Potential for Higgs Coupling Measurements

Markus Klute (MIT)
FCC Week 2015, Washington
**March 26th, 2015**

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
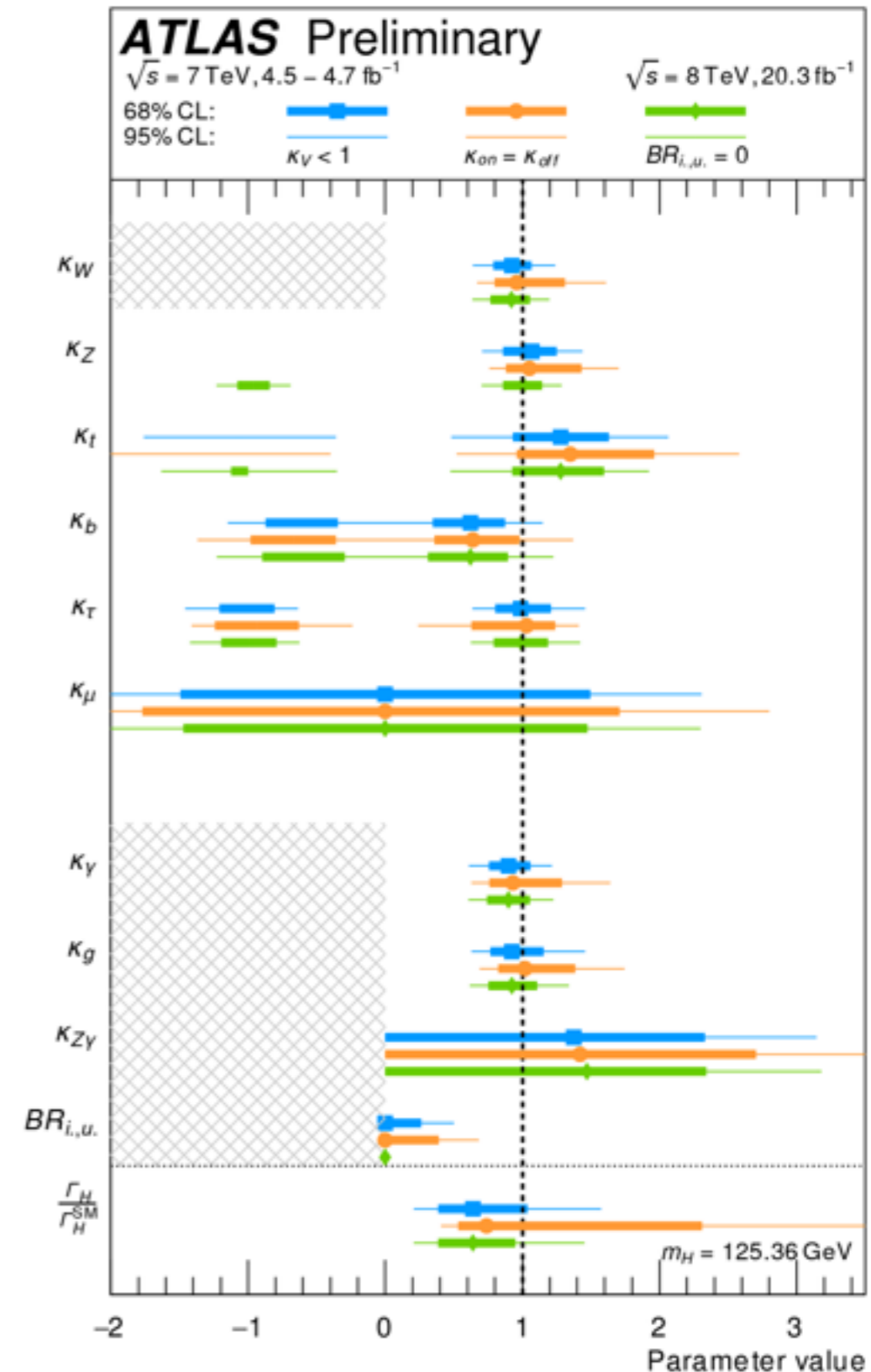
Case for precision Higgs physics

➡ **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**

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

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

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

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

Higgs prospects for the HL-LHC

Rare-decays

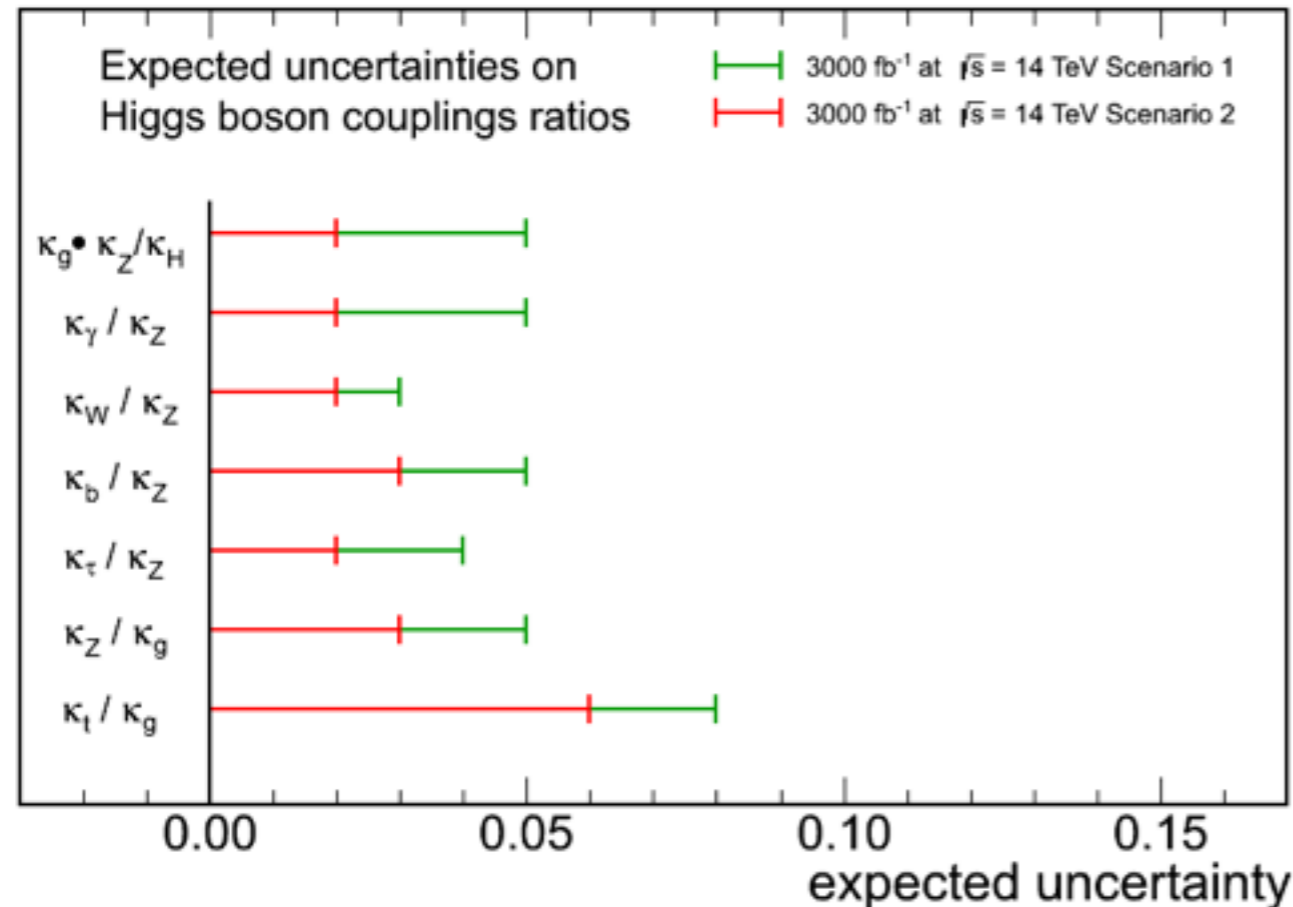**CMS Projection for precision of Higgs coupling measurement**

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
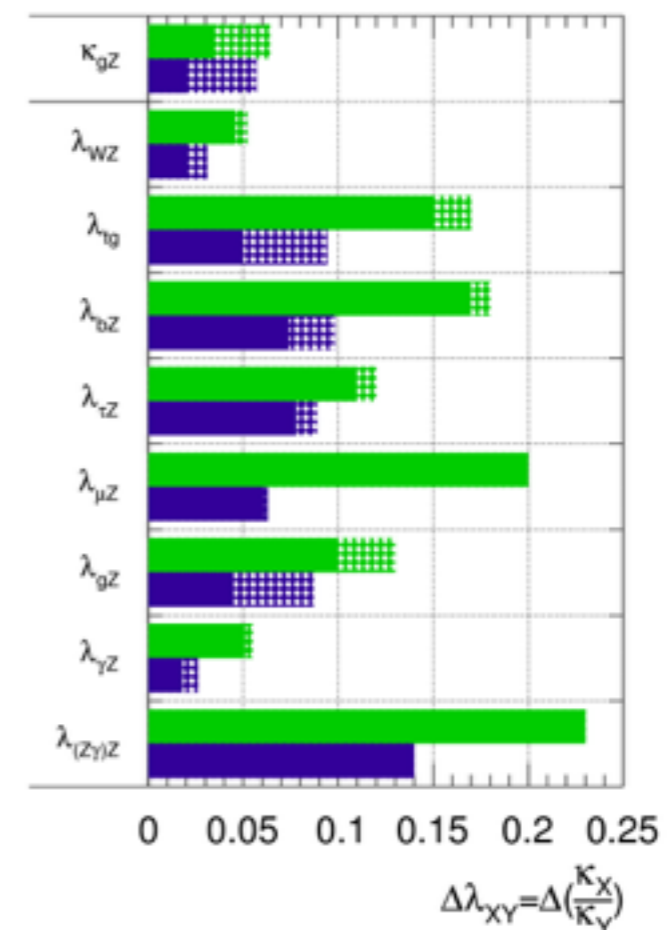
Key question is the
evolution systematic uncertainty

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

CMS Projection

Expected uncertainties on
Higgs boson couplings ratios

3000 fb^{-1} at $\sqrt{s}$ = 14 TeV Scenario 1
3000 fb^{-1} at $\sqrt{s}$ = 14 TeV Scenario 2

ATLAS Simulation Preliminary
$\sqrt{s}$ = 14 TeV: $\int Ldt=300$ fb^{-1} ; $\int Ldt=3000$ fb^{-1}

Higgs prospects for the HL-LHC

ATLAS Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by ≲10% for 300 fb^{-1}			by ≲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

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**

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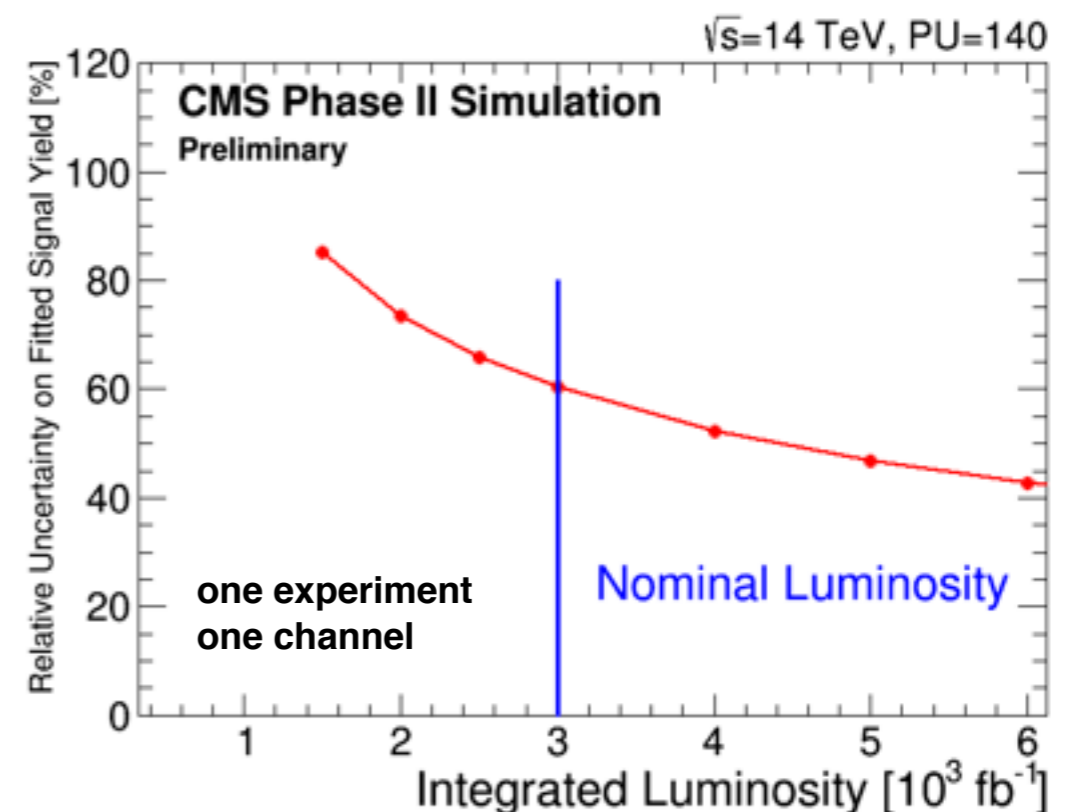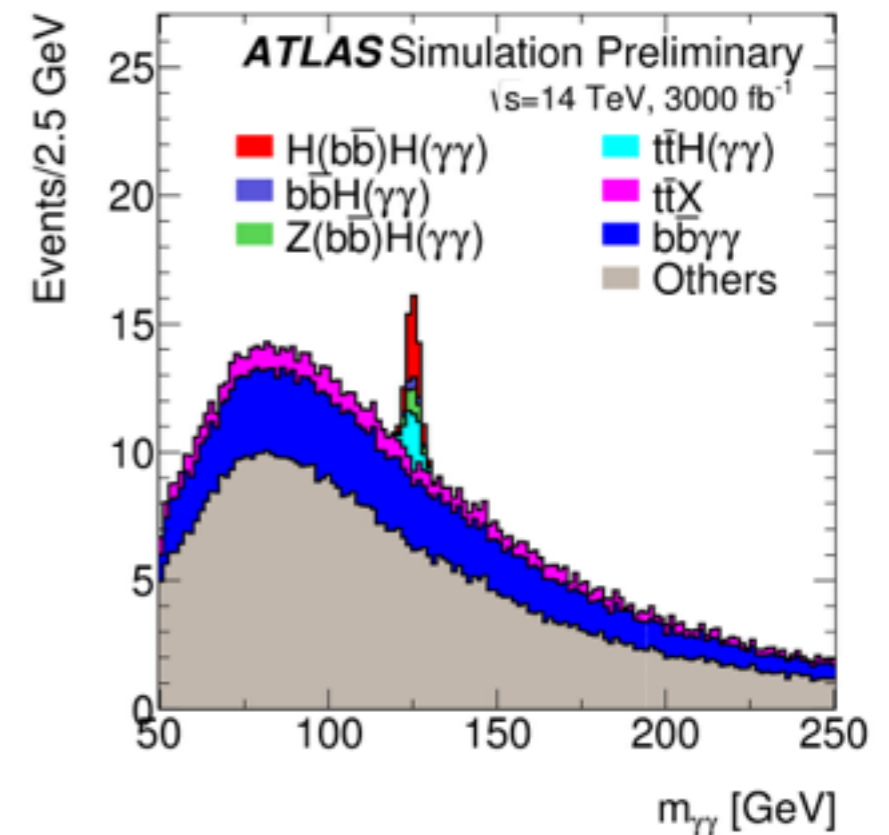
Process / Selection Stage	HH	ZH	$t\bar{t}H$	$b\bar{b}H$	γγ+jets	γ+jets	jets	$t\bar{t}$
Object Selection & Fit Mass Window	22.8	29.6	178	6.3	2891	1616	292	113
Kinematic Selection	14.6	14.6	3.3	2.0	128	96.9	20	20
Mass Windows	9.9	3.3	1.5	0.8	8.5	6.3	1.1	1.1

CMS - central photon yield

Higgs physics at the FCC

	FCC-ee Z	FCC-ee W	FCC-ee H	FCC-ee TOP	FCC-hh	FCC-ep
$\sqrt{s}$ [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
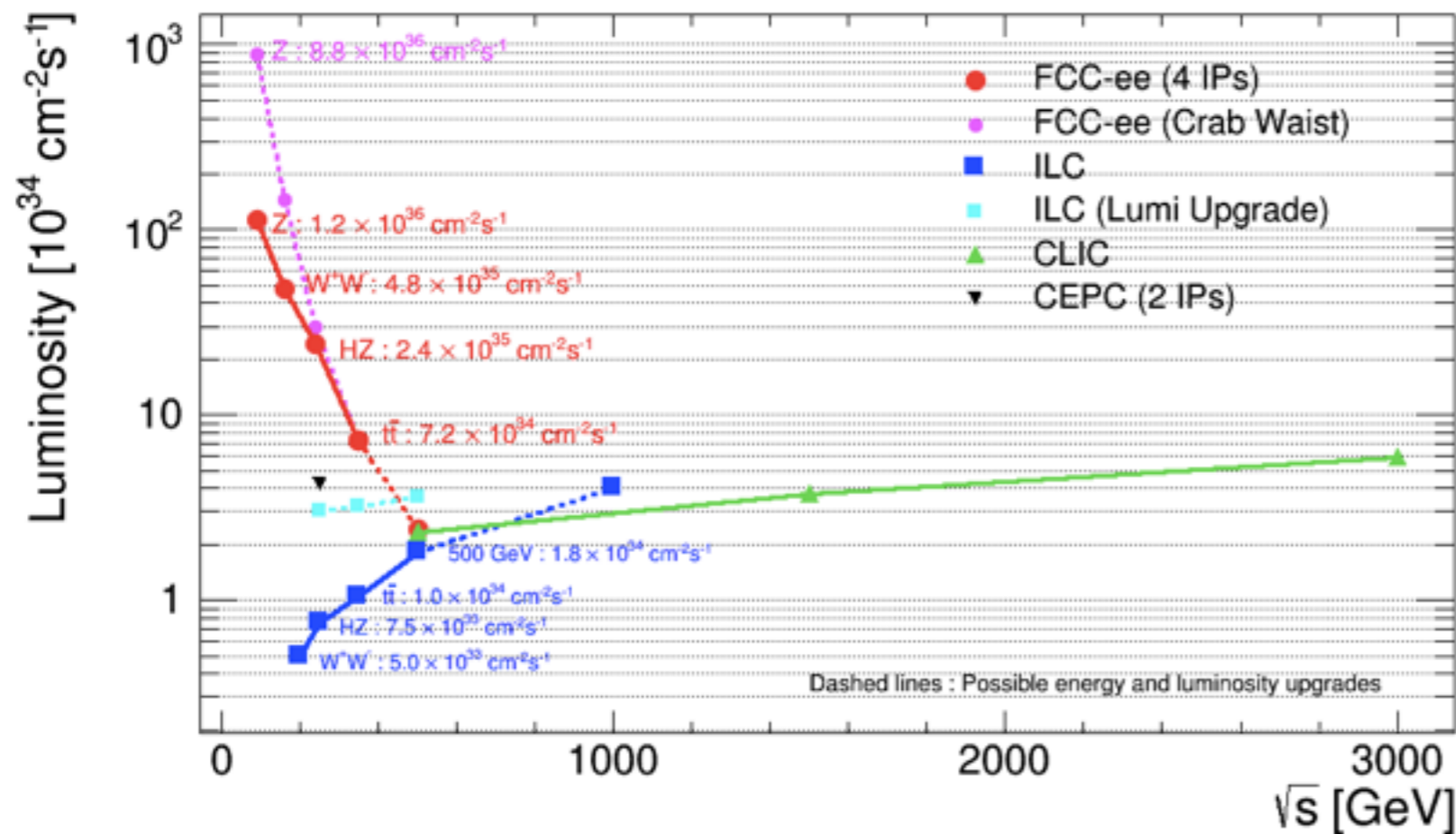
design parameter from
http://indico.cern.ch/event/
282344/material/3
and private communication

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
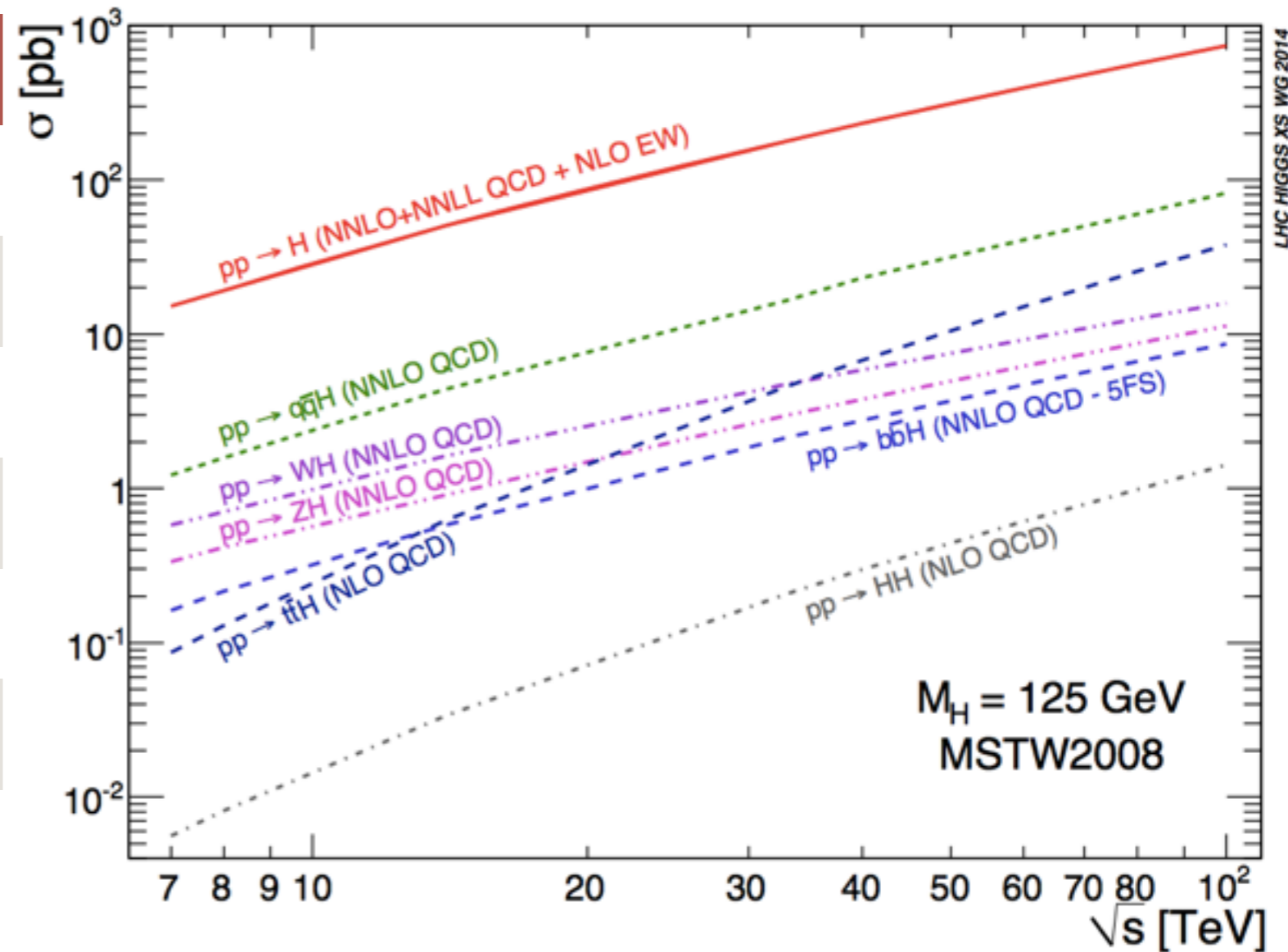
Higgs production: FCC-pp

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

M_H = 125 GeV
MSTW2008
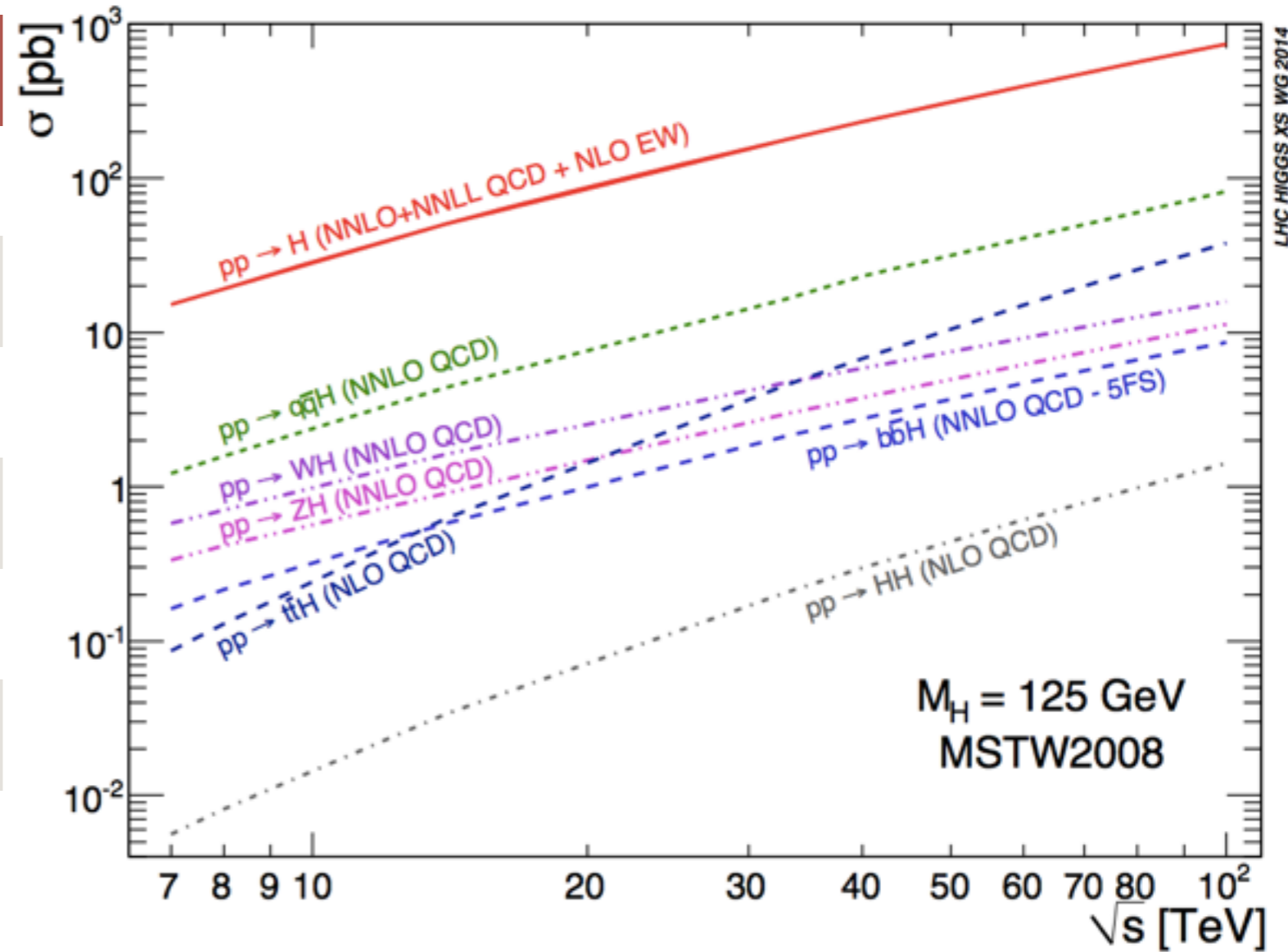
Proton-proton Higgs datasets — **LHC Run I** → **HL LHC** → **FCC pp**

x300-600   x10-400

Higgs physics program: FCC-pp

➡ Rare SM and non-SM decays

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

➡ Higgs self coupling (more from Minho Son)

➡ BSM (heavy) Higgs boson production (more from David Curtin)

➡ 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
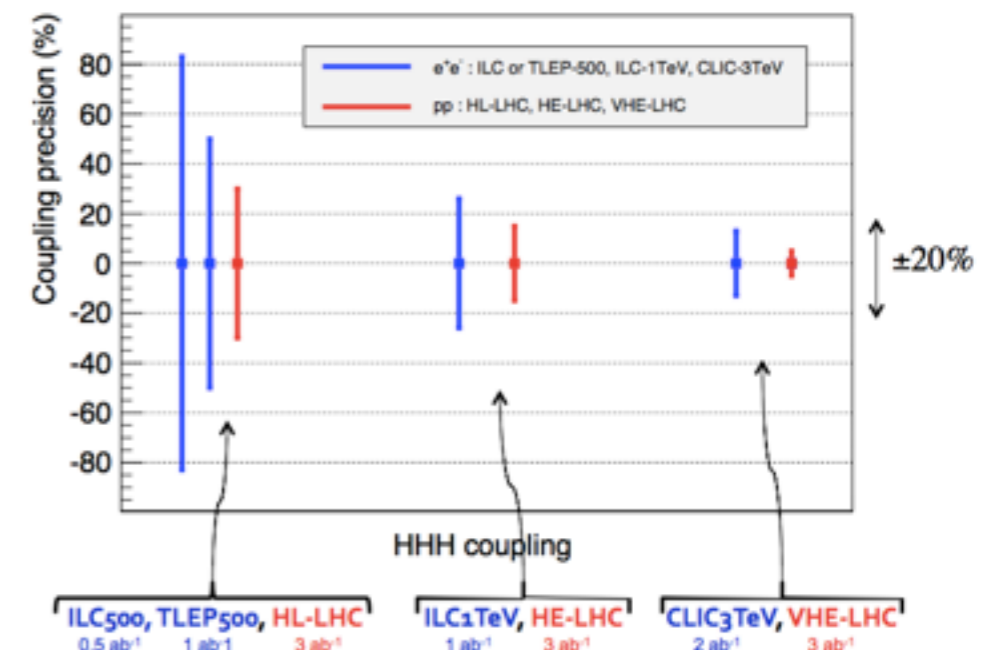
Higgs physics program: FCC-pp

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

ttH / ttZ
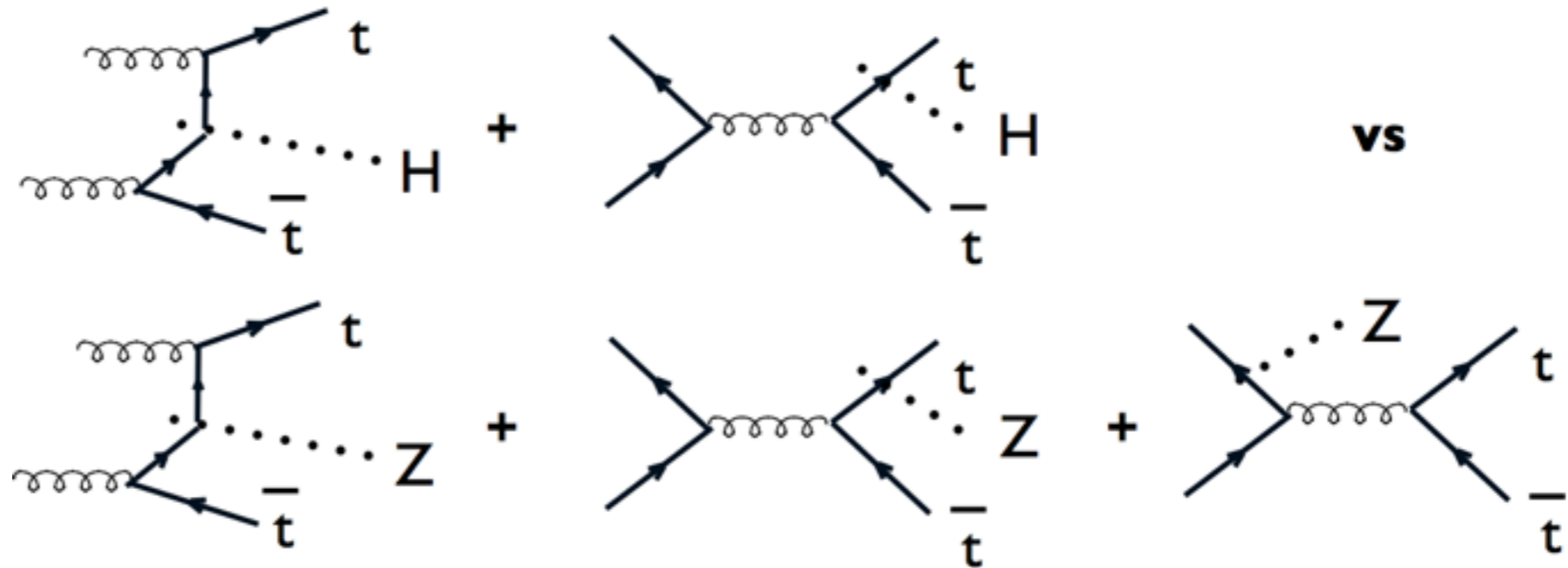
➡ Theoretical uncertainties cancel mostly

- ◉ 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 prospects for the HL-LHC

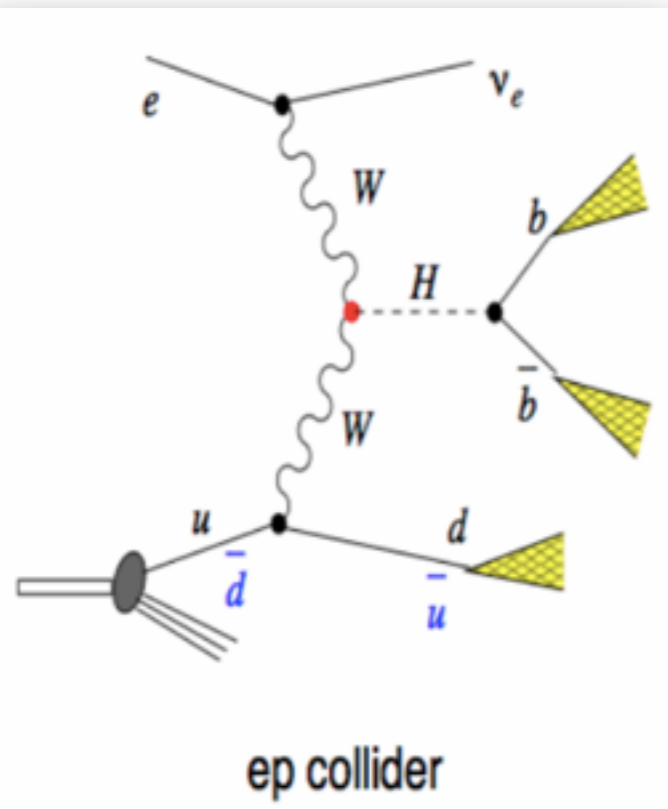| ATLAS Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty							
		by $\lesssim 10\%$ for 300 fb^{-1}			by $\lesssim 10\%$ for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j $\to$ 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-pp analyses need to explore the size of the dataset to limit systematic uncertainties and require theoretical improvements

12

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

➡ Details in Max Klein's presentation

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

ep collider

ep collider

Simulation of H→ bb Measurement at the LHeC, 100fb^{-1}

LHeC Higgs Group U.Klein et al.

13
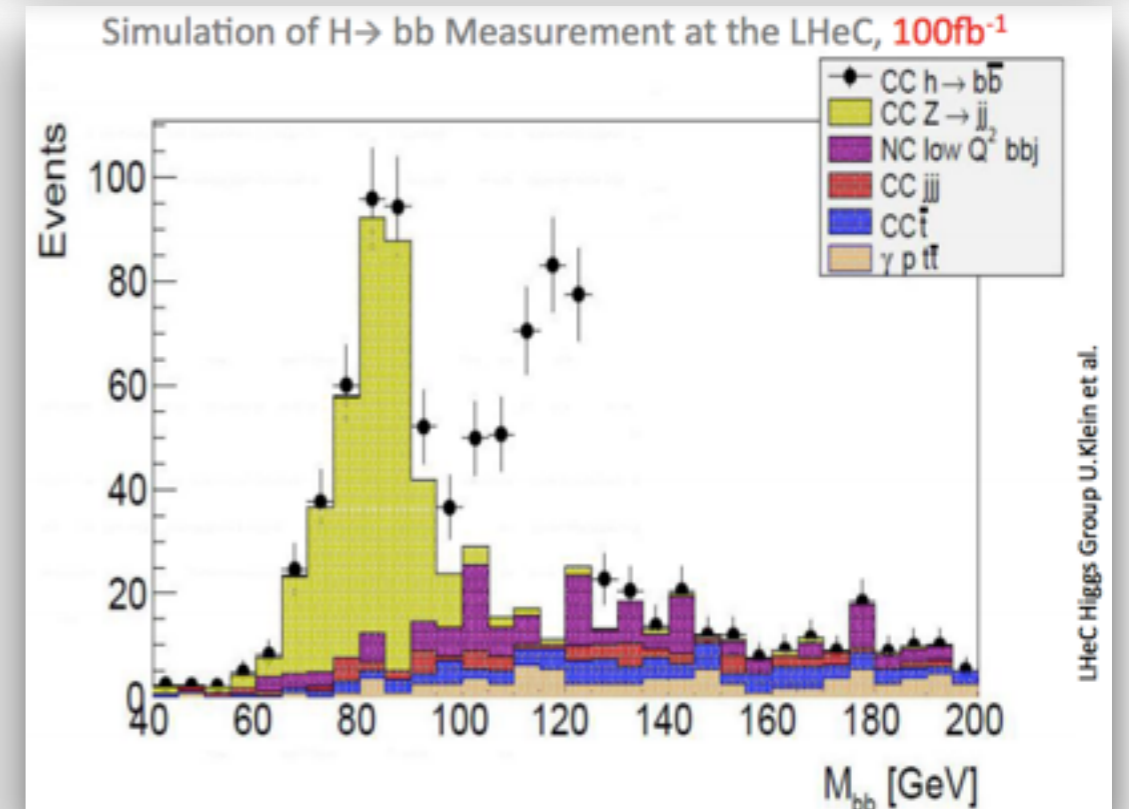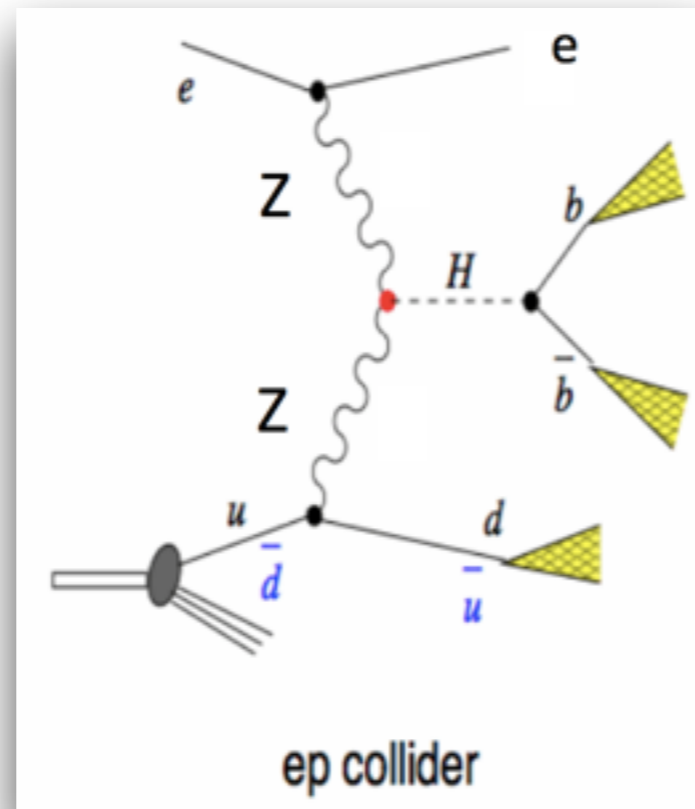
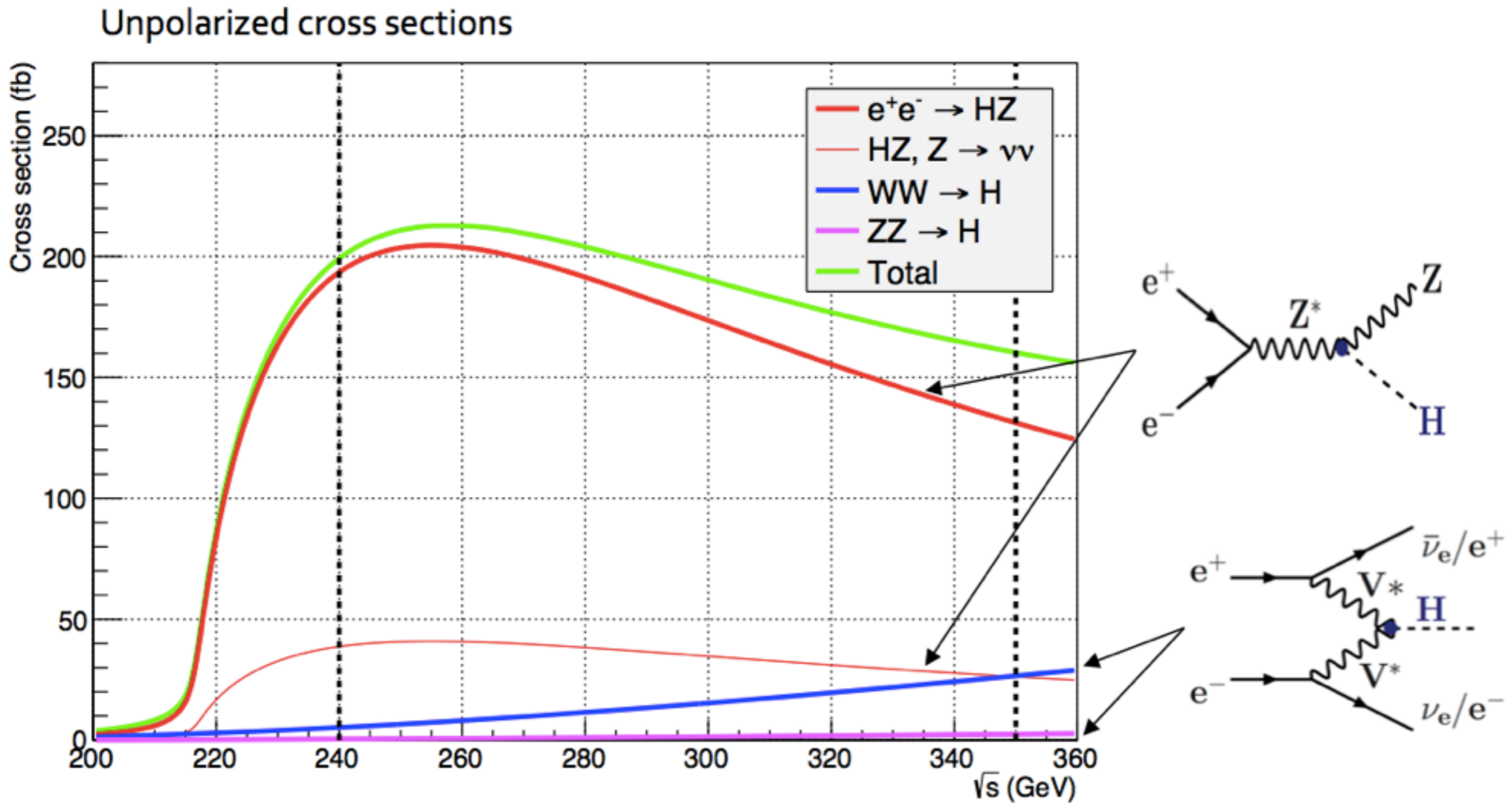# Higgs Production: FCC-ep

➡ Study of di-H production possible in bbbb final state

➡ O(15%) precision on di-H cross section in 10ab⁻¹

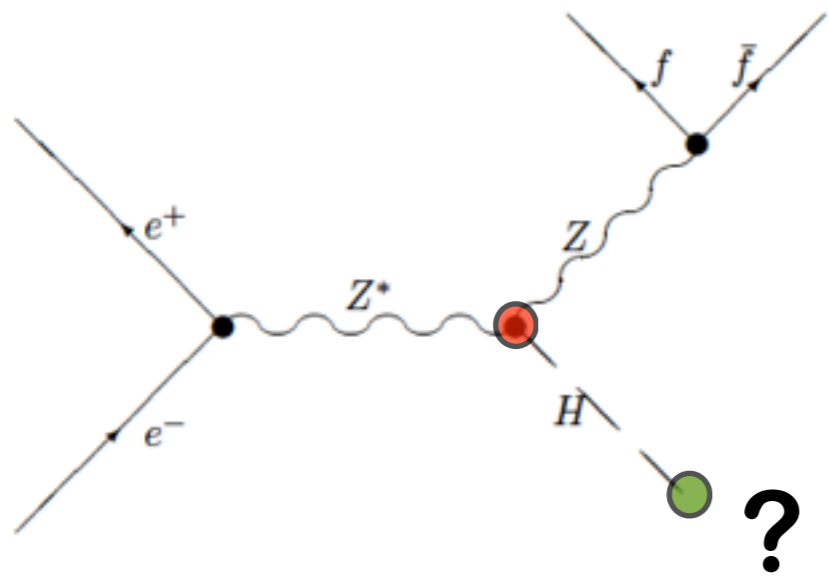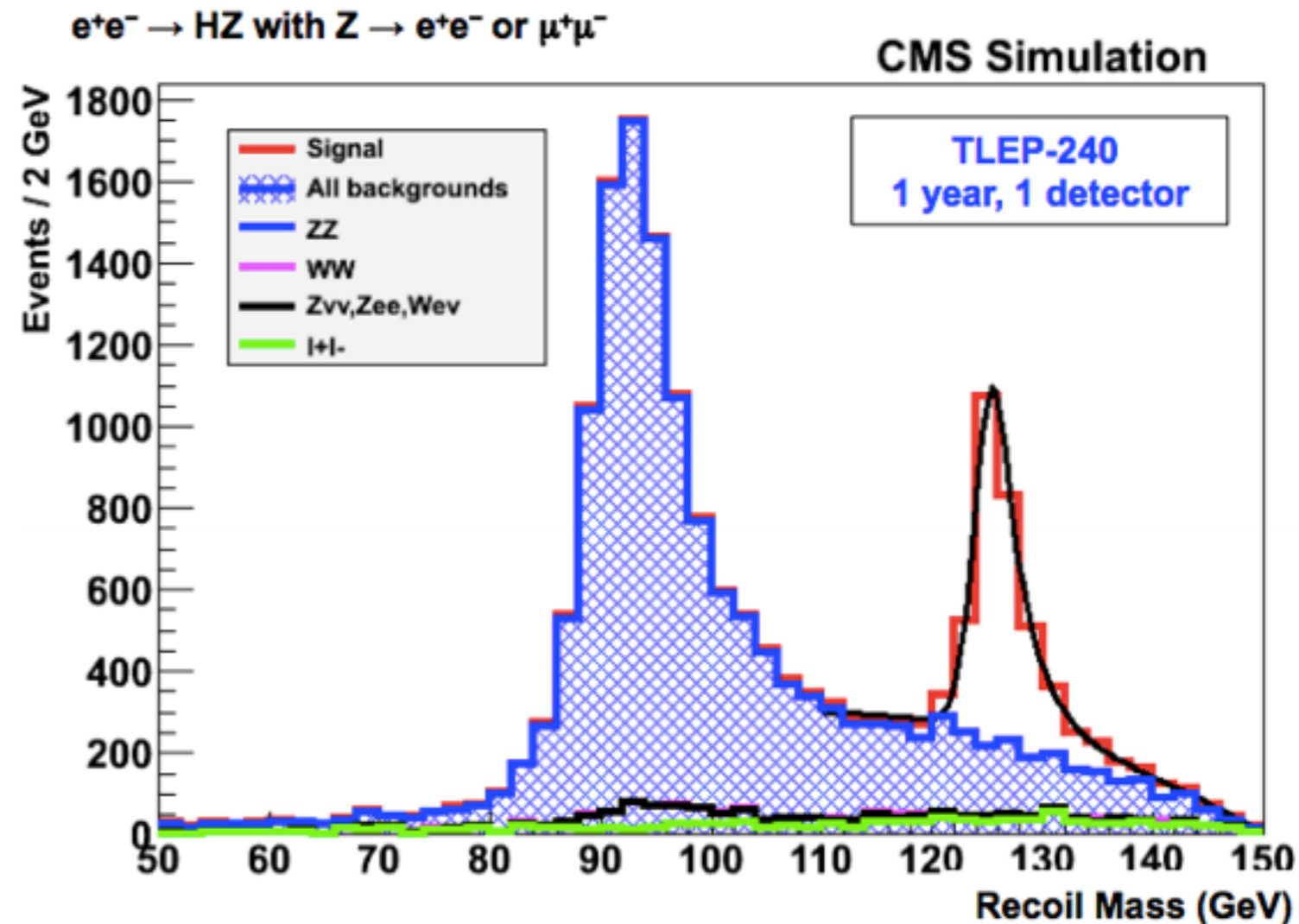Unpolarized cross sections
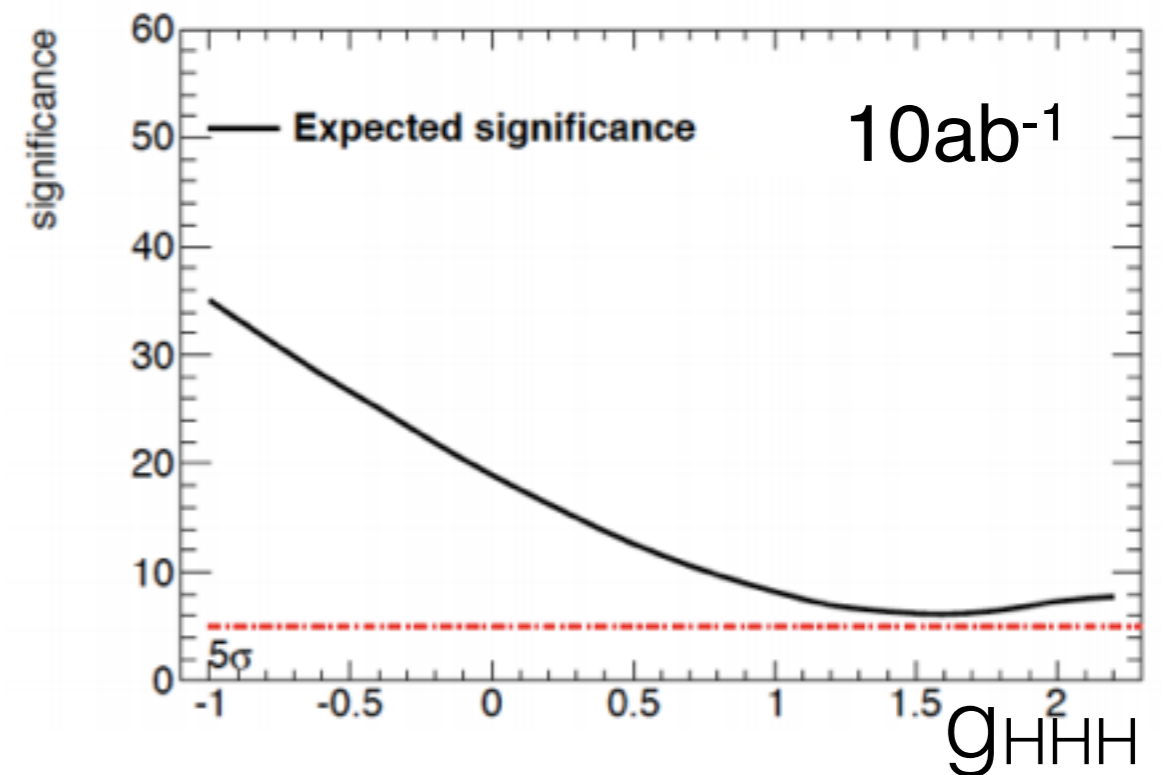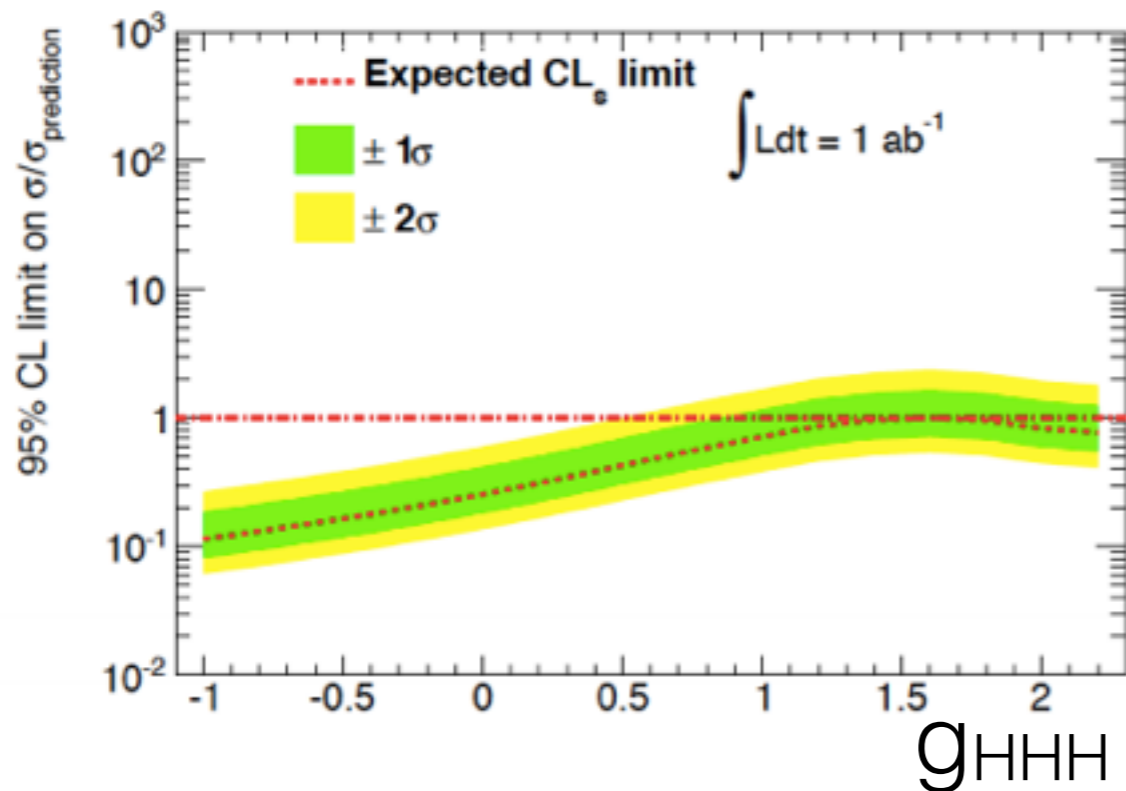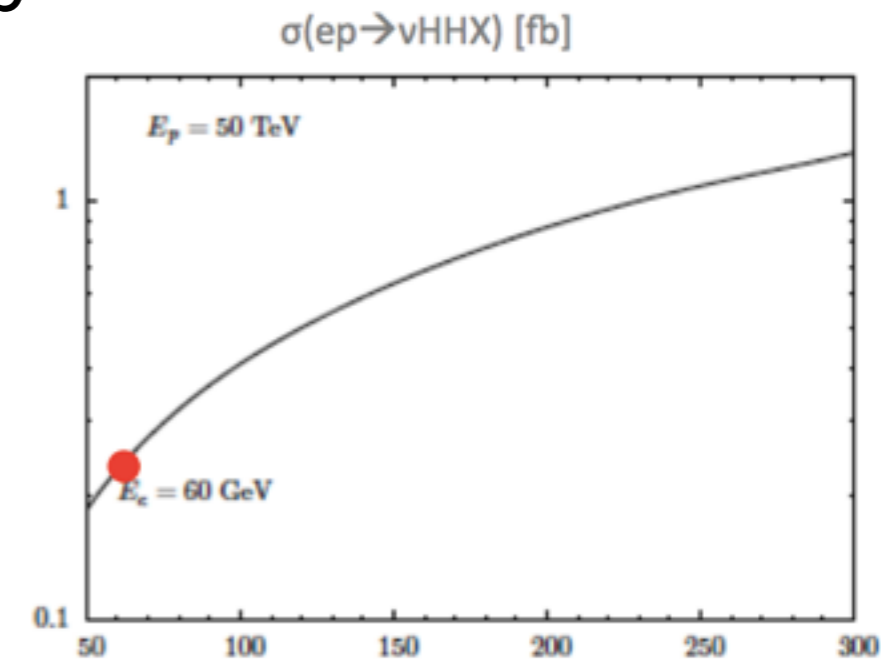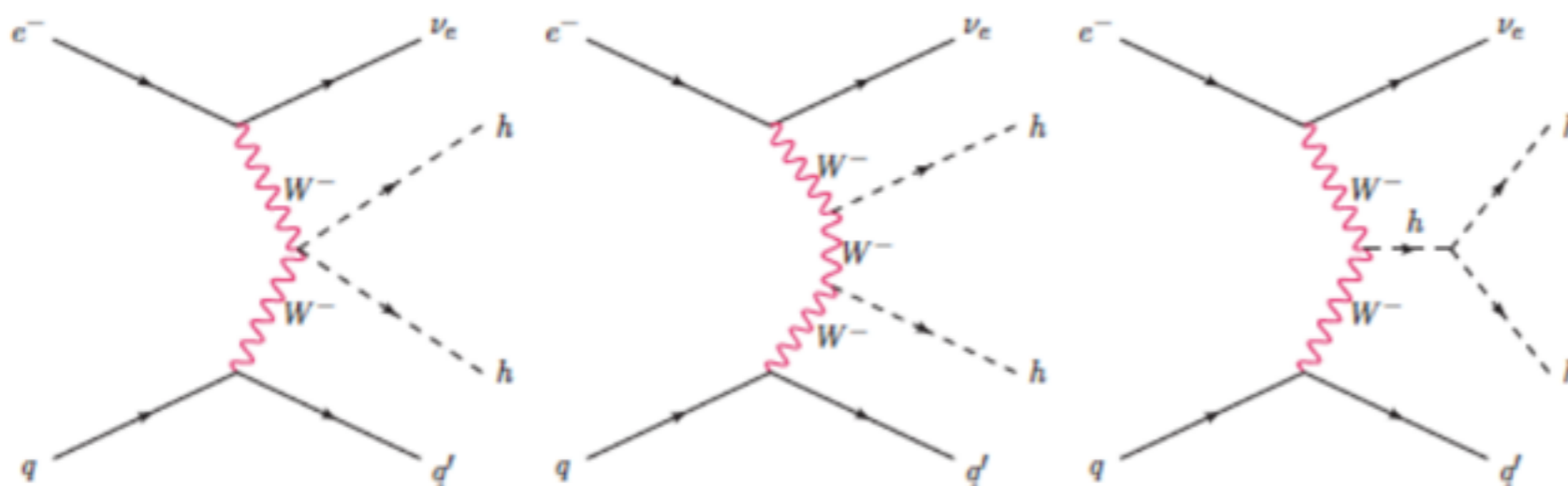
Precision Higgs Couplings

➡ Recoil method unique to lepton collider

➡ Tag Higgs event independent of decay mode

➡ Provide precision measurement of σ(ee→ZH)

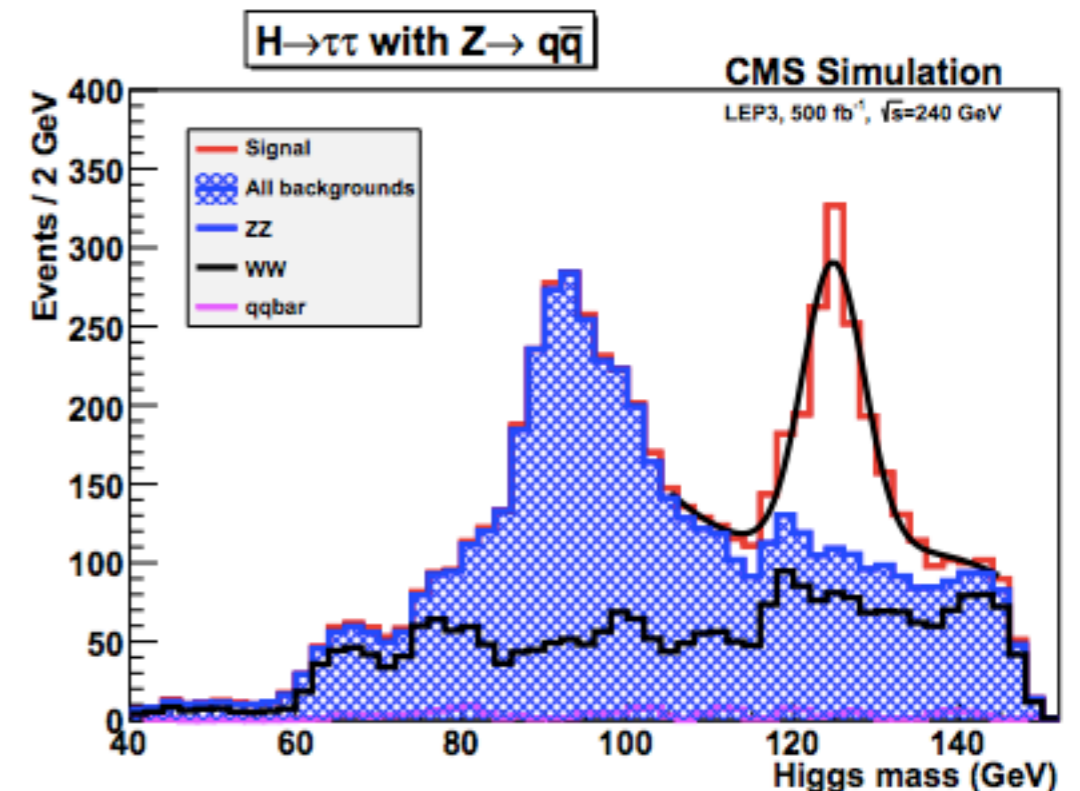$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

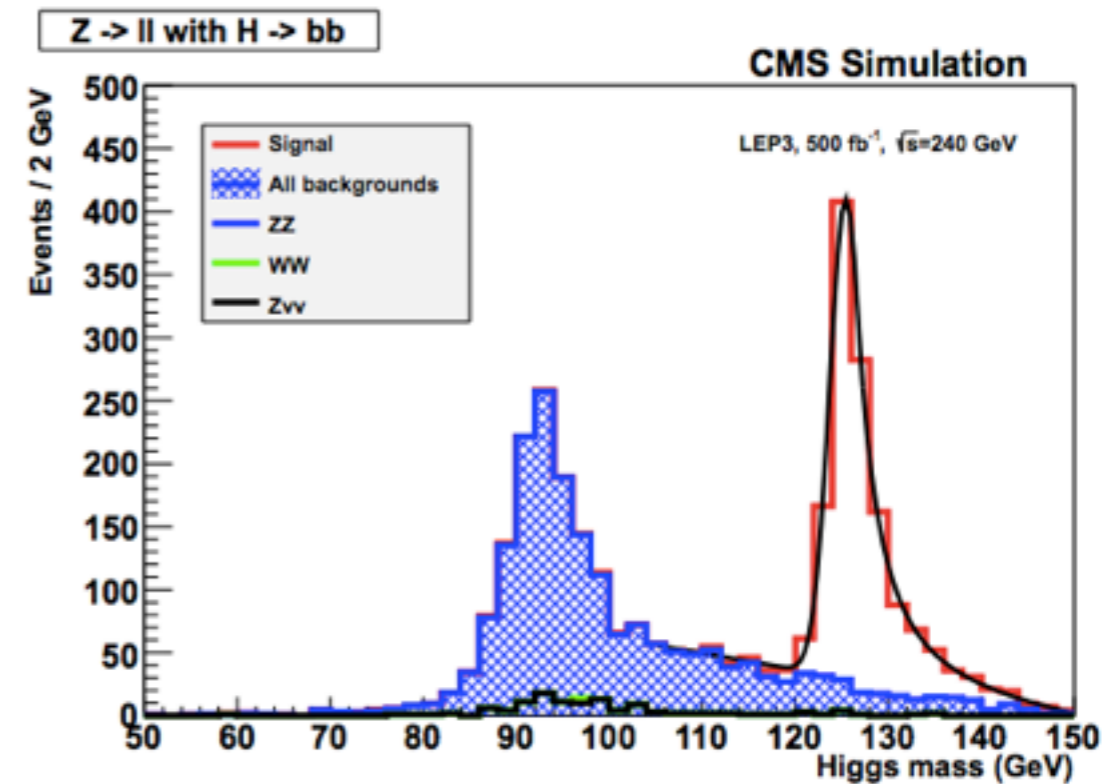$e^+e^- \to$ HZ with Z → e^+e^- or $\mu^+\mu^-$

CMS Simulation

TLEP-240
1 year, 1 detector

- Signal
- All backgrounds
- ZZ
- WW
- Zνν,Zee,Weν
- l+l-

Recoil Mass (GeV)

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

Coupling	Model-independent fit		
	TLEP-240	TLEP	
g_{HZZ}	0.16%	**0.15%**	(0.18%)
g_{HWW}	0.85%	**0.19%**	(0.23%)
g_{Hbb}	0.88%	**0.42%**	(0.52%)
g_{Hcc}	1.0%	**0.71%**	(0.87%)
g_{Hgg}	1.1%	**0.80%**	(0.98%)
$g_{H\tau\tau}$	0.94%	**0.54%**	(0.66%)
$g_{H\mu\mu}$	6.4%	**6.2%**	(7.6%)
$g_{H\gamma\gamma}$	1.7%	**1.5%**	(1.8%)
BR_{exo}	0.48%	**0.45%**	(0.55%)

stat. uncertainties

17

Z → ll with H → bb

CMS Simulation

LEP3, 500 fb⁻¹, √s=240 GeV

Signal
All backgrounds
ZZ
WW
Zνν

H→ττ with Z→ qq̄

CMS Simulation

LEP3, 500 fb⁻¹, √s=240 GeV

Signal
All backgrounds
ZZ
WW
qqbar

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

Unpolarized cross sections
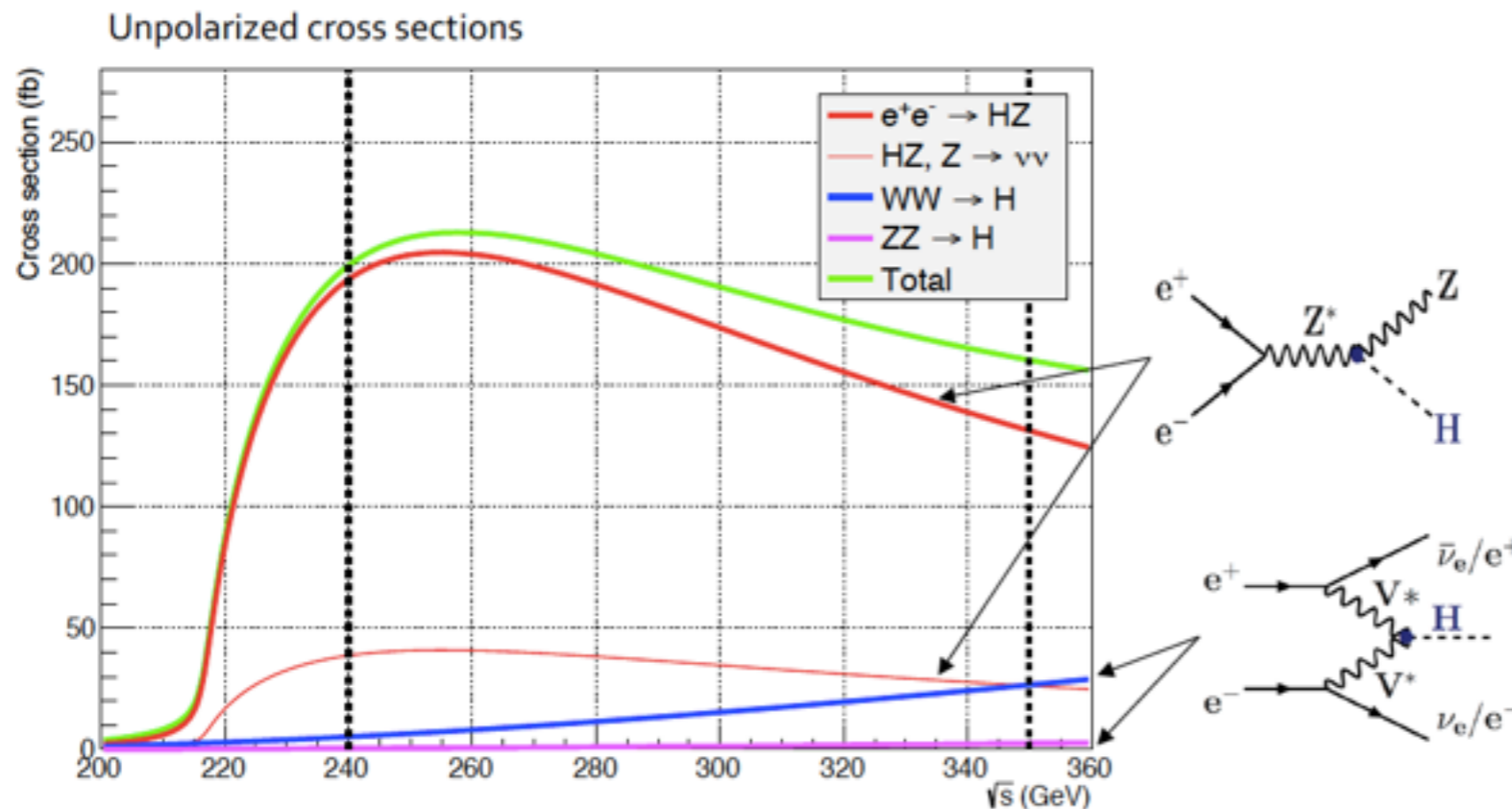
	TLEP 240
σ_{HZ}	0.4%
$\sigma_{HZ} \times$ BR($H \to bb$)	0.2%
$\sigma_{HZ} \times$ BR($H \to c\bar{c}$)	1.2%
$\sigma_{HZ} \times$ BR($H \to gg$)	1.4%
$\sigma_{HZ} \times$ BR($H \to WW$)	0.9%
$\sigma_{HZ} \times$ BR($H \to \tau\tau$)	0.7%
$\sigma_{HZ} \times$ BR($H \to ZZ$)	3.1%
$\sigma_{HZ} \times$ BR($H \to \gamma\gamma$)	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
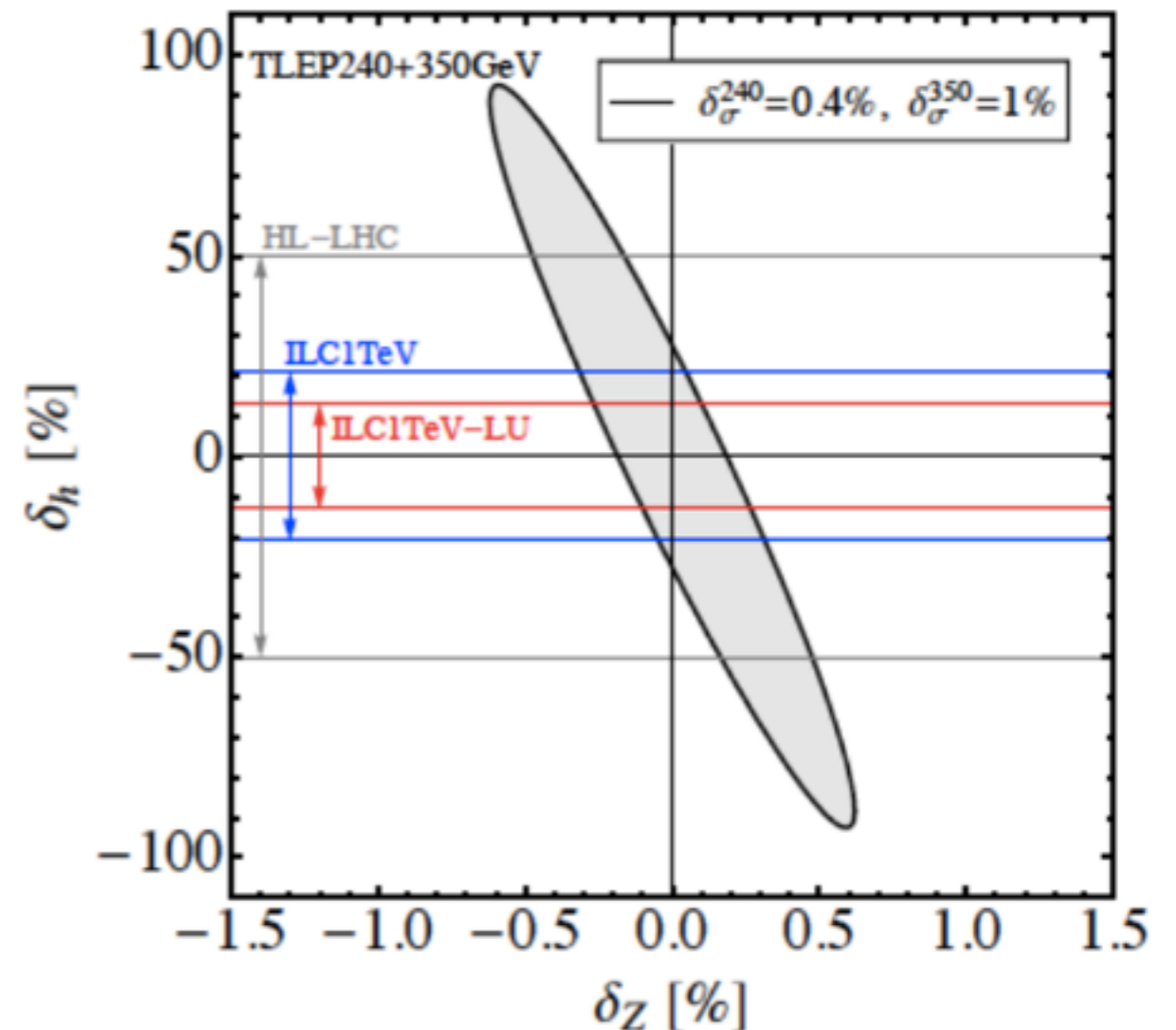
First generation couplings

➡ **s-channel Higgs production**

  ◉ Unique opportunity for measurement close to SM sensitivity

  ◉ Highly challenging; $\sigma(ee \rightarrow H)$ = 1.6fb; 7 Higgs decay channels studied
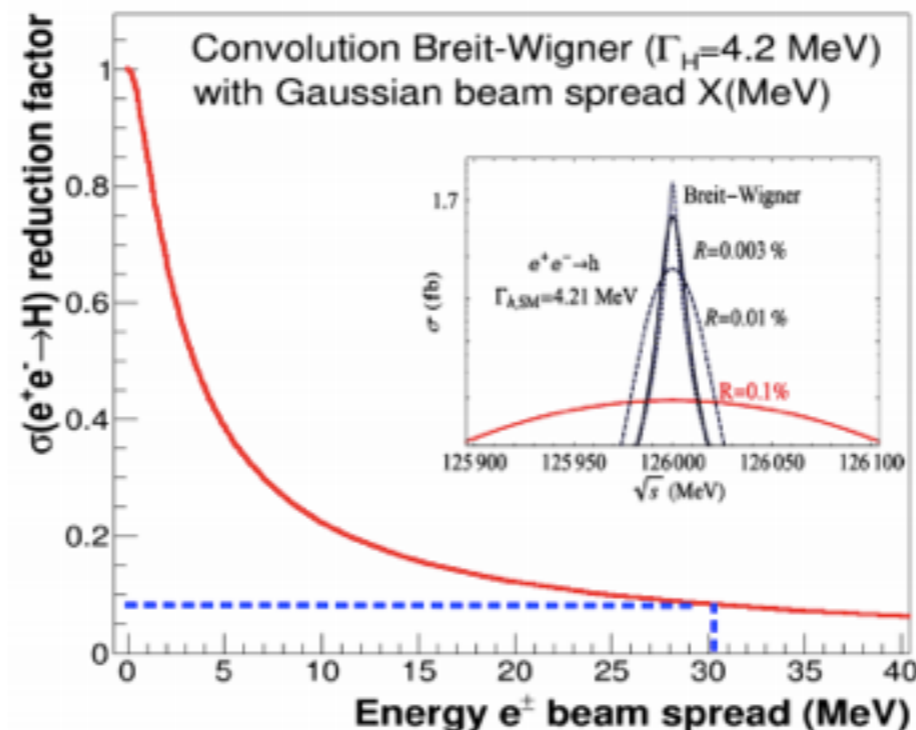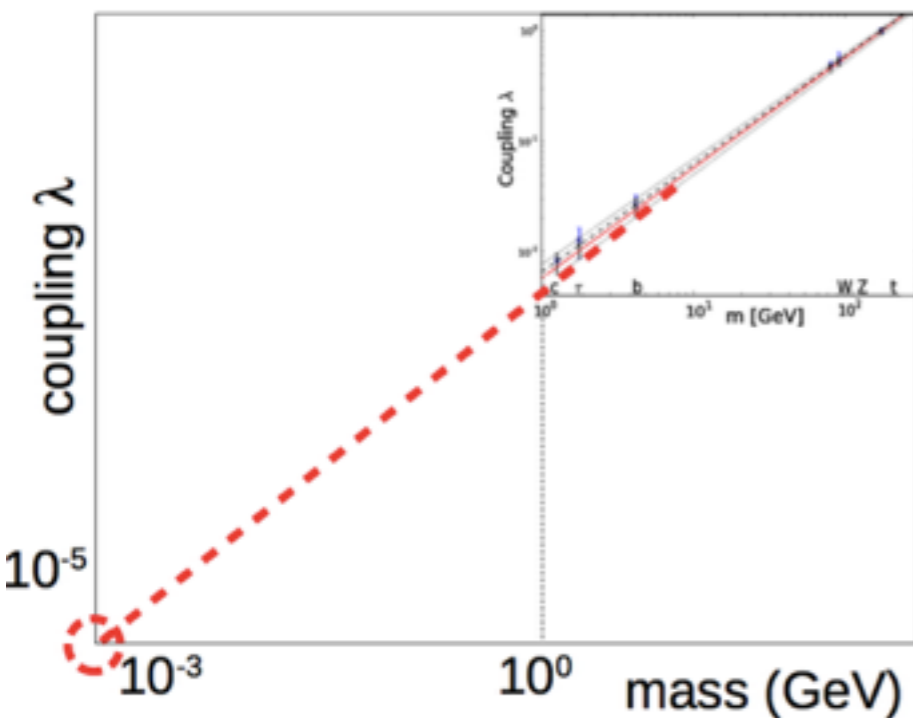
Preliminary Results

$L = 10\ ab^{-1}$

$\kappa_e < 2.2$ 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?[20]

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
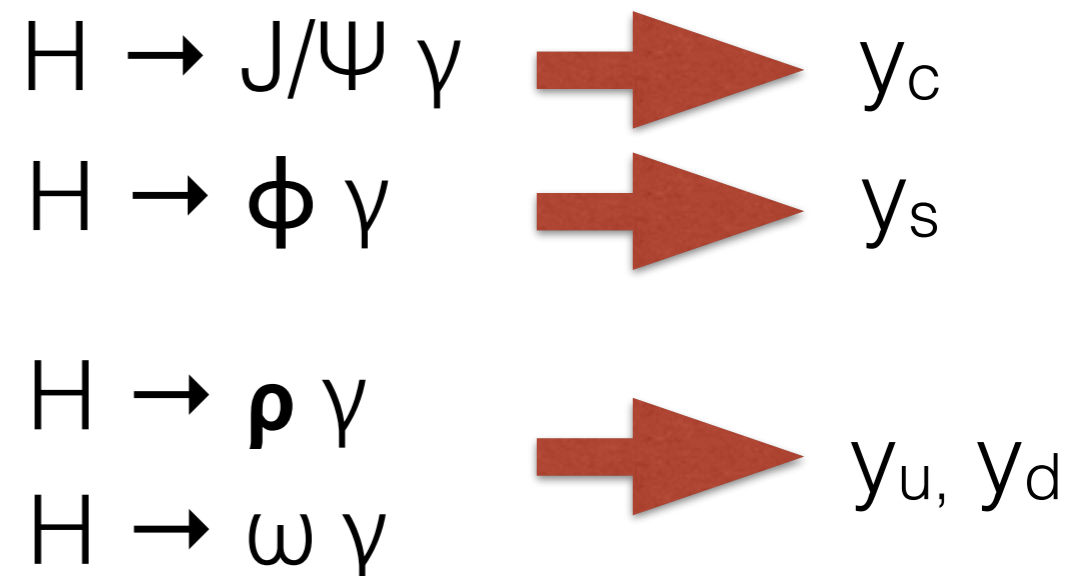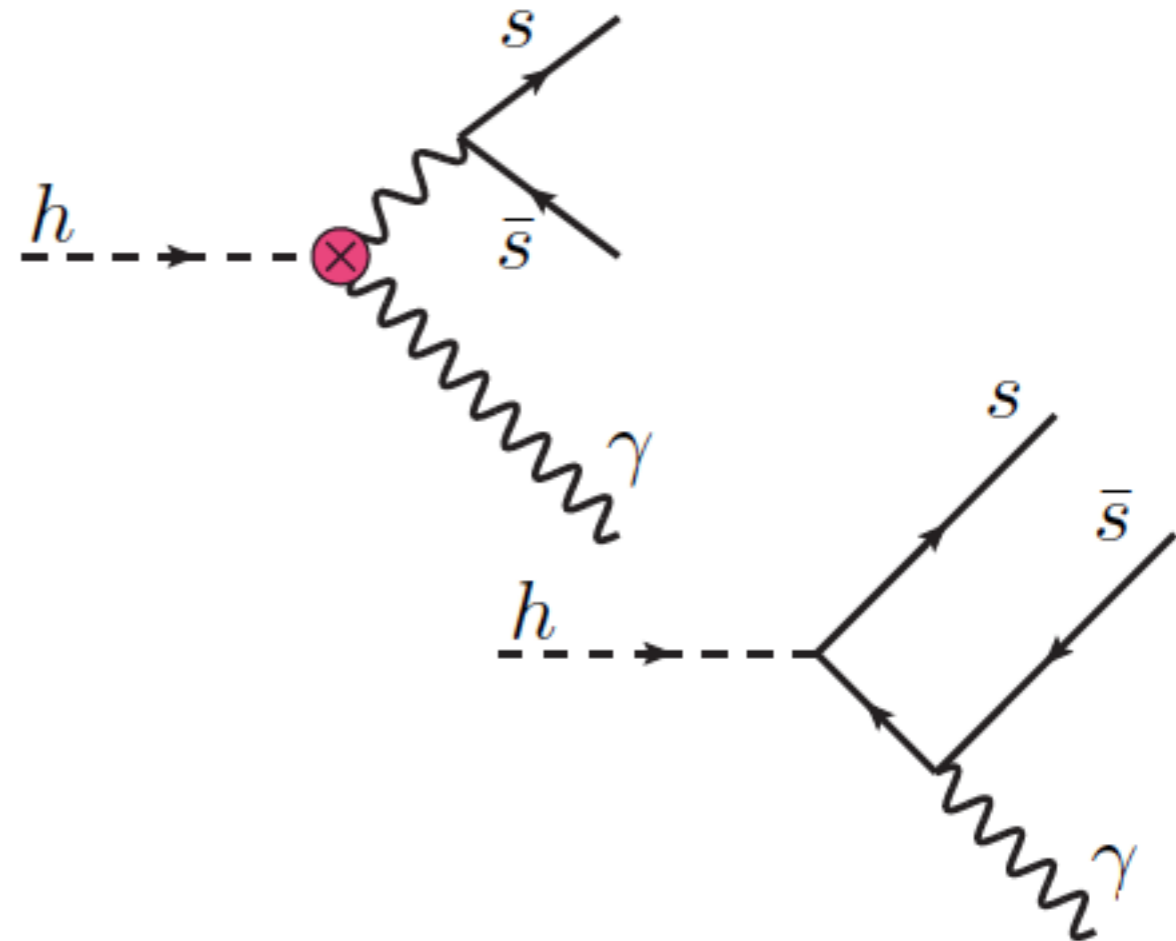
CP Measurements

for HVV couplings

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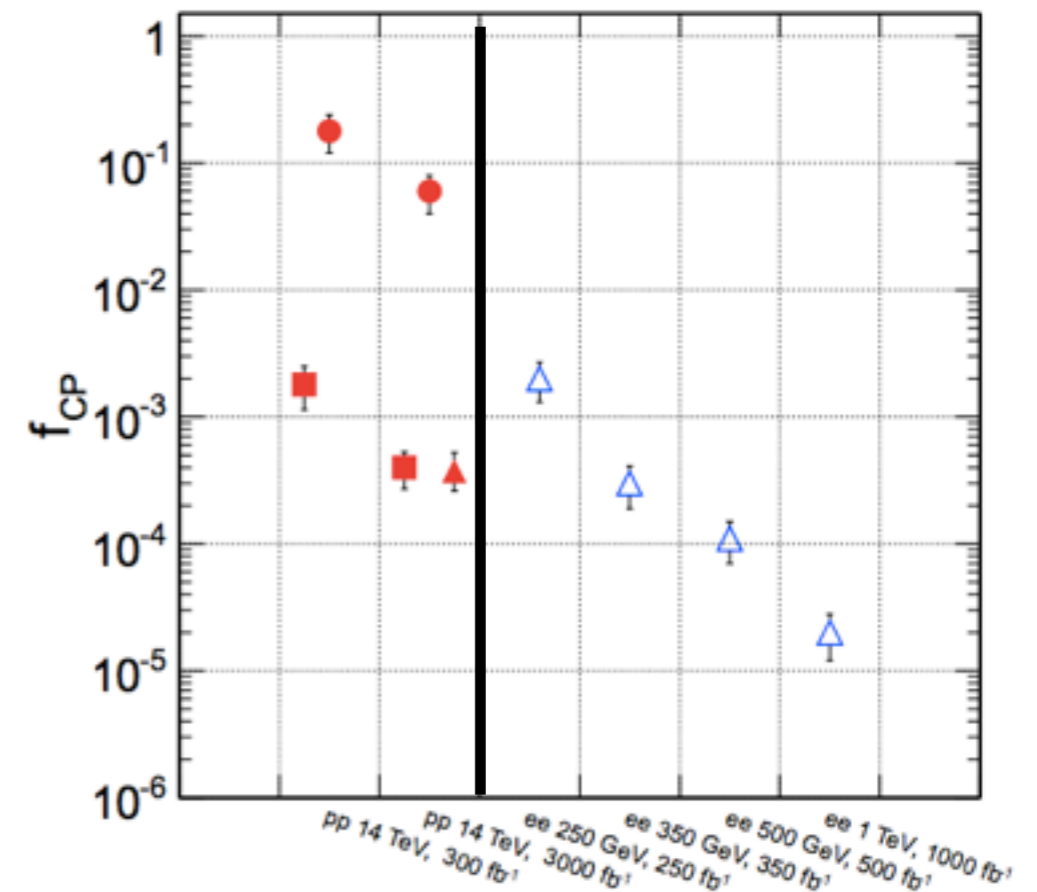
$$\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5 \sin\Delta)f$$

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 <u>Phys. Rev. D 90, 075004 (2014)</u> More from David Curtin

$$h \to \not{E}_T$$
$$h \to 4b$$
$$h \to 2b2\tau$$
$$h \to 2b2\mu$$
$$h \to 4\tau, 2\tau2\mu$$
$$h \to 4j$$
$$h \to 2\gamma2j$$
$$h \to 4\gamma$$
$$h \to ZZ_D, Za \to 4\ell$$
$$h \to Z_D Z_D \to 4\ell$$
$$h \to \gamma + \not{E}_T$$
$$h \to 2\gamma + \not{E}_T$$
$$h \to 4 \text{ ISOLATED LEPTONS} + \not{E}_T$$
$$h \to 2\ell + \not{E}_T$$
$$h \to \text{ONE LEPTON-JET} + X$$
$$h \to \text{TWO LEPTON-JETS} + X$$
$$h \to b\bar{b} + \not{E}_T$$
$$h \to \tau^+\tau^- + \not{E}_T$$

Conclusion

➡ Exploration of Higgs Physics at the LHC on its way

⦿ So far all results SM-like

➡ HL-LHC will set a high bar for Higgs precision measurements

⦿ Large discovery potential

➡ FCC Higgs program opens new windows

⦿ Complementarity of FCC-ee, ep, and pp

➡ Need significant theoretical improvements to exploit full potential

➡ Substantial program of work ahead in FCC study

⦿ Novel ideas appeared in recent workshops

⦿ Many opportunities to contribute

References / Input from

- s-channel Higgs production: D.d'Enterria, R.Aleksan, G.Wojcik

- 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

- Exclusive Higgs decays: Y. Soreq

- …