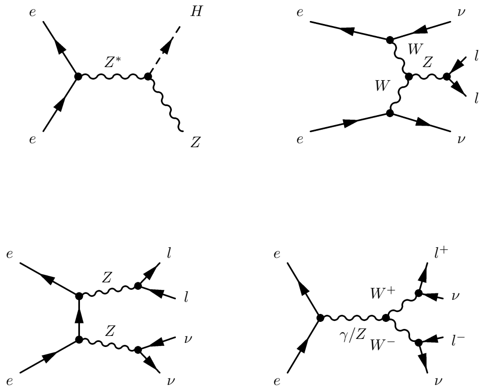
Higgs to invisible limits at FCC-ee

Stephen Farry, Andrew Mehta

FCC-ee Physics & Performance Meeting

July 19, 2021

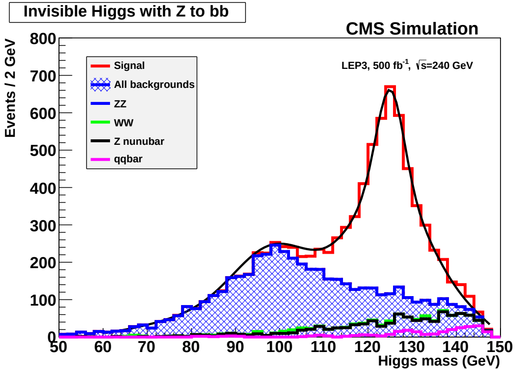
Introduction



- Standard Model Higgs to invisible decays occur through neutrinos, BR $\sim 0.1\%$
  - Can be enhanced through decays to dark matter particles
- Current LHC limits stand at ∼11% [ATLAS-CONF-2020-052]
- Clean environment of the FCC-ee present a great opportunity to improve limits by an order of magnitude

Previous Studies

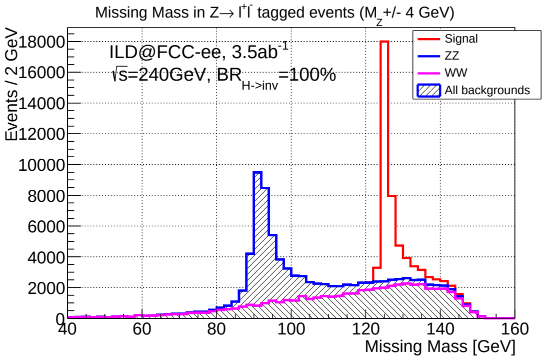
[1208.1662 [hep-ex]]

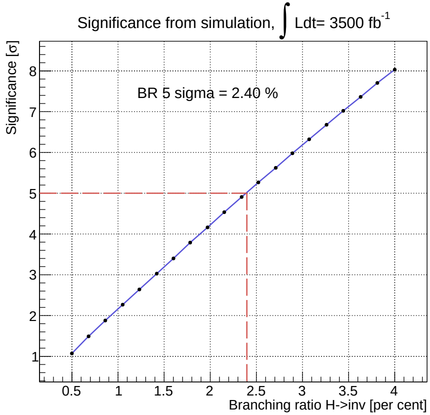


- 5 σ observation of $H \to inv.$ for branching fractions > 4.0% for 0.5 ab^{-1} in combined $Z \to \ell\ell$ and $Z \to bb$ final states

Previous Studies

[*Eur. Phys. J. C* (2017) 77:p. 116]





5 sigma observation of $H \rightarrow inv.$ for branching fractions > 1.7% with ILD design for 3.5 ab^{-1} using $Z \rightarrow \ell\ell$ channels

Simulation

Setup

- Simulated events generated using PYTHIA and DELPHES
  - IDEA detector
  - e^+e^- at 240 GeV
- Analysis performed primarily in the FCCAnalyses framework

Samples

- WW and ZZ, inclusive samples of 10M events each
- ZH samples split into signal ($H \rightarrow inv$) and background of 1M events each
  - Separate samples for $Z \rightarrow \mu\mu$, $Z \rightarrow ee$ and $Z \rightarrow q\bar{q}$

ZH Final States

- We consider five different final states corresponding to the Z decay with simple kinematic selections

  $Z \rightarrow \mu\mu$, $p_T(\mu) > 10$ GeV, $80 < M_{\mu\mu} < 100$ GeV

  $Z \rightarrow \mu\mu$, $p_T(e) > 10$ GeV, $80 < M_{ee} < 100$ GeV

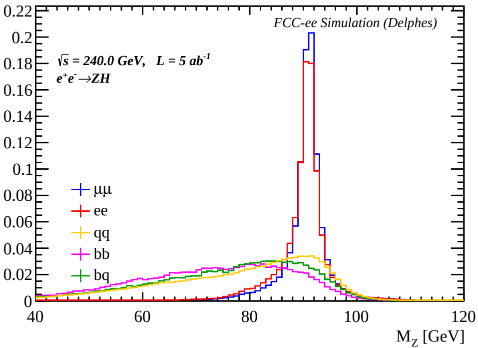
  $Z \rightarrow bb$, $p_T(b) > 10$ GeV, $60 < M_{bb} < 100$ GeV

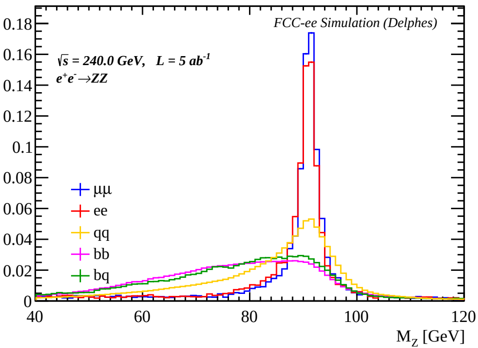
  $Z \rightarrow bj$, $p_T(b) > 10$ GeV, $60 < M_{bj} < 100$ GeV

  $Z \rightarrow jj$, $p_T(j) > 10$ GeV, $60 < M_{jj} < 100$ GeV

- b refers to a b-tagged jet, j is any other jet
- We only consider events where there is exactly one Z candidate, except for the jj final state, where we require at least one candidate

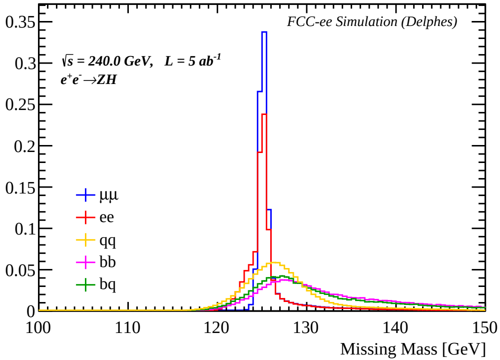
M_Z resolution

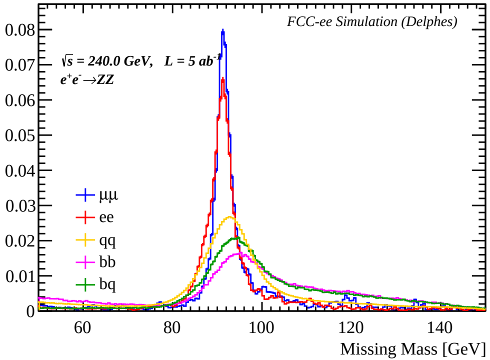




- Normalised for comparison, no requirement on $M_{\text{miss.}}$
- Clear leptonic peaks, jets smeared to lower values
- Candidate “closest” to Z mass displayed for qq channel
- b jet final states smeared to lowest values

M_{miss} Mass resolution





- Missing mass computed by subtracting visible momentum from initial beam energy
  - Initial energy of 240 GeV smeared by 0.2 GeV to simulate BES
- Lower Z mass peak manifests as high mass M_{miss} tail
- Normalised for comparison

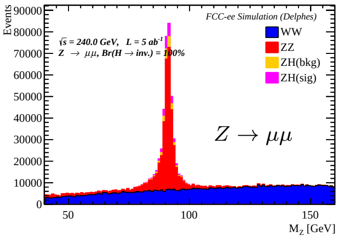
Yields

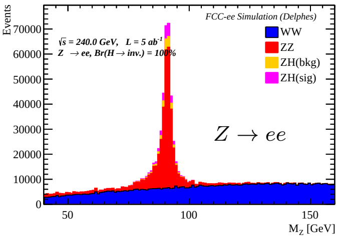
- Expected yields normalised using Pythia cross-sections and branching fractions to an integrated luminosity of 5 ab^{-1}
  - $\sigma_{WW} = 16.4385\,\mathrm{pb}^{-1}$
  - $\sigma_{ZZ} = 11.358\,\mathrm{pb}^{-1}$
  - $\sigma_{ZH} = 0.201\,\mathrm{pb}^{-1}$
- Yield comparisons after Z mass requirement, where $M_{\mathrm{miss}} > 20$ GeV

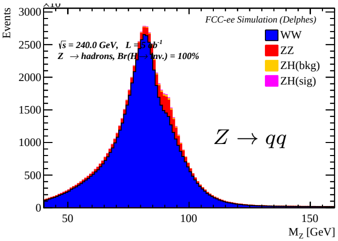
	$ZH(H \to inv.)$ $\mathcal{B} = 100\%$	$ZH(H \nrightarrow inv.)$	WW	ZZ
$\mu\mu$	28k	7k	129k	75k
ee	27k	7k	127k	71k
qq	300k	155k	14087k	1295k
bq	37k	6k	484k	117k
bb	46k	24k	16k	253k

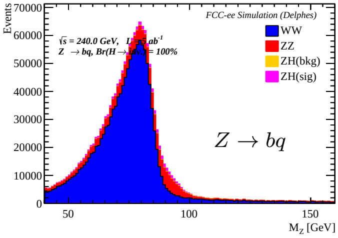
- Comparable yield across all final states, with exception of high stats, low purity dijet channel

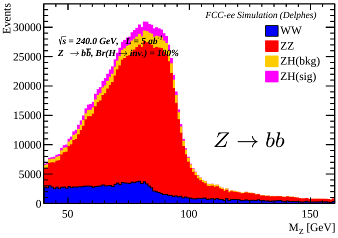
M_Z





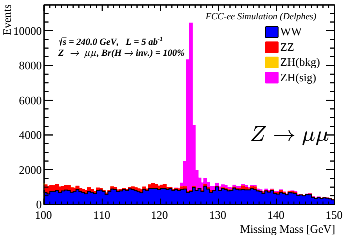


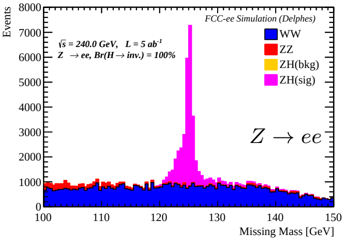


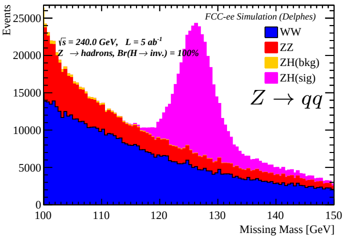


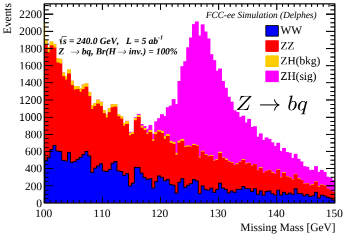
- $H \rightarrow inv$ branching fraction set to 100% throughout the plots for visual comparison
- WW background dominates across all the channels, most prominent in hadronic, suppressed by b tagging requirement

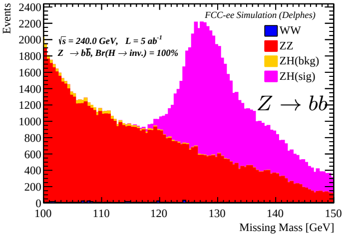
M_{miss}





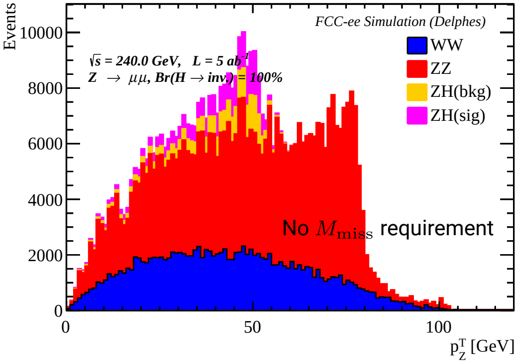


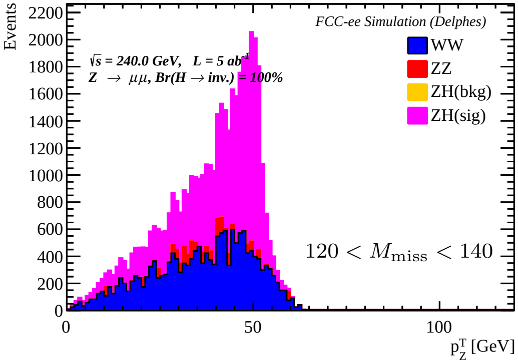




- Larger ZZ backgrounds in bb and bq channels due to high M_{miss} tail

Other requirements



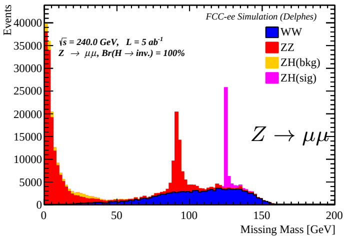


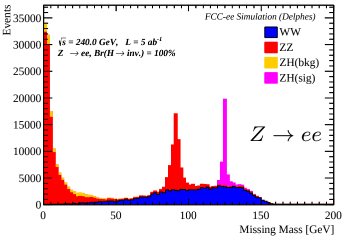
- We've explored additional requirements, $p_{\text{T}}^{\ell\ell}$, photon multiplicity etc...
- However, no significant separation once we restrict ourselves to the Higgs mass region in the m_{miss} distribution
- For now, focus just on our two key variables, M_{miss}, M_Z

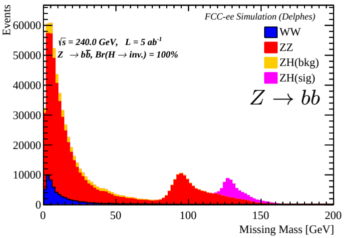
Limit Calculation

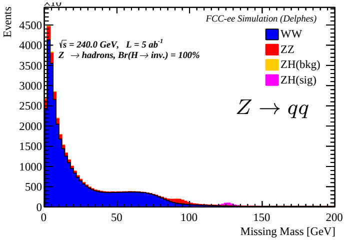
- Significance evaluated using HistFitter [*Eur. Phys. J. C* (2015) 75:p. 153]
- Template fit using signal and background shapes for each signal hypothesis
  - ZH background fixed, WW and ZZ allowed to float
- Confidence interviews are based on a profile-likelihood-ratio test statistic
- Only considering statistical uncertainties currently
- Performed individually for each final state and for the combination

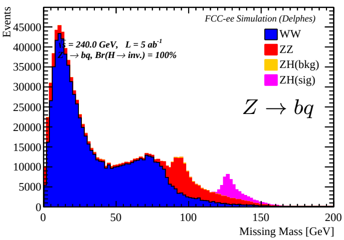
M_{miss} (full range)





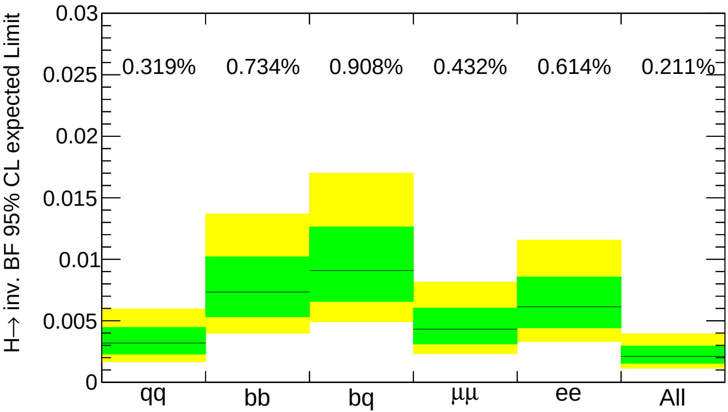




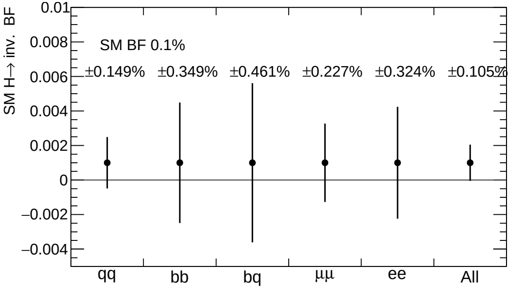


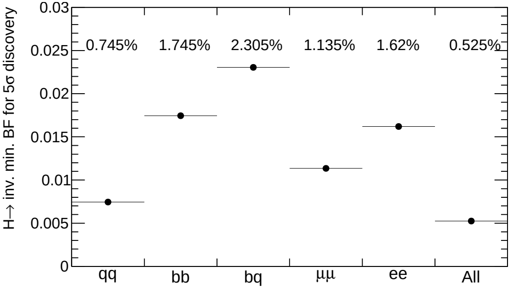
- We fit the full range to take advantage of the background peaks

Limits


H→ inv. BF 95% CL expected Limit
0.03
0.025
0.02
0.015
0.01
0.005
0
0.319%
0.734%
0.908%
0.432%
0.614%
0.211%
qq
bb
bq
μμ
ee
All

Discovery Prospects





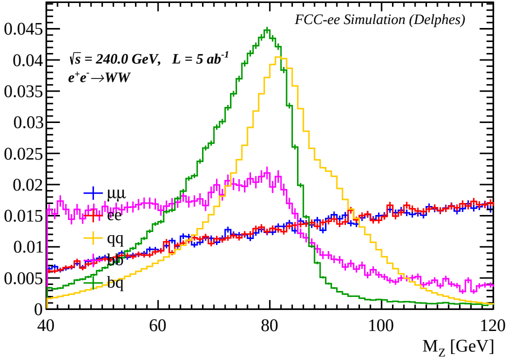
We can (left) measure SM BR with an uncertainty of 100% or (right) discover non-SM BR with significance of 5σ if BR $\gtrsim$ 5xSM
5σ limit defined as $\mu/\delta(\mu) = 5$

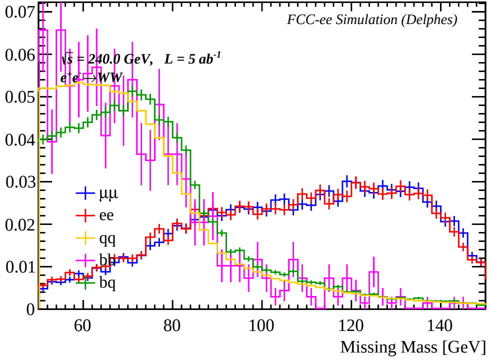
Conclusion and to-do

- A first study indicates that it may be possible to discover $\sim$ 5xSM in the Higgs to invisible BR through a combination of final states
  - Individually, the best limit comes from the light dijet final state
- Further optimisations should be possible (selection, constrained Z mass, jet energy corrections etc...)
- Statistics only, systematic uncertainties yet to be considered
- Rarer backgrounds should also be considered
- Switch to using centrally produced EDM4HEP samples

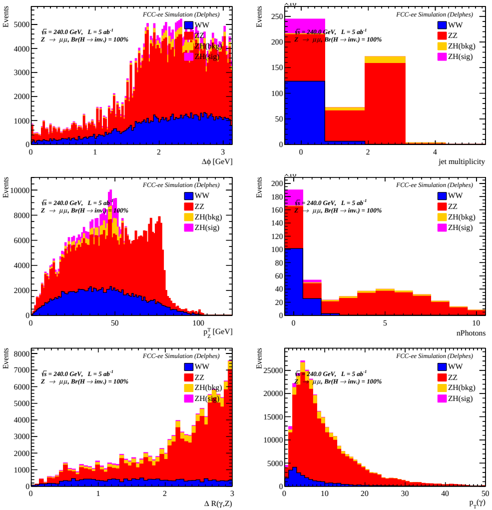
backup

WW

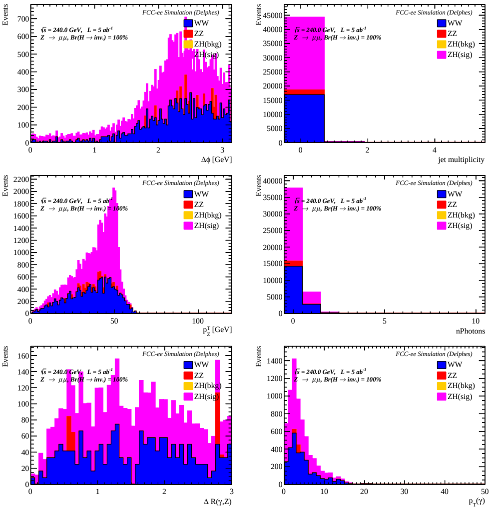

FCC-ee Simulation (Delphes)
√s = 240.0 GeV, L = 5 ab-1
e+e-→WW
μμ
ee
qq
bb
bq
MZ [GeV]


FCC-ee Simulation (Delphes)
√s = 240.0 GeV, L = 5 ab-1
e+e-→WW
μμ
ee
qq
bb
bq
Missing Mass [GeV]

$Z \to \mu\mu$

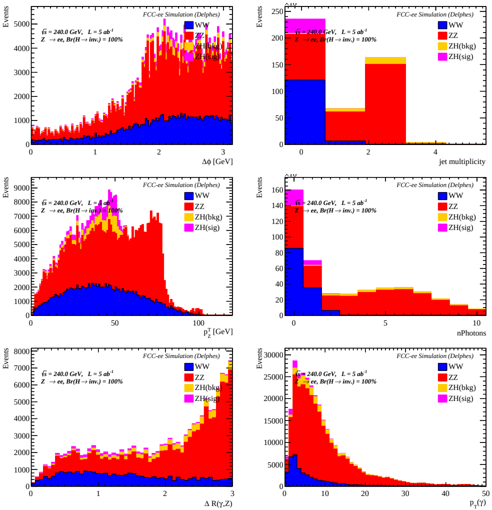


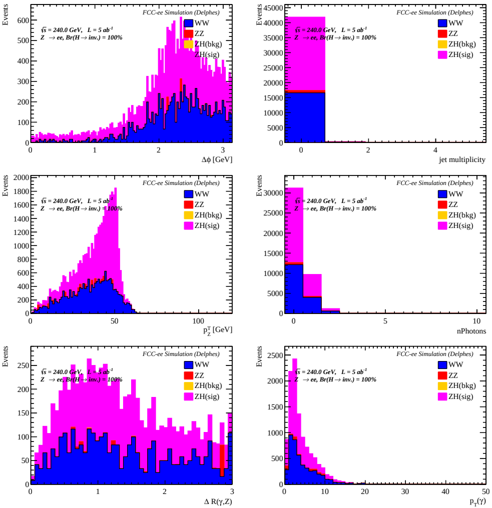
FCC-ee Simulation (Delphes)
$\sqrt{s}$ = 240.0 GeV, L = 5 ab^{-1}
$Z \to \mu\mu$, Br(H → inv.) = 100%
WW
ZZ
ZH(bkg)
ZH(sig)
Events
Δϕ [GeV]
jet multiplicity
p_Z^T [GeV]
nPhotons
Δ R(γ,Z)
$p_T(\gamma)$



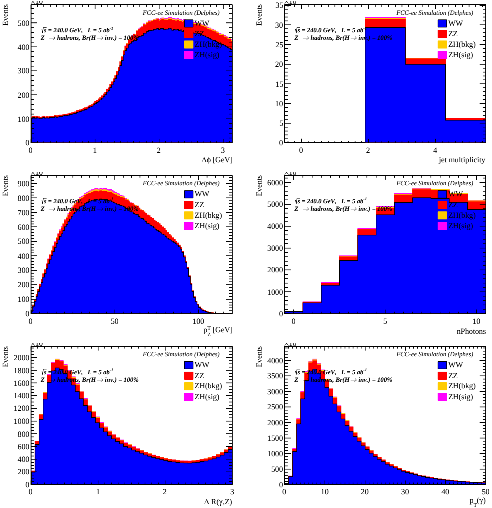
FCC-ee Simulation (Delphes)
$\sqrt{s}$ = 240.0 GeV, L = 5 ab^{-1}
$Z \to \mu\mu$, Br(H → inv.) = 100%
WW
ZZ
ZH(bkg)
ZH(sig)
Events
Δϕ [GeV]
jet multiplicity
p_Z^T [GeV]
nPhotons
Δ R(γ,Z)
$p_T(\gamma)$

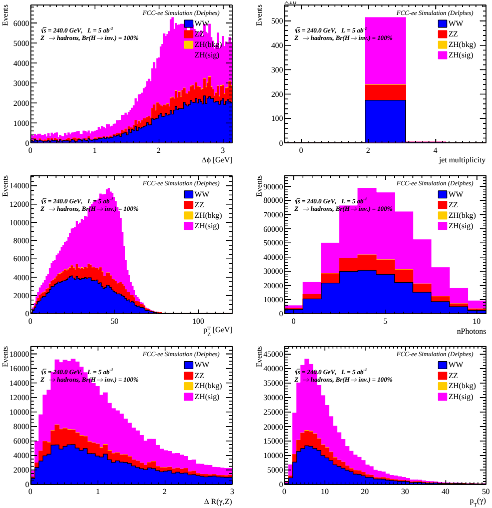
$Z \rightarrow ee$



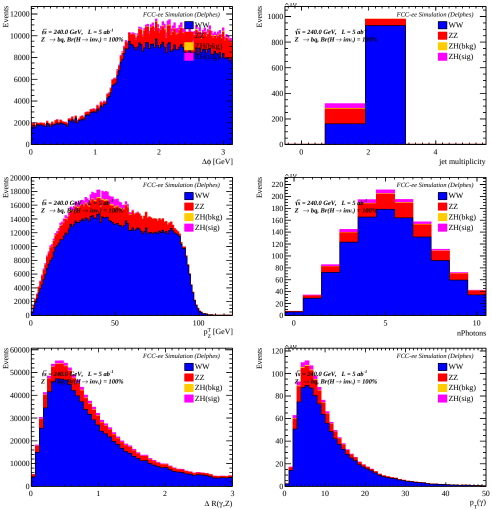


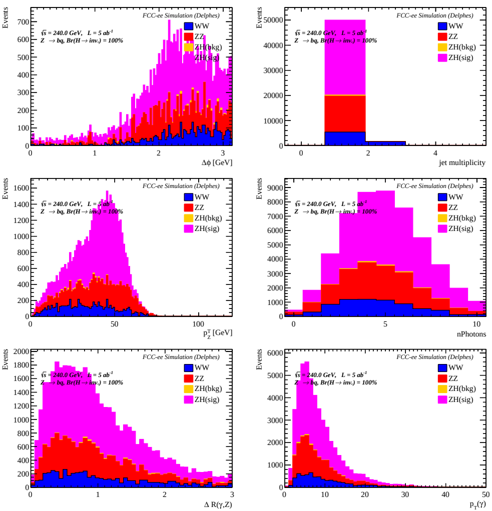
$Z \to qq$


FCC-ee Simulation (Delphes)
√s = 240.0 GeV, L = 5 ab⁻¹
Z → hadrons, Br(H → inv.) = 100%
WW
ZZ
ZH(bkg)
ZH(sig)
Events
Δϕ [GeV]
jet multiplicity
p_Z^T [GeV]
nPhotons
Δ R(γ,Z)
p_T(γ)


FCC-ee Simulation (Delphes)
√s = 240.0 GeV, L = 5 ab⁻¹
Z → hadrons, Br(H → inv.) = 100%
WW
ZZ
ZH(bkg)
ZH(sig)
Events
Δϕ [GeV]
jet multiplicity
p_Z^T [GeV]
nPhotons
Δ R(γ,Z)
p_T(γ)

$Z \to bq$


FCC-ee Simulation (Delphes)
√s = 240.0 GeV, L = 5 ab⁻¹
Z → bq, Br(H → inv.) = 100%
WW
ZZ
ZH(bkg)
ZH(sig)
Events
Δϕ [GeV]
jet multiplicity
p_Z^T [GeV]
nPhotons
Δ R(γ,Z)
p_T(γ)


FCC-ee Simulation (Delphes)
√s = 240.0 GeV, L = 5 ab⁻¹
Z → bq, Br(H → inv.) = 100%
WW
ZZ
ZH(bkg)
ZH(sig)
Events
Δϕ [GeV]
jet multiplicity
p_Z^T [GeV]
nPhotons
Δ R(γ,Z)
p_T(γ)

$Z \rightarrow bb$