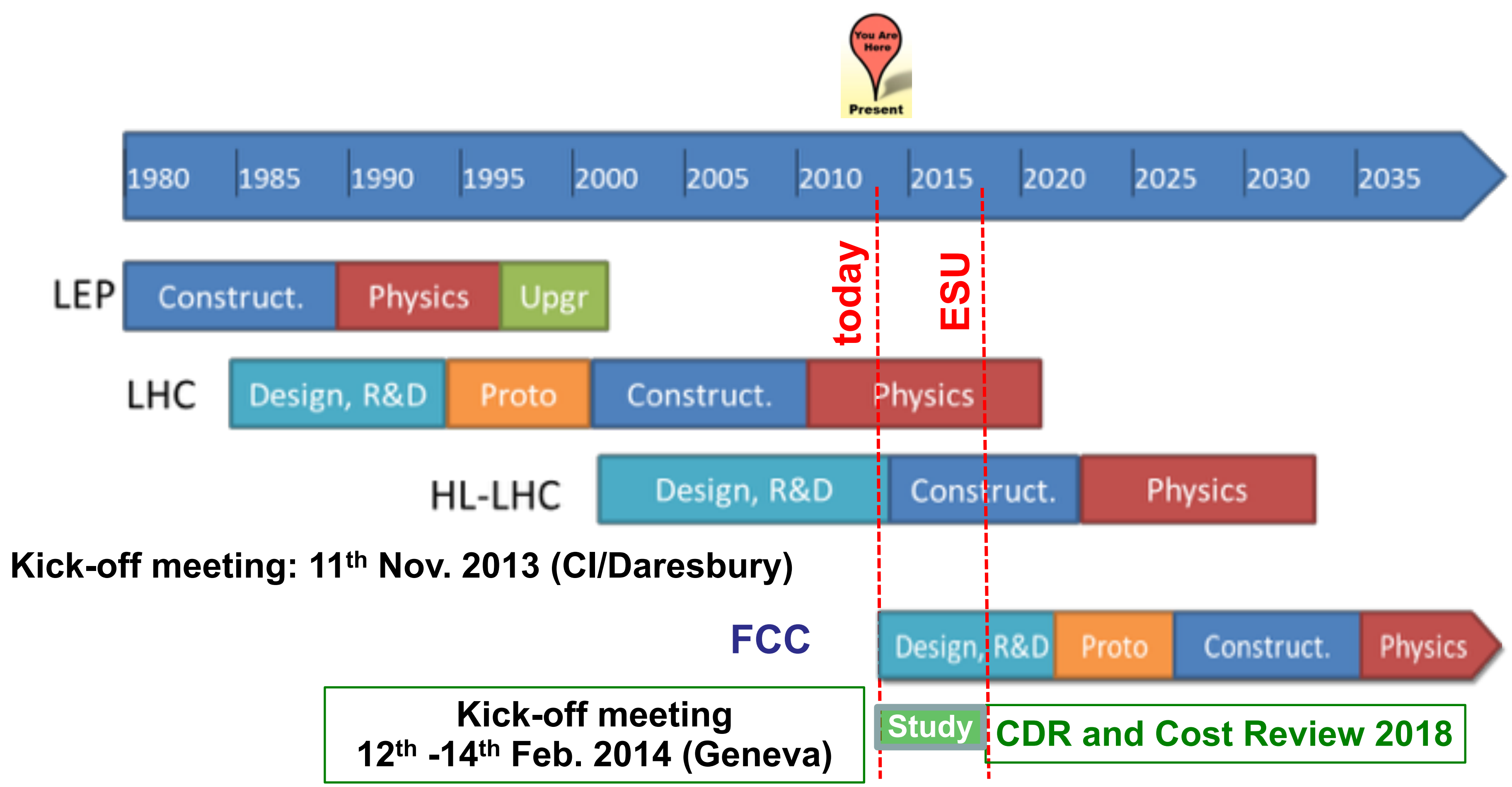
2013 — 2016 — 2018 — 2027

as proposed by LC Collaboration



Kitakami site (north of Sendai)

CERN (FCC) Timelines



- LHC and HL-LHC operation until ~2035
- Must start now developing FCC concepts to be ready in time

CEPC-SppC Timelines