at FCC-ee

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^*	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$
$\bar{u}u$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$
$\bar{d}d$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$
$\ell^+\ell^-$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$

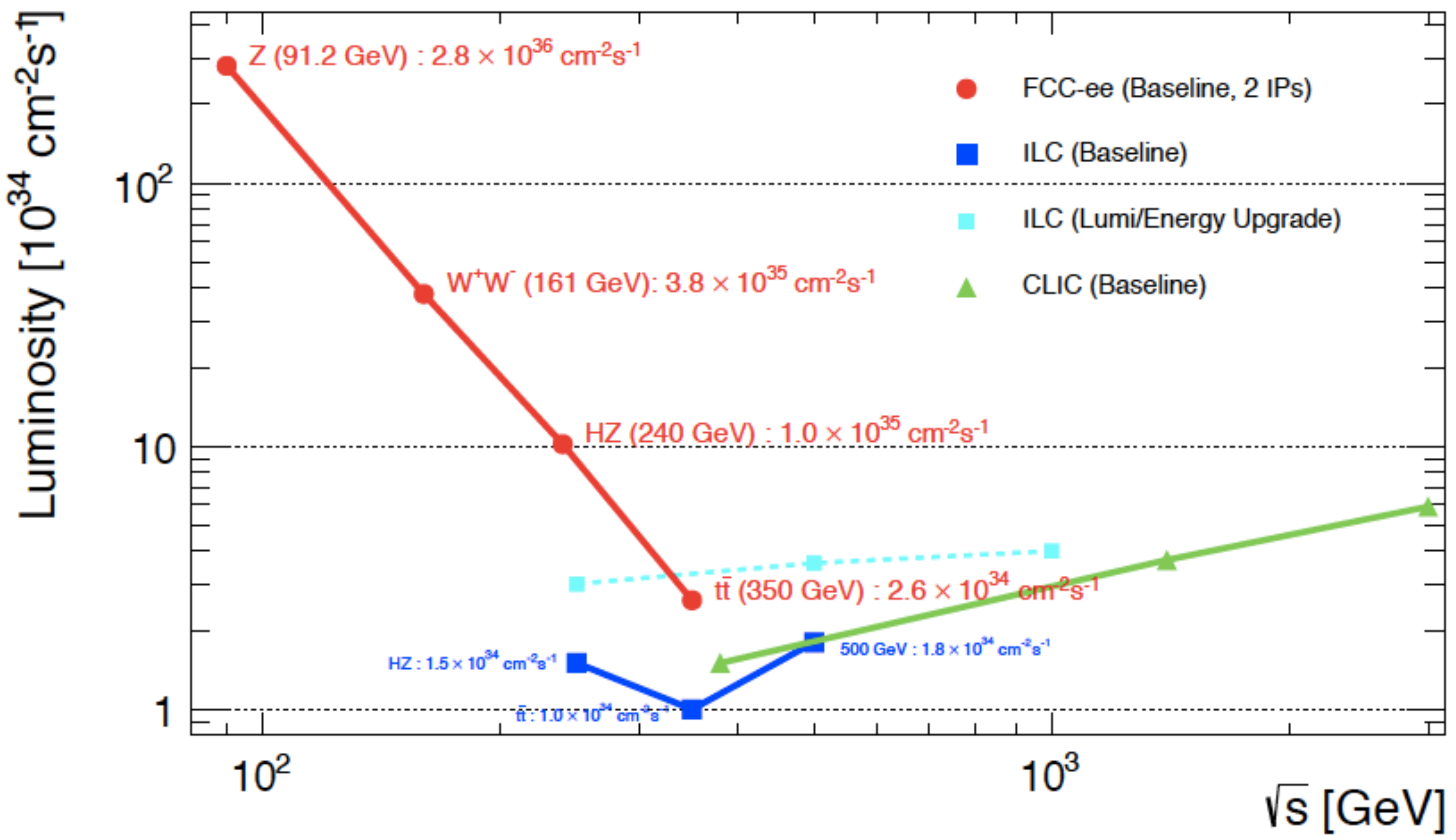
arXiv:1310.8361

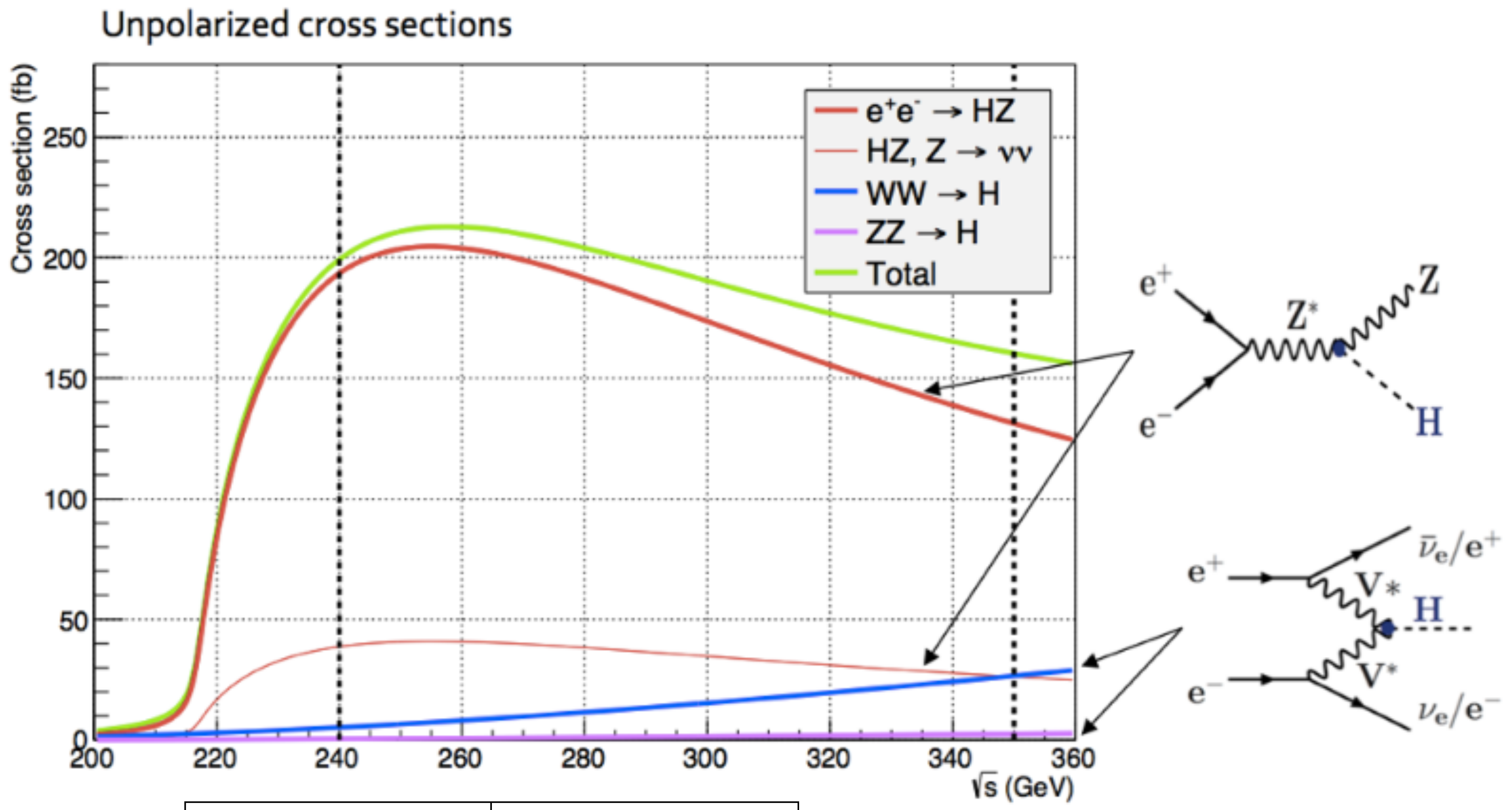
➡Testing multi-TeV scale with sub-percent level measurements

➡There is no strict limit to the precision needed!

FCC-ee Higgs Program

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



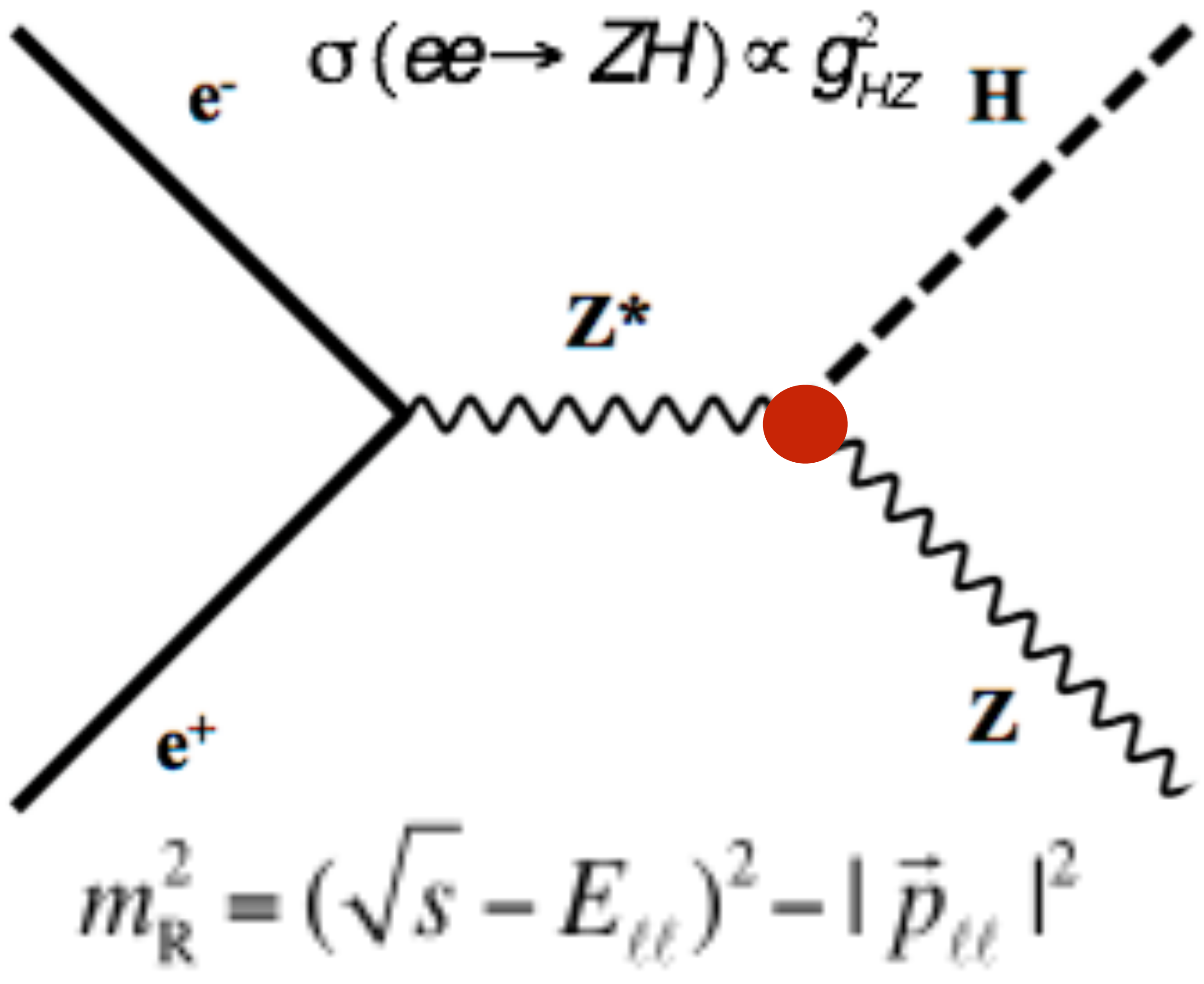


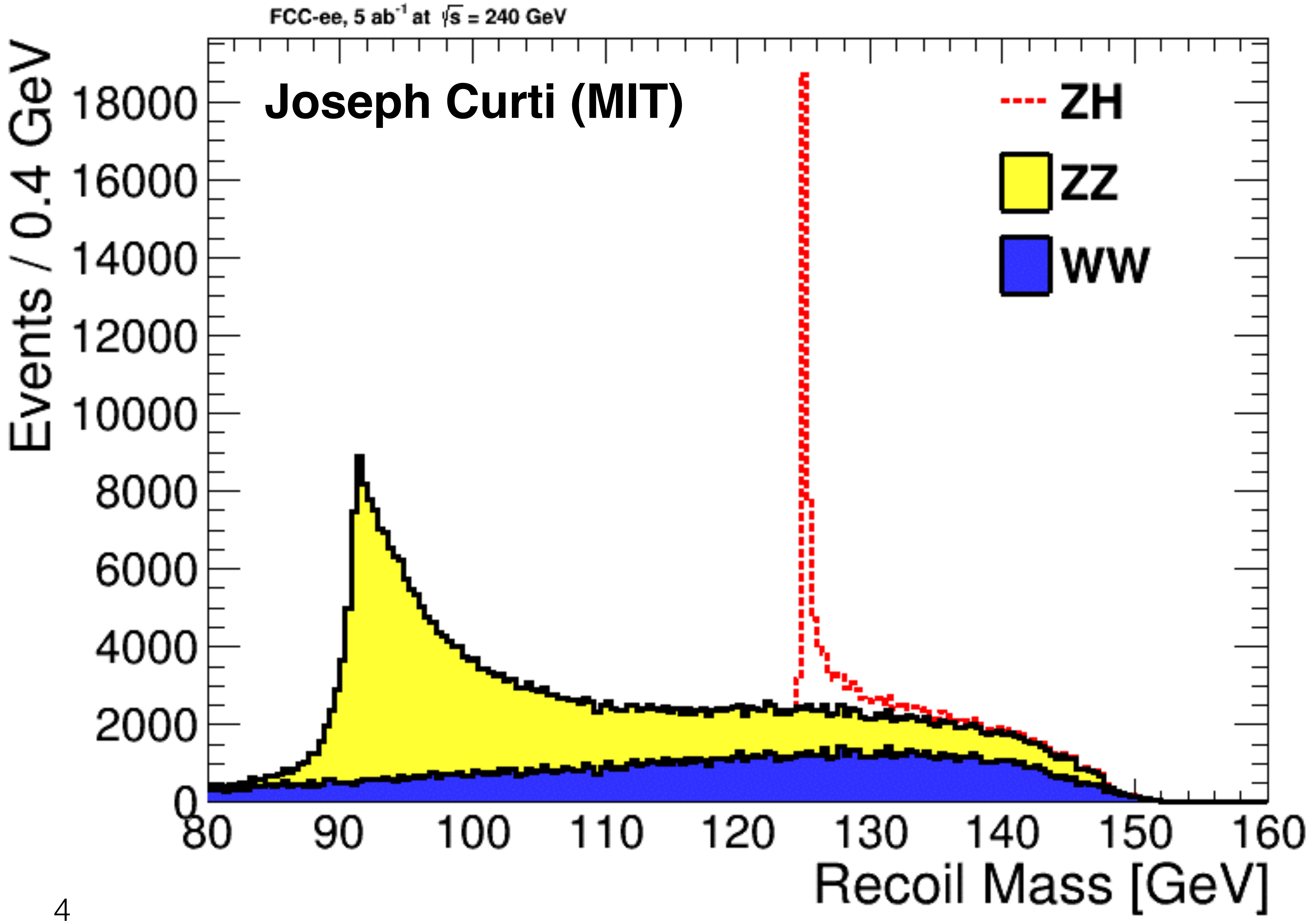
	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab-1)	5	1.5
Number of Higgs bosons from $e^+e^-\rightarrow HZ$	1,000,000	200,000
Number of Higgs bosons form fusion process	25,000	40,000

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





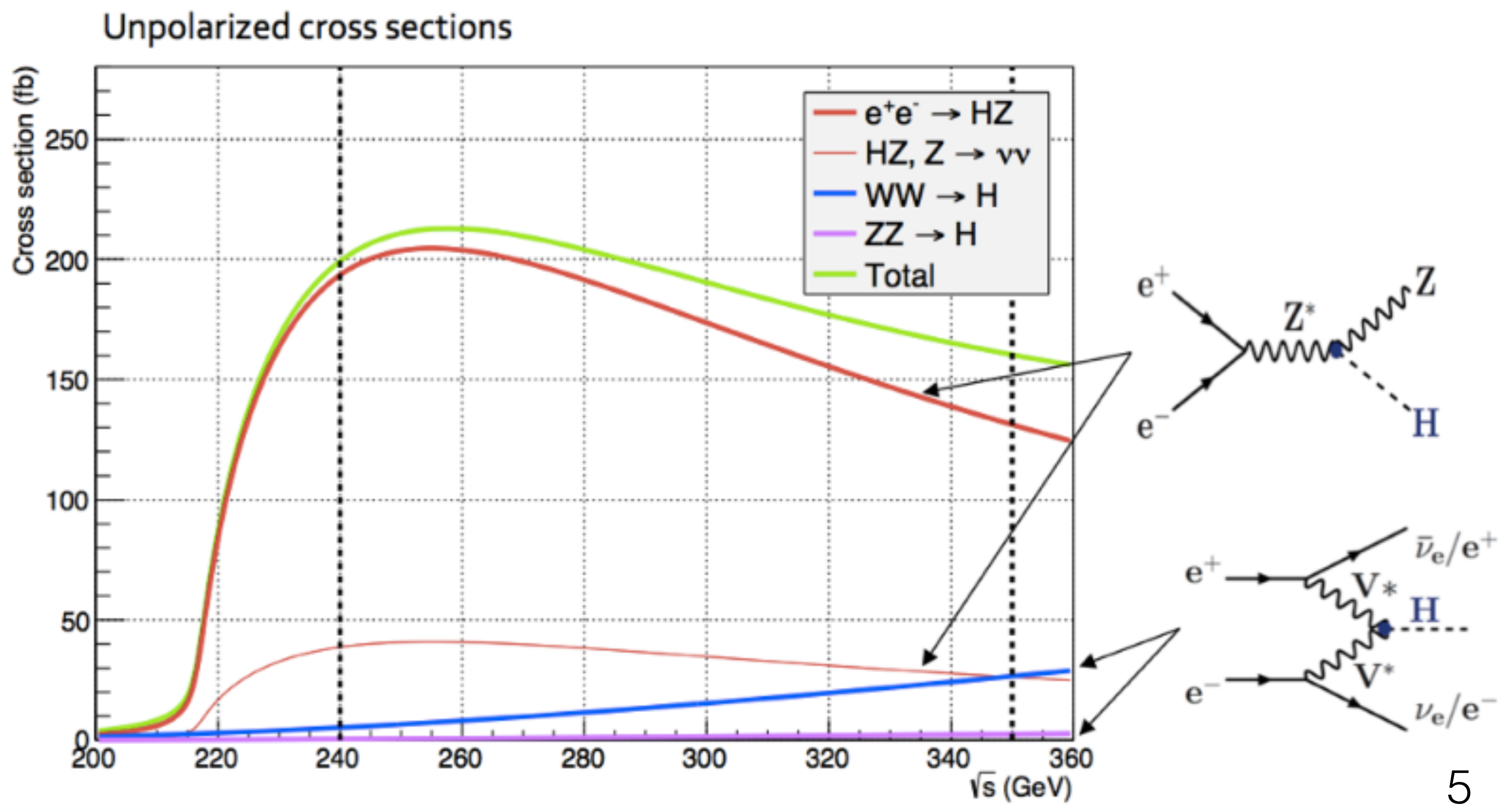
Total Higgs Boson Width

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

- tagging Higgs final states

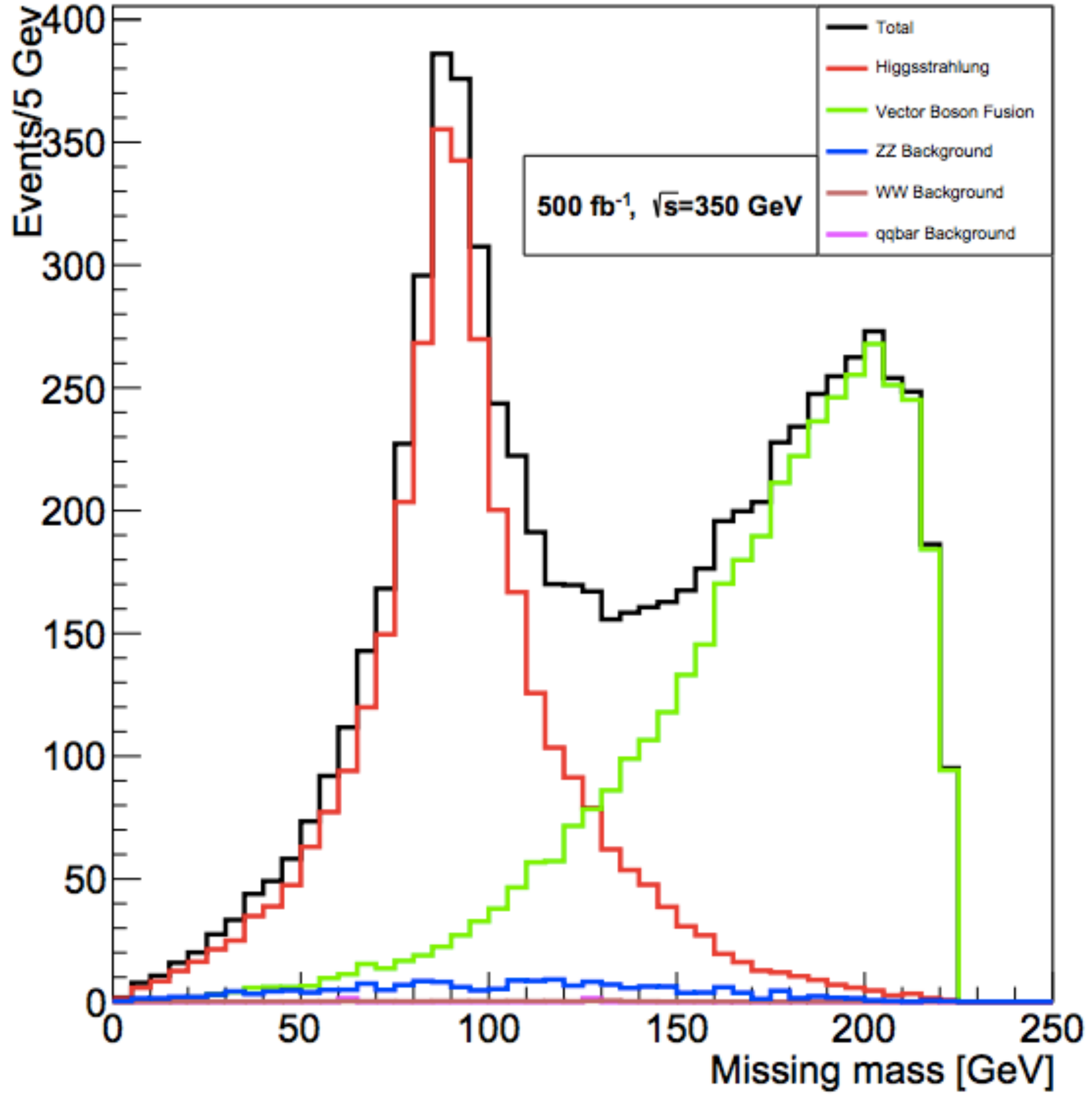
$$\sigma(ee \to ZH) \cdot BR(H \to ZZ) \propto \frac{g_{HZ}^4}{\Gamma_H}$$

- measurements of vector boson fusion production at 350 GeV
- combination of all measurements



$$\sigma(ee \to \nu\nu H) \cdot BR(H \to bb)$$

by Janick von Ahnen (DESY)



Higgs Boson Couplings

➡ Precision Higgs coupling measurements

- absolute coupling measurements enabled by HZ cross section measurement
  - only leptonic modes used so far
- tagging individual Higgs final states
- data at 350 GeV constrain total width
  - only used $H \to bb$ in fusion production so far
- couplings extracted from model-independent fit
- statistical uncertainties are shown for $5 ab^{-1}$@240 GeV and $1.5 ab^{-1}$@350GeV (from arXiv:1308.6176)
  - all measurements are under review / are being redone
  - most result use 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

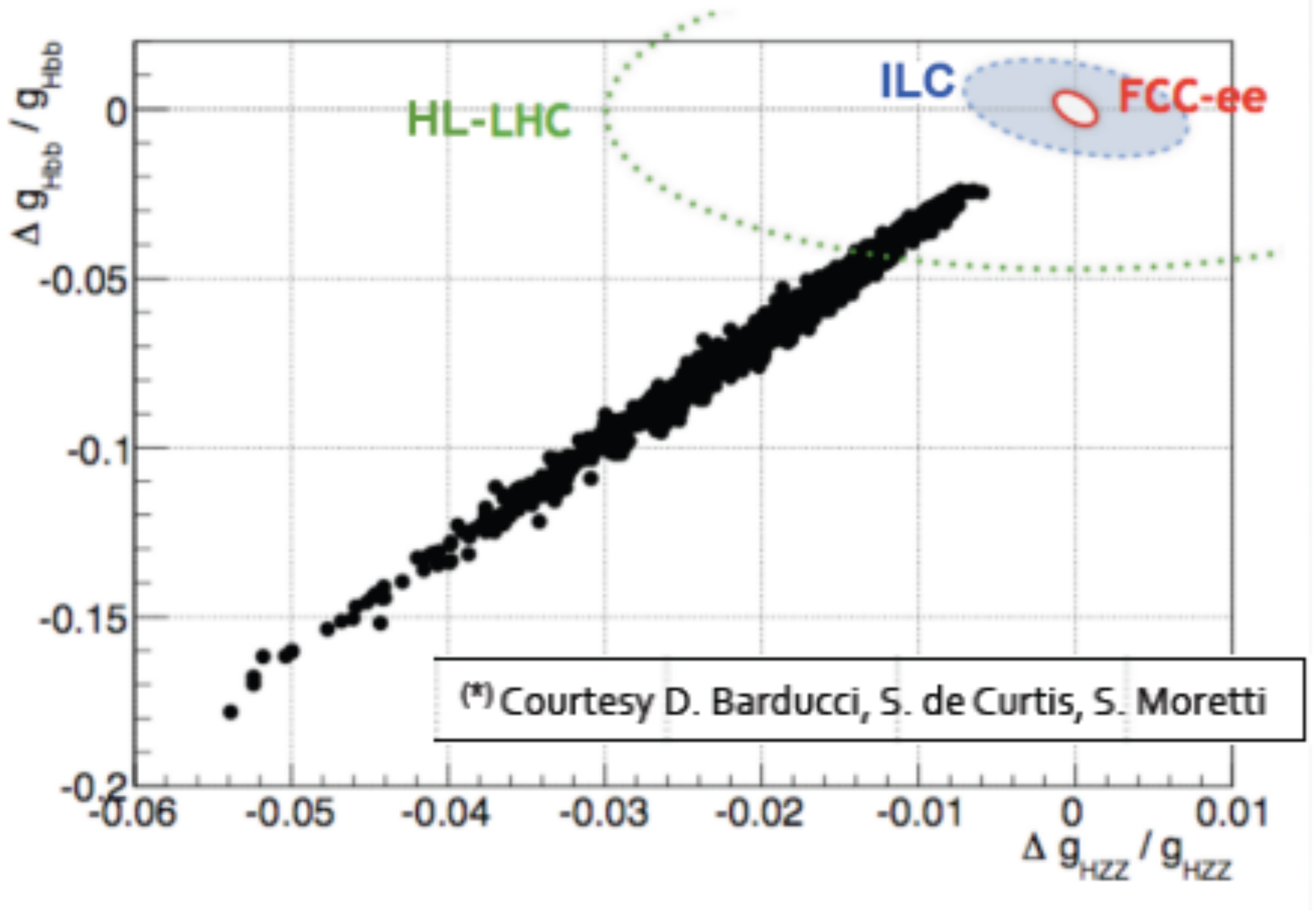
➡ **Factor ~10 improvement for most couplings**

- 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)

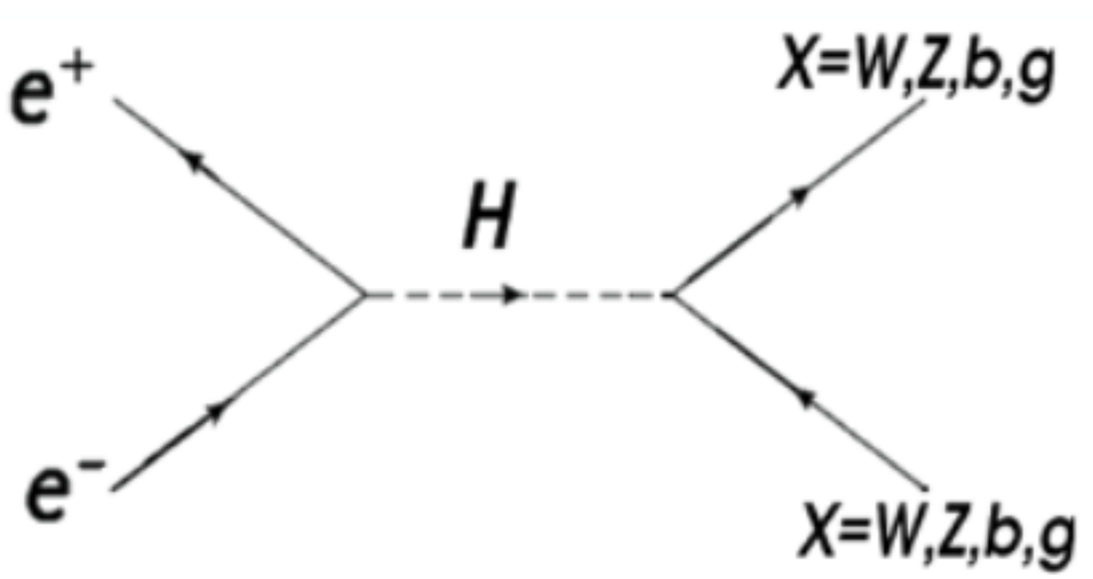
Current impact from parametric uncertainty (α_s, m_c, and m_b) on Higgs couplings - arXiv:1404.0319. Authors argue that significant progress (factor 7) is possible.

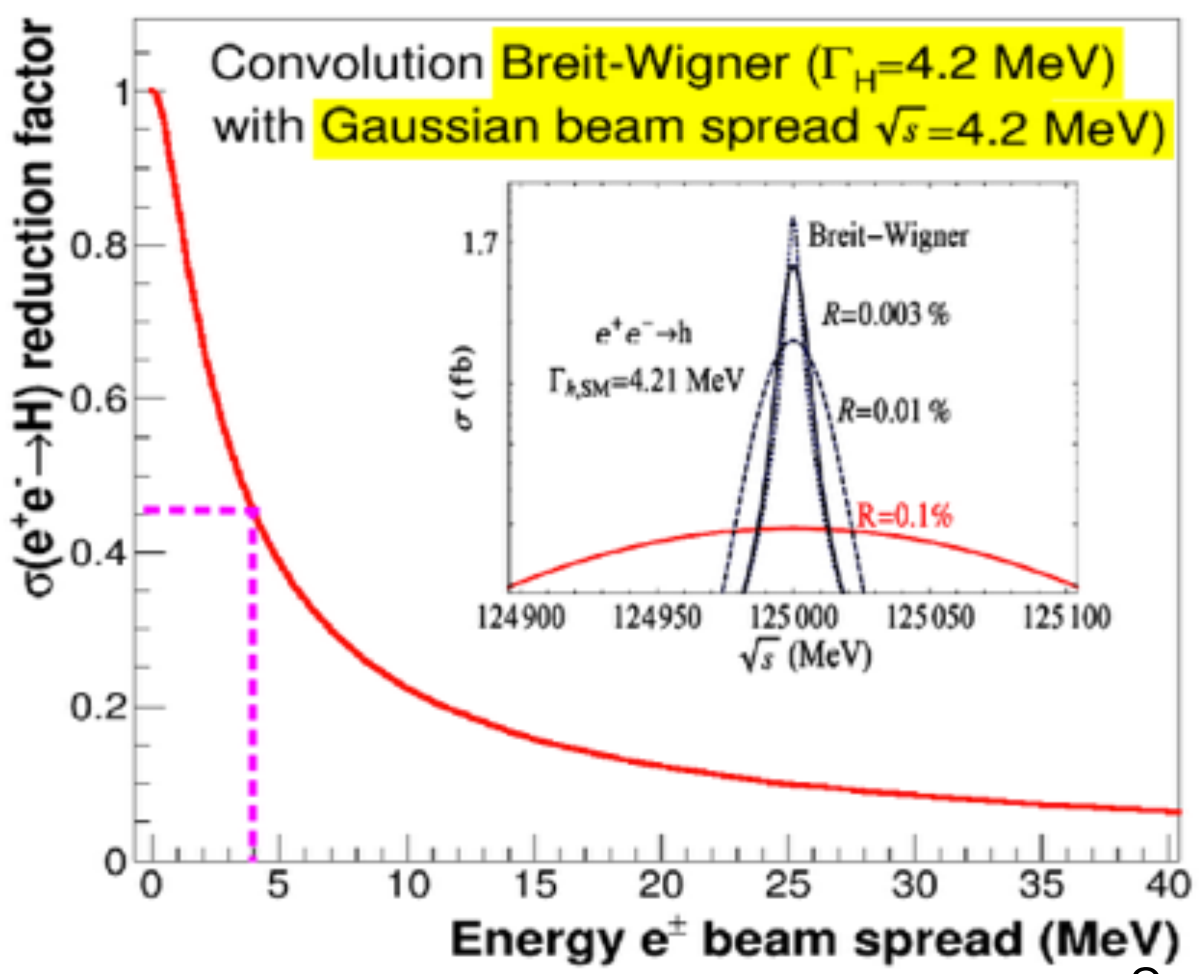
$$\delta_b = 0.7\% \ , \quad \delta_c = 0.7\% \ , \quad \delta_g = 0.6\%$$

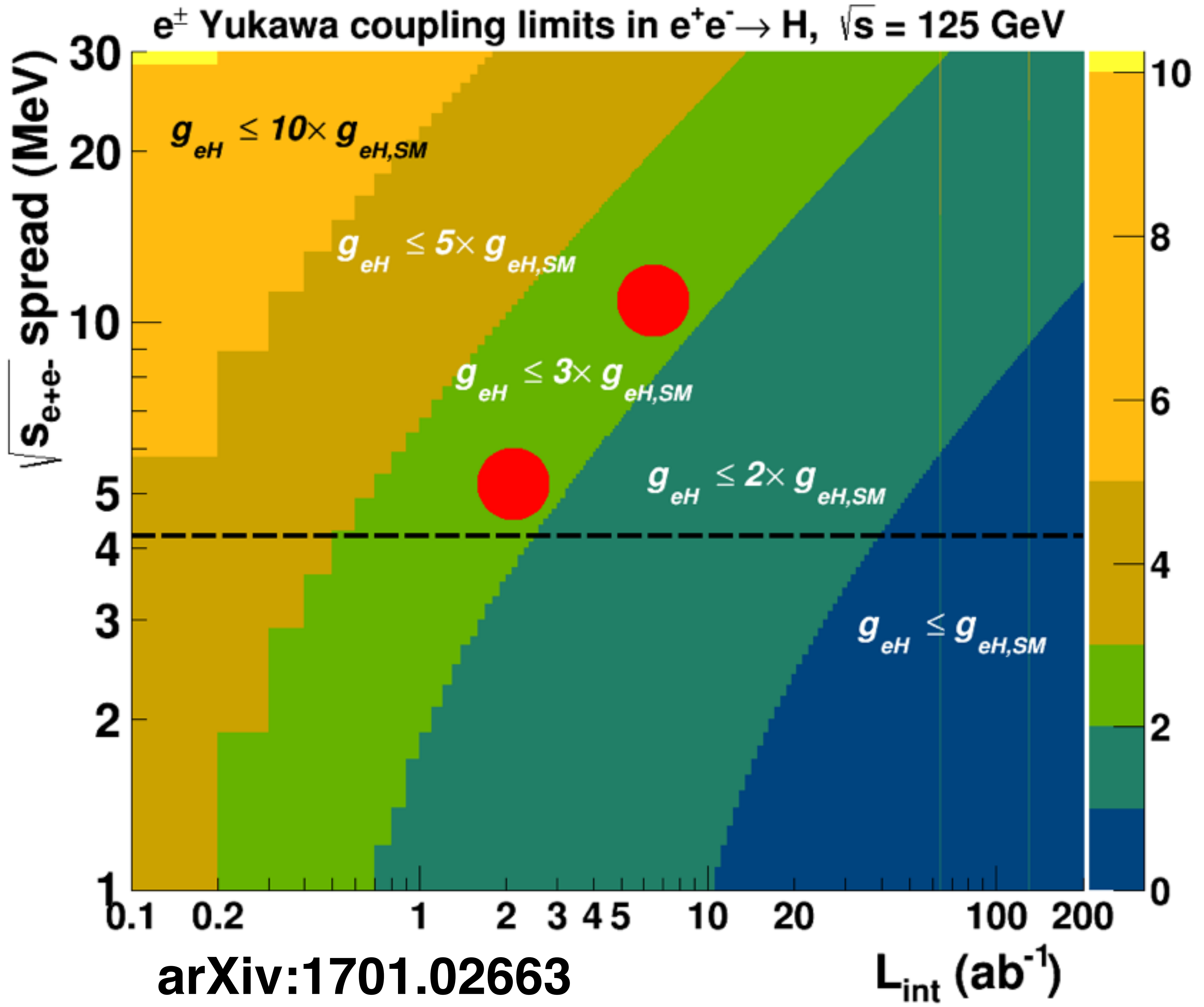
Electron Yukawa Couplings

➡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 = 2 ab-1
  - optimized: 10 MeV energy spread, L = 7 ab-1
  - limit ~3.5 times SM in both cases







Link to summary of monochromatization study

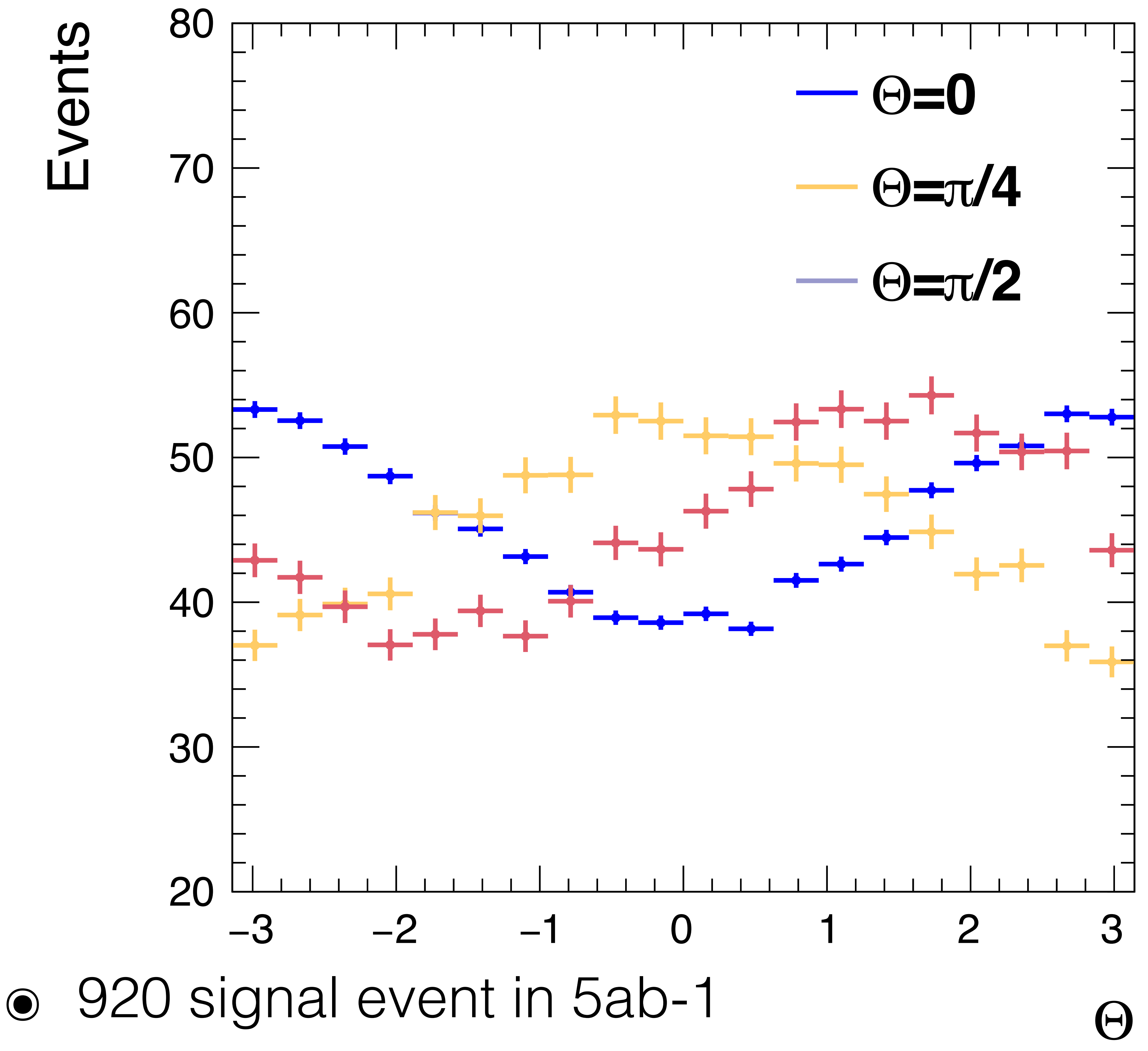
Higgs CP Studies

- ➡ **$H \to \tau\tau$ 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
  - exploring $\tau^{\pm} \to \rho^{\pm} \nu_{\tau} \to \pi^{\pm} \pi^{0} \nu_{\tau}$
  - model using effective lagrangian

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

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)

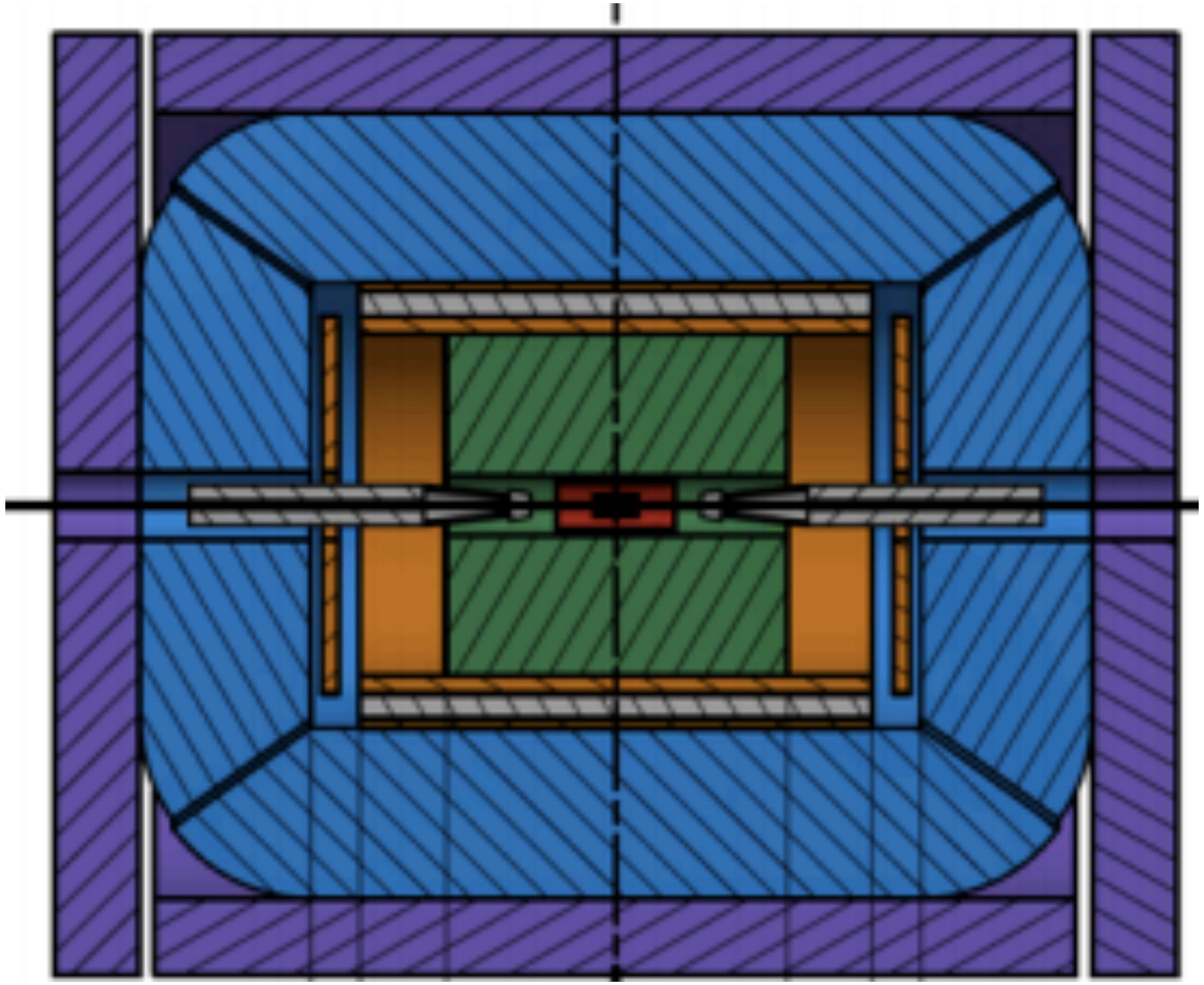
Detector Qualification

➡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

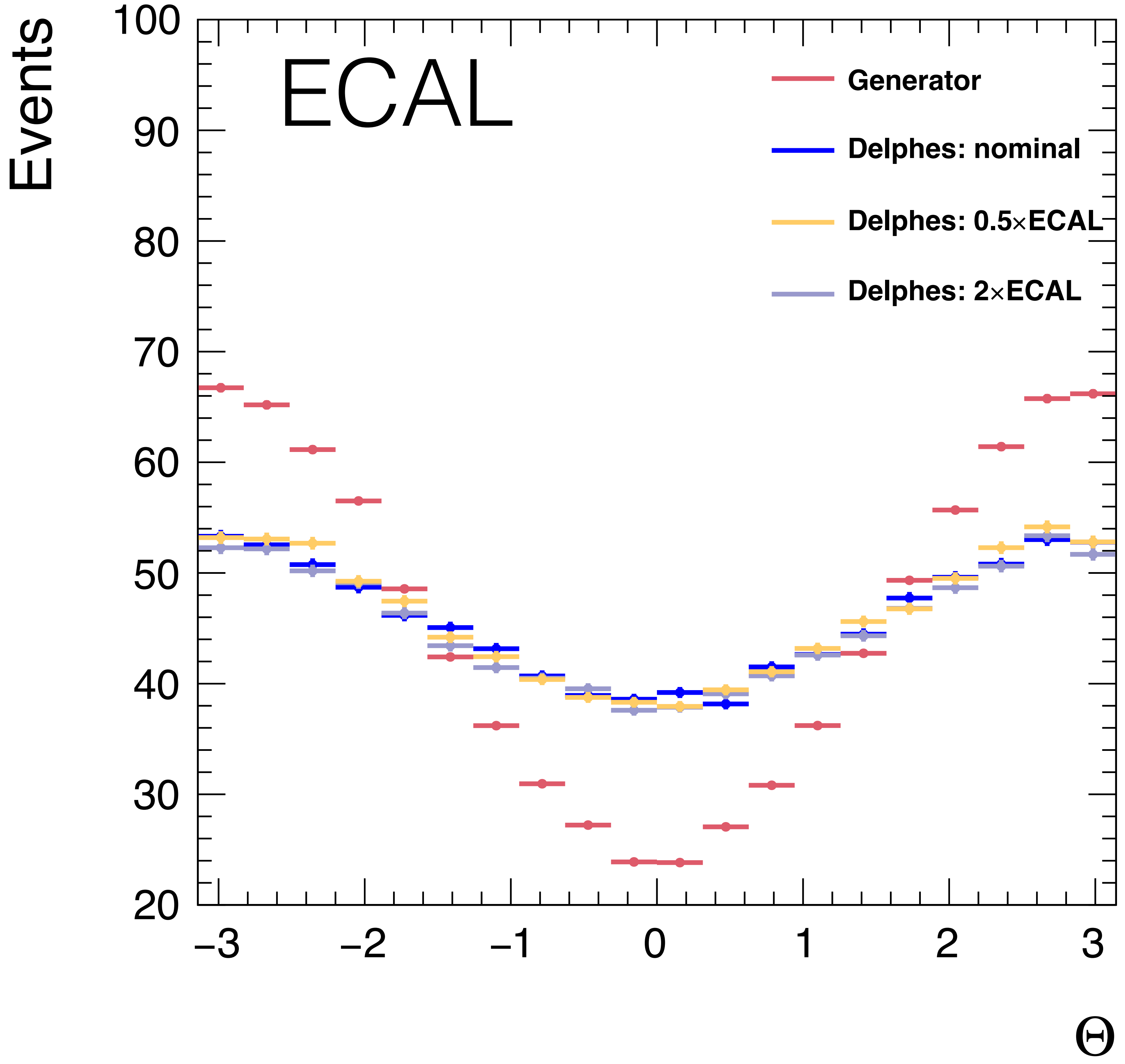
➡**Checked impact of ECAL and HCAL resolution on Higgs CP study**

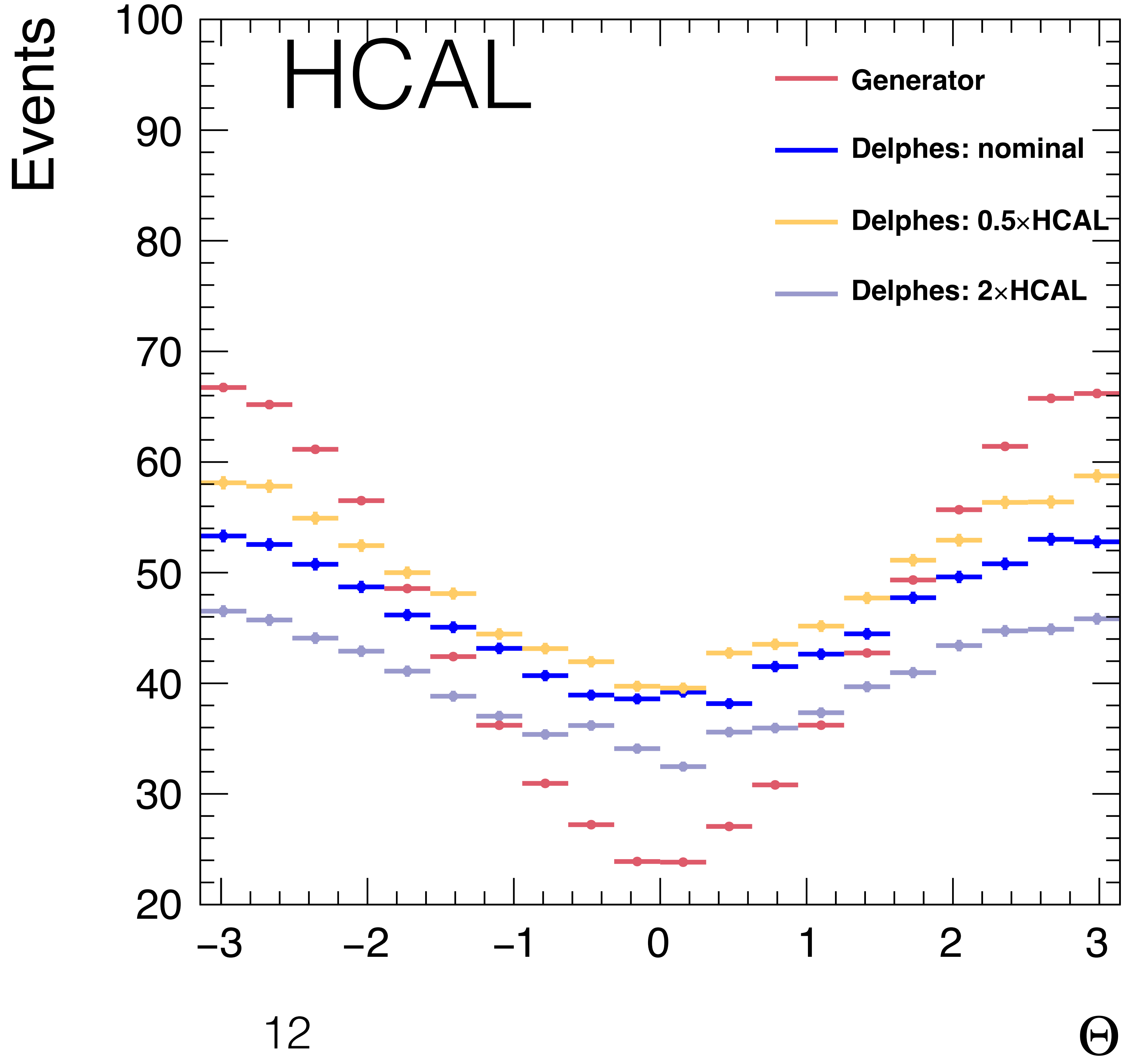
➡**Nominal detector performance ILC-like**

- varied ECAL and HCAL resolution by factor of 2 from nominal value
- next: checking impact of photon separation

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

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

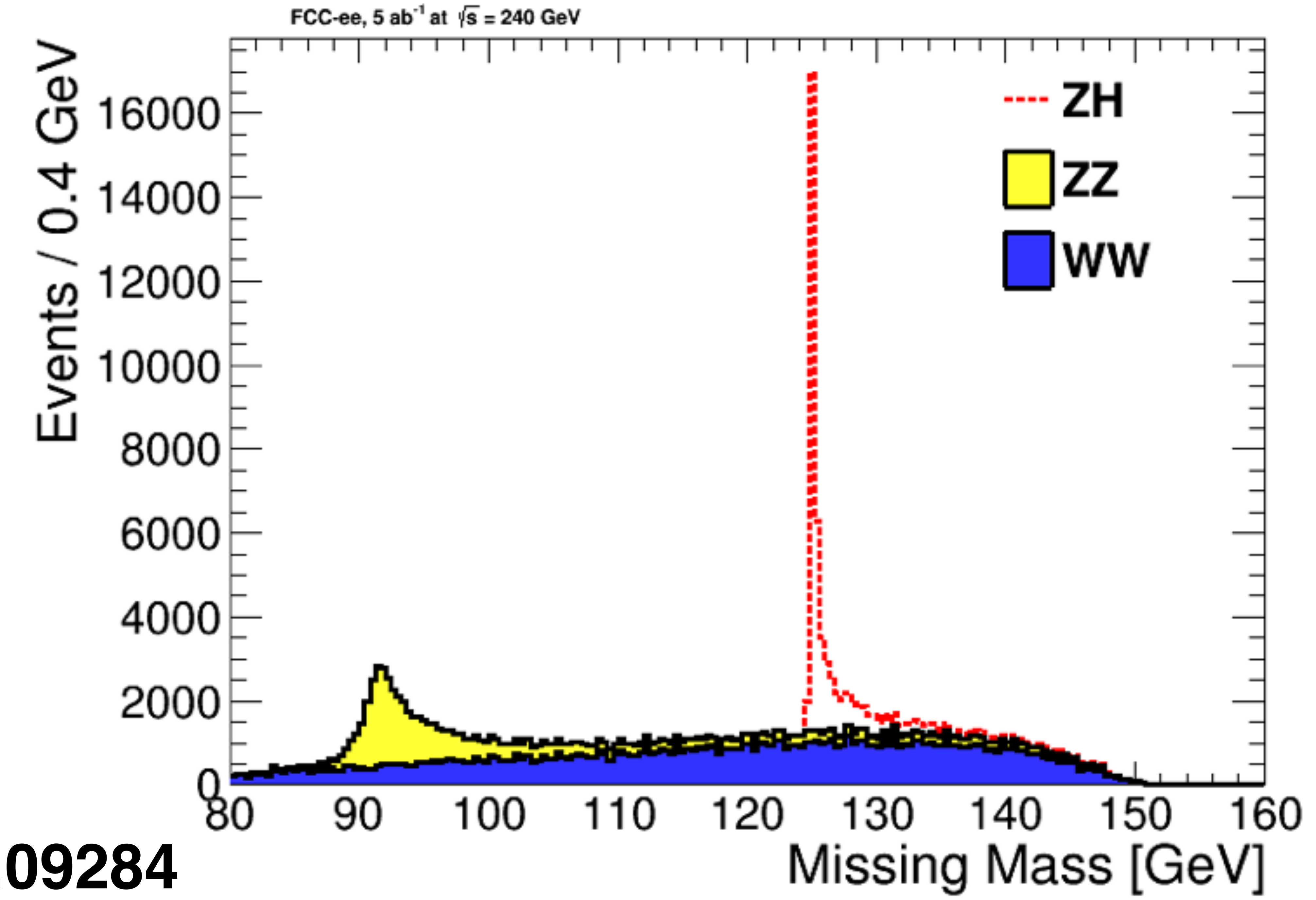


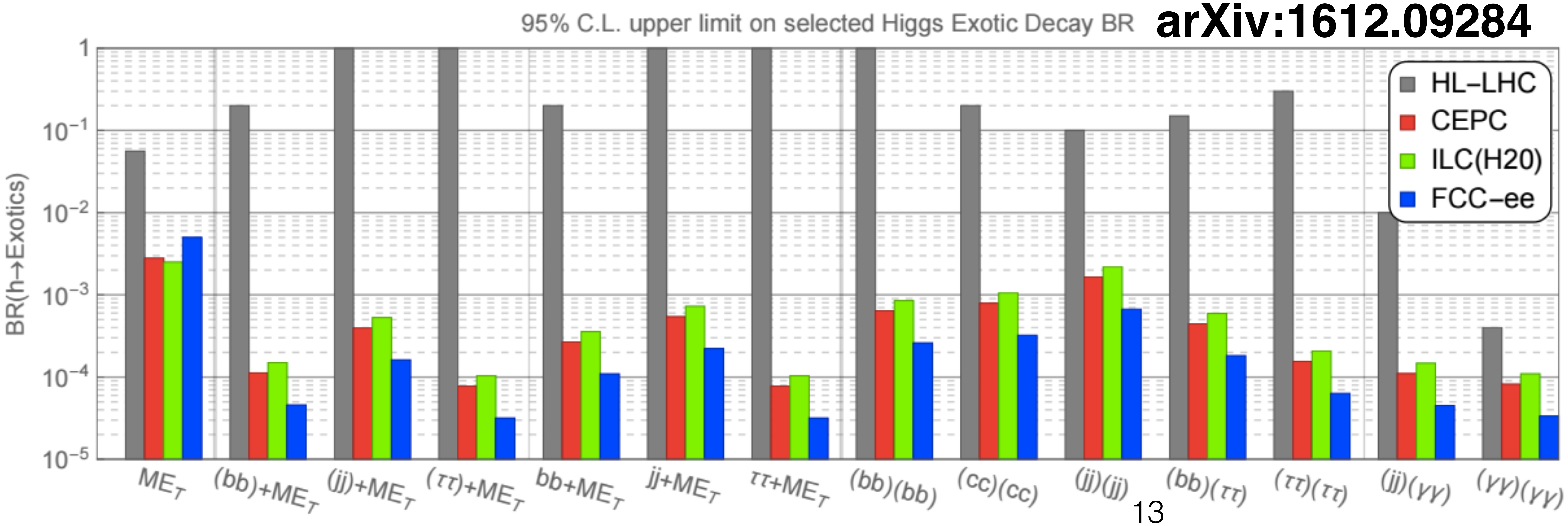


- Gen: 0.05 radians
- Nominal: 0.17 radians
- HCAL resolution
  - 0.5: 0.15 radians
  - 2.0: 0.19 radians
- ECAL resolution
  - 0.5: 0.15 radians
  - 2.0: 0.18 radians

BSM Higgs Studies

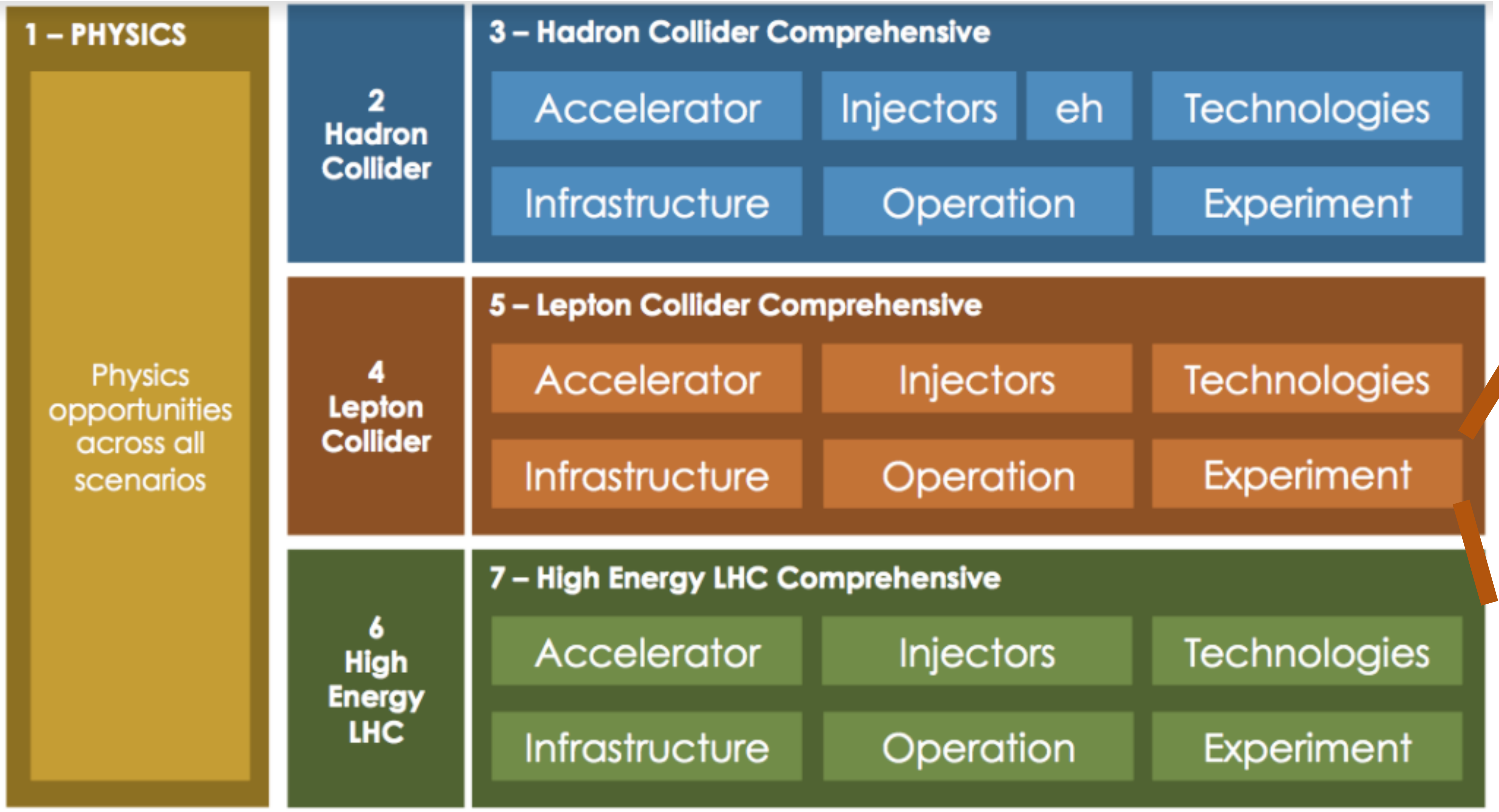
- ➡ **Example: Higgs to invisible decays**
  - follows ZH cross section measurement
  - for visualization BR(H->inv) = 100%
  - 95%CL upper limit using $5ab^{-1}$ is 0.44%
  - study published using leptonic Z decays in Eur. Phys. J. C (2017) 77: 116
  - hadronic Z decays under study. Shows similar performance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





arXiv:1612.09284

Outline of CDR Section



Higgs Physics at FCC-ee

.1 Introduction

.2 Signal and Background Processes

3 Detector Requirements

.4 Recoil Mass Measurements

4.1 ZH Cross Section

4.2 Higgs Boson Mass

.5 Higgs Boson Branching Fraction Measurements

6 Higgs Boson Coupling and Total Width

.7 Theoretical Uncertainties

8 Higgs Boson CP Measurements

.9 Exotic Higgs Boson Decays

10 Summary

Higgs Working Group

- ➡ **Work structured around a series of workshops**
  - ◉ planning workshop end of 2017 to consolidate and summarize the results
- ➡ Follow-up in FCC-ee physics meeting or dedicated FCC-ee Higgs meetings
- ➡ Worker bees are typically undergraduate students. A fresh group of summer students lined up to boost the effort
- ➡ Working group would benefit from ~3 postdocs (or experienced students) to consulted the work fill in the missing pieces

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
  - ★ Dedicated talk on Higgs synergies by Christophe Grojean later in this session

➡**Investigating requirements on detector and machine**

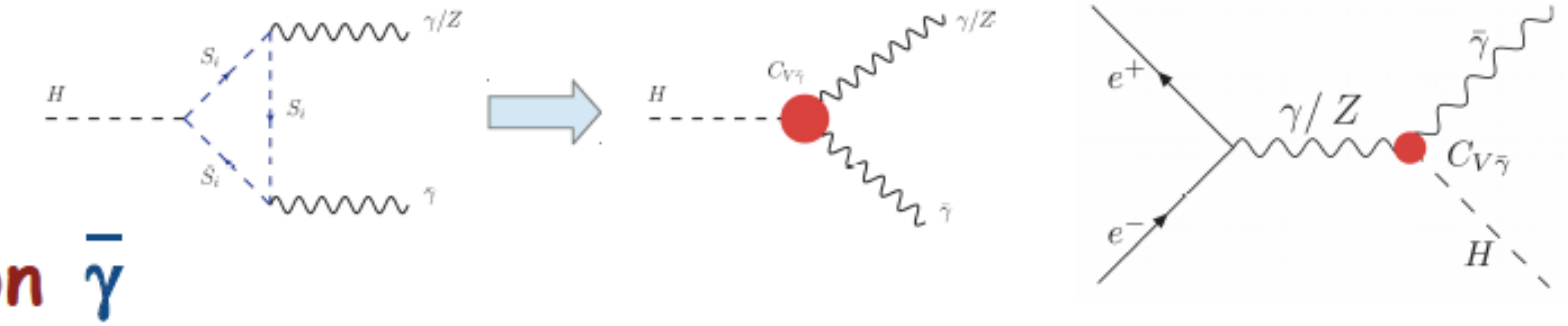
➡**Tentative outline for Higgs physics section in FCC CDR Book #5:**

Additional Material

Dark Photon Searches via Higgs Production

Biswas, Gabrielli, Heikinheimo, Mele

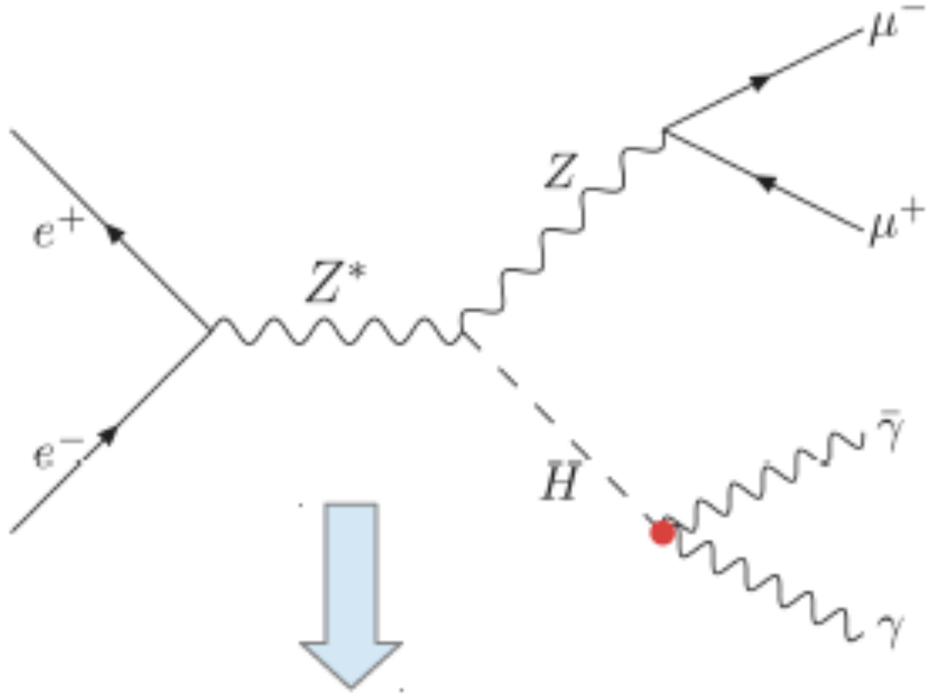
JHEP 1506 (2015) 102 + arxiv:1703.00402



Massless Dark Photon $\bar{\gamma}$

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

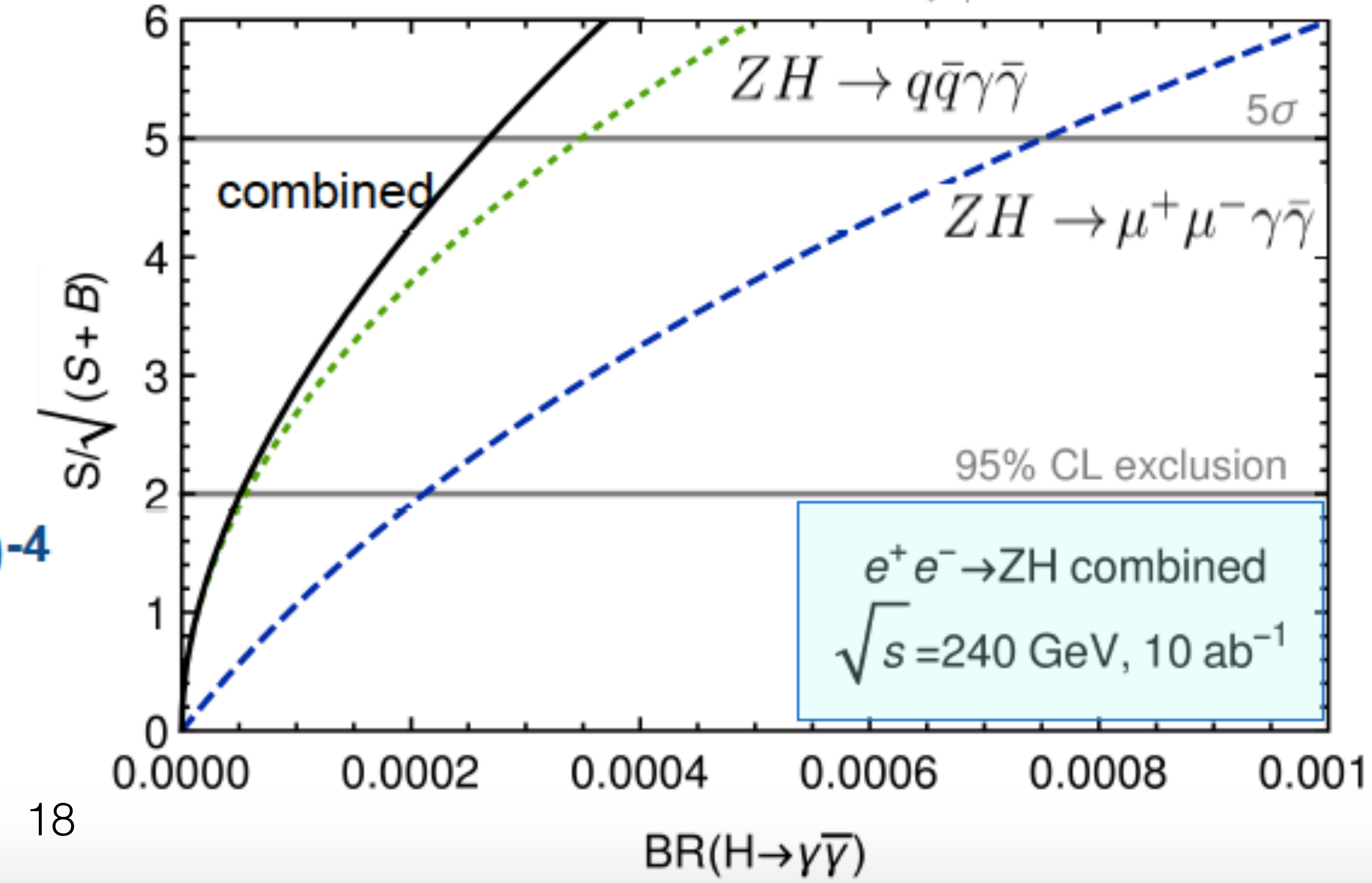
$$e^+e^- \to ZH \to (\mu^+\mu^-, q\bar{q})(\gamma\bar{\gamma})$$



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}

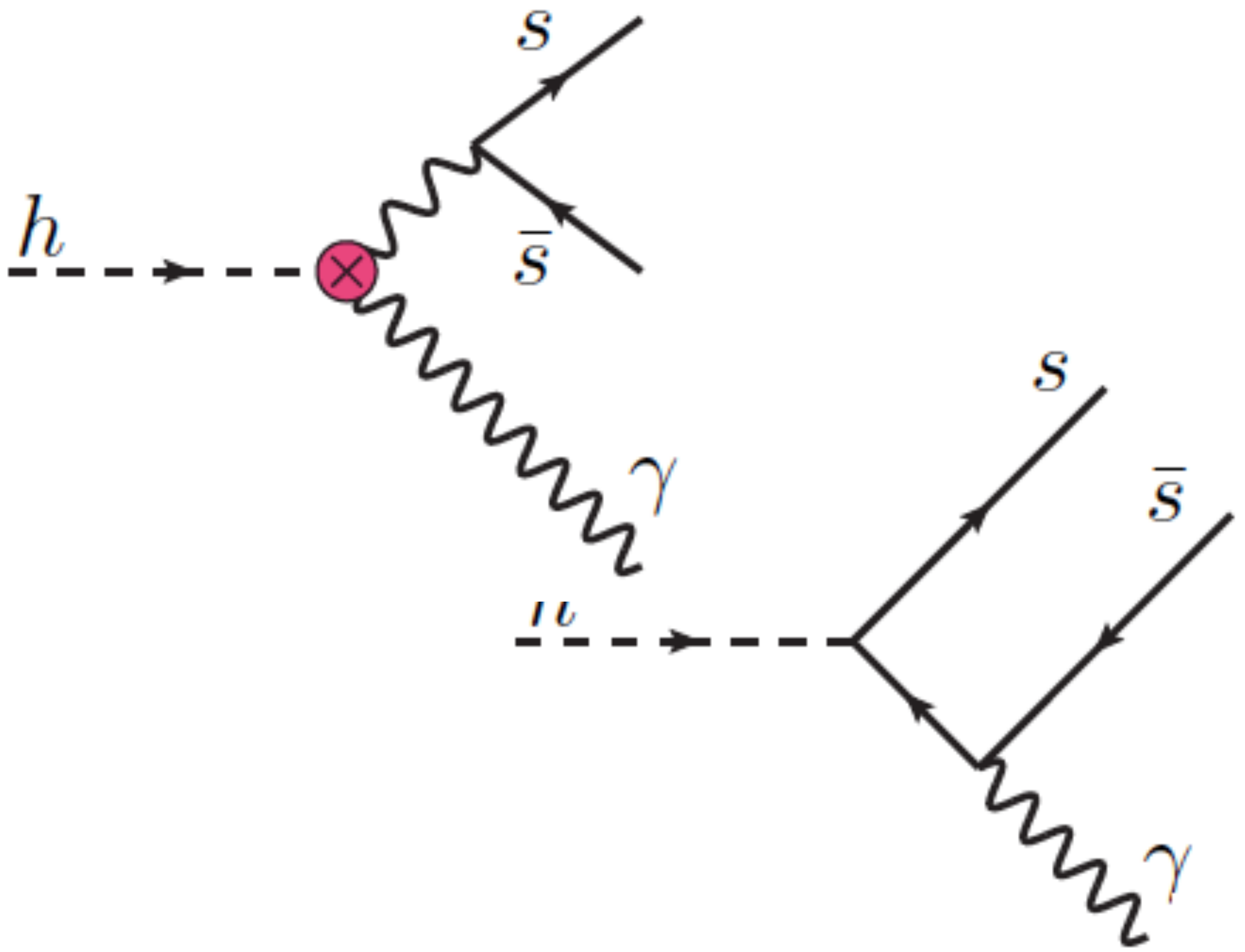
Biswas et al. PRD 93 (2016) 093011



Exclusive Higgs Boson Decays

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

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



- ➡ 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