$H \rightarrow$ invisible at FCC ee

FCC Physics Workshop

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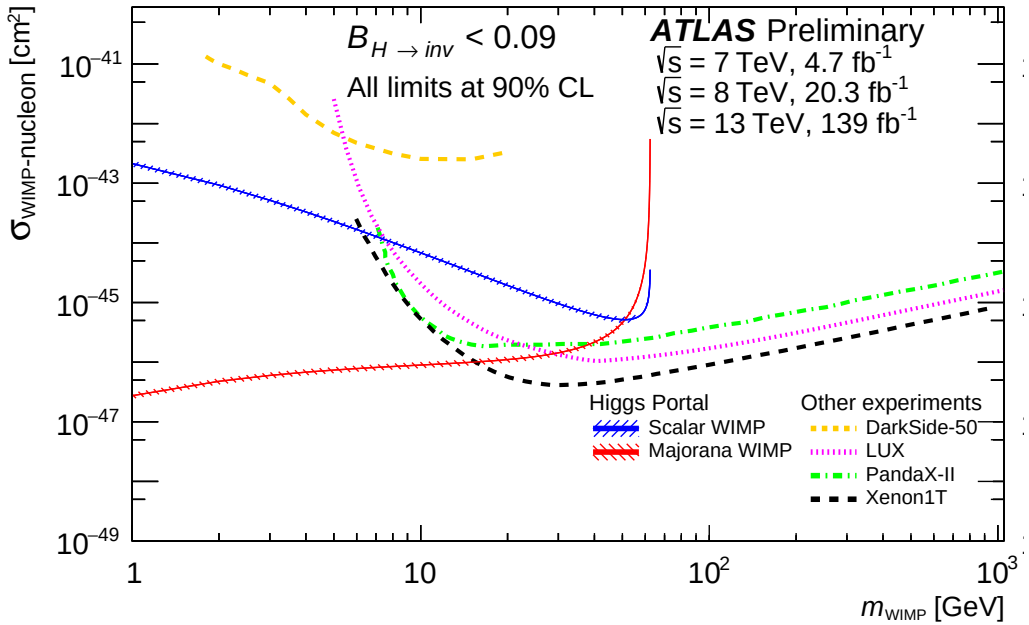
Introduction

- Dark matter may couple to ordinary matter only via the Higgs (Higgs Portal models)
- In this case maybe the only way of producing dark matter is via Higgs decay
- Even present results are much better than direct detection at low masses



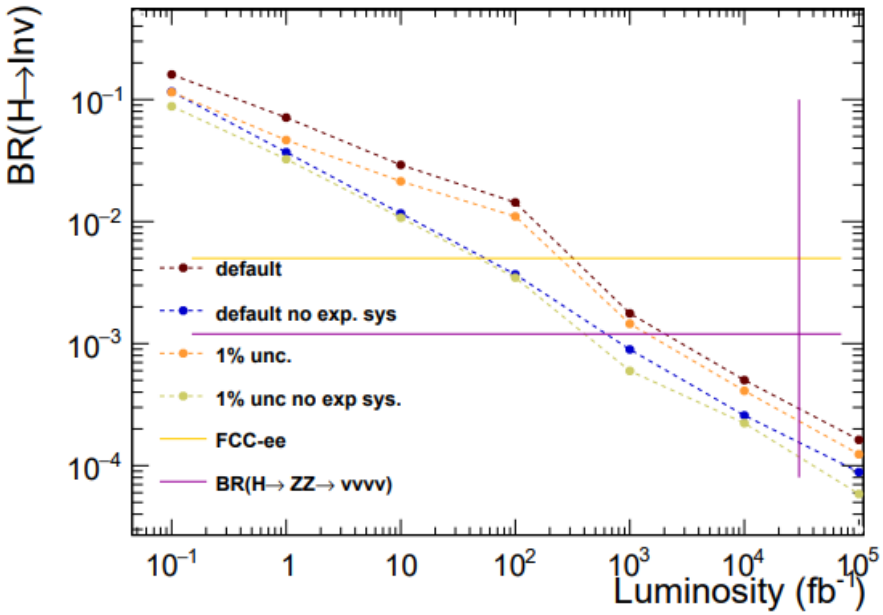
Previous Studies

For e^+e^-

- https://link.springer.com/content/pdf/10.1140/epjc/s10052-019-6904-3.pdf get 0.3% on $H \rightarrow$invis. but no details
- https://iopscience.iop.org/article/10.1088/1674-1137/abb4d8
  get 0.26% limit with ee, $\mu\mu$ and bb channels using CEPC detector simulation
- Other studies available using ee and $\mu\mu$ channels e.g.
  https://link.springer.com/article/10.1140%2Fepjc%2Fs10052-017-4680-5

For FCC pp

- https://cds.cern.ch/record/2642471
- Look at events with jets and missing p_T
- Dominant background $Z \rightarrow \nu\nu$+jets esimated from $Z \rightarrow l^+l^-$
- Control regions constrain experiment and theory errors to give a precise prediction of $Z \rightarrow \nu\nu$
- Expected limit of 0.02% - much better than possible at e^+e^-
- Will need work to prove errors can be constrained to the levels needed



Analaysis Overview

- Aim look at sensitivity using all decays in simulated data
- Only studied $\sqrt{s} = 240$ GeV events
- Assume $\int L = 5$ ab^{-1}
- Using $Z \to ee$, $\mu\mu$, bb and qq channels
- Delphes simulation
- Backgrounds dilepton (Z), ZZ, WW and ZH
- Some diagrams not included in ZZ and WW samples labelled 'WZ'
  - WIP b-tagging needs fixing with this sample
- Will need dedicated four fermion samples with interference, but not expected to make a large difference to results
- SM $ZH \to \nu\nu\nu\nu$ treated as a background when determining limits
- Taus not studies yet but could be useful in reducing backgrounds

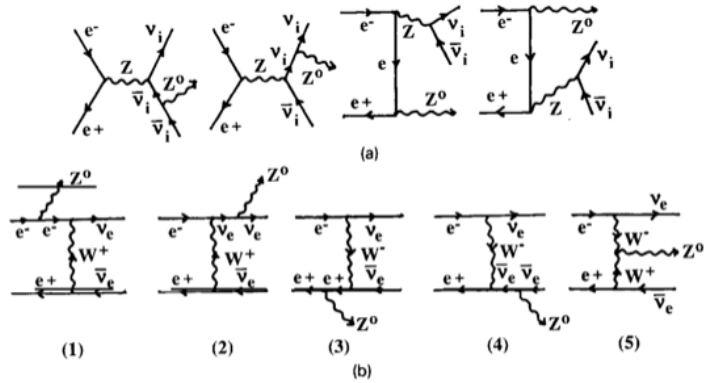
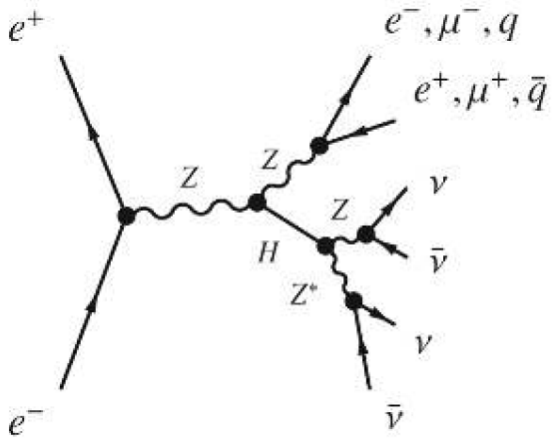


Fig. 1. Feynman diagrams contributing to the process $e^+e^- \to Z^0\nu\bar{\nu}$: (a) Z-exchange diagrams (with Z^0 in the s-channel); (b) W-exchange diagrams (with $W^\pm$('s) in the t-channel).

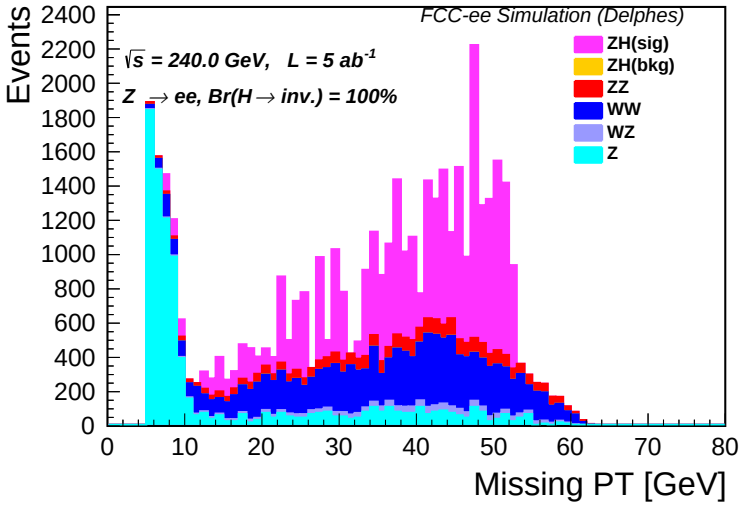


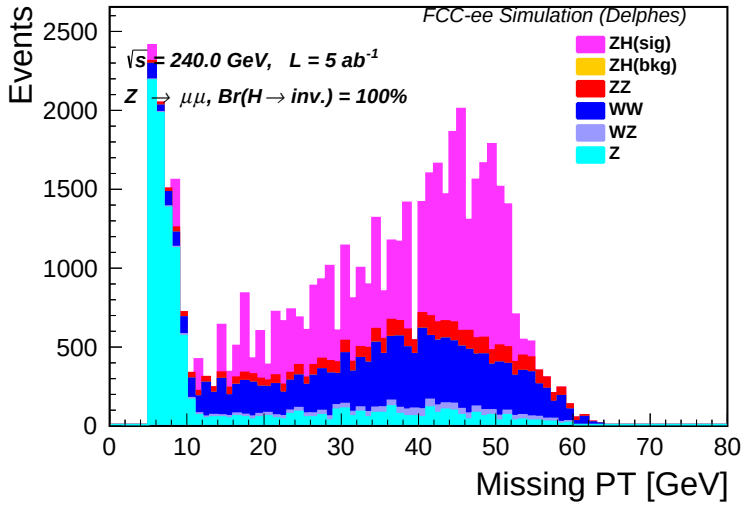
Method

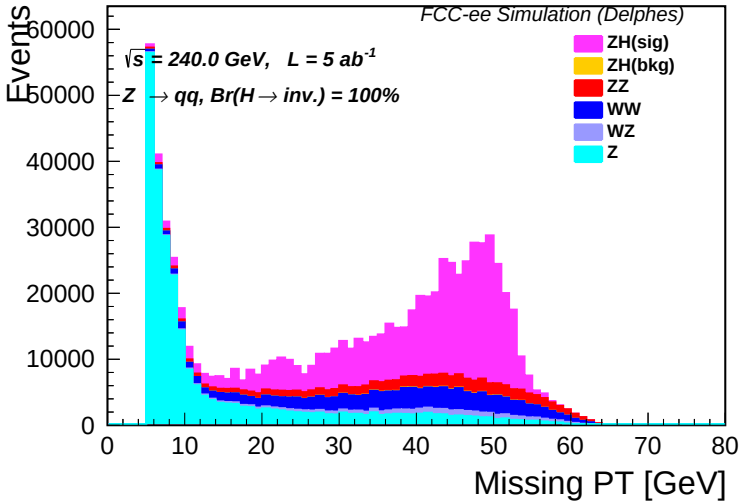
- Split events into exactly $2e$, 2μ and 0 $e{+}\mu$
- Reject events with 1 or $\geq$ 3 leptons
- bb channel defined if at least one of the two leading jets is b-tagged
- Require $p_T^{\mathrm{miss}} > 10/15/20$ GeV for $ee, \mu\mu/qq/bb$ to suppress dilepton background
- Reconstruct Z from 2 leptons or M_{vis} (Invariant Mass of all particles)
- Cut on 4/5 GeV around $M_Z = 91$ GeV for $ee, \mu\mu/qq$ channels
- Cut on $60 < M_Z < 100$ GeV for bb channel
- In bb channel to improve M_{miss} resolution scale visible 4 vector by 91/ M_{vis} and recalculate M_{miss}
- Use distribution of M_{miss} in likelihood fit using HistFitter
- Float signal, ZZ and WW backgrounds. Fix ZH and dilepton background
- Easy to add systematics but only lumi (1%) added for now
- Split qq channel into jet multiplicity

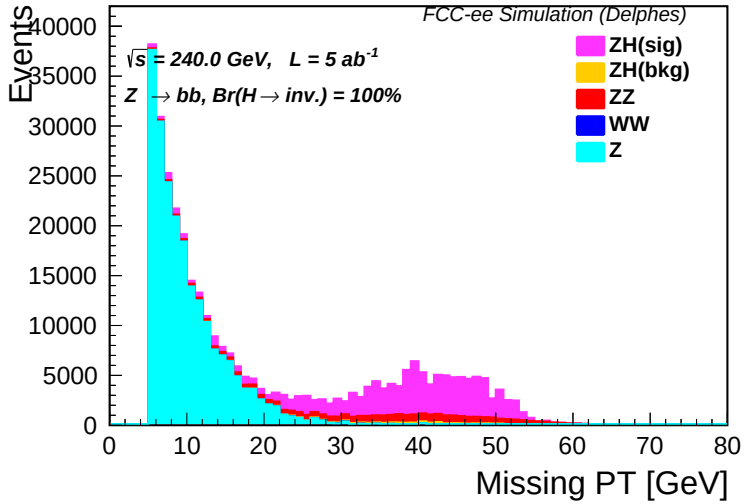
Dilepton Background

Shown after m_Z and M_{miss} cuts
$p_T^{\text{miss}} < 5$ GeV not shown for plot clarity





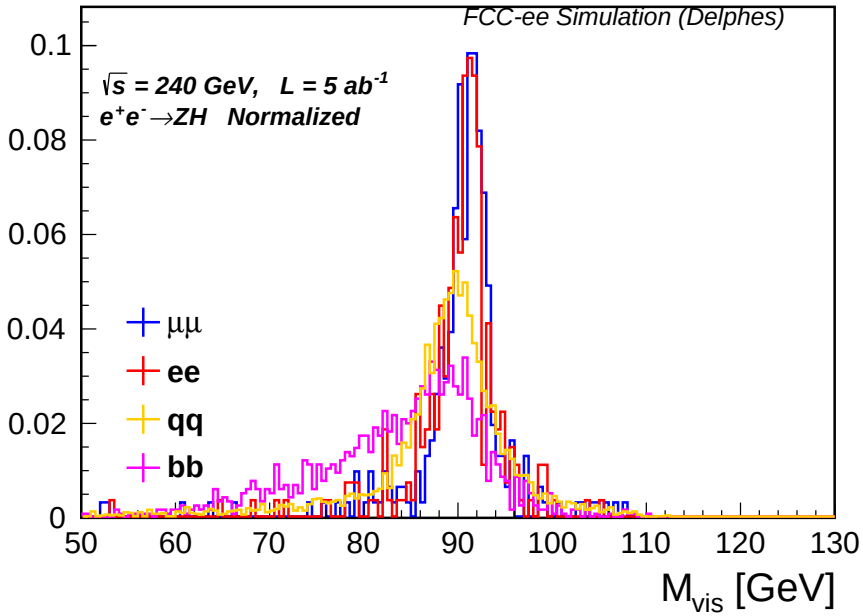


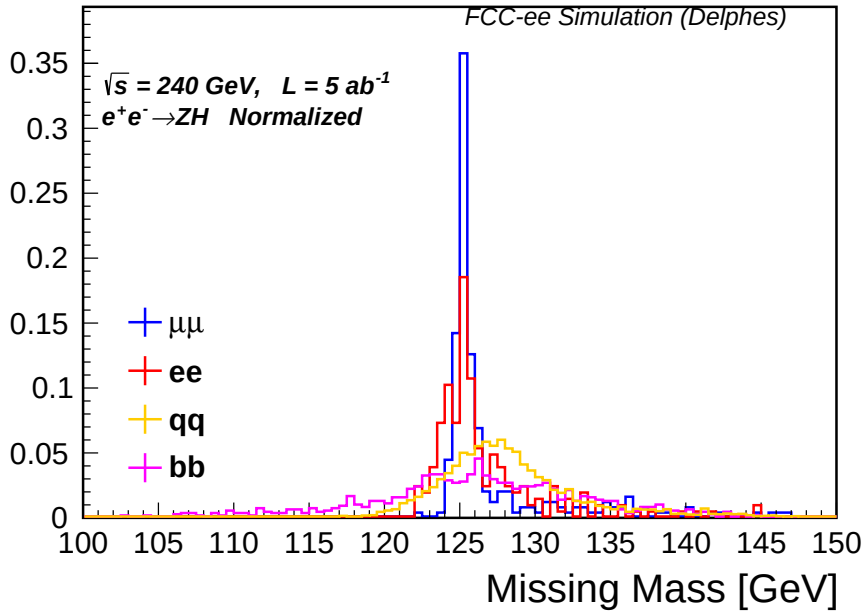


Very effective cut against dilepton background
Best to have different cuts for the different channels

Signal Resolution

Normalized



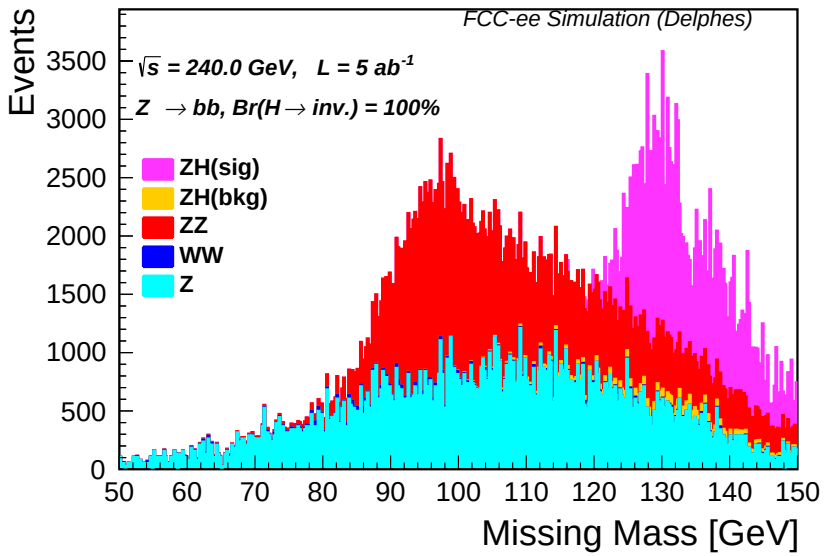


As expected worse qq resolution than ee or $\mu\mu$.
ee worse than $\mu\mu$ for M_{miss}
bb very bad due to neutrinos in b hadron decays

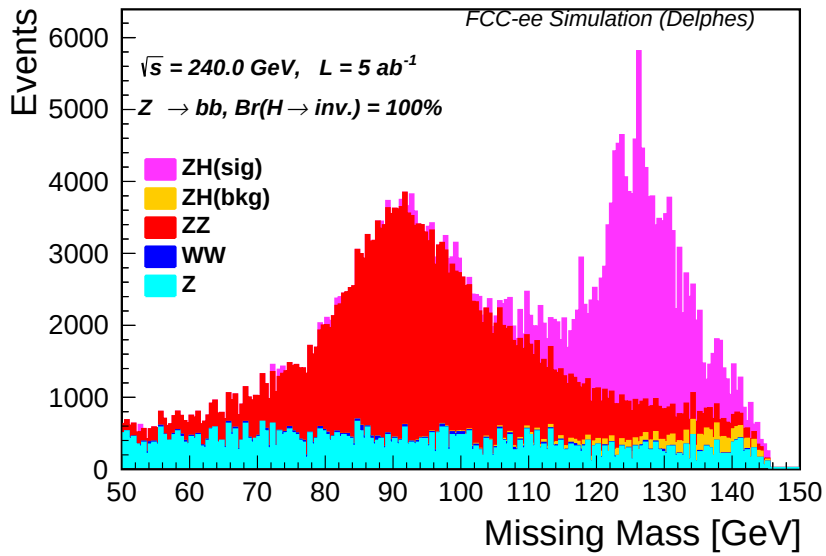
M_Z Constraint in bb Channel

M_Z Constraint

Without

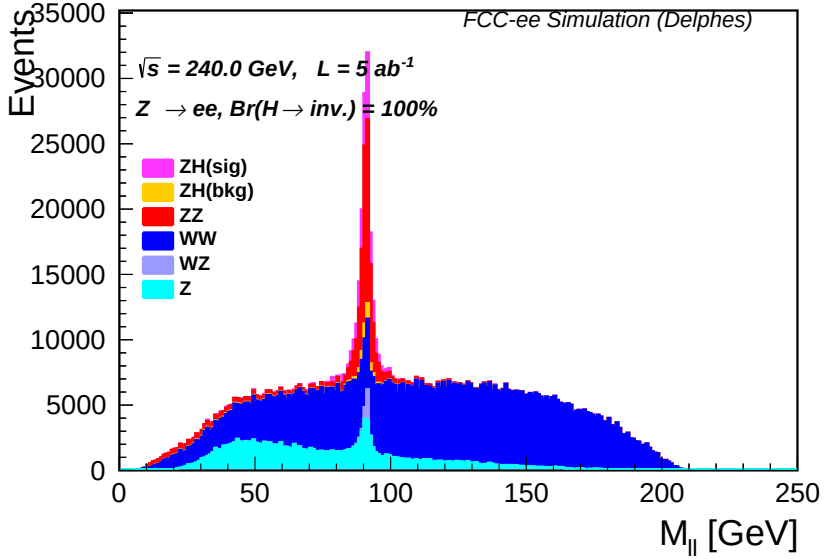


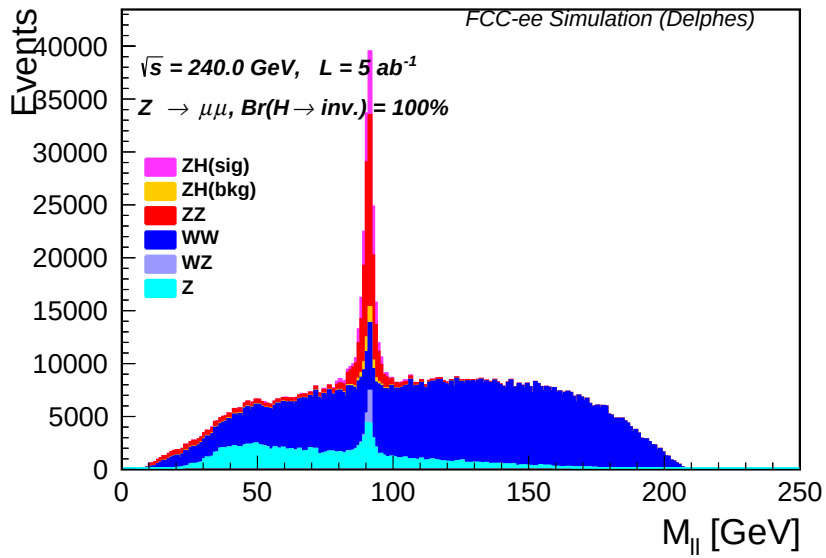
With

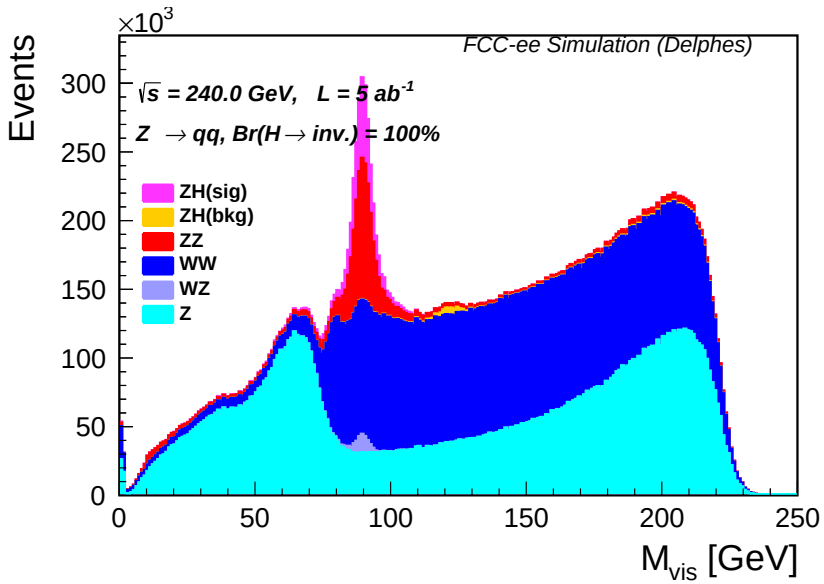


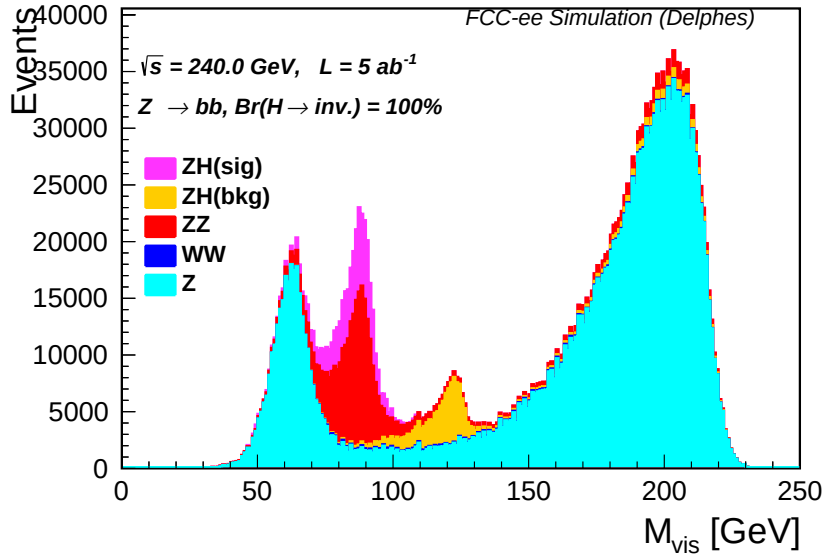
Scale visible 4 vector by 91/ M_{vis} and recalculate M_{miss}
bb channel much worse without the M_Z constraint

M_Z Full Range After p_T^{miss} cut



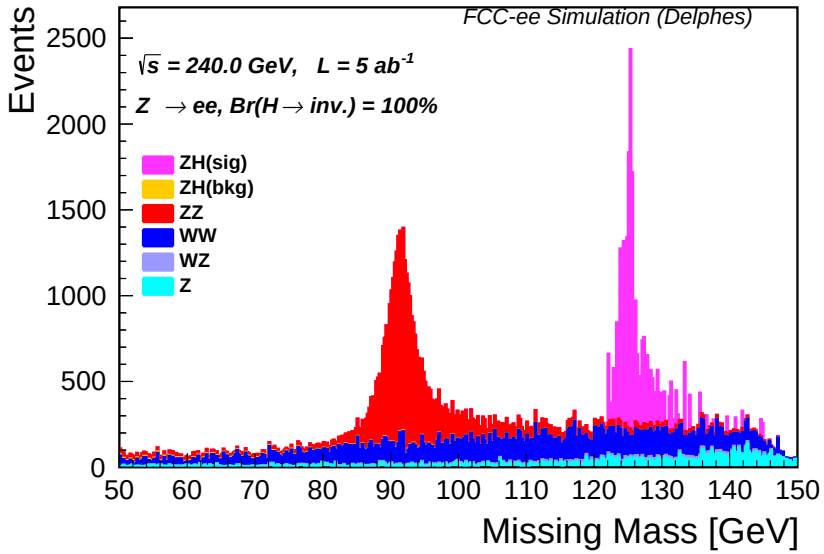


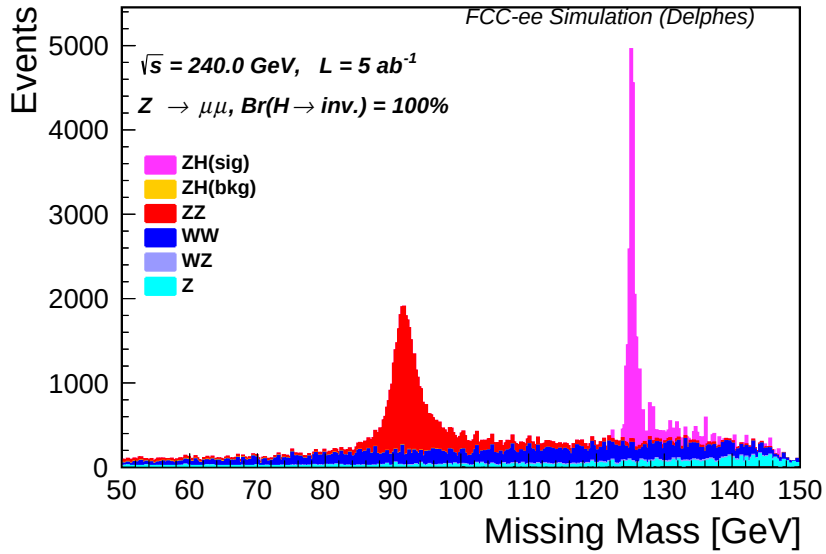


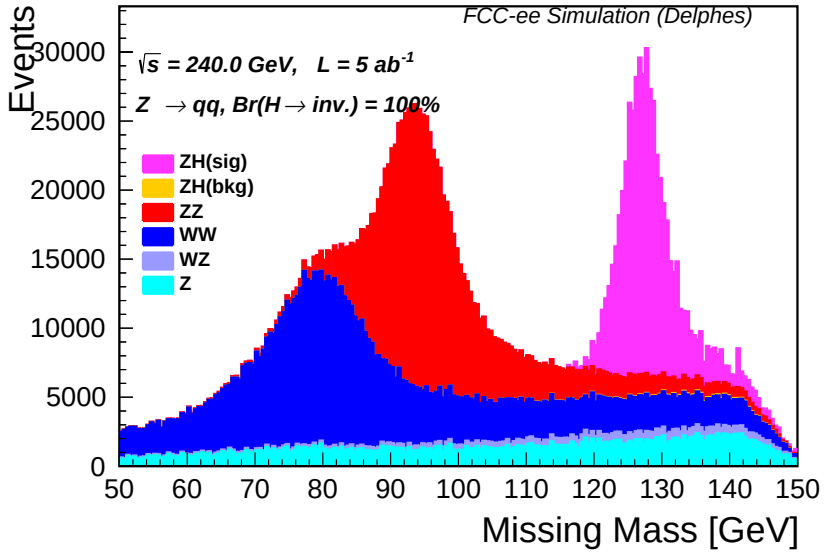


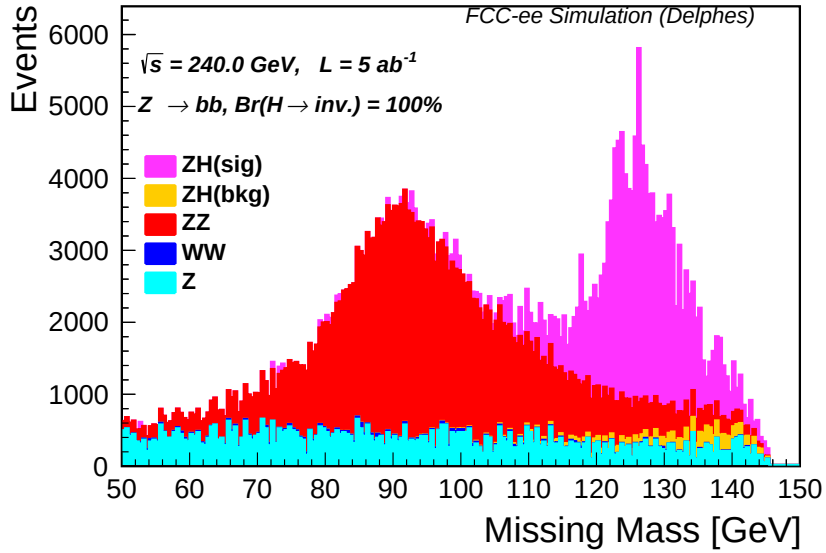
As there is no jet selection qq channel also includes $ZZ/WW \rightarrow qqqq$

M_{miss}, M_Z cut, Zoom







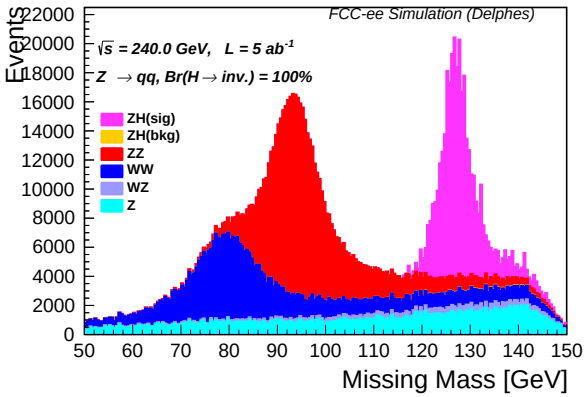


Range shown is is used in the fit

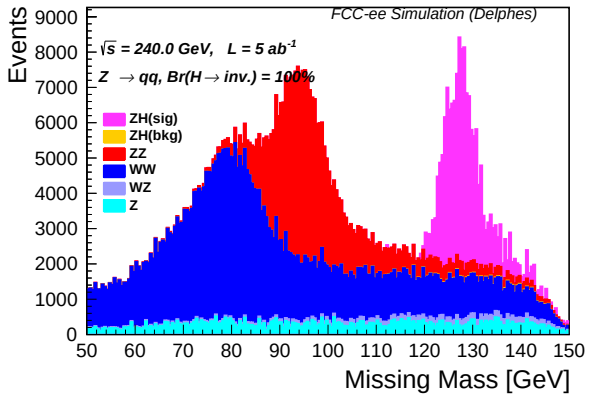
Jet Splitting in qq channel

Split qq into N jet categories
Using Valencia
Cone size 0.5
Inclusive jets
5 GeV energy cut
E ordering
E scheme

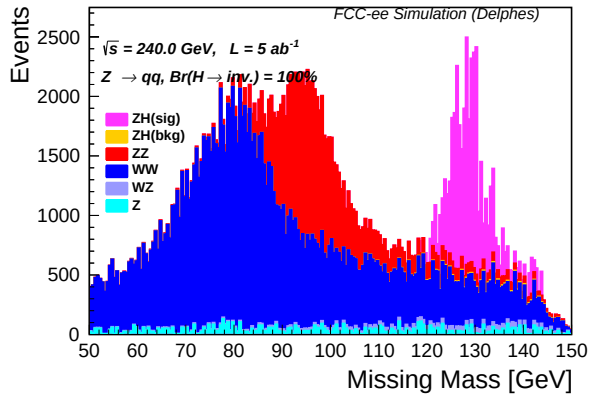
$\leq$ 2 jets



3 jets

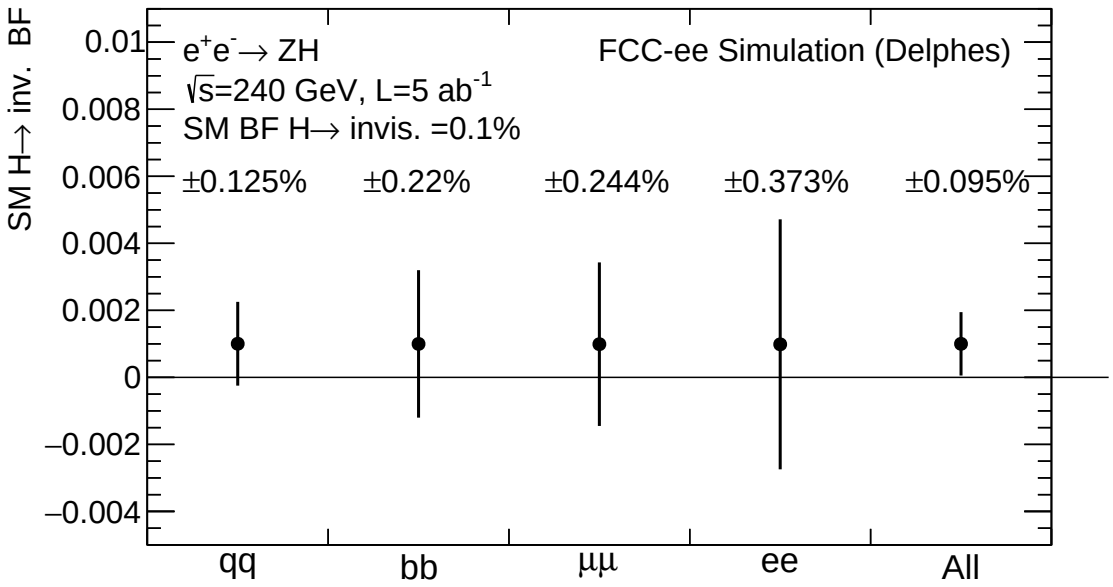


$\geq$ 4 jets



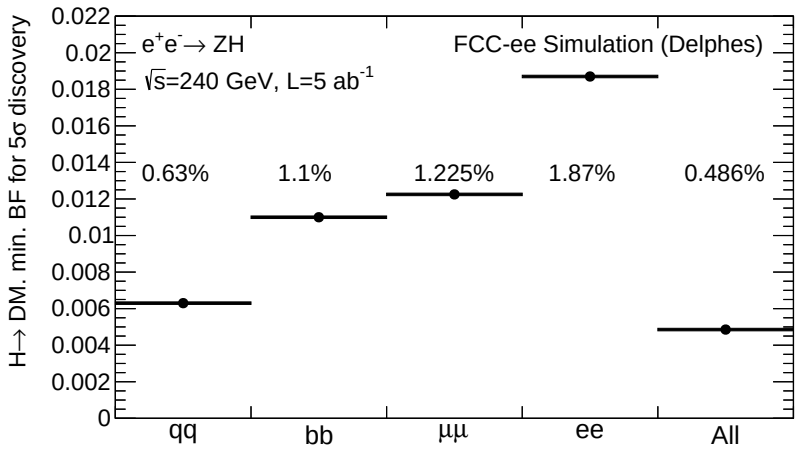
WW background increases with jet multiplicity
dilepton background decreases with jet multiplicity
Use 3 categories in the fit

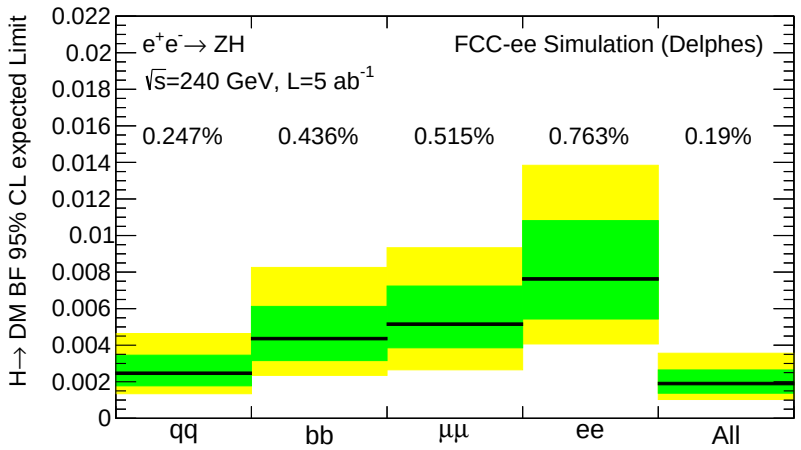
Results SM fit



Floating SM signal
100% measurement possible

Discovery Fit





SM signal treated as a background
Could discover $H \rightarrow$new invisible above SM background with BF=0.5%

Summary

- Estimated FCC ee $H \rightarrow$ invisble potential using Delphes simulated data
- $Z \rightarrow qq$ channel much better than $Z \rightarrow ee$ or $Z \rightarrow bb$
- b-tagging and jet multiplicity splitting improves the result a little
- Reach SM precision of $\simeq 0.1\%$

Backup

Samples

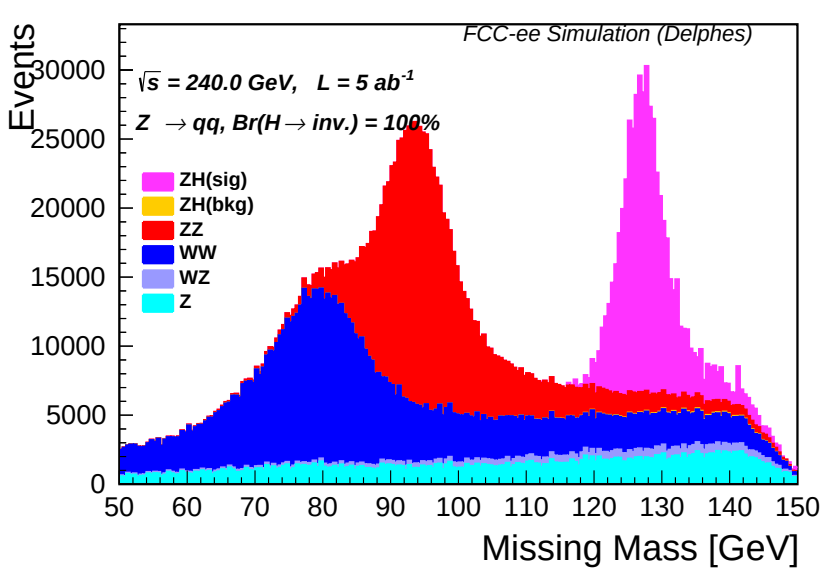
```
/eos/experiment/fcc/ee/generation/DelphesEvents/spring2021/IDEA/p8_ee_ZZ_ecm240/
/eos/experiment/fcc/ee/generation/DelphesEvents/spring2021/IDEA/p8_ee_WW_ecm240/
/eos/experiment/fcc/ee/generation/DelphesEvents/spring2021/IDEA/p8_ee_ZH_ecm240/
/eos/experiment/fcc/ee/generation/DelphesEvents/spring2021/IDEA/p8_ee_Zll_ecm240/
/eos/experiment/fcc/ee/generation/DelphesEvents/spring2021/IDEA/p8_ee_Zqq_ecm240/
```

- 10 M events in each sample
- Must split the ZH MC into signal ($H \to \nu\nu\nu\nu$) and background
- Switched to 2T samples
- Include Z backgrounds

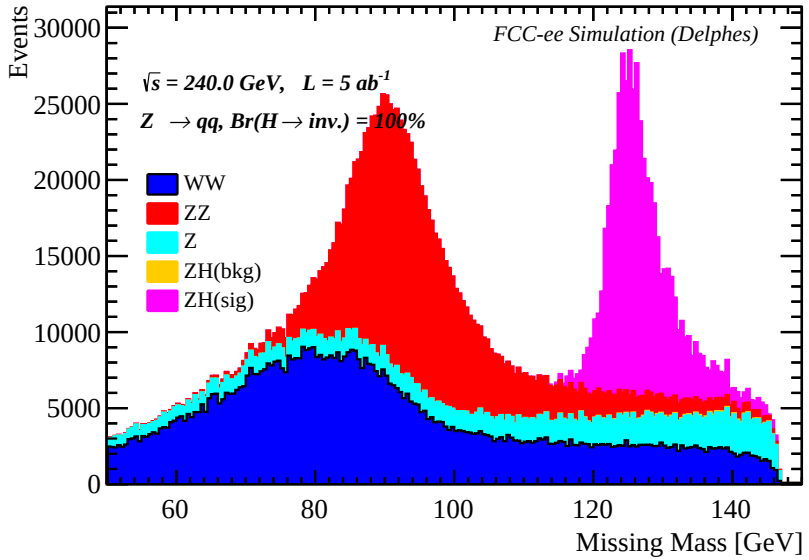
M_Z Constraint in qq Channel ?

M_Z Constraint

Without

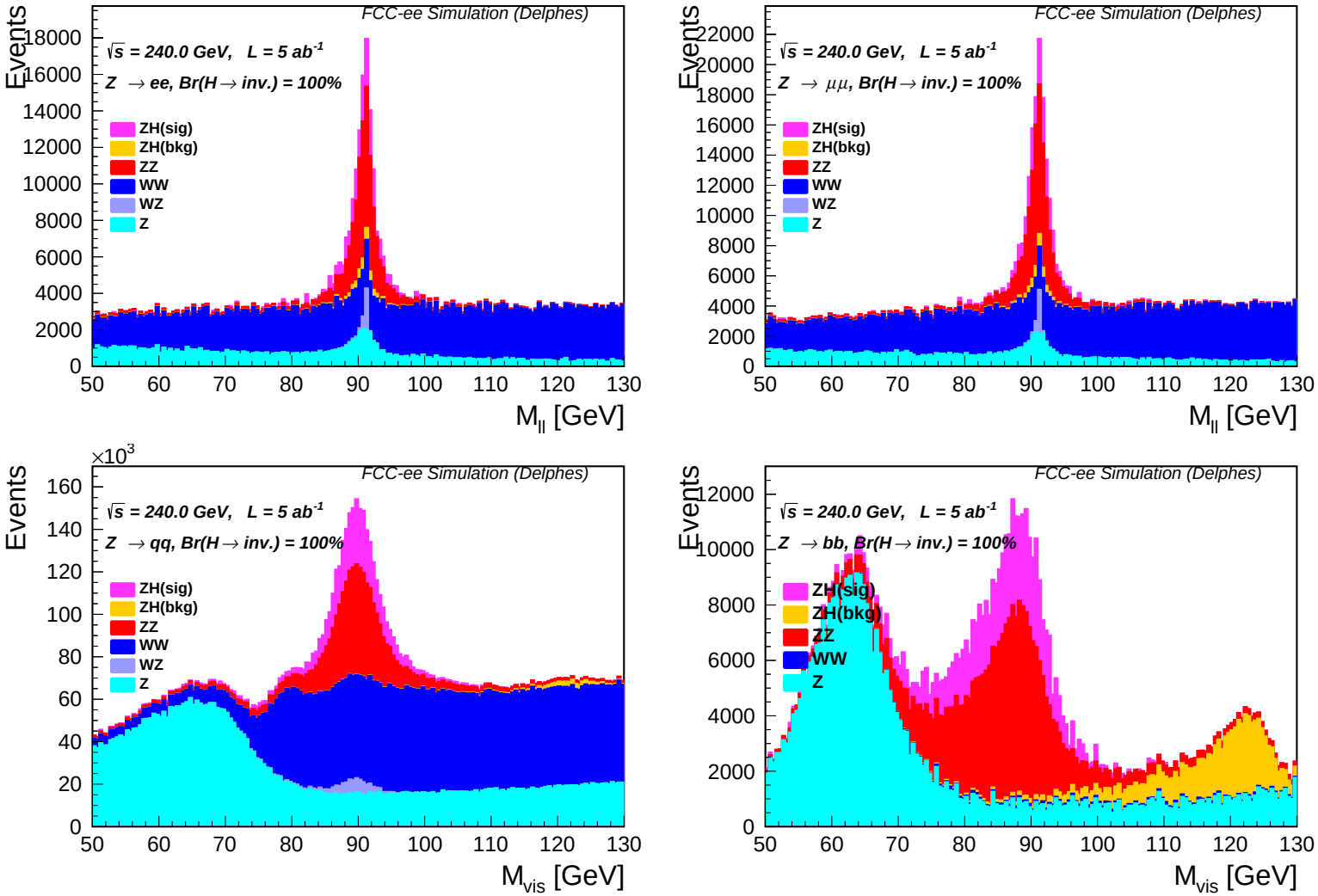


With



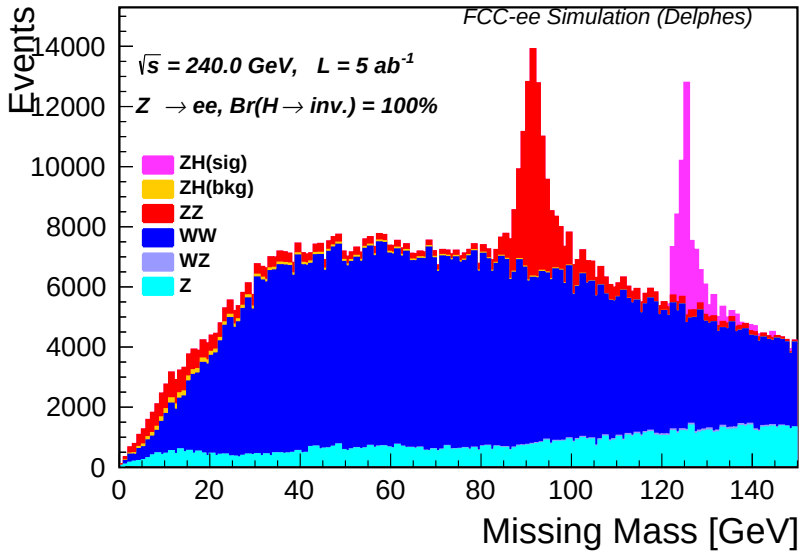
qq channel doesn't show improvement

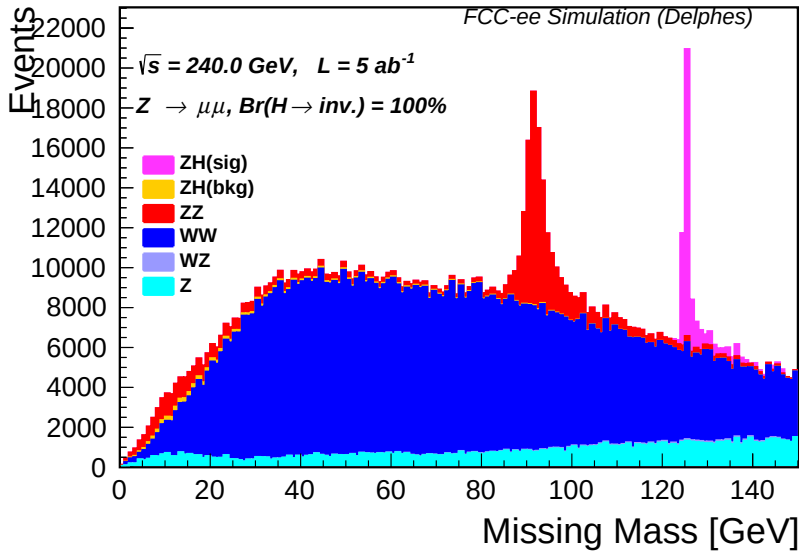
M_Z Zoomed

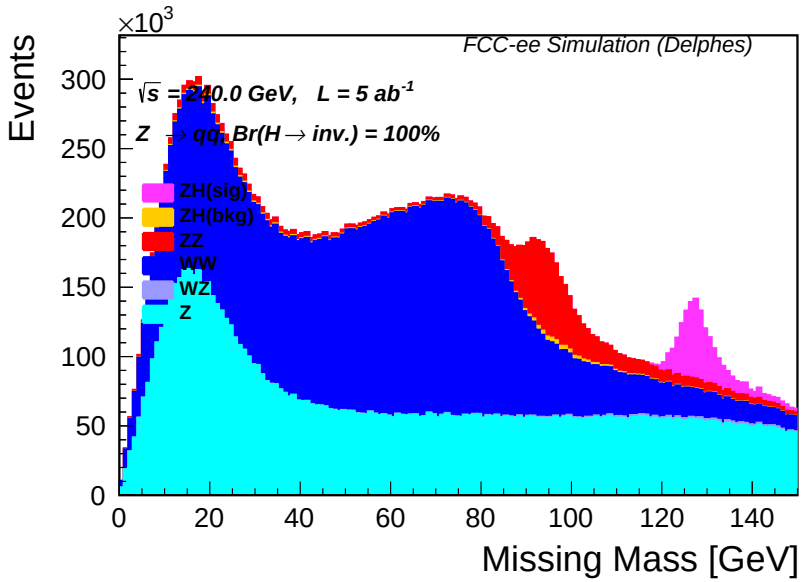


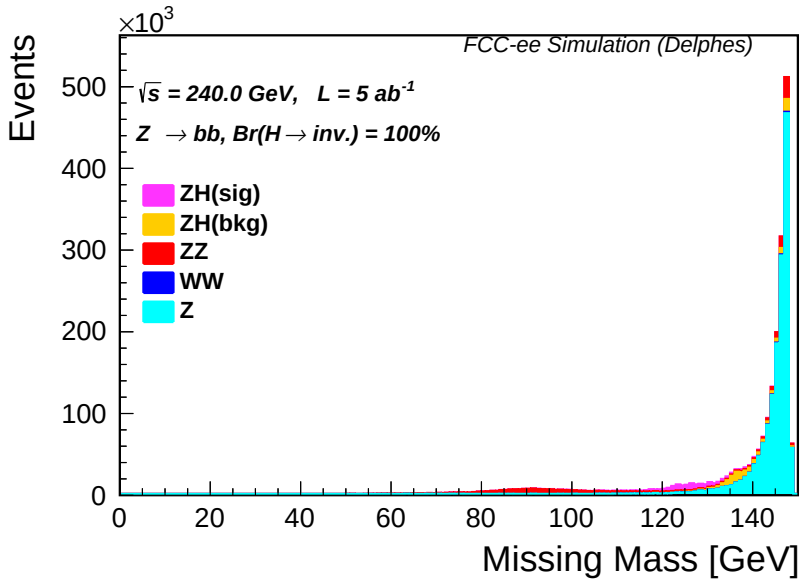
ZH background already very small. Handronic Higgs decay ($ZH \to \nu\nu bb$ or $ZH \to \nu\nu qqqq$) well separated from Z peak.
dilepton background small but not negligible

M_{miss} w/o M_Z cut



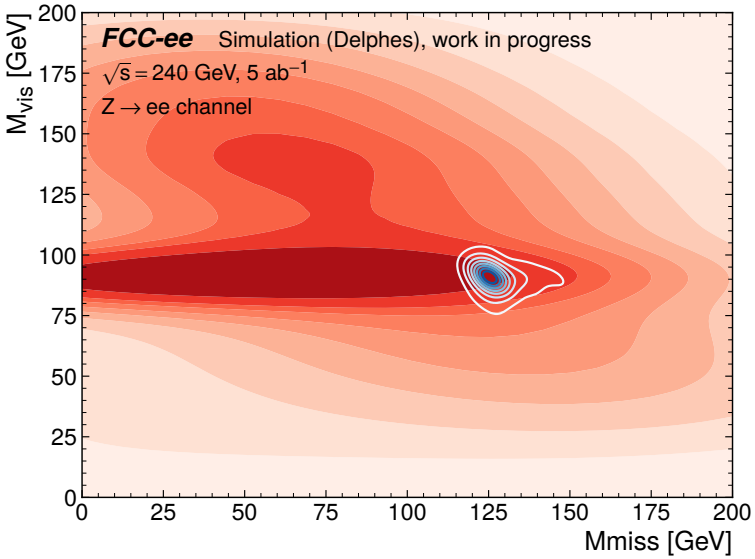


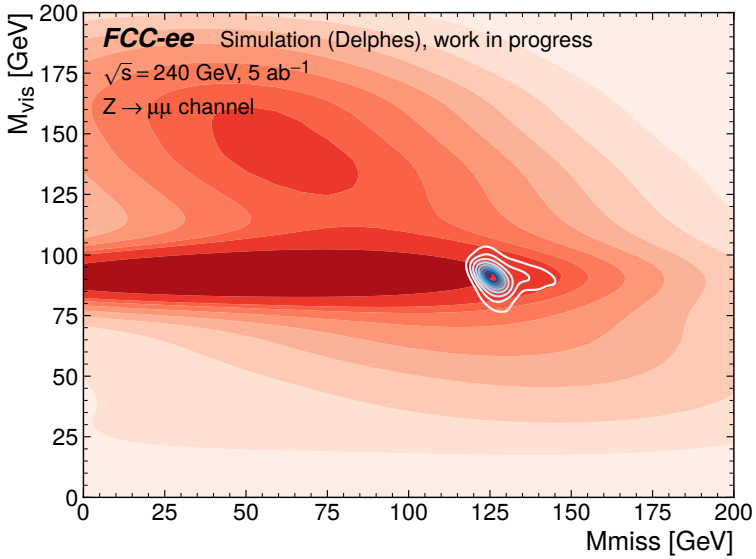


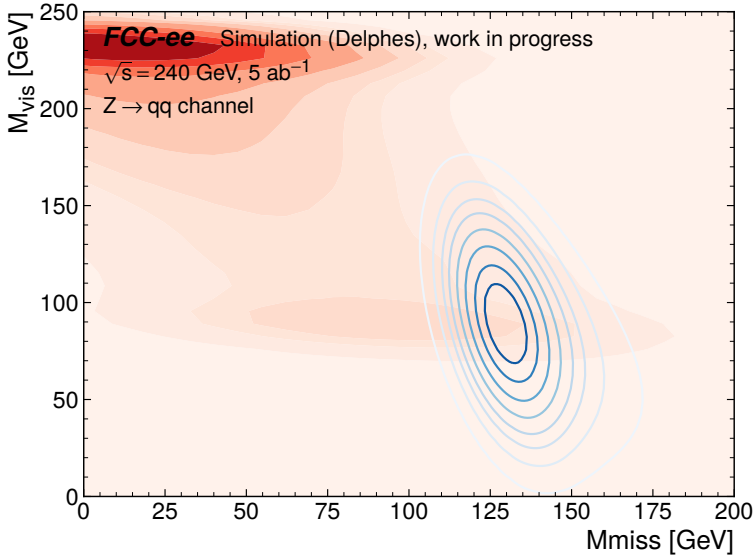


M_{miss} very effective against ZZ background

2D correlations







Possible gains to be made with non-rectangular cuts