THE HIGGS BOSON

at FCC-ee

Markus Klute (MIT)

2nd FCC Physics Workshop, Jan 16th, 2018

Case for Higgs precision

➡**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

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

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

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

➡**Testing multi-TeV scale with sub-percent level measurements**

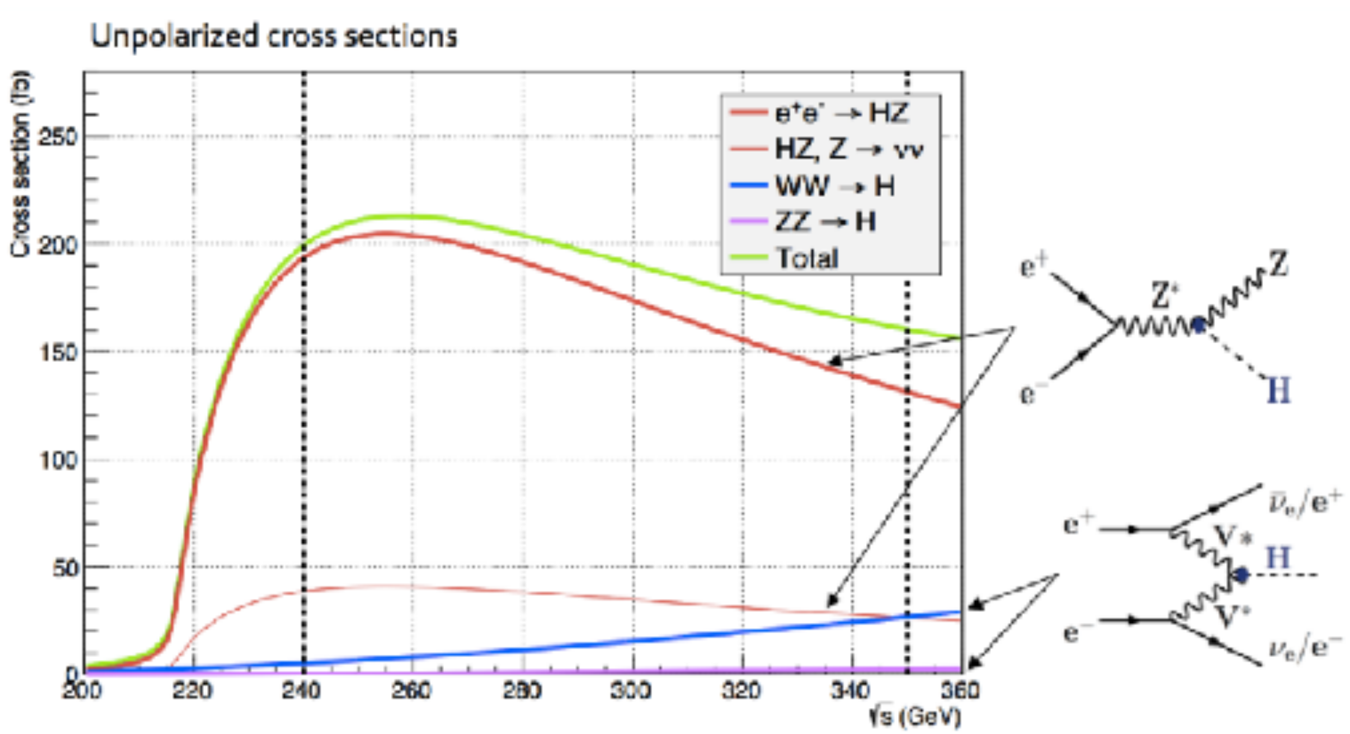
➡**There is no strict limit to the precision needed!**

arXiv:1310.8361

FCC-ee Higgs Program

➡ **Exploiting a very large Higgs boson sample, produced under clean experimental conditions, and collected with superb precision detectors**

working point	luminosity/IP $[10^{34}\ cm^{-2}s^{-1}]$	total luminosity (2 IPs)/ year	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	52 ab^{-1}/year		
W	30	7.8 ab^{-1}/year	10 ab^{-1}	~1
H	7.0	1.8 ab^{-1}/year	5 ab^{-1}	3
top	1.6	0.4 ab^{-1}/year	1.5 ab^{-1}	4



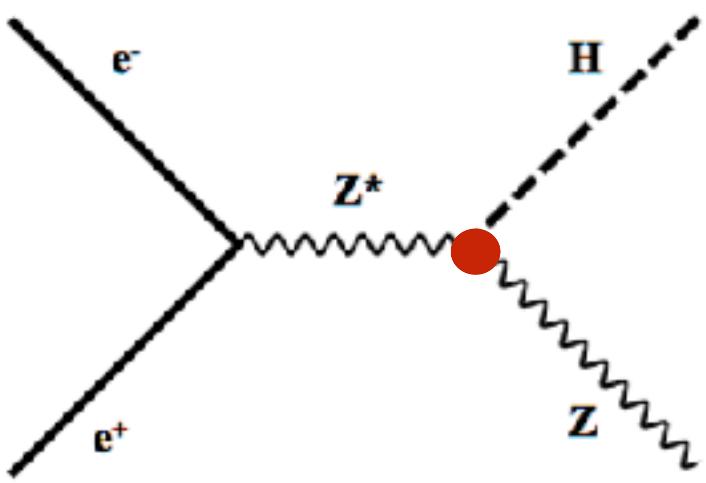
	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab-1)	**5**	**1.5**
Number of Higgs bosons from $e^+e^- \to HZ$	**1,000,000**	**200,000**
Number of Higgs bosons form fusion process	**25,000**	**40,000**

Higgs coupling to Z bosons

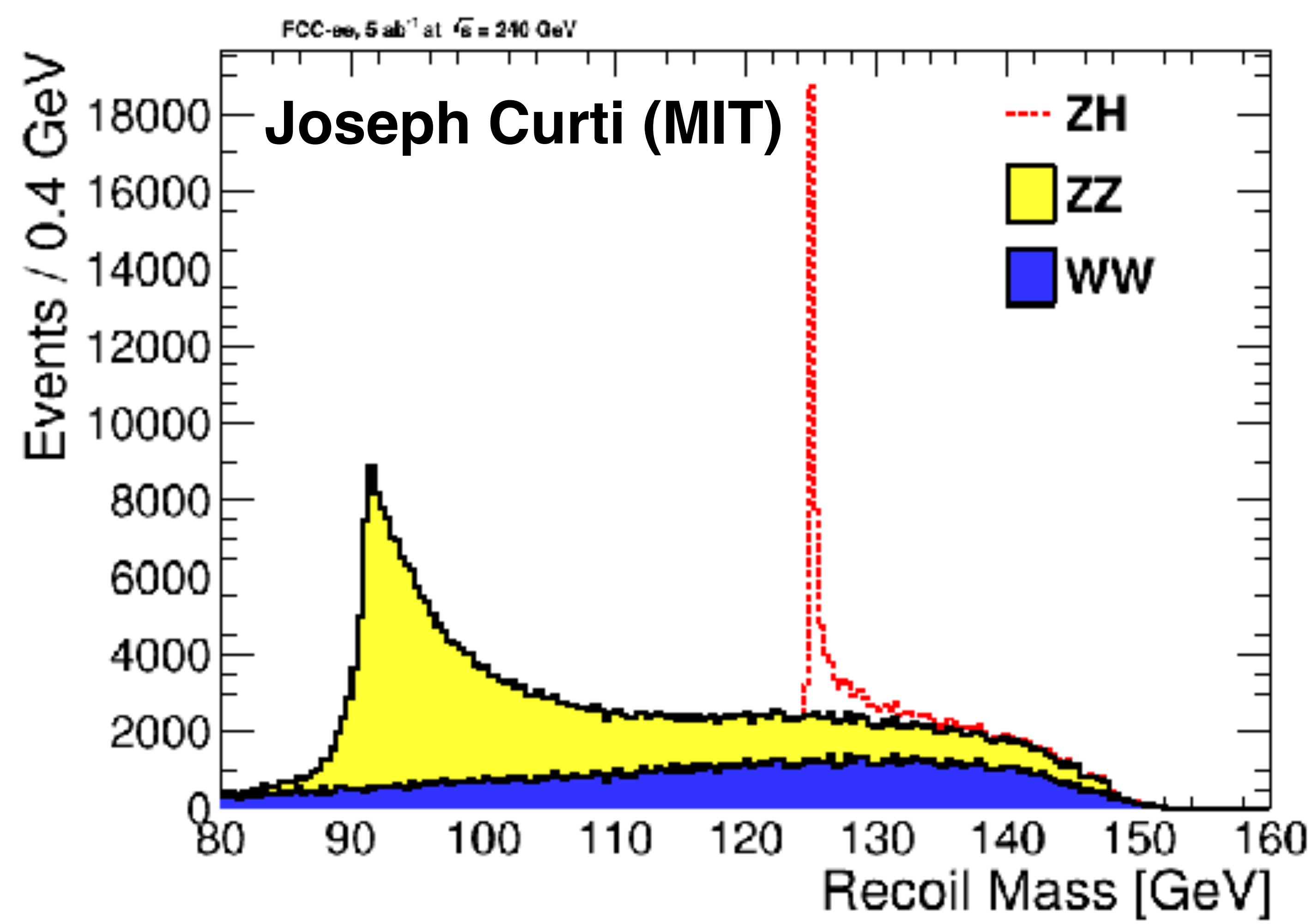
➡ **Recoil method provides unique opportunity for model independent measurement of HZ coupling**

- Higgs events are tagged Higgs decay mode independent
- expected precision **~0.5%** on ZH cross section
- using only leptonic Z decays and only measurement at 240 GeV so far

$$\boxed{\sigma(\mathrm{ee} \to \mathrm{ZH}) \propto \mathrm{g}^2_{\mathrm{HZ}}}$$



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



Total Higgs Boson Width

➡ **Total Higgs boson width can be extracted from a combination of measurements in a model independent way**

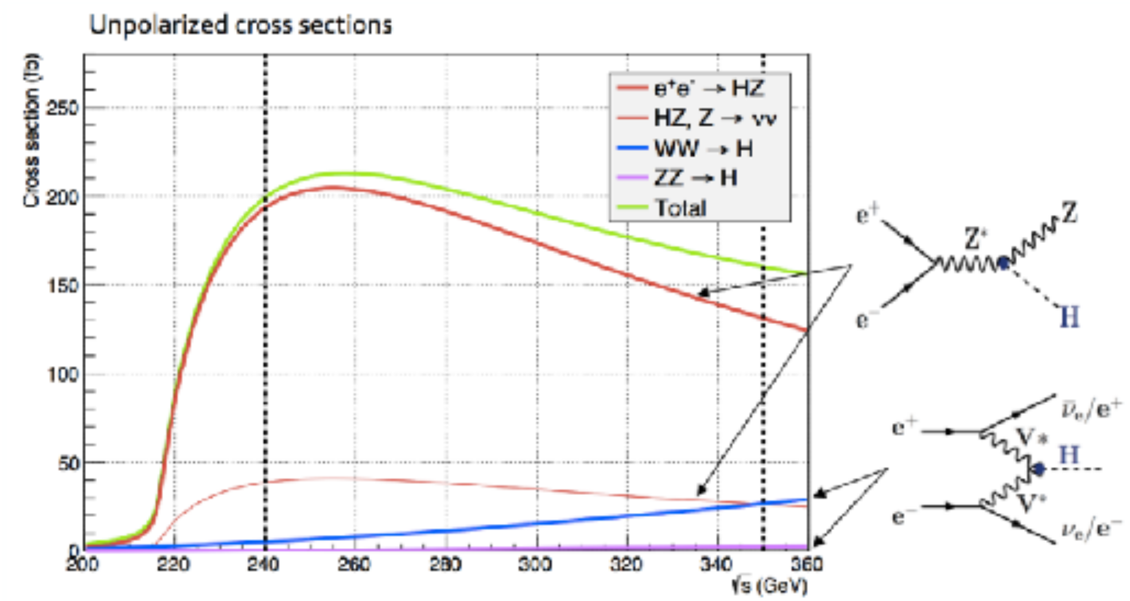
- **1) tagging Higgs final states**

$$\sigma(\mathrm{ee} \to \mathrm{ZH}) \cdot \mathrm{BR}(\mathrm{H} \to \mathrm{ZZ}) \propto \frac{\mathrm{g}_{\mathrm{HZ}}^4}{\Gamma}$$

- **2) measurements of vector boson fusion production at 350 GeV**

$$\frac{\sigma(\mathrm{ee}\to\mathrm{ZH})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{WW})\cdot\sigma(\mathrm{ee}\to\mathrm{ZH})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{bb})}{\sigma(\mathrm{ee}\to\nu\nu\mathrm{H})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{bb})}$$

$$\propto \frac{\mathrm{g}_{\mathrm{HZ}}^2\cdot\cancel{\mathrm{g}_{\mathrm{HW}}^2}}{\Gamma}\cdot\frac{\mathrm{g}_{\mathrm{HZ}}^2\cdot\cancel{\mathrm{g}_{\mathrm{Hb}}^2}}{\cancel{\Gamma}}\cdot\frac{\cancel{\Gamma}}{\cancel{\mathrm{g}_{\mathrm{HW}}^2}\cdot\cancel{\mathrm{g}_{\mathrm{Hb}}^2}} = \frac{\mathrm{g}_{\mathrm{HZ}}^4}{\Gamma}$$



- **3) combination of all measurements**

Higgs Boson Couplings

➡ **Precision Higgs coupling measurements**

- absolute coupling measurements enabled by HZ cross section and total width measurement
- tagging individual Higgs final states to extract various Higgs couplings
- data at 350 GeV constrain total width
  - only used H→bb in fusion production so far
- couplings extracted from model-independent fit
- statistical uncertainties are shown for 5ab^{-1}@240 GeV and 1.5ab^{-1}@350GeV (from arXiv: 1308.6176)
  - all measurements are under review / are being redone
  - most result used CMS detector performance and will be improved
- optimization of relative size of datasets (240 GeV and 350 GeV) to be done

in %	FCC-ee 240 GeV	+FCC-ee 350 GeV
g_{HZ}	0.21	0.21
g_{HW}	1.25	0.43
g_{Hb}	1.25	0.64
g_{Hc}	1.49	1.04
g_{Hg}	1.59	1.18
$g_{H\tau}$	1.34	0.81
$g_{H\mu}$	8.85	8.79
$g_{H\gamma}$	2.37	2.12
Γ_H	2.61	1.55

Higgs Boson Couplings

➡ **Comparison with (HL-LHC)**

- model dependent fit shown for HL-LHC results
- results shown for one LHC experiment

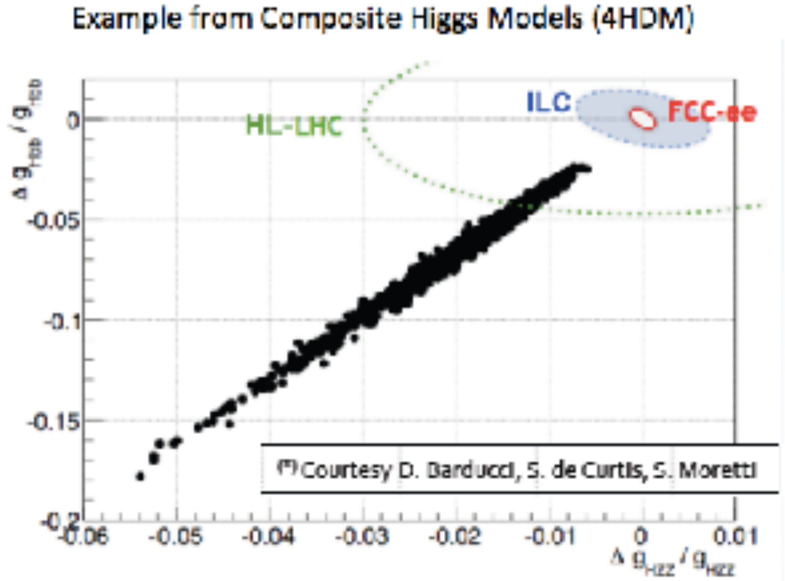
➡ **Factor ~10 improvement for most couplings**

- FCC-ee measurements turn hadron collider Higgs measurements into absolute coupling measurements **(synergy)**
- rare decays favored by hadron collider searches **(complementarity)**

➡ **Testing new physics at multi-TeV scale**

- start probing quantum structure

Example from Composite Higgs Models (4HDM)



in %	HL-LHC	FCC-ee
g_{HZ}	2-4	0.21
g_{HW}	2-5	0.43
g_{Hb}	5-7	0.64
g_{Hc}	-	1.04
g_{Hg}	3-5	1.18
$g_{H\tau}$	5-8	0.81
$g_{H\mu}$	5	8.79
$g_{H\gamma}$	2-5	2.12
Γ_H	5-8%	1.55

arXiv:1307.7135 arXiv:1308.6176

Theoretical Precision

- ➡ **Experimental precision must be accompanied by theoretical precision program**
  - ideally we want: $\Delta_{th} << \Delta_{exp}$
  - current theoretical precision O(1%)
- ➡ **Higgs observable**
  - inputs like α_s and m_H will be measured well by FCC-ee
  - good control over m_b essential, i.e. improvements for lattice QCD.
  - significant work needed on Higgs production in e^+e^- (tools are available)

Study of SM Higgs partial width and BR - Table of inputs - arXiv:1311.6721

m_H	125.7(4)	pole mass m_t	173.5(10)
pole mass m_c	1.67(7)	pole mass m_b	4.78(6)
pole mass M_Z	91.1535(21)	G_F	$1.1663787(6) \times 10^{-5}$
pole mass m_τ	1.77682(16)	$\alpha_S(M_Z)$	0.1184(7)
$\alpha(M_Z)$	1/128.96(2)	$\Delta\alpha^{(5)}_{had}$	0.0275(1)

Current impact from parametric uncertainty (α_s, m_c, and m_b) on Higgs couplings - arXiv:1404.0319. Authors argue that significant progress (factor 7) is possible.

$$\delta_b = 0.7\% \ , \quad \delta_c = 0.7\% \ , \quad \delta_g = 0.6\%$$

Higgs CP Studies

➡ $H \rightarrow \tau\tau$ decay is promising channel to study CP violation

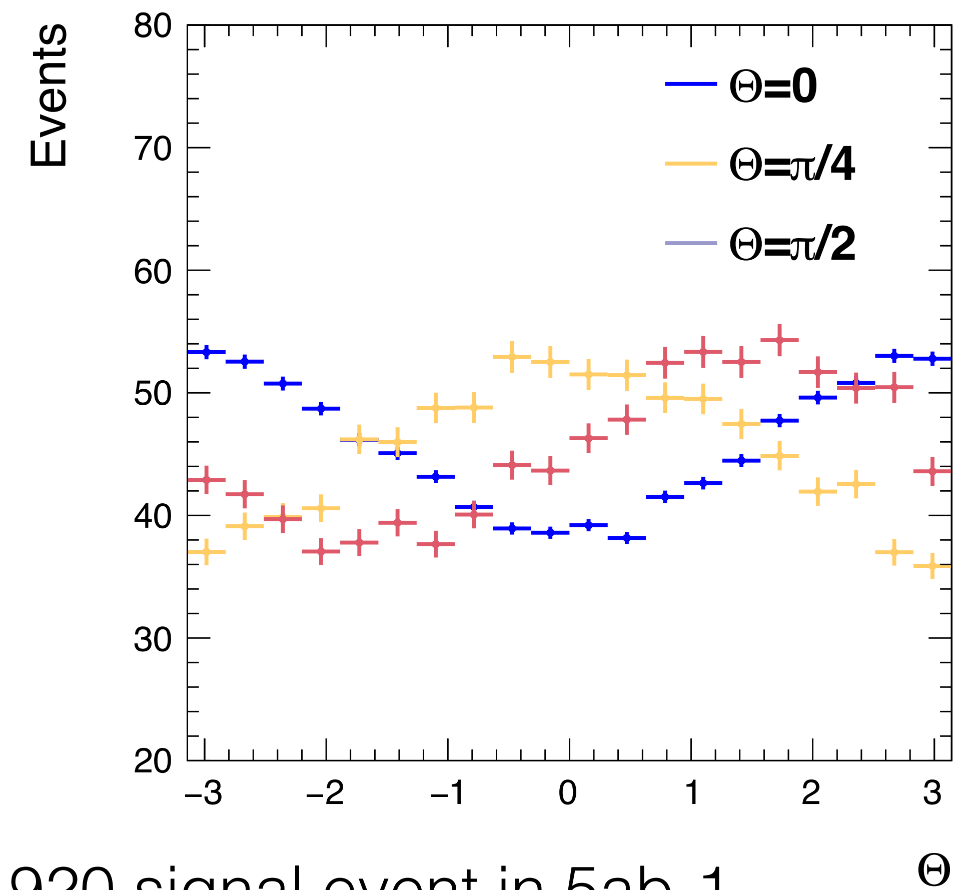
- tree level couplings to quarks and leptons
- CP-even and CP-odd couplings induced at the same order

➡ CP violation can be probed through τ polarization

- τ decays clean enough that the spin information is not washed out by hadronization effects
- pion emission preferred in the direction of the τ spin in rest frame $\tau^{\pm} \rightarrow \rho^{\pm}\nu_{\tau} \rightarrow \pi^{\pm}\pi^{0}\nu_{\tau}$
- exploring $\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5 \sin\Delta)f$
- model using effective lagrangian

Andres Rios (MIT), Aram Apyan (FNAL)

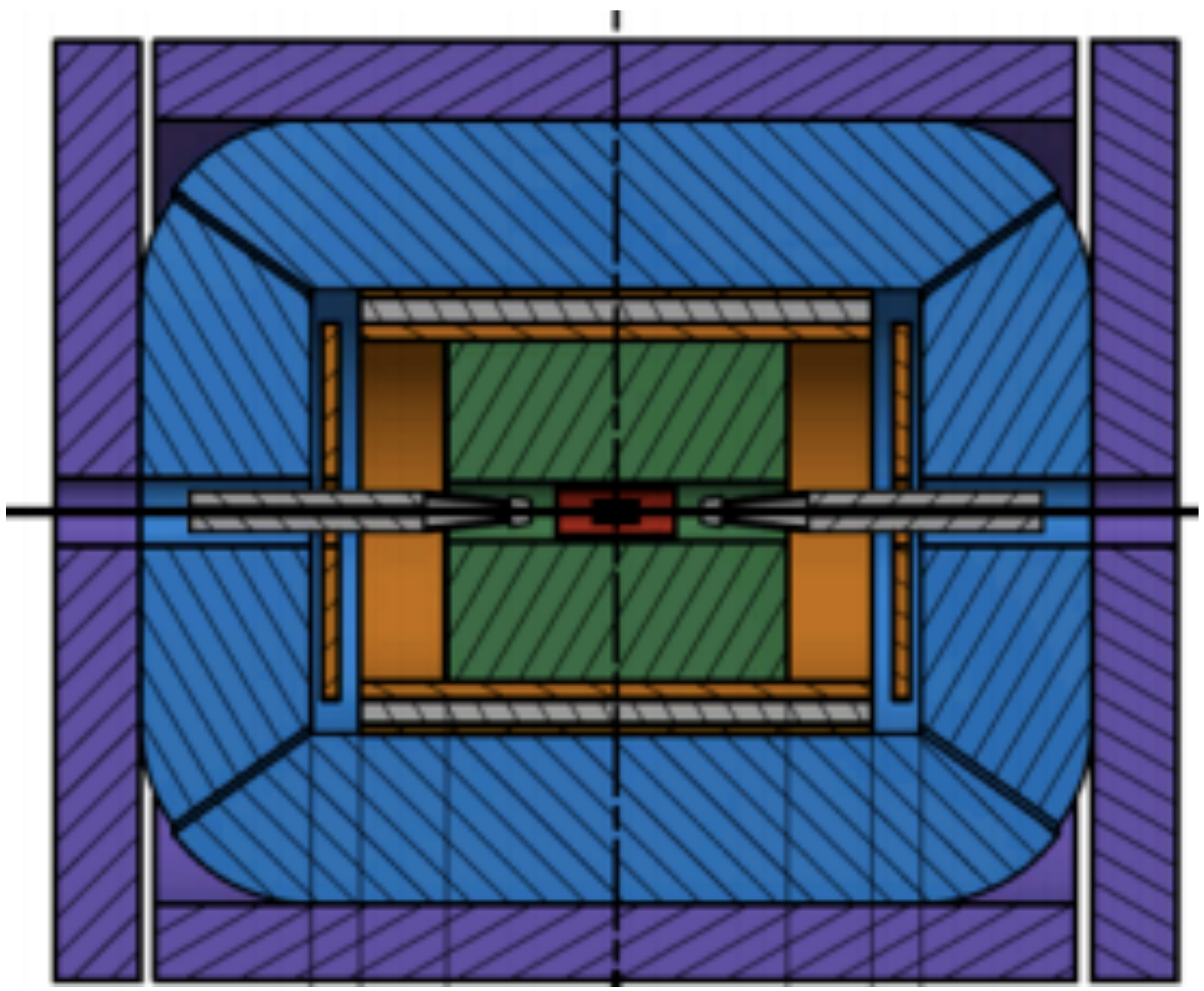
following arXiv:1308.1094



- 920 signal event in 5ab-1
- expected 68% CL
  - 0.17 radian (0.05 in GEN level study)
  - 9.7 degree (2.9 in GEN level study)

Detector Qualification

- ➡ **Physics motivation for detector design choices**
- ➡ **Testing detector requirements for the high precision Higgs measurements**
  - muon momentum resolution
  - jet resolution
  - photon separation for tau identification
  - b and c-tagging with vertex detector
  - …
- ➡ **Ongoing efforts to analyze the impact of detector performance using a subset of Higgs studies**

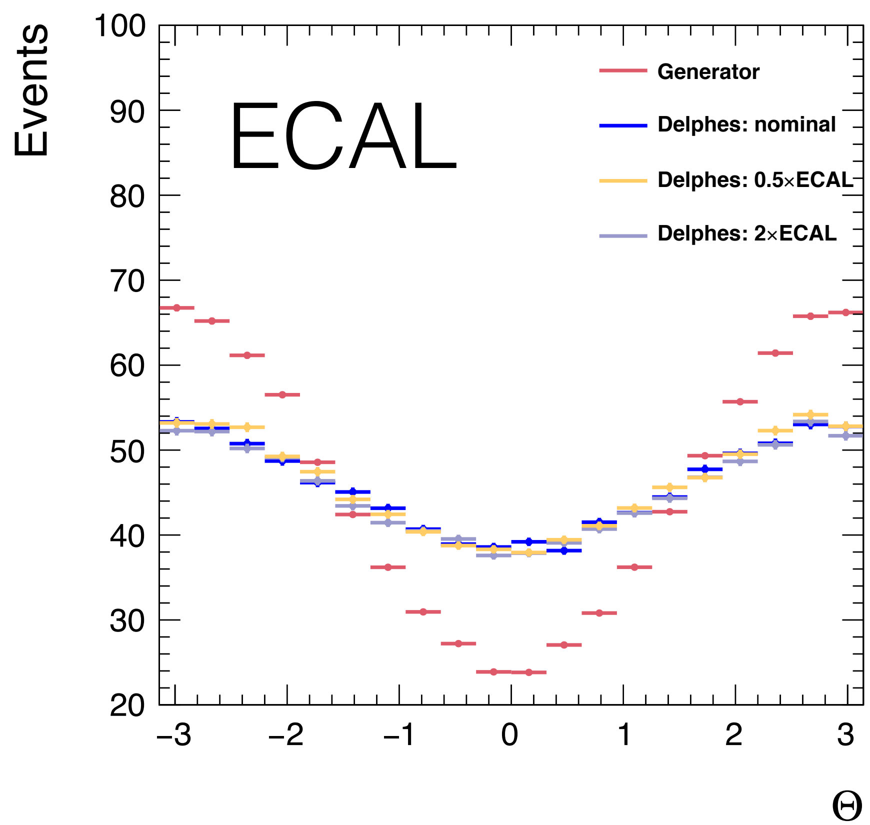


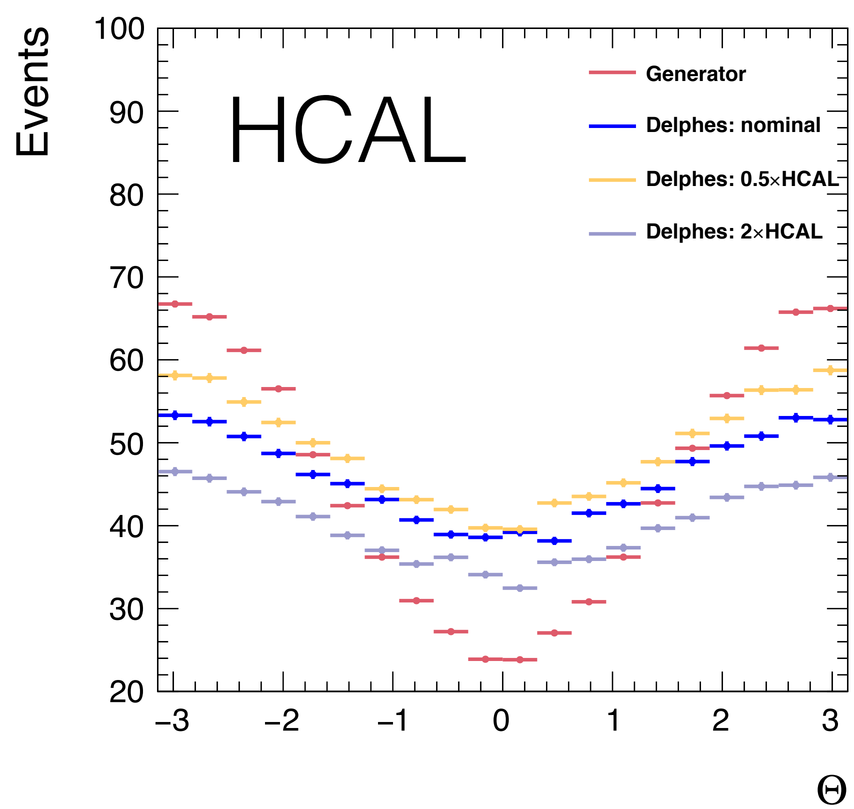
Higgs CP use case for Detector Qualification

- ➡**Checked impact of ECAL and HCAL resolution on Higgs CP study**
- ➡**Nominal detector performance ILC-like**
  - varied ECAL and HCAL resolution by factor of 2 from nominal value

ECAL: $\sqrt{0.01^2 E^2 + 0.15^2 E}$

HCAL: $\sqrt{0.015^2 E^2 + 0.50^2 E}$



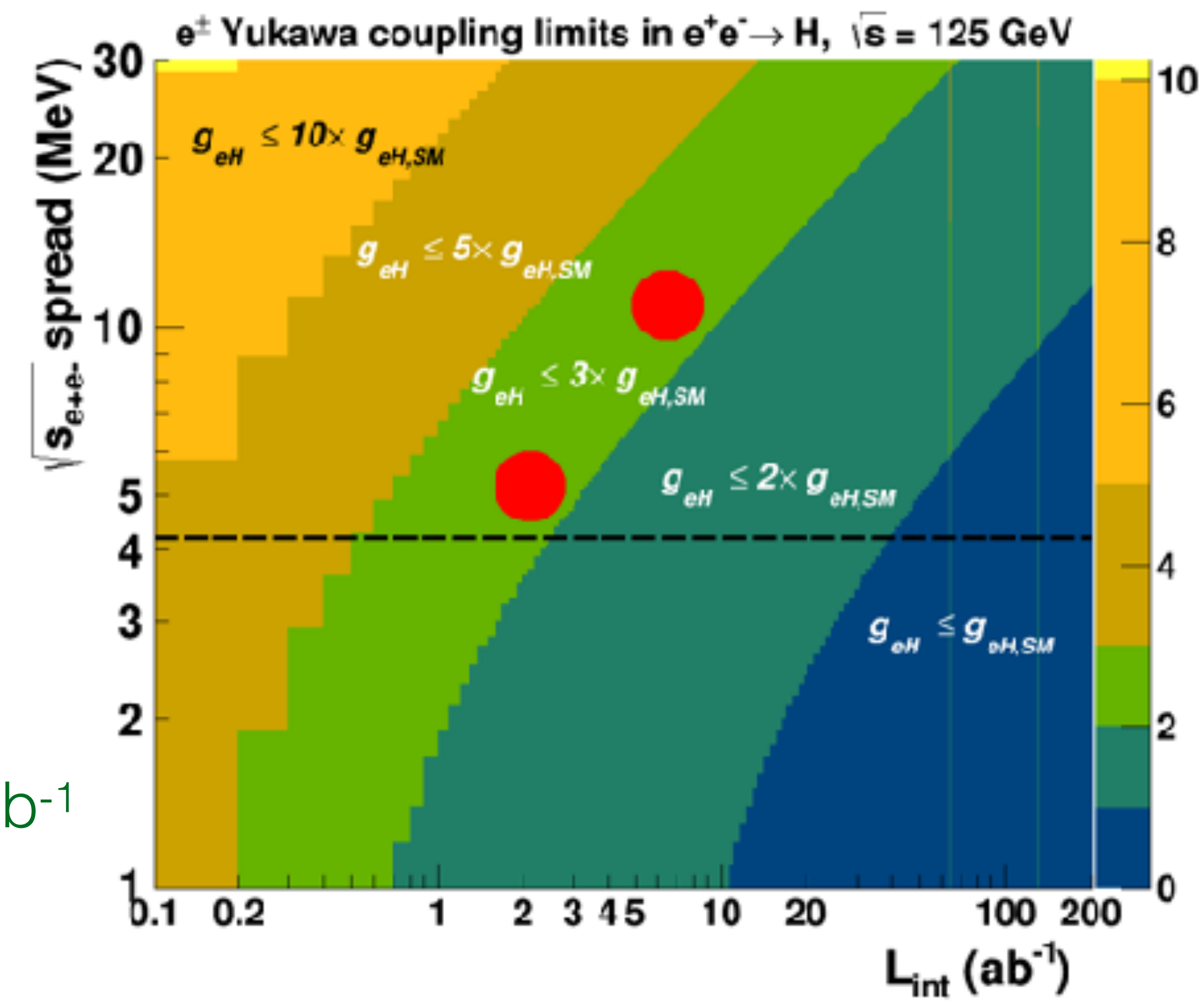


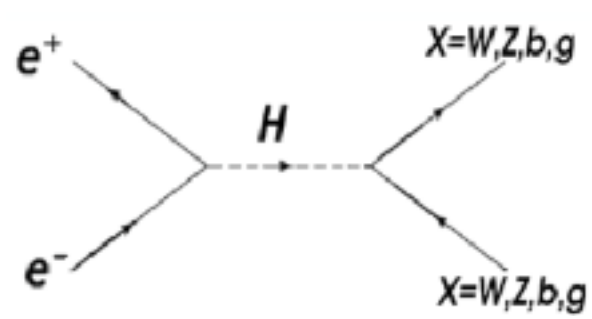
- Gen: 0.05 radians
- Nominal: 0.17 radians
- HCAL resolution
  - 0.5: 0.15 radians
  - 2.0: 0.19 radians
- ECAL resolution
  - 0.5: 0.15 radians
  - 2.0: 0.18 radians

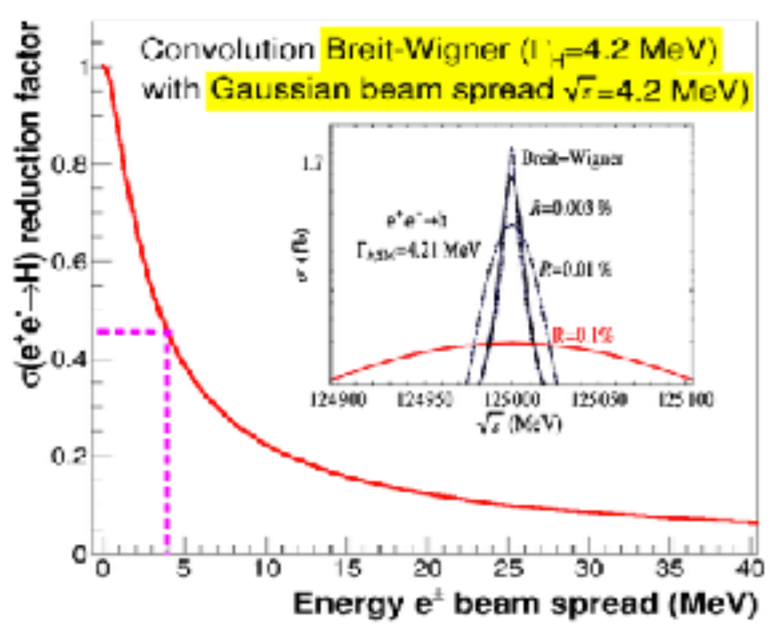
Electron Yukawa Couplings

➡s-channel Higgs production

- unique opportunity for measurement close to SM sensitivity
- highly challenging; σ(ee→H) = 1.6fb; σ(e^+e^-→H) = 50ab (nominal δE/E)
- various Higgs decay channels studied
- studied monochromatization scenarios
    - baseline: 6 MeV energy spread, L = 2ab^{-1}
    - optimized: 10 MeV energy spread, L = 7ab^{-1}
    - limit ~3.5 times SM in both cases







arXiv:1701.02663

[Monochromatization study]

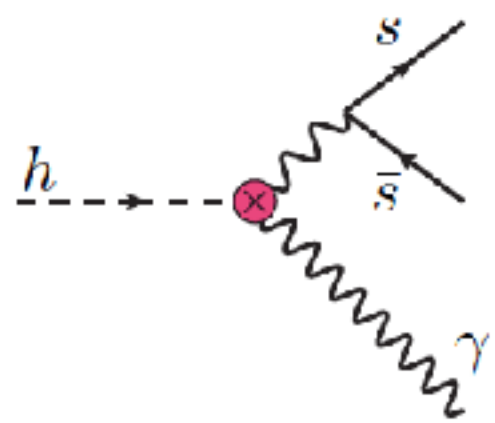
Tuesday, 16 January

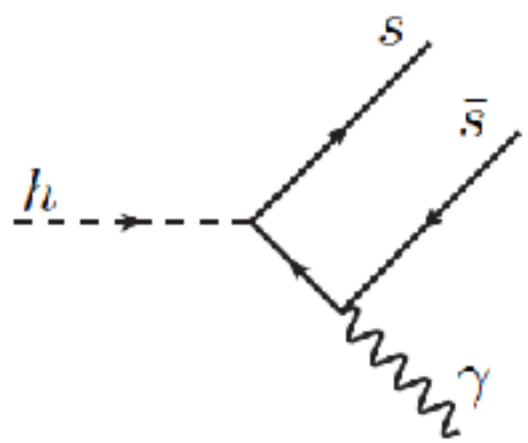
12:30 FCC-ee → H

Light Quark Yukawa Couplings

➡ 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)

➡ ~40 events expected in H → **ρ**(ππ) γ

$H \to J/\Psi\,\gamma$ ➡ y_c

$H \to \phi\,\gamma$ ➡ y_s

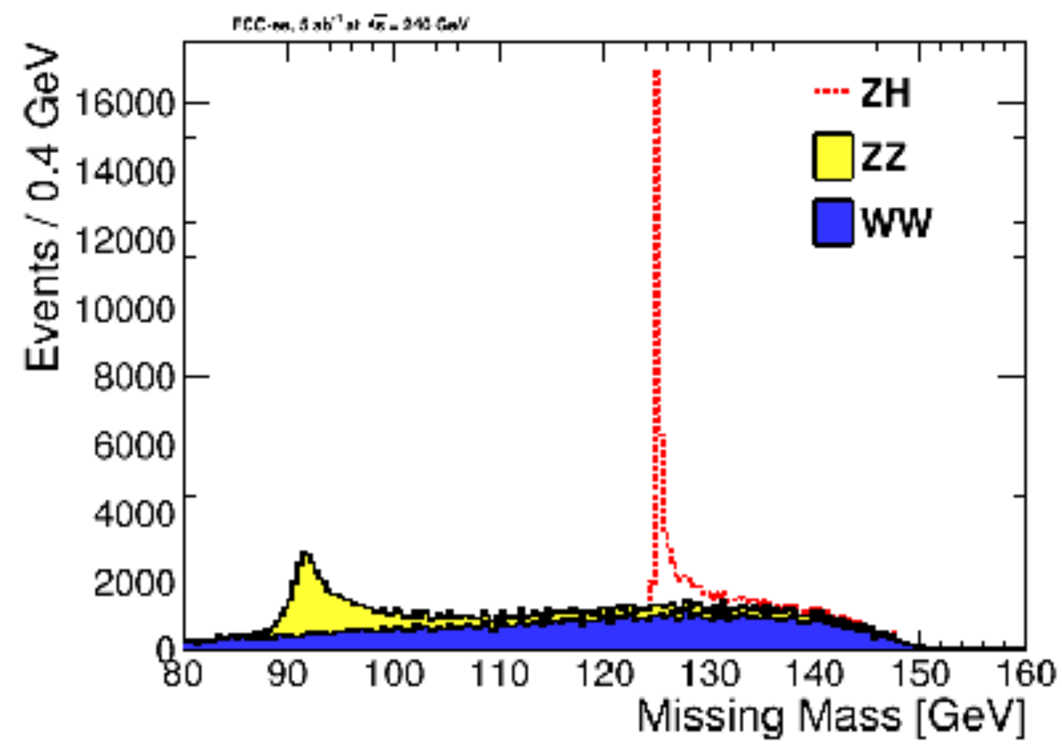
$H \to \boldsymbol{\rho}\,\gamma$

$H \to \omega\,\gamma$ ➡ y_u, y_d

BSM Higgs Studies

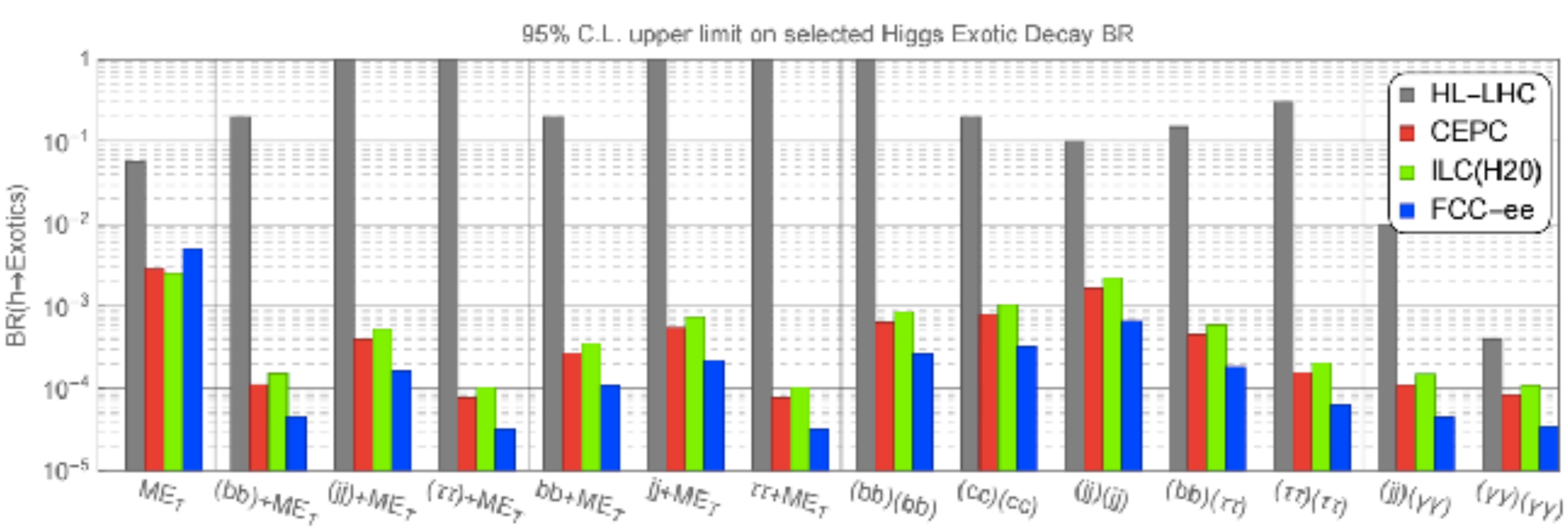
➡ **Example: Higgs to invisible decays**

- follows ZH cross section measurement
- for visualization BR(H->inv) = 100%
- 95%CL upper limit using 5ab^{-1} is 0.44%
- study published using leptonic Z decays in Eur. Phys. J. C (2017) 77: 116
- hadronic Z decays under study. Shows similar performance



➡ **Incredible opportunities for BSM Higgs searches**

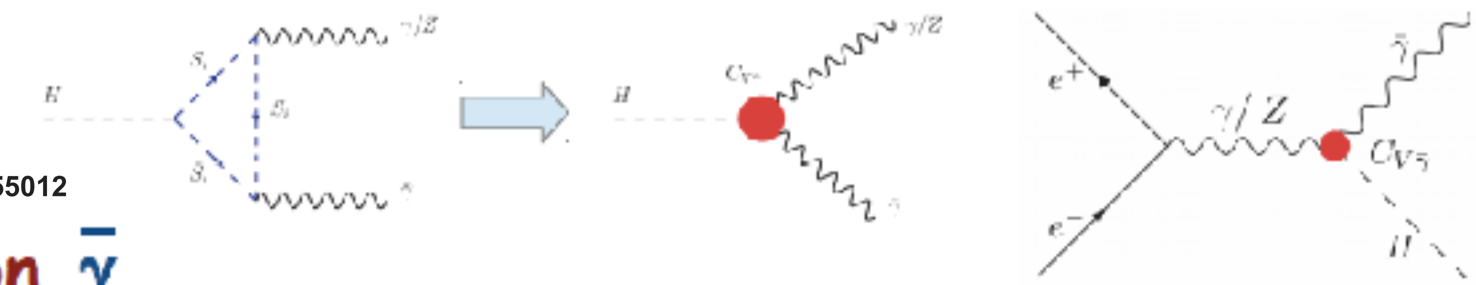
arXiv:1612.09284



Dark Photon Searches via Higgs Production

Biswas, Gabrielli, Heikinheimo, Mele
JHEP 1506 (2015) 102 + arxiv:1703.00402

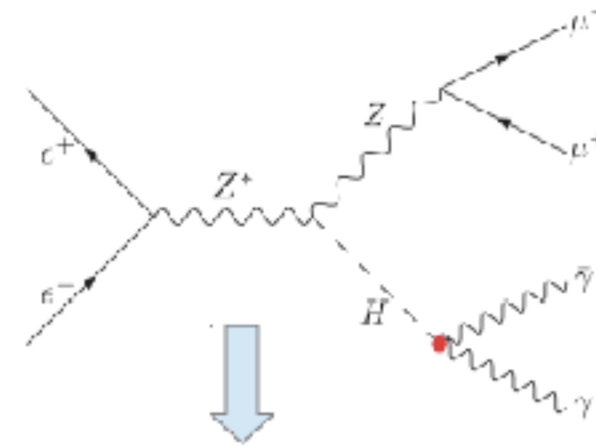
Phys.Rev. D96 (2017) no.5, 055012



Massless Dark Photon $\bar{\gamma}$

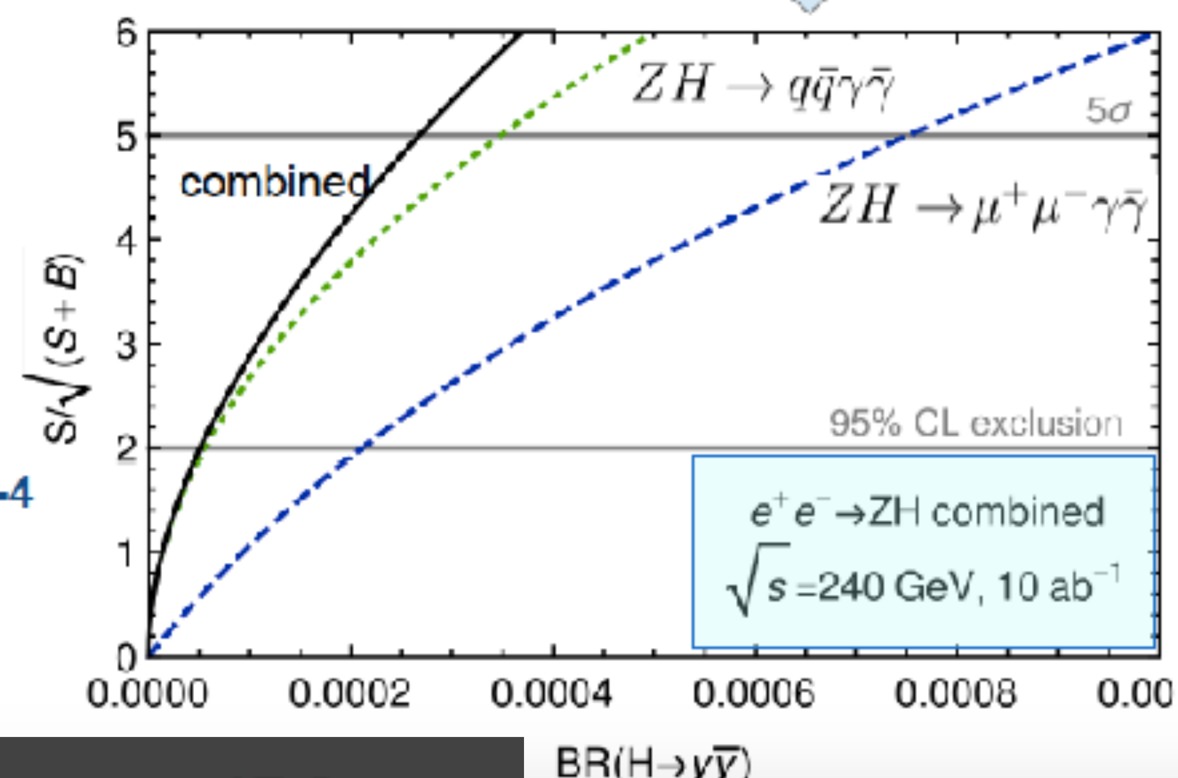
$$e^+e^- \to H\bar{\gamma} \to b\bar{b}\bar{\gamma}$$

$$e^+e^- \to ZH \to (\mu^+\mu^-, q\bar{q})(\gamma\bar{\gamma})$$



Large effects expected due to
→ Higgs non-decouplings
→ large U(1) couplings in dark sector

- unexplored signatures !
  massless invisible system
- 5 σ sensitivity for BR(H → $\gamma\bar{\gamma}$) ~ 3x10^{-4}
- 3 times better than LHC @ 300 fb^{-1}
  Biswas et al. PRD 93 (2016) 093011

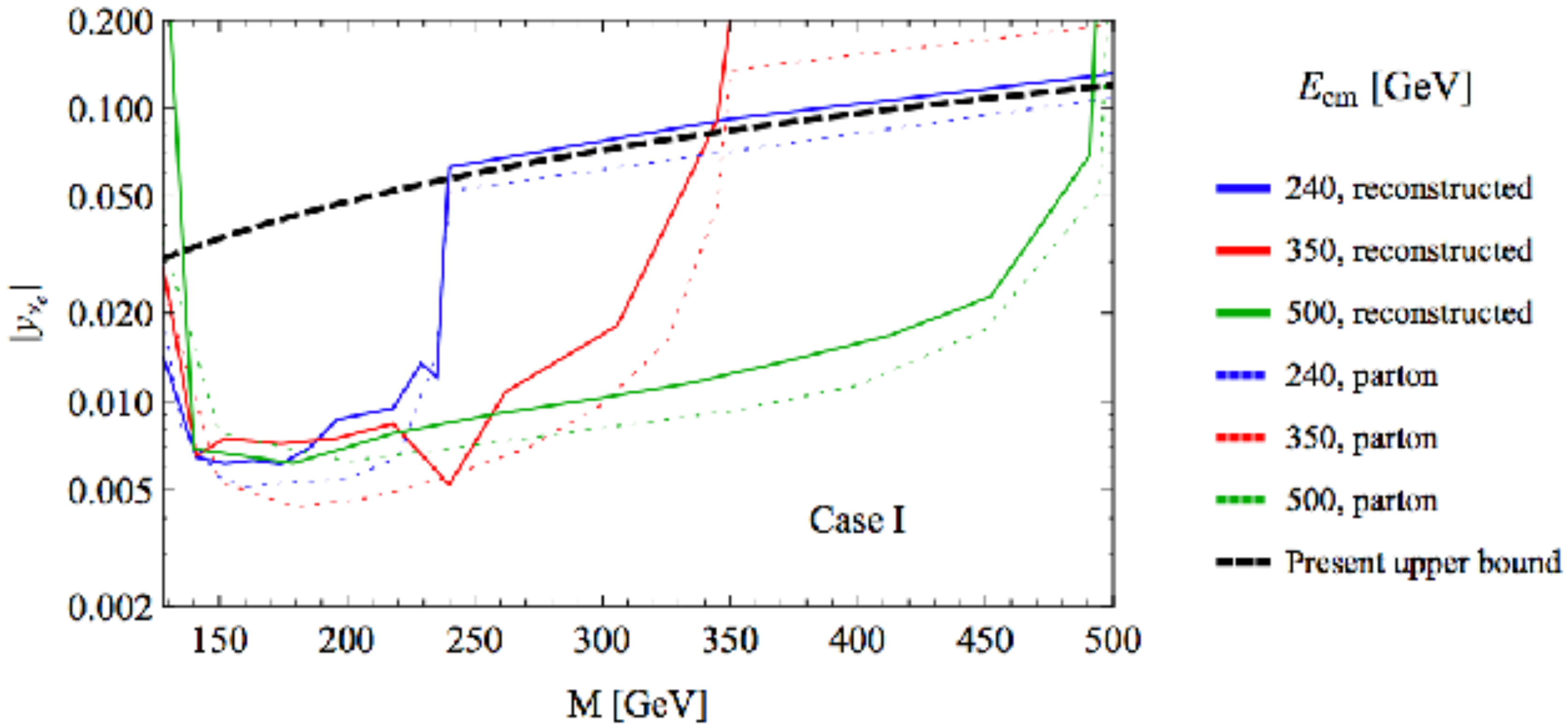


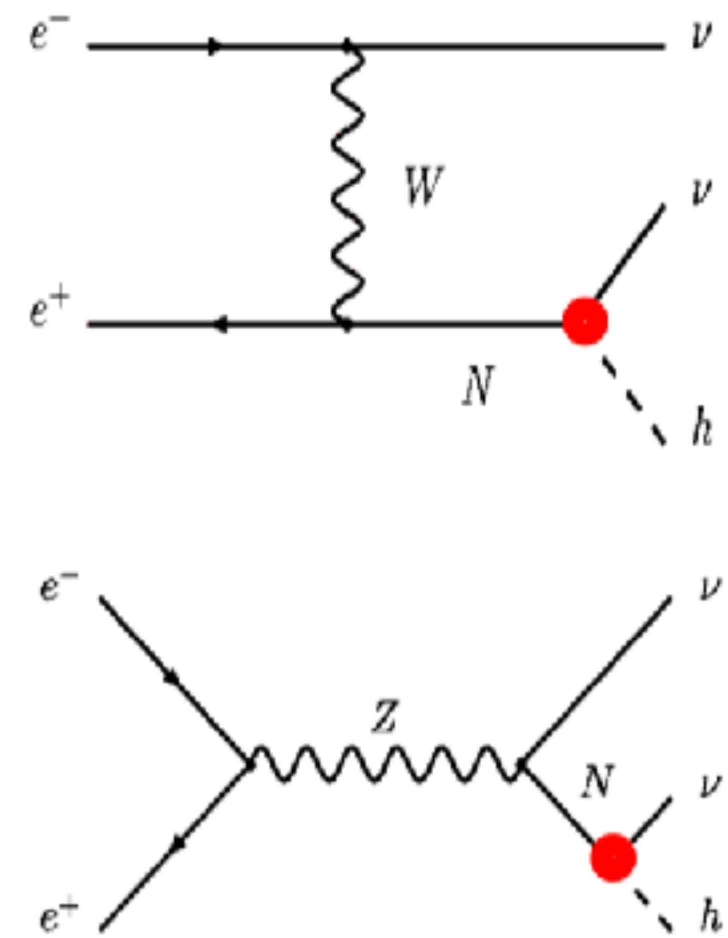
WEDNESDAY, 17 JANUARY

16:50 **Dark photons in ZH and associated Higgs production (FCC-ee)**
Speaker: Barbara Mele (Sapienza Universita e INFN, Roma I (IT))

Heavy Neutrinos

- ➡ **Low-mass seesaw scenario with 2 sterile neutrinos (N)**
- ➡ **Studied N decay to h+v in mono-Higgs plus missing energy signature**





- ➡ **FCC-ee with sensitivity to $|y_{\nu e}|$ ~ 5x10-3 for m_N ~ 100-300 GeV**

WEDNESDAY, 17 JANUARY

14:55 **Heavy neutrino discovery prospects at FCC**

Speaker: Oliver Fischer (Unibas)

Conclusion

➡**Fantastic prospects to probe the Higgs sector with FCC-ee**

- unique measurements of g_{ZH} and total width
- precision measurements of Higgs boson properties (coupling, mass, CP)
- precision Higgs program needs to be accompanied by precision program for m_c, m_b, and α_s
- BSM Higgs physics through direct and indirect measurements
- Synergy and complementarity to hadron collider Higgs physics