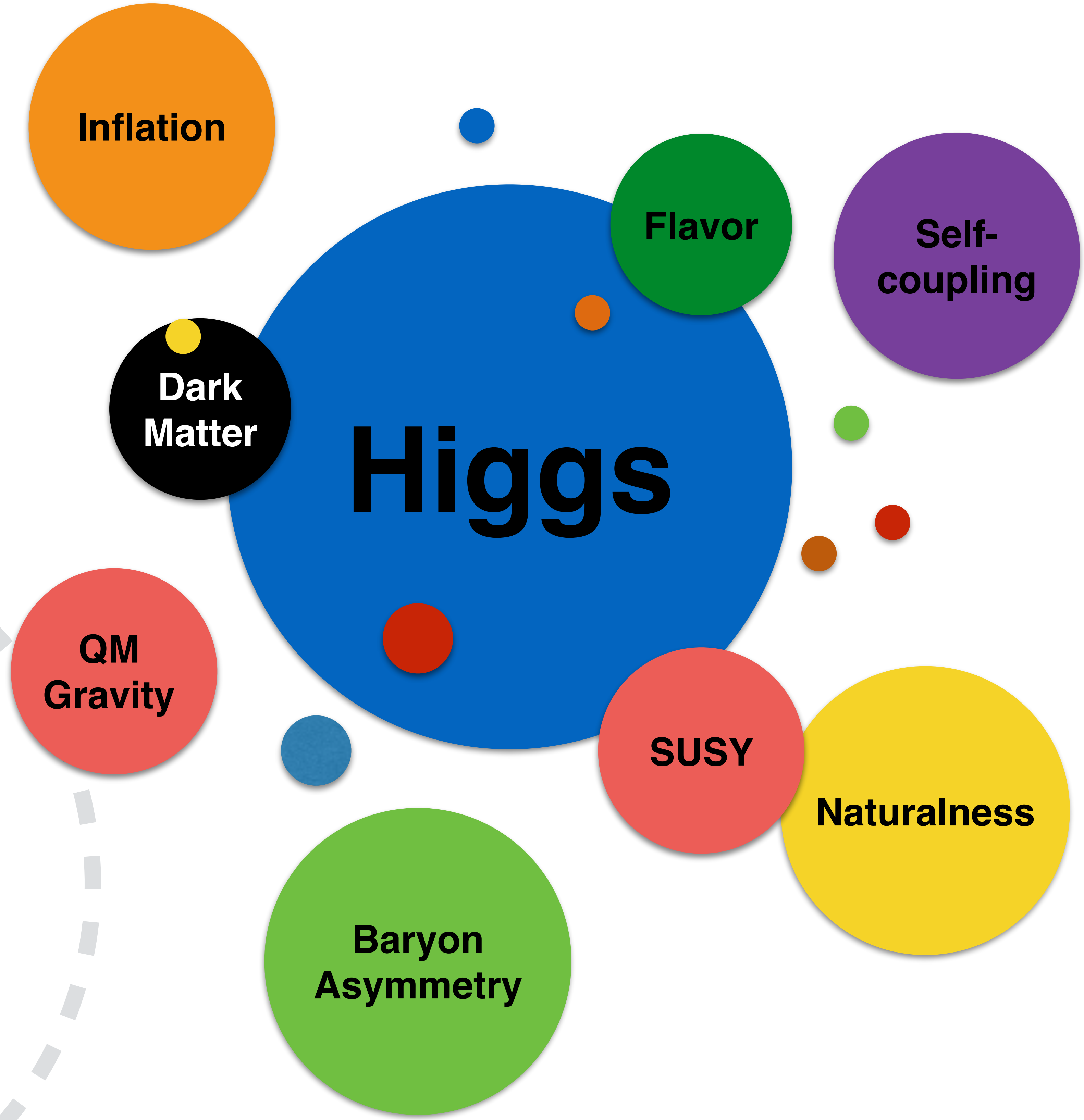


Summary of FCC-ee Higgs Results

Markus Klute
September 24th, 2015
First FCC-ee Workshop on Higgs Physics

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**

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Generic size of coupling modification
for new particles at M ~1 TeV

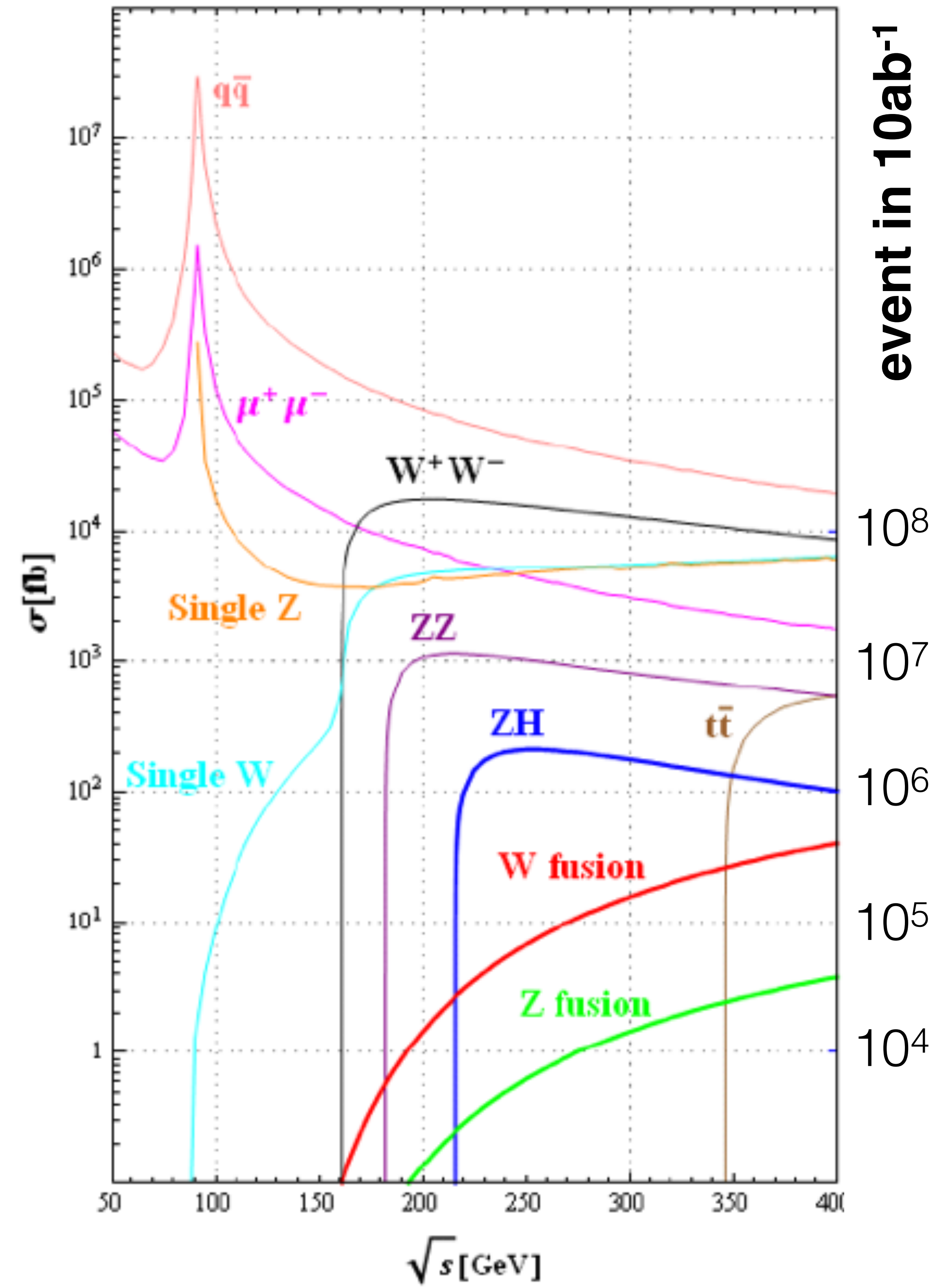
$\frac{\Gamma_{\rm 2HDM}[h^0 \to X]}{\Gamma_{\rm SM}[h \to X]}$	type I	type II	lepton-spec.	flipped
VV^*	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$
$\bar{u}u$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$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

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

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

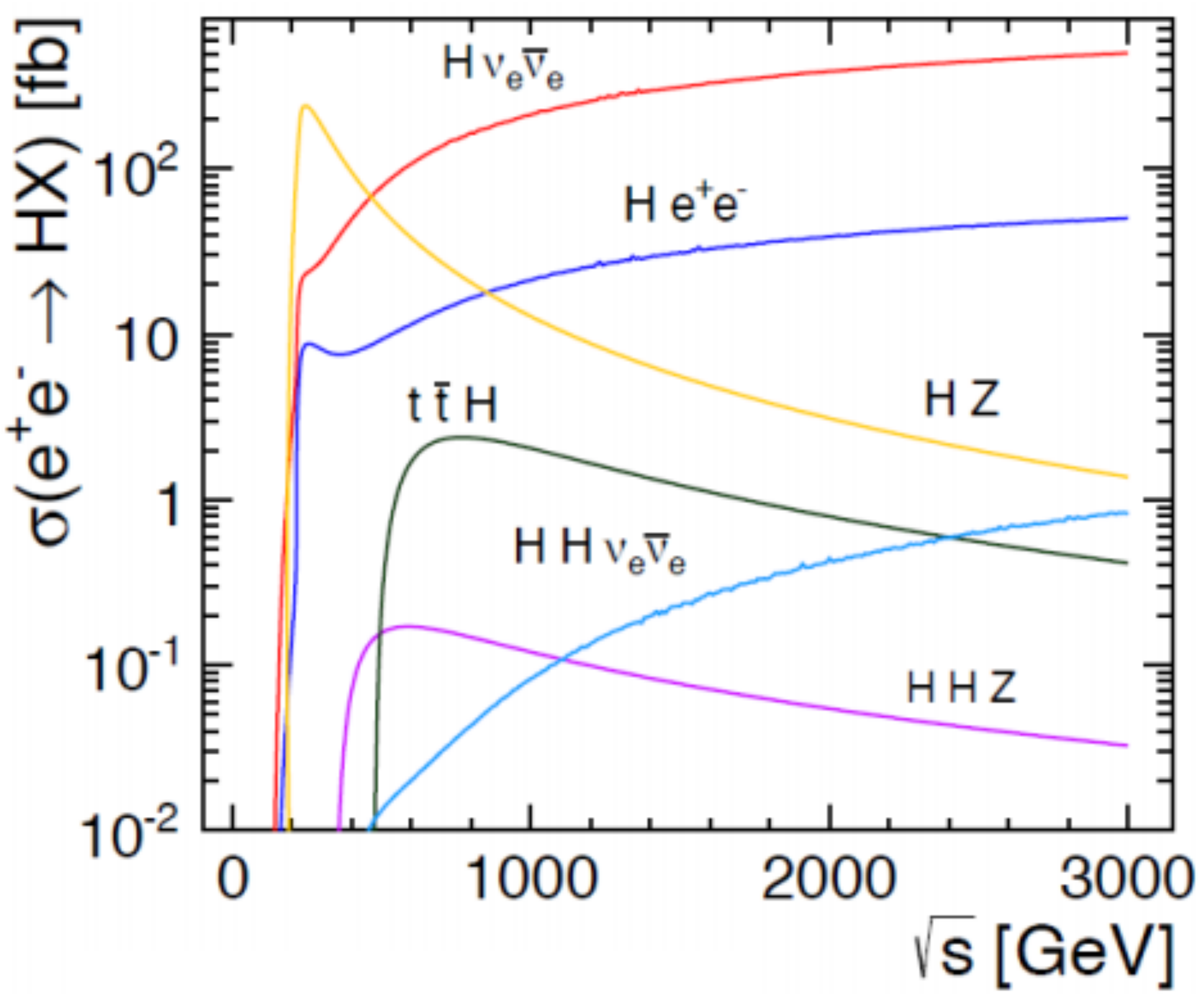
e^+e^- collider

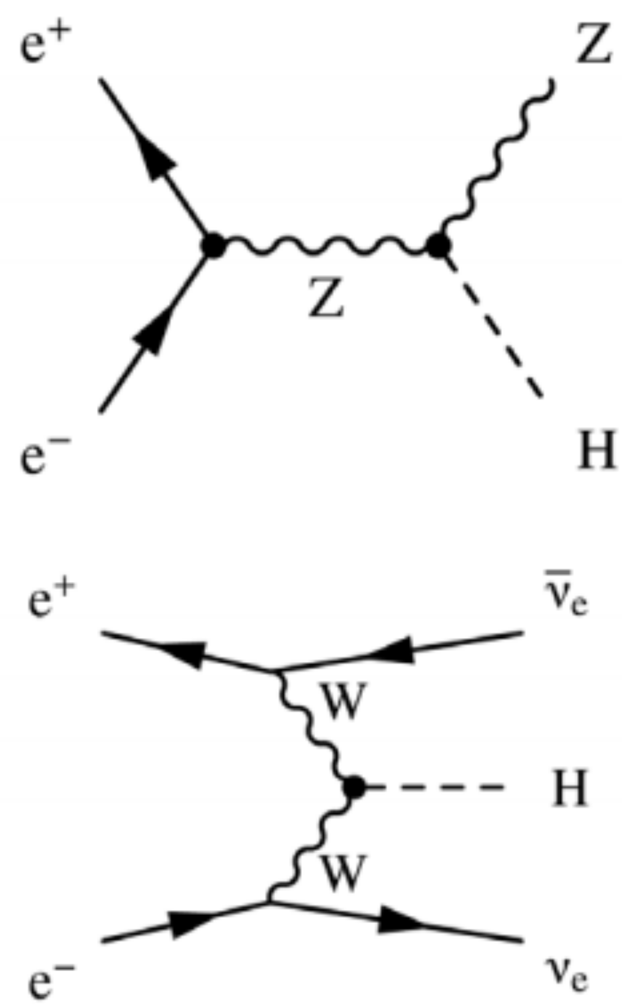
- ➡ **Electroweak production**
  - cross sections are predicted with (sub)percent precision
- ➡ **Relative low rate**
  - trigger on every event
- ➡ **Well defined collision rate**
  - missing mass reconstruction
- ➡ **Clean events, smaller backgrounds**
  - comparing to pp machine



Higgs Boson Production

- ➡ $e^+e^- \to ZH$ production maximal at 240-250 GeV





Higgs Boson Production

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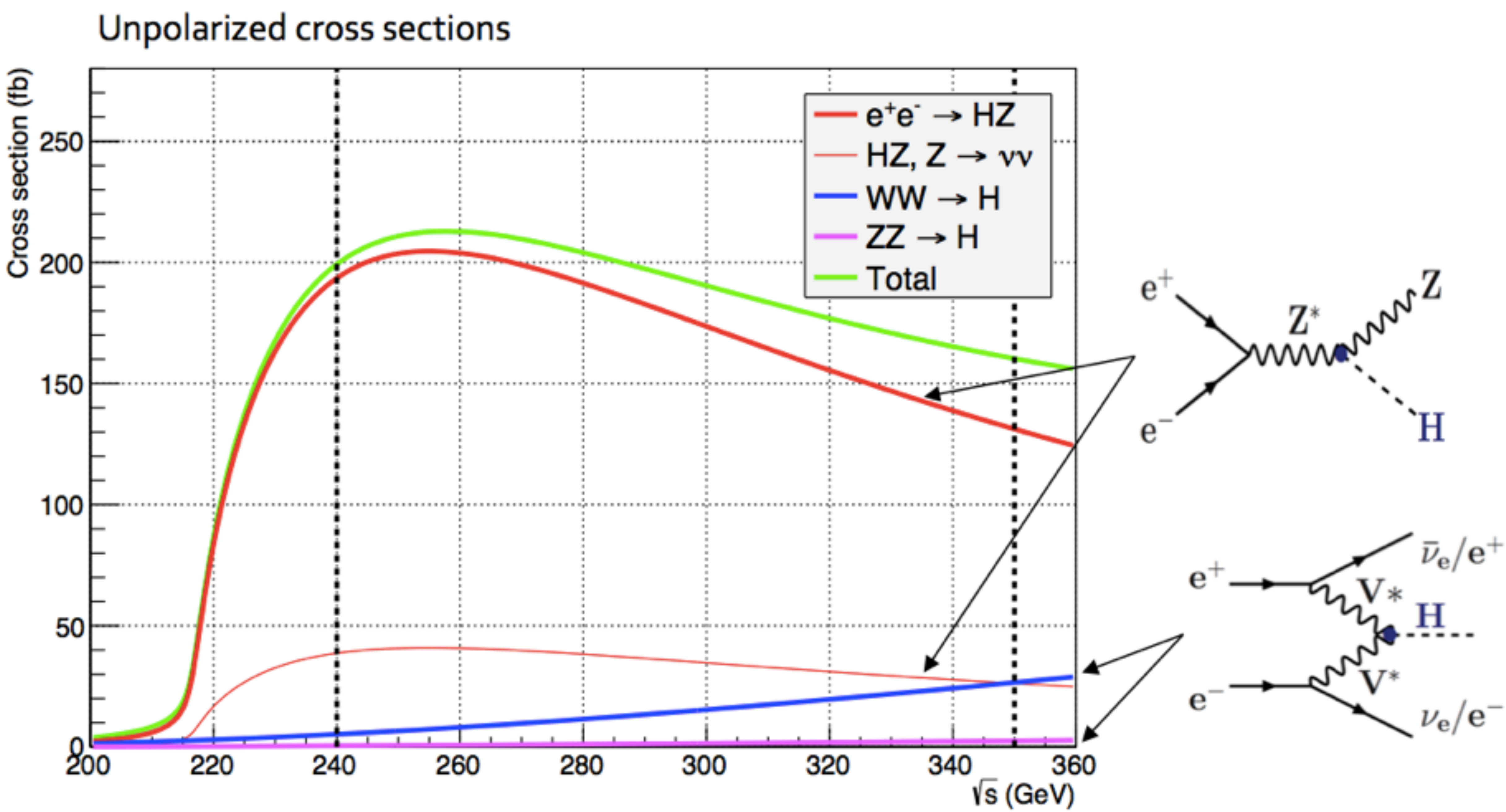
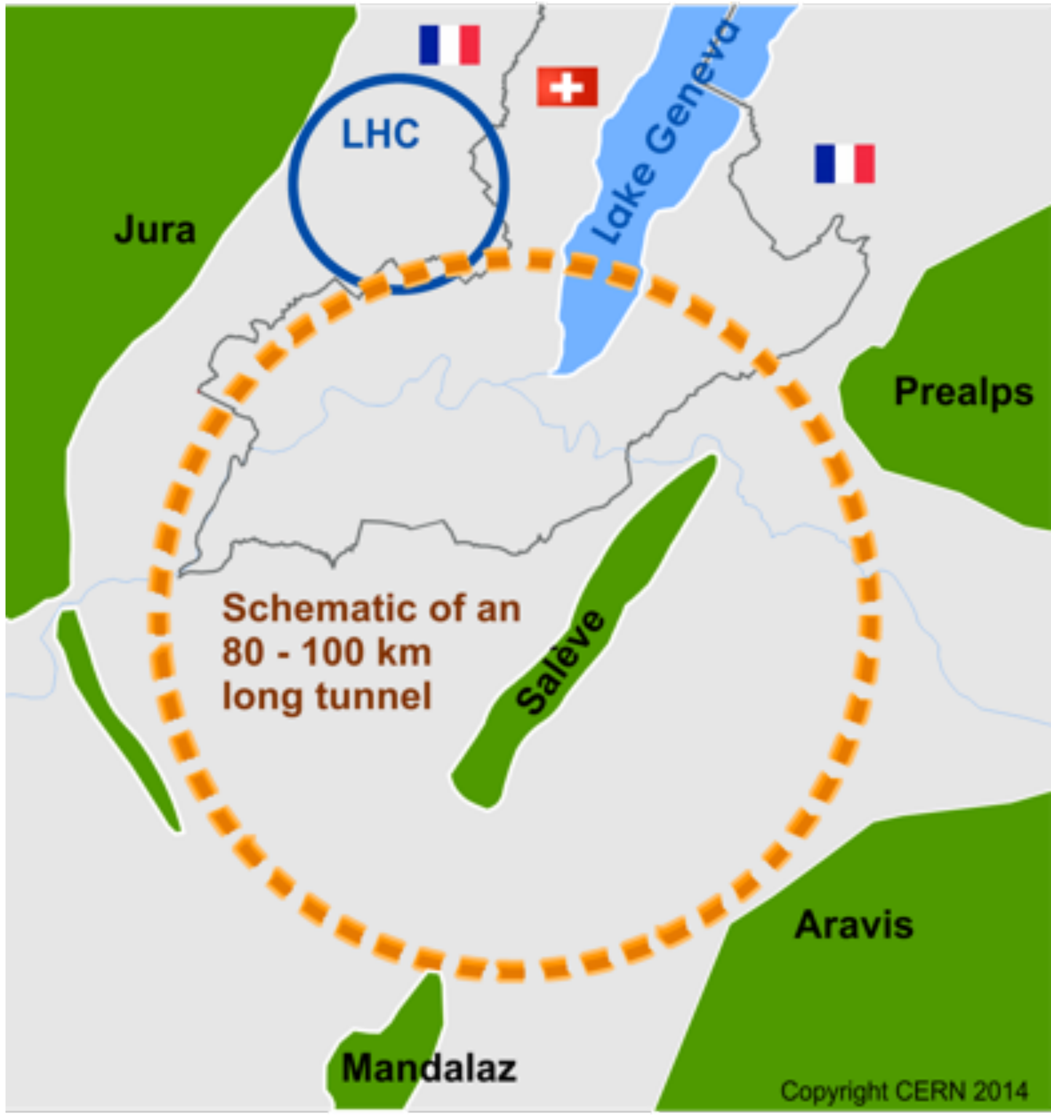


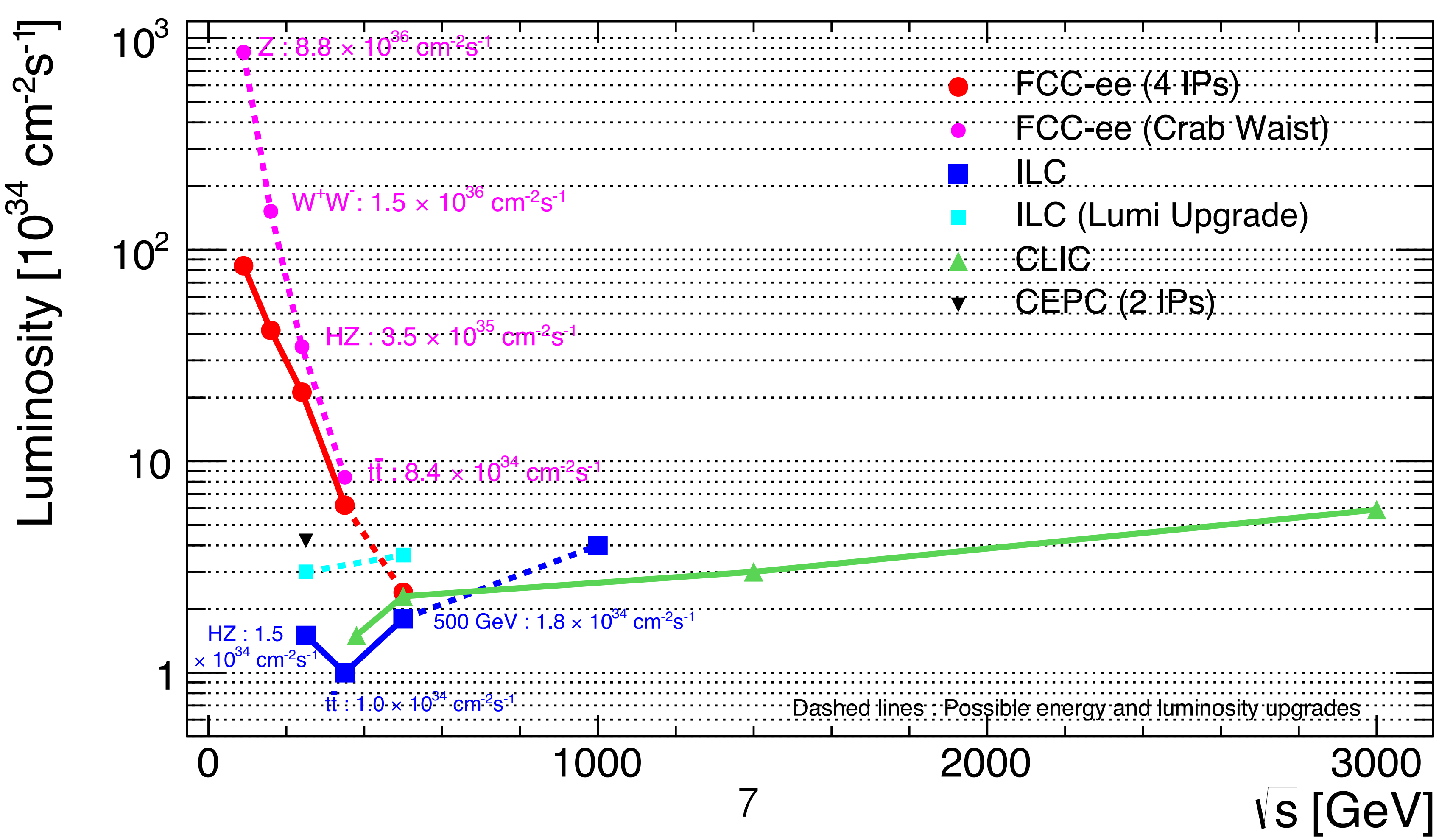
Future Circular Collider Study

- ➡ **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



TLEP / LEP3 Higgs studies

➡ **Work started well before the Higgs discovery**

➡ **Bibliography**

- Prospective Studies for LEP3 with the CMS detector http://arxiv.org/abs/1208.1662
- TLEP/FCC-ee: TLEP Case Study http://arxiv.org/abs/1308.6176 JHEP 01 (2014) 164

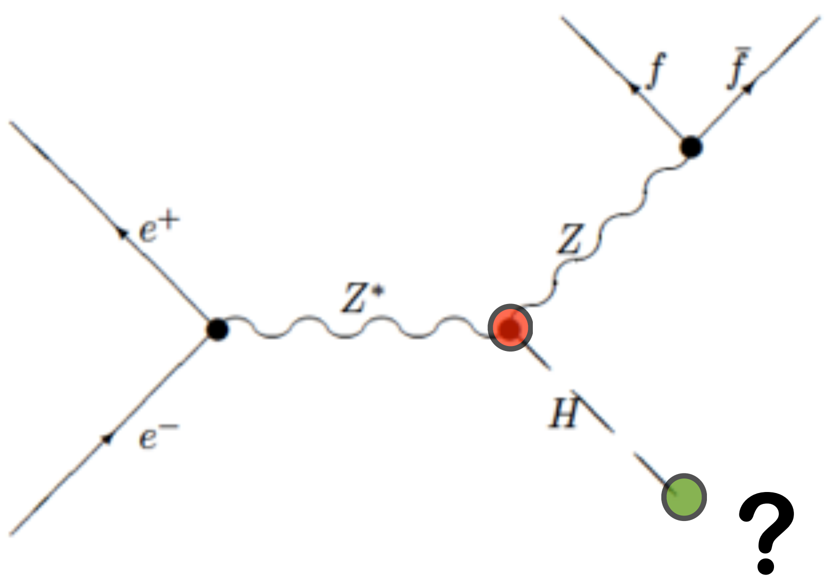
➡ **FullSim studies with CMS detector**

- supplemented some important performance parameter, e.g. c-tagging performance

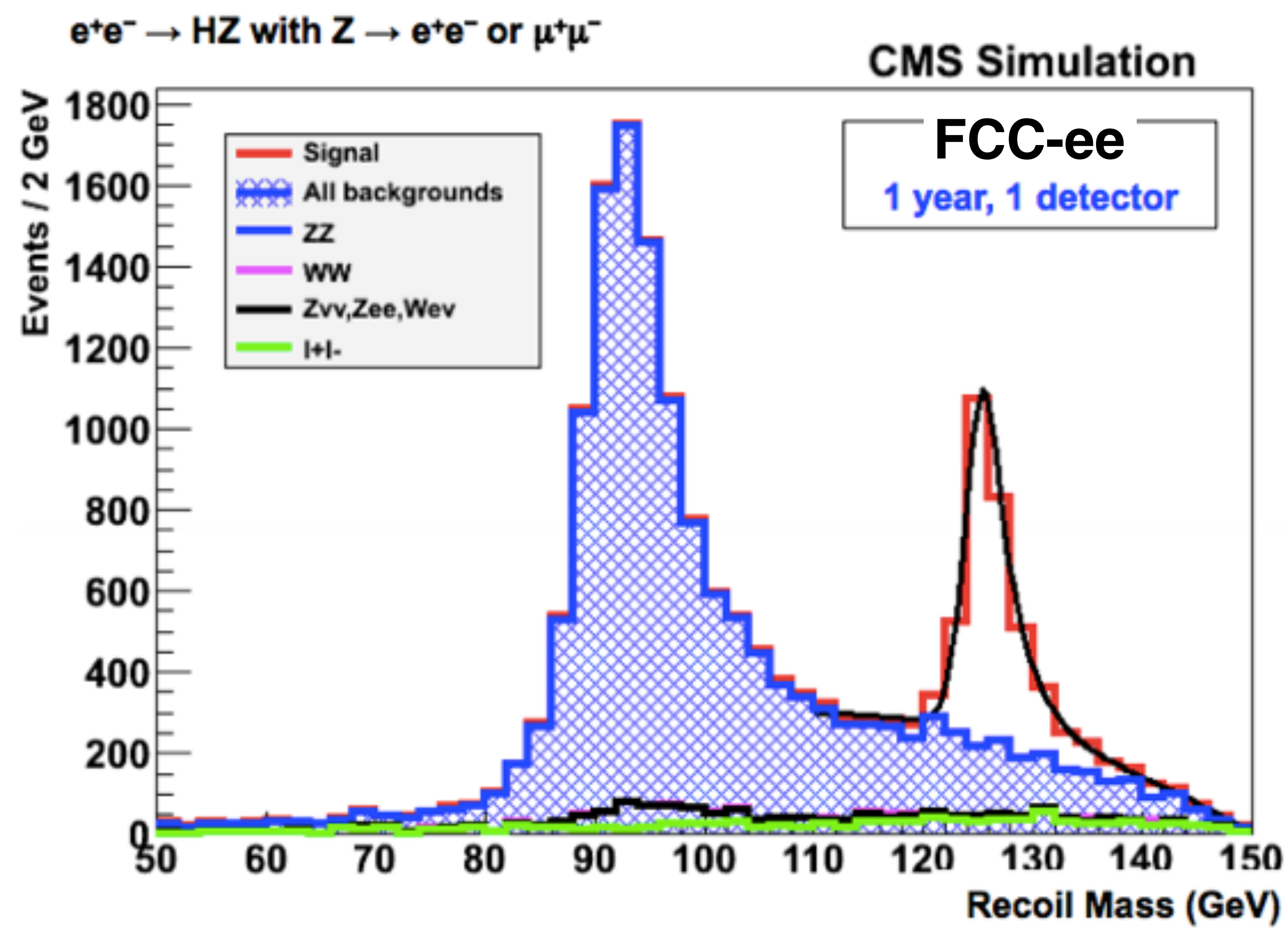
➡ **Some later discussion of FCC-ee performance derived with parametric simulations**

Precision Higgs Couplings

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

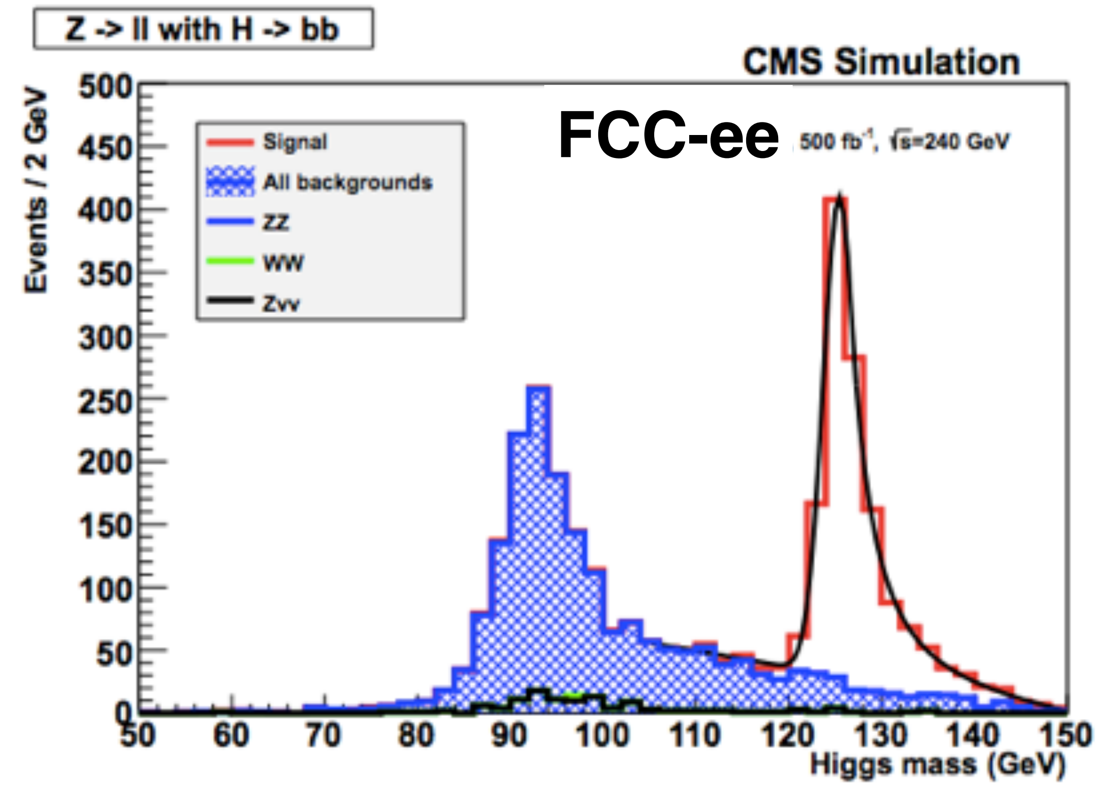


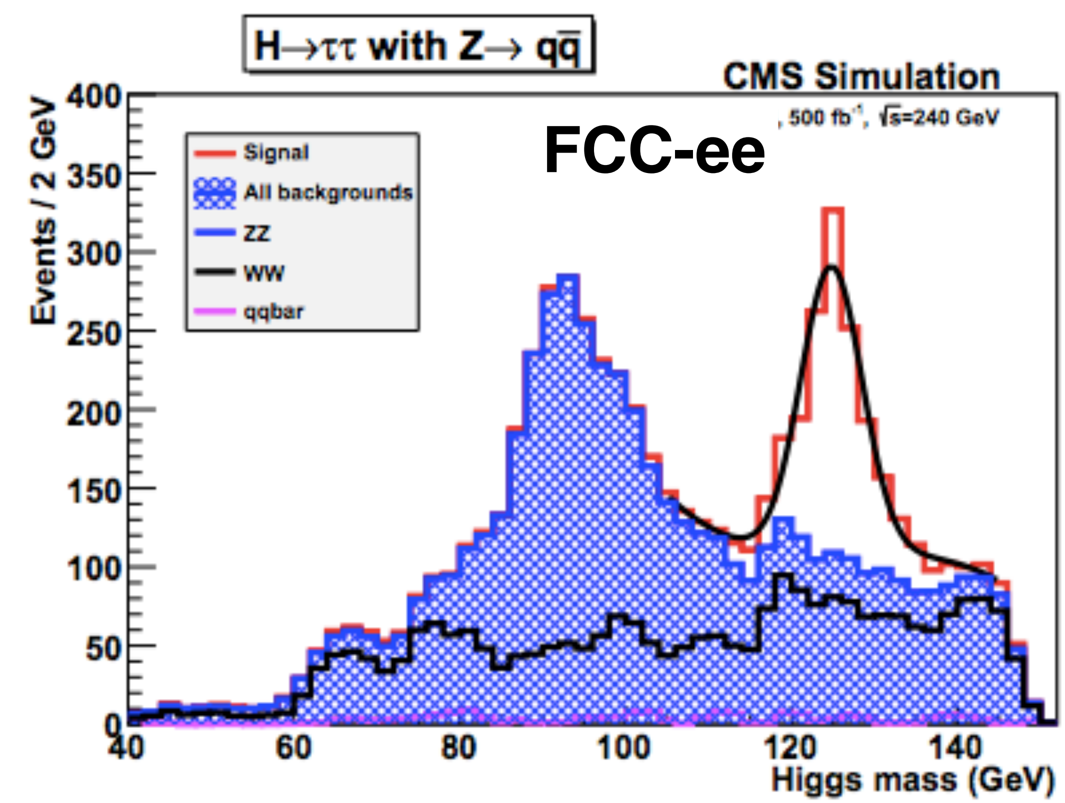
$$m_{\rm recoil}^2 = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$



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
- ➡ Δm_H = 11 MeV



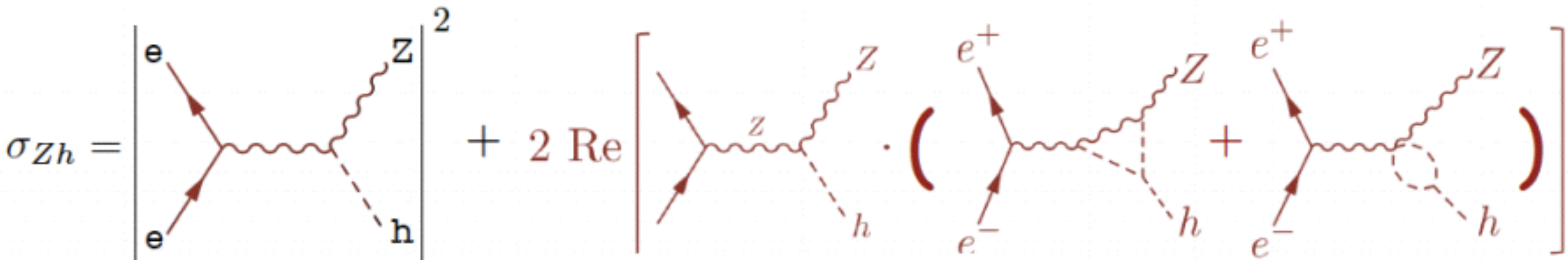


Precision Coupling Measurements

	Model-independent fit				Constrained fit		
Coupling	FCC-ee (240)	FCC-ee		ILC	FCC-ee		ILC
g_{HZZ}	0.16%	**0.15%**	(0.18%)	0.9%	0.05%	(0.06%)	0.31%
g_{HWW}	0.85%	**0.19%**	(0.23%)	0.5%	0.09%	(0.11%)	0.25%
g_{Hbb}	0.88%	**0.42%**	(0.52%)	2.4%	0.19%	(0.23%)	0.85%
g_{Hcc}	1.0%	**0.71%**	(0.87%)	3.8%	0.68%	(0.84%)	3.5%
g_{Hgg}	1.1%	**0.80%**	(0.98%)	4.4%	0.79%	(0.97%)	4.4%
$g_{\mathrm{H}\tau\tau}$	0.94%	**0.54%**	(0.66%)	2.9%	0.49%	(0.60%)	2.6%
$g_{\mathrm{H}\mu\mu}$	6.4%	**6.2%**	(7.6%)	45%	6.2%	(7.6%)	45%
$g_{\mathrm{H}\gamma\gamma}$	1.7%	**1.5%**	(1.8%)	14.5%	1.4%	(1.7%)	14.5%
$\mathrm{BR}_{\mathrm{exo}}$	0.48%	**0.45%**	(0.55%)	2.9%	0.16%	(0.20%)	0.9%

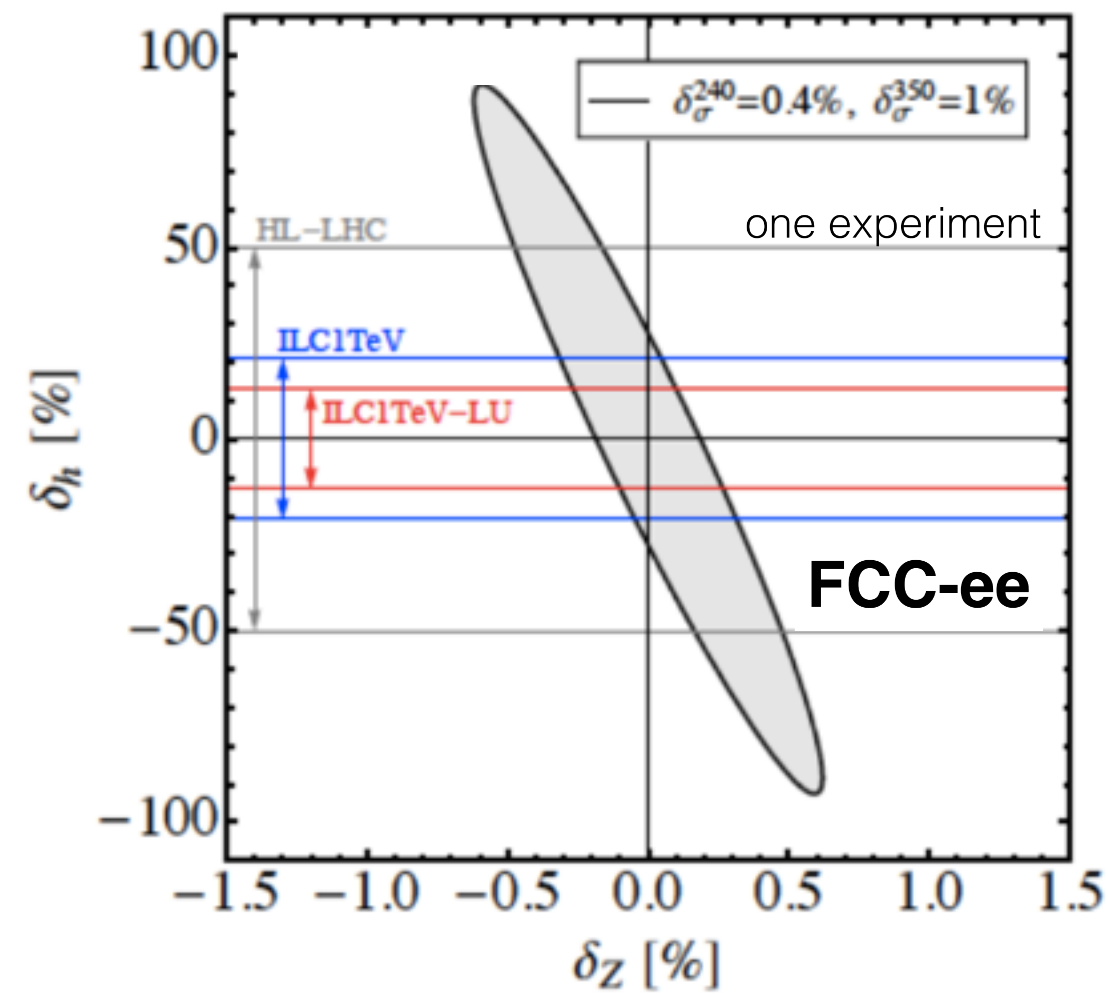
➡ **Detailed comparisons with other facilities in the following talks by Lorenzo, Heather, Tim, and Patrick**

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

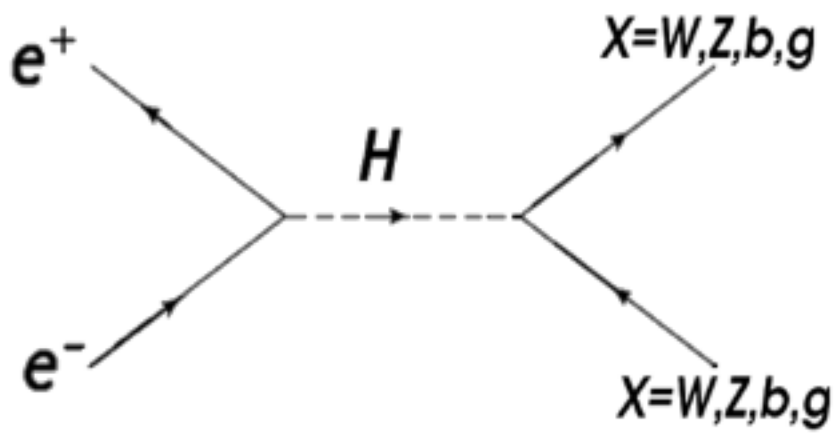


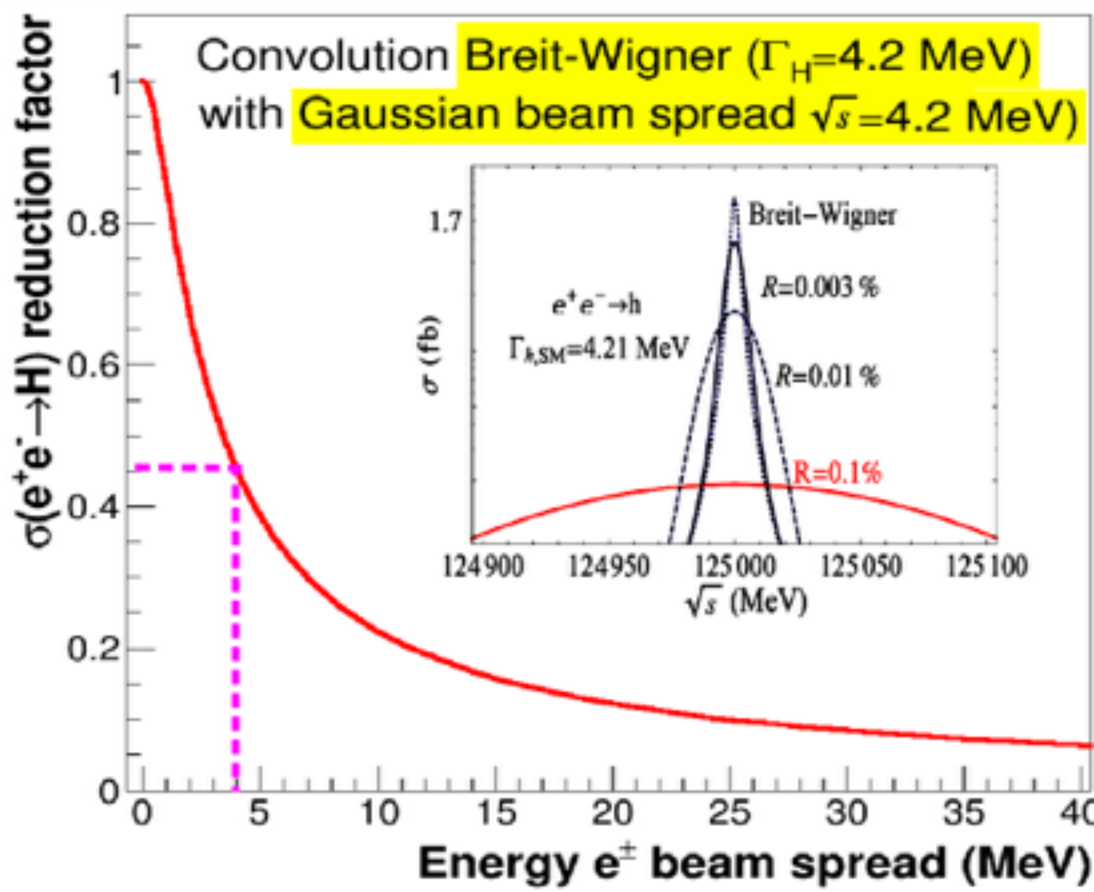
Matthew McCullough

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





Preliminary Results

L = 10 ab^{-1}

κ_e < 2.2 at 3σ

- **Update tomorrow by David**

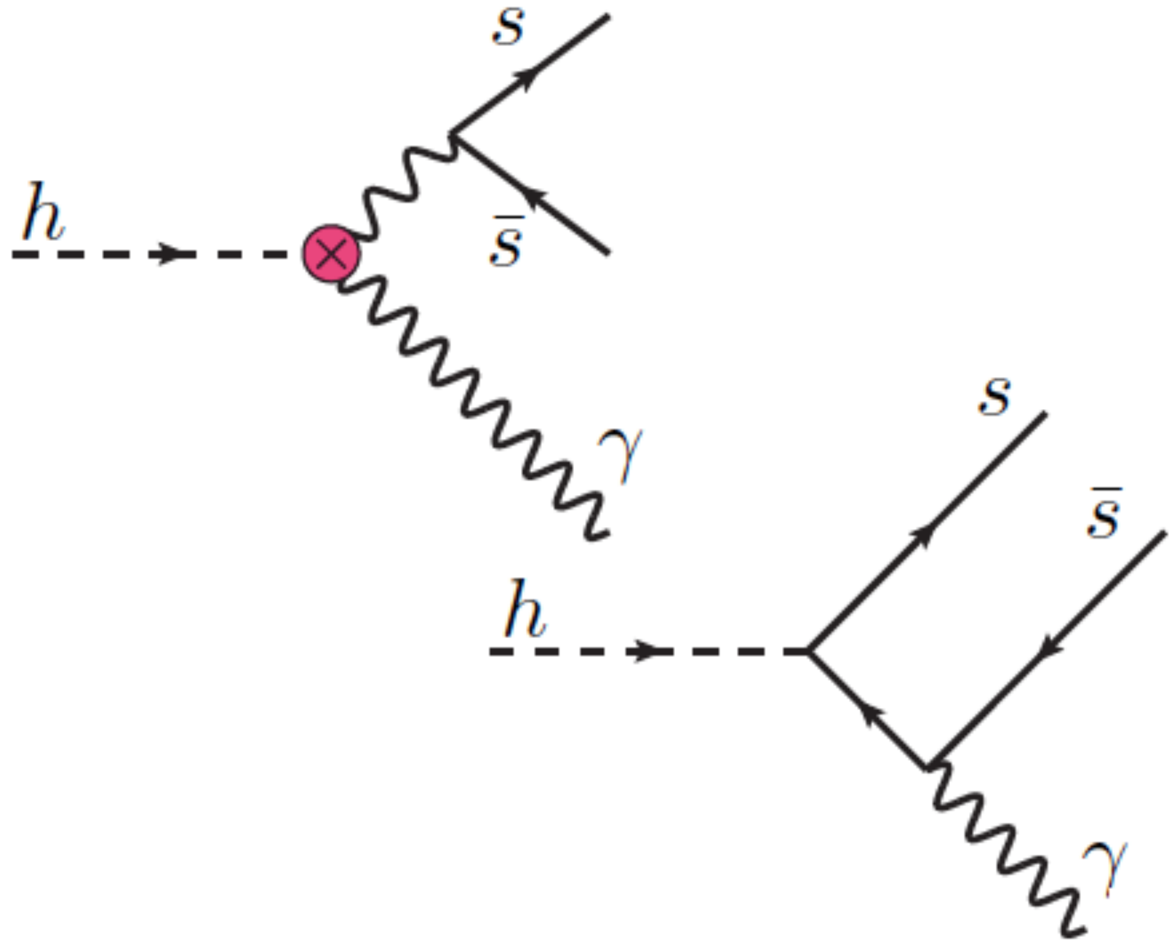
d'Enterria-Wojcik-Aleksan

Exclusive Higgs boson decays

- **First and second generation couplings accessible**
  - Sensitivity to u/d quark Yukawa coupling
  - Sensitivity due to interference

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2}\times10^{-5}$$

- Also interesting to FCC-hh program
- Alternative H→MV decays should be studied (V= γ, W, and Z)
- **Discussion by Rick tomorrow**



$H \to J/\Psi\,\gamma \Rightarrow y_c$

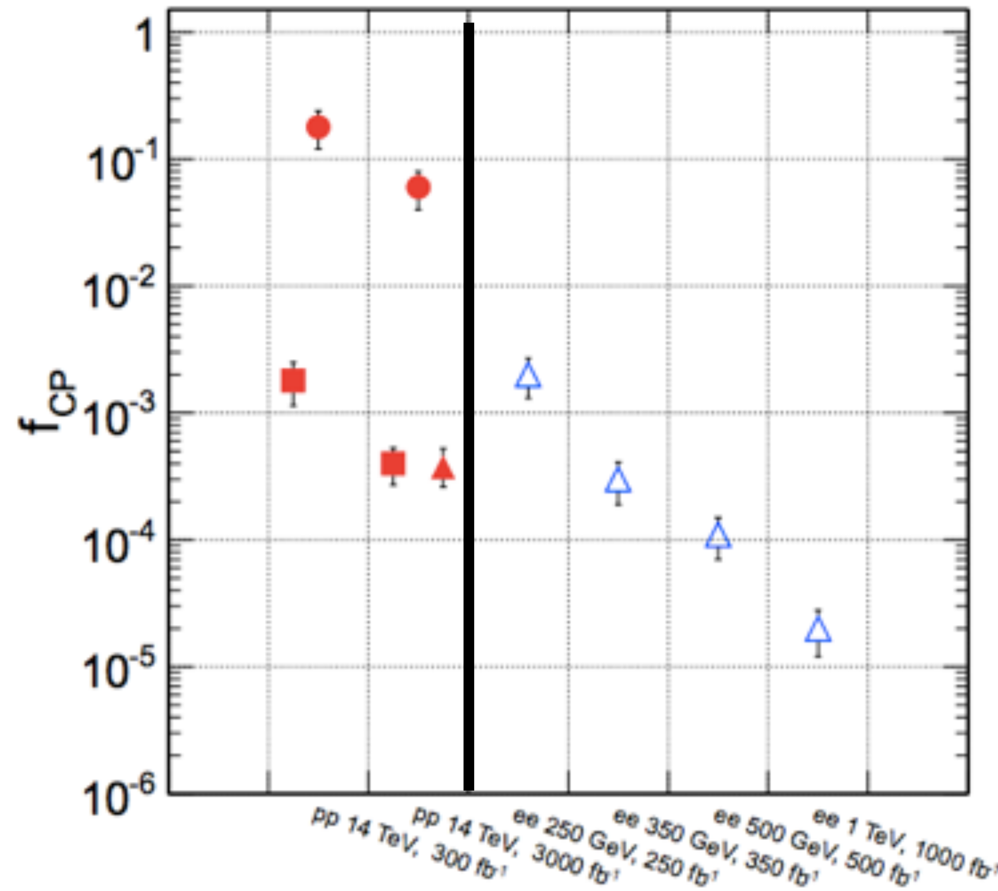
$H \to \phi\,\gamma \Rightarrow y_s$

$H \to \rho\,\gamma$, $H \to \omega\,\gamma \Rightarrow y_u, y_d$

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
- ➡Discussion by Aram tomorrow

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
- ➡ 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)
- ➡ **Presentation this afternoon by Jessie**

$h \to \not{E}_T$

$h \to 4b$

$h \to 2b2\tau$

$h \to 2b2\mu$

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

$h \to 4j$

$h \to 2\gamma2j$

$h \to 4\gamma$

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

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

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

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

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

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

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

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

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

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

Conclusion

- ➡ **FCC-ee offers fantastic opportunities to gain understanding of the Higgs boson and EWSB**
  - Sub-precent level Higgs coupling measurements
  - Access to first and second generation Higgs couplings
  - Precision mass measurement
  - Higgs CP studies
  - BSM and exotic Higgs
- ➡ **First look at FCC-ee physics case**
  - Focused on Higgs couplings
  - A lot of progress since
- ➡ **Substantial program of work ahead in FCC-ee Higgs study**
  - Novel ideas appeared in recent workshops
  - Many opportunities to contribute
  - Program needs to be extended and repeated in the FCC-ee context
  - Qualify detector requirements
  - **Goal:** CDR and cost review by 2018