

Probing Effective $HZ\gamma$ Couplings via $H\gamma$ Production at FCC-ee

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Abstract

This work investigates the $e^+e^- \rightarrow H\gamma$ production mode in $\sqrt{s} = 240$ GeV collisions at the FCC-ee. The utilized event reconstruction is based on IDEA, a detector concept study for FCC-ee.

Loops contribute to the production of the $H\gamma$ final state, which provides insight in the effective $H\gamma\gamma$ and $H\gamma Z$ coupling. Based on the recoil mass method, the analysis comprises both, an inclusive as well as an exclusive study of the $H \rightarrow b\bar{b}$ channel. The final measurement precision is evaluated by a cut & count analysis in comparison with a likelihood fit. The inclusive measurement results in an expected precision of 230%. The exclusive study yields a precision of 150%.

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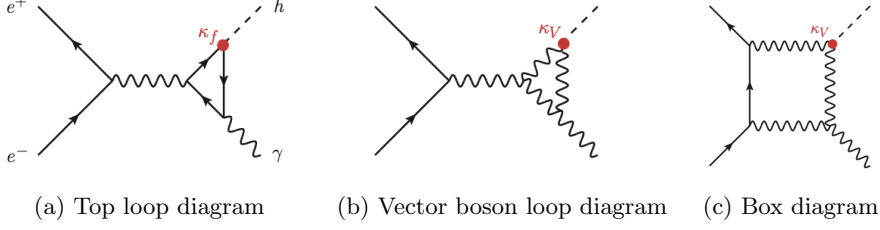


Fig. 1: Feynman diagrams of the $e^+e^- \rightarrow H\gamma$ process [3].

1 Outline

The key player in particle physics research of the early 21st century is the Higgs boson. It is not only the basis of the Standard Model theory but also serves as an anchor point for possible extensions of the model. An ambitious physics program is assembled to precisely explore the Higgs bosons properties. Among these efforts is the investigation of the $H\gamma$ final state. It presents an alternative Higgs production mode sensitive to $HZ\gamma/H\gamma\gamma$ effective vertices making it a promising channel for probing physics beyond the Standard Model. Figure 1 presents the Feynman diagrams of the $e^+e^- \rightarrow H\gamma$ signal production. The loop-induced production modes (Figure 1a and 1b) interfere destructively with box-induced modes (Figure 1c). This destructive interference results in a cross-section that is highly sensitive to the center-of-mass energy, as demonstrated in Figure 2.

The $H\gamma$ process comes along with significant experimental challenges due to its low cross-section of 82 ab (see Figure 2). At the FCC-ee collisions with an integrated luminosity of 10.8 ab^{-1} , 886 signal events are expected among large irreducible radiative $e^+e^- \rightarrow Z^*(f\bar{f})\gamma$ backgrounds ($f=e, \mu, \tau, b, c, u, d, s$). Also vector boson related states like $(\gamma WW, \gamma ZZ)$ and non-signal Higgs production modes (ZH) contribute. Individual contributions feature cross-sections in the $\mathcal{O}(\text{pb})$. In total, 2.4×10^9 background events are expected at pre-selection stage (Section 4.1), eight orders of magnitude more than the signal process.

Large background contributions motivate the use of channel-dependent selection criteria for precision evaluation. A high $H \rightarrow b\bar{b}$ branching ratio of 58% [1] and a good b-tagging performance [2] yield ~ 500 signal events. Those predominantly need to be compared against the $\gamma b\bar{b}$ background, which makes up a $\sim 1\%$ share of the overall background contribution.

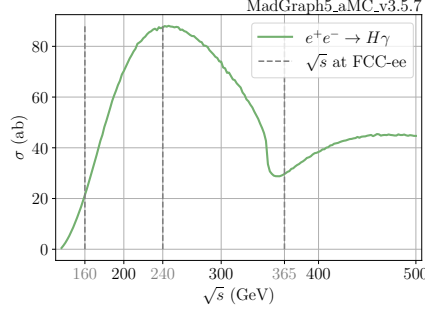


Fig. 2: Cross section σ of $e^+e^- \rightarrow H\gamma$ as a function of center-of-mass energy $\sqrt{s}$. The dashed gray lines indicate the center-of-mass energies at FCC-ee.

2 Methodology

The following analysis is based on the recoil mass method to select events of interest. The $e^+e^- \rightarrow H\gamma$ analysis focuses on the recoil partner of the Higgs, the photon, to tag signal-like events.

2.1 Recoil Mass Method

A given signal signature is identified by tagging the particle that serves as the recoil partner for the desired particle of interest. The method requires a known initial state, which is the case for collisions at e^+e^- colliders. In the process-specific equation of four-momenta

$$(P_{e^+} + P_{e^-})^2 = (P_\gamma + P_H)^2, \text{ with } s = (P_{e^+} + P_{e^-})^2 = (240 \text{ GeV})^2 \text{ and } P_H^2 = m_H^2 \quad (1)$$

the photon momentum is monochromatic with a fixed value of $p_\gamma = 87 \text{ GeV}$. This prerequisite can be used to select signal events by determining the recoil mass as proxy for m_H . It acts as an observable for statistical analysis and follows from four-momentum calculation:

$$m_{\text{recoil}}^2 = P_H^2 = ((P_{e^+} + P_{e^-}) - P_\gamma)^2 \quad (2)$$

3 Processes

Signal and background processes are simulated in FCC-ee conditions at $\sqrt{s} = 240 \text{ GeV}$ center-of-mass-energy. The Monte Carlo events are either generated by MADGRAPH5_AMC v3.5.7 [4, 5] or WHIZARD [6]. The subsequent detector simulation is performed by the fast simulation framework DELPHES [7–9], using the IDEA detector concept [10]. Production-related configurations follow the winter 2023 campaign

[11]. The considered Standard Model processes as well as production-related specifications as the generator type, Monte Carlo event count and cross-sections are listed in Table 1. The provided cross-sections originate from the event generator output ¹.

3.1 Signal Specifications

The event generator utilized in the official production of the winter 2023 campaign is WHIZARD, which, consequently, also is the first choice for private productions. However, MADGRAPH5_AMC was used to produce signal events, since this framework is better suited for generating loop-induced processes. The applied configuration is documented in Listing 1 and 2. In order to validate the settings, the cross-section was produced at several center-of-mass energies. The results (see Figure 2) are consistent with theory [3], showing $\sigma(\sqrt{s} = 240 \text{ GeV}) = 82 \text{ ab}$ and the aforementioned destructive interference pattern.

3.2 Background Specifications

The considered backgrounds are categorized in nine dedicated samples. The private production contains one sample describing ZH production, six samples of the $e^+e^- \rightarrow Z^*(f\bar{f})\gamma$ process containing three samples for leptonic decays (γe^+e^- , $\gamma\mu^+\mu^-$, $\gamma\tau^+\tau^-$), one sample for $\gamma b\bar{b}$ and $\gamma c\bar{c}$ each and a final sample that summarizes the remaining hadronic decays $\gamma q\bar{q}$ with $q \in [u, d, s]$. The $\gamma Z(\nu\nu)$ final state is neglected as the event selection, discussed in Section 4, eliminates this process. The configurations used for production are summarized in listing 3, 4, 5, 6, 7, 8 and 9. WW and ZZ samples are taken from official production.

Process	$\sigma[pb]$	Generator	Generated Event Count	Official Production
γH	$8.2 \cdot 10^{-5}$	MADGRAPH	75.000	no
ZH	0.2	WHIZARD	100.000	no
$\gamma\mu^+\mu^-$	0.8	WHIZARD	100.000	no
γe^+e^-	190	WHIZARD	100.000	no
$\gamma\tau^+\tau^-$	0.77	WHIZARD	100.000	no
$\gamma b\bar{b}$	2.35	WHIZARD	100.000	no
$\gamma c\bar{c}$	2.15	WHIZARD	100.000	no
$\gamma q\bar{q}$	2.15	WHIZARD	100.000	no
WW	16.4385	WHIZARD	37.337.500	p8_ee_WW_ecm240
ZZ	1.359	WHIZARD	56.150.000	p8_ee_ZZ_ecm240

Table 1: Process related specifications.

4 Event Selection

The selection of events that match the desired detector signatures is facilitated by a series of cuts. The goal is to enhance the signal over background ratio (S/B).

¹The cross-sections are cross-checked by generating the same process with the remaining generator and comparing the numbers.

4.1 Pre-selection Cuts at Generator Level

Prior to event selection, pre-selection cuts (Table 2) are applied at generator level. These cuts are applied to aid the convergence of the matrix element integration and are largely tightened at a later stage of the analysis.

Cut	Comment
$m(q\bar{q}/f\bar{f}) > 5 \text{ GeV}$	Invariant mass cut on $q\bar{q}$ or $f\bar{f}$ system respectively
$\Delta R(\gamma f/\gamma q) > 0.01$	Minimum distance between final state fermions and targeted photon
$ \cos(\theta)_{l/q/\gamma} < 0.998$	Minimum polar angle of final state particles from beam line

Table 2: Pre-selection cuts applied at generator level.

4.2 Kinematic Selection

The kinematic selection (Table 3) emphasizes the expected signature of the targeted $H\gamma$ process. The driving cuts mainly result from the recoil mass method, discussed in Section 2.1.

	Cut	Comment
1	$\text{iso}(\gamma) < 0.2$ for $\Delta R < 0.5$	Isolated photon
2	$60 \text{ GeV} < p_\gamma^{\text{leading}} < 100 \text{ GeV}$	Expected photon momentum from recoil mass method
3	$ \cos(\theta)_\gamma < 0.9$	Minimum photon polar angle to reduce ISR background
4	$\# \text{ particles} > 5$	Minimum number of reconstructed particles
5	$\text{b_score_j0} + \text{b_score_j1} > 1$	Minimum requirement on summed b-scores

Table 3: Kinematic selection applied at analysis level. Cut 1 - 4 are applied in the inclusive analysis, cut 5 comes on top for the exclusive one.

The distributions of observables used for cutting are shown in Figure 3. The photon isolation in Figure 3a measures the activity in a cone of $\Delta R < 0.5$ ² around the reconstructed photon. The isolation is defined as the sum of object momenta p_i within the cone, normalized to the momentum of the photon p_γ :

$$\text{iso}(\gamma) = \frac{\sum p_i}{p_\gamma}$$

The background processes discussed in Section 3.2 typically exhibit photons produced inside jets, which is why the isolation requirement suppresses the background. The highest-energy photon within the pool of remaining, isolated photons is tagged as signal candidate.

In addition, the photon momentum needs to align with the expected momentum (Figure 3c), determined by the recoil mass method (see Section 2.1). The allowed range of $60 \text{ GeV} < p_\gamma^{\text{leading}} < 100 \text{ GeV}$ around the signal peak at 87 GeV leaves a large

²The distance measure is defined as $\Delta R = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2}$

margin to high momenta. The range is chosen to maintain reasonable sidebands in the recoil mass for the likelihood fit.

To reduce initial state radiation (ISR) photons, small polar angles of the reconstructed photon need to be rejected, as shown in Figure 3b.

The cut on the reconstructed particle count (distribution 3d) is motivated by the large cross-section of the γe^+e^- background from BhaBha scattering (Table 1)³, which has a significant contribution to the relevant phase space of the recoil mass (see Figure 4a). A cut on the reconstructed particle count (excluding the photon) (Figure 3d) reduces leptonic backgrounds (γe^+e^- , $\gamma\mu^+\mu^-$, $\gamma\tau^+\tau^-$) and maintains most of the signal. More than 66 % of Higgs boson decays are of hadronic nature [1] and result in many particle final states, which is why the cut on the particle count does not largely compromise model independency of the study. This series of four cuts defines the inclusive selection. The impact of the observable in question is shown in Figure 4b.

In order to select the $H(b\bar{b})\gamma$ channel, one additional cut on the b-score is applied. Two jets are reconstructed in the event with the exclusive N=2 Durham k_T algorithm [12] using all reconstructed particles in the event except the isolated photon candidate. The jets are classified by their flavor using a jet tagger [2]. The b-score quantifies the probability with which the reconstructed jet originates from a b-quark. Summing the b-scores of the two jets and setting a minimum requirement at one, drastically reduces other channels than $b\bar{b}$ and retains most of the $H \rightarrow b\bar{b}$ signal events.

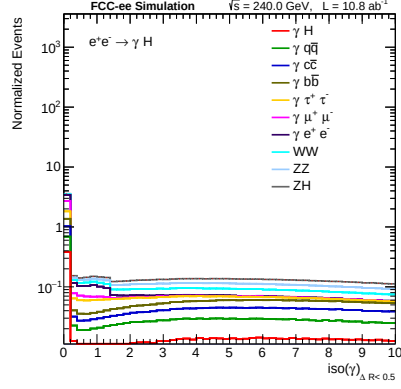
The impact of the applied cuts on the signal and background yields is shown in Table 4, 5 and 6. Notably, the restrictions on the photon momentum lead to a substantial reduction in background events. The cut on the particle count is designed to eliminate the purely leptonic final states e^+e^- and $\mu^+\mu^-$. The inclusive signal process remains largely suppressed by the hadronic final states.

The b-score requirement effectively suppresses all backgrounds except ($b\bar{b}\gamma$), while maintaining a large fraction of signal events.

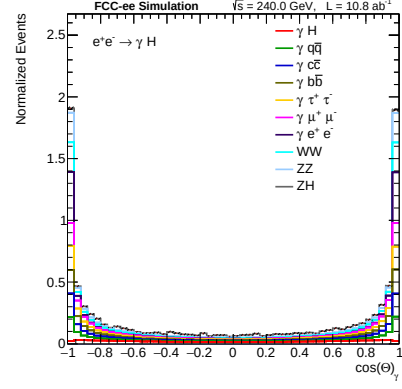
Cut	$\gamma\mathbf{H}$	$\gamma q\bar{q}$	$\gamma c\bar{c}$	$\gamma b\bar{b}$
All events	886 (100%)	74520k (100%)	23220k (100%)	25380k (100%)
$\text{iso}(\gamma)_{\Delta R < 0.5} < 0.2$	860 (97.1%)	60970k (81.8%)	19000k (81.8%)	20680k (81.5%)
$60 \text{ GeV} < p_{\gamma}^{\text{leading}} < 100 \text{ GeV}$	832 (94.0%)	34800k (46.7%)	10480k (45.1%)	11940k (47.0%)
$ \cos(\theta)_{\gamma} < 0.9$	720 (81.3%)	15230k (20.4%)	4719k (20.3%)	5274k (20.8%)
# particles > 5	679 (76.7%)	15230k (20.4%)	4719k (20.3%)	5274k (20.8%)
$\text{b_score_j0} + \text{b_score_j1} > 1$	402 (45.4%)	2981 (0.0%)	232 (0.0%)	4899k (19.3%)

Table 4: Kinematic selection applied at analysis level. The signal process as well as the quark background are shown.

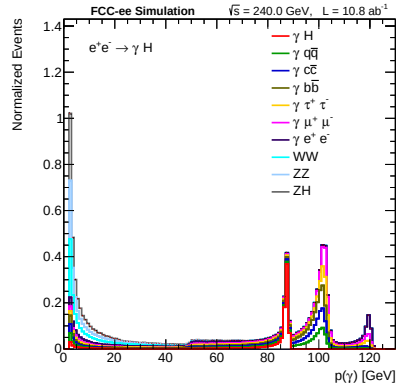
³The e^+e^- production from BhaBha scattering has a much larger cross-section than other leptonic final states like $\mu^+\mu^-$ since apart from the s-channel, also t-channel production becomes available.



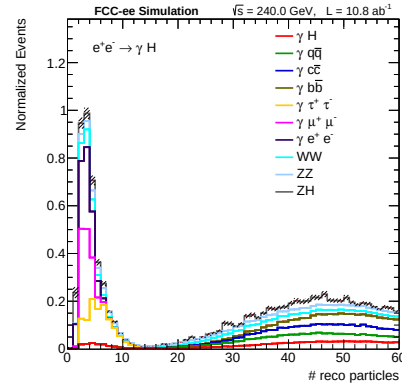
(a) Photon isolation



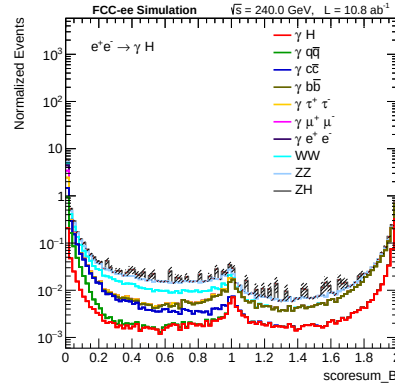
(b) Photon polar angle



(c) Photon momentum



(d) Reconstructed particle count



(e) Summed jet b-scores

Fig. 3: Kinematic distributions of observables relevant for cutting. The individual contributions are normalized and stacked, so that the shapes become accesible.

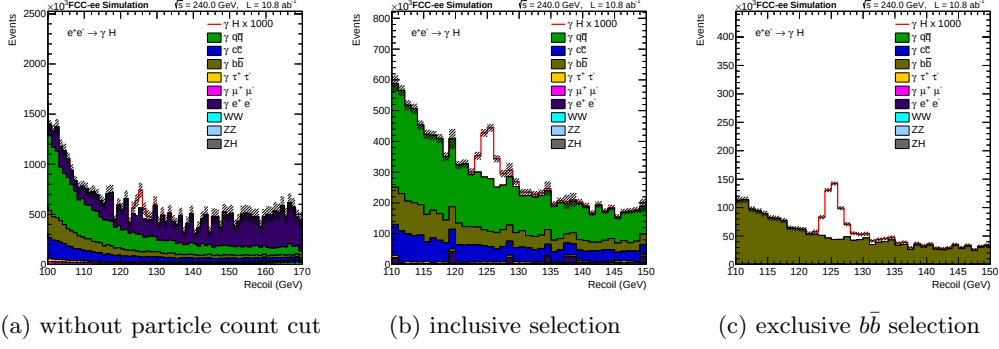


Fig. 4: Reconstructed recoil mass. The signal process is scaled by a factor 1000.

Cut	$\gamma\tau^+\tau^-$	$\gamma\mu^+\mu^-$	γe^+e^-
All events	8316k (100%)	8640k (100%)	2052000k (100%)
$\text{iso}(\gamma)\Delta R_{<0.5} < 0.2$	6827k (82.1%)	6868k (79.5%)	923800k (45.0%)
$60 \text{ GeV} < p_{\gamma}^{\text{leading}} < 100 \text{ GeV}$	2192k (26.4%)	2180k (25.2%)	201000k (9.8%)
$ \cos(\theta)_{\gamma} < 0.9$	997.1k (12.0%)	982.3k (11.4%)	16810k (0.8%)
# particles > 5	455k (5.5%)	12.27k (0.1%)	287.3k (0.0%)
$\text{b_score_j0} + \text{b_score_j1} > 1$	83 (0.0%)	0 (0.0%)	0 (0.0%)

Table 5: Kinematic selection applied at analysis level. The leptonic related background are shown.

Cut	WW	ZZ	ZH
All events	177500k (100%)	14680k (100%)	2160k (100%)
$\text{iso}(\gamma)\Delta R_{<0.5} < 0.2$	28400k (16.0%)	2182k (14.9%)	232.2k (10.7%)
$60 \text{ GeV} < p_{\gamma}^{\text{leading}} < 100 \text{ GeV}$	918.8k (0.5%)	92.25k (0.6%)	8834 (0.4%)
$ \cos(\theta)_{\gamma} < 0.9$	391.8k (0.2%)	39.44k (0.3%)	7841 (0.4%)
# particles > 5	321.5k (0.2%)	35.15k (0.2%)	6005 (0.3%)
$\text{b_score_j0} + \text{b_score_j1} > 1$	1279 (0.0%)	5391 (0.0%)	1274 (0.0%)

Table 6: Kinematic selection applied at analysis level. The ZH as well as the vector boson related background are shown.

5 Results

In the presented scope, two statistical analysis techniques are followed. A **Cut & Count** approach, which is often used for a first estimate due to its simplicity and a **Likelihood Fit**, which is a more powerful tool incorporating full kinematic distributions from signal and background.

5.1 Cut & Count

In the cut & count approach, the statistical significance is calculated as

$$\text{significance} = \frac{N_S}{\sqrt{N_S + N_B}}, \quad (3)$$

where N_S and N_B are the numbers of signal and background events after the event selection, respectively. To optimize the extraction of the signal, the observable that facilitates the best signal to background discrimination is chosen. In this analysis, the recoil mass (see Figure 4b) serves this purpose. The significance is evaluated within the interval defined by the full width at half maximum (FWHM) of the signal peak, determined to be $123 \text{ GeV} < m_{\text{recoil}} < 128 \text{ GeV}$.

5.1.1 Inclusive Channel

Within the selected recoil mass range, $N_S = 400$ signal and $N_B = 834166$ background events⁴ are observed in the inclusive channel. The expected significance is:

$$\text{significance} = \frac{400}{\sqrt{400 + 834490}} = 0.44$$

The precision is defined as the inverse of the significance and the cut and count approach results in an expected precision of

$$\text{precision} = \frac{1}{\text{significance}} \sim \frac{1}{0.44} \sim 228\%$$

5.1.2 Exclusive $b\bar{b}$ Channel

In the $b\bar{b}$ selection, $N_S = 237$ signal and $N_B = 137314$ background events⁵ are observed. Therefore, an improved signal over background ratio of

$$\text{significance} = \frac{237}{\sqrt{237 + 137314}} = 0.64$$

can be determined. The expected precision yields

$$\text{precision} = \frac{1}{\text{significance}} \sim \frac{1}{0.64} \sim 156\%$$

5.2 Profile Likelihood Fit

The profile likelihood fit relies fundamentally on a counting experiment, much like the cut and count method. In this approach, the measured event rates, are compared to the expected rates predicted by the Standard Model.

⁴The $N_B = 834490$ background events result from $N(\gamma q\bar{q})=503800$, $N(\gamma c\bar{c})=150900$, $N(\gamma b\bar{b})=156800$, $N(\gamma\tau^+\tau^-)=15380$, $N(\gamma\mu^+\mu^-)=259$, $N(\gamma e^+e^-)=0$, $N(WW)=6096$, $N(ZZ)=937$ and $N(ZH)=324$ events

⁵The $N_B = 137314$ background events result from $N(\gamma c\bar{c})=232$, $N(\gamma b\bar{b})=136800$, $N(\gamma\tau^+\tau^-)=83$, $N(ZZ)=156$, $N(ZH)=43$ events. The remaining processes are completely eliminated.

In this analysis, one parameter of interest is included in the fit and is denoted as $\mu_{H\gamma}$. It describes the signal strength of the $H\gamma$ process. As nuisance parameters, nine normalization factors are included, one per background sample. Since the background normalization could be extracted from control regions, a prior constraint of 1% is assumed. The fit observable, the recoil mass, is considered in a range from $110 \text{ GeV} < m_{\text{recoil}} < 150 \text{ GeV}$. The fit is performed on Asimov data⁶.

5.2.1 Inclusive Channel

The recoil mass distribution of the inclusive selection, that enters the fit setup is shown in Figure 4b. The post-fit parameter uncertainties are summarized in Table 7. Background processes that significantly contribute (e.g. $q\bar{q}\gamma$ or $c\bar{c}\gamma$) get constrained by the fit and those that are nearly completely eliminated (e.g. $\mu^+\mu^-\gamma$) are not further constrained. In a more advanced analysis setup, those normalization factors could be measured in dedicated control regions. The final analysis precision yields 234%.

$\sigma(\mu_{H\gamma})$	$\sigma(k_{q\bar{q}\gamma})$	$\sigma(k_{c\bar{c}\gamma})$	$\sigma(k_{b\bar{b}\gamma})$	$\sigma(k_{\tau^+\tau^-\gamma})$	$\sigma(k_{\mu^+\mu^-\gamma})$	$\sigma(k_{e^+e^-\gamma})$	$\sigma(k_{WW})$	$\sigma(k_{ZZ})$	$\sigma(k_{ZH})$
234%	0.36%	0.83%	0.82%	0.98%	0.99%	0.67%	0.96%	0.99%	0.99%

Table 7: Post-fit uncertainties in the inclusive likelihood fit.

5.2.2 Exclusive $b\bar{b}$ Channel

The recoil mass distribution of the exclusive $b\bar{b}$ selection is shown in Figure 4c. The post-fit parameter uncertainties are summarized in Table 8. Since solely the $b\bar{b}$ background withstands the b-score selection, the corresponding normalization factor is measured very precisely in the sidebands of the recoil mass distribution. The precision on the parameter of interest is 149%.

$\sigma(\mu_{H(b\bar{b})\gamma})$	$\sigma(k_{q\bar{q}\gamma})$	$\sigma(k_{c\bar{c}\gamma})$	$\sigma(k_{b\bar{b}\gamma})$	$\sigma(k_{\tau^+\tau^-\gamma})$	$\sigma(k_{\mu^+\mu^-\gamma})$	$\sigma(k_{e^+e^-\gamma})$	$\sigma(k_{WW})$	$\sigma(k_{ZZ})$	$\sigma(k_{ZH})$
149%	0.99%	0.99%	0.05%	0.99%	1.00%	1.00%	0.99%	0.99%	0.99%

Table 8: Post-fit uncertainties in the exclusive $b\bar{b}$ likelihood fit.

6 Discussion

This note presents the first investigation of the $e^+e^- \rightarrow H\gamma$ process at the FCC-ee. The process has been analyzed inclusively and in the exclusive $b\bar{b}$ final state using two distinct strategies. Both, the cut & count method and the likelihood fit yield compatible results, with precisions of 228% and 234% in the inclusive as well as 156% and 149% in the exclusive analysis, respectively. The latter profits from the large Higgs branching ratio in the $b\bar{b}$ -channel in combination with an excellent b-tagging performance.

⁶ Asimov data refers to pseudo-data that aligns with the Standard Model expectation.

More advanced analysis techniques can help to exploit the full physics potential of the inclusive $H\gamma$ process, although large irreducible backgrounds from hadronic final states are expected to dominate the relevant phase space.

Future studies may explore other exclusive channels like $H \rightarrow gg$ or $H \rightarrow \tau^+\tau^-$, which come with increased difficulty due to small Higgs branching ratios and low background suppression. The $\tau^+\tau^-$ channel for example, requires a loosened cut on the reconstructed particle number, which in turn drastically increases the e^+e^- background.

Acknowledgements

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Appendix

6.1 Event Generation Configurations

The generated events discussed in Section 3 are partially privately produced. In order to ensure reproducibility, the configuration files are listed below.

Listing 1: MadGraph configuration file for $H\gamma$ signal data creation

```
import model loop_qcd_qed_sm_Gmu
generate e+ e- > h a [noborn=QED]

output /path/to/output/

launch /path/to/output/ -n run_name
set pdlabel fcce24011
set lpp1 -3
set lpp2 +3
set ebeam1 120
set ebeam2 120

set nevents 100000
set mml 5
set maxjetflavor 5
set etal 3.68867
done
```

Listing 2: Pythia configuration file for $H\gamma$ signal data creation. After `source /cvmfs/sw.hsf.org/spackages6/key4hep-stack/2022-12-23/x86_64centos7-gcc11.2.0opt/113gi/setup.sh`, the LHE files from Madgraph can be passed through pythia and delphes with `DelphesPythia8_EDM4HEP card_IDEA.tcl edm4hep_IDEA.tcl pythia_config.cmd output.root`.

! 1) Settings used **in** the main program.

```
Main:numberOfEvents = 100000
Main:timesAllowErrors = 150      ! how many aborts before
run stops (Problem: 'fastjet::Error: Requested 2 exclusive
jets , but there were only 0 particles in the event')
! 2) Settings related to output in init(), next() and stat().
```

```
Init:showChangedSettings = on
Init:showChangedParticleData = off
Next:numberCount = 100
Next:numberShowInfo = 1
Next:numberShowProcess = 1
Next:numberShowEvent = 1
```

```
! Vertex smearing : (from https://github.com/HEP-FCC/
FCC-config/blob/winter2023/FCCee/Generator/Pythia8/
p8_ee_ZZ_ecm240.cmd#L16C1-L20C42)
! Check official values here: https://github.com/HEP-FCC/
FCCeePhysicsPerformance/blob/master/General/
README.md#vertex-distribution
```

```
Beams:allowVertexSpread = on
Beams:sigmaVertexX = 9.80e-3    ! 9.80 mm
Beams:sigmaVertexY = 25.4E-6    ! 25.4 mm
Beams:sigmaVertexZ = 0.64      ! 0.64 mm
```

! 3) Set the input LHE file

```
Beams:frameType = 4 ! Reads info of beam parameters from LHE file
Beams:LHEF = /path/to/madgraphlhe/run_name/unweighted_events.lhe
! LHE file from MadGraph
```

Listing 3: Whizard configuration for $q\bar{q}\gamma$ simulation

```
model = SM
```

```
# Center of mass energy
sqrts = 240 GeV
```

```

# Processes

?vis_diags = true

process proc = e1, E1 => (A, u, U) + (A, d, D) + (A, s, S)

#define photon subset to skip the first two photons which are ISR
photons by default
cuts = let subevt @meA = select if Index > 2 [A] in
    all E > 50 GeV [@meA]
    and all 0.01 < Dist [@meA, u:U]
    and all 0.01 < Dist [@meA, d:D]
    and all 0.01 < Dist [@meA, s:S]
    and all -0.998750 < cos (Theta) < 0.998750 [@meA]
    and all -0.998750 < cos (Theta) < 0.998750 [u:U]
    and all -0.998750 < cos (Theta) < 0.998750 [d:D]
    and all -0.998750 < cos (Theta) < 0.998750 [s:S]
    and all M > 5 GeV [u, U]
    and all M > 5 GeV [d, D]
    and all M > 5 GeV [s, S]

beams = e1, E1 => gaussian => isr
?keep_beams = true
?keep_remnants = true

gaussian_spread1 = 0.221%
gaussian_spread2 = 0.221%

?isr_handler = true
$isr_handler_mode = "recoil"
isr_alpha = 0.0072993
isr_mass = 0.000511

! Parton shower and hadronization
?ps_fsr_active = true
?ps_isr_active = false
?hadronization_active = true
$shower_method = "PYTHIA6"
!?ps_PYTHIA_verbose = true

```

```

$ps_PYTHIA_PYGIVE = "MSTJ(28)=0; -PMAS(25,1)=125.;
PMAS(25,2)=0.4143E-02; -MSTJ(41)=2; -MSTU(22)=2000;
PARJ(21)=0.40000; -PARJ(41)=0.11000; -PARJ(42)=0.52000;
PARJ(81)=0.25000; -PARJ(82)=1.90000; -MSTJ(11)=3;
PARJ(54)=-0.03100; -PARJ(55)=-0.00200; -PARJ(1)=0.08500;
PARJ(3)=0.45000; -PARJ(4)=0.02500; -PARJ(2)=0.31000;
PARJ(11)=0.60000; -PARJ(12)=0.40000; -PARJ(13)=0.72000;
PARJ(14)=0.43000; -PARJ(15)=0.08000; -PARJ(16)=0.08000;
PARJ(17)=0.17000; -MSTP(3)=1;MSTP(71)=1; -MSTP(151)=1;
PARP(151)=0.0273; -PARP(152)=4.88e-5; -PARP(153)=1.33;
PARP(154)=1.337; -MSTJ(22)=4; -PARJ(73)=2250; -PARJ(74)=2500"

```

```

integrate (proc) { iterations = 10:100000:"gw", 5:200000:"" }

# n_events should be passed by the EventProducer
n_events = 100000

```

```

sample_format = stdhep
$extension_stdhep = "stdhep"
simulate (proc) {checkpoint = 10}

```

Listing 4: Whizard configuration for $b\bar{b}\gamma$ simulation. The configuration is identical to listing 3 except the following lines that need to be interchanged.

```

process proc = e1, E1 => b, B, A

```

```

cuts = let subevt @meA = select if Index > 2 [A] in
    all E > 50 GeV [@meA]
    and all 0.01 < Dist [@meA, b:B]
    and all -0.998750 < cos (Theta) < 0.998750 [@meA]
    and all -0.998750 < cos (Theta) < 0.998750 [b:B]
    and all M > 5 GeV [b, B]

```

Listing 5: Whizard configuration for $c\bar{c}\gamma$ simulation. The configuration is identical to listing 3 except the following lines that need to be interchanged.

```

process proc = e1, E1 => c, C, A

```

```

cuts = let subevt @meA = select if Index > 2 [A] in
    all E > 50 GeV [@meA]
    and all 0.01 < Dist [@meA, c:C]
    and all -0.998750 < cos (Theta) < 0.998750 [@meA]
    and all -0.998750 < cos (Theta) < 0.998750 [c:C]
    and all M > 5 GeV [c, C]

```

Listing 6: Whizard configuration for $e^+e^-\gamma$ simulation. The configuration is identical to listing 3 except the following lines that need to be interchanged.

```
process proc = e1, E1 => e1, E1, A

cuts = let subevt @meA = select if Index > 2 [A] in
  all E > 50 GeV [@meA]
  and all 0.01 < Dist [@meA, e1:E1]
  and all -0.998750 < cos (Theta) < 0.998750 [@meA]
  and all -0.998750 < cos (Theta) < 0.998750 [e1:E1]
  and all M > 5 GeV [e1, E1]
```

Listing 7: Whizard configuration for $\mu^+\mu^-\gamma$ simulation. The configuration is identical to listing 3 except the following lines that need to be interchanged.

```
process proc = e1, E1 => e2, E2, A

cuts = let subevt @meA = select if Index > 2 [A] in
  all E > 50 GeV [@meA]
  and all 0.01 < Dist [@meA, e2:E2]
  and all -0.998750 < cos (Theta) < 0.998750 [@meA]
  and all -0.998750 < cos (Theta) < 0.998750 [e2:E2]
  and all M > 5 GeV [e2, E2]
```

Listing 8: Whizard configuration for $\tau^+\tau^-\gamma$ simulation. The configuration is identical to listing 3 except the following lines that need to be interchanged.

```
process proc = e1, E1 => e3, E3, A

cuts = let subevt @meA = select if Index > 2 [A] in
  all E > 50 GeV [@meA]
  and all 0.01 < Dist [@meA, e3:E3]
  and all -0.998750 < cos (Theta) < 0.998750 [@meA]
  and all -0.998750 < cos (Theta) < 0.998750 [e3:E3]
  and all M > 5 GeV [e3, E3]
```

Listing 9: Whizard configuration for ZH simulation. The configuration is identical to listing 3 except the following lines that need to be interchanged.

```
process proc = e1, E1 => Z,H
```