FCC Week 2018

9-13 April 2018
Beurs van Berlage

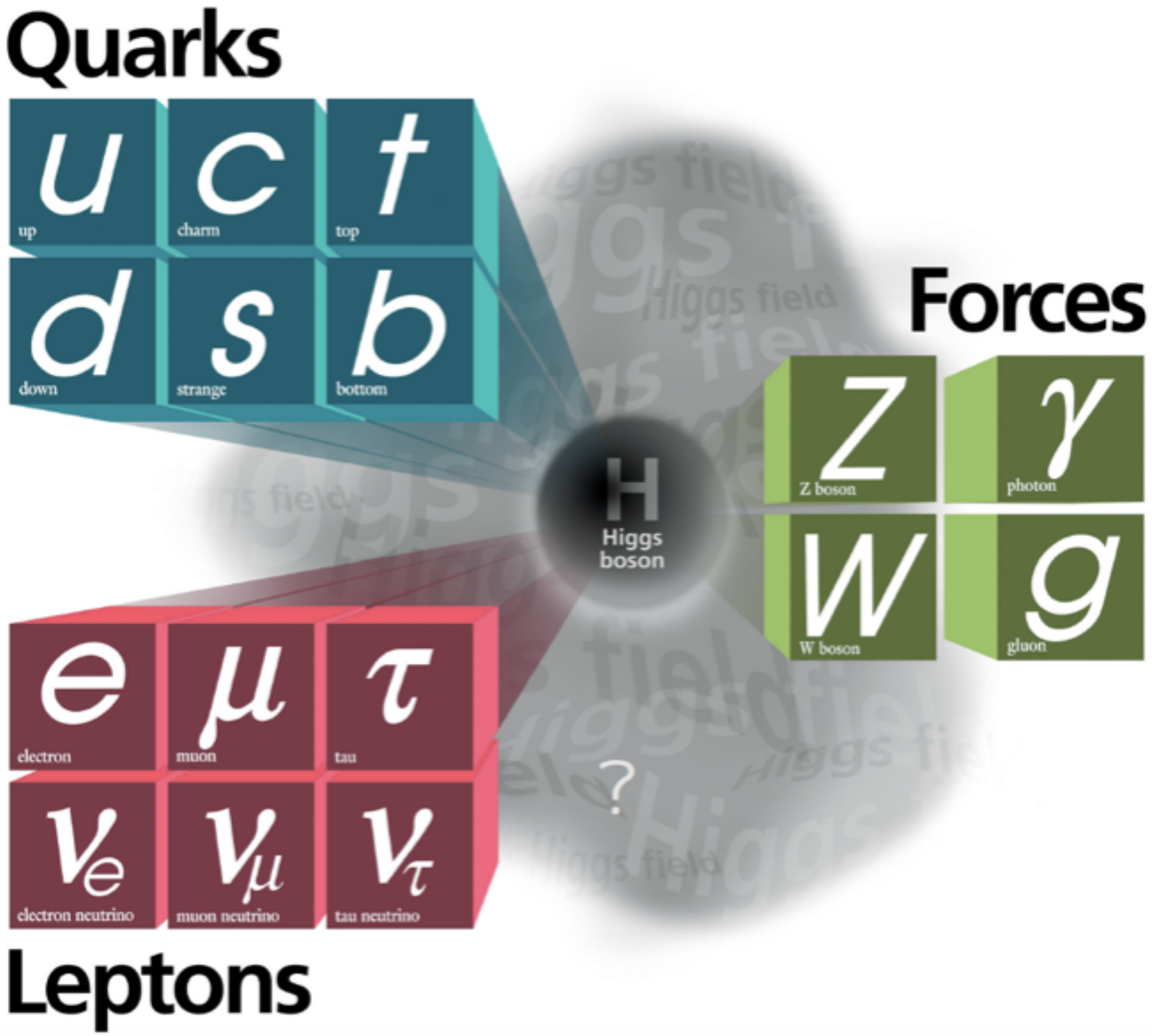
at FCC

Markus Klute (MIT)

Higgs Physics Program

- ➡ **Cornerstone of the LHC, HL-LHC, HE-LHC, and FCC (ee, ep, pp) physics program**
  - Post-discovery: The Higgs Boson as Tool for Discovery

- ➡ **Many open questions and opportunities, ways to study Higgs bosons**
  - Interactions with SM particles
  - Interactions with new particles (including Higgs as portal to DM)
  - Role of the Higgs boson in vector boson scattering
  - Extended Higgs sectors
  - Interactions with itself



Standing on the shoulder of giants

➡ **LHC experiments not only discovered the Higgs boson but will leave a legacy of precision measurements and constraints on new physics**

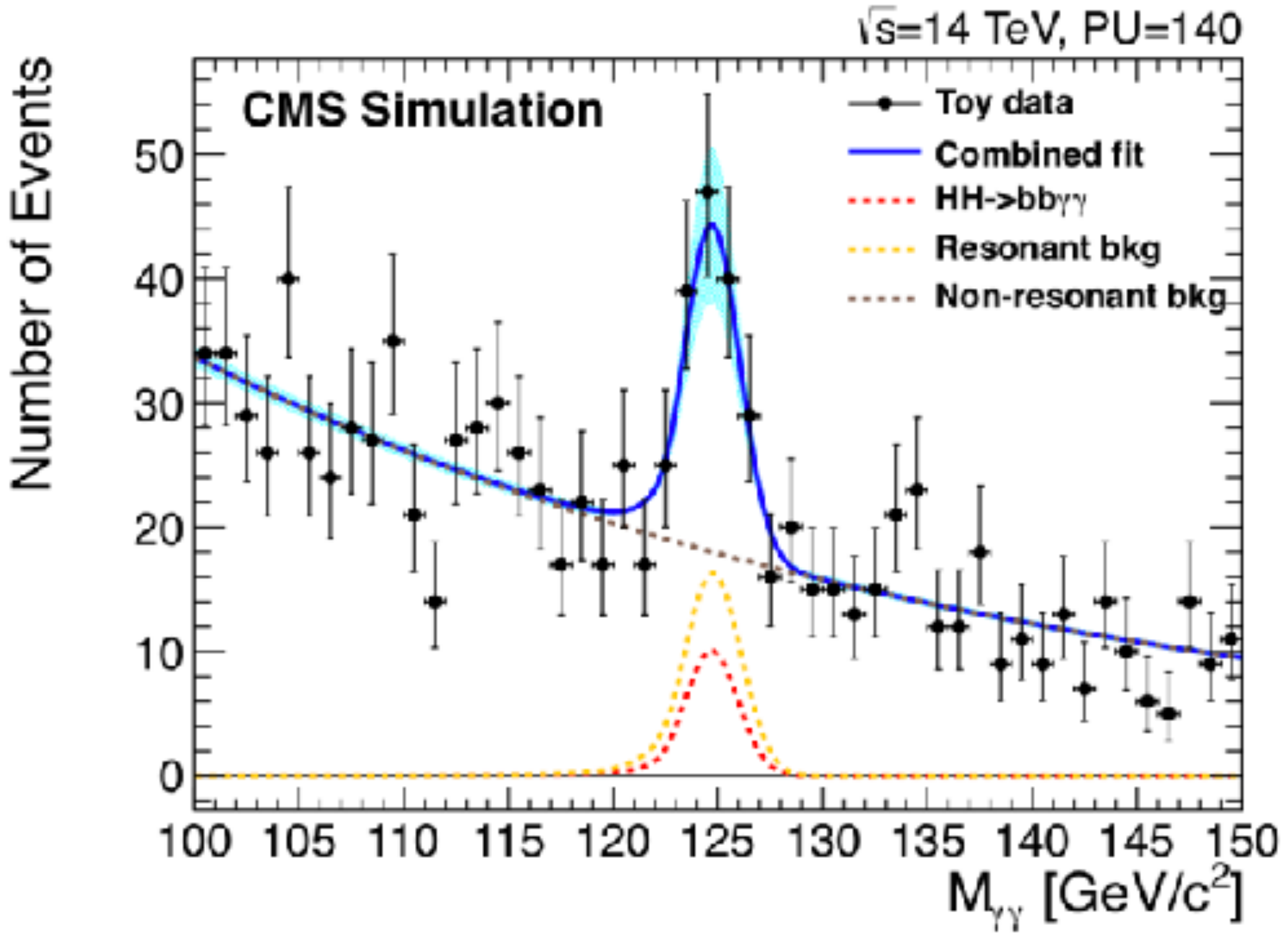
➡ **FCC offers unique measurements and an enormous dataset**

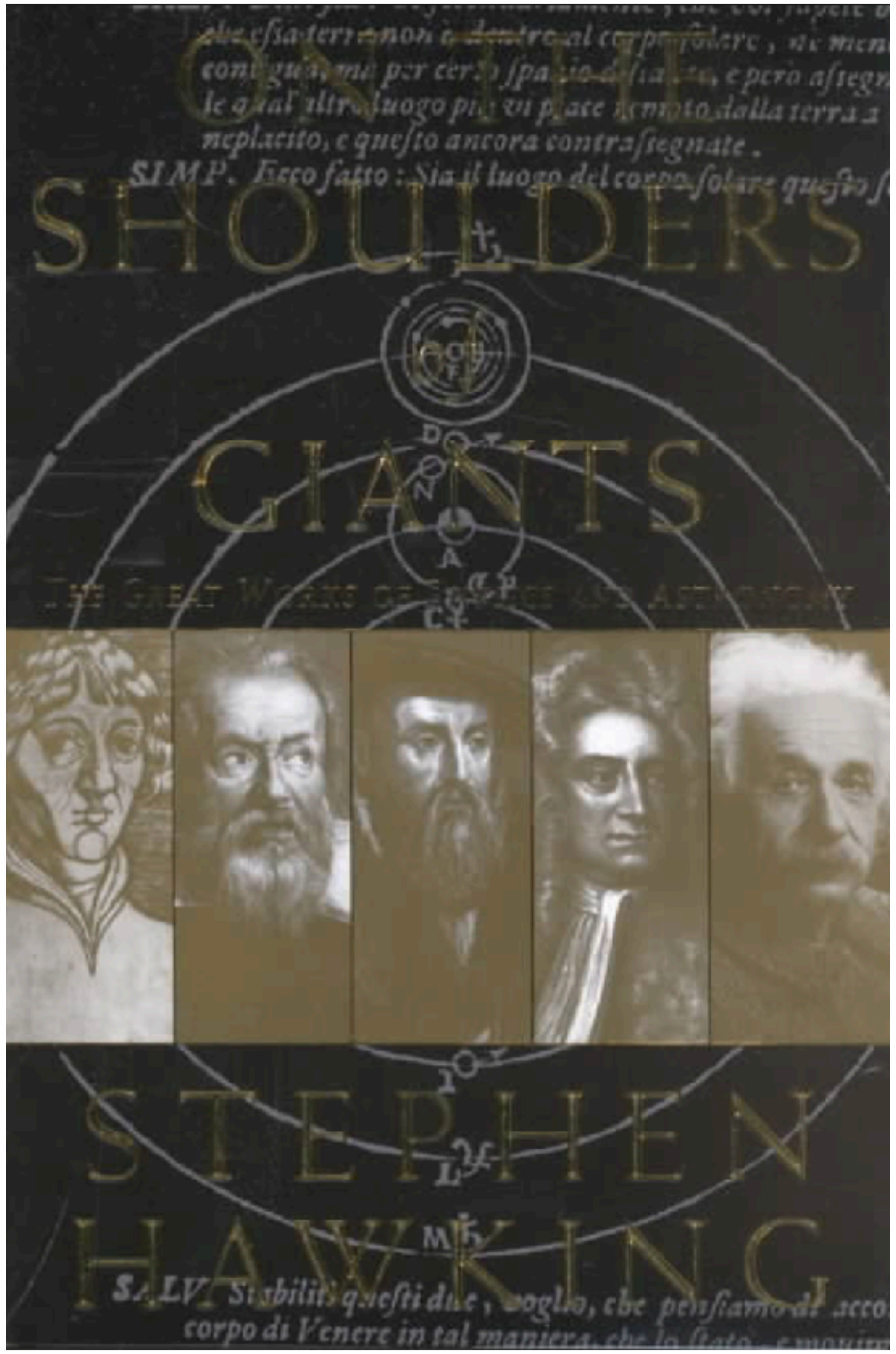
➡ **Selected highlights**

- Study of Higgs boson couplings with O(%) accuracy

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

- Probing di-Higgs production with 3σ sensitivity





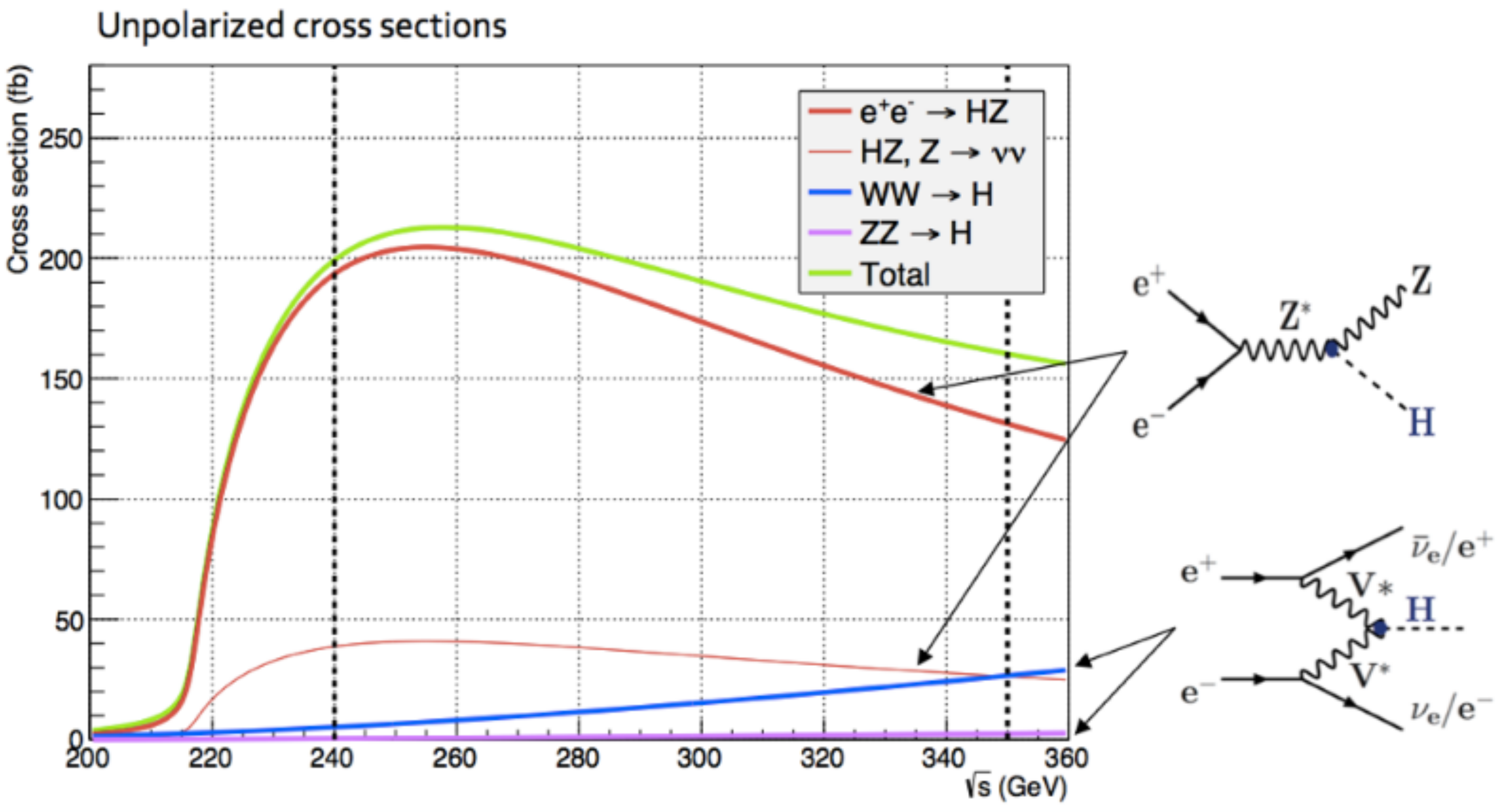
Higgs Boson Datasets: FCC-ee

FCC-ee

$5ab^{-1}$ @ 240 GeV

~$1.5ab^{-1}$@ 350-365 GeV

working point	luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	total luminosity (2 IPs)/ yr	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	25	7 ab^{-1}/year	**10 ab^{-1}**	**1**
H	7.0	1.8 ab^{-1}/year	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: **1 year**				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.4	0.36 ab^{-1}/year	**1.5 ab^{-1}**	**4**

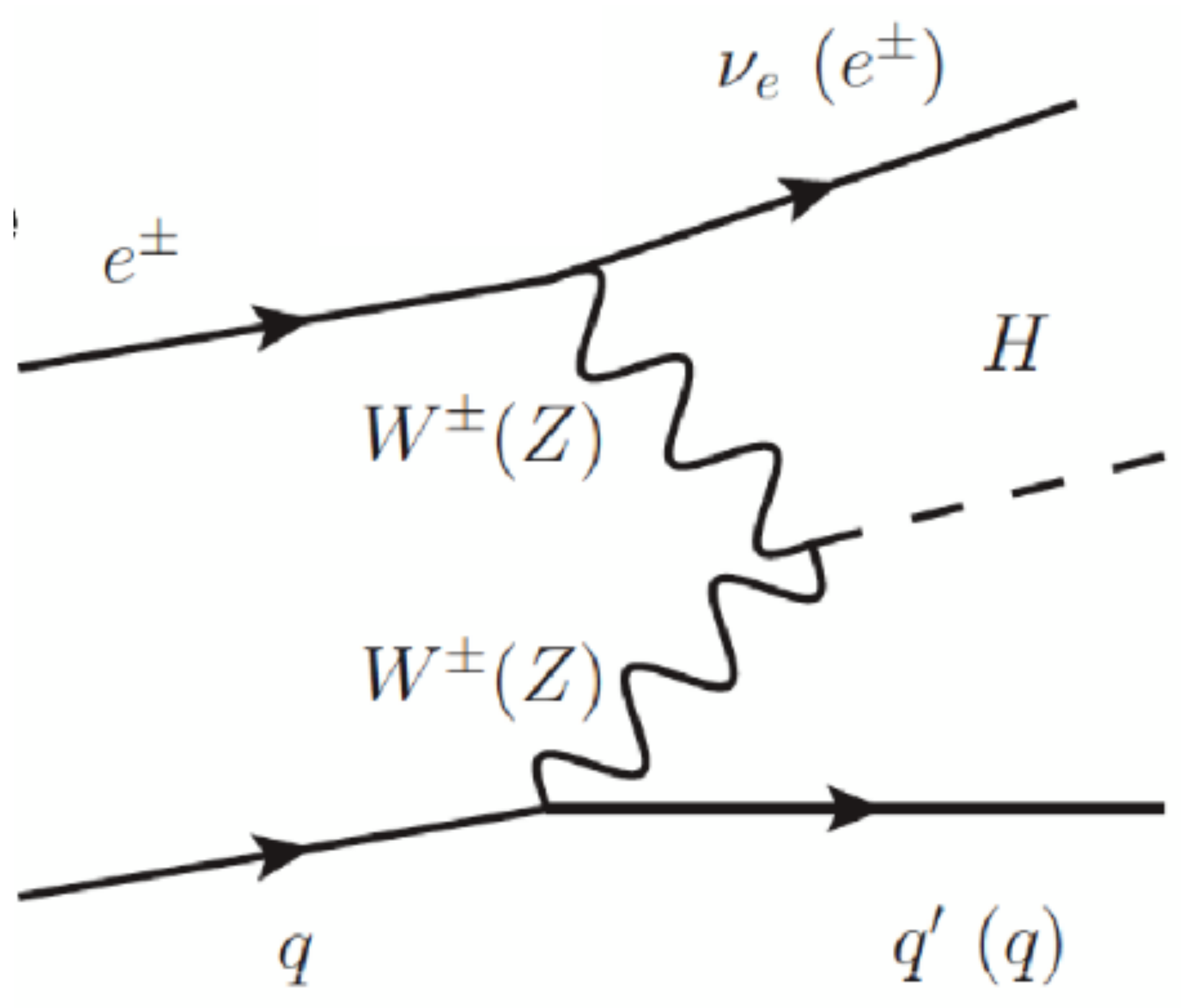


	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab-1)	5	1.5
# Higgs bosons from e^+e^-→HZ	1,000,000	200,000
# Higgs bosons form fusion process	25,000	40,000

Higgs Boson Datasets: FCC-eh

FCC-eh

2ab^{-1} @ 60GeV x 50 TeV, 3.5 TeV



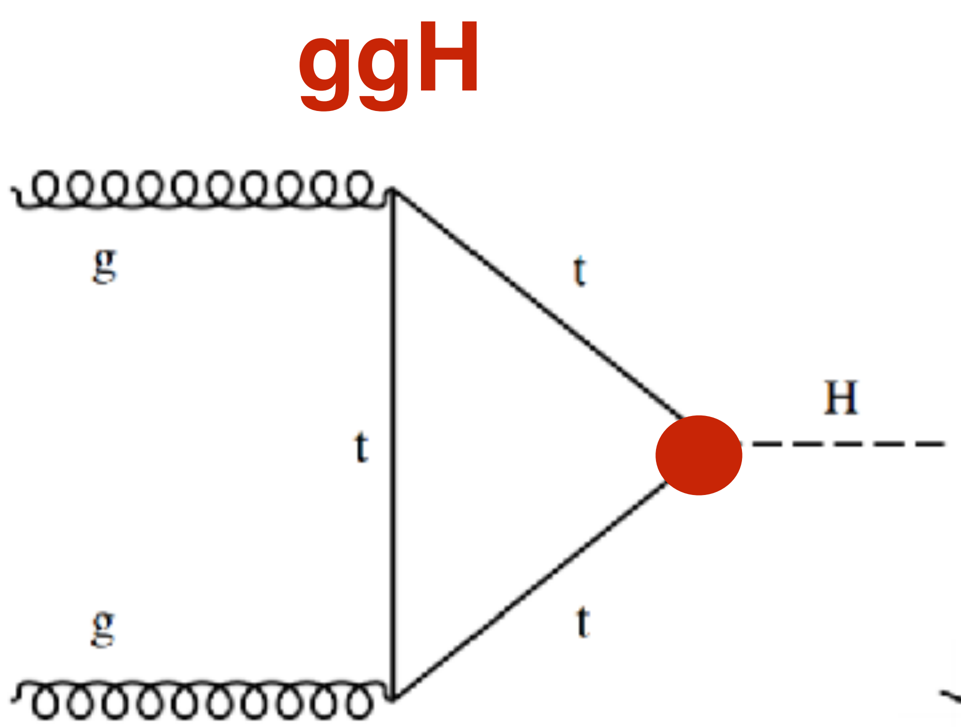
Luminosity for LHeC, HE-LHeC and FCC

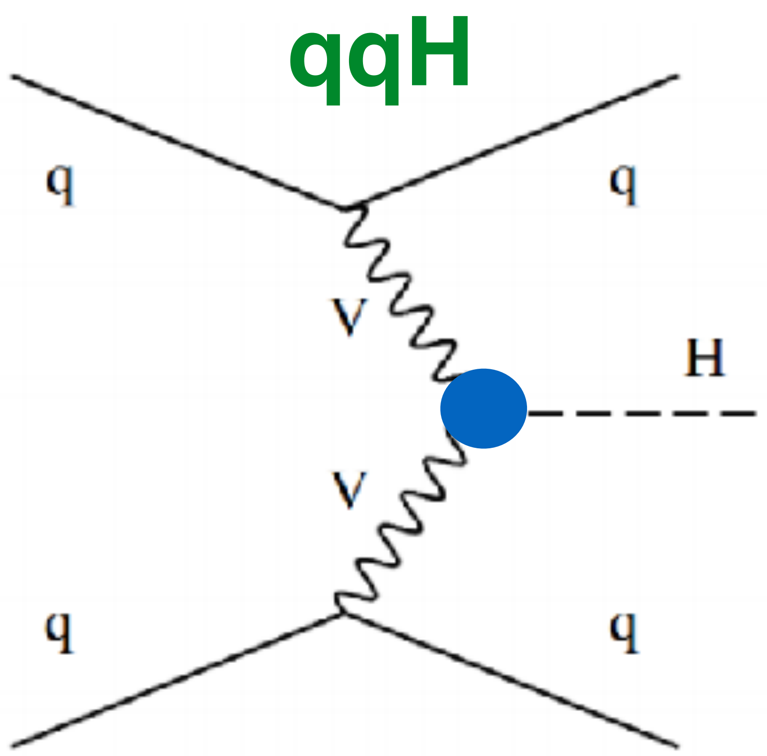
parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [$10^{33}\text{cm}^{-2}\text{s}^{-1}$]	1	8	12	15

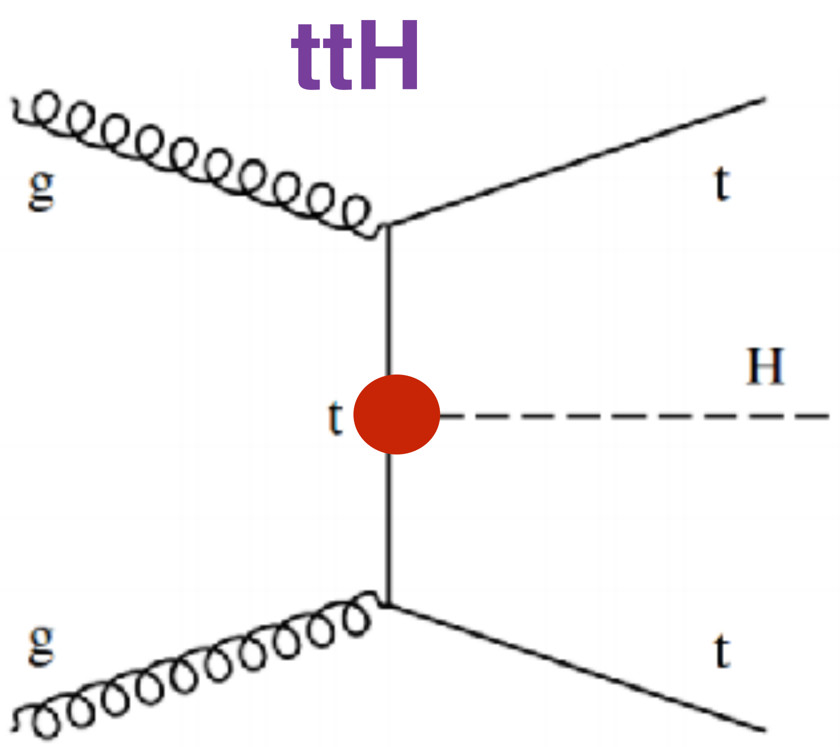
Oliver Brüning[1], John Jowett[1], Max Klein[1,2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool
April 6^{th}, 2017

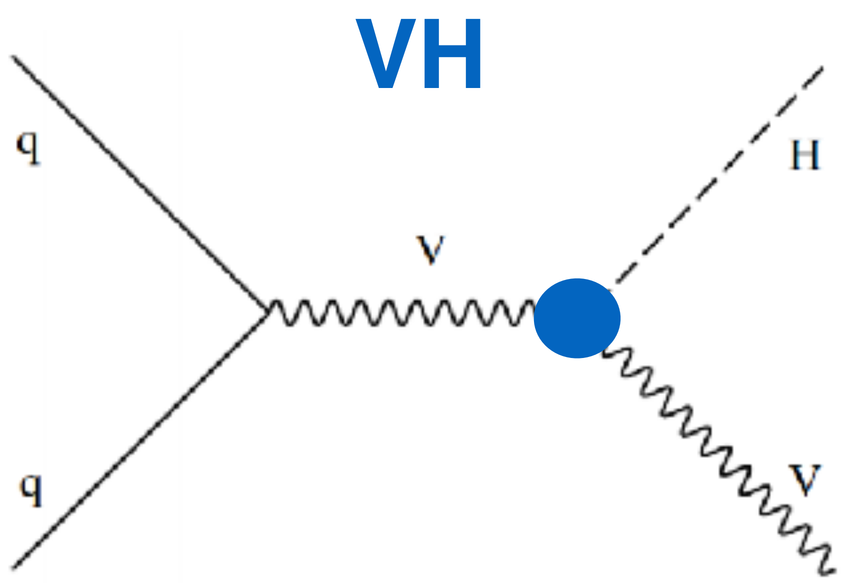
	FCC-ep 3.5 TeV
Total Integrated Luminosity (ab-1)	2
# Higgs bosons from NC [LO]	254,000
# Higgs bosons form CC [LO]	1,120,000
# Higgs boson from CC with 80% polarization [LO]	2,016,000

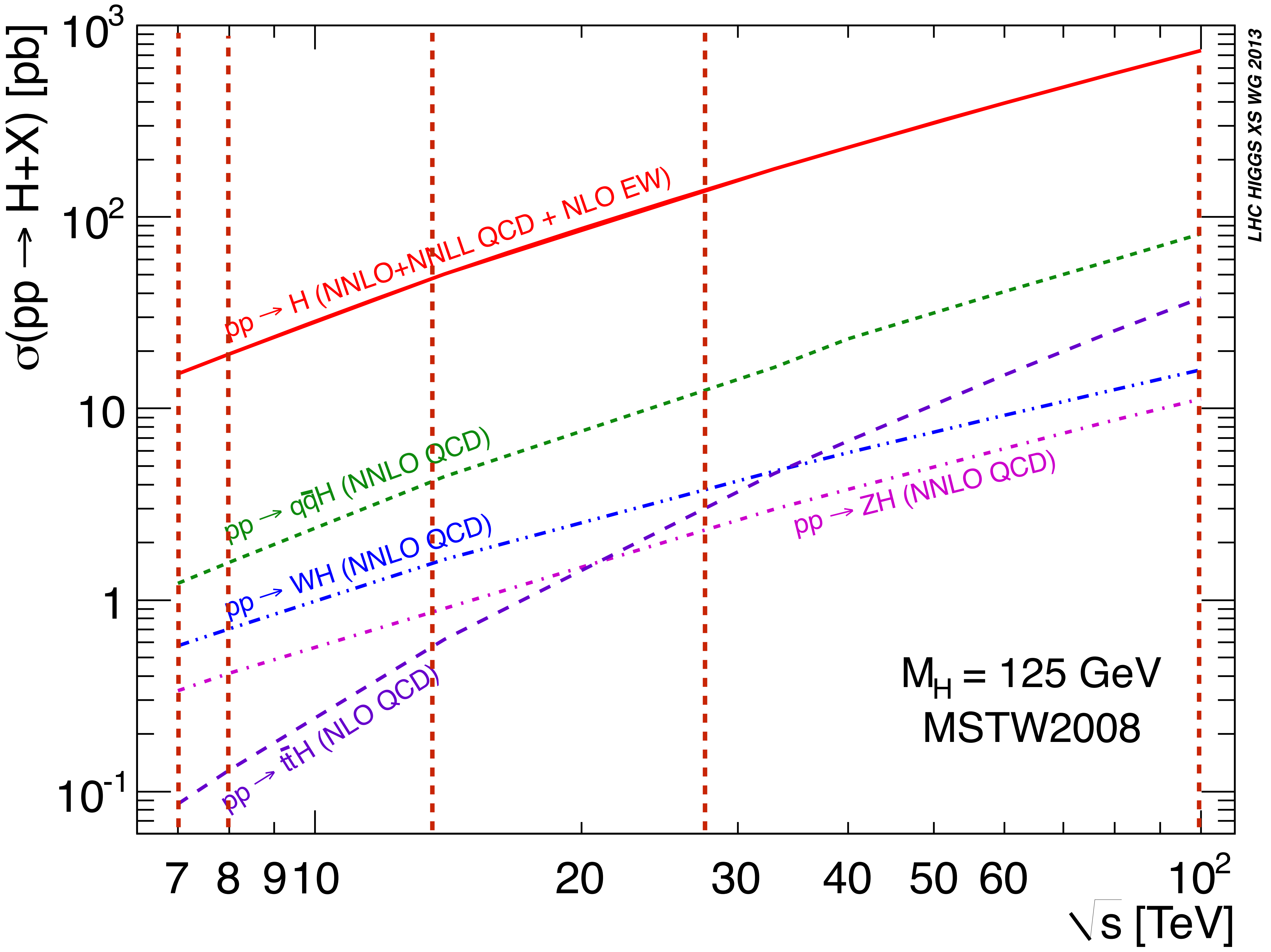
LHC, HL-LHC, HE-LHC, FCC-pp Higgs Production











	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N^3LO)	49 pb	803 pb	16
VBF (N^2LO)	3.8 pb	69 pb	16
VH (N^2LO)	2.3 pb	27 pb	11
ttH (N^2LO)	0.5 pb	34 pb	55

Higgs Boson Datasets: FCC-hh

FCC-hh
$30ab^{-1}$ @ 100 TeV

➡ Extrapolation for Higgs Physics

- 10 times larger dataset, better detectors, more difficult environment
- 11-55 times larger cross section for single Higgs production
- 40 times larger cross section for double Higgs production

➡ Effective statistical gain in Higgs measurements w.r.t HL-LHC

- Factor > 10 for single Higgs production
- Factor 20 for double Higgs production

parameter	FCC-hh	
collision energy cms [TeV]	100	
dipole field [T]	16	
circumference [km]	97.75	
beam current [A]	0.5	
bunch intensity [10^{11}]	1	1
bunch spacing [ns]	25	25
synchr. rad. power / ring [kW]	2400	
SR power / length [W/m/ap.]	28.4	
long. emit. damping time [h]	0.54	
beta* [m]	1.1	0.3
normalized emittance [μm]	2.2	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30
events/bunch crossing	170	1000
stored energy/beam [GJ]	8.4	

Higgs Boson Datasets: HE-LHC

HE-LHC

$12ab^{-1}$ @ 27 TeV

➡ Extrapolation for Higgs Physics

- 4 times larger dataset, better detectors, more difficult environment
- 2.5 times larger cross section for single Higgs production
- 5 times larger cross section for double Higgs production

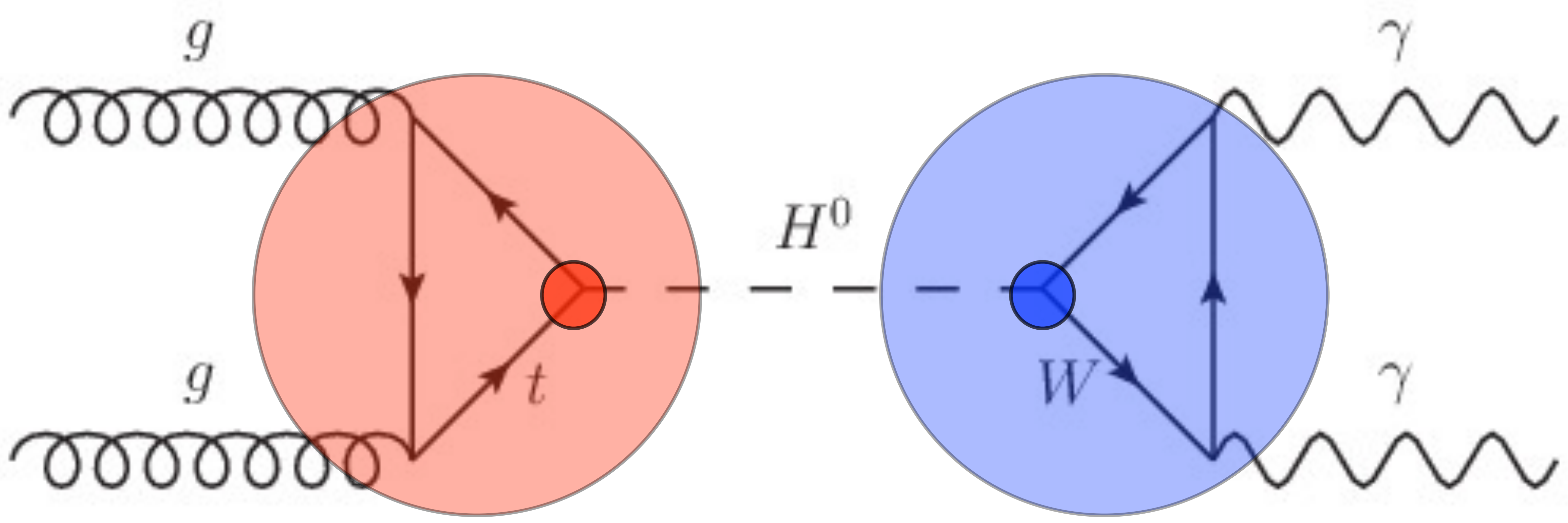
➡ Effective statistical gain in Higgs measurements w.r.t HL-LHC

- Factor 3 for single Higgs production
- Factor 5 for double Higgs production

➡ Studies can interpolated between HL-LHC and FCC-hh

parameter	HE-LHC
collision energy cms [TeV]	27
dipole field [T]	16
circumference [km]	27
straight section length [m]	528
# IP	2 & 2
beam current [A]	1.12
bunch intensity [10^{11}]	2.2 (0.44)
bunch spacing [ns]	25 (5)
rms bunch length [cm]	7.55
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	25
events/bunch crossing	~800 (160)
stored energy/beam [GJ]	1.3
beta* [m]	0.25
norm. emittance [μm]	2.5 (0.5)

Extracting Higgs Boson Couplings: FCC-ep, hh

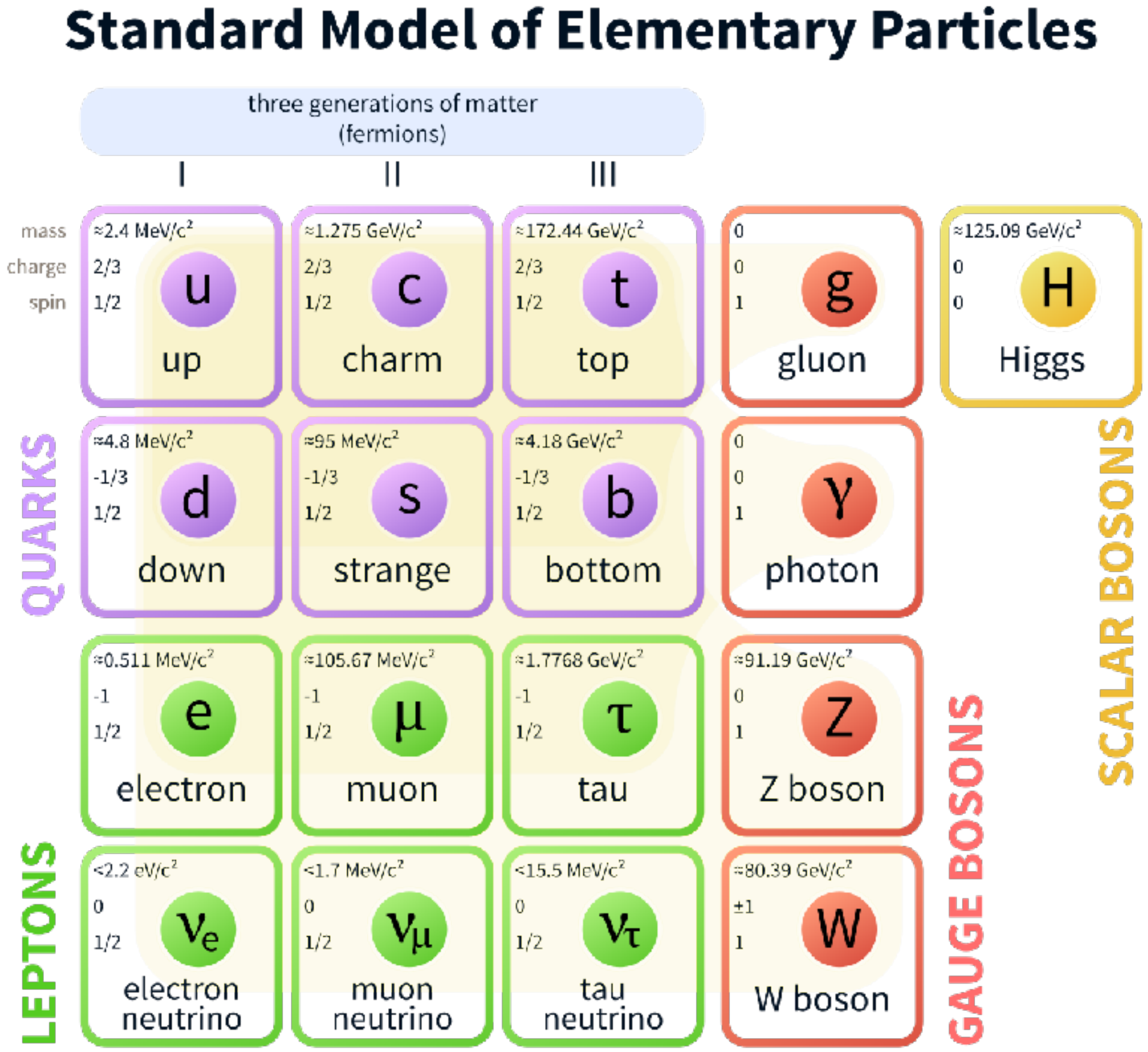


$$(\sigma \cdot \mathrm{BR})(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) = \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_\mathrm{H}^2}$$

➡ Total Higgs width (Γ_H) can not be measured at the FCC-eh or FCC-hh with precision

➡ Higgs couplings can only be measured with precise knowledge of Γ_H (or one Higgs coupling) or using theoretical assumptions

➡ Ratio measurements eliminate this problem, also allow for cancelation of systematic uncertainties

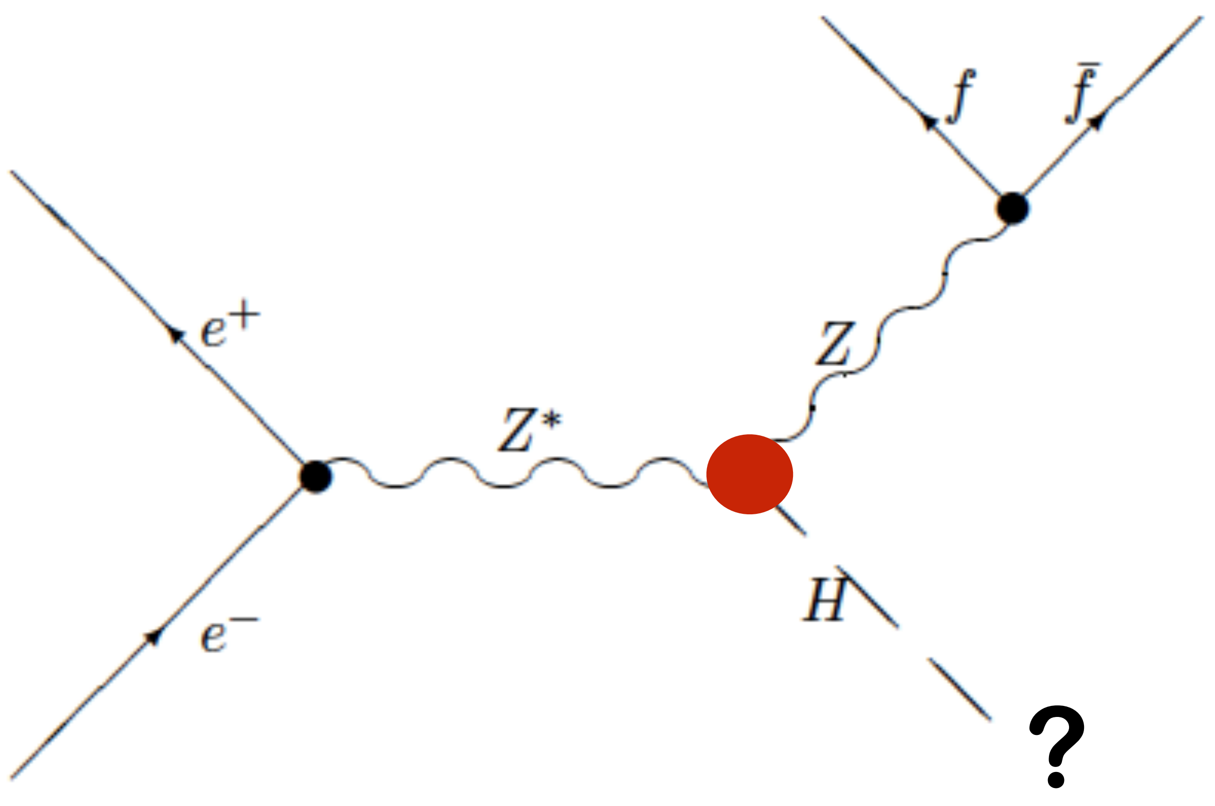


Higgs coupling to Z bosons: FCC-ee

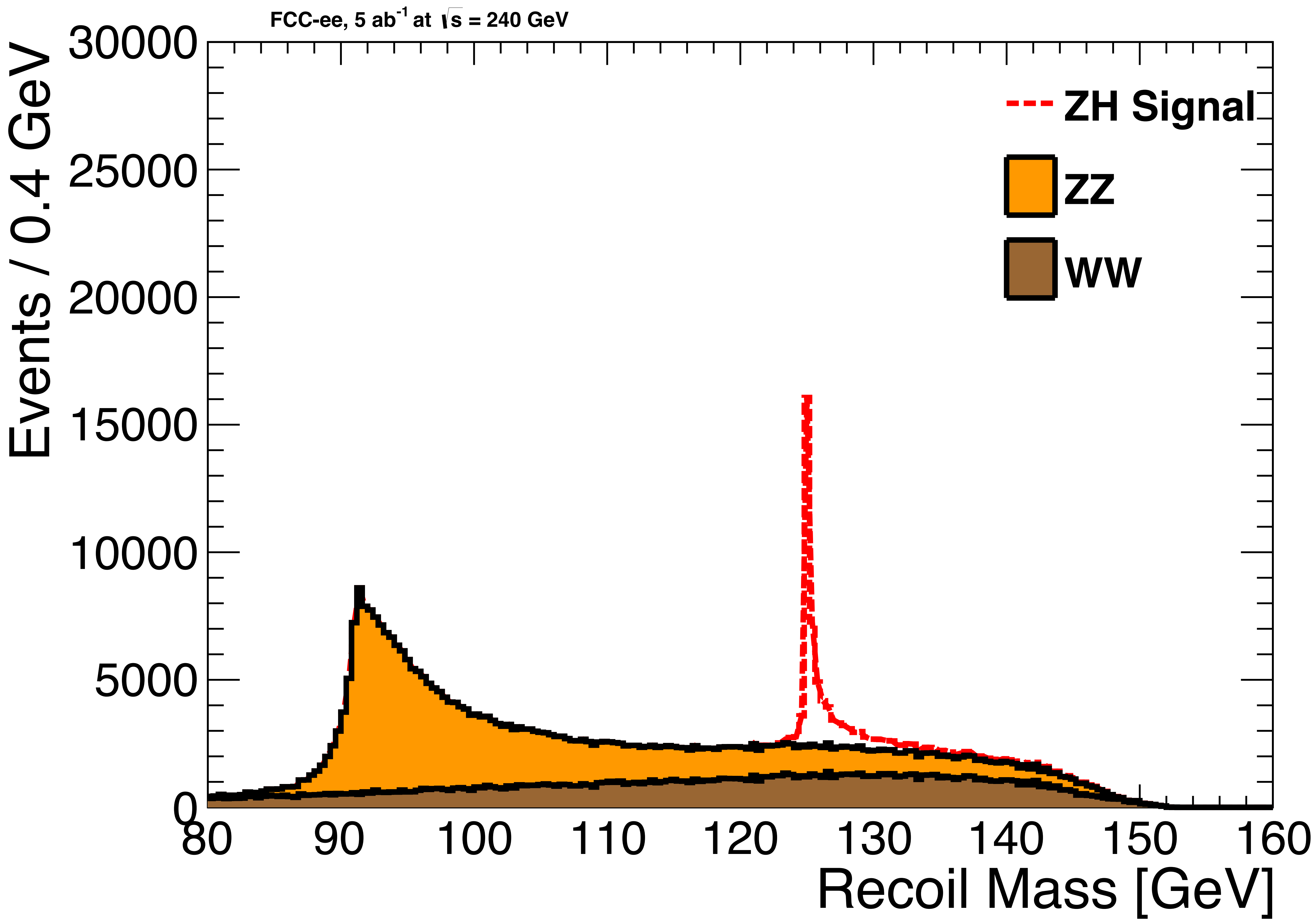
➡ **Recoil method provides unique opportunity for decay-mode independent measurement of HZ coupling**

- Higgs events are tagged Higgs decay mode independent
- expected precision **0.7%** on ZH cross section
- using only leptonic Z decays and only a measurement at 240 GeV so far

$$\sigma(ee \rightarrow ZH) \propto g_{HZ}^2$$



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



Total Higgs Boson Width: FCC-ee

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

- 1) tagging Higgs final states

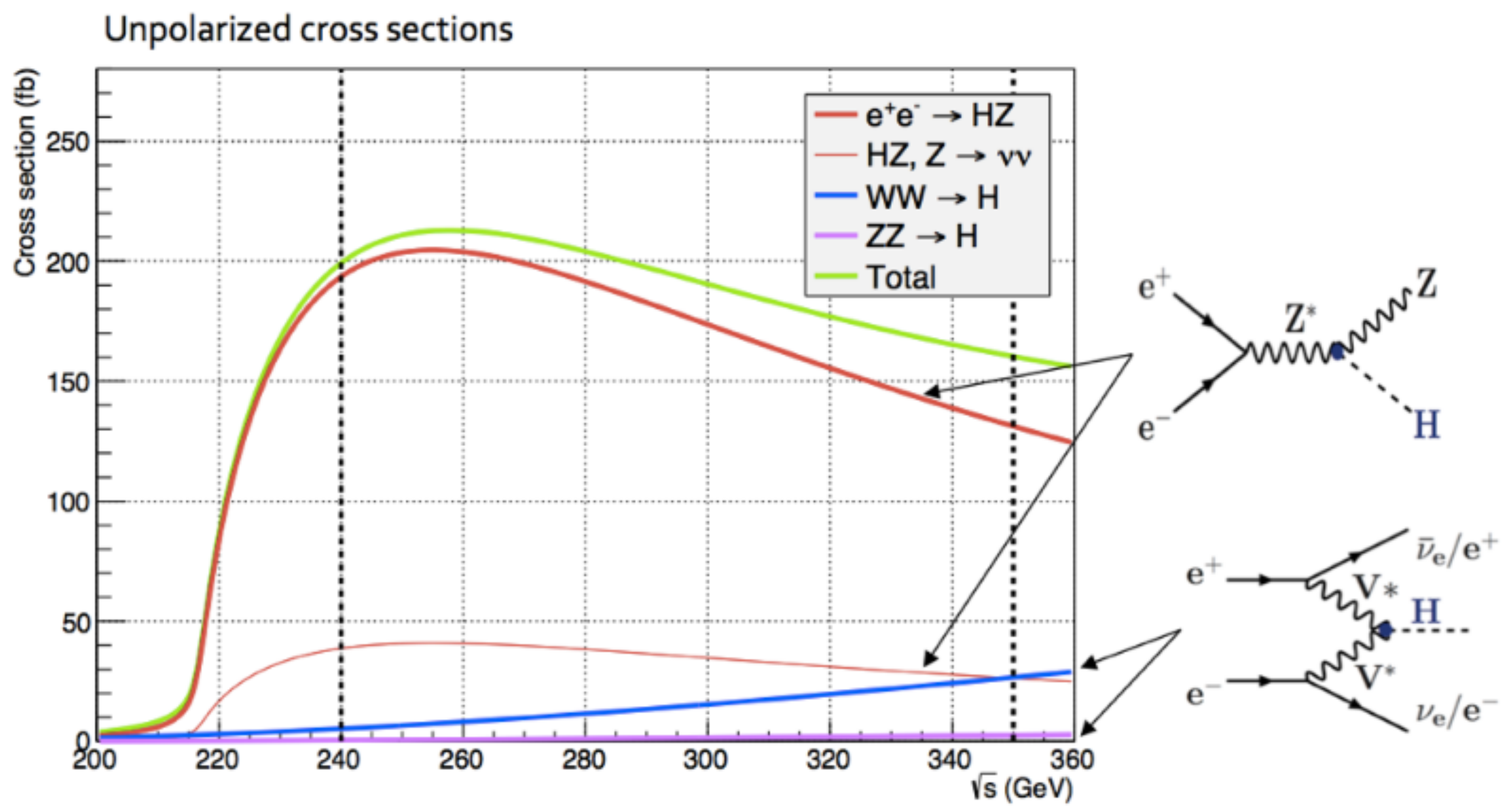
$$\sigma(\mathrm{ee} \rightarrow \mathrm{ZH}) \cdot \mathrm{BR}(\mathrm{H} \rightarrow \mathrm{ZZ}) \propto \frac{g_{\mathrm{HZ}}^4}{\Gamma}$$

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

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

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

- 3) combination of all measurements



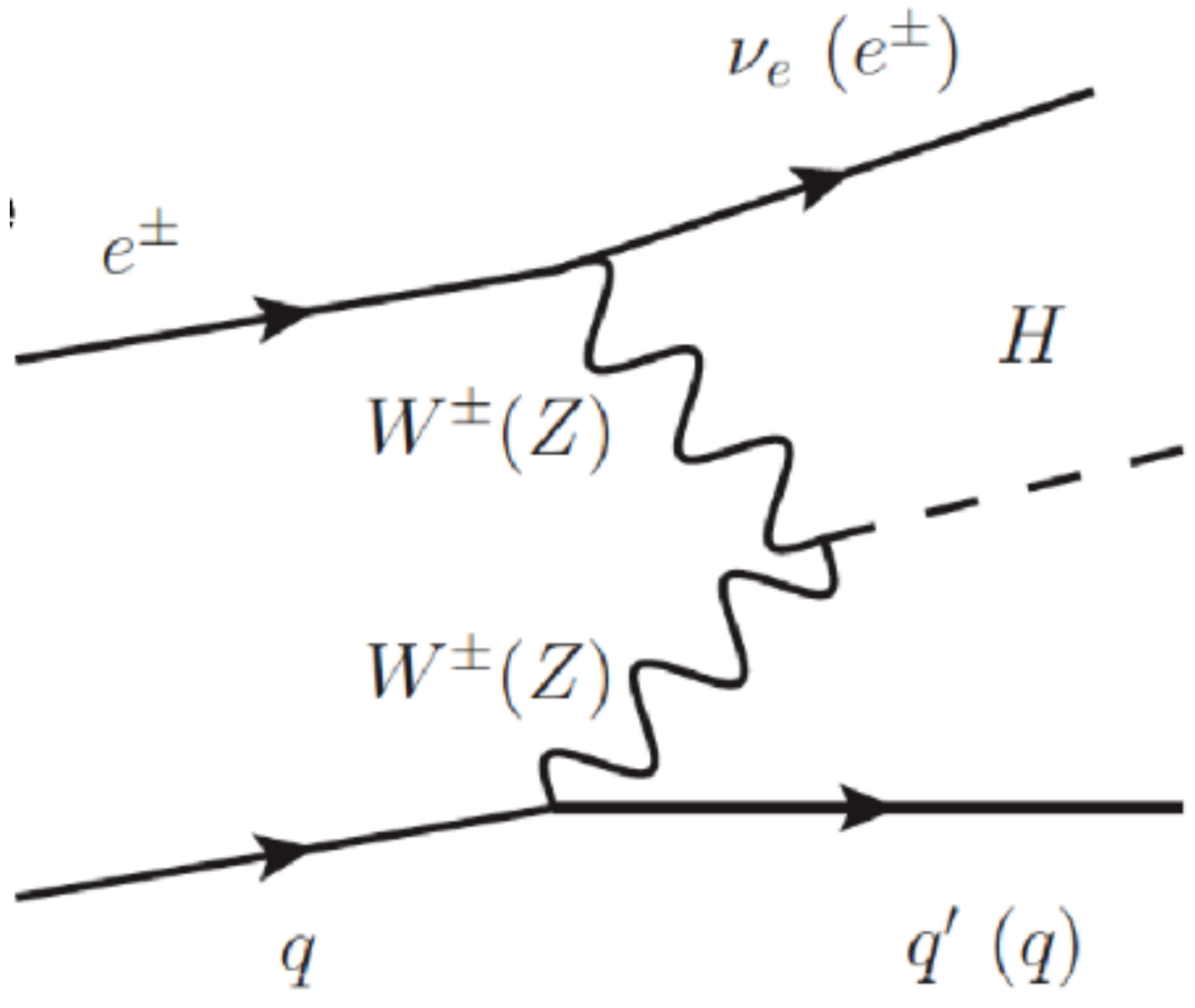
Higgs Boson Couplings: FCC-ee

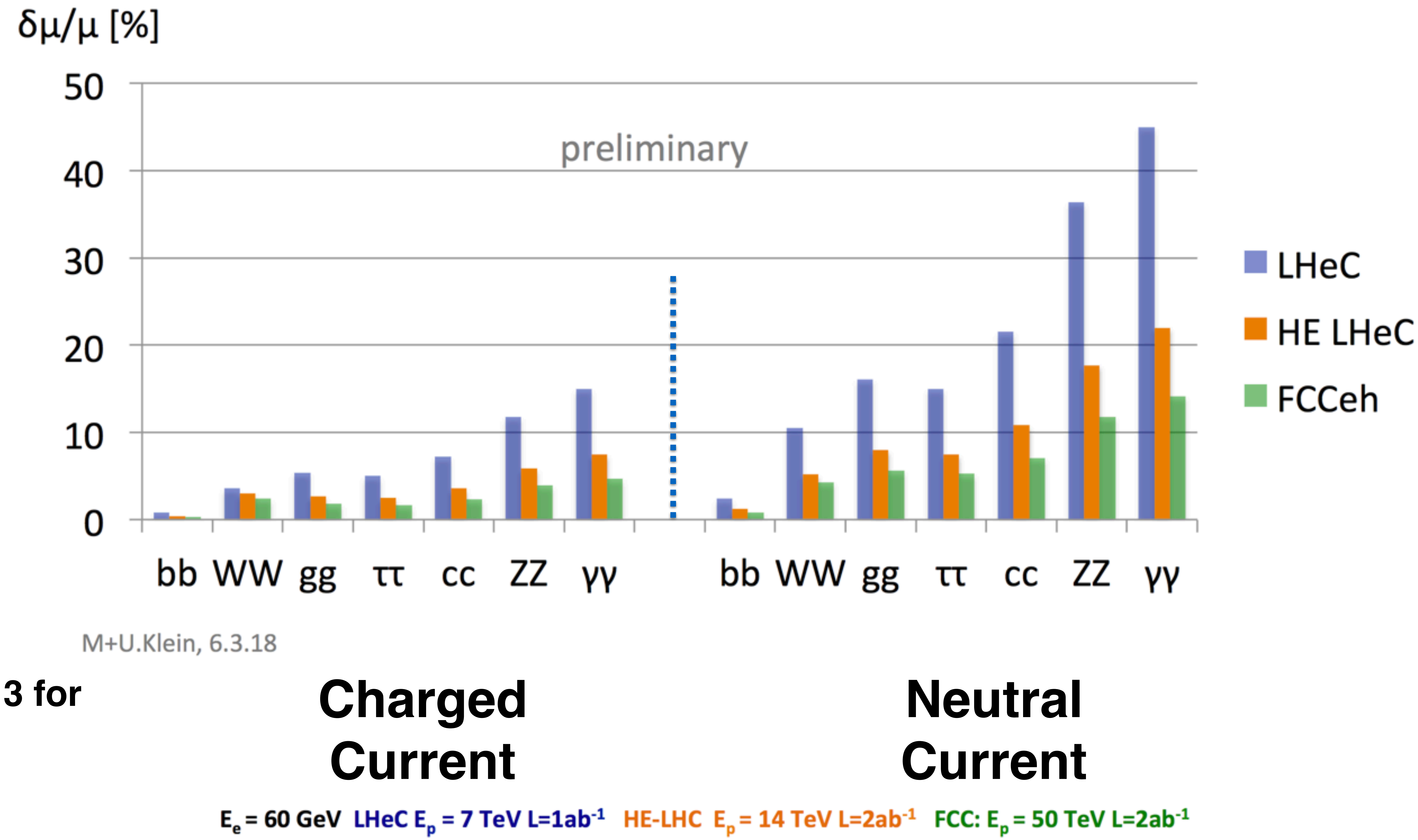
➡ Precision Higgs coupling measurements

- absolute coupling measurements enabled by HZ cross section and total width measurement
- data at 350 GeV constrain total width
  - only used H→bb in fusion production so far
- tagging individual Higgs final states to extract various Higgs couplings
- 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
  - improvements 10-35% on cross section measurements
    - see Colin Bernet's talk in Tuesday session
- Discussion of coupling fits in Jorge de Blas' talk later in this session

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 Cross Section Measurements: FCC-eh



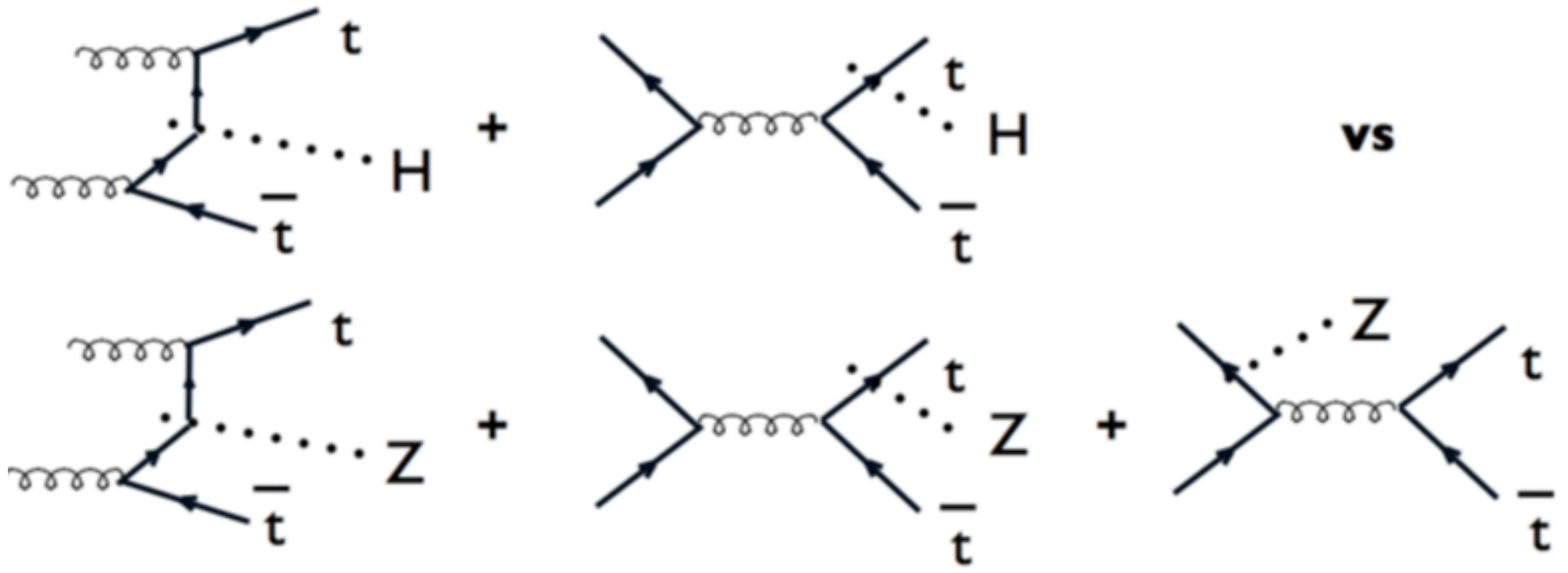


- ➡ **Summary of Higgs boson Xsec. measurements for charged and neutral current Higgs production**
- ➡ **Good S/B in most channels, e.g. S/B ~ 3 for bb mode**
- ➡ **Statistical uncertainties only**
- ➡ **Coupling measurements enabled by FCC-ee total width measurement**

More details in Uta Klein's talk Thursday

Top Yukawa: FCC-hh

➡ **Extract Y_t from σ(ttH) / σ(ttZ)**

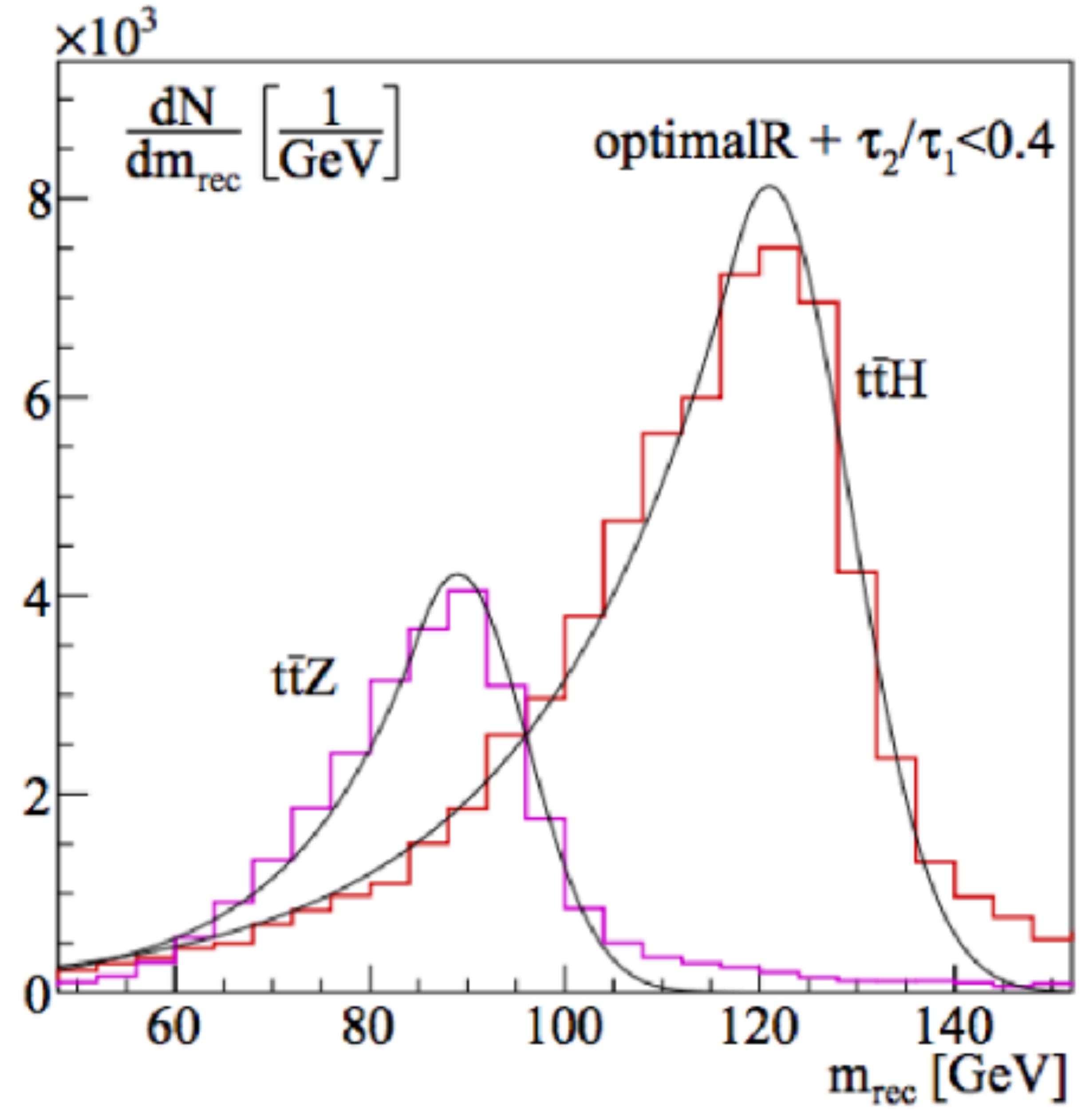


➡ **Final states**

- Boosted Higgs
- Boosted hadronic top
- Leptonic decays

➡ **Precision measurement of top-Z coupling and Higgs total width from FCC-ee**

➡ **Theory uncertainties discussed in [arXiv: 1507.08169](arXiv:1507.08169)**



δY_t (stat + syst $_{Th}$) ~ 1%

Fit and extract N_H / N_Z to ≈1% accuracy

Ratio Measurements: FCC-hh

➡ **Ratio measurements allow for low systematic uncertainties**

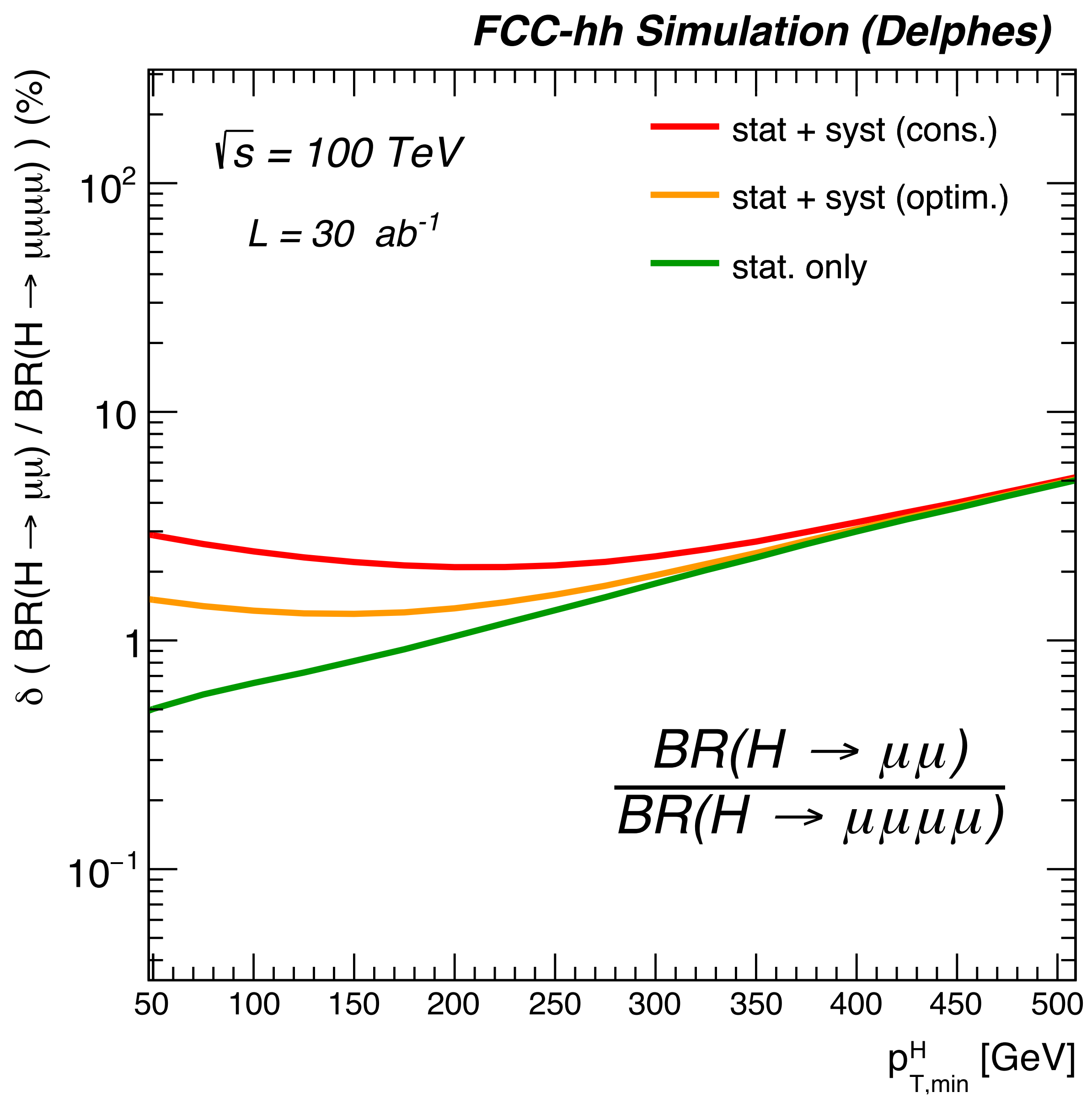
➡ **The large dataset allows exploitation of low background (high S/B) regions**

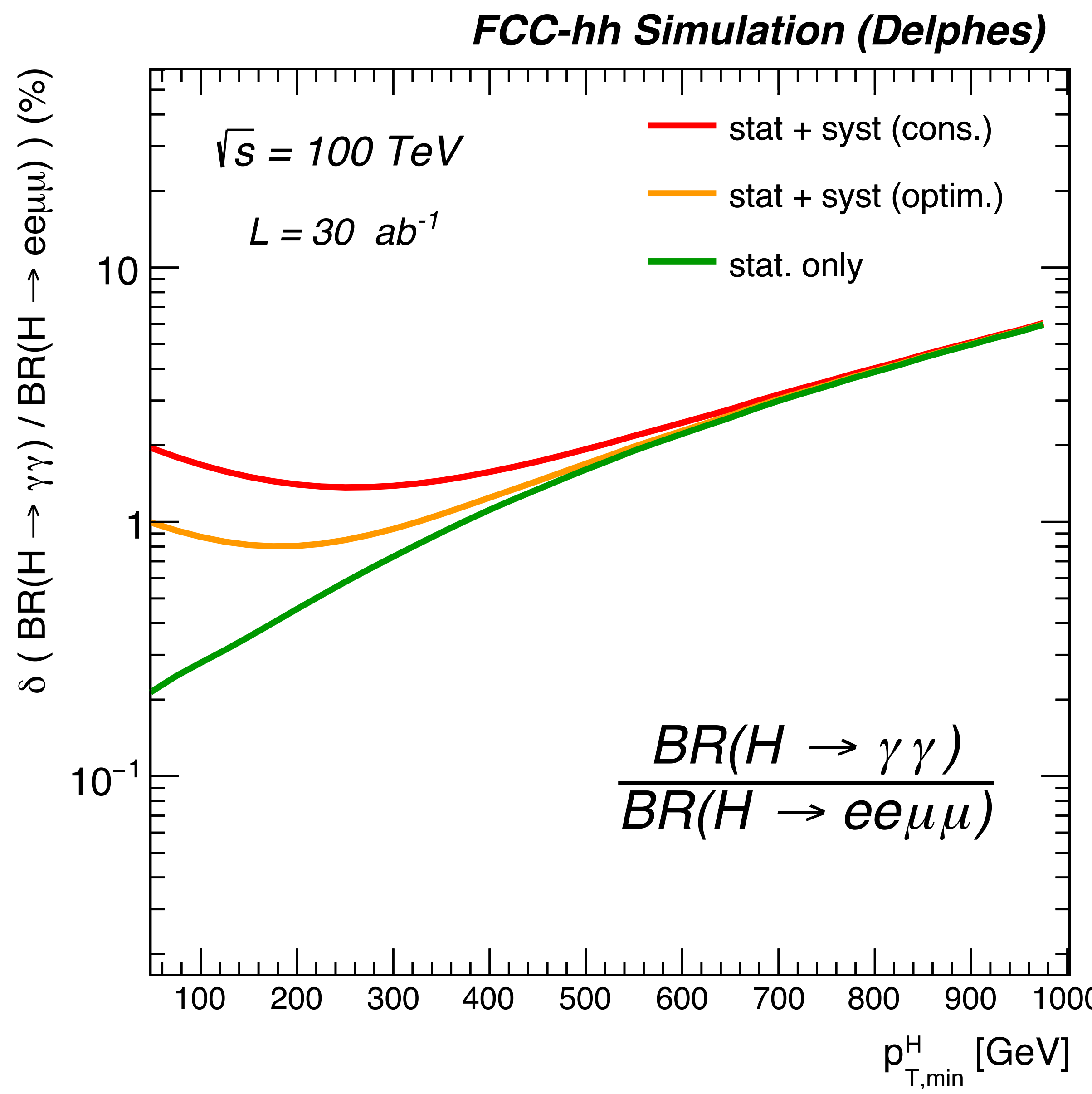
➡ **Examples shown here:**

- systematic uncertainties on objects included
- assumption that e and ɣ systematics cancel
- signal extraction systematics not included

➡ **Illustrating O(1%) precision measurements including systematic uncertainties**

➡ **Higgs coupling measurements enabled in combination with FCC-ee**





Higgs CP Studies at FCC-ee

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

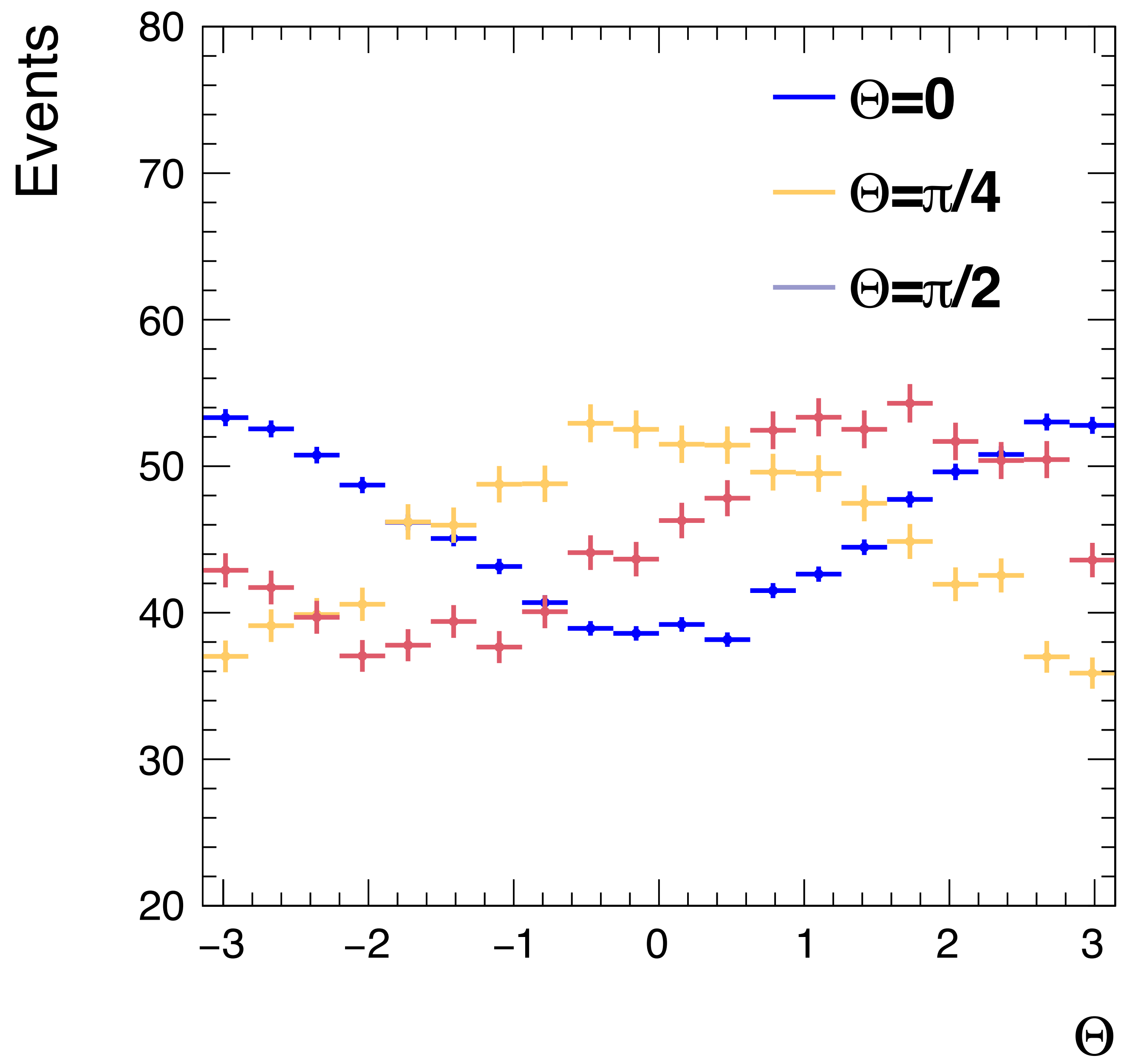
- Tree level couplings to quarks and leptons
- CP-even and CP-odd couplings induced at the same order

➡ **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

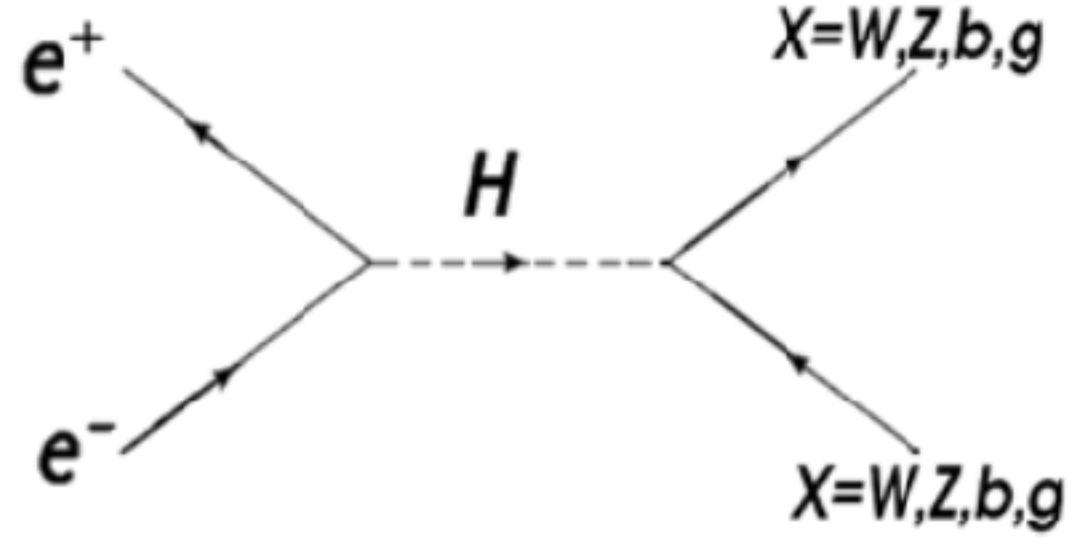


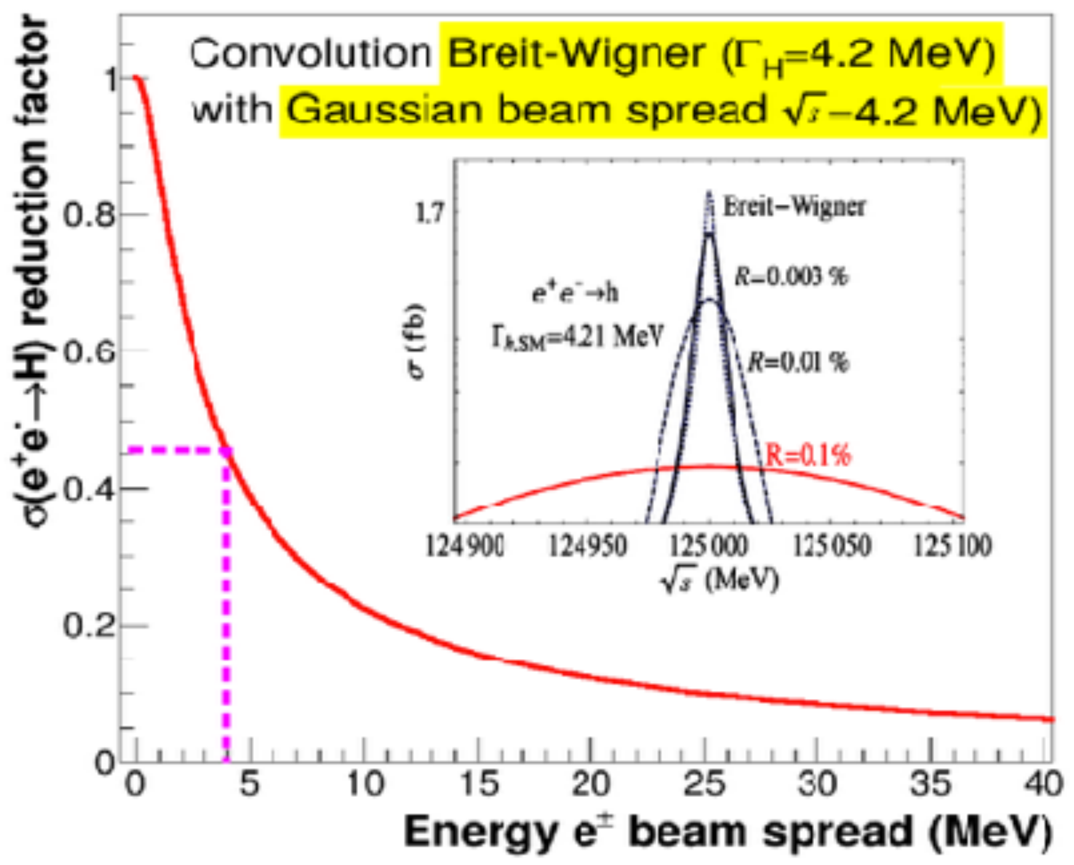
- 920 signal event in 5ab-1
- expected 68% CL
  - ❖ 0.17 radian (0.05 in GEN level study)
  - ❖ 9.7 degree (2.9 in GEN level study)

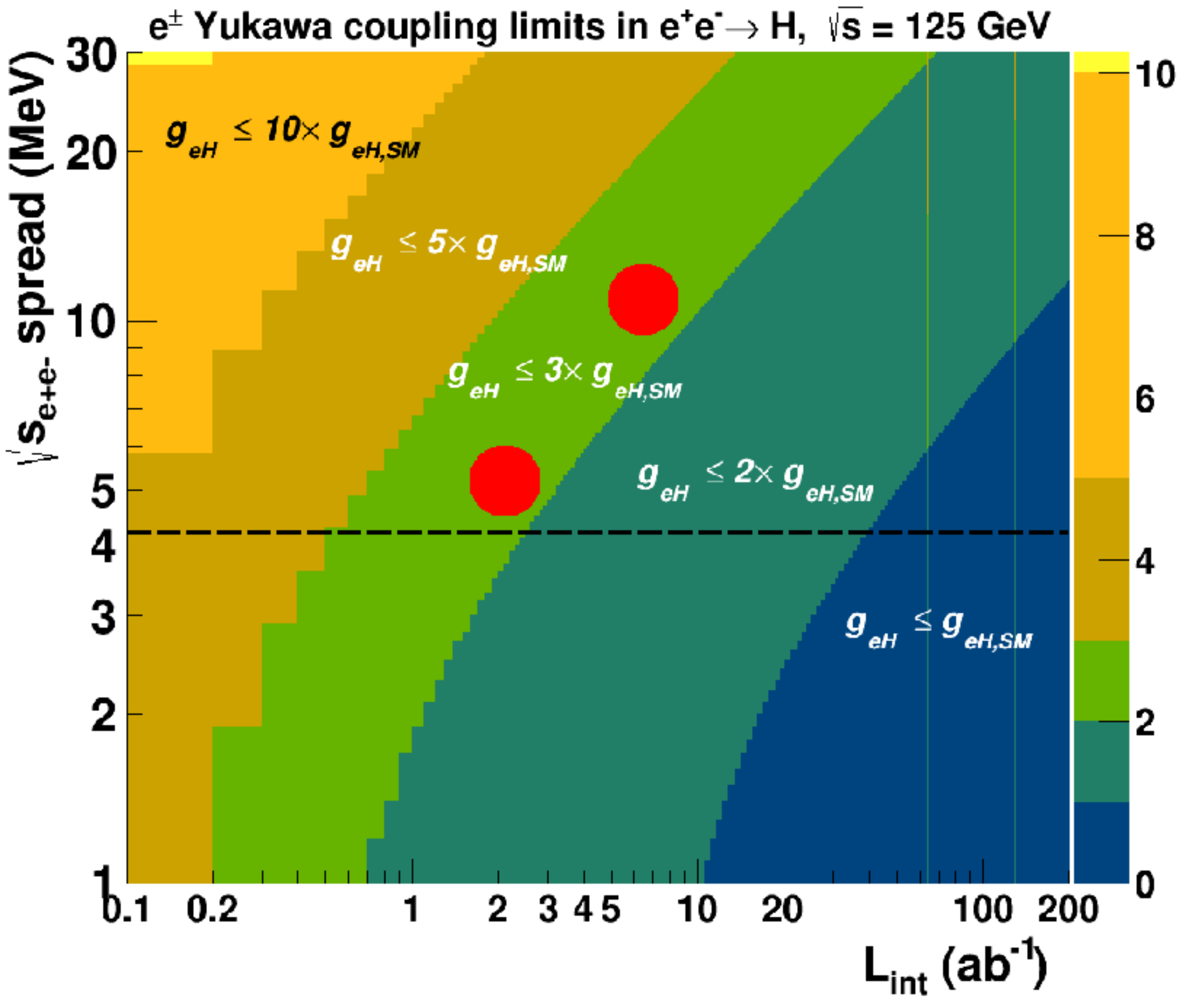
Electron Yukawa Couplings at FCC-ee

➡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





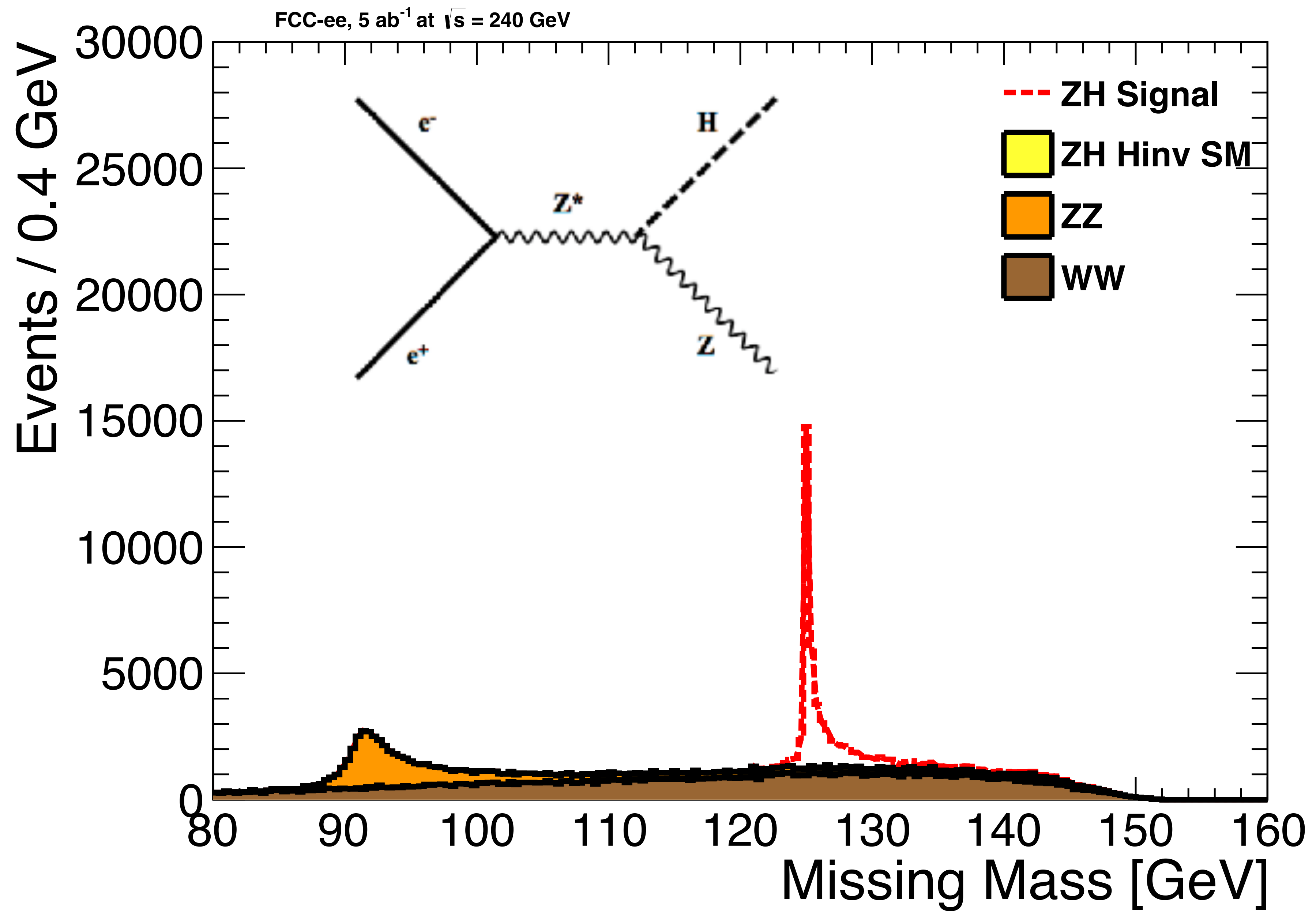


arXiv:1701.02663

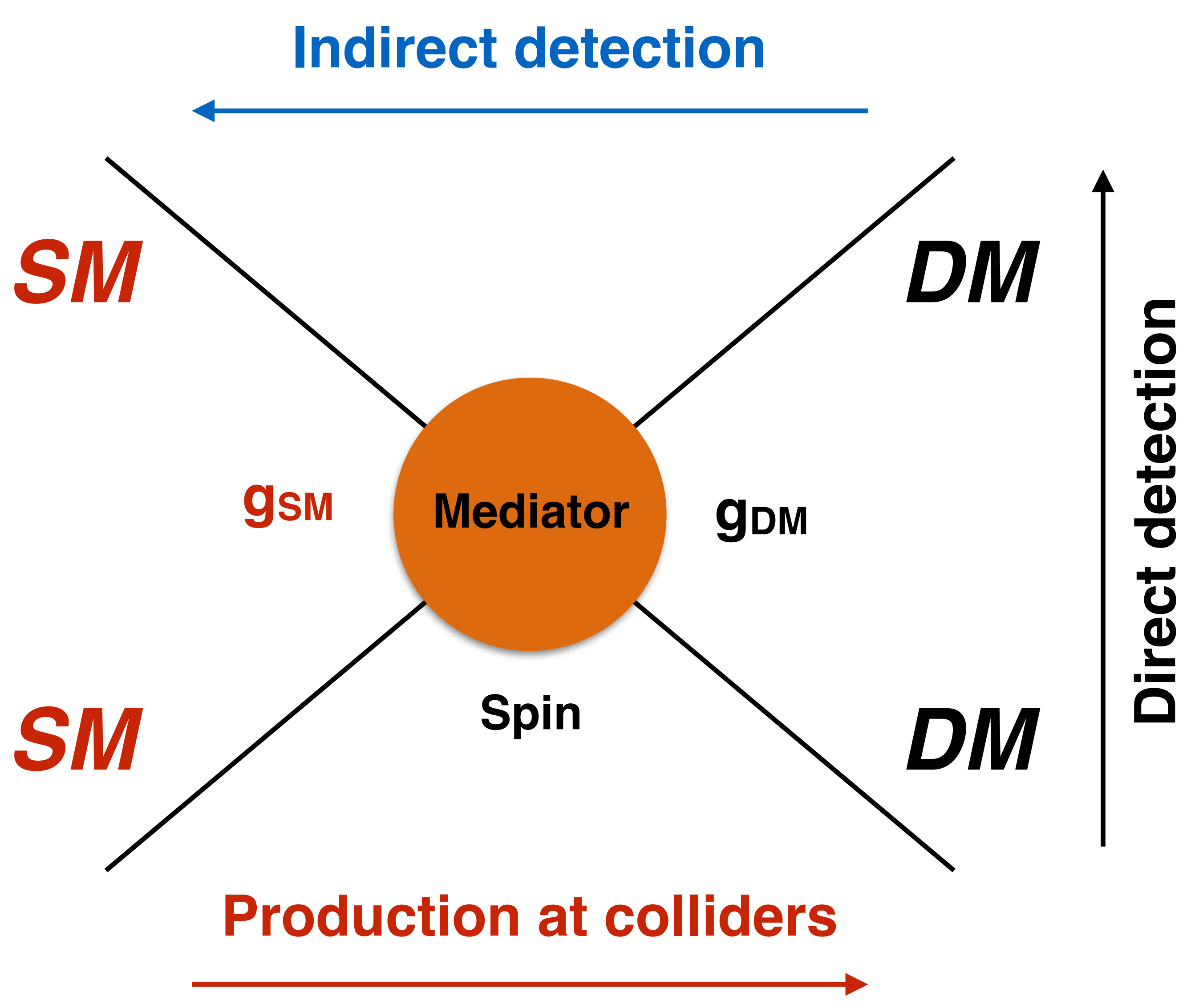
Monochromatization study

Higgs-Portal Dark Matter Searches

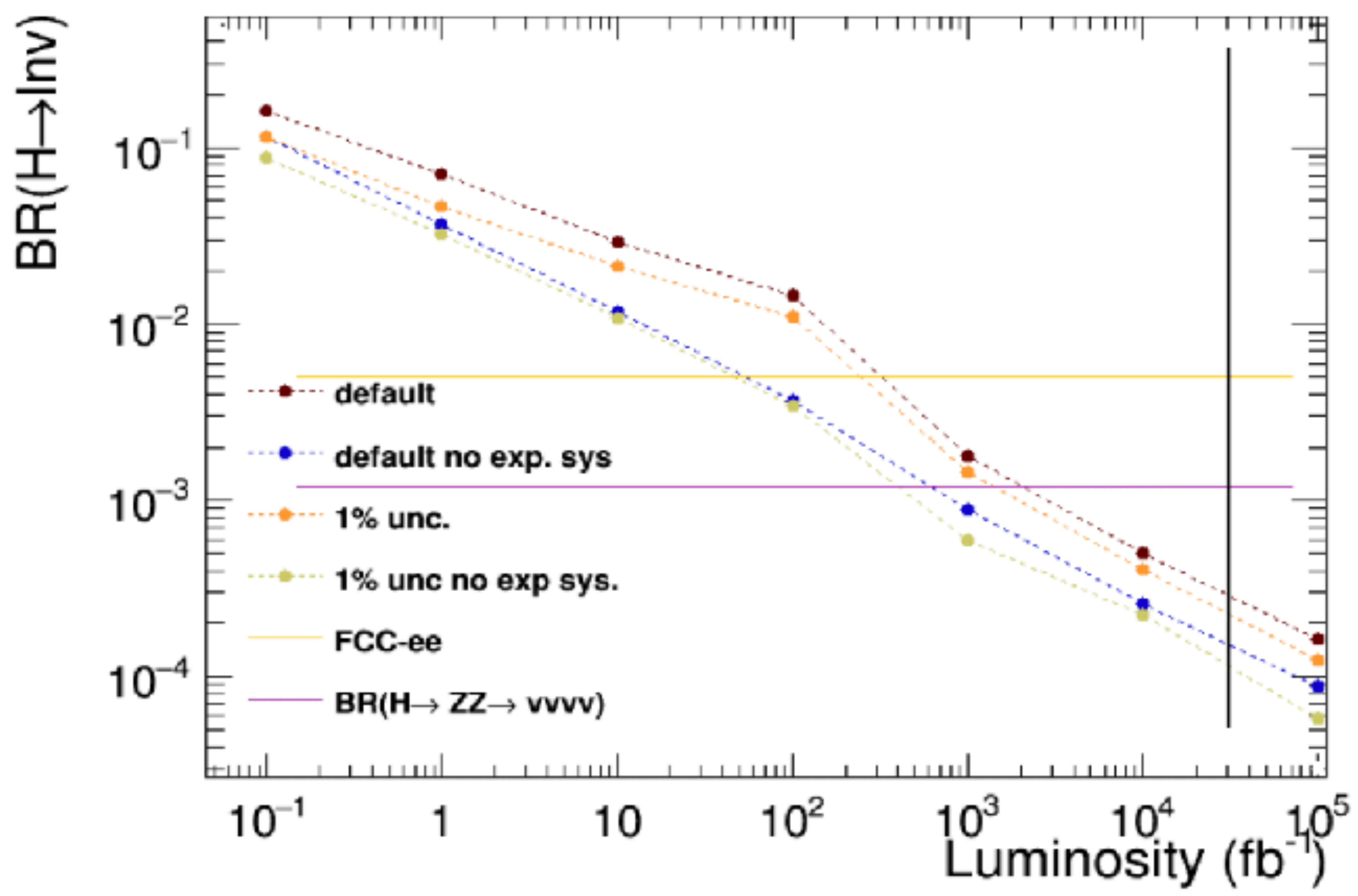
➡ **Higgs boson to invisible decays can be tested in FCC-ee, eh, and hh**



- follows FCC-ee ZH cross section measurement
- for visualization BR(H->inv) = 100%
- 95%CL upper limit using $5ab^{-1}$ is 0.47%
- study published using leptonic Z decays in Eur. Phys. J. C (2017) 77: 116
- hadronic Z decays under study. Shows similar performance



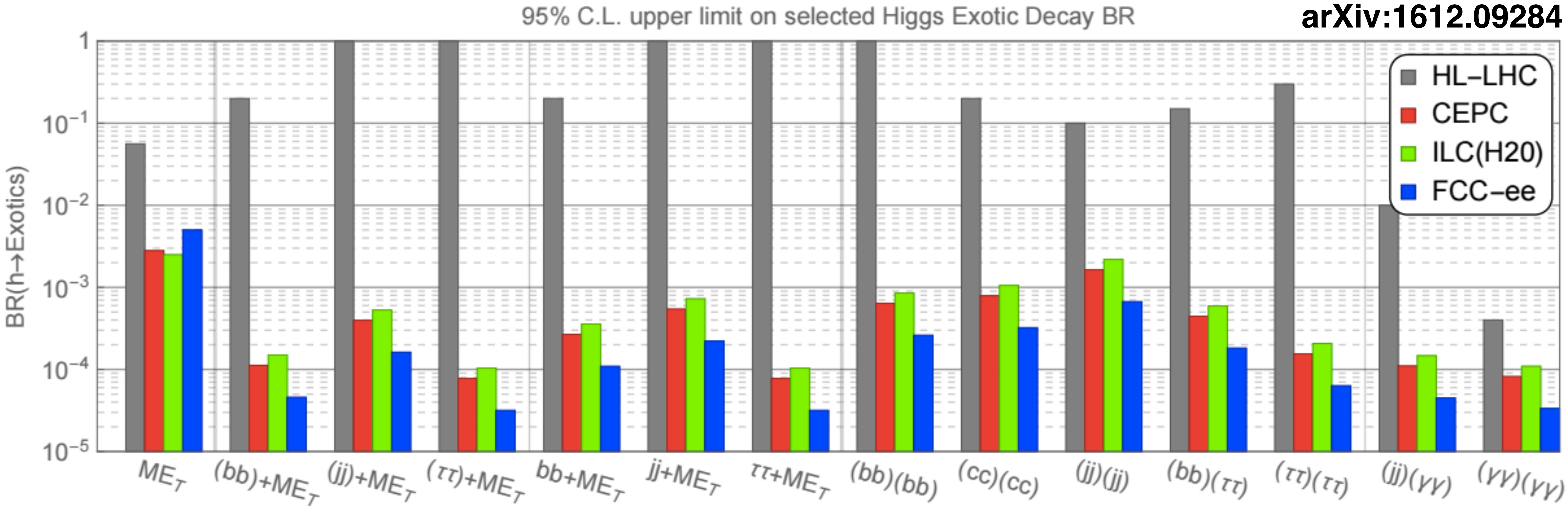
- VBF channel most promising at HL-LHC, mono-jet and ttH channels promising at FCC-hh
- Key to control systematic uncertainties
- Preliminary results shown



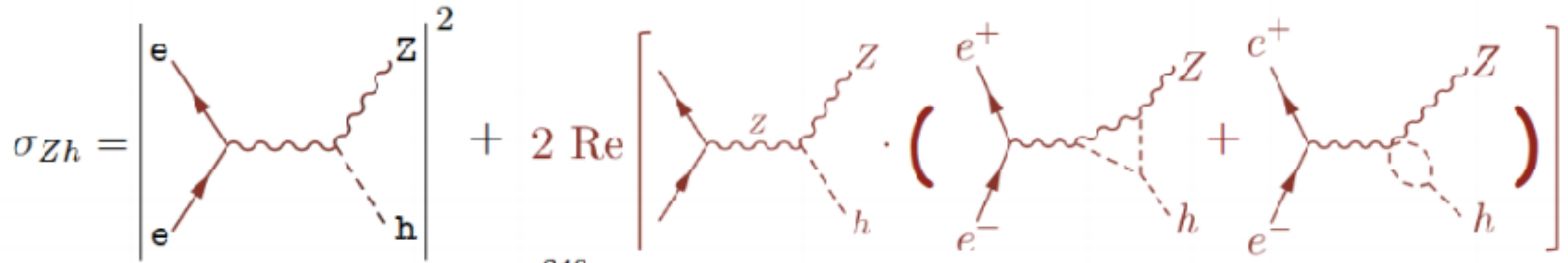
BSM Higgs Studies: FCC-ee

➡**Incredible opportunities for BSM Higgs searches**

arXiv:1612.09284

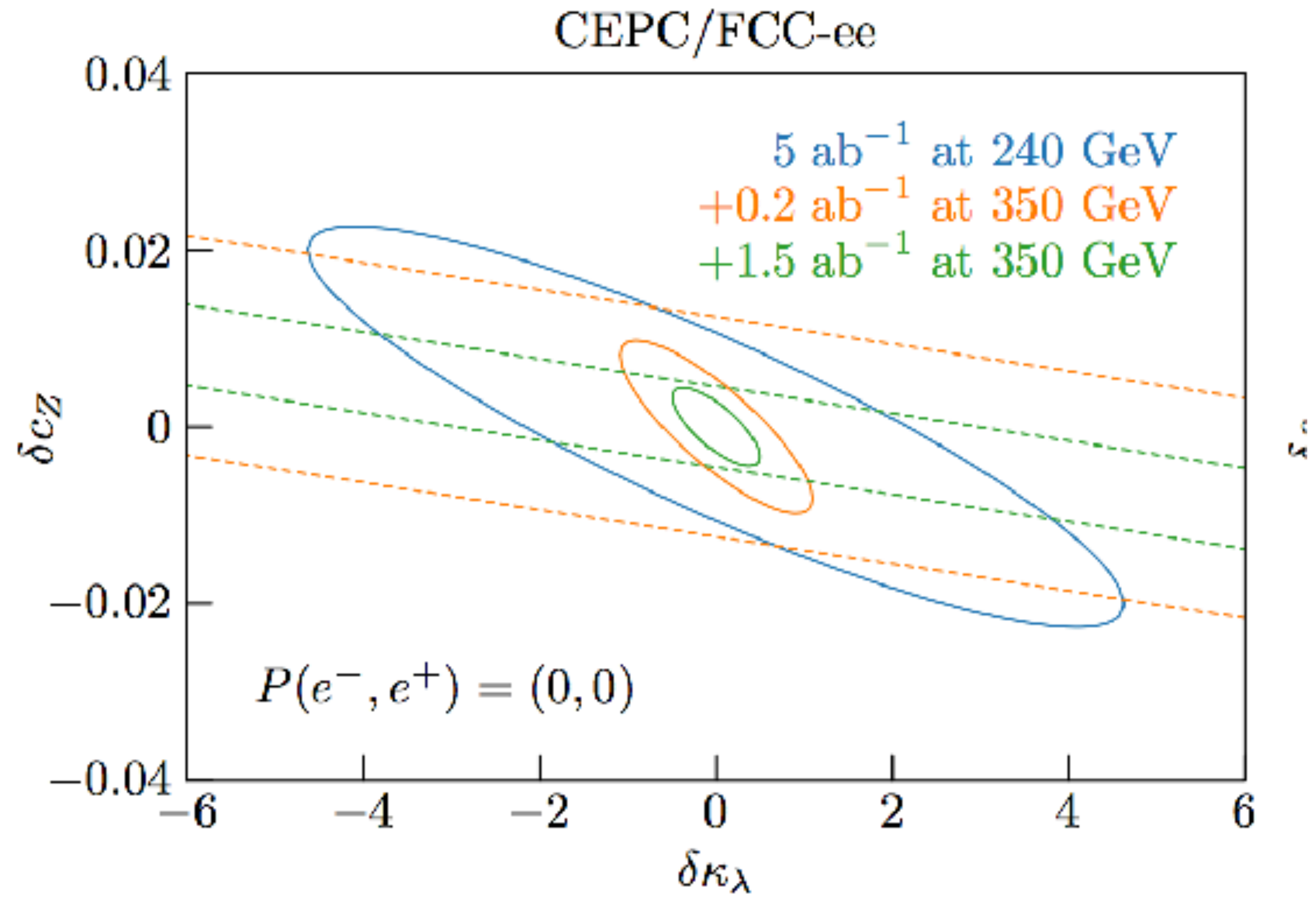


Higgs Self Coupling



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

- ➡ Very large datasets at high energy allow extreme precision g_{ZH} measurements
- ➡ Indirect and model-dependent probe of Higgs self-coupling

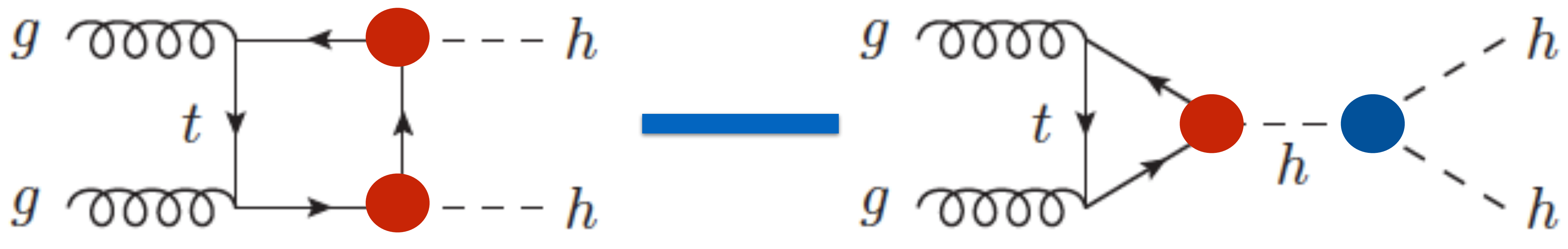


arxiv:1312.3322

arxiv:1711.03978

➡ Probing triple-Higgs coupling with double Higgs production

- Consistency of check of EWSB
- Reconstructing the Higgs potential
- Sensitivity through yields and kinematics
- Large enhancement through BSM possible
- Exhaustive program at the (HL-)LHC

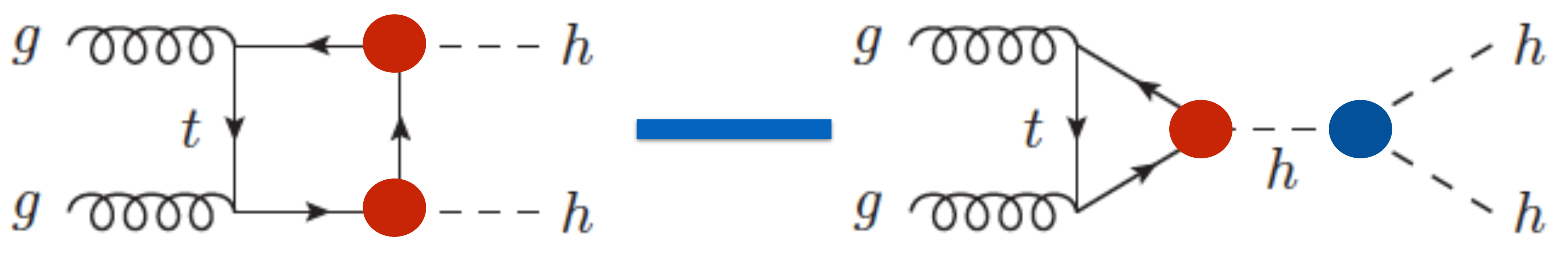


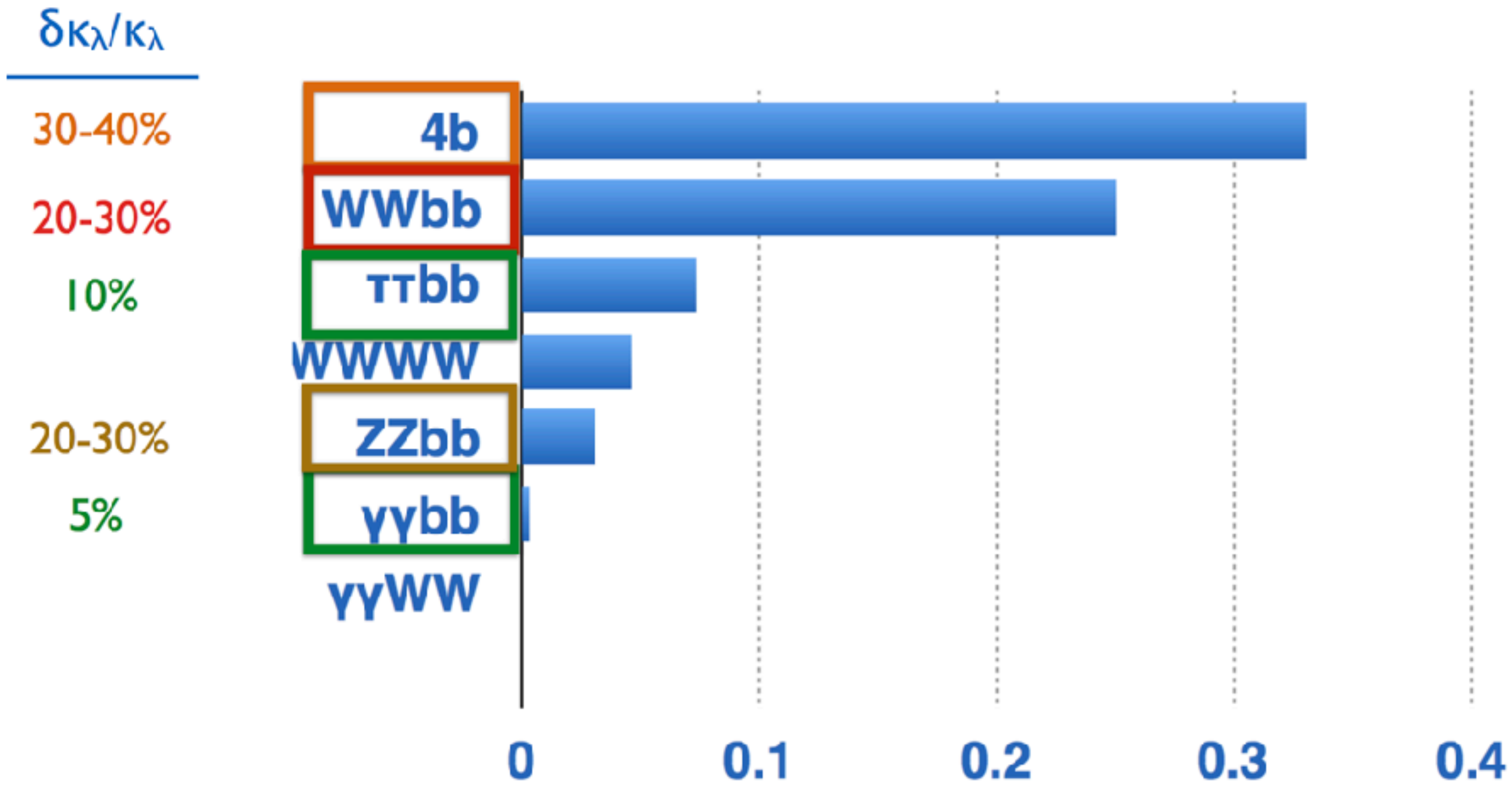
$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

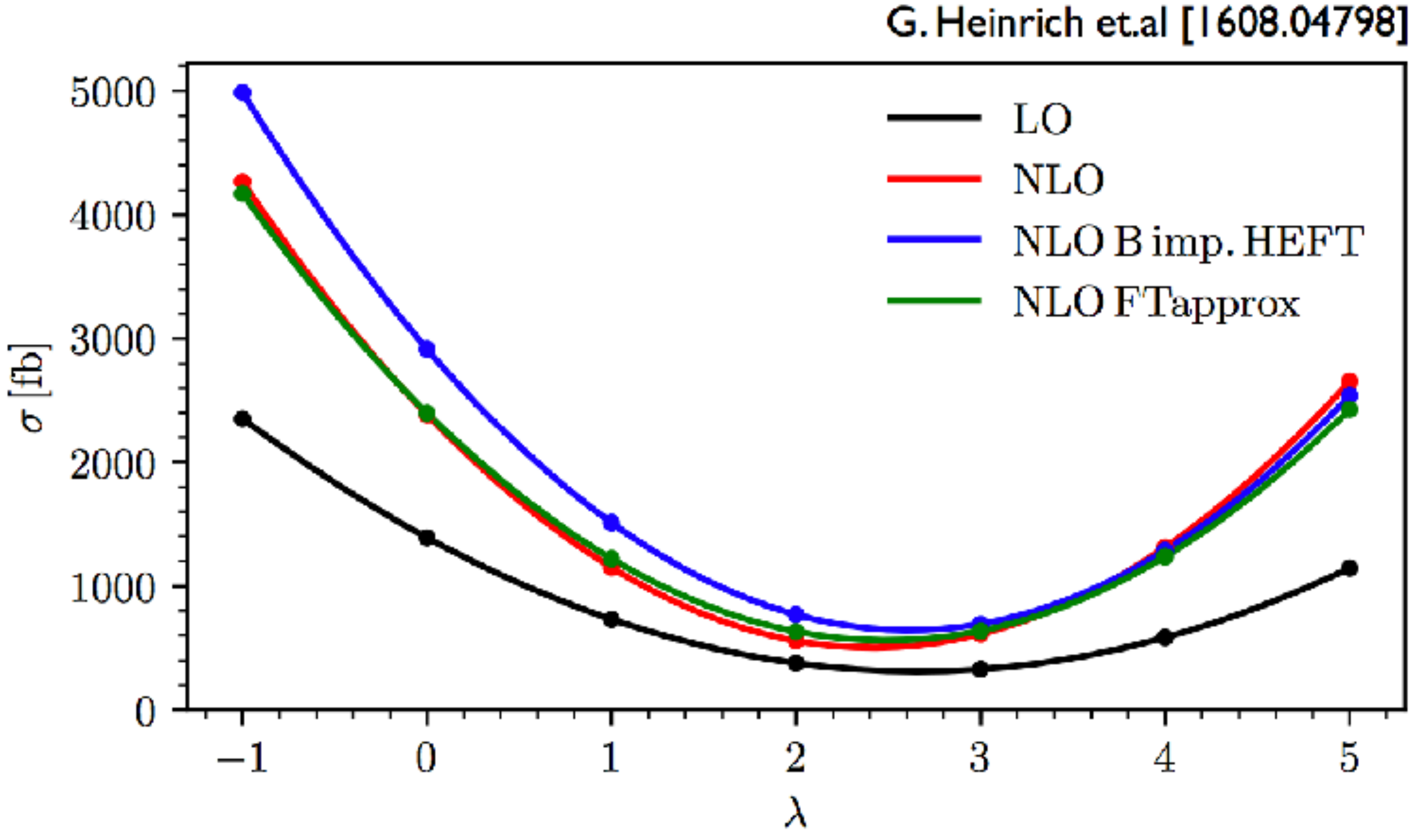
EFT Lagrangian

Higgs Self Coupling: FCC-hh

- ➡ **Enormous di-Higgs samples produced at FCC-hh**
  - σ(100 TeV) / σ(14 TeV) ≅ 40
  - L (FCC-hh) / L (HL-LHC) ≅ 10
  - Naively, factor 20 smaller statistical uncertainty
- ➡ **Studied a number of final states**
  - bbɣɣ most sensitive channel



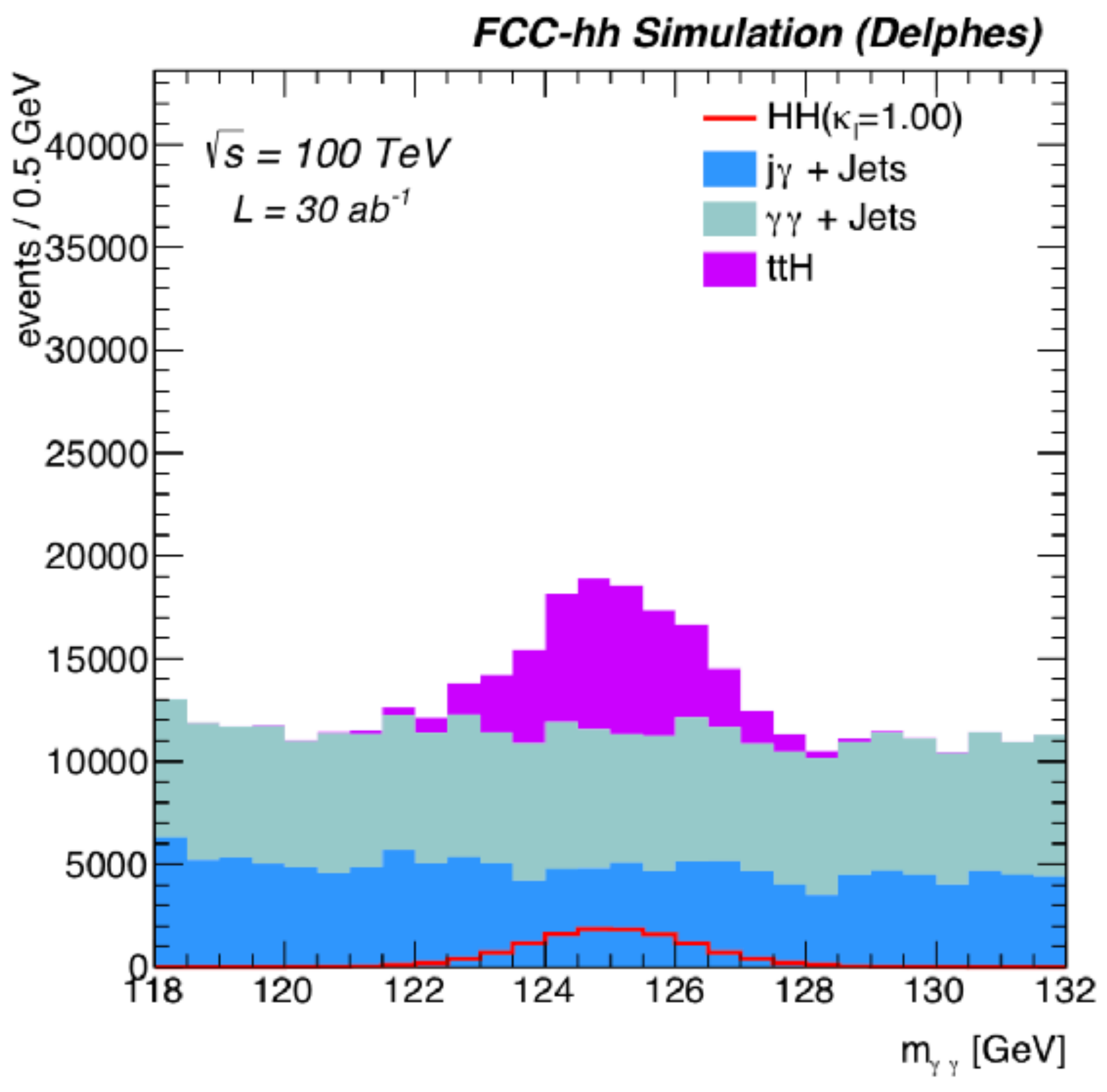




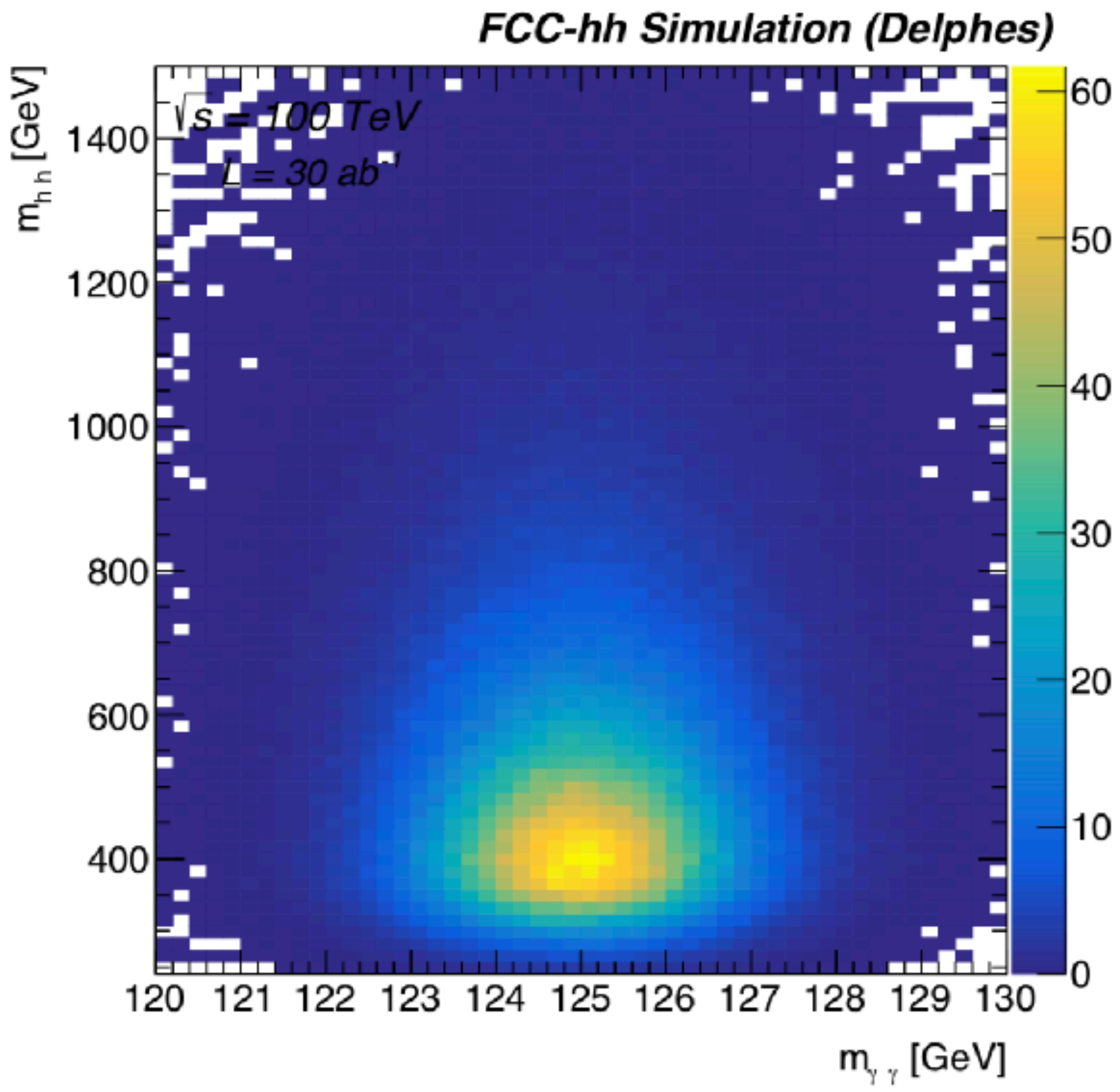
Details in arXiv:1606.09408 and arXiv1802.01607

Higgs Self Coupling: FCC-hh

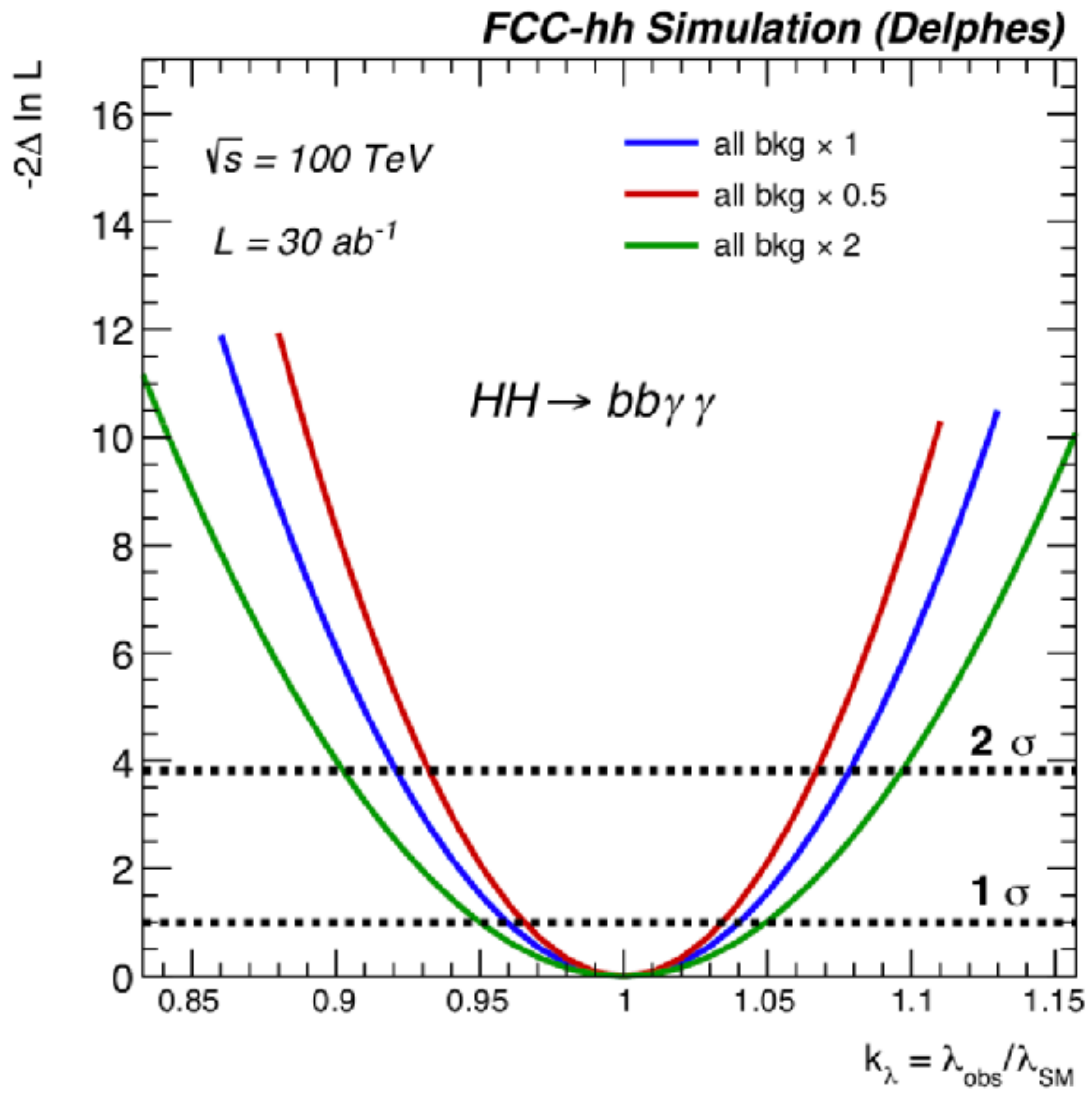
➡ **bbɣɣ results**



ttH resonant and j(ɣ)ɣ+jets non-resonant background



2d likelihood scan using m_{hh} and $m_{ɣɣ}$



δμ ≅ 2-4%

δϰ ≅ 3-5%

Conclusion

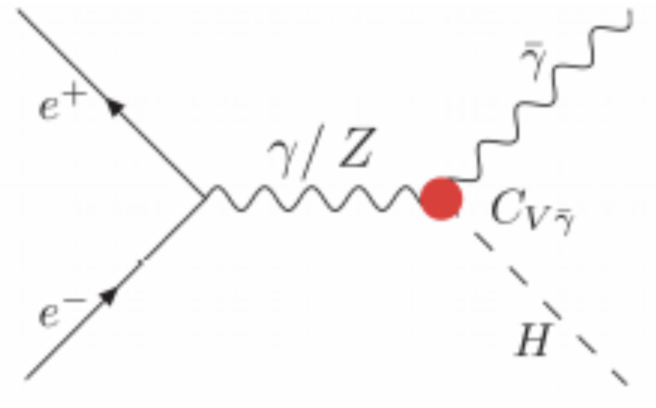
➡**Fantastic prospects to probe the Higgs sector with FCC (ee,eh,hh)**

- unique measurements of g_{ZH} and total width with FCC-ee enable HL-LHC, FCC-eh, and FCC-hh Higgs coupling precision measurements
- precision measurements of Higgs boson properties (coupling [including self coupling], mass, CP)
- large Higgs samples open new possibilities
- precision Higgs program needs to be accompanied by precision program for theoretical or parametric uncertainties
- BSM Higgs physics through direct and indirect measurements
- synergy and complementarity between lepton and hadron collider Higgs physics

Additional Slides

Dark Photon Searches via Higgs Production

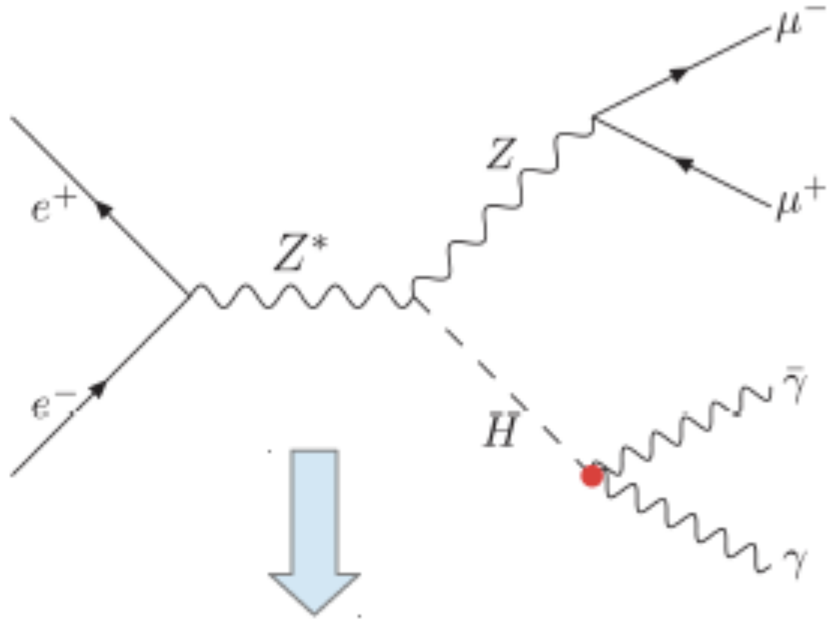
Biswas, Gabrielli, Heikinheimo, Mele
JHEP 1506 (2015) 102 + arxiv:1703.00402
Phys.Rev. D96 (2017) no.5, 055012



Massless Dark Photon $\bar{\gamma}$

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

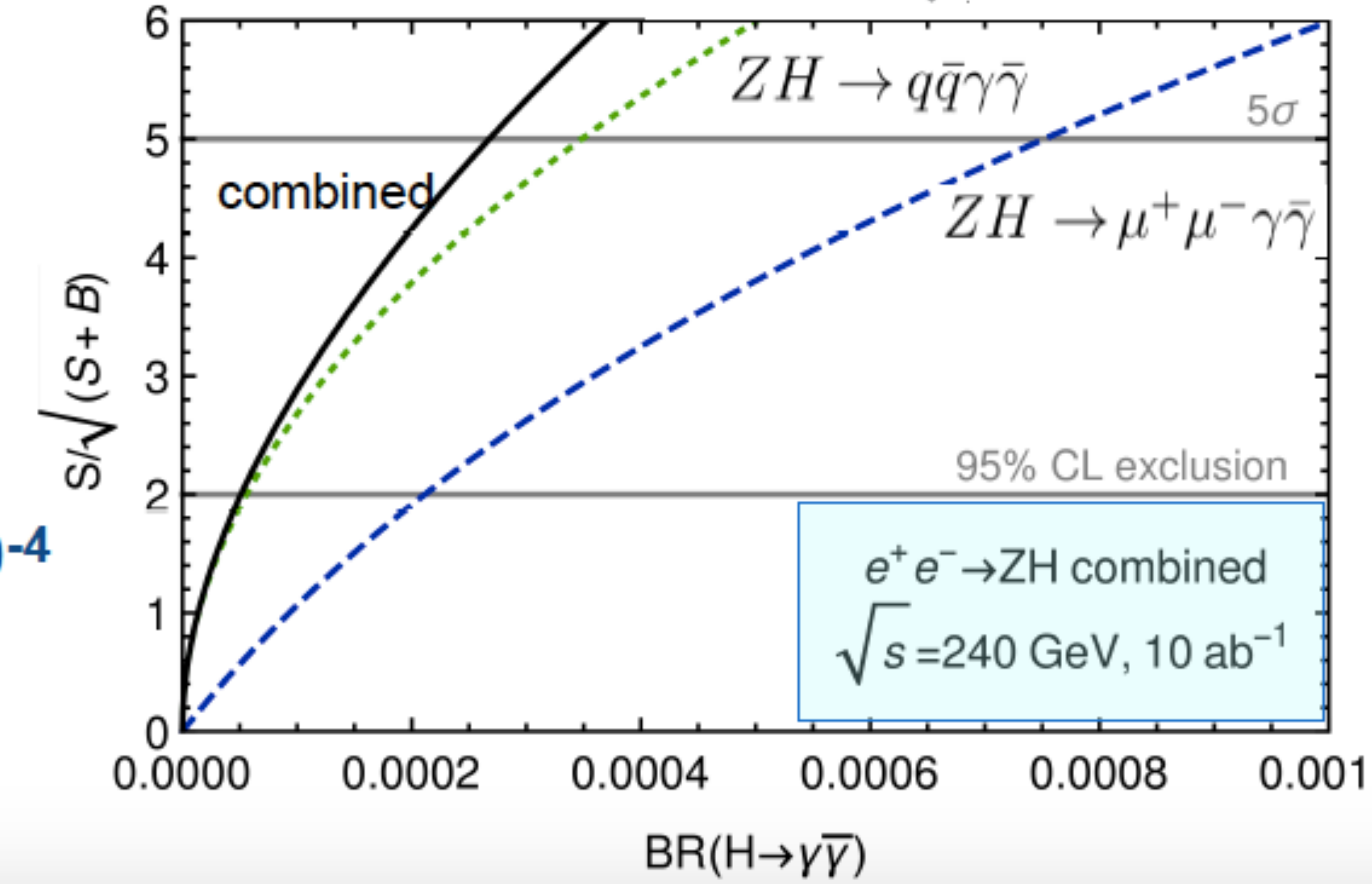
$$e^+e^- \to ZH \to (\mu^+\mu^-, q\bar{q})(\gamma\bar{\gamma})$$



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($H \to \gamma\bar{\gamma}$) ~ 3x10^{-4}**
- **3 times better than LHC @ 300 fb^{-1}**

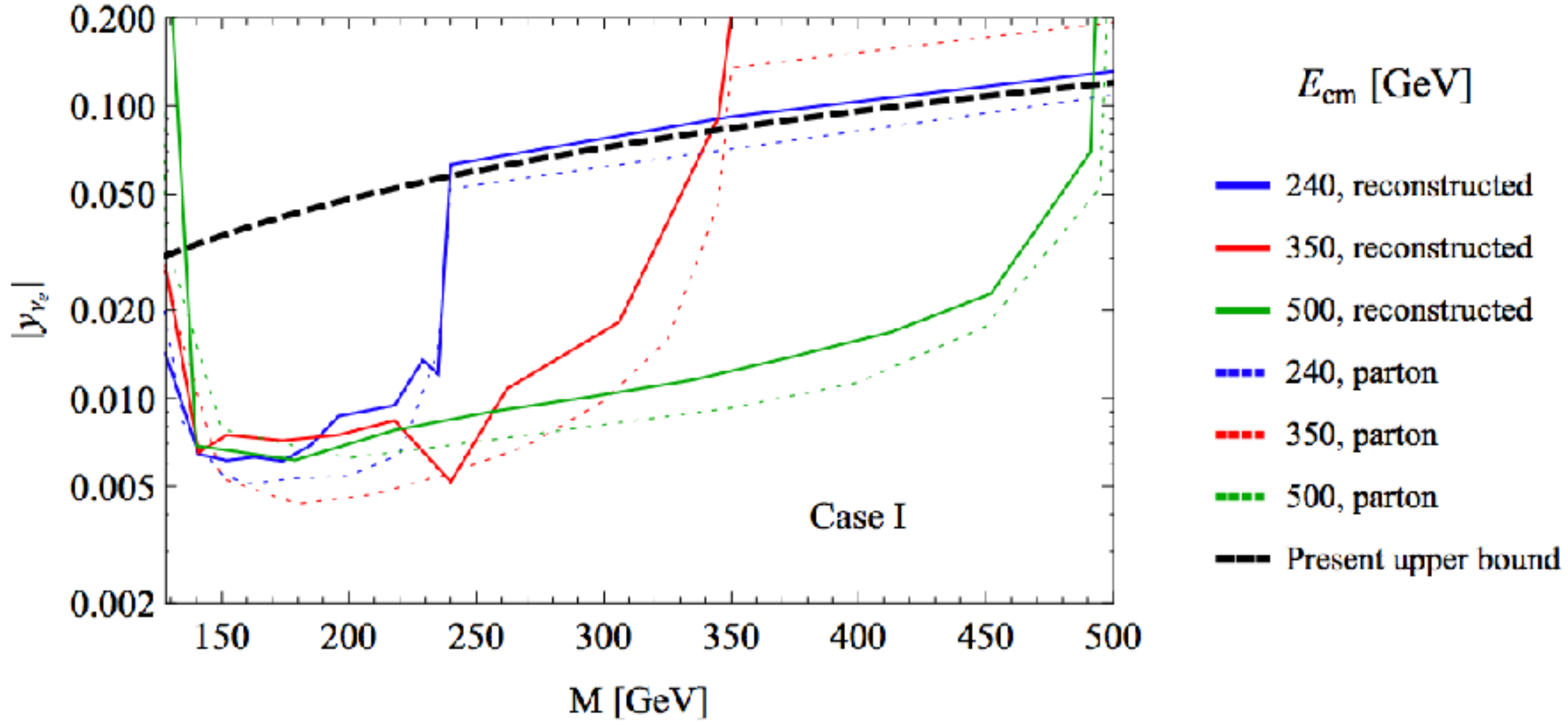
Biswas et al. PRD 93 (2016) 093011

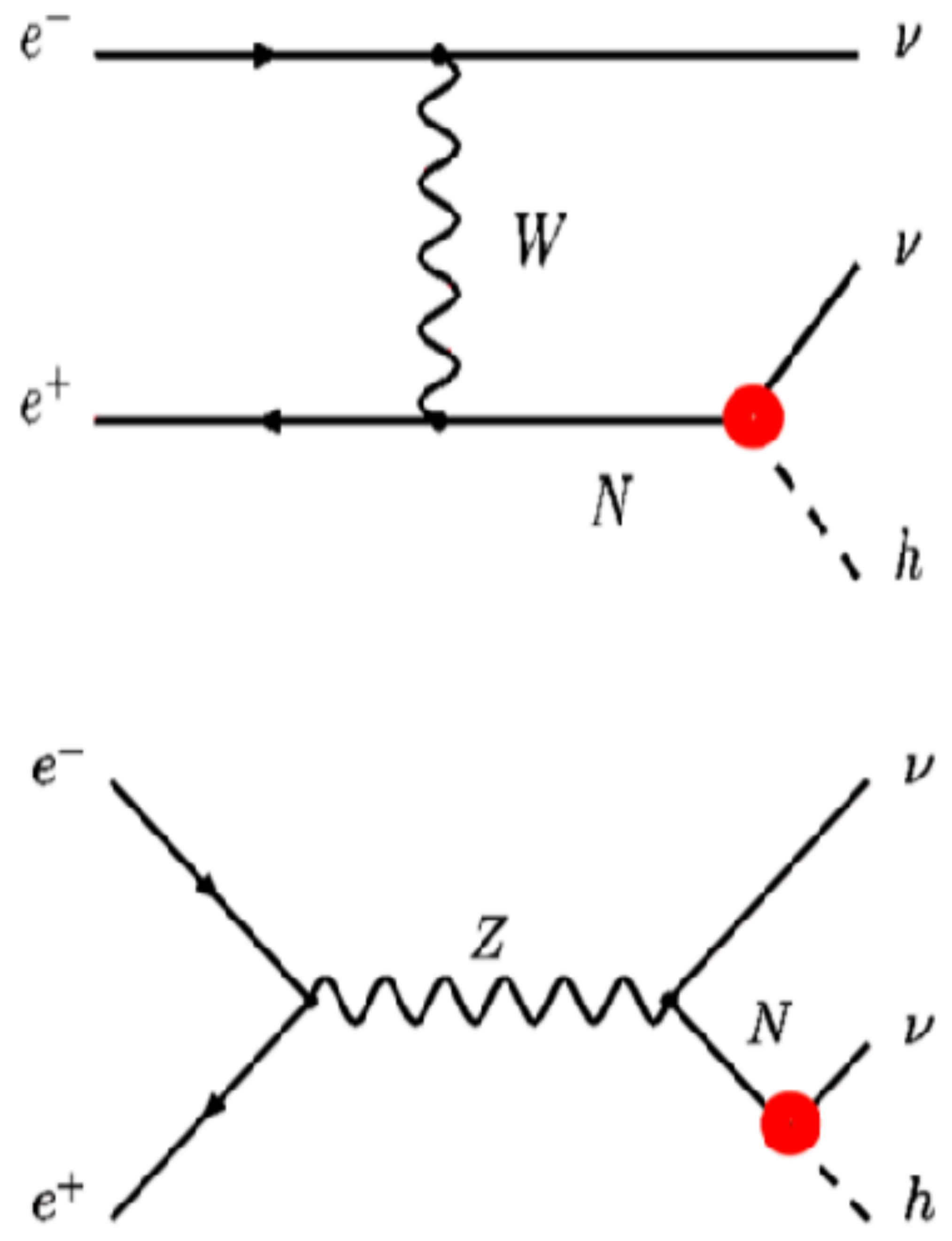


Heavy Neutrinos

➡ **Low-mass seesaw scenario with 2 sterile neutrinos (N)**

➡ **Studied N decay to h+v in mono-Higgs plus missing energy signature**



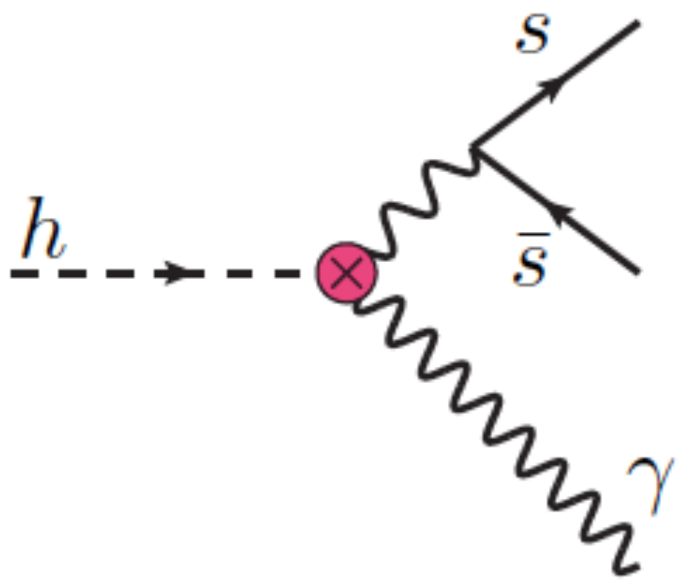


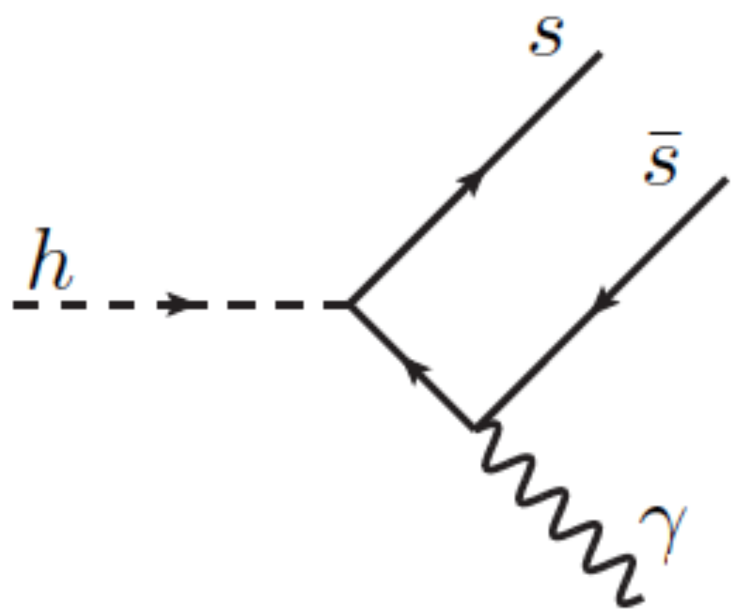
➡ **FCC-ee with sensitivity to $|y_{\nu e}|$ ~ 5x10-3 for m_N ~ 100-300 GeV**

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

H → J/Ψ γ → y_c

H → ϕ γ → y_s

H → **ρ** γ
H → ω γ → y_u, y_d