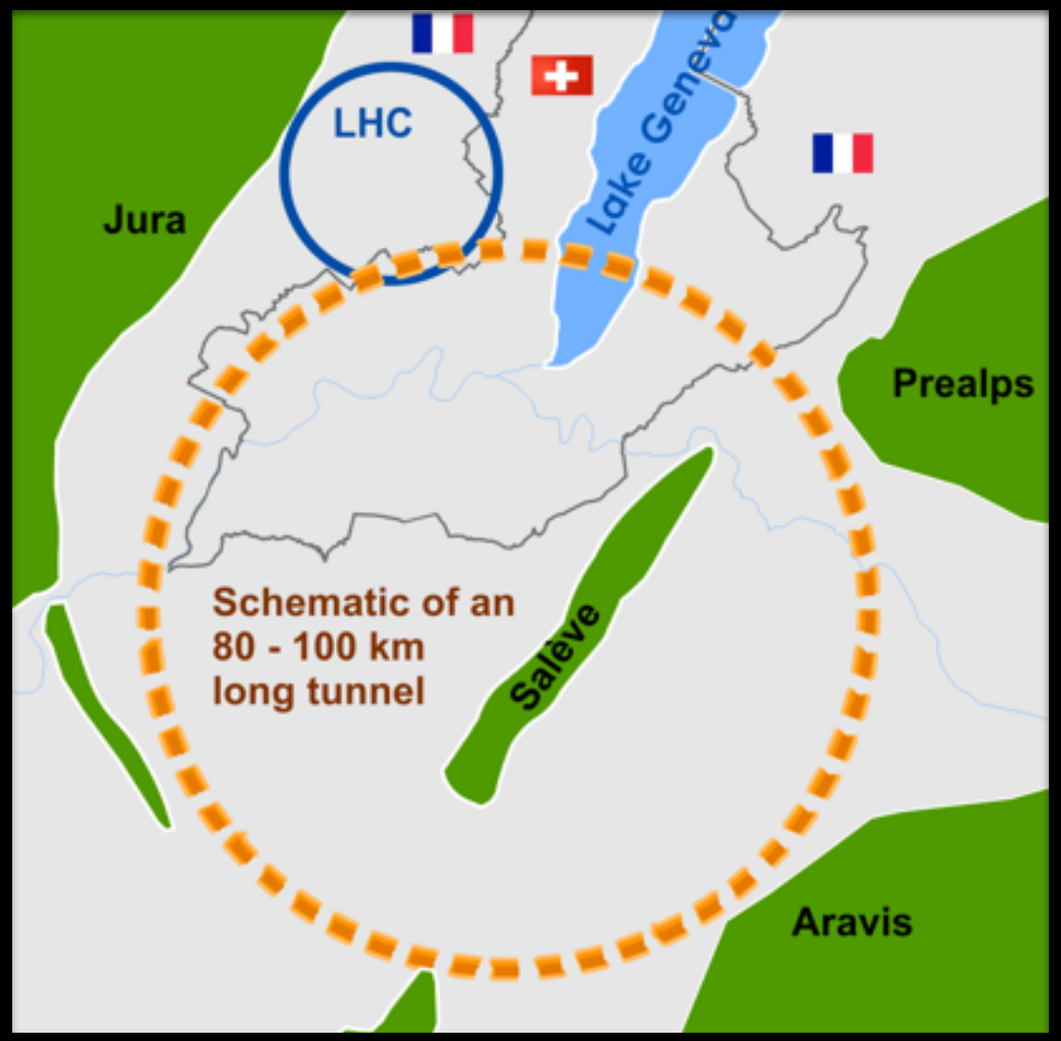
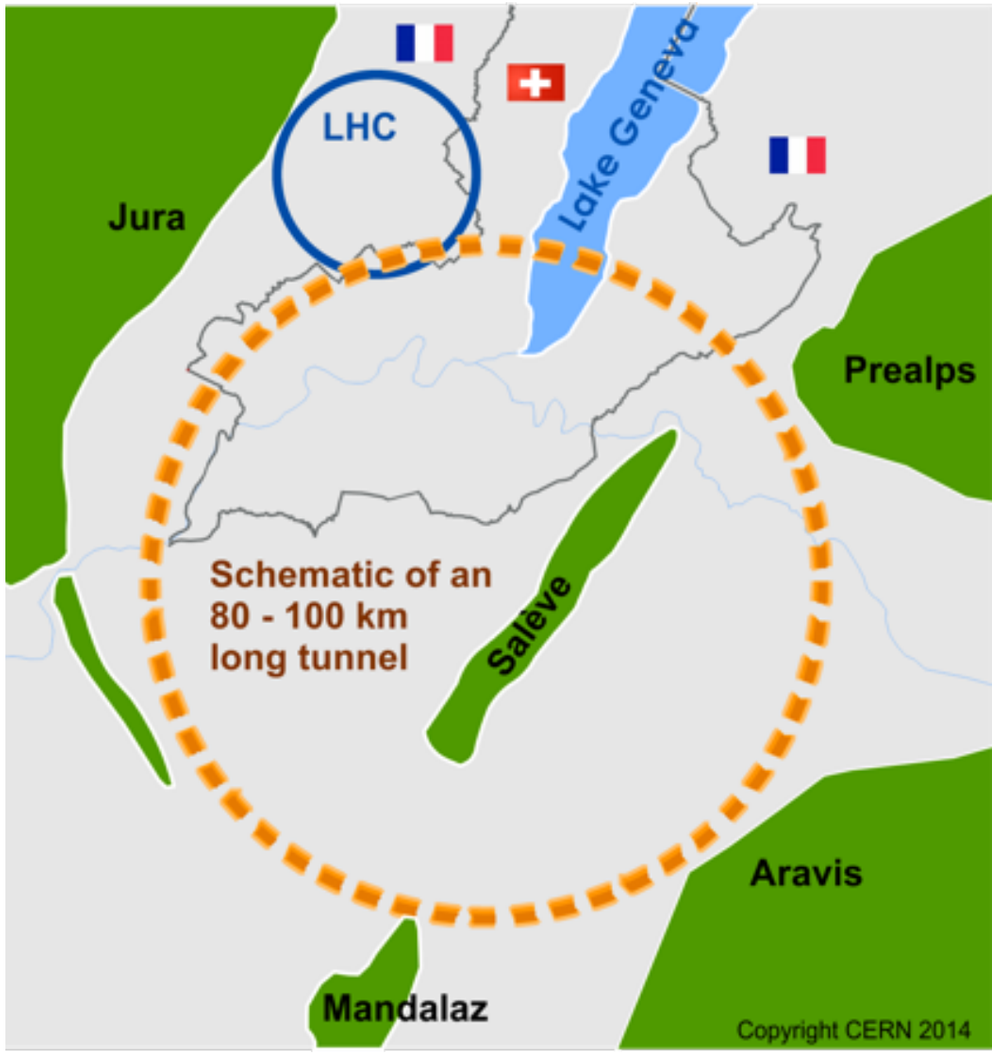
Higgs Physics at the Future Circular Colliders (FCC)



Markus Klute (MIT)
EPS, Vienna
July 25th, 2015

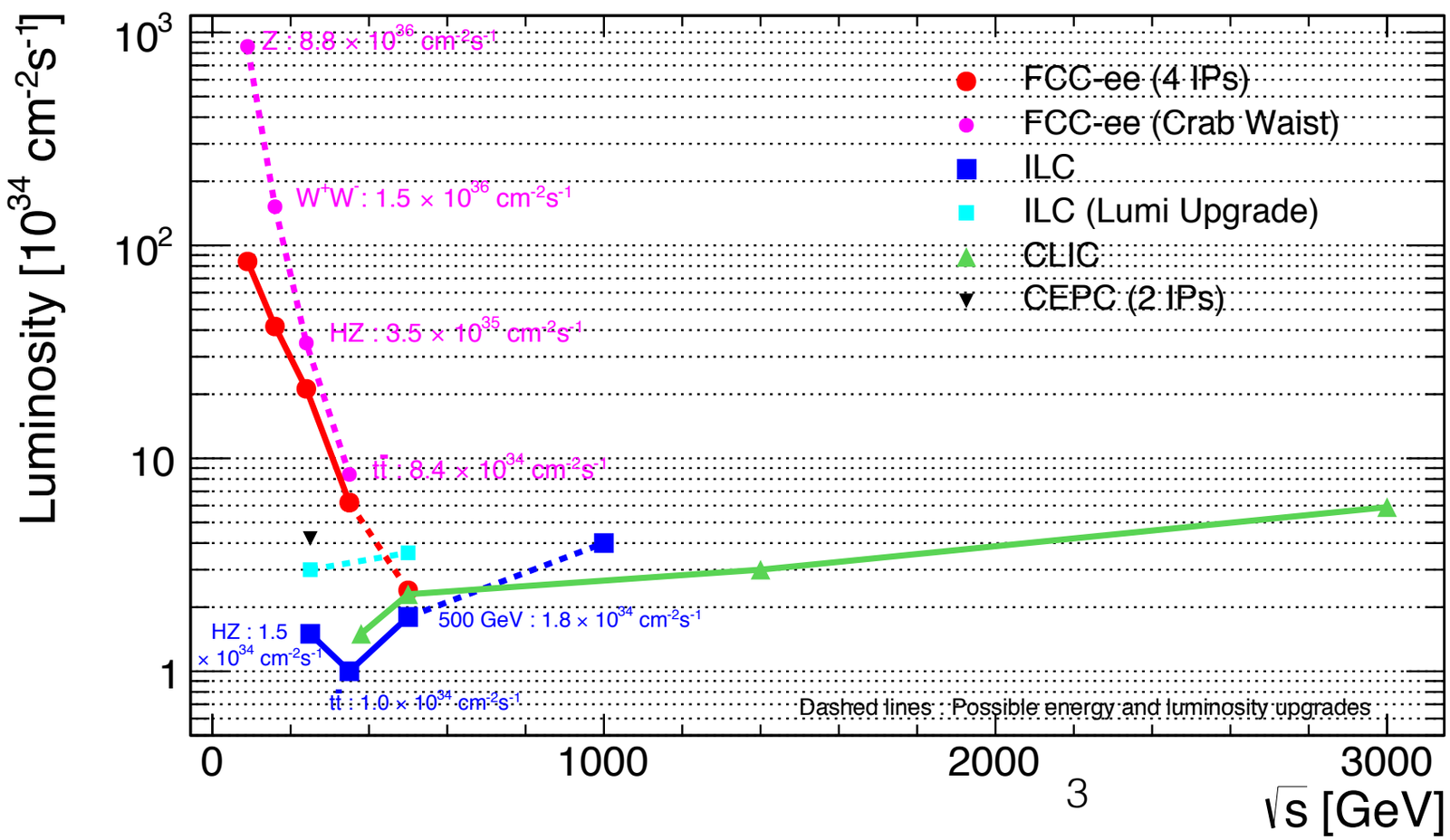
Future Circular Collider Study

- ➡ **International FCC collaboration to study**
  - pp-collider (FCC-hh)
  - e^+e^- collider (FCC-ee)
  - p-e (FCC-he)
- ➡ 80-100 km infrastructure in Geneva area
- ➡ **Goal:** CDR and cost review by 2018
- ➡ Similar studies in China (50-70 km infrastructure)
  - pp-collider (SppS)
  - e^+e^- collider (CepC)



Future Circular Collider Program

	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]	215	38	8.8	2.5	5-30	6.2
L_{int} [ab^{-1}/year/IP]	21.5	3.8	0.9	0.25	0.3-1.8	0.4
Beam current [mA]	1450	152	30	6.6	500-3000	480 / 500

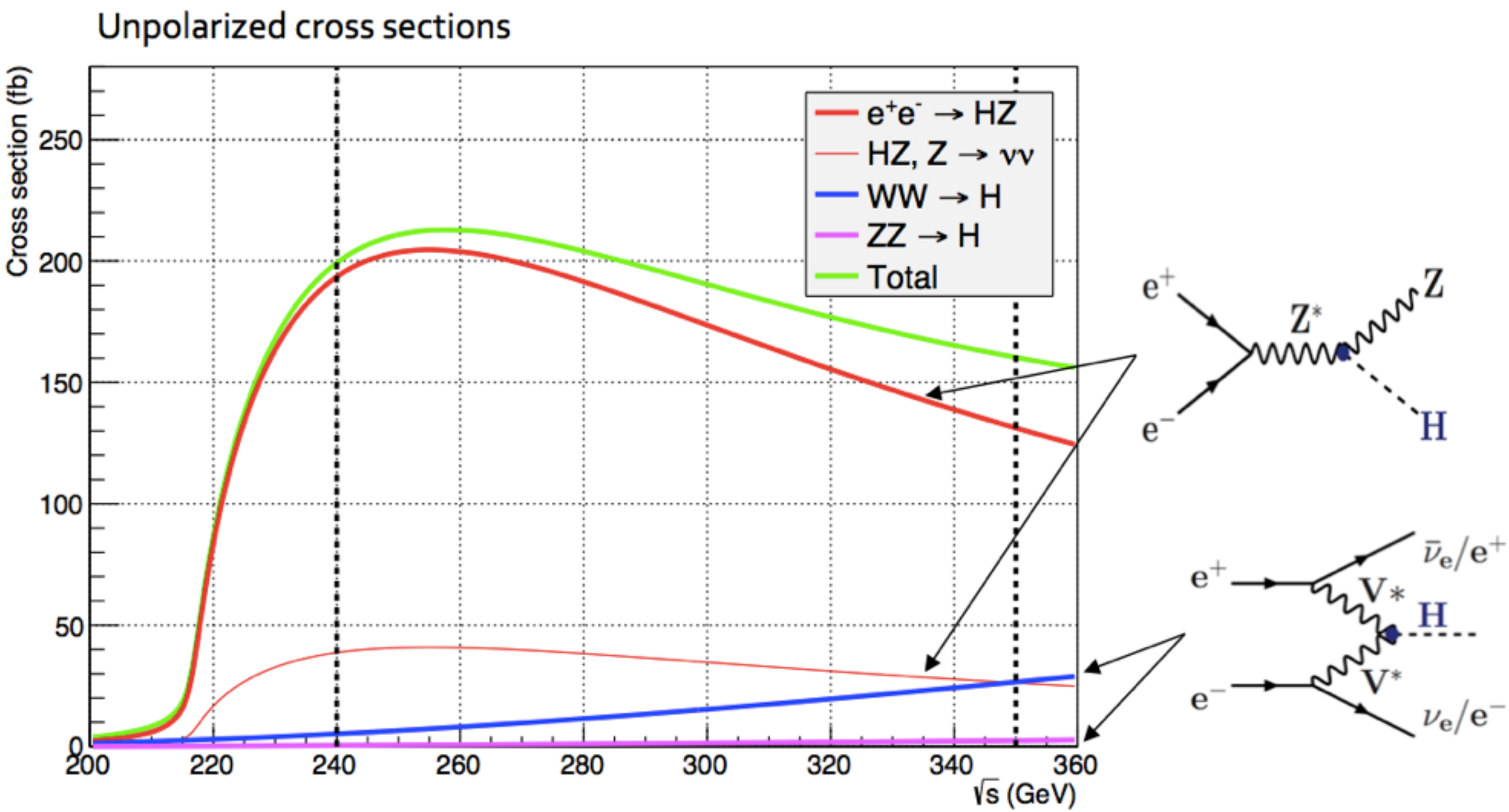


FCC-ee EW: M. Dam

FCC-ee Top: P. Janot

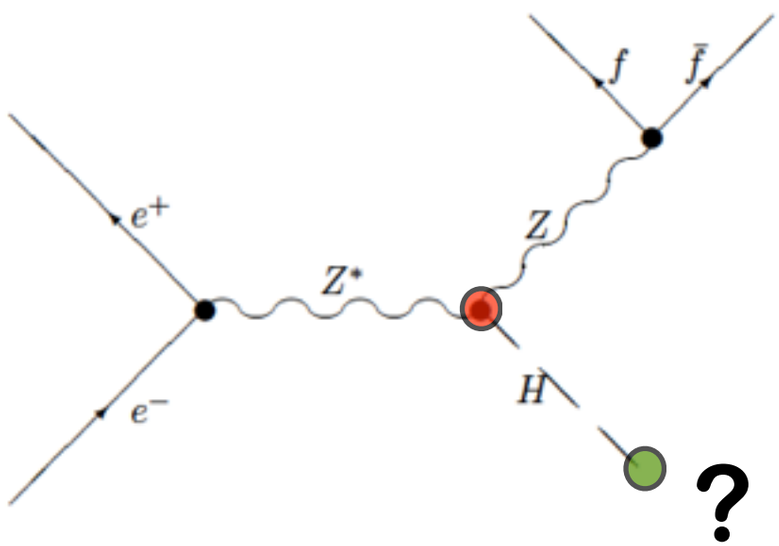
FCC-ee Flavor: St. Monteil

Higgs Production: FCC-ee

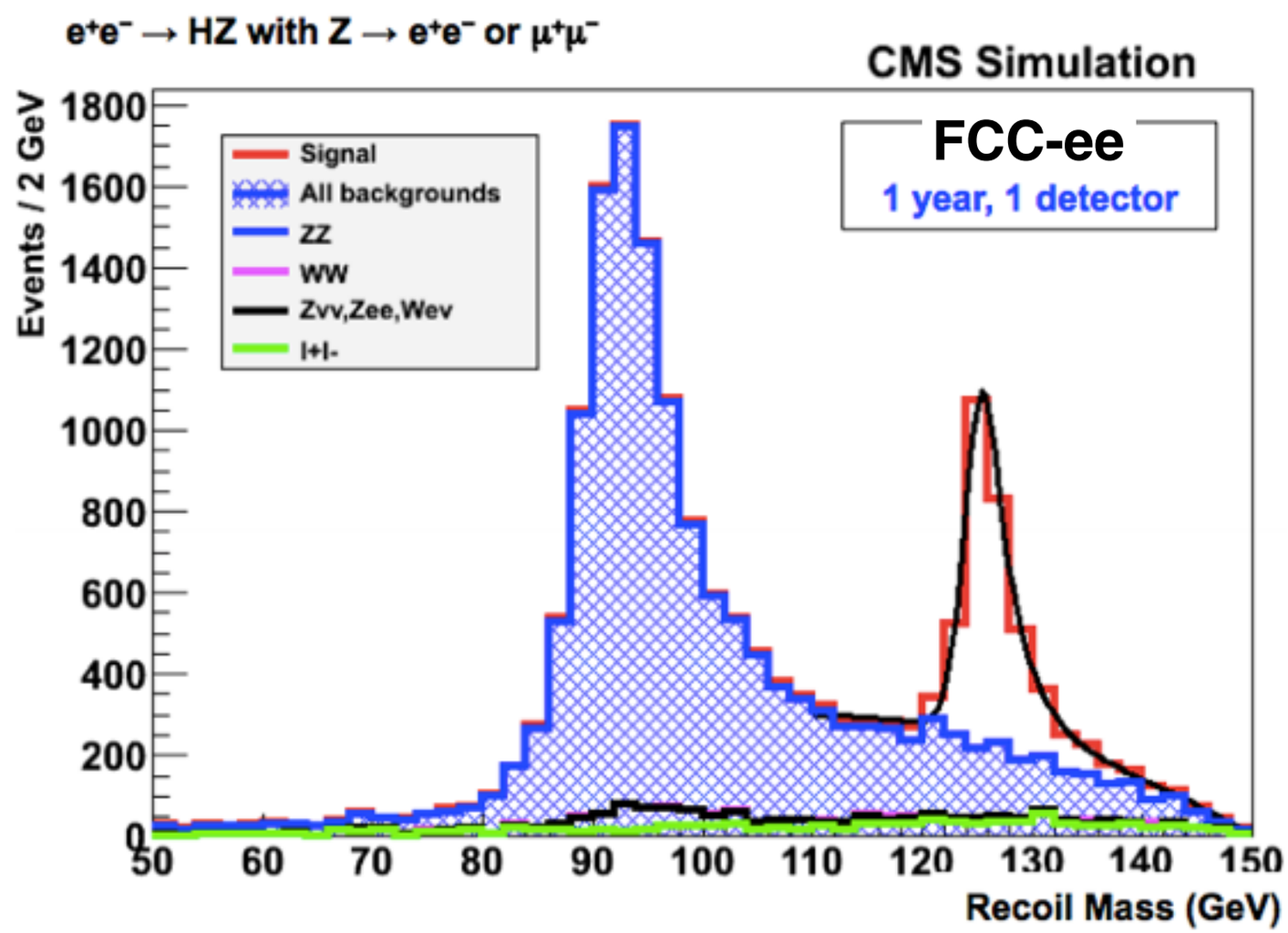


Precision Higgs Couplings

- ➡ Recoil method unique to lepton collider
- ➡ Tag Higgs event independent of decay mode
- ➡ Provide precision measurement of $\sigma(ee \rightarrow ZH) \propto g_{HZ}^2$



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

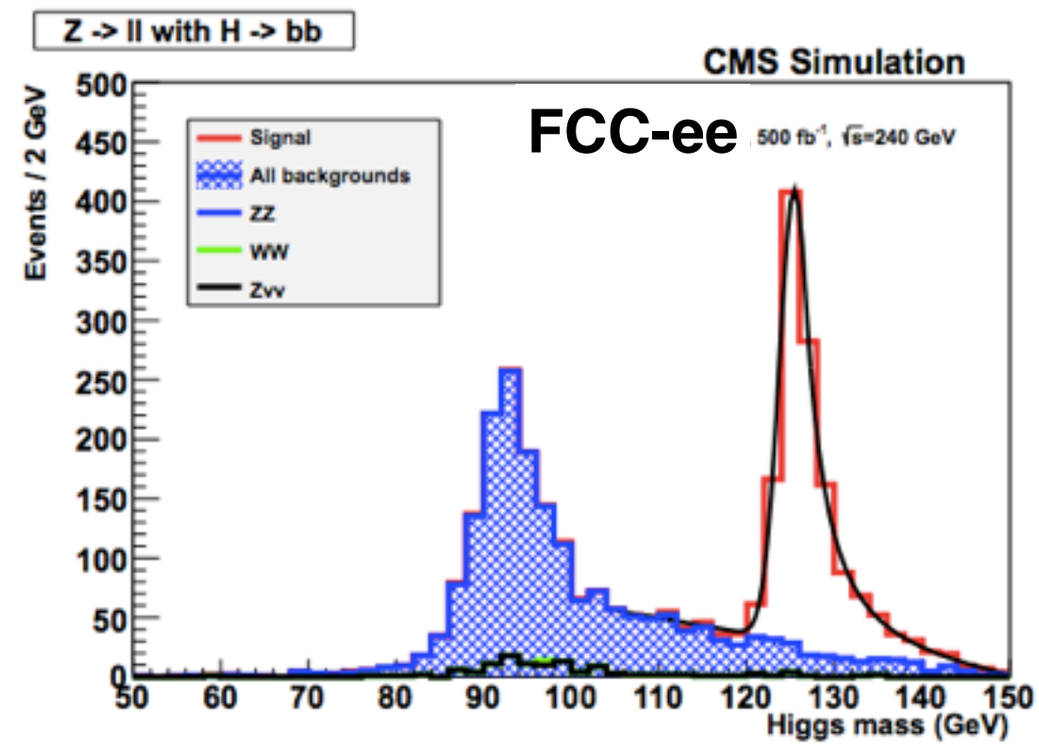


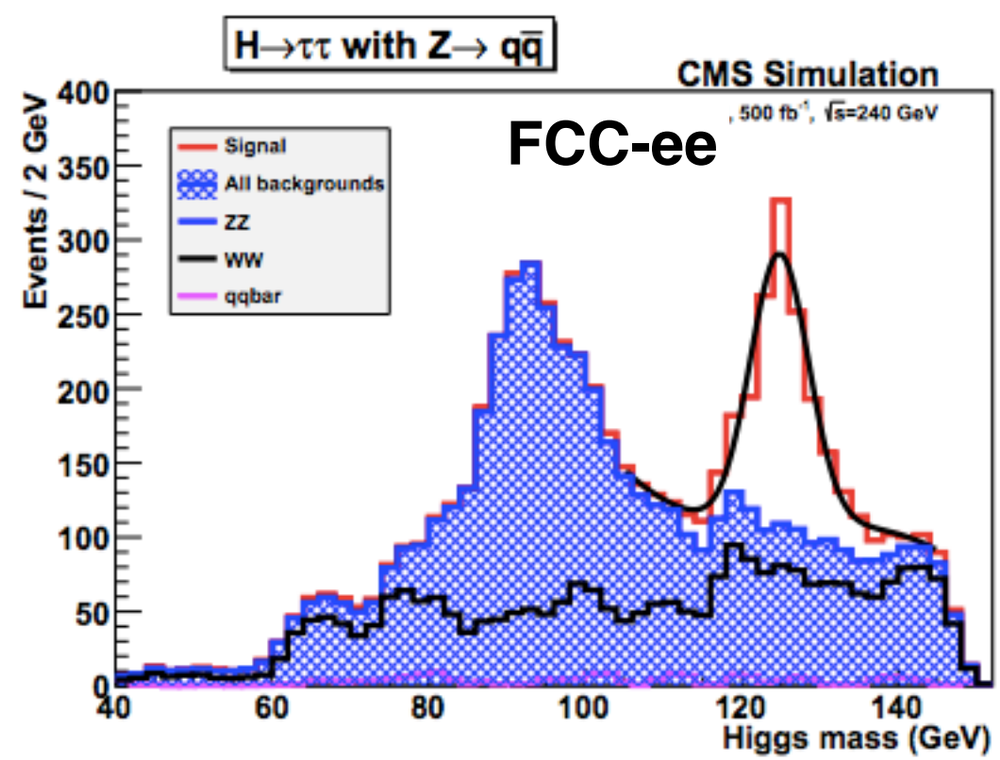
Precision Higgs Couplings

- Measure σ(ee→ZH) * BR (H→X) by identifying X
- Example: σ(ee→ZH) * BR (H→ZZ) $\propto g_{HZ}^4/\Gamma_H$
- Total width from combination of measurements or fit
- Hadronic and invisible Z decays increase precision
- Branching fraction to invisible tested directly to 0.19% @ 95% CL

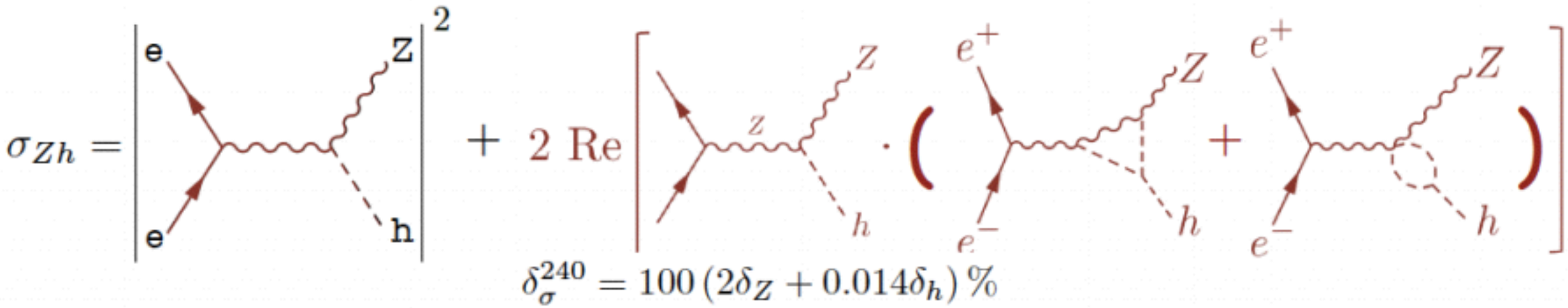
	Model-independent fit		
Coupling	FCC-ee -240	FCC-ee	
g_{HZZ}	0.16%	**0.15%**	(0.18%)
g_{HWW}	0.85%	**0.19%**	(0.23%)
g_{Hbb}	0.88%	**0.42%**	(0.52%)
g_{Hcc}	1.0%	**0.71%**	(0.87%)
g_{Hgg}	1.1%	**0.80%**	(0.98%)
$g_{H\tau\tau}$	0.94%	**0.54%**	(0.66%)
$g_{H\mu\mu}$	6.4%	**6.2%**	(7.6%)
$g_{H\gamma\gamma}$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

stat. uncertainties



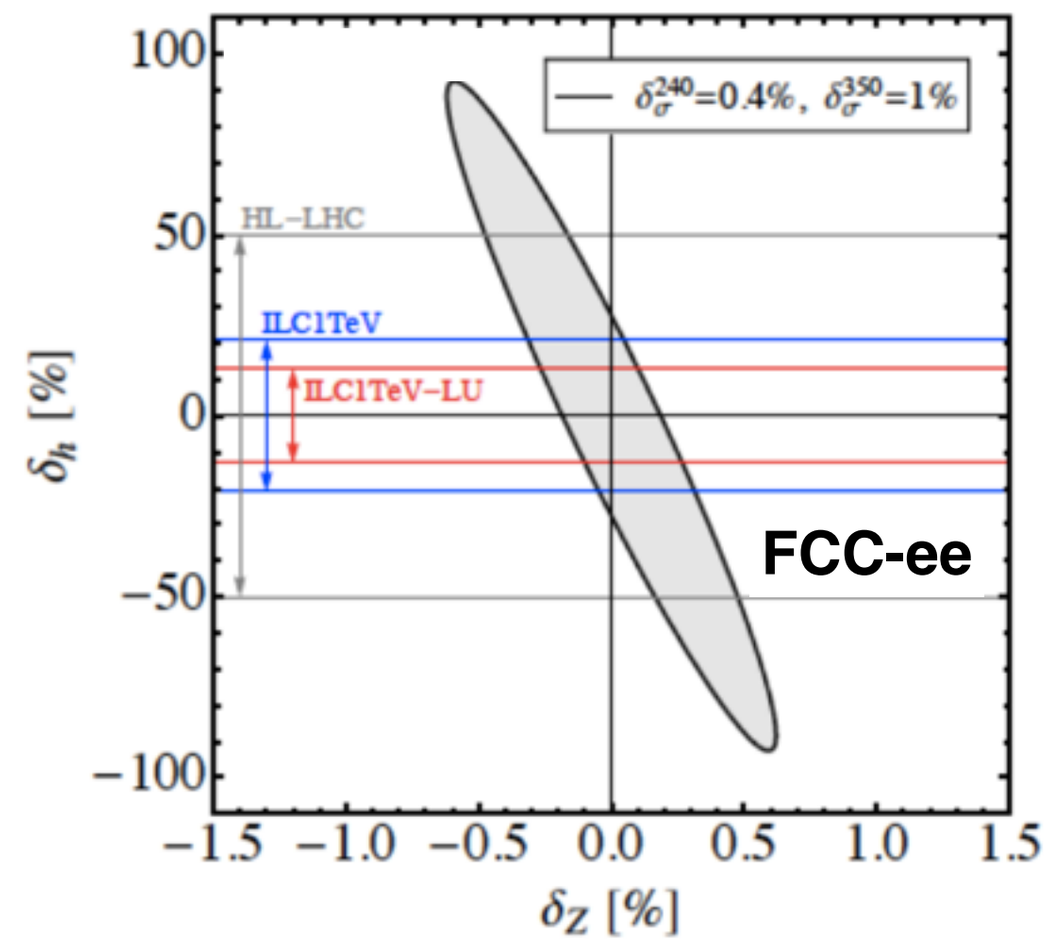


Higgs self-coupling through loop corrections



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

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



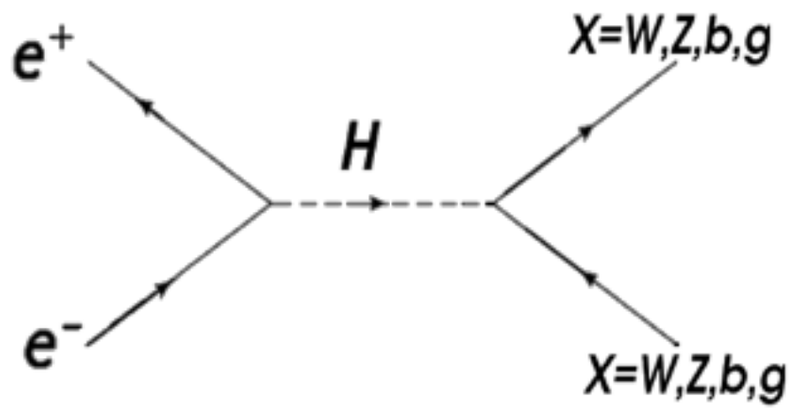
Matthew McCullough

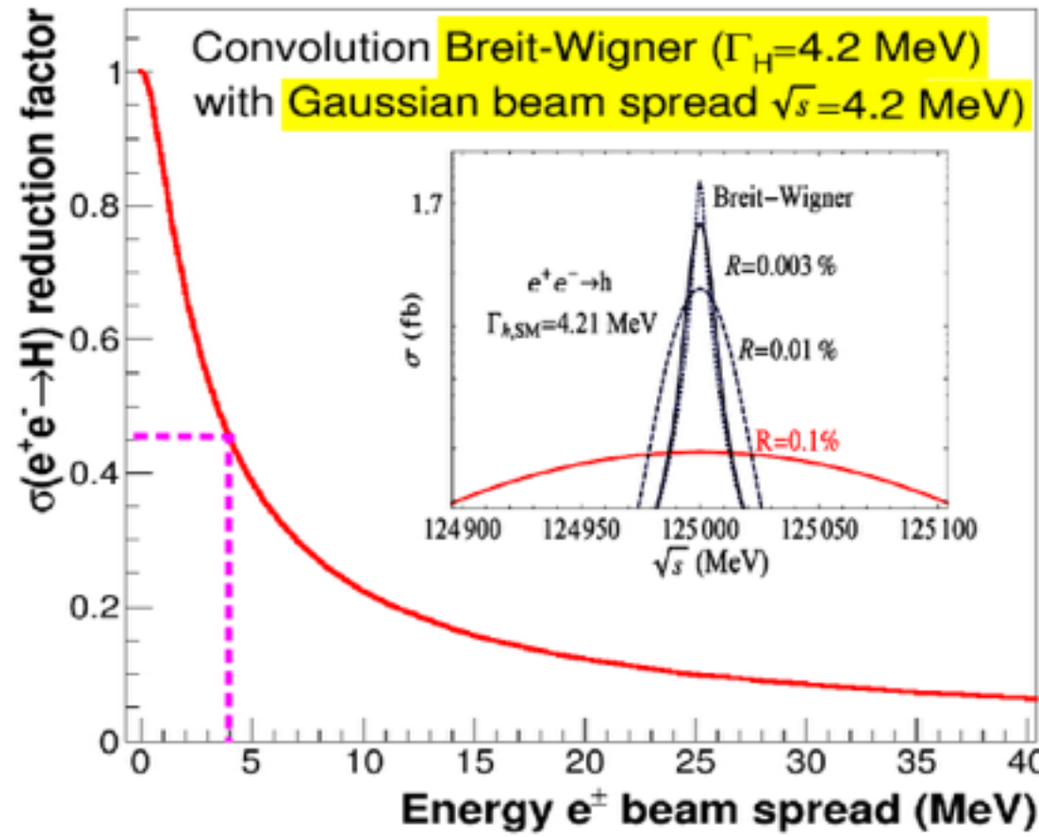
arxiv:1312.3322

First generation couplings

➡ **s-channel Higgs production**

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





➡ **Work in progress**

- Loop-induced production channels have cross section than pure s-channel. But, how large are BSM effects?
- Can monochromators yields energy spread of Higgs width or smaller? At what luminosity cost?
- Energy scan O(10MeV) around mH will be needed to locate exact sqrt(s)
- Polarization increases cross section (e.g. by x2 at P=70%). At what luminosity cost?

Preliminary Results

L = 10 ab^{-1}

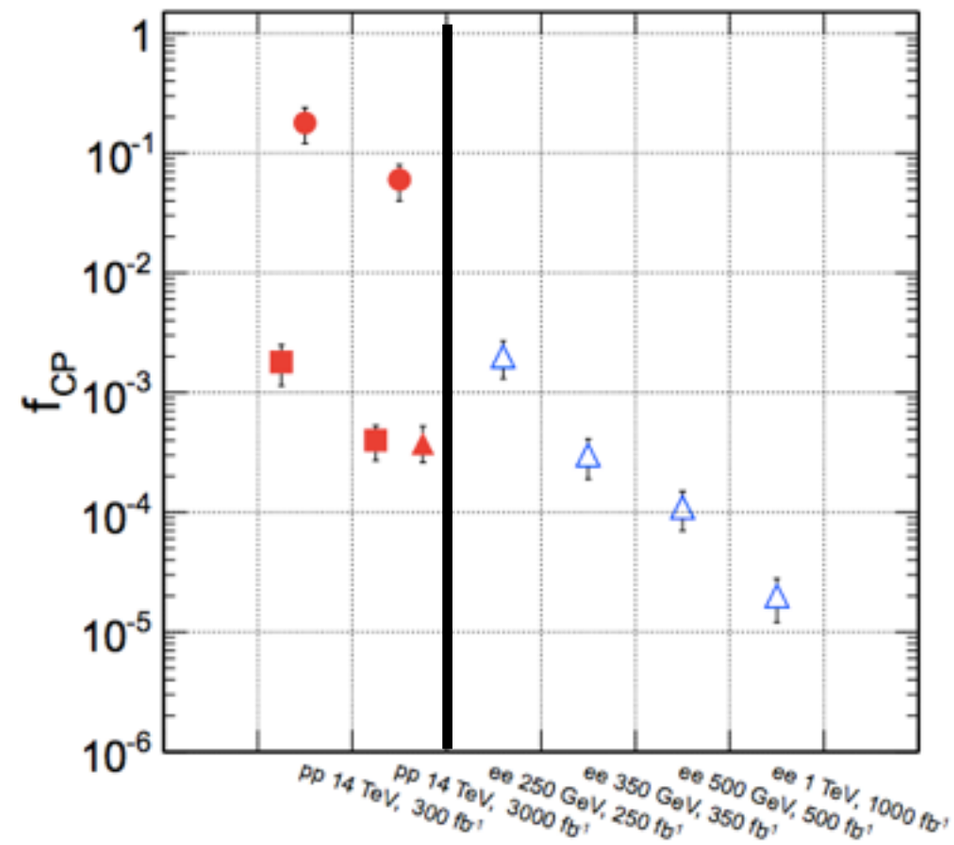
κ_e < 2.2 at 3σ

d'Enterria-Wojcik-Aleksan

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

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°

Felix Yu

http://arxiv.org/abs/1308.1094

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
- ➡ 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)

$h \to \not{E}_T$

$h \to 4b$

$h \to 2b2\tau$

$h \to 2b2\mu$

$h \to 4\tau, 2\tau2\mu$

$h \to 4j$

$h \to 2\gamma2j$

$h \to 4\gamma$

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

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

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

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

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

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

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

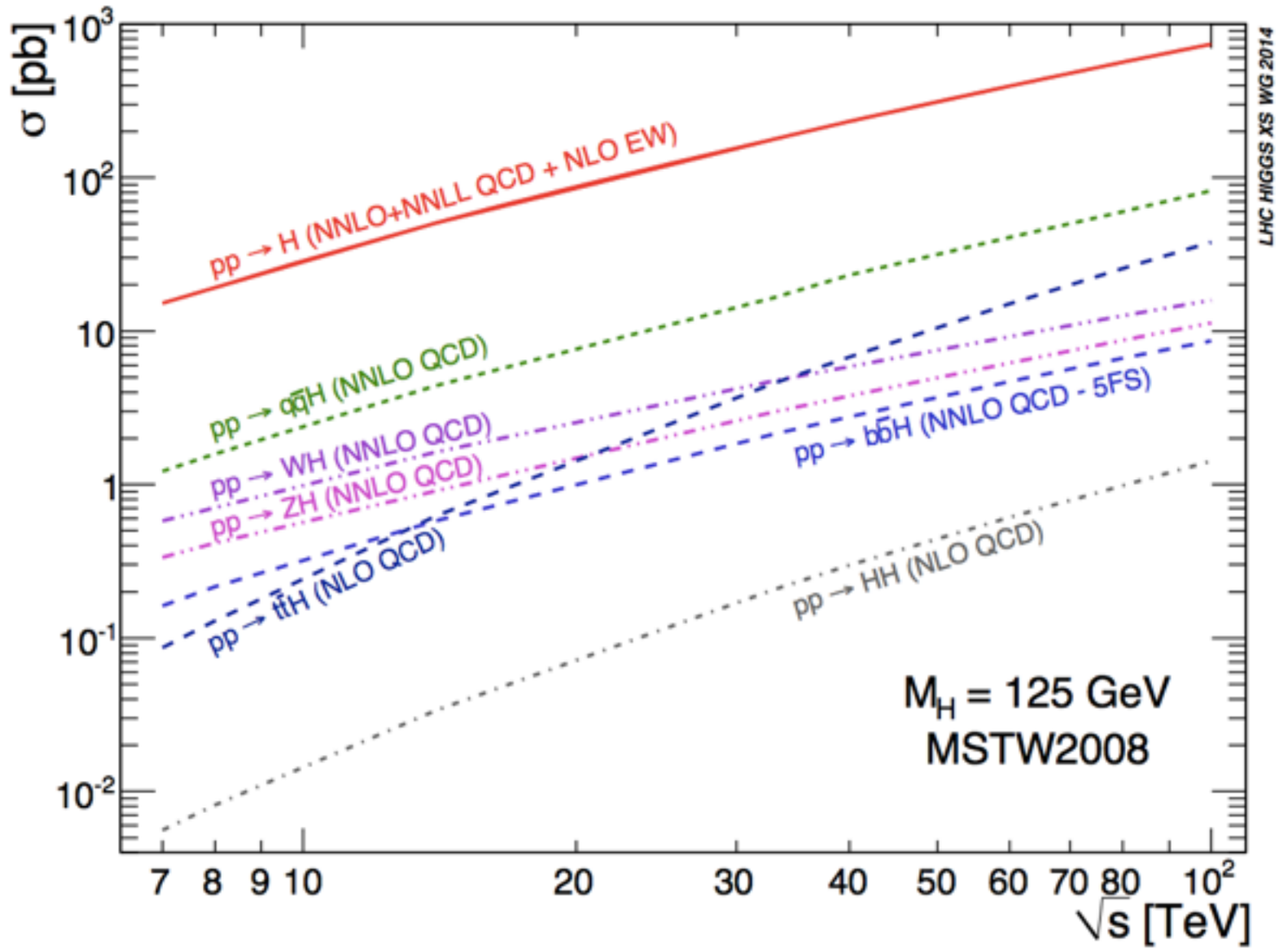
$h \to$ TWO LEPTON-JETS $+ X$

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

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

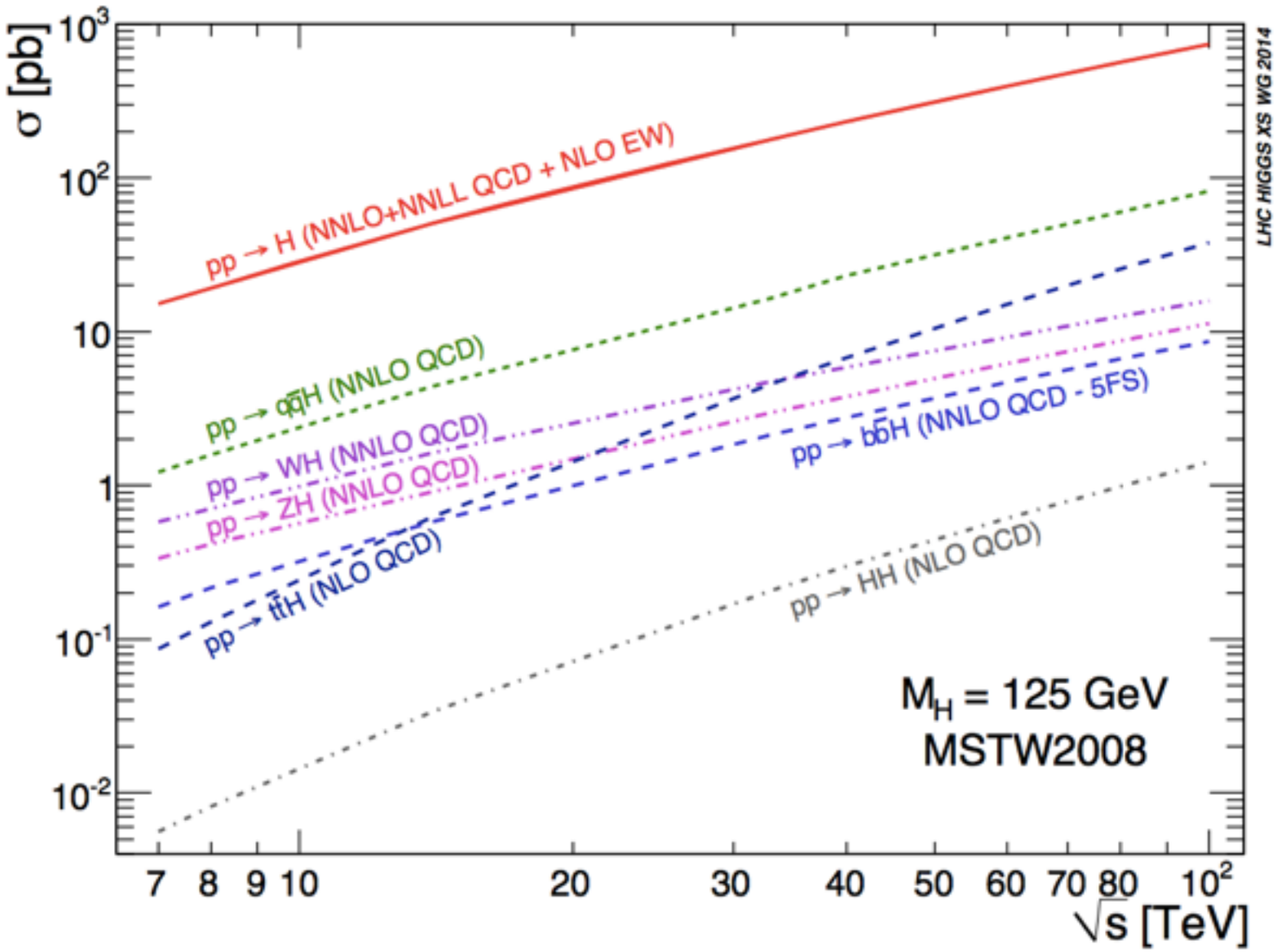
Higgs production: FCC-pp

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

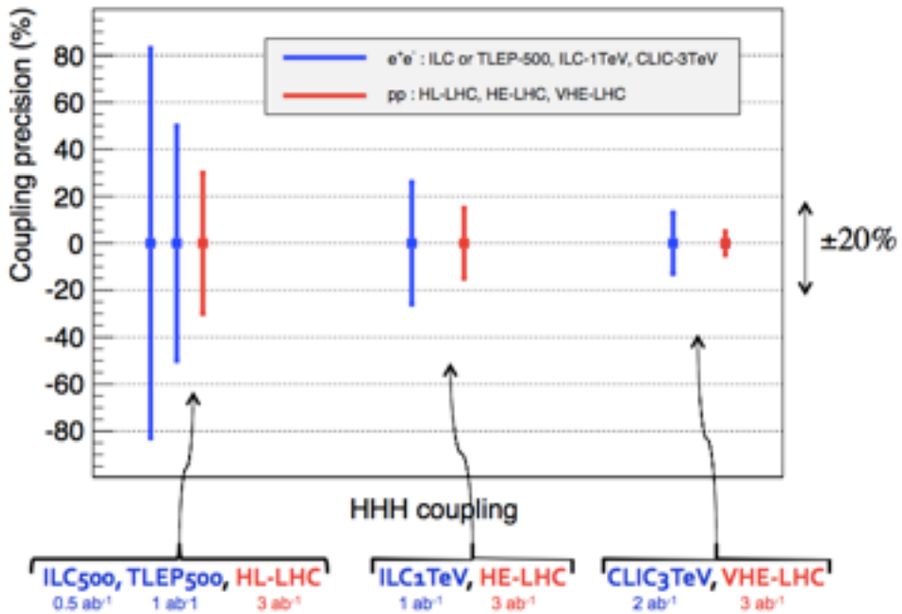
LHC Run I → **x300-600** → **HL LHC** → **x10-400** → **FCC pp**

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

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 → 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

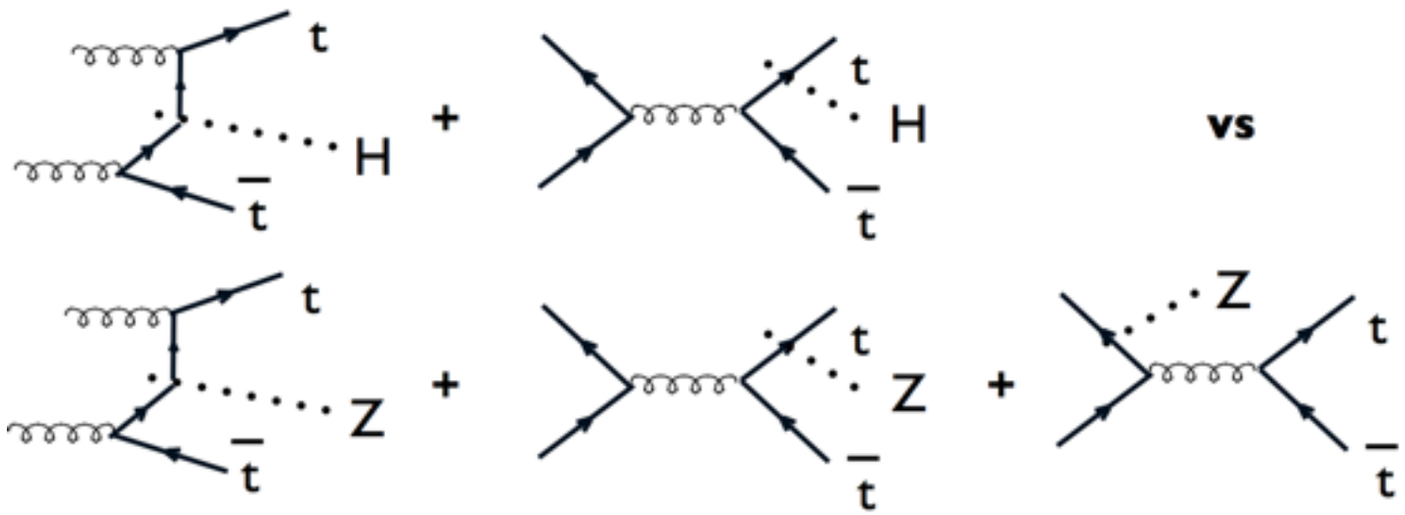
Key question is the
evolution systematic uncertainty

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

Higgs physics program: FCC-pp

➡ … but also new measurements are possible

ttH / ttZ



➡ Theoretical uncertainties cancel mostly

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

➡ Complementarity with FCC-ee program

- ttZ coupling can be measured with precision by FCC-ee
- Higgs branching fraction

FCC-ee Top: P. Janot

➡ Opens the possibility to measure top-Yukawa coupling with percent level precision

➡ More studies are needed to verify that < 1% level target can be reached

FCC Higgs physics program

gH_{XY}	ZZ	WW	γγ	Zγ	tt	bb	ττ	cc	ss	μμ	uu,dd	ee	Γ_H	HH	BR_{exo}
FCC-ee	0.15	0.19	1.5			0.42	0.54	0.71	H→Vγ	6.2	H→Vγ	ee→H	0.9		0.45
FCC-hh			< 1?	1 ?	1 ?					2 ?				5 ?	$<10^{-6}$?

- ➡ Summary of FCC-ee studies and “guesses” for FCC-hh performance. Uncertainty in %.
- ➡ Almost perfect complementarity between FCC-ee and FCC-hh program

Conclusion

- ➡ Exploration of Higgs Physics at the LHC on its way
  - HL-LHC will set a high bar for Higgs physics
- ➡ **Exciting 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
  - **Goal:** CDR and cost review by 2018

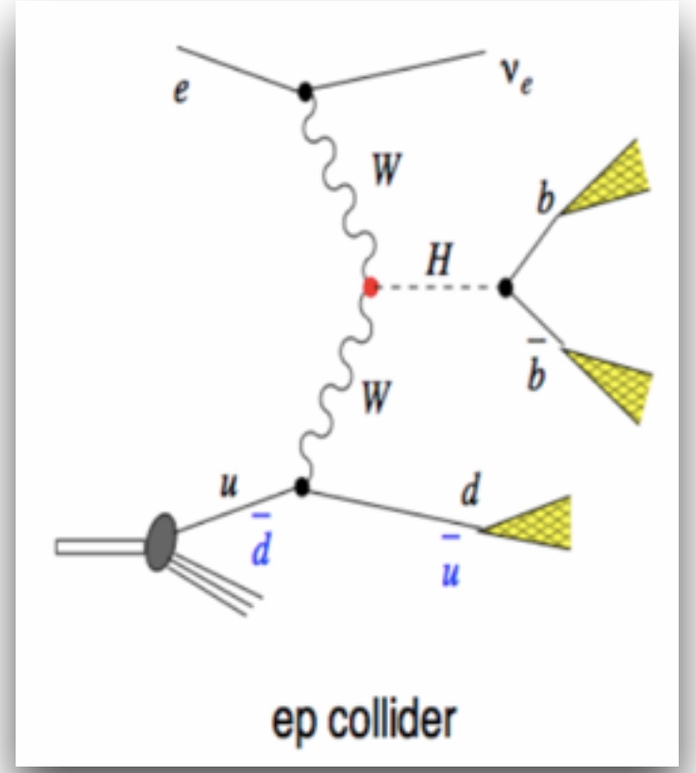
References / Input from

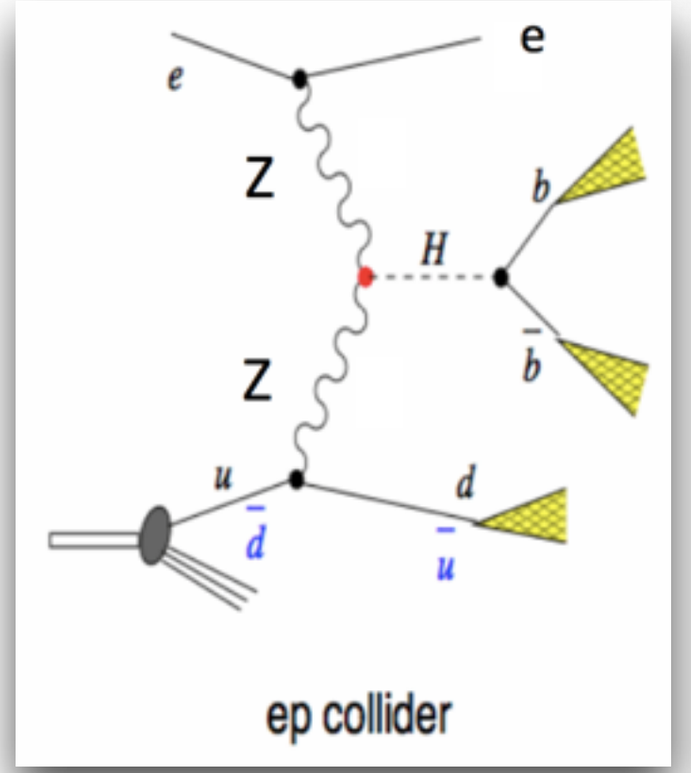
- s-channel Higgs production: D.d'Enterria, R.Aleksan, G.Wojcik
- FCC-ep: M.Klein
- CMS: Snowmass report, ECFA report
- ATLAS: ATL-CONF-15-007, ATL-PHYS-PUB-2014-016, 019
- TLEP/FCC-ee: TLEP Case Study http://arxiv.org/abs/1308.6176 JHEP 01 (2014) 164
- Prospective Studies for LEP3 with the CMS detector http://arxiv.org/abs/1208.1662
- 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 and Higgs @ 100 TeV: M.Mangano
- Exclusive Higgs decays: Y. Soreq
- …

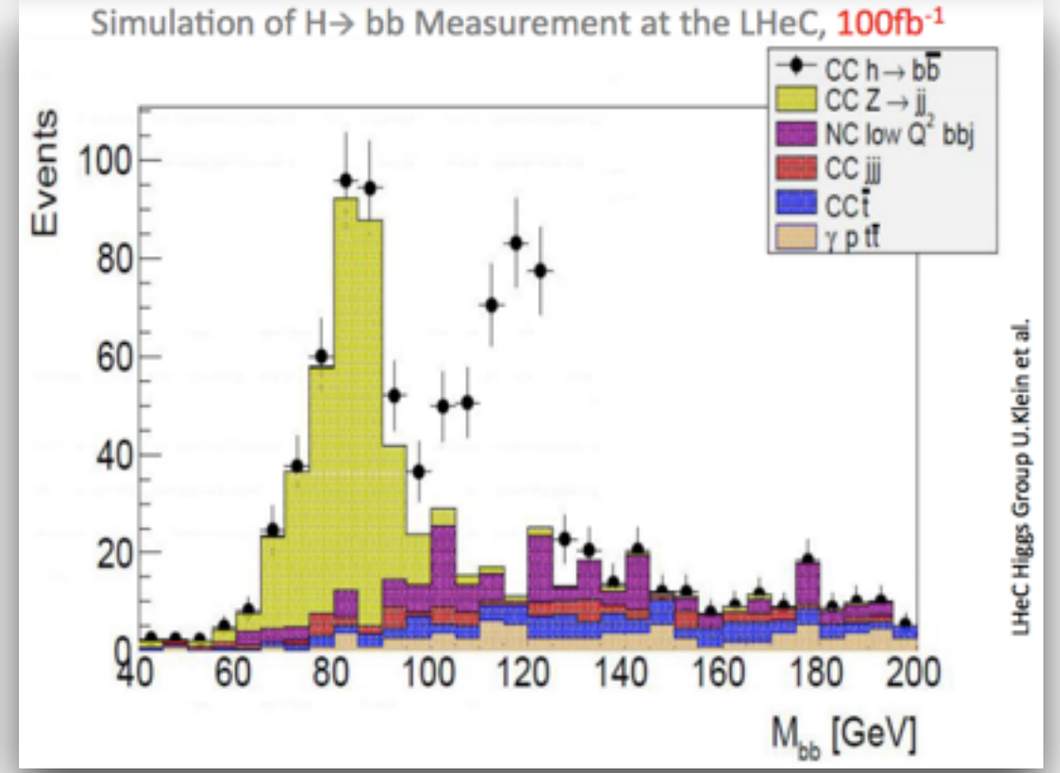
Higgs Production: FCC-ep

- ➡ 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
- ➡ Potential for Higgs self coupling studies

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







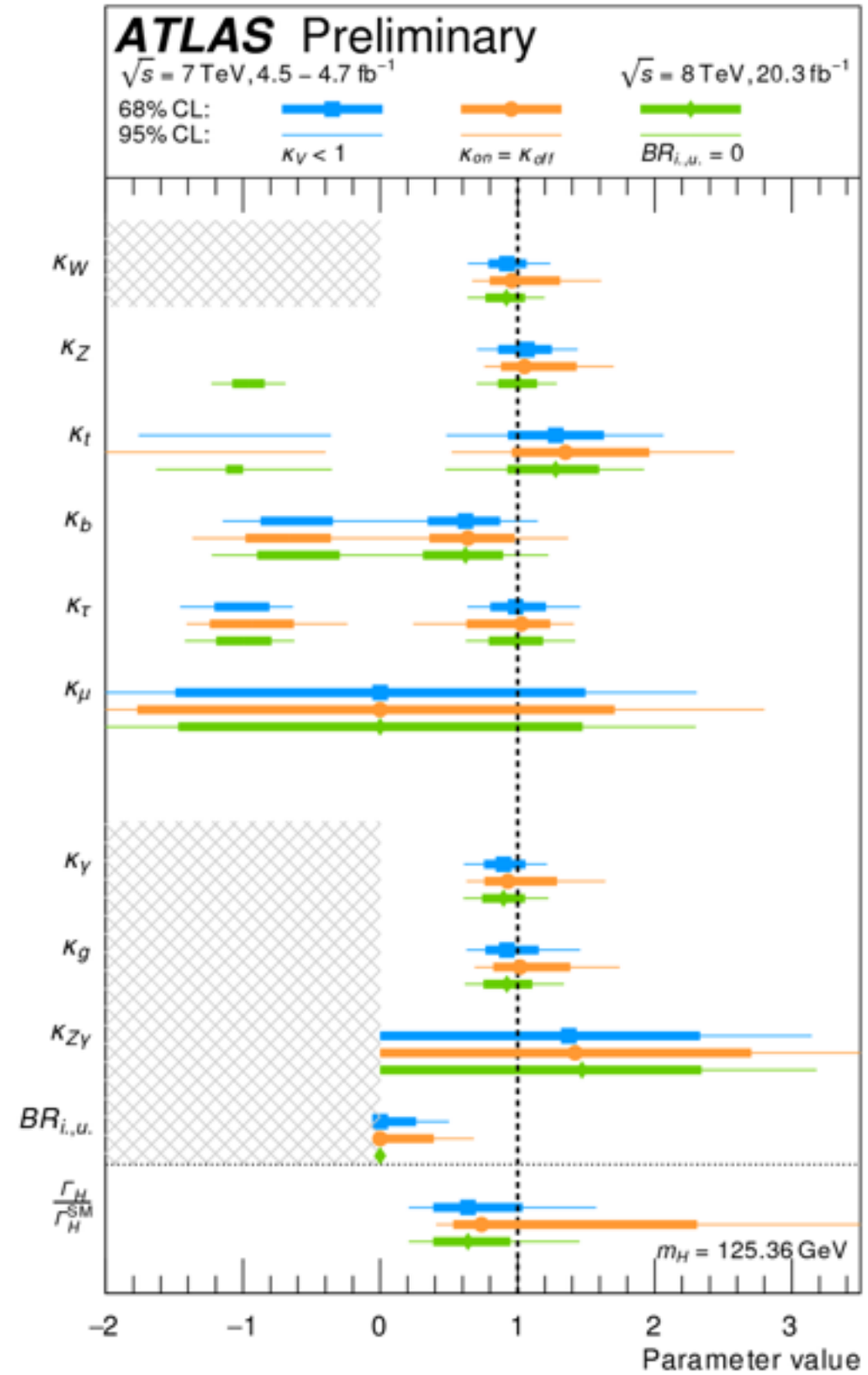
Status of Higgs studies at the LHC

➡ **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!

Higgs prospects for the HL-LHC

CMS Projection for precision of Higgs coupling measurement

Rare-decays

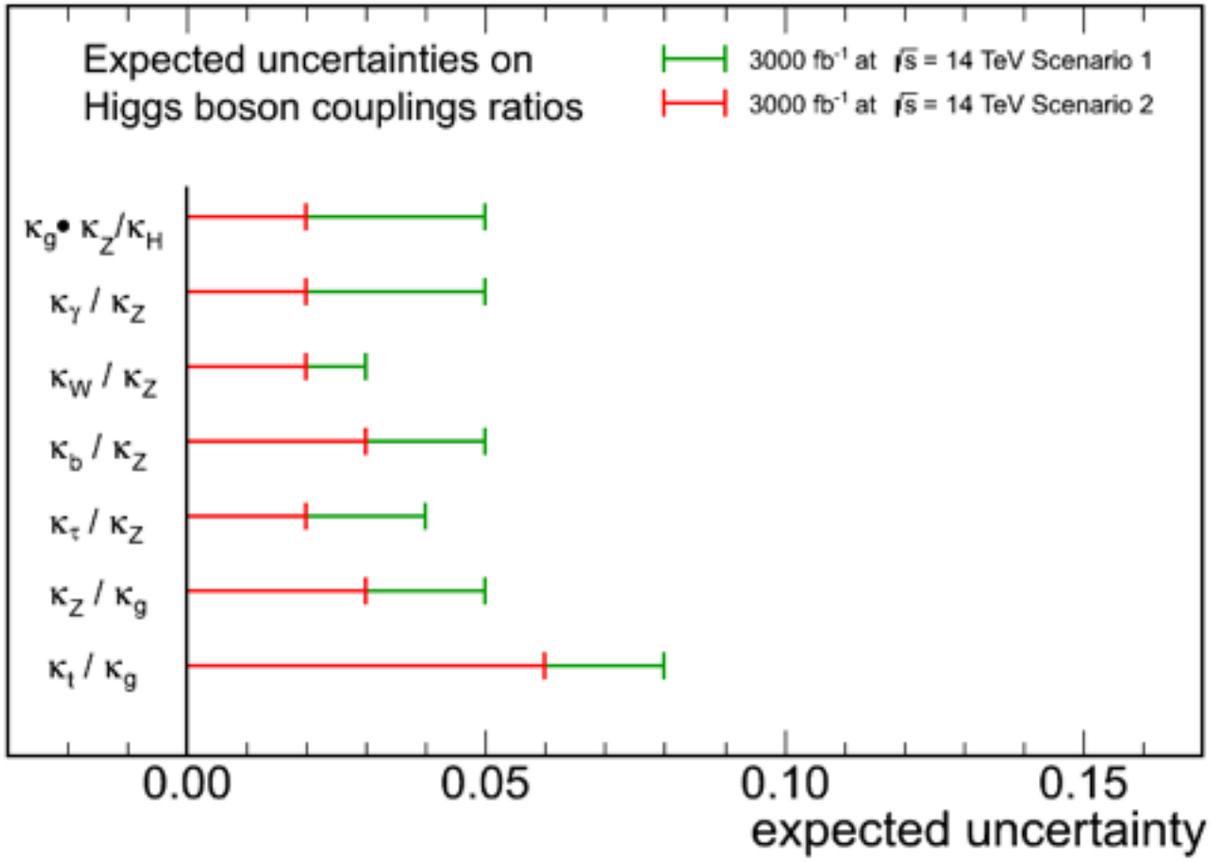
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

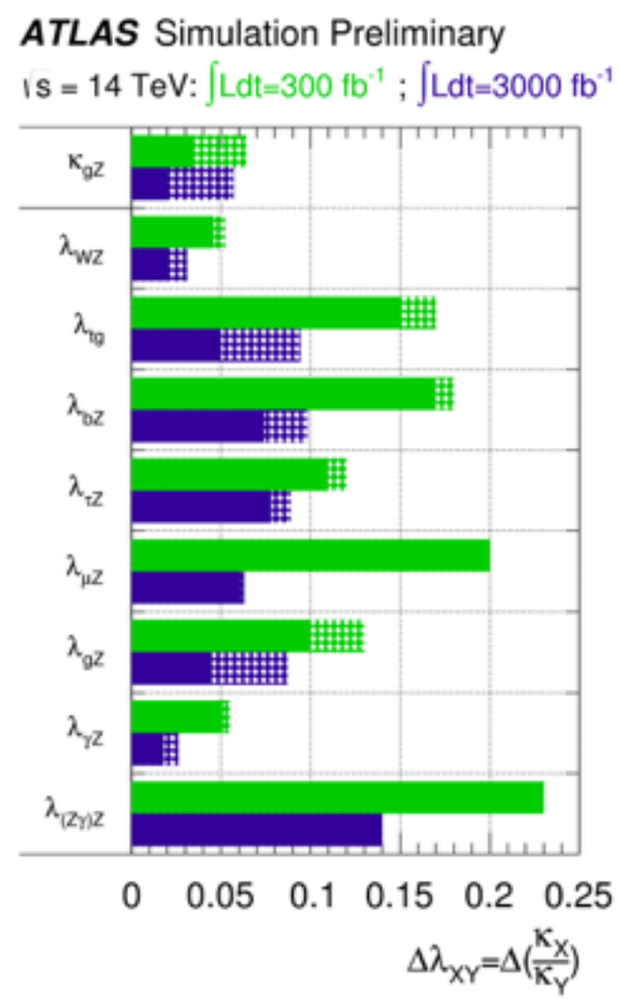
Coupling precision 2-10 %
factor 2-3 improvement from HL-LHC

Key question is the
evolution systematic uncertainty

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

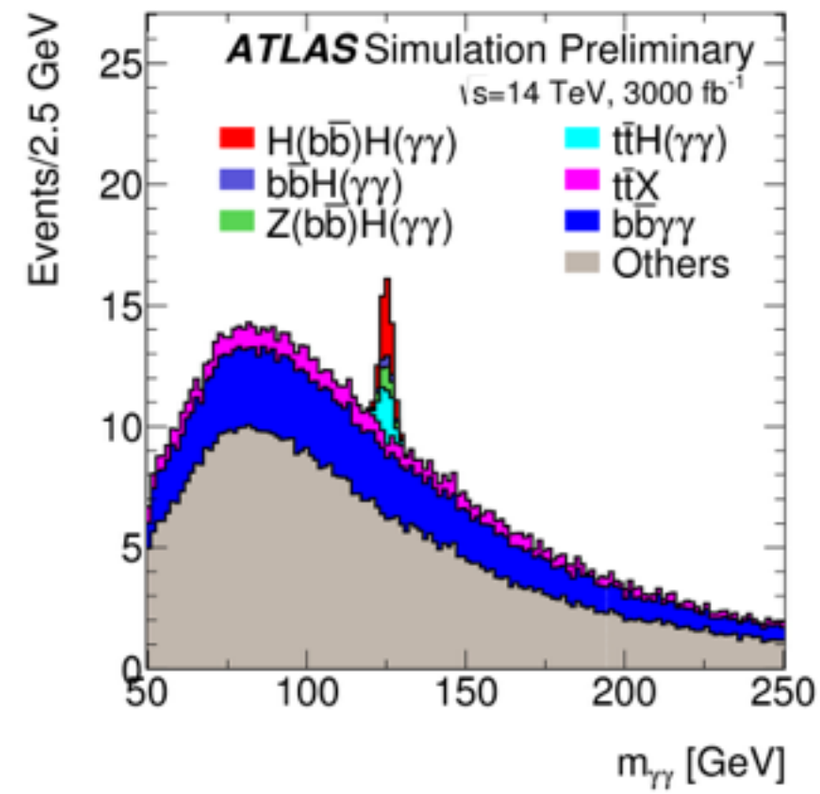
CMS Projection

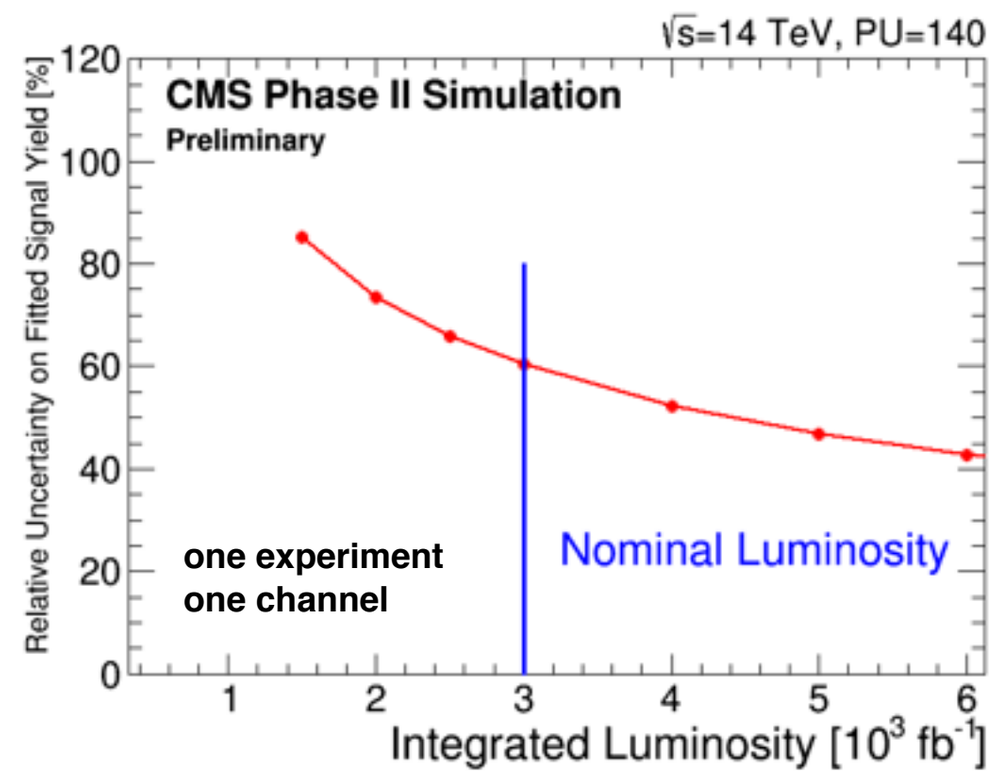




Higgs prospects for the HL-LHC

- **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

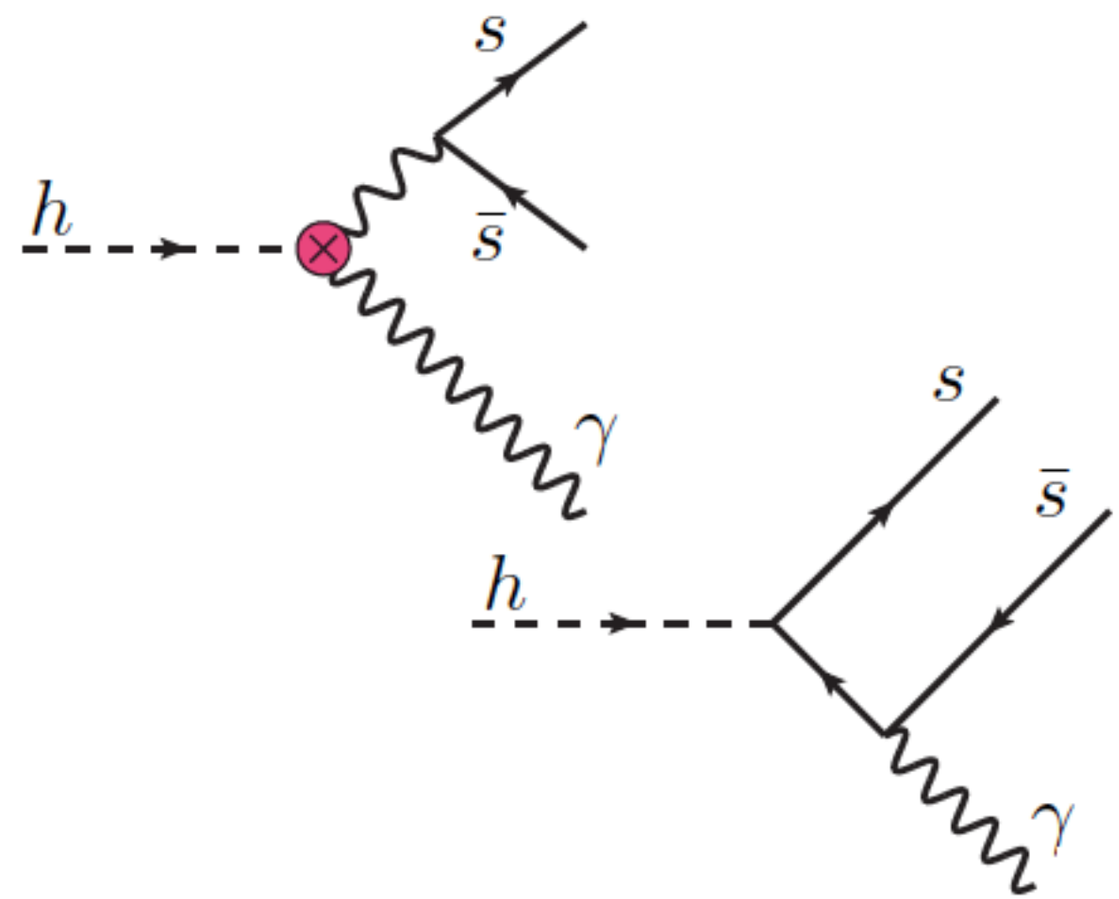
CMS - central photon yield

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

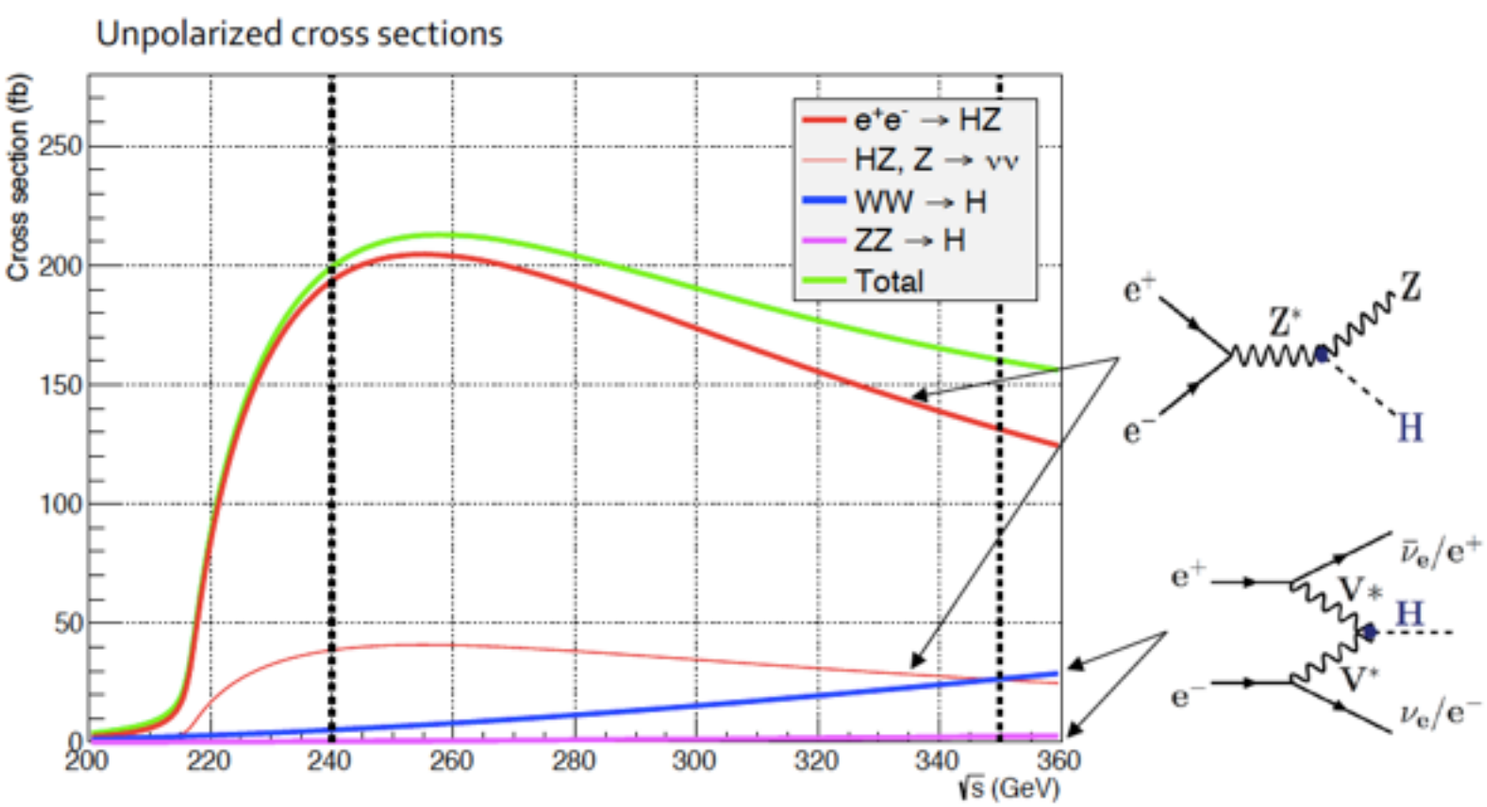
H → **ϕ** γ → y_s

H → **ρ** γ
H → ω γ → y_u, y_d

Higgs 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
- ➡ ...

	FCC-ee
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**



	FCC-ee
σ_{HZ}	**0.4%**
$\sigma_{HZ} \times BR(H \to b\bar{b})$	**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