Higgs measurements at future e^+e^- colliders

XXVII Cracow EPIPHANY
Conference on the Future of Particle Physics
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Introduction: European Strategy

Preamble: The particle physics community is ready to take the next step towards even higher energies and smaller scales. The vision is to prepare a Higgs factory, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated technical and environmental challenges.

High-priority future initiatives

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

the particle physics community should ramp up its R&D effort focused
· on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;

· Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

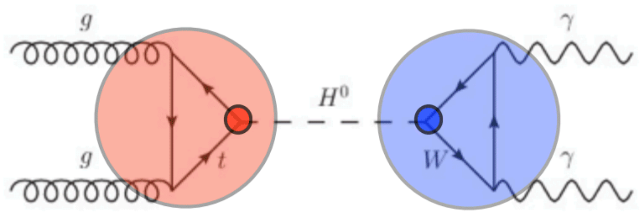
The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

Collider Options

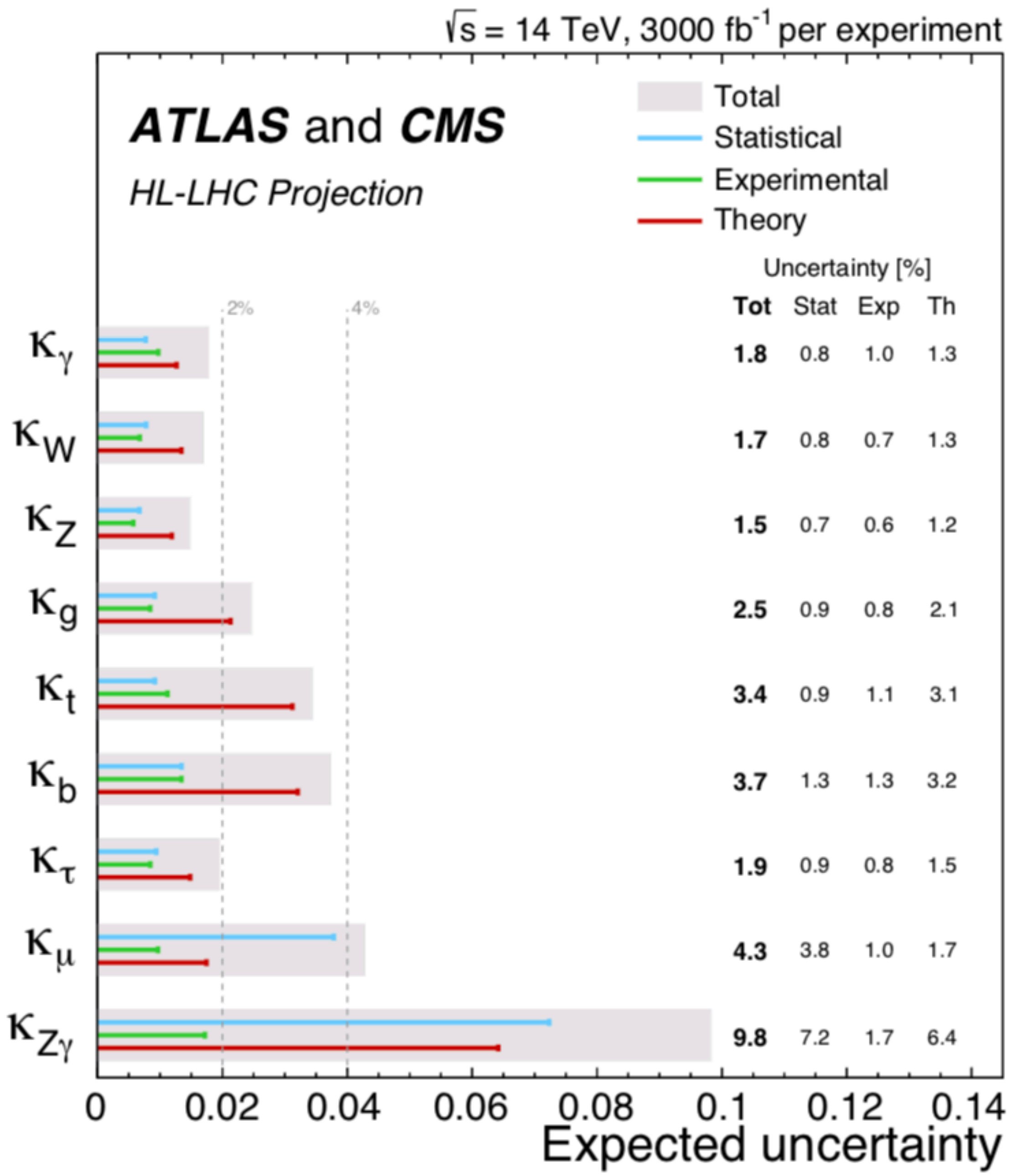
	T_0				+5					+10					+15					+20			...	+26
ILC	0.5/ab 250 GeV						1.5/ab 250 GeV						1.0/ab 500 GeV				0.2/ab $2m_{top}$	3/ab 500 GeV						
CEPC	5.6/ab 240 GeV							16/ab M_Z		2.6 /ab $2M_W$										SppC =>				
CLIC	1.0/ab 380 GeV										2.5/ab 1.5 TeV									5.0/ab => until +28 3.0 TeV				
FCC	150/ab ee, M_Z				10/ab ee, $2M_W$		5/ab ee, 240 GeV				1.7/ab ee, $2m_{top}$												hh,eh =>	
LHeC	0.06/ab						0.2/ab					0.72/ab												
HE-LHC	10/ab per experiment in 20y																							
FCC eh/hh	20/ab per experiment in 25y																							

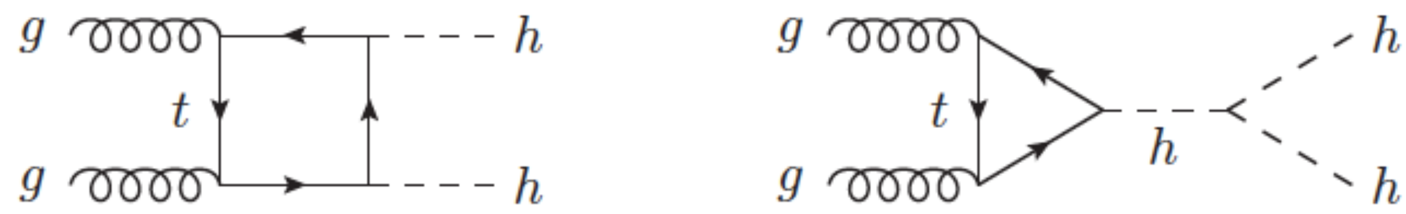
arXiv:1905.03764

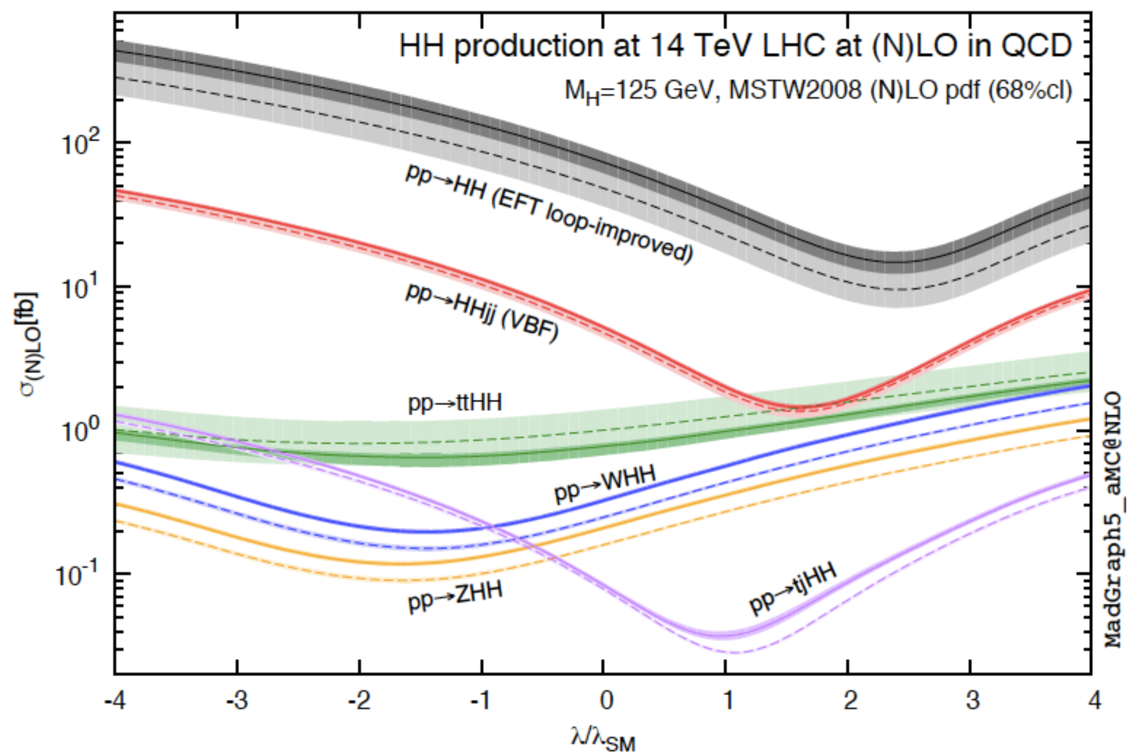
HL-LHC Higgs Legacy



$$(\sigma \cdot \mathrm{BR})\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$







	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

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

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

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

arXiv:1310.8361

➡ **Fingerprints of BSM Physics on Higgs**

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

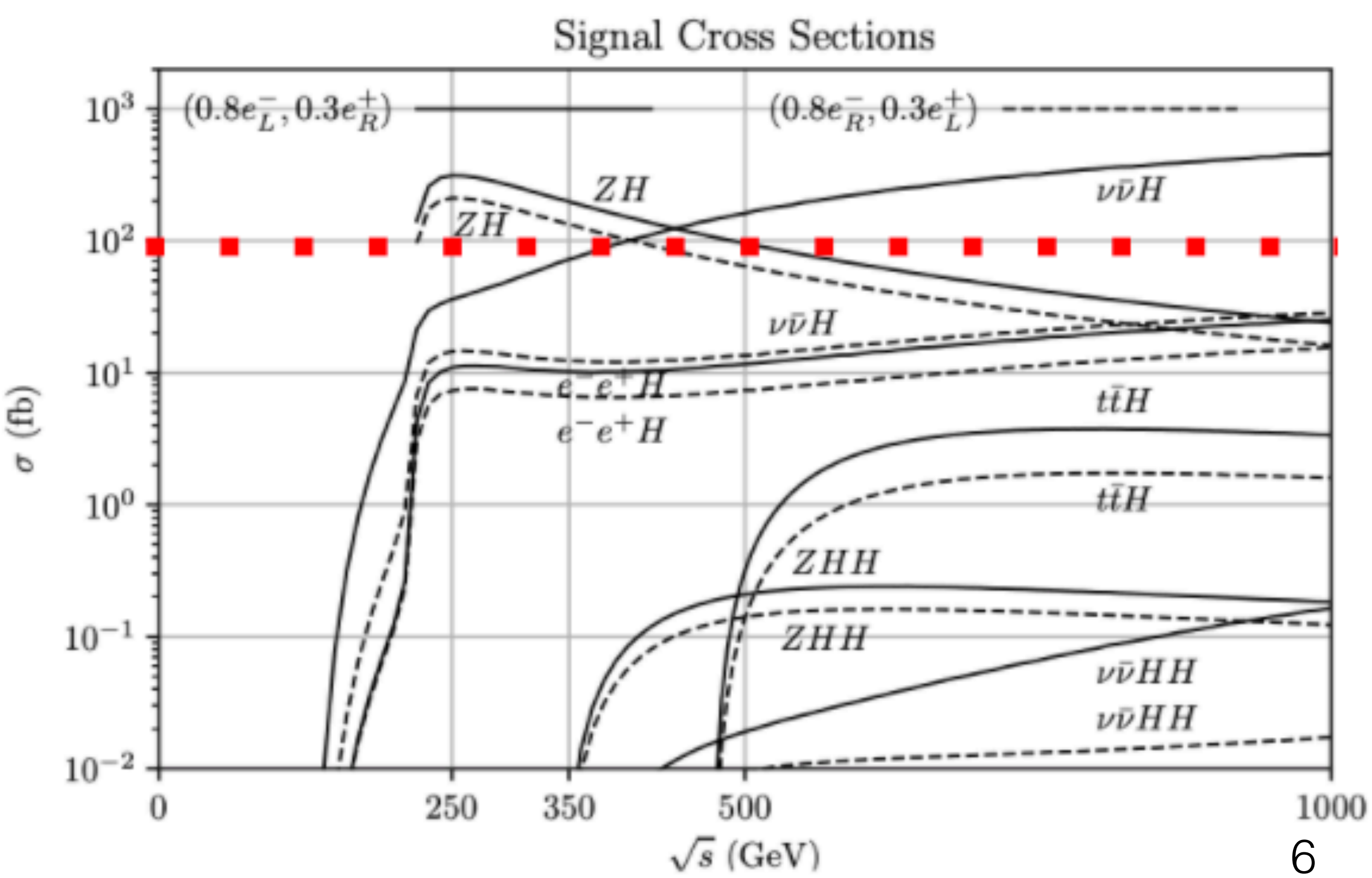
- ➡ **Requires 10^6 Higgs events**

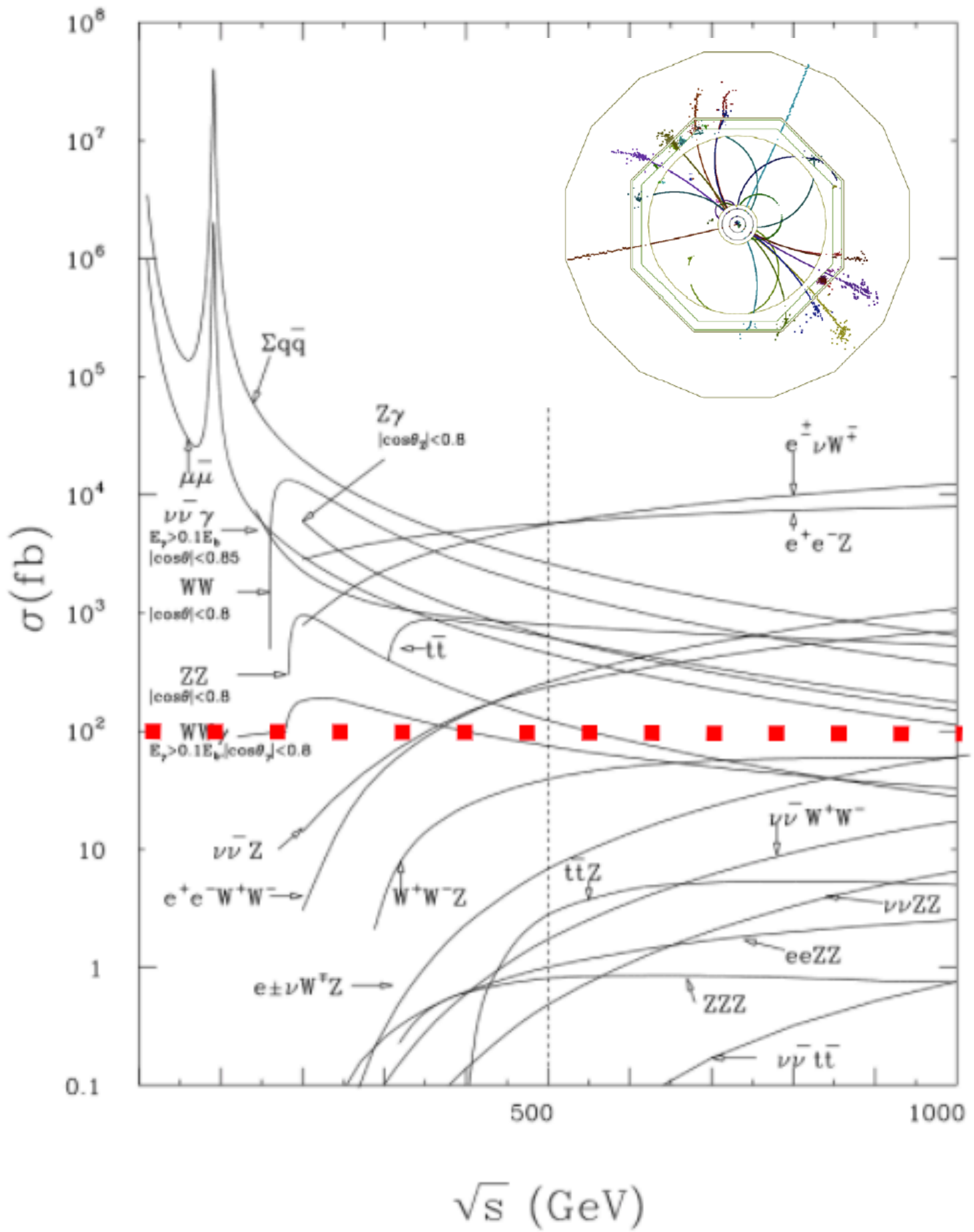
➡ **There is no strict limit to the precision needed!**

Experimental Setup

➡ **Collisions dominated by electroweak processes**

- Low event rates
- Trigger-less readout possible
- Low occupancy and no pileup
- Limited radiation damage



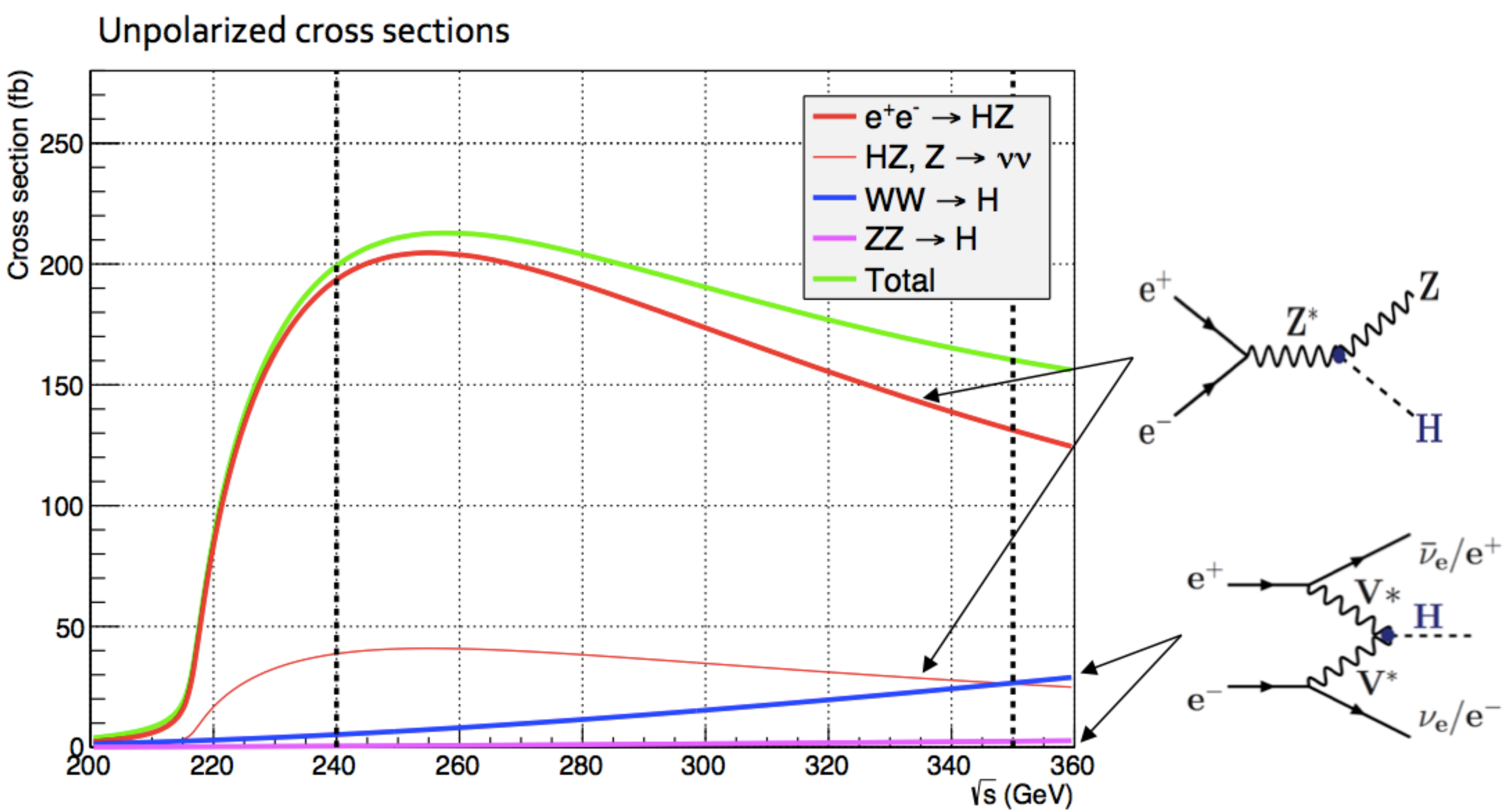


Higgs Related Physics at Lepton Colliders

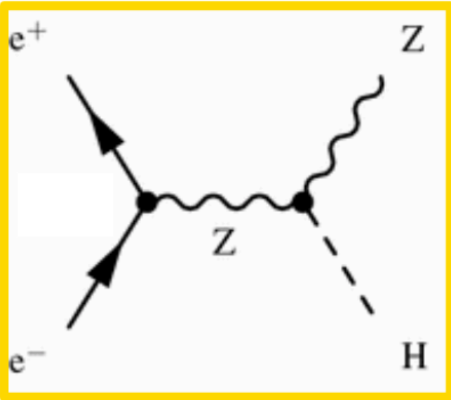
$\sqrt{s}$ [GeV]	$\sqrt{s}$	Measurements (incomplete list)
90	$\mathbf{m_Z}$	m_Z, Γ_Z, α_s, α_{QED}, flavor, QCD
125	$\mathbf{m_H}$	s-channel Higgs production
160	$\mathbf{2m_W}$	m_W, α_s
240-250	$\mathbf{m_H+m_Z+\ldots}$	m_H, Γ_H, J^{CP}, g_{HXX}, BSM decays, indirect g_{HHH}
340-355	$\mathbf{2*m_{top}}$	g_{HWW}, Γ_H, indirect g_{Htt}, m_{top}
500	$\mathbf{2*m_{top}+m_H+\ldots}$	g_{HHH}, g_{Htt}
> 500	$\mathbf{m_{NP}}$	g_{Htt}, g_{HHH}, BSM Higgs

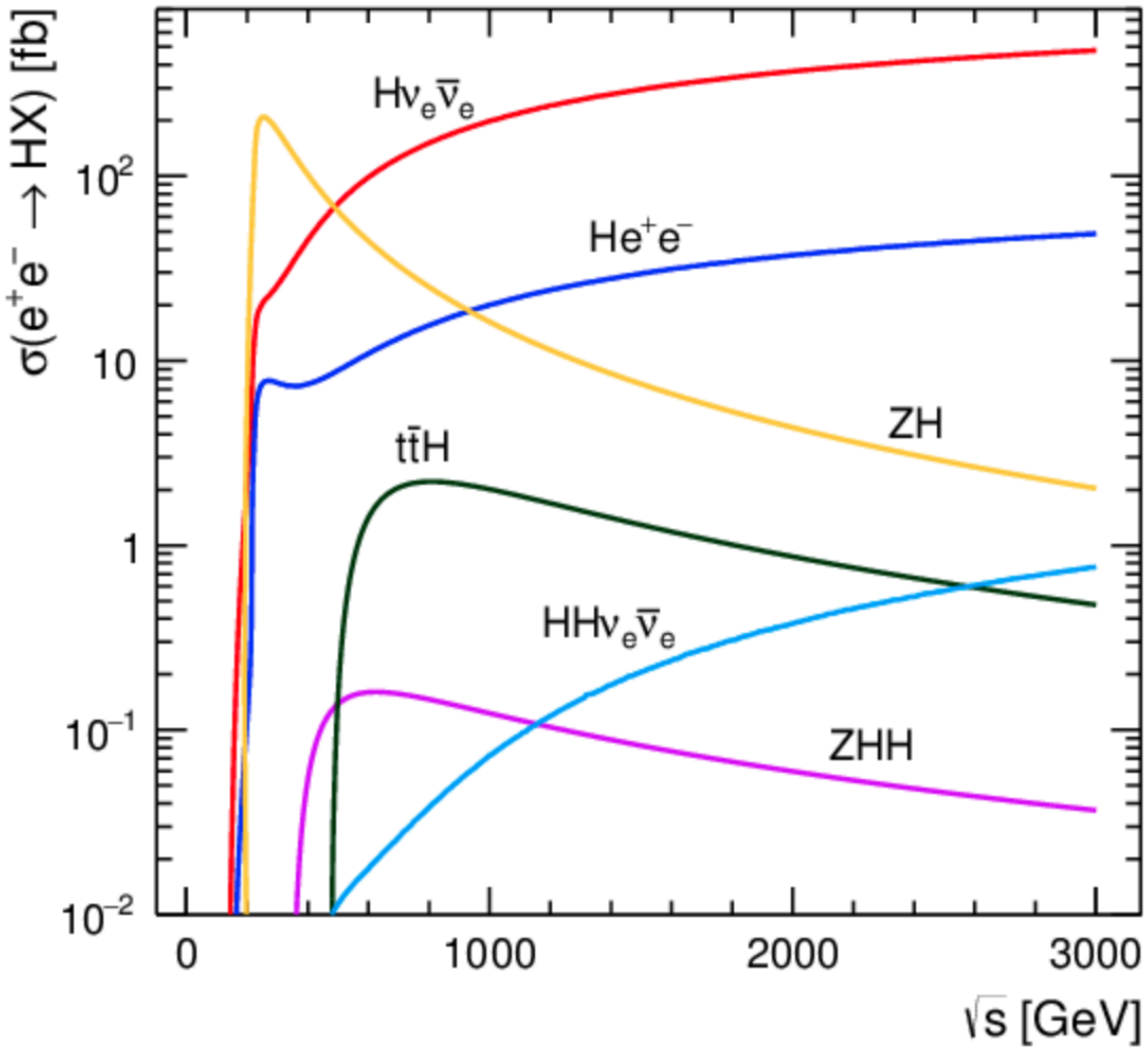
Higgs Production

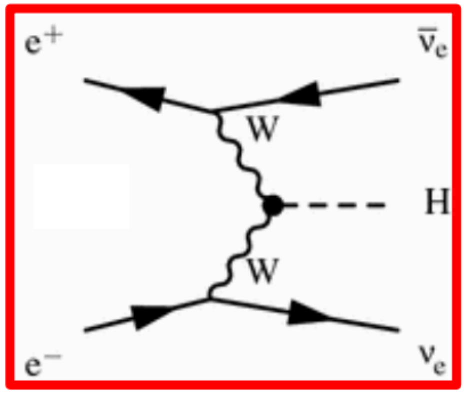
➡ $e^+e^- \to ZH$ production maximal at 240-260 GeV

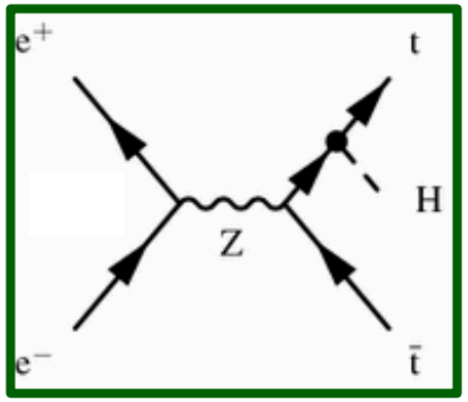


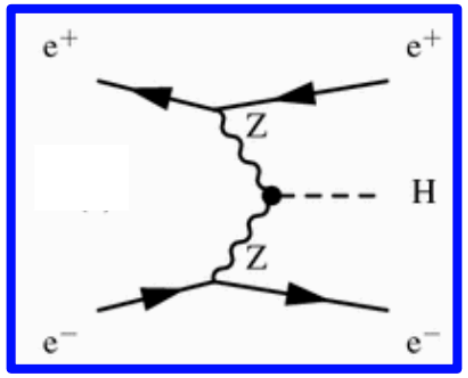
Higgs Production

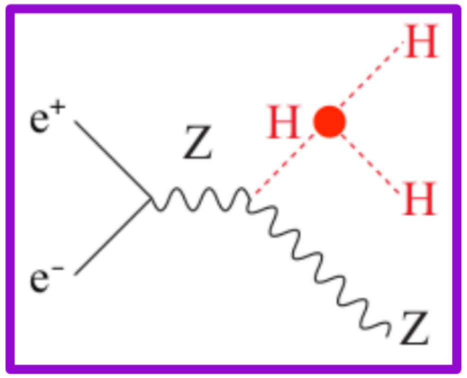


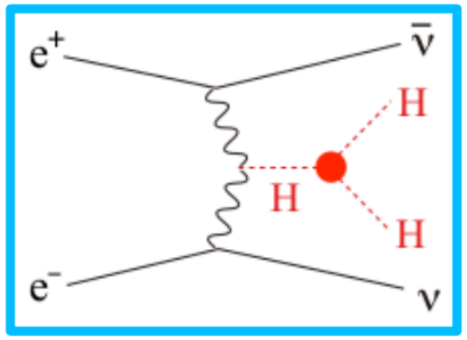




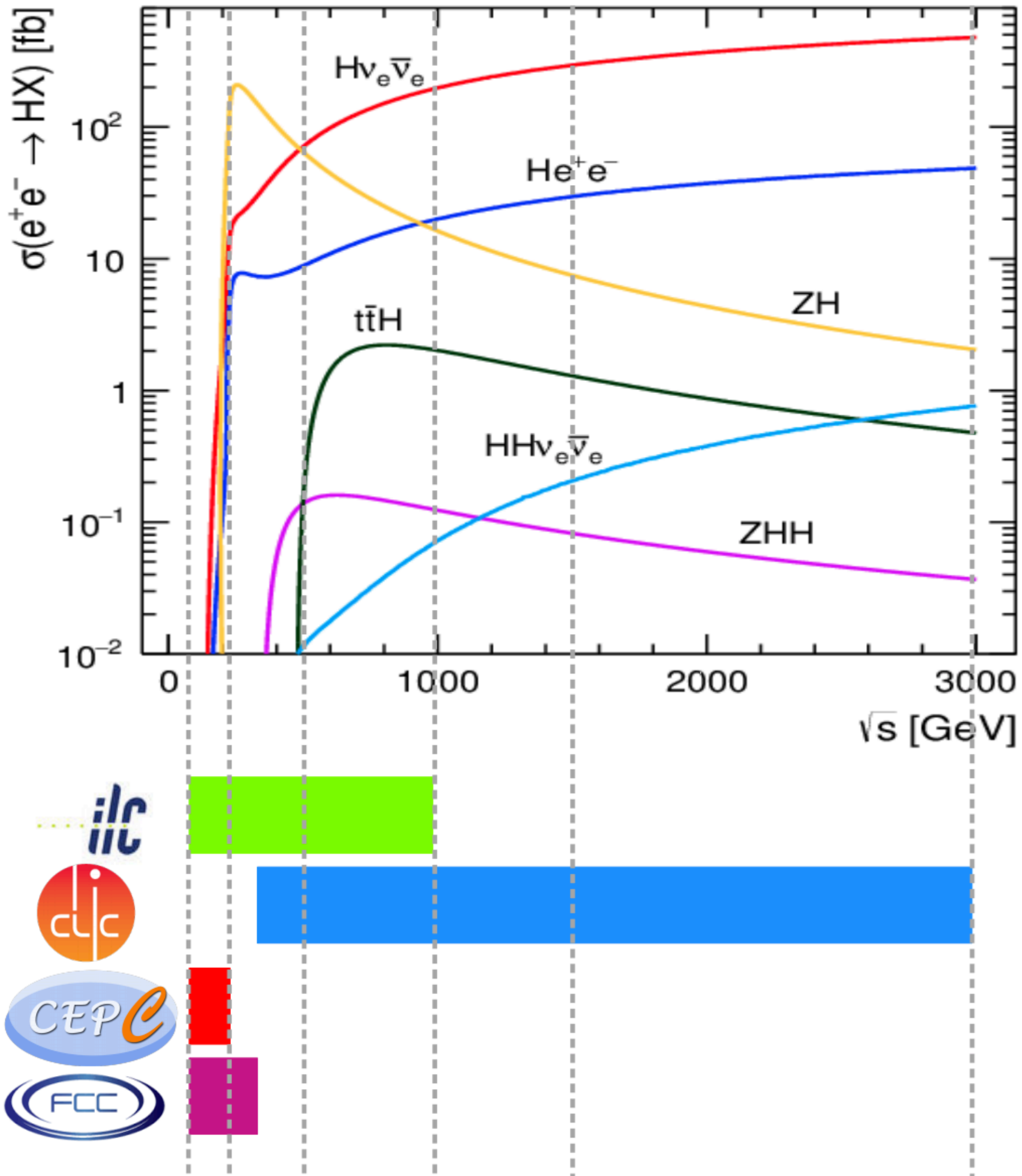








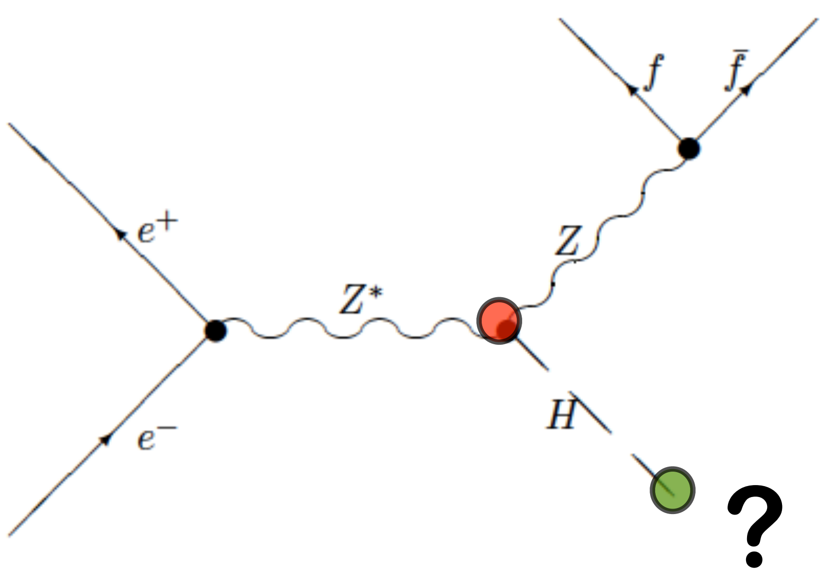
Higgs Factories



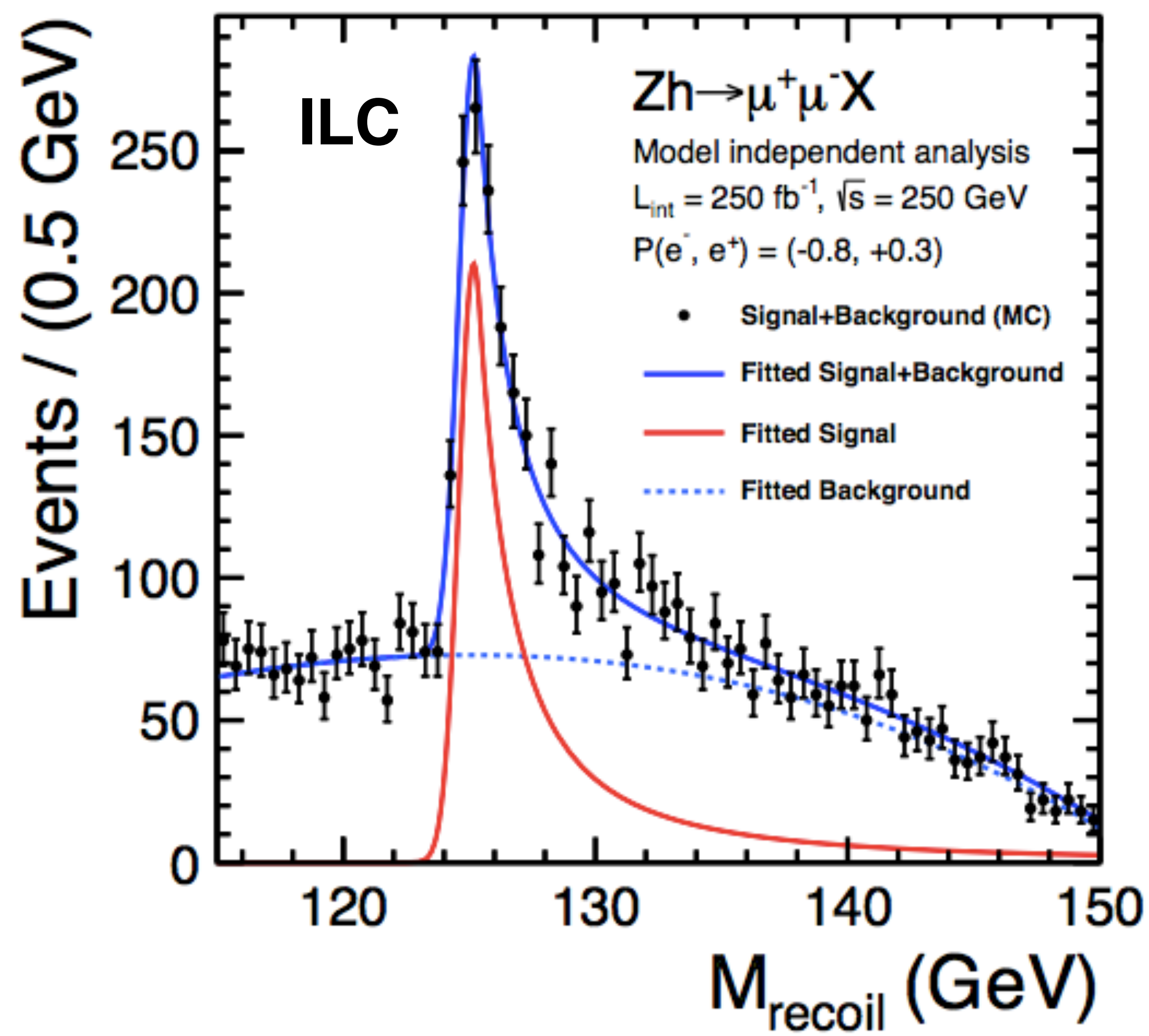
Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\rm inst}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]
HL-LHC	pp	14 TeV	-	2	5	6.0	12
HE-LHC	pp	27 TeV	-	2	16	15.0	20
FCC-hh$^{(*)}$	pp	100 TeV	-	2	30	30.0	25
FCC-ee	ee	M_Z	0/0	2	100/200	150	4
		$2M_W$	0/0	2	25	10	1-2
		240 GeV	0/0	2	7	5	3
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5
							(+1)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5
		350 GeV	±80/±30	1	1.6	0.2	1
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5
							(+1)
		1000 GeV	±80/±20	1	3.6/7.2	8.0	8.5
							(+1-2)
CEPC	ee	M_Z	0/0	2	17/32	16	2
		$2M_W$	0/0	2	10	2.6	1
		240 GeV	0/0	2	3	5.6	7
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8
		1.5 TeV	±80/0	1	3.7	2.5	7
		3.0 TeV	±80/0	1	6.0	5.0	8
							(+4)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25

Higgs Precision Measurements

- ➡ Recoil method unique to lepton collider
- ➡ Tag Higgs event independent of decay mode
- ➡ Provides precision and model independent measurements of
  - ◉ $\sigma(ee \rightarrow ZH) \propto g_{HZZ}^2$
  - ◉ m_H
- ➡ Key input to Γ_H
- ➡ Sensitive channel for Higgs to invisible search (sub-percent BRs)

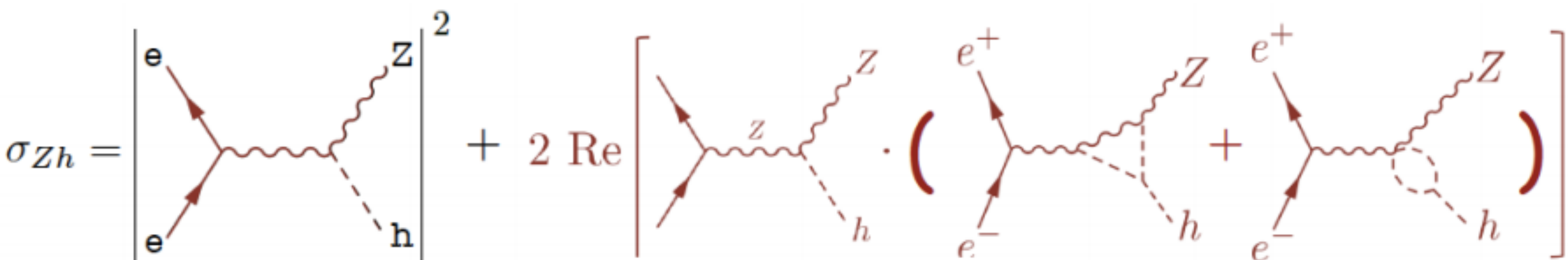


$$m_{\mathrm{recoil}}^2 = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$



$$(\sigma \cdot \mathrm{BR})(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \rightarrow H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Higgs self-coupling through loop corrections



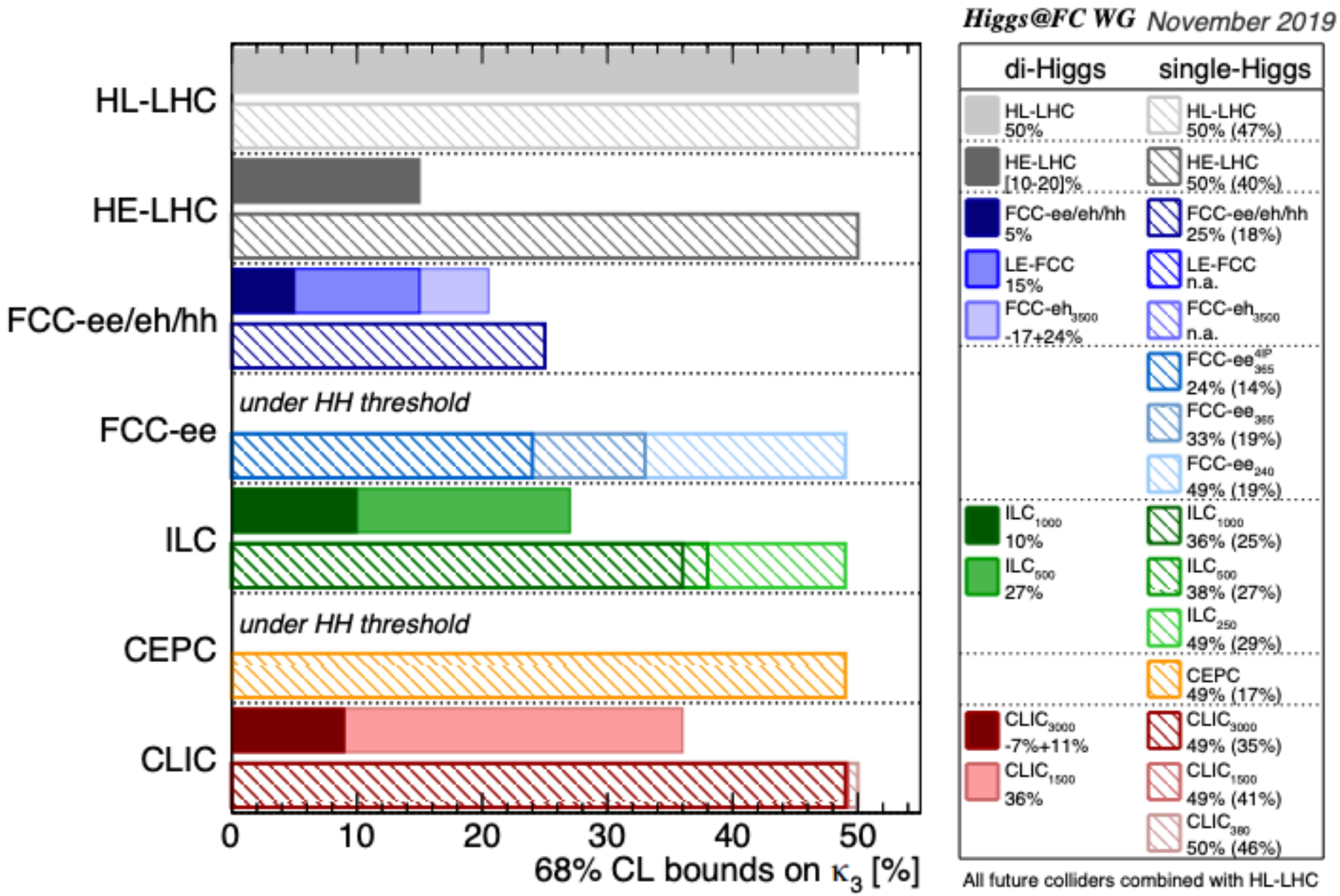
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- ➡ Very large datasets at high energy allow extreme precision g_{ZH} measurements
- ➡ Indirect and model-dependent probe of Higgs self-coupling

collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-

arxiv:1312.3322
arxiv:1910.00012

Higgs self-coupling through loop corrections



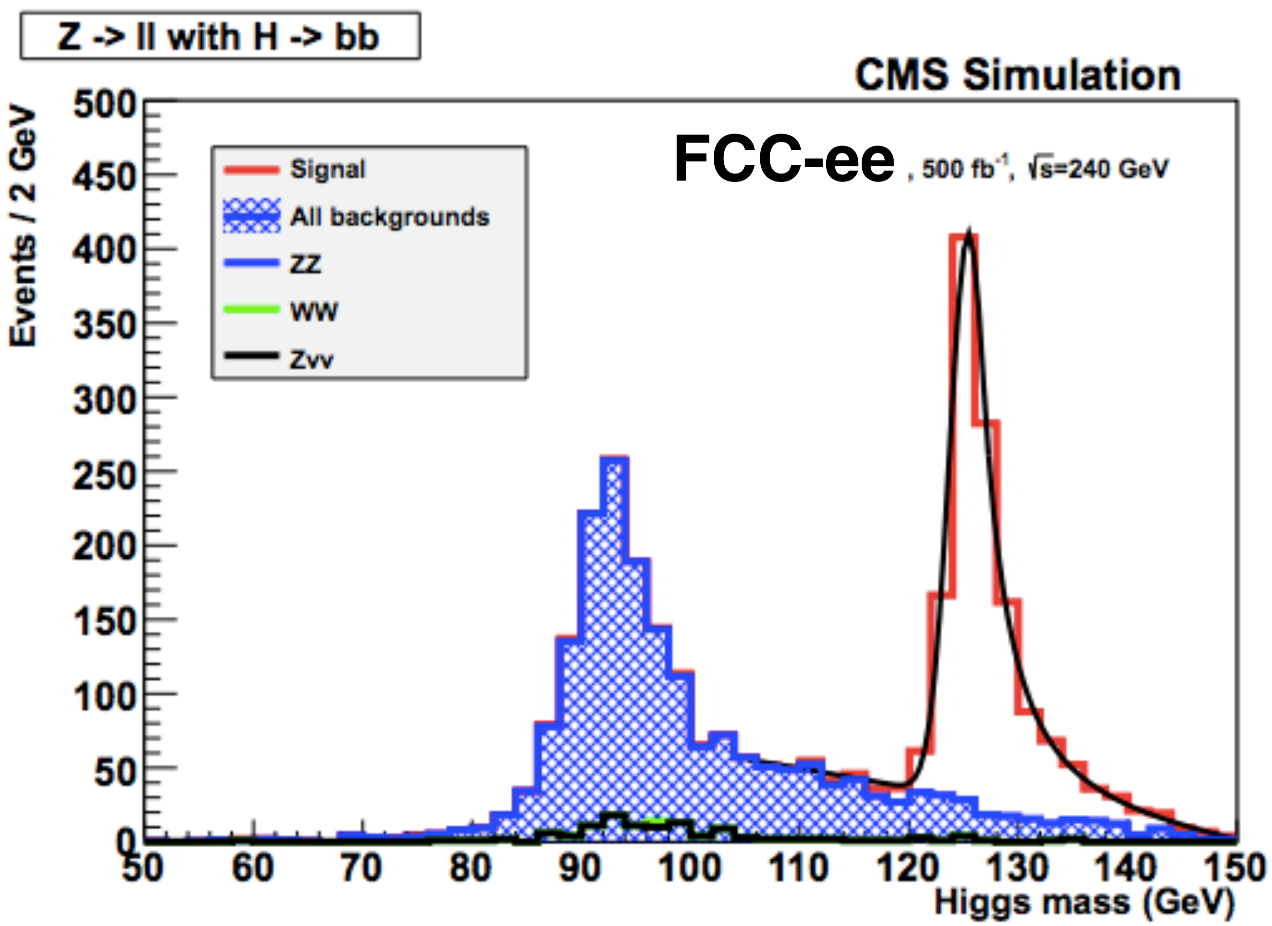
arxiv:1312.3322

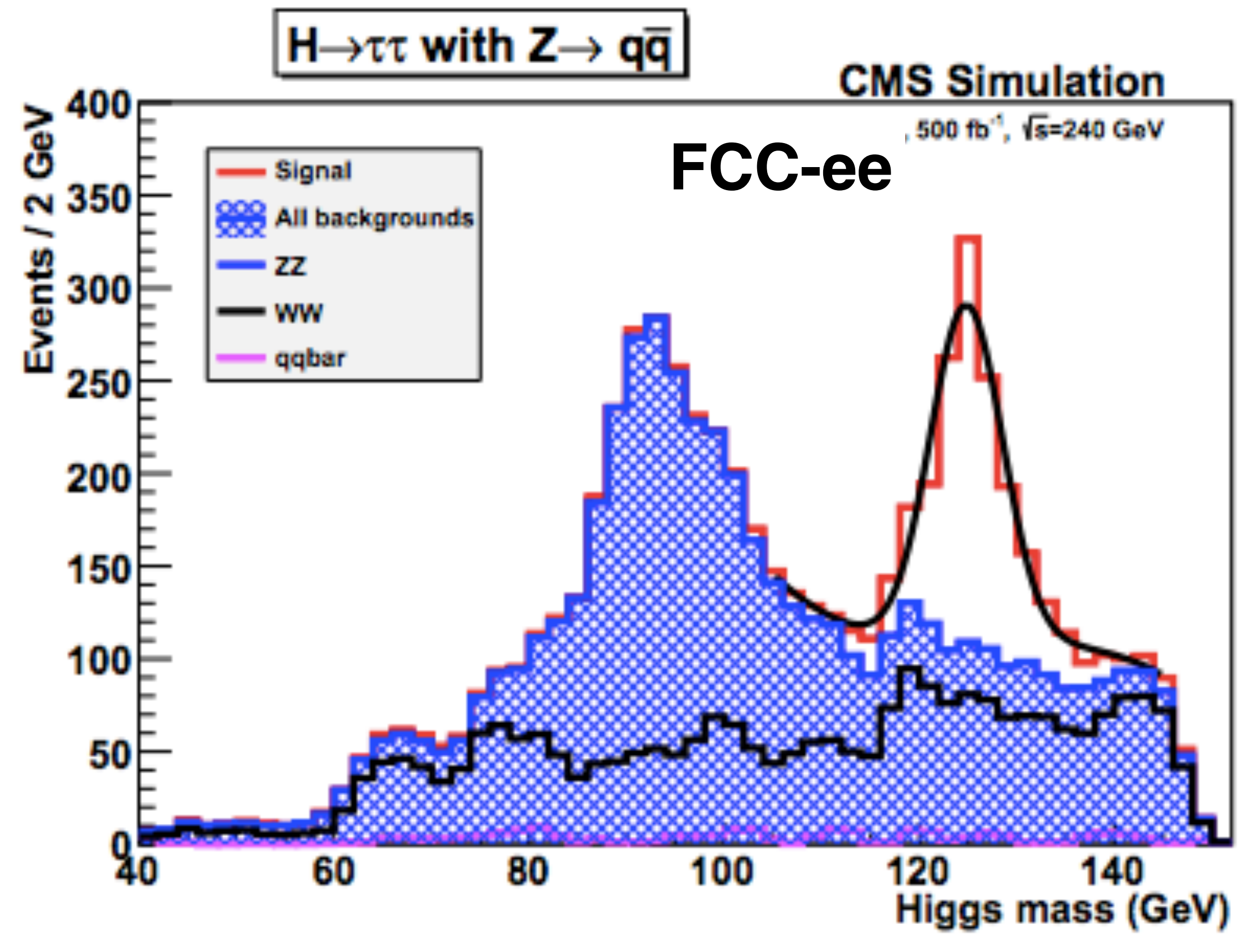
arxiv:1910.00012

Precision Higgs Couplings

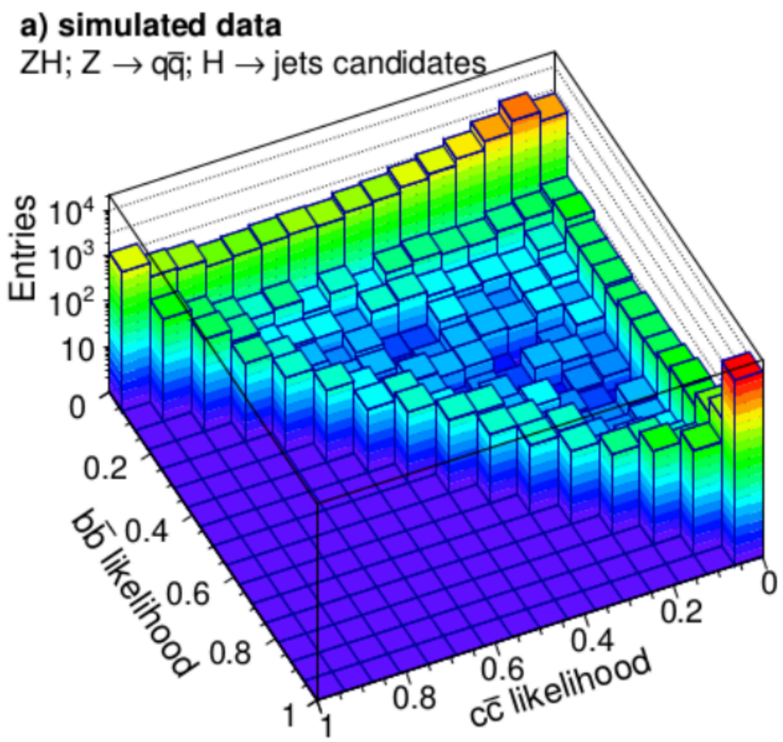
- ➡ Measure σ(ee→ZH) * BR (H→X) by identifying X
- ➡ Example: σ(ee→ZH) * BR (H→ZZ) $\propto g_{HZZ}^4/\Gamma_H$
- ➡ Total width from combination of measurements or fit

- ➡ Branching fraction to invisible tested directly

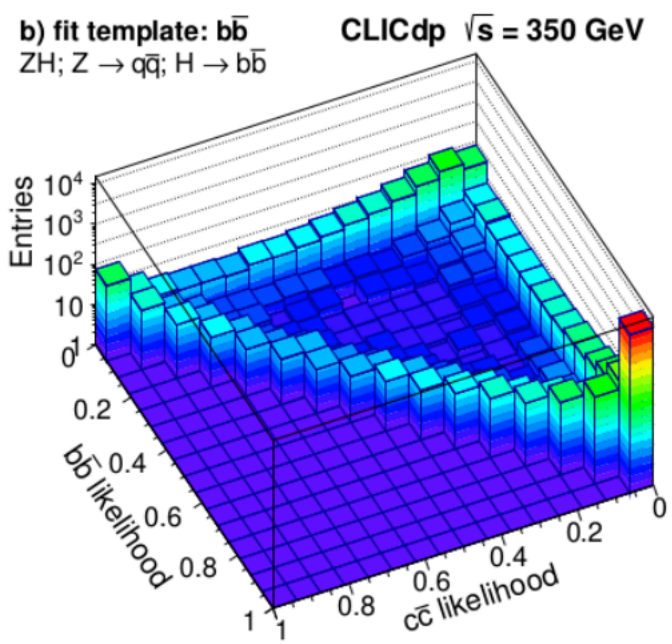


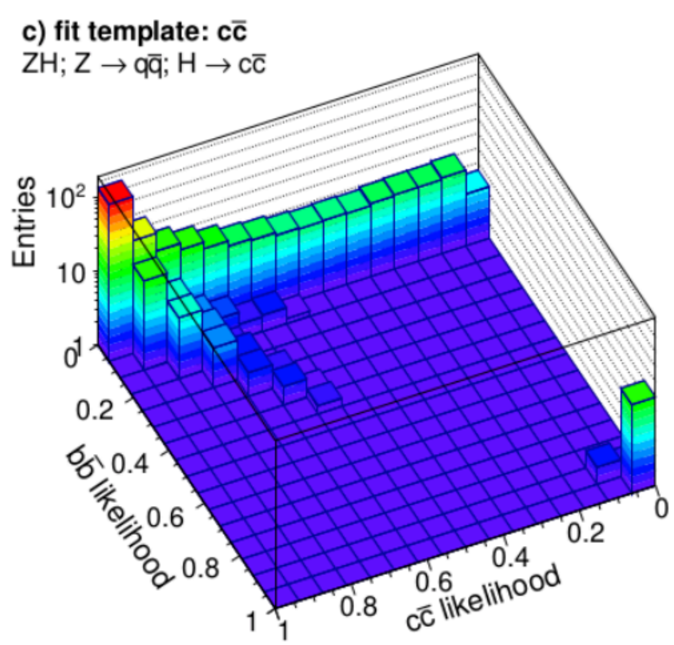


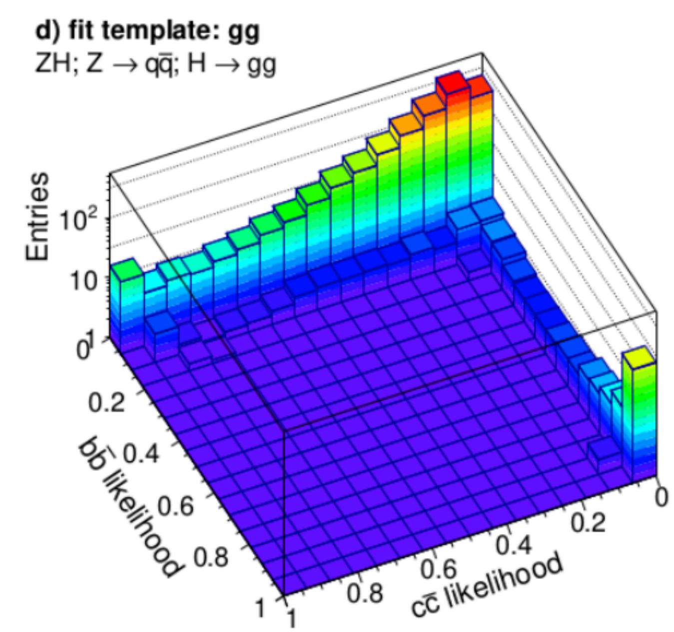
Hadronic Higgs Decays



H → bb **H → cc** **H → gg**

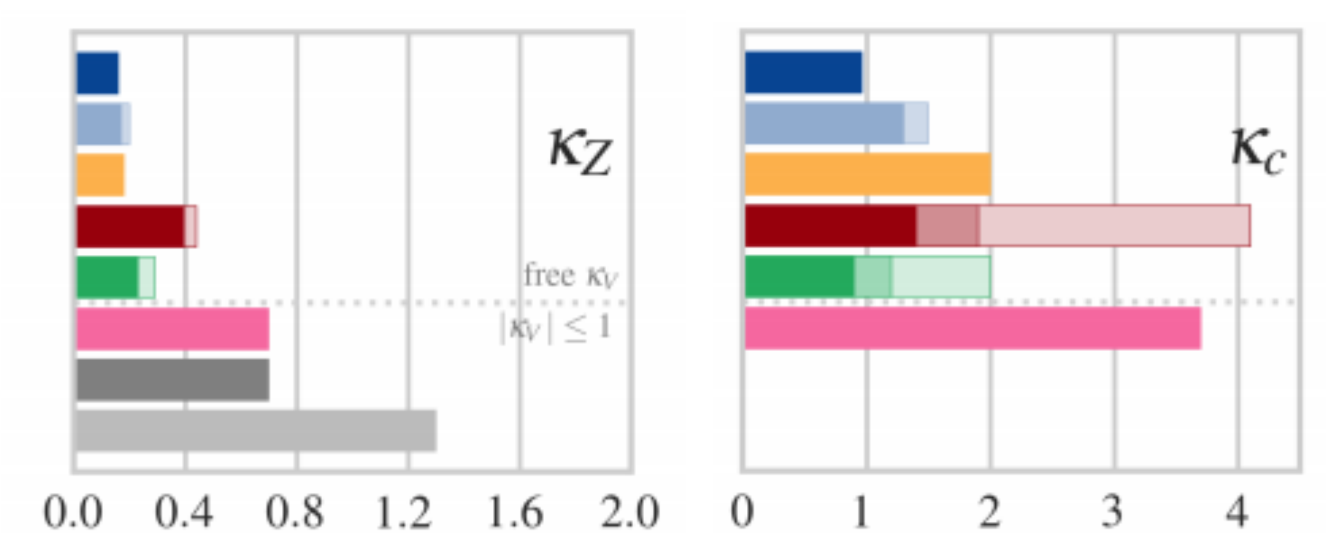


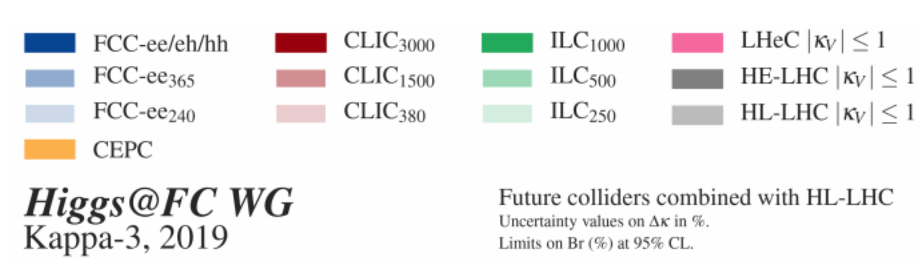




Precision Higgs Couplings

kappa-3 scenario	HL-LHC+ ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCC\text{-}ee_{240}$	$FCC\text{-}ee_{365}$	FCC-ee/eh/hh
κ_W [%]	1.0	0.29	0.24	0.73	0.40	0.38	0.88	0.88	0.41	0.19
κ_Z[%]	0.29	0.22	0.23	0.44	0.40	0.39	0.18	0.20	0.17	0.16
κ_g[%]	1.4	0.85	0.63	1.5	1.1	0.86	1.	1.2	0.9	0.5
κ_γ [%]	1.4	1.2	1.1	1.4*	1.3	1.2	1.3	1.3	1.3	0.31
$\kappa_{Z\gamma}$ [%]	10.*	10.*	10.*	10.*	8.2	5.7	6.3	10.*	10.*	0.7
κ_c [%]	2.	1.2	0.9	4.1	1.9	1.4	2.	1.5	1.3	0.96
κ_t [%]	3.1	2.8	1.4	3.2	2.1	2.1	3.1	3.1	3.1	0.96
κ_b [%]	1.1	0.56	0.47	1.2	0.61	0.53	0.92	1.	0.64	0.48
κ_μ [%]	4.2	3.9	3.6	4.4*	4.1	3.5	3.9	4.	3.9	0.43
κ_τ [%]	1.1	0.64	0.54	1.4	1.0	0.82	0.91	0.94	0.66	0.46
BR_{inv} (<%, 95% CL)	0.26	0.23	0.22	0.63	0.62	0.62	0.27	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	1.8	1.4	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.

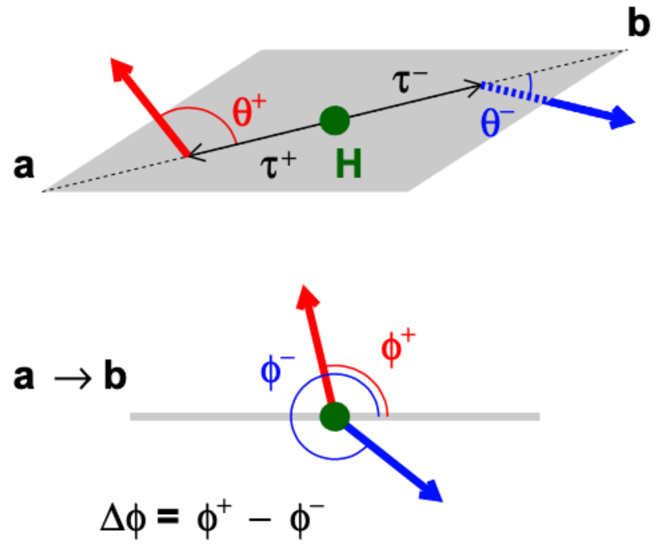


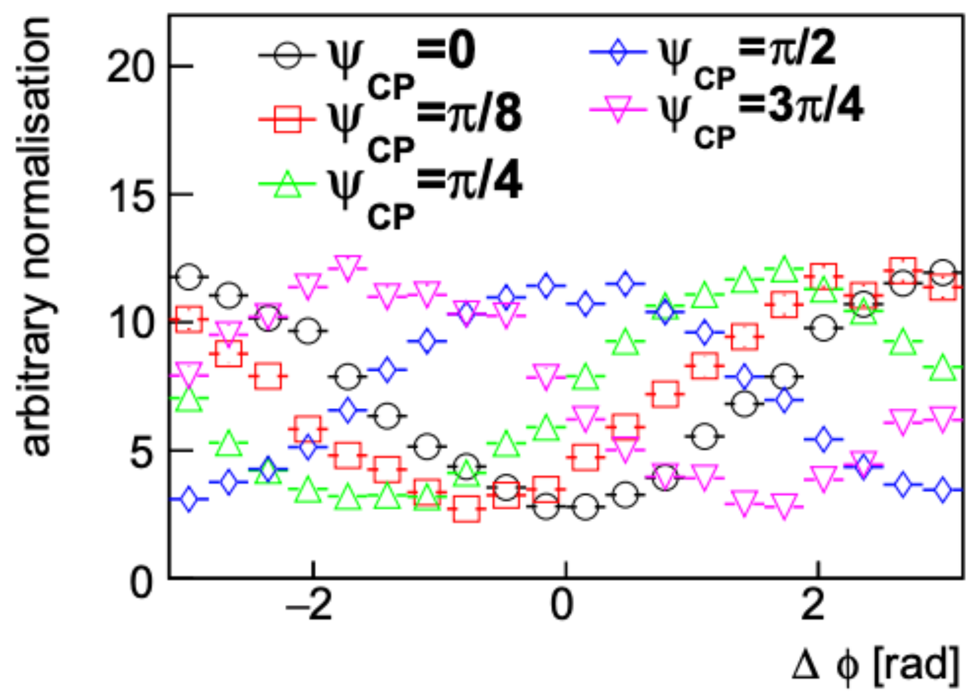


arXiv:1905.03764

CP Measurements

- ➡ CP violation can be studied by searching for CP-odd contributions; CP-even already established
- ➡ Higgs to Tau decays of interest



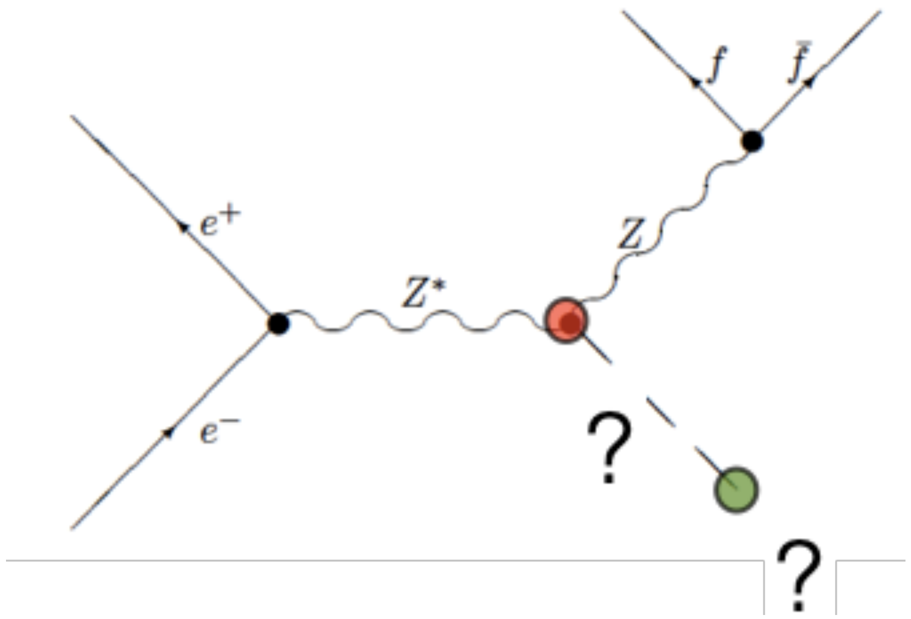


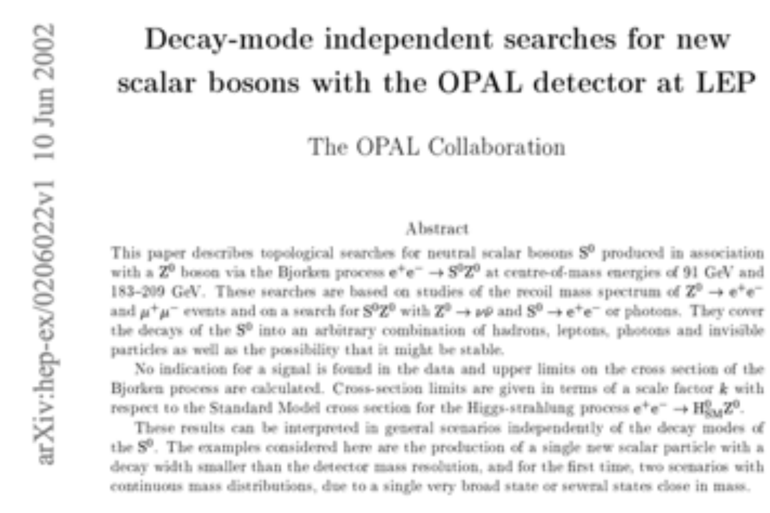
$$\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5 \sin\Delta)f$$

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°

http://arxiv.org/abs/1308.1094
http://arxiv.org/abs/1804.01241

Additional light scalars




arXiv:hep-ex/0206022v1 10 Jun 2002

Decay-mode independent searches for new scalar bosons with the OPAL detector at LEP

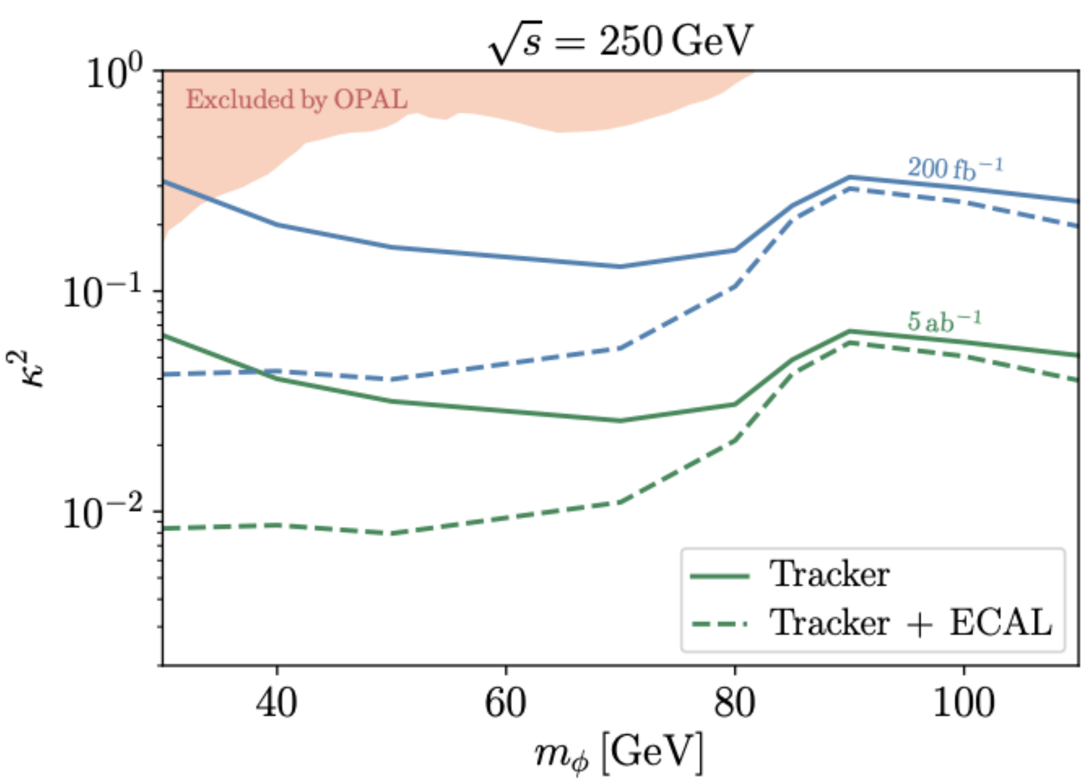
The OPAL Collaboration

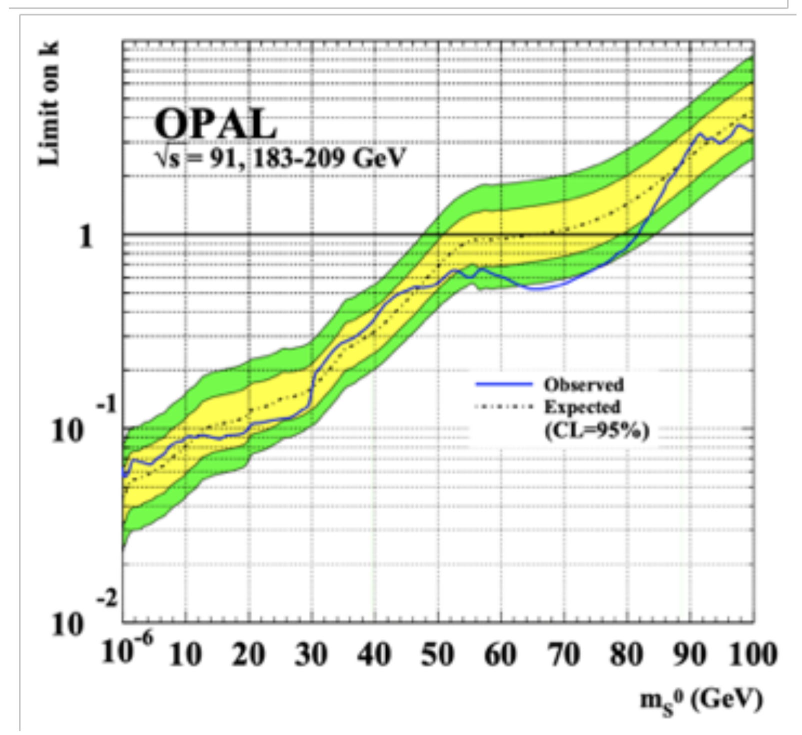
Abstract

This paper describes topological searches for neutral scalar bosons S^0 produced in association with a Z^0 boson via the Bjorken process $e^+e^- \to S^0Z^0$ at centre-of-mass energies of 91 GeV and 183–209 GeV. These searches are based on studies of the recoil mass spectrum of $Z^0 \to e^+e^-$ and $\mu^+\mu^-$ events and on a search for S^0Z^0 with $Z^0 \to \nu\bar{\nu}$ and $S^0 \to e^+e^-$ or photons. They cover the decays of the S^0 into an arbitrary combination of hadrons, leptons, photons and invisible particles as well as the possibility that it might be stable.

No indication for a signal is found in the data and upper limits on the cross section of the Bjorken process are calculated. Cross-section limits are given in terms of a scale factor k with respect to the Standard Model cross section for the Higgs-strahlung process $e^+e^- \to H^0_{SM}Z^0$.

These results can be interpreted in general scenarios independently of the decay modes of the S^0. The examples considered here are the production of a single new scalar particle with a decay width smaller than the detector mass resolution, and for the first time, two scenarios with continuous mass distributions, due to a single very broad state or several states close in mass.





Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events

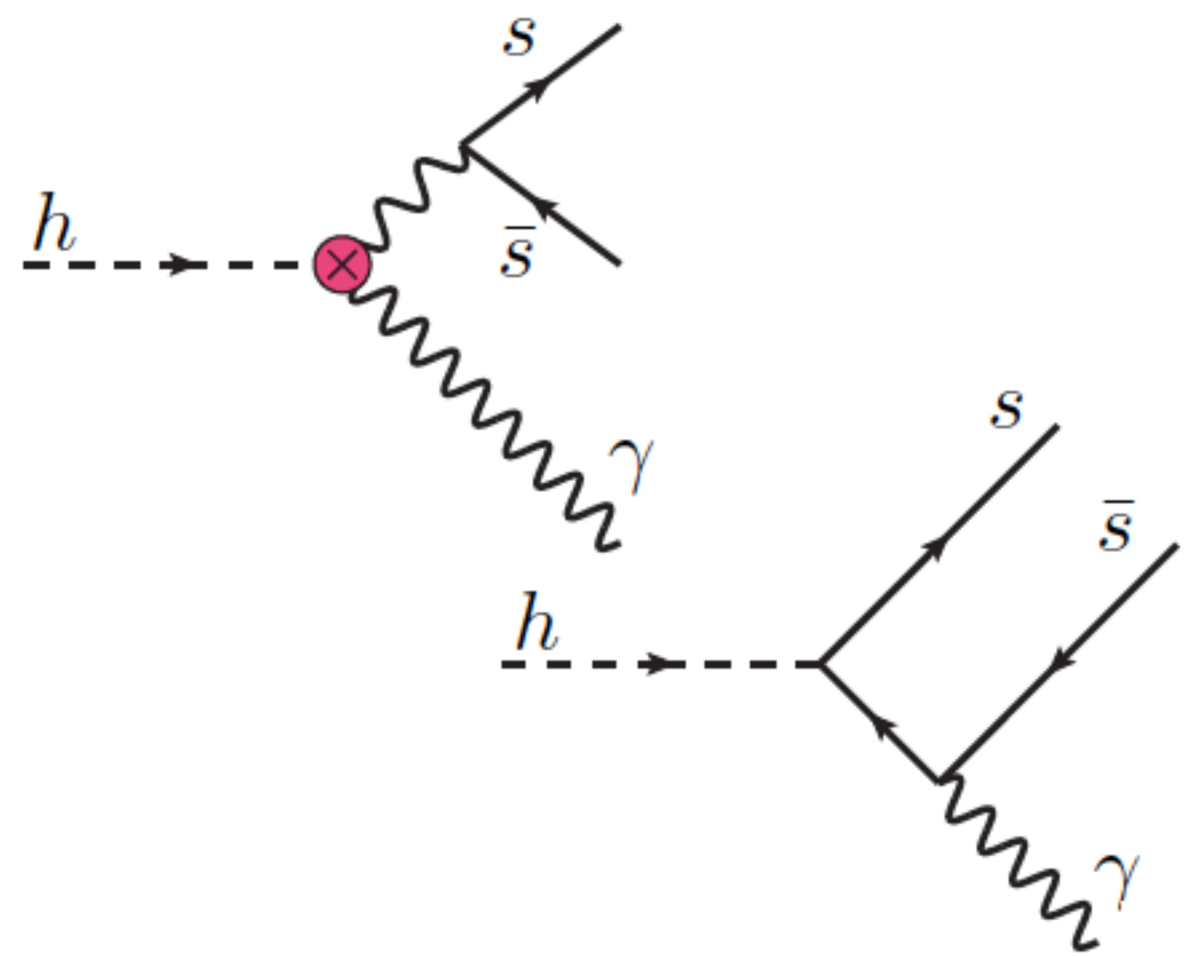
https://arxiv.org/abs/1801.08164
https://arxiv.org/abs/1812.08289

Exclusive Higgs boson decays

➡ First and second generation couplings accessible

- Sensitivity to u/d quark Yukawa coupling
- Sensitivity due to interference

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



➡ Also interesting to hadron collider 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

Rare and Exotics Higgs Bosons

- ➡ Largely unexplored!
- ➡ ZH events allow for detailed studies of rare and exotic decays
  - ◉ improved with hadronic and invisible Z decays
  - ◉ set requirements for lepton collider 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
- ➡ Modes with of limited LHC sensitivity are of particular importance to lepton collider program
- ➡ 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 $+ X$

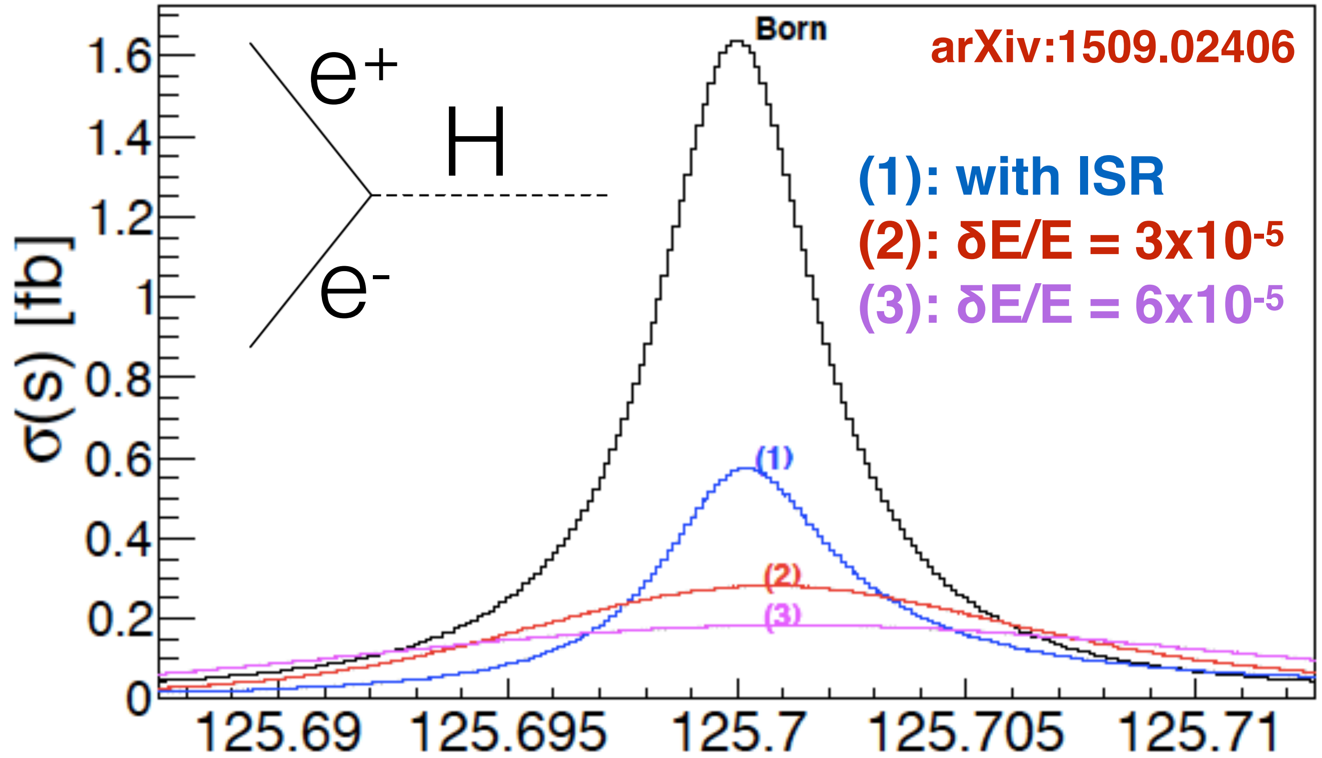
$h \to b\bar{b} + \not{E}_T$

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

S-channel Higgs Production

➡ **s-channel production**

- very small cross section
- reduced by ISR and beam spread
- $\sigma^{born}(\mu^+\mu^- \to H) \approx 40.000\ \sigma^{born}(e^+e^- \to H)$
- $\sigma(e^+e^- \to H) = 50ab$ (nominal $\delta E/E$)
- $\sigma(\mu^+\mu^- \to H) = 15pb$ (nominal $\delta E/E$)

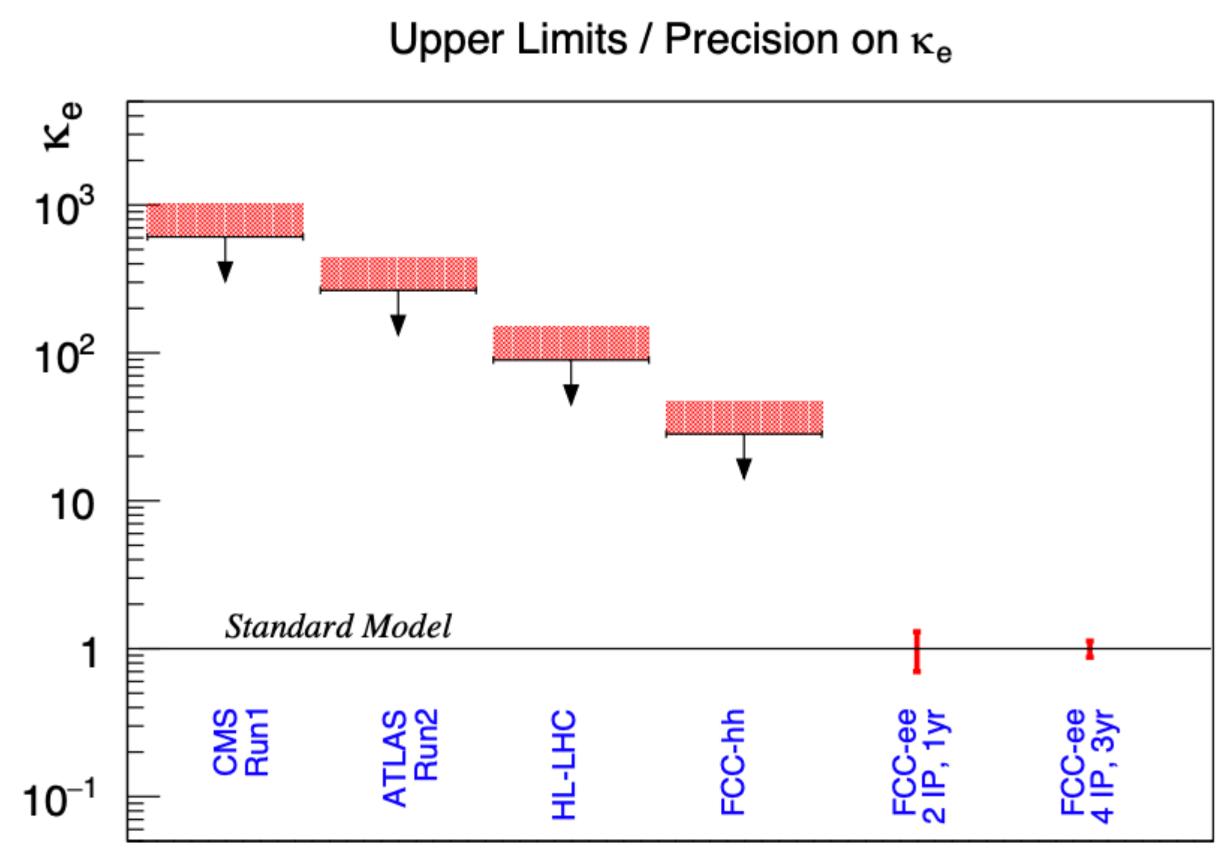


➡ **Beam-spread improvements**

- FCC-ee via monochromators
- Feasibility and impact on luminosity need study

➡ **Expected significance > 1σ / 10ab-1**

- Set an electron Yukawa coupling upper limit: $k_e < 2.5$ @95% CL



- Unique to FCC-ee (see David d'Enterria's talk)

Conclusion

- Future lepton colliders **offers a broad physics program**
- Will **precisely map the Higgs sector** building on HL-LHC foundation
- Adding **unique measurements** of Higgs properties
- **Ambitious programs** aiming for significant progress (order(s) of magnitude) in understanding of nature and the Higgs boson

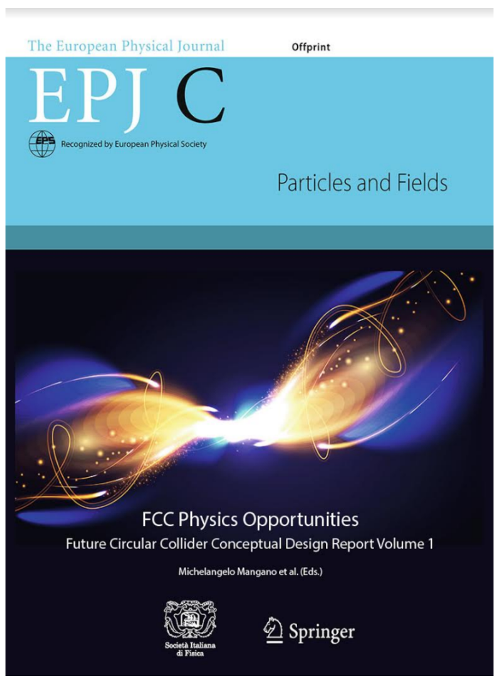
FCC-ee: The Higgs Factory

(4y)	Z peak	E_{cm} = 91 GeV	$5\ 10^{12}$	e+e- → Z
(2y)	WW threshold	E_{cm} = 161 GeV	10^{8}	e+e- → WW
(3y)	ZH threshold	E_{cm} = 240 GeV	10^{6}	e+e- → ZH
(4y)	$\overline{tt}$ threshold	E_{cm} = 350 GeV	10^{6}	e+e- → $\overline{tt}$
(ny)	H(optional)	E_{cm} = 125 GeV	10^{4}	e+e- → $\overline{H}$

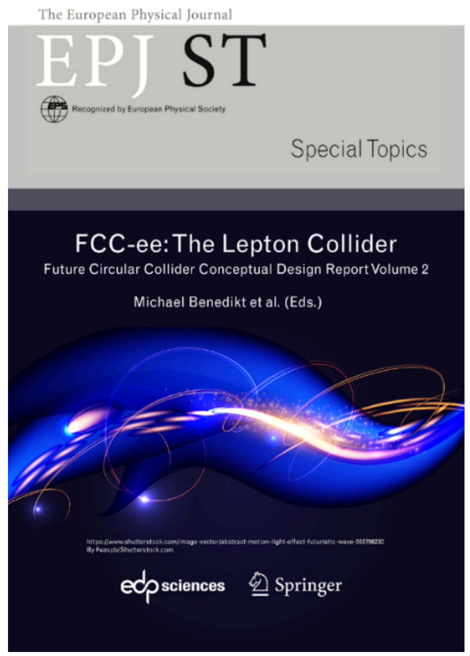
FCC documentation

Outcome of design studies recommended by the 2013 European Strategy

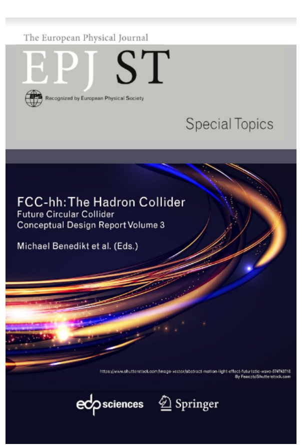
4 CDR volumes published in EPJ



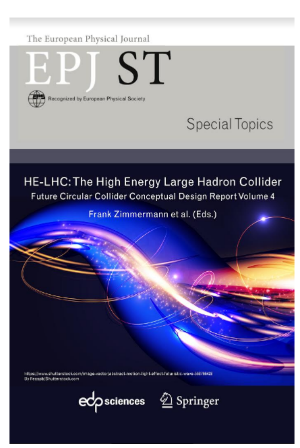
FCC Physics Opportunities



FCC-ee: The Lepton Collider



FCC-hh: The Hadron Collider



HE-LHC: The High Energy Large Hadron Collider

Recent FCC publications

1) Future Circular Collider - European Strategy Update Documents

(FCC-ee), (FCC-hh), (FCC-int)

2) FCC-ee: Your Questions Answered - arXiv:1906.02693

3) Circular and Linear e+e- Colliders: Another Story of Complementarity

arXiv:1912.11871

4) Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders arXiv:1901.02648

5) Polarization and Centre-of-mass Energy Calibration at FCC-ee, arXiv:1909.12245