Expected precision of Higgs boson decays to two photons and Z boson with a photon at the FCC-ee

Eysermans Jan [1*]

[1] Particle Physics Collaboration, Massachusetts Institute of Technology, 77 Massachusetts Ave, Boston, Cambridge, 02139, MA, USA .

Corresponding author(s). E-mail(s): jan.eysermans@cern.ch;

Abstract

Despite the small branching fractions of $\mathbf{H} \to \gamma\gamma$ and $\mathbf{H} \to \boldsymbol{Z\gamma}$, the clean environment of electron–positron collisions allows for the measurement of their cross sections and branching ratios with a precision comparable to that expected at the HL-LHC. This note presents an analysis of the cross-section measurements and projected uncertainties at center-of-mass energies of 240 and 365 GeV for the production mode, as well as for the vector boson fusion (VBF) process at 365 GeV. The analysis employs a basic cut-based strategy, with event categorization according to the associated Z boson decay mode in the $\boldsymbol{\gamma\gamma}$ analysis. A similar approach is followed for the $\boldsymbol{Z\gamma}$ final state, but further refined using machine learning techniques. Results are interpreted under varying assumptions for the electromagnetic calorimeter resolution.

Higgs → γγ and Zγ at FCC-ee

Jan Eysermans

Higgs $\rightarrow Z\gamma$

Overview

Probe the H→Zγ cross-section uncertainty at FCC-ee

- Using IDEA detector (crystal ECAL)
- At center-of-mass energy of 240 GeV, 365 GeV will follow later

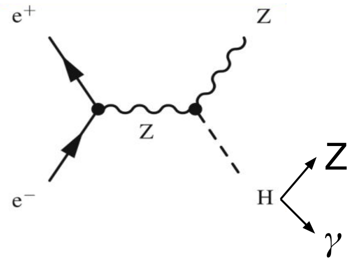
At 10.8 ab^{-1} → 2.2 M Higgs produced		
BR(H→Zγ)	# Events N	Unc. √N/N (%)
1.53E–3	3311	1.73

Expectations at 240 GeV

- CDR does not quote a number
- Ultimate uncertainty 1.73% (no backgrounds, 100 % selection efficiency)

Analysis strategy

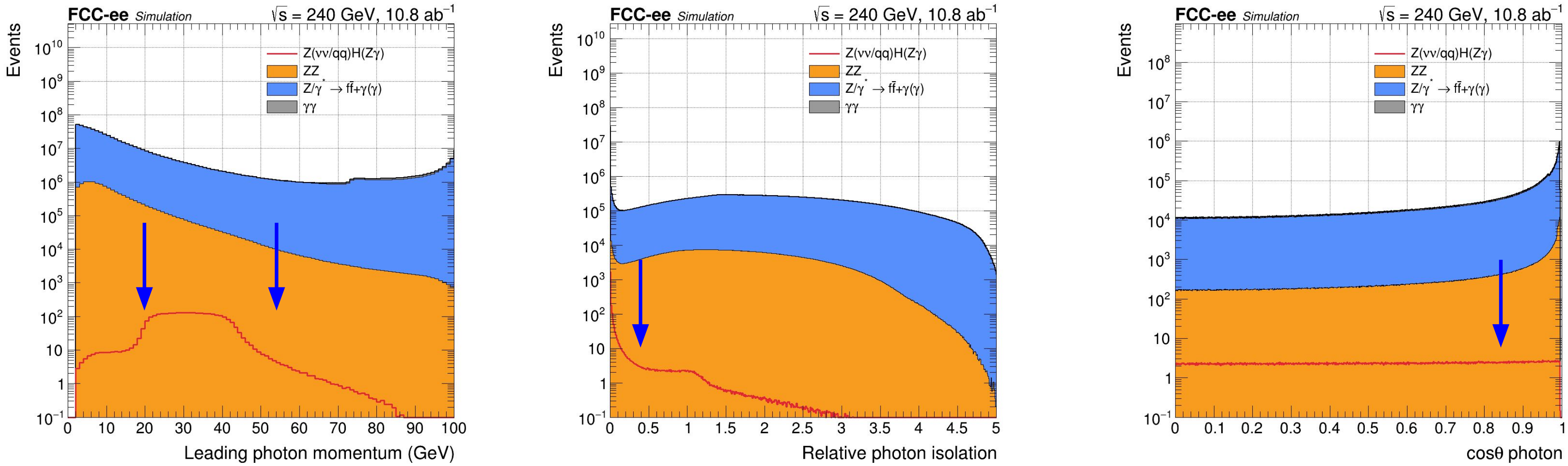
- Final state ZZγ
- Hadronic final states highest BR but overwhelming backgrounds (WW, ZZ, Z/γ)
- Leptonic final states not considered due to low BR
- Focus on specific final state with Z($\nu\nu$)H(qq)γ or Z(qq)H($\nu\nu$)γ
    - Require single isolated photon + hadronic activity
    - Veto on leptons and high missing energy kills WW
    - Z/γ with hard ISR suppressed as visible ISR photon suppresses missing energy
    - ZZ remaining (irreducible) background
- Background modeled with Whizard (Z/γ) and Pythia (ZZ) – which likely is not accurate enough to simulate properly the single photon Z/γ+a and ZZ+a (see more details next presentation by Lena)



Isolated photon

Selection starts by requiring a single isolated photon

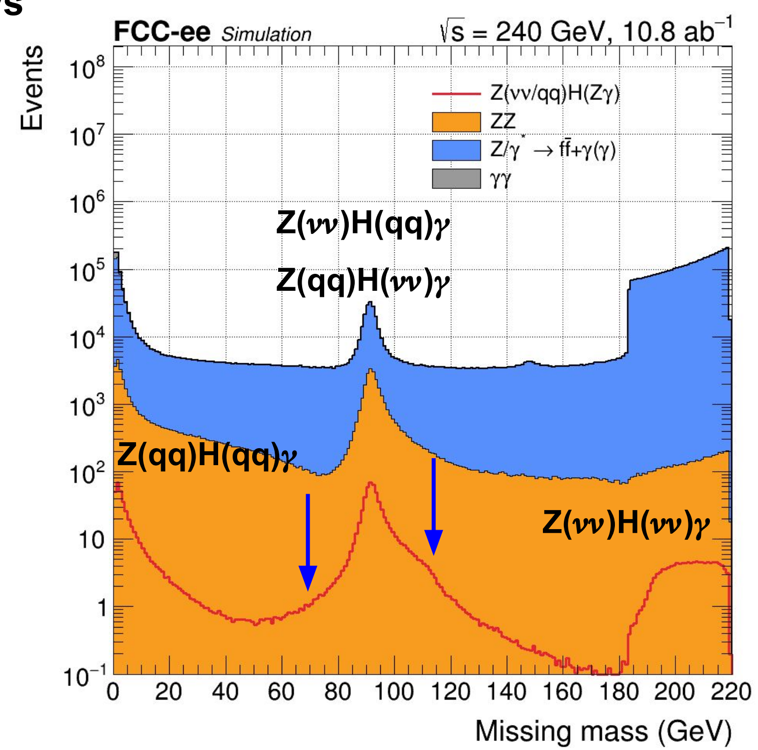
- Momentum 20–55 GeV
- Relative isolation < 0.3
- $\cos(\theta_\gamma) < 0.85$



Missing mass

Missing mass used to categorize hadronic and invisible Z decays

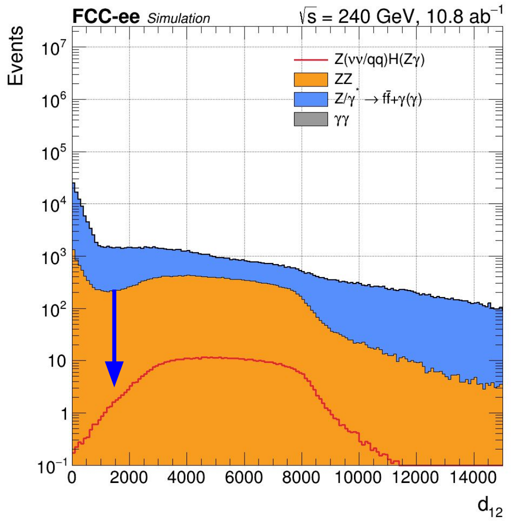
- Target Z($\nu\nu$)H(qq)γ or Z(qq)H($\nu\nu$)γ
- Missing mass selected +/– 25 GeV around Z mass

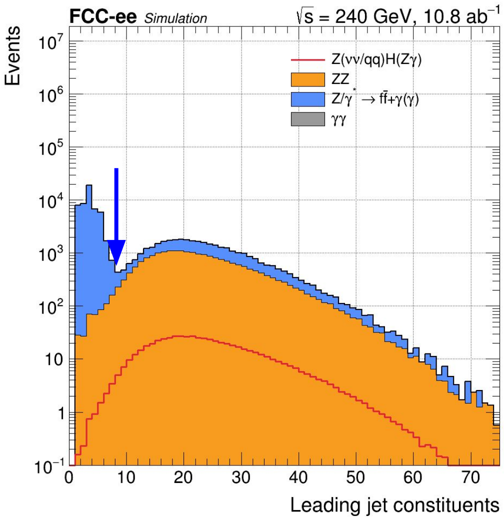


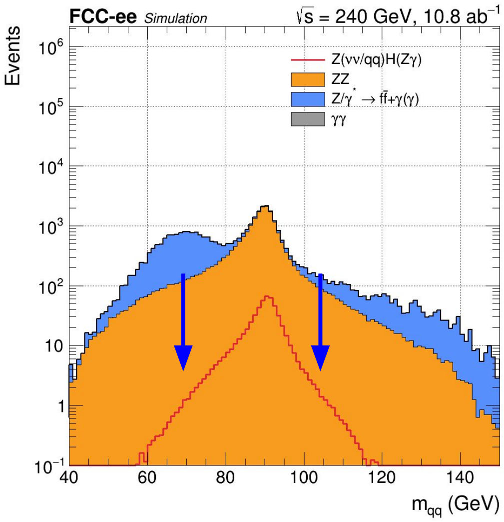
Jet clustering

Exclusive clustering of PF candidates excluding the photon to 2 jets

- dmerge d_{12} cut to suppress Z/γ hadronic and tau
- Jet ID: requirements on number of constituents and momenta > 15 GeV
- Invariant mass of qq system to match the Z mass within +/– 25 GeV





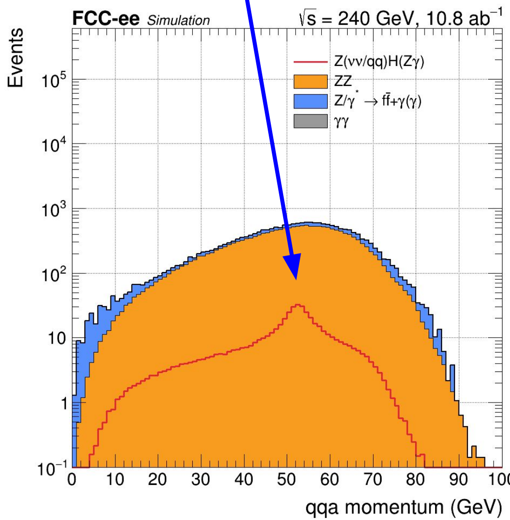


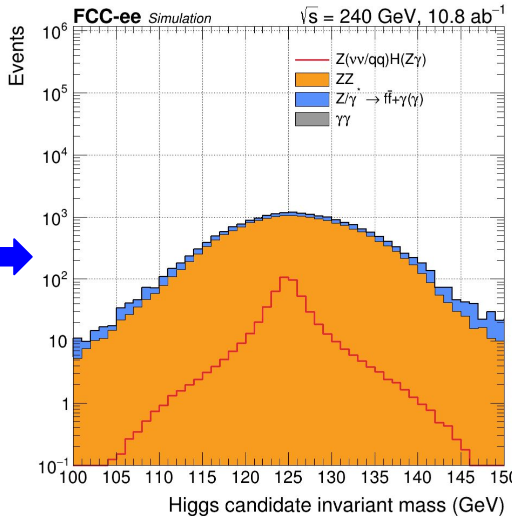
Jet pairing

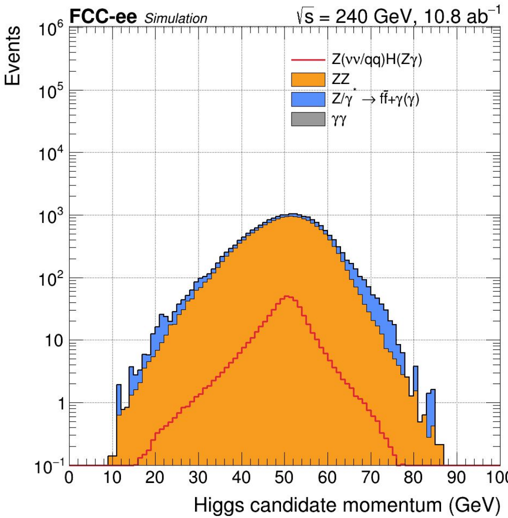
Jets (qq) or missing energy (vv) are paired with the photon to form the Higgs candidate

- Take pair with lowest $\chi^2 = (m_{xxa} - 125)^2 + (\text{recoil}_{xx} - 125)^2 + (p_{xxa} - 50)^2$ (with xx = qq or $\nu\nu$)
- Form Higgs and associated Z candidates

Before pairing, qqa momentum peaks at ~ 50 GeV
Both correct pairs and incorrect pairs contribute to this plot



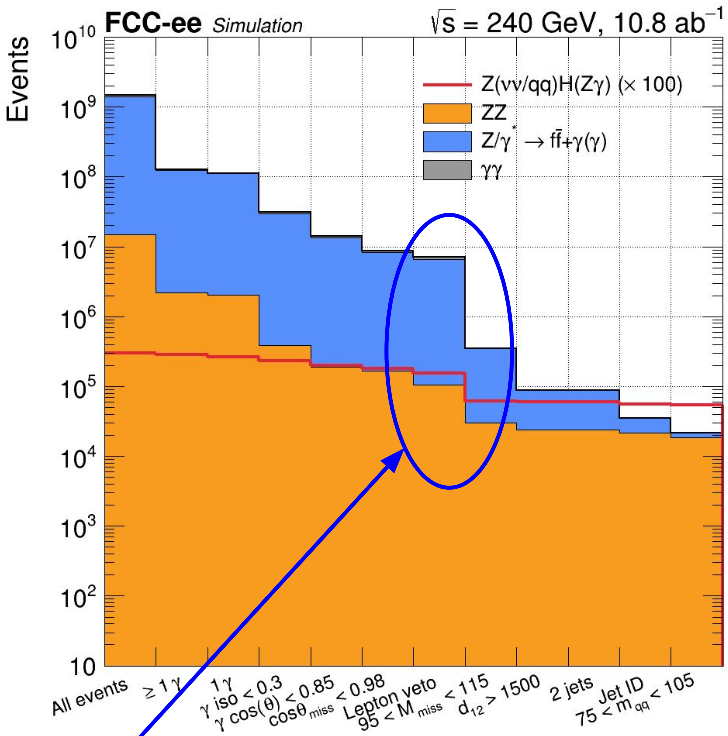




Cutflow summary

Additional cuts on $\cos(\theta_{miss})$ and lepton veto

Cut	Significance	Signal	ZZ	Zgamma	gaga
Cut 0	0.079	3.0223e+03	1.4677e+07	1.3717e+09	7.0830e+07
Cut 1	0.253	2.8374e+03	2.1912e+06	1.2226e+08	1.6443e+06
Cut 2	0.247	2.6218e+03	2.0047e+06	1.0919e+08	1.6313e+06
Cut 3	0.421	2.3404e+03	3.8420e+05	2.8888e+07	1.5851e+06
Cut 4	0.526	1.9716e+03	1.8863e+05	1.3195e+07	6.5180e+05
Cut 5	0.608	1.7997e+03	1.6534e+05	8.0483e+06	5.5757e+05
Cut 6	0.571	1.5301e+03	1.0508e+05	6.5138e+06	5.5757e+05
Cut 7	1.039	6.1066e+02	2.9727e+04	3.1468e+05	6.9116e-01
Cut 8	2.003	6.0075e+02	2.3568e+04	6.5200e+04	0.0000e+00
Cut 9	2.003	6.0075e+02	2.3568e+04	6.5200e+04	0.0000e+00
Cut 10	2.943	5.6042e+02	2.1664e+04	1.3472e+04	0.0000e+00
Cut 11	3.564	5.3678e+02	1.8449e+04	3.1642e+03	0.0000e+00



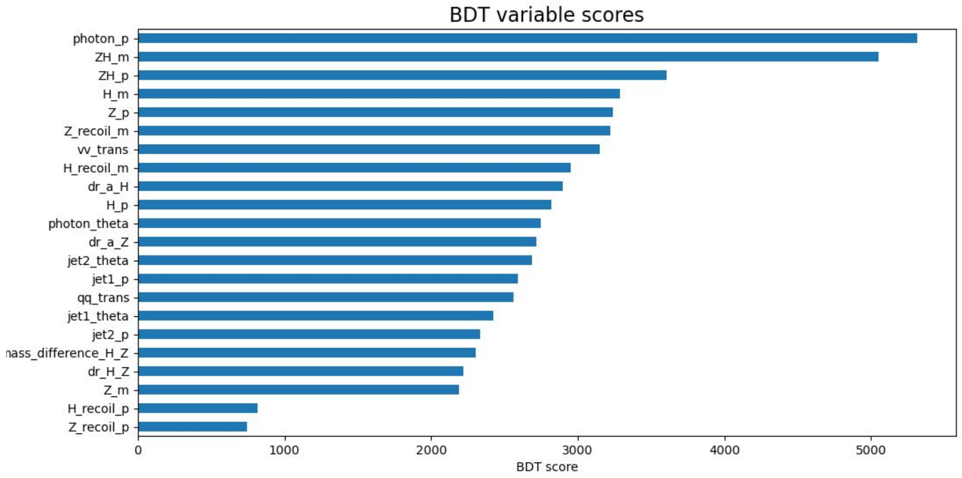
Missing mass drastically reduces Z/γ with hard ISR as visible ISR photon suppresses missing energy

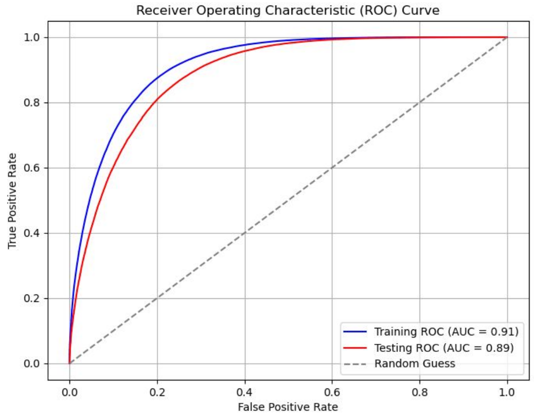
Boosted Decision Tree

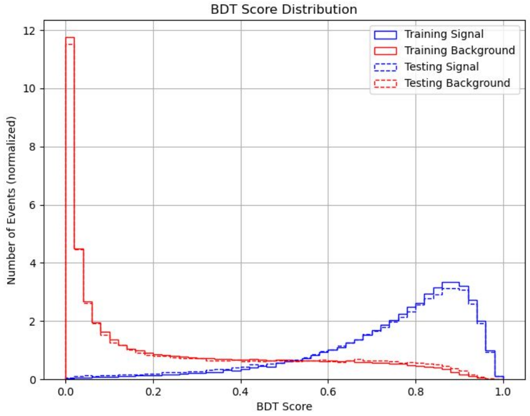
BDT trained on remaining events to further improve the signal/background discrimination

Many variables used that defines the entire ZZγ system

- Photon and jet properties (momentum, angle)
- Mass/recoil/momentum variables of the Higgs candidate, associated Z candidate
- Angular variables between those objects



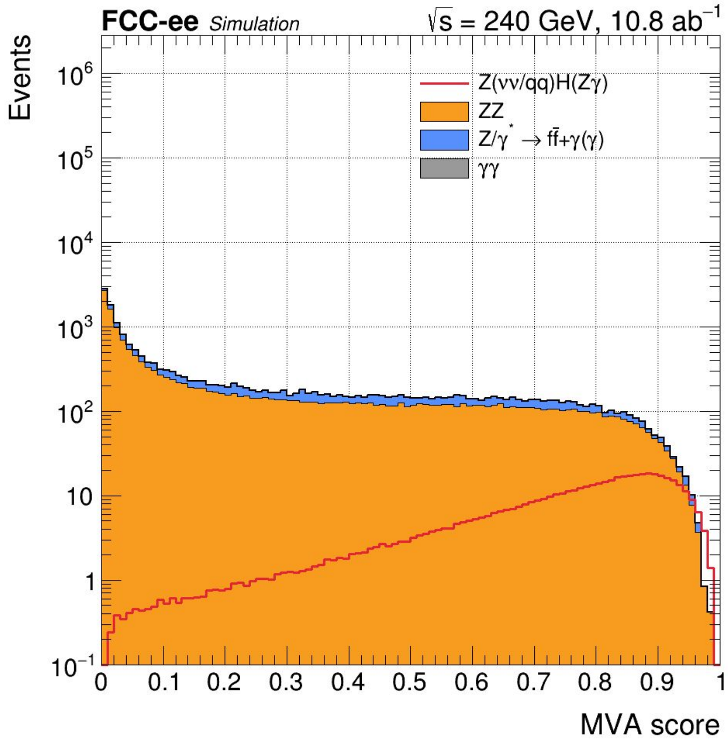




Fit and results

Fit performed on MVA discriminator

- Backgrounds have a 1% normalization uncertainty (constrained)
- **Total uncertainty of 11.81%**
- Results with background normalization fixed 11.28%



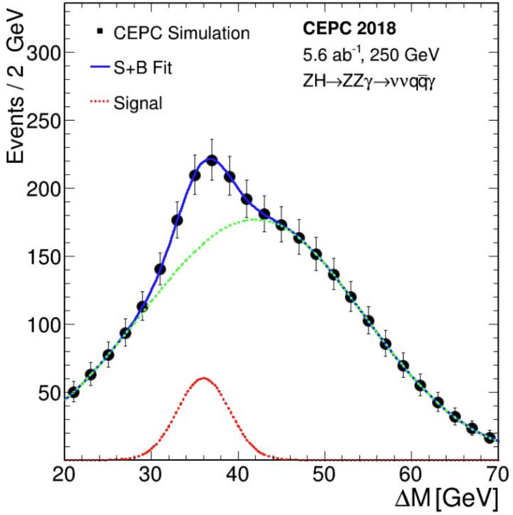
Other colliders

Comparison with HL-LHC

- 11.81% on σ*BR translates to ~ 5.9 % on $\kappa_{Z\gamma}$
- HL-LHC projections $\kappa_{Z\gamma}$ ~ 6.8%

CEPC https://arxiv.org/pdf/1810.09037

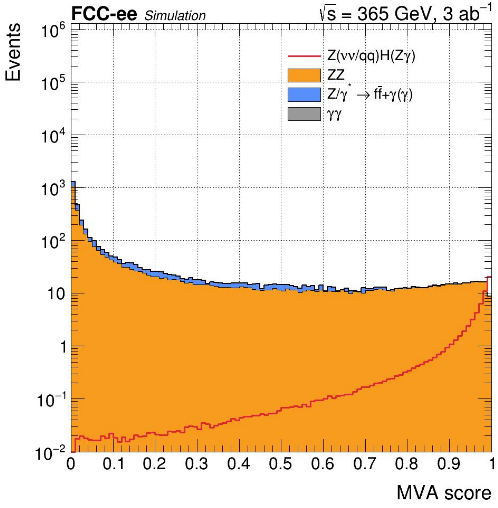
- Quotes a 13% uncertainty in the same Z($\nu\nu$)H(qq)γ or Z(qq)H($\nu\nu$)γ final state, with integrated luminosity 5.6 ab^{-1} (= 9.36% at 10.8 ab^{-1})
- Backgrounds seems much lower than our analysis, but no specific details of analysis given, nor fitting procedure
- Figure can be indicative rather than to be taken at face value

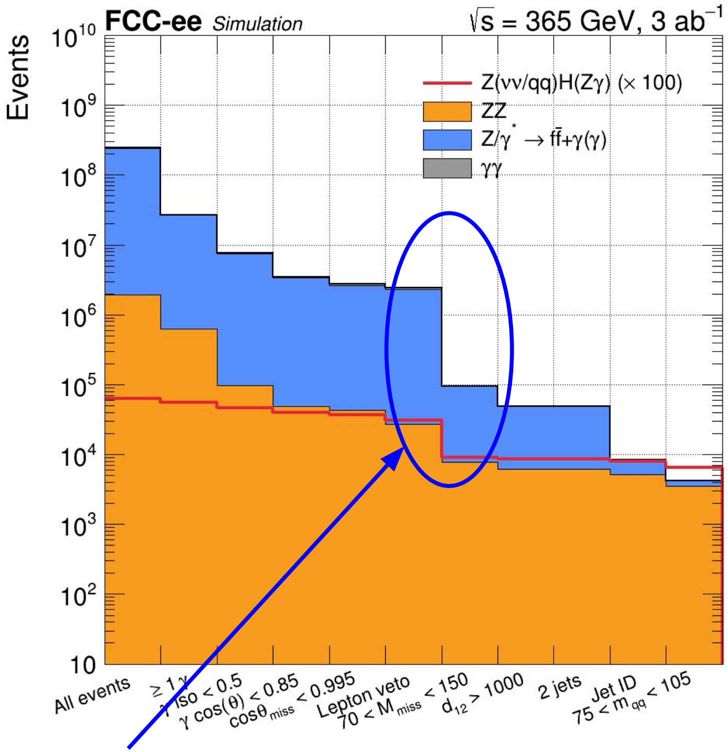


ILC/CLIC do not mention studies for this analysis

ZH at √s = 365 GeV

Cut	Significance	Signal	ZZ	Zgamma	gaga
Cut 0	0.040	6.3603e+02	1.9284e+06	2.3823e+08	8.5102e+06
Cut 1	0.108	5.6060e+02	6.2729e+05	2.6066e+07	2.9806e+05
Cut 2	0.168	4.6464e+02	9.6436e+04	7.2917e+06	2.8915e+05
Cut 3	0.215	3.9962e+02	4.8828e+04	3.2888e+06	1.1978e+05
Cut 4	0.222	3.6856e+02	4.2727e+04	2.6039e+06	1.0770e+05
Cut 5	0.196	3.0583e+02	2.7033e+04	2.3058e+06	1.0770e+05
Cut 6	0.294	9.0103e+01	7.7427e+03	8.5830e+04	1.1567e+01
Cut 7	0.388	8.6158e+01	6.1304e+03	4.3018e+04	0.0000e+00
Cut 8	0.388	8.6158e+01	6.1304e+03	4.3018e+04	0.0000e+00
Cut 9	0.856	7.9235e+01	5.2143e+03	3.1982e+03	0.0000e+00
Cut 10	0.992	6.4930e+01	3.4963e+03	6.5966e+02	0.0000e+00

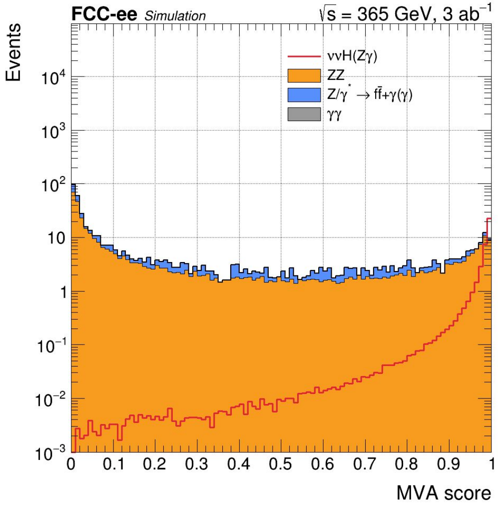


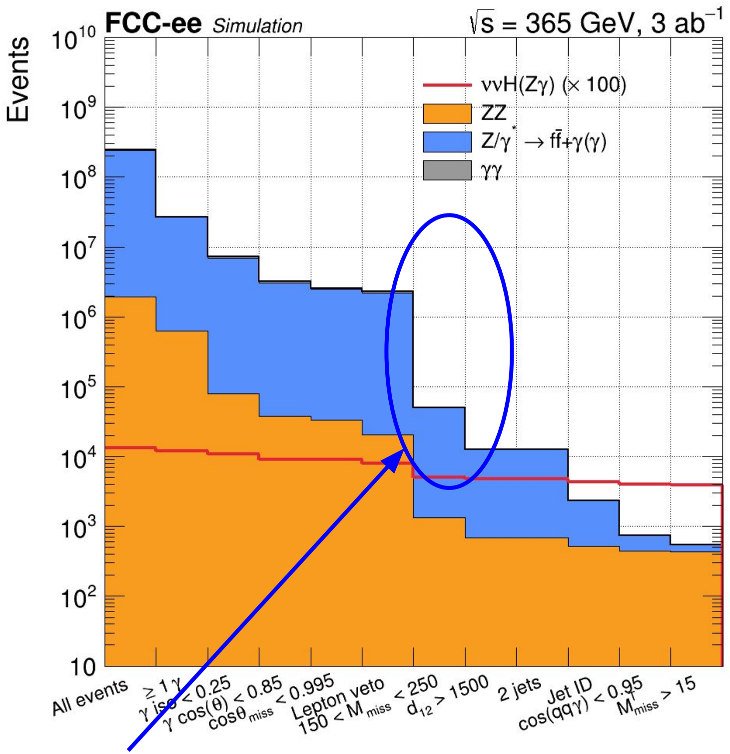


Missing mass drastically reduces Z/γ with hard ISR as visible ISR photon suppresses missing energy

VBF at $\sqrt{s}$ = 365 GeV

Cut	Significance	Signal	ZZ	Zgamma	gaga
Cut 0	0.009	1.3422e+02	1.9284e+06	2.3823e+08	8.5102e+06
Cut 1	0.023	1.2025e+02	6.2729e+05	2.6066e+07	2.9806e+05
Cut 2	0.040	1.0836e+02	8.0191e+04	6.8087e+06	2.8913e+05
Cut 3	0.051	9.0079e+01	3.7845e+04	3.0181e+06	1.1976e+05
Cut 4	0.056	8.9444e+01	3.3153e+04	2.4405e+06	1.0768e+05
Cut 5	0.052	7.8670e+01	2.0525e+04	2.1886e+06	1.0768e+05
Cut 6	0.225	5.0360e+01	1.3330e+03	4.8484e+04	2.8257e+01
Cut 7	0.418	4.7254e+01	6.7832e+02	1.2023e+04	0.0000e+00
Cut 8	0.418	4.7254e+01	6.7832e+02	1.2023e+04	0.0000e+00
Cut 9	0.878	4.3263e+01	5.2399e+02	1.8160e+03	0.0000e+00
Cut 10	1.412	4.0242e+01	4.4899e+02	2.8283e+02	0.0000e+00
Cut 11	1.579	[illegible]	[illegible]	[illegible]	0.0000e+00



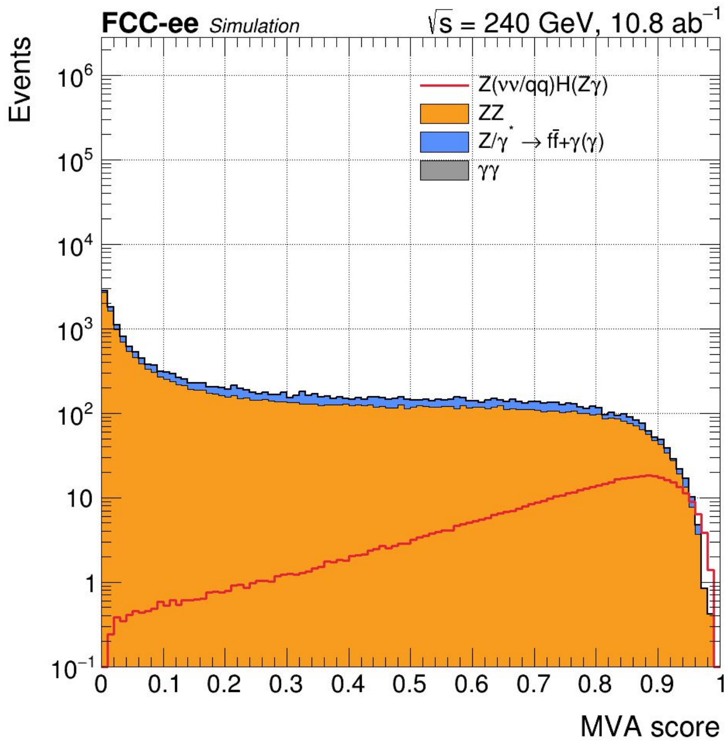


Missing mass drastically reduces Z/γ with hard ISR as visible ISR photon suppresses missing energy

Results at √s = 365 GeV

Fit performed on MVA discriminators

- Simultaneous fit on ZH and VBF POI
- Backgrounds have a 1% normalization uncertainty (constrained)
- **Total uncertainty of 21.94% for ZH, 23.14% for VBF**



Conclusions

Evaluated expected precision of H→Zγ at FCC-ee

- In specific final state Z($\nu\nu$)H(qq)γ or Z(qq)H($\nu\nu$)γ which suppresses Z/γ background
- Quoted uncertainty of 11.81% at 240 GeV
- Quoted uncertainty of 21.94% for ZH, 23.14% for VBF at 365 GeV
- Competitive with HL-LHC expectations

Higgs $\rightarrow \gamma\gamma$

Overview

Probe the $H \to \gamma\gamma$ cross-section uncertainty at FCC-ee

- Using IDEA detector (crystal ECAL)
- Both center-of-mass energies of 240 and 365 GeV

At 10.8 ab^{-1} → 2.2 M Higgs produced		
BR($H \to \gamma\gamma$)	# Events N	Unc. $\sqrt{N}/N$ (%)
2.27E–3	4937	1.42

Expectations at 240 GeV

- CDR quotes a 6.1% uncertainty (scaled from 5 to 10.8 ab^{-1})
- Ultimate uncertainty 1.42% (no backgrounds, 100 % selection efficiency)

Analysis strategy

- Cut-based analysis
- Very clean invariant mass at the Higgs mass → use mass distribution to fit
- Backgrounds
    - Mainly from Z/γ with hard multiple ISR, modeled with Whizard (high stat samples – 5×10^8 events)
    - Direct di-photon production ($e^+e^- \to \gamma\gamma$) can be totally suppressed
    - WW/ZZ with ISR found to be negligible

Event selection at 240 GeV

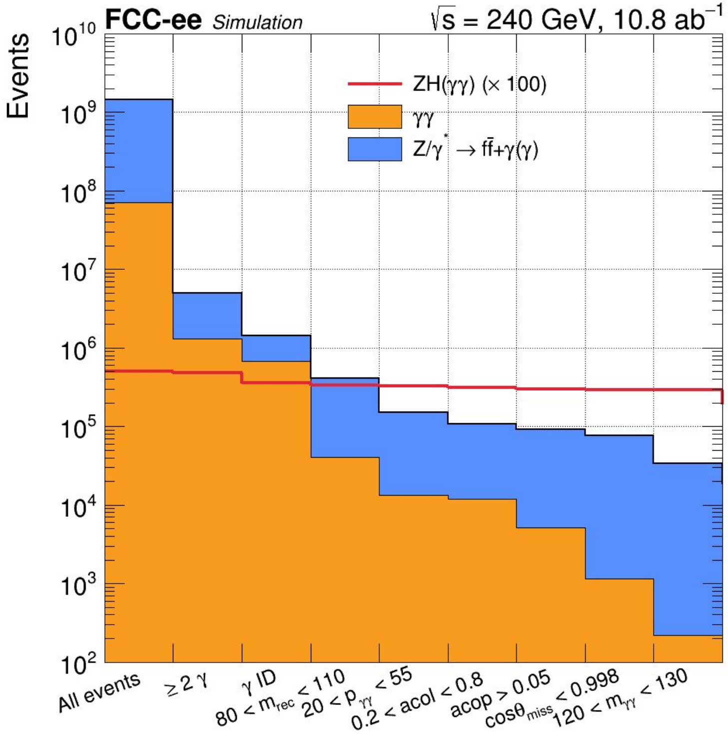
1. Photon pair selection

- Photon momentum between 40–95 GeV
- Select pair that matches Higgs mass and recoils against the Z
- Identification requirements:
    - Isolation of leading photon
    - $\cos(\theta_\gamma)$ requirements on leading and subleading photons

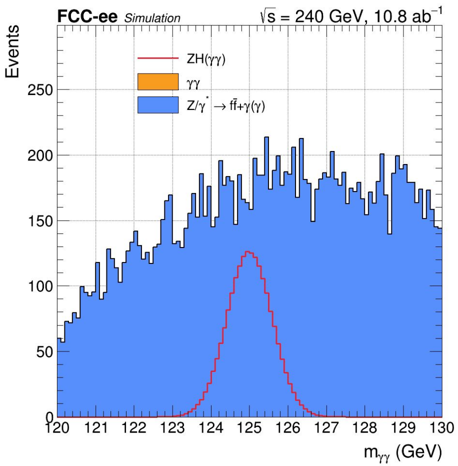
2. Baseline selection using kinematic and event variables

3. Categorize according to associated Z decays (qq, vv, $\mu\mu$, ee)

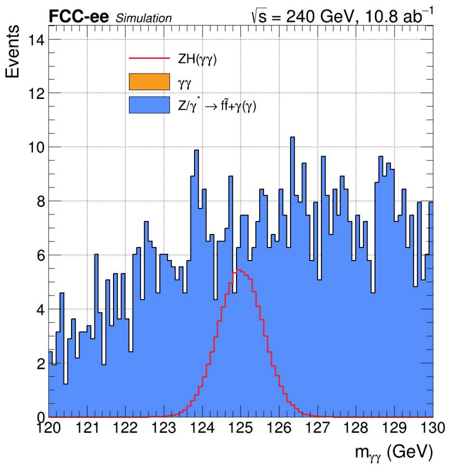
- Based on presence of leptons and amount of missing mass
- For qq, $\mu\mu$, ee: further optimize event selection based on kinematics of Z decay products



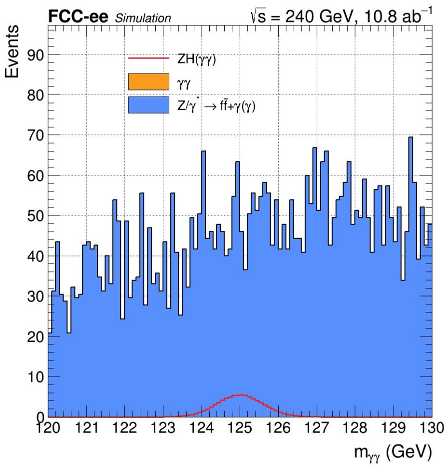
Invariant mass distributions



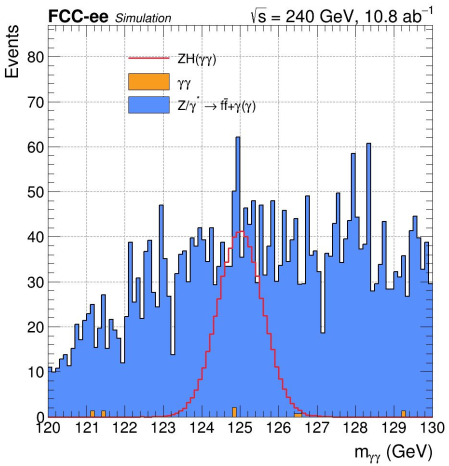
Z→qq



Z→$\mu\mu$



Z→ee



Z→vv

Shown final invariant mass distributions for each category

- qq and vv channels most promising (highest significance)
- Electron channel background-dominated (t-channel)
- Rather poor background statistics (despite using 5×10^8 qq events) → distributions smoothed before fitting

Results at 240 GeV

Simultaneous fit over 4 categories using the invariant mass distributions

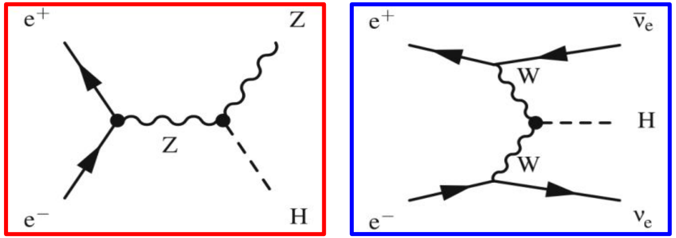
- Backgrounds have a 5% normalization uncertainty
- Total uncertainty of 3.63%
- Results dominated by qq and vv channels

Expected uncertainties ZH($\gamma\gamma$) at 240 GeV	
qq	4.47
vv	6.83
ee	45.58
$\mu\mu$	20.06
Combined	3.63

Splitting production mechanisms at 365 GeV

At 365 GeV center-of-mass, significant contribution from VBF vvH

- Interferes with the ZH process where Z→vv
- Split the production mode
    - **ZH:** use muon neutrino sample with weight 3
    - **VBF:** use (veveH – vmuvmuH) – contains the pure VBF component + interference

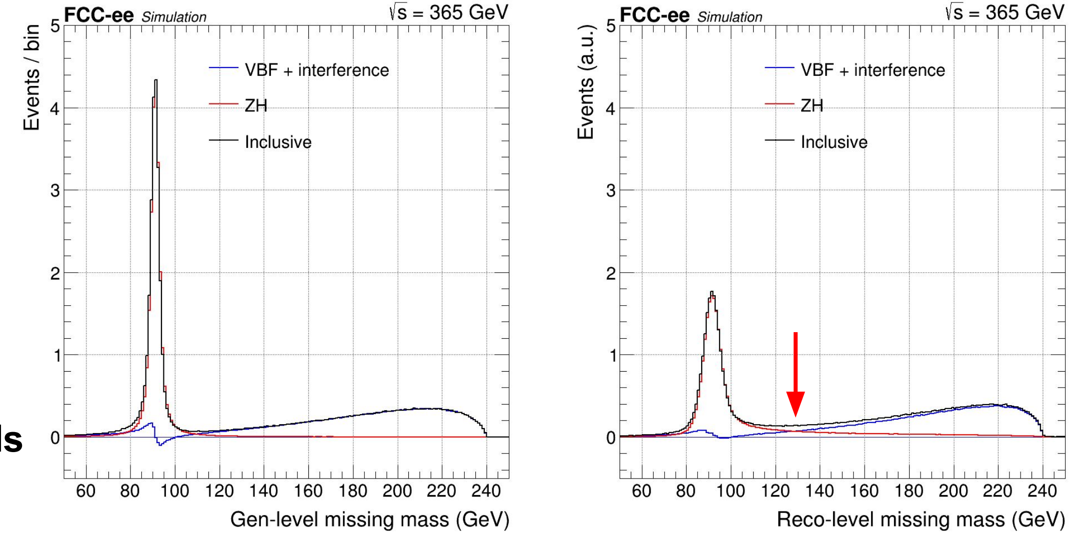


Split events based on missing mass

- ZH enhanced: missing mass < 130 GeV
- VBF enhanced: missing mass < 130 GeV

Optimize event selection in both categories

Simultaneous fit in both categories with 2 POIs



Event selection at 365 GeV – ZH

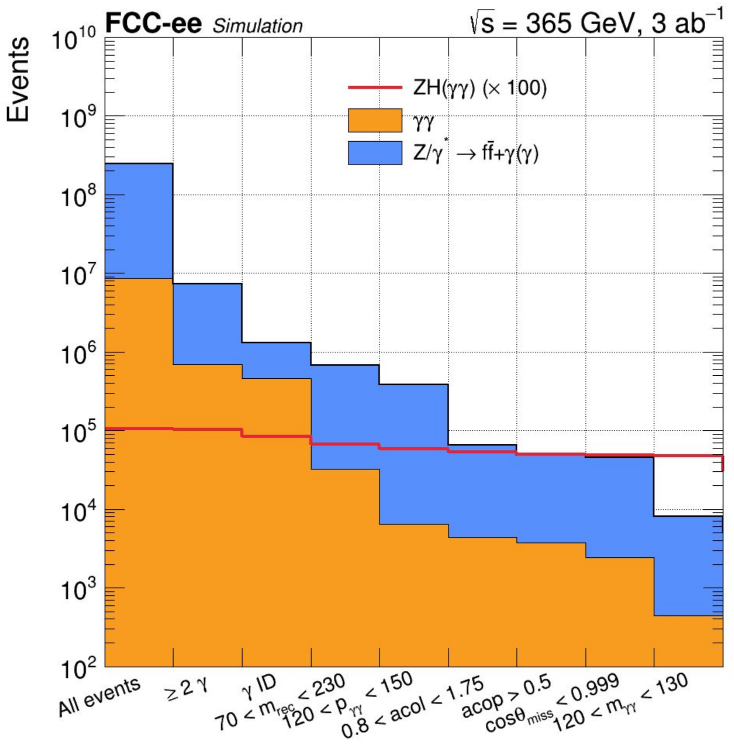
1. Photon pair selection

- Photon momentum between 20–170 GeV
- Select pair that matches Higgs mass and recoils against the Z
- Identification requirements:
    - Isolation of leading photon
    - $\cos(\theta_{\gamma})$ requirements on leading and subleading photons

2. Baseline selection using kinematic and event variables

3. Categorize according to associated Z decays (qq, vv, $\mu\mu$, ee)

- Based on presence of leptons and amount of missing mass
- For qq, $\mu\mu$, ee: further optimize event selection based on kinematics of Z decay products

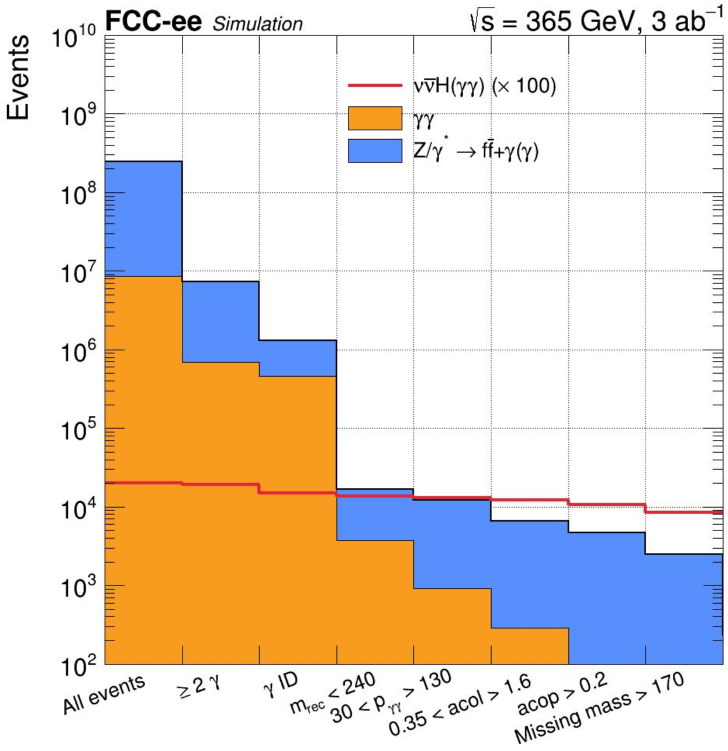


Event selection at 365 GeV – VBF

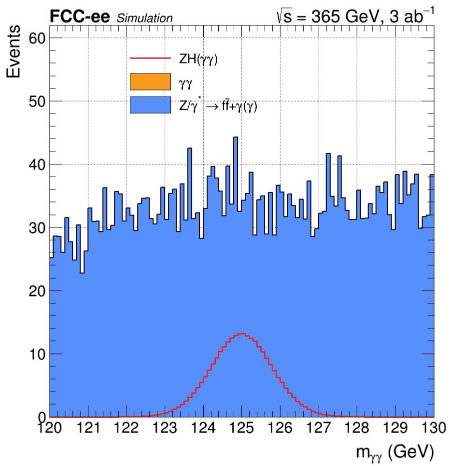
1. Photon pair selection

- Photon momentum between 20–170 GeV
- Select pair that matches Higgs mass and recoils against the Z
- Identification requirements:
  - Isolation of leading photon
  - $\cos(\theta_{\gamma})$ requirements on leading and subleading photons

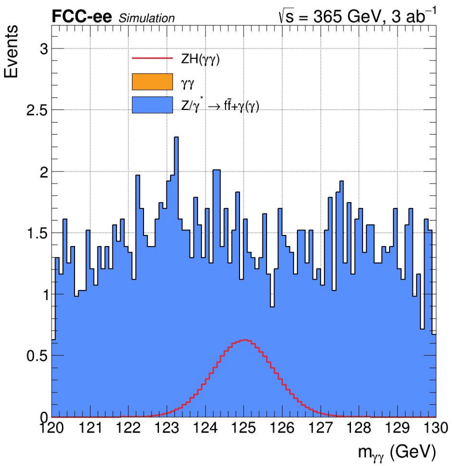
2. Baseline selection using kinematic and event variables



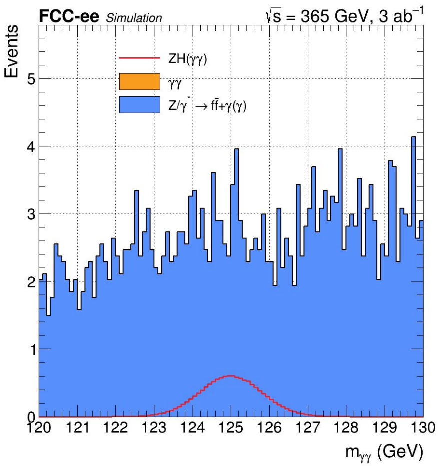
Invariant mass distributions



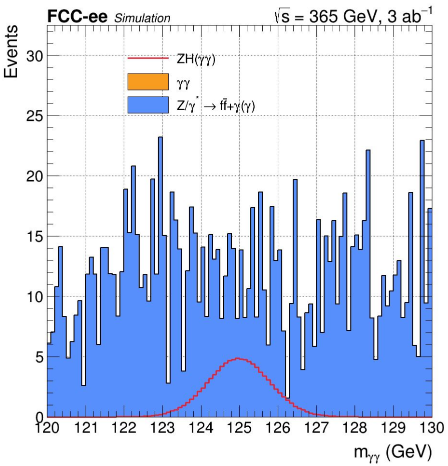
Z→qq



Z→$\mu\mu$



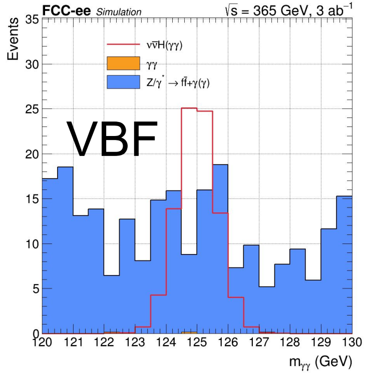
Z→ee



Z→vv

Shown final invariant mass distributions for each category

- qq and vv channels most promising (highest significance)
- Electron channel background-dominated (t-channel)
- Distributions smoothed before fitting



Results at 240 GeV

Simultaneous fit over 5 categories using the m(γγ) distribution

- 2 POIs: ZH and VBF – simultaneous fit
- Backgrounds have a 5% normalization uncertainty
- Total uncertainty of 12.90% for ZH and 14.71 for VBF

Expected uncertainties ZH($\gamma\gamma$) at 365 GeV	
ZH (Z=qq,vv,ee,mumu)	12.90
VBF (vvH)	14.71

ECAL variations

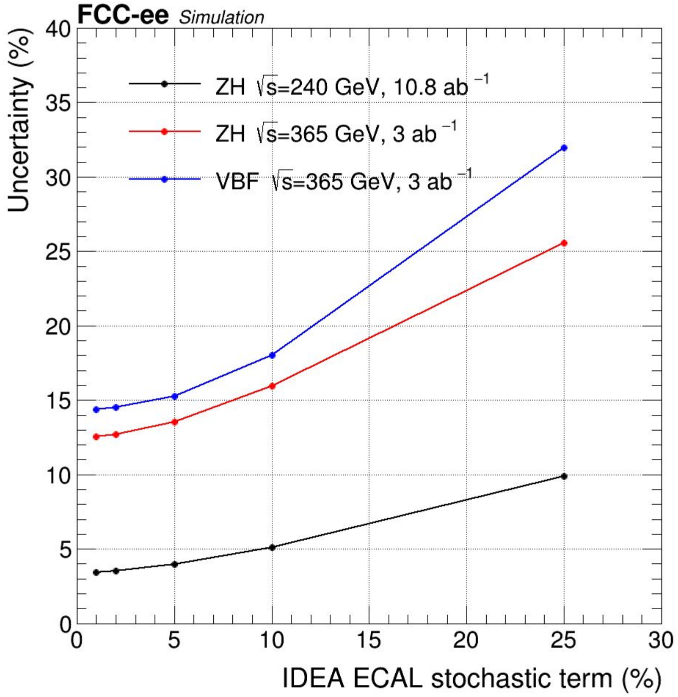
$$\frac{\sigma_E}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

IDEA nominal $$\frac{\sigma_E}{E} = \frac{0.03}{\sqrt{E}} \oplus \frac{0.002}{E} \oplus 0.005$$

IDEA perturbed stochastic variation S from 1→ 25%

Dual Readout $$\frac{\sigma_E}{E} = \frac{0.11}{\sqrt{E}} \oplus \frac{0.05}{E} \oplus 0.01$$

Variation	ZH (240 GeV)	ZH (365 GeV)	VBF (365 GeV)
IDEA Stoch. Term 3%	3.63	12.90	14.71
IDEA Stoch. Term 1 %	3.42	12.56	14.37
IDEA Stoch. Term 5%	3.97	13.55	15.27
IDEA Stoch. Term 10%	5.12	15.94	18.00
Dual Readout	5.97	17.99	18.03



Conclusions

Analysis $H \rightarrow \gamma\gamma$ at both 240 and 365 GeV

- Cut and count analysis with categorization
- At 240, combined uncertainty of 3.63%
- ZH and VBF simultaneous fit at 365 GeV yielding 12.90% 14.71 % respectively