Higgs decay to muons at the Future Circular electron-positron Collider

Stephen Randles sgsrandl@liverpool.ac.uk

3rd year BSc project

Under supervision of Professor Andrew Mehta

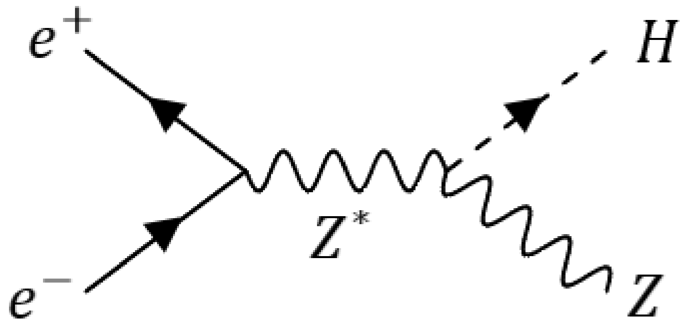
and Dr Nikolaos Rompotis

Higgs decay to muons

- At the FCC-ee the main Higgs production takes place at the 240 GeV centre-of-mass energy. With 4 interaction points this has an integrated luminosity of $10ab^{-1}$.

- The main Higgs production is through Higgs-strahlung and this has a cross-section of 201fb resulting in approximately 2 million Higgs events.

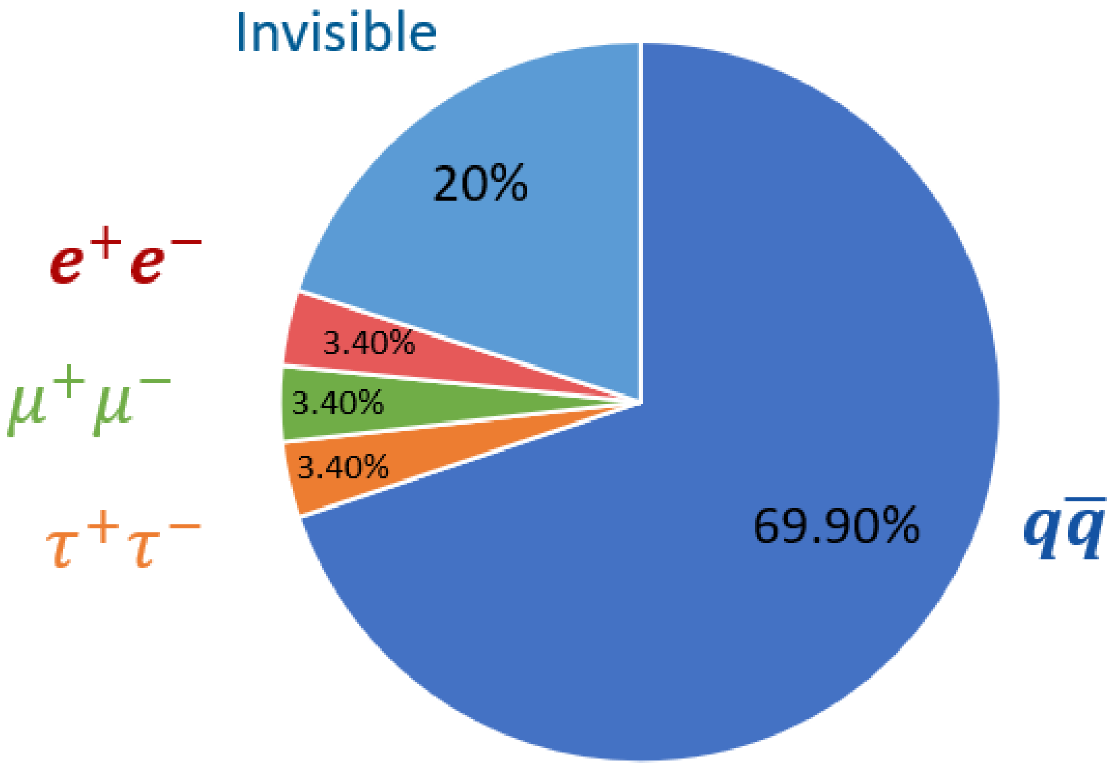
- The Higgs decay to muons has a branching fraction of 2.18×10^{-4}. Resulting in over 400 Higgs to muons expected to be produced at the FCC-ee.



Z boson decay

- Due to the Higgs-strahlung production a Z boson is also produced therefore will have its decay products in the final state.

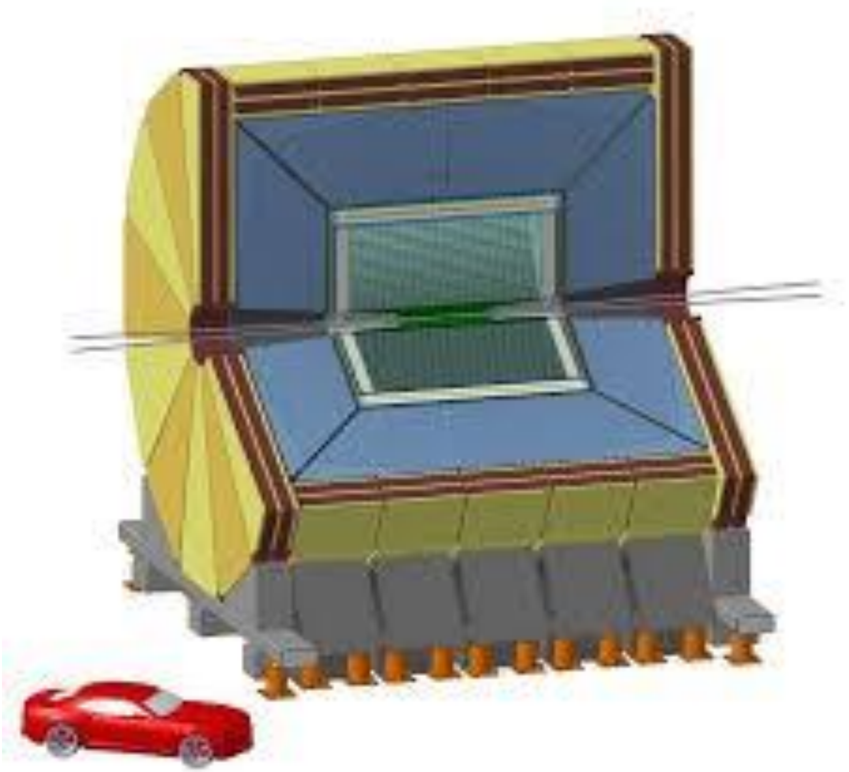
- The Z boson decays mostly to quarks followed by neutrinos then rarely to charged leptons.



Tuples

The Monte Carlo samples used were based on the IDEA detector
/eos/experiment/fcc/ee/generation/DelphesEvents/**winter2023**/**IDEA**/

Signal (ZH) Include all Higgs decays:
$Z \to \upsilon\bar{\upsilon}$: wzp6_ee_nunuH_ecm240.root
$Z \to q\bar{q}$: wzp6_ee_qqH_ecm240.root
$Z \to e^+e^-$: wzp6_ee_eeH_ecm240.root
$Z \to \mu^+\mu^-$: wzp6_ee_mumuH_ecm240.root
Background:
ZZ: p8_ee_ZZ_ecm240_p01.root
WW: p8_ee_WW_ecm240_p0_012.root
$Z \to \mu^+\mu^-$: wzp6_ee_mumu_ecm240_p00.root



Method of the analysis

1. Significance and distribution plots
2. Invariant Mass plots
3. Kernel Smoothing for background
4. Calculating uncertainty through HistFitter
5. Background + Signal fit for precision mass measurement

Significance plots

- The significance plots allow to investigate the effect of different variables on the signal and background and the distribution plots help to
- The significance was calculated from:

$$Z = \frac{S}{\sqrt{S+B}}$$

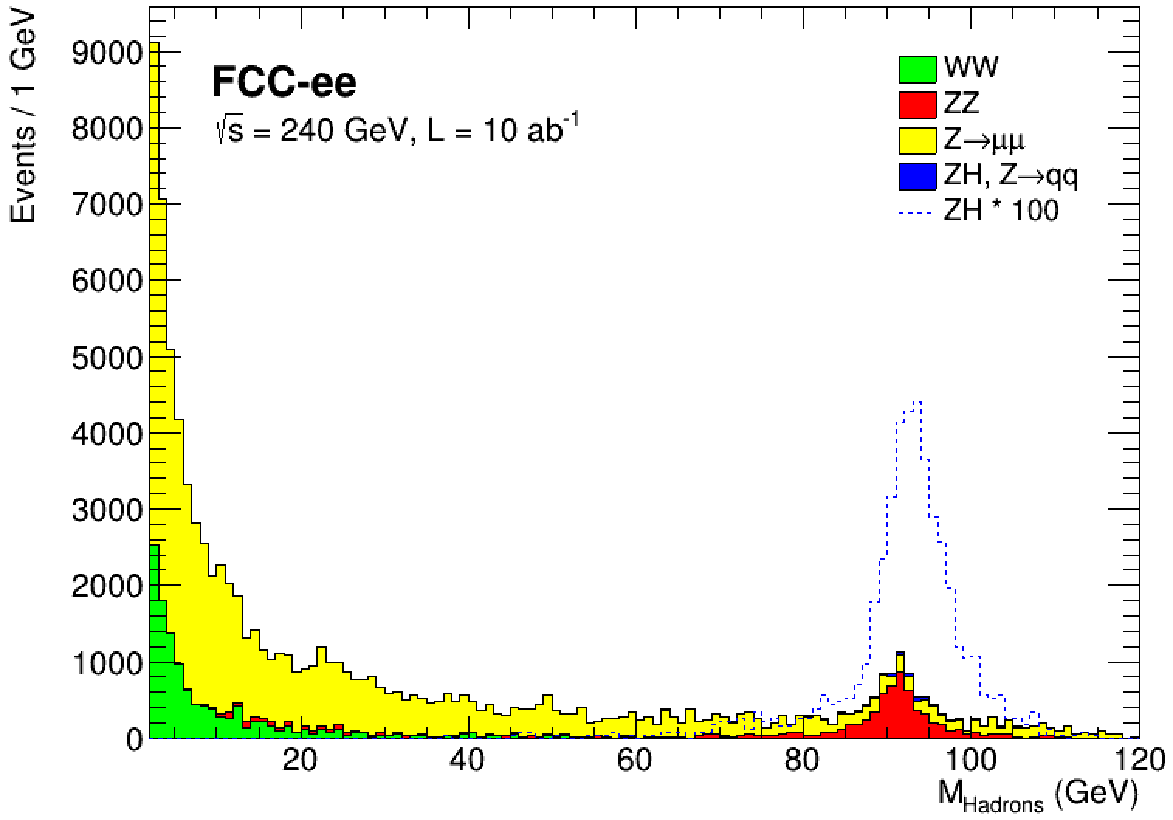
- To find the best place to make a selection, a lower bound and upper bound were calculated by summing up the amount of signal or background events in increasing or decreasing order. With the place of highest significance at the peak of the graph.

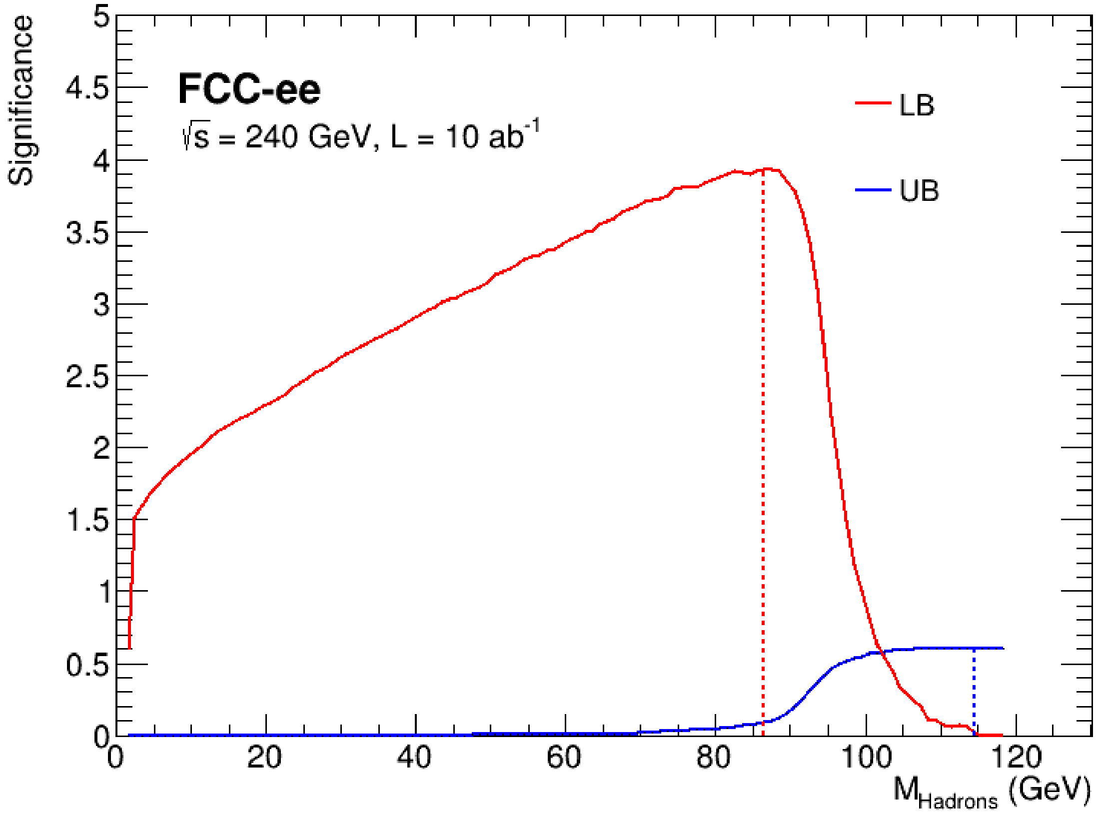
Significance plots $Z \rightarrow qq$ channel

Mass of Hadrons

$$M_{Hadrons} = \sqrt{(E_{vis} - E_{\mu\mu})^2 - (\vec{p}_{vis} - \vec{p}_{\mu\mu})^2}$$

Signal expected around Z boson mass (90 GeV)
Selection placed between 70 GeV and 115 GeV

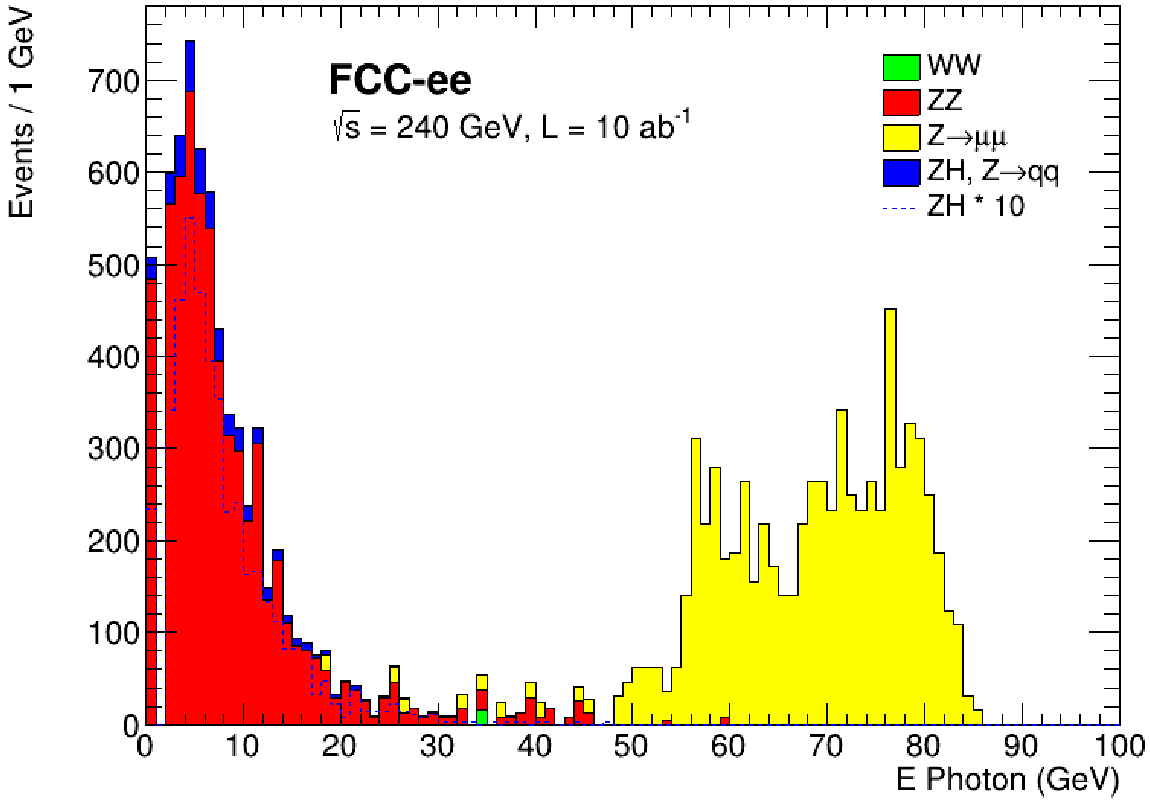


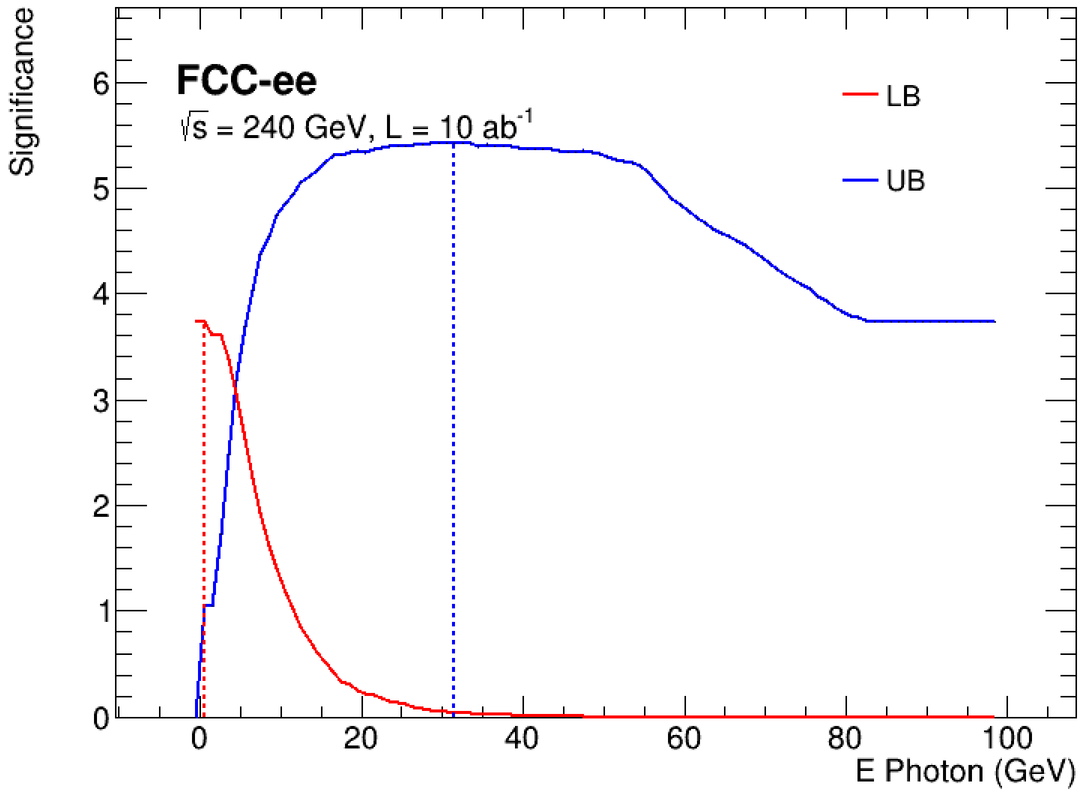


Energy of photon

As the Z boson decays to quarks, π^0 are produced and decay into two photons.
These photons are relatively low energy compared to the high energy photon produced in the $Z \rightarrow \mu\mu$ background (yellow).
As the photon is produced alongside the on-shell Z boson allowing the conservation of energy and momentum.

Selection placed at photon Energy < 35 GeV





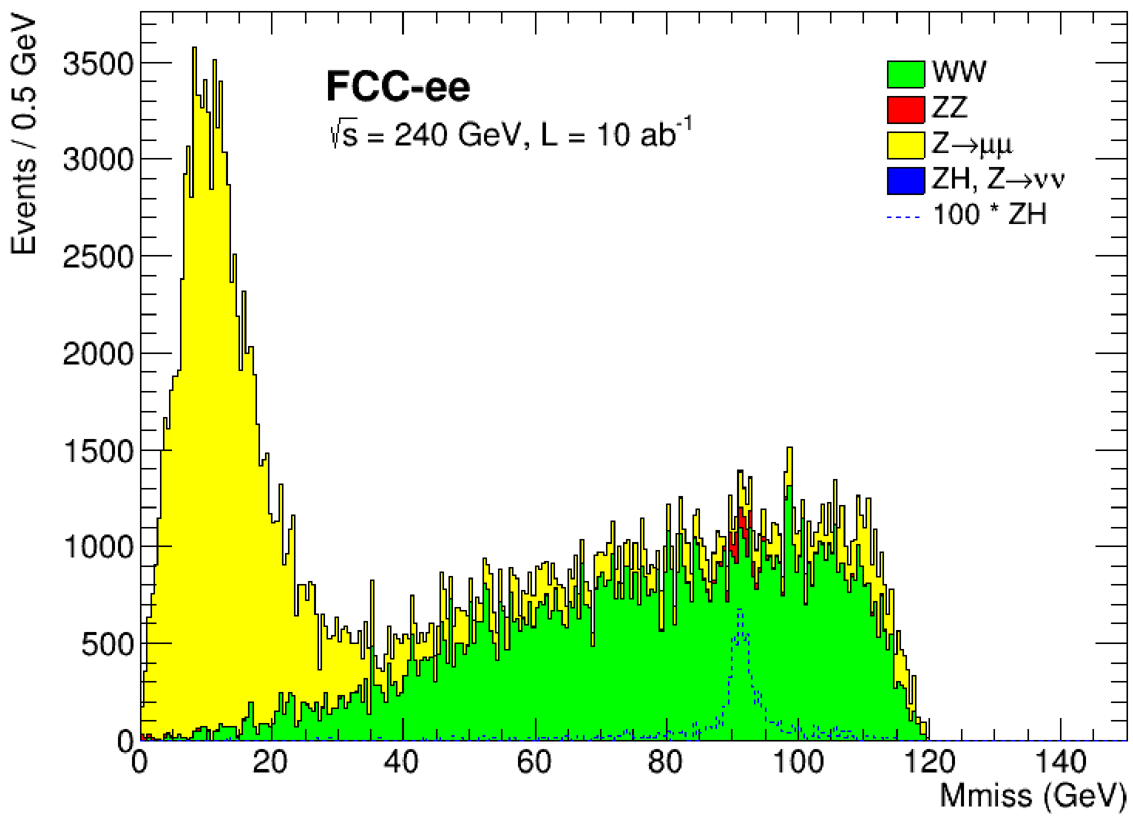
$Z \rightarrow \nu\nu$ channel significance plots

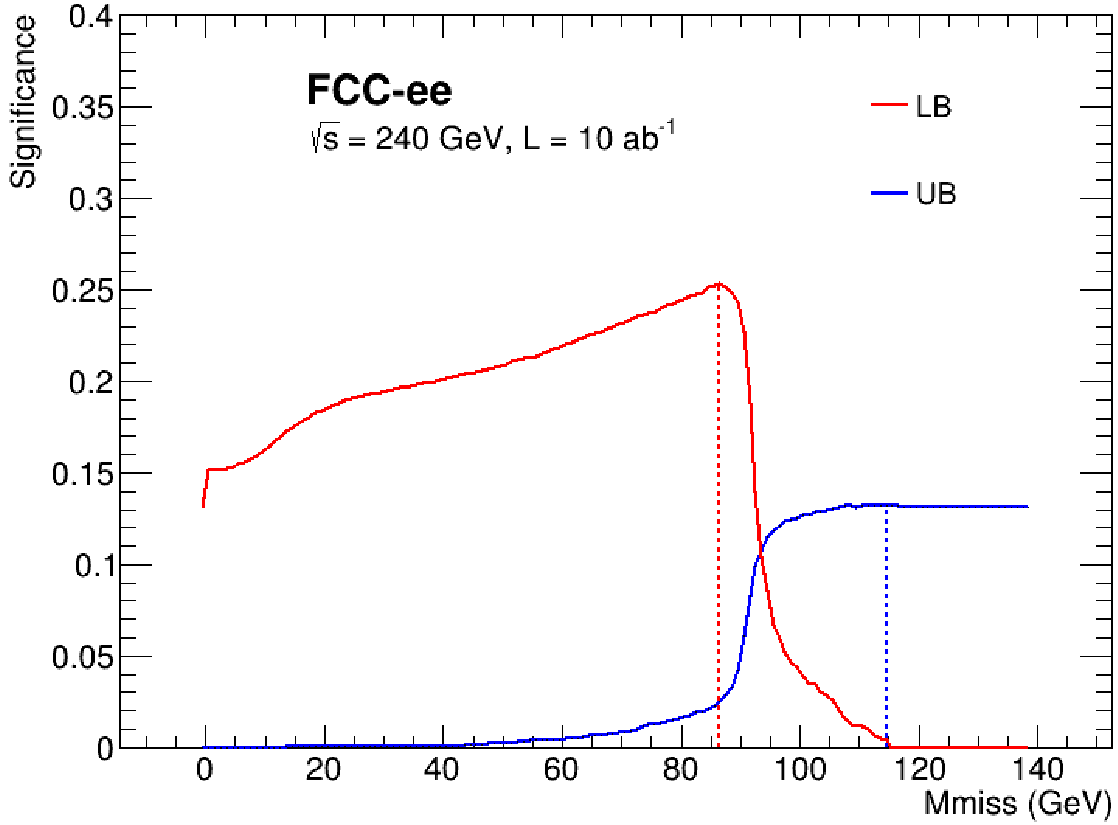
Missing Mass

$$M_{miss} = \sqrt{(240 - E_{\mu\mu})^2 - (0 - \vec{p}_{\mu\mu})^2}$$

The missing mass is the mass from the neutrinos, for the signal expected to be the Z boson mass (90 GeV)

Selection placed between 88 and 95 GeV

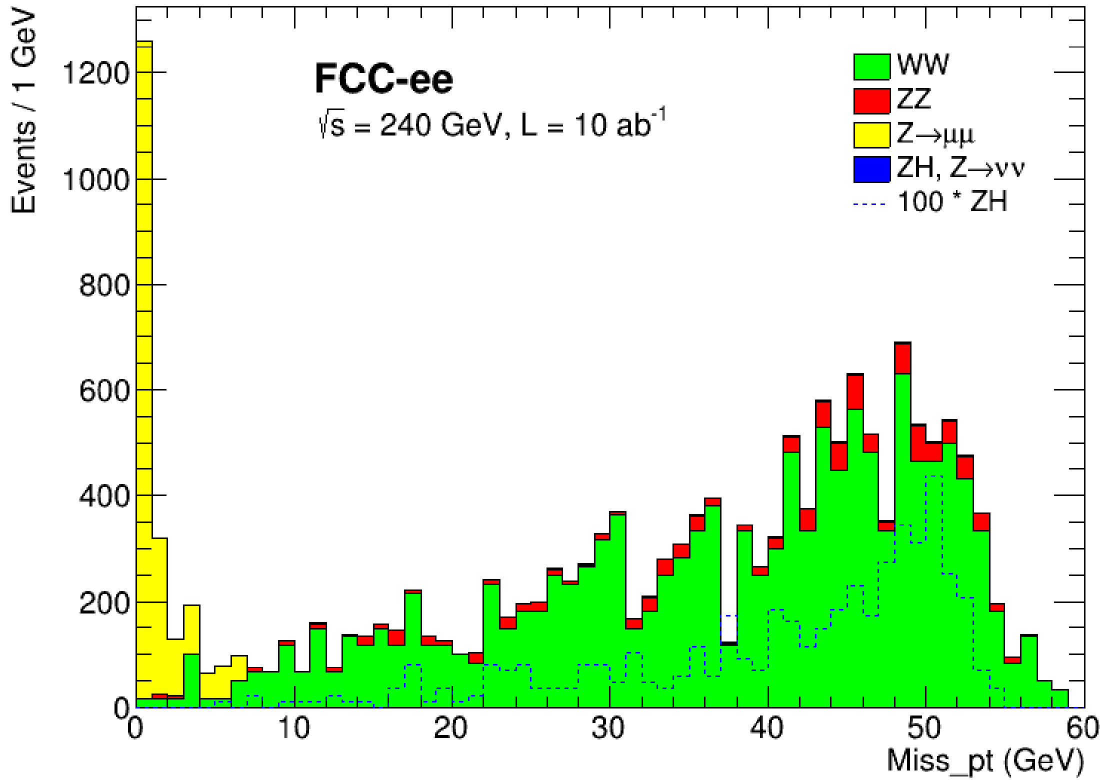


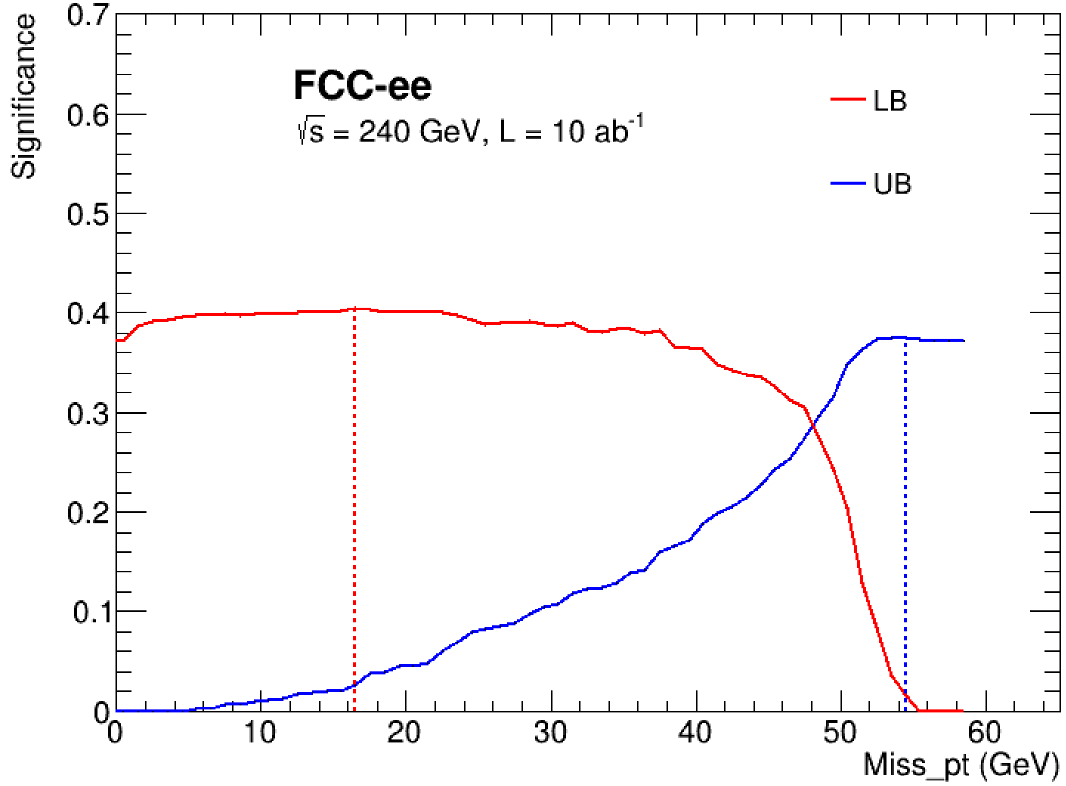


Missing transverse momentum

The $Z \rightarrow \mu\mu$ background (yellow) has a photon produced which if not detected has gone down the beam path. Therefore, there is little missing transverse momentum as all the missing momentum is in the z direction.

Selection placed between 17 and 78 GeV.





Cut Flow tables

$Z \rightarrow qq$

Cuts	Signal (ZH)	ZZ	WW	Z->μμ
$N_{muons} = 2$	356	60432	805653	2288845
70 < Diff < 115	341	38913	182	34543
Max E_{Photon} < 35 GeV	340	38345	133	264
Max $E_{Electron}$ < 25 GeV	339	36153	132	264

$Z \rightarrow \nu\nu$

Cuts	Signal (ZH)	ZZ	WW	Z->μμ
Only 2 muons detected	80	12218	612376	1298157
88 < Mmiss < 95	47	6583	59328	13982
17 < Mmiss_pt < 78	46	5831	48202	0
Diff < 0.5 GeV	45	5695	47174	0

$Z \rightarrow ee$

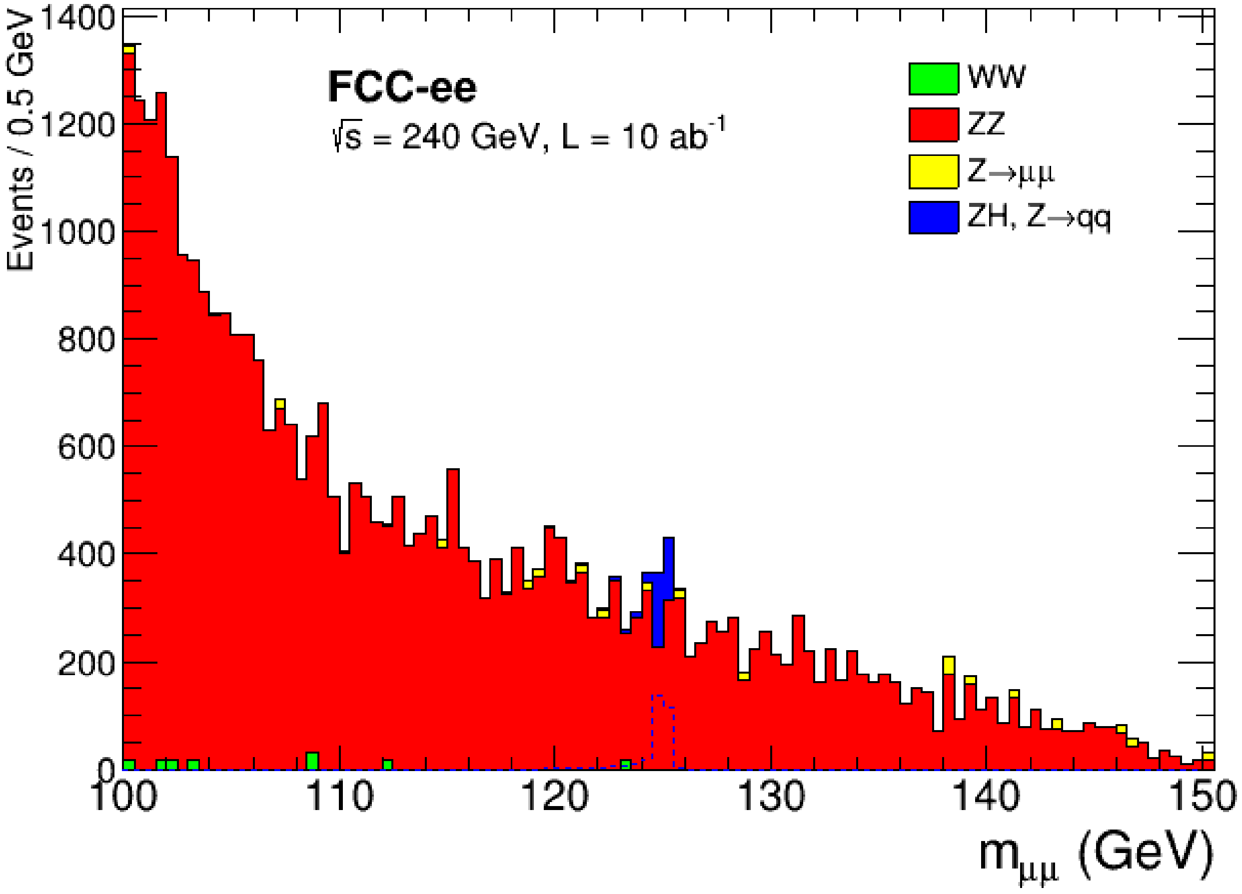
Cuts	Signal (ZH)	ZZ	WW	Z->μμ
Only 2 muons and 2 electrons detected	10	1597	66	0
Max $E_{Electron}$ > 40 GeV	10	1571	0	0

$Z \rightarrow \mu\mu$

Cuts	Signal (ZH)	ZZ	WW	Z->μμ
Only 4 muons detected, and Z boson muons tagged between 80 and 100 GeV	8	900	0	0

*Events with muons invariant mass between 100-150 GeV

Invariant mass plot for $Z \rightarrow qq$ channel



- The invariant mass from the two muons in the quark channel shows a clear signal. Background from ZZ is a Z boson mass peak centred at 90 GeV.
- There is large fluctuations between neighbouring bins which would not be expected.
- The fluctuations between neighbouring bins is coming from the statistics of the Monte Carlo samples. Therefore, smoothing could be used to create more realistic results.

Kernel Smoothing

- Kernel Smoothing is a type of smoothing which weights events by a function referred to as the Kernel.

$$K(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}}$$

Where x is the distance between bins and σ is the strength of the smoothing.

- A weight is calculated for each neighbouring bin. Then the new value of the initial bin is the summation of the different weights times the events in each bin.

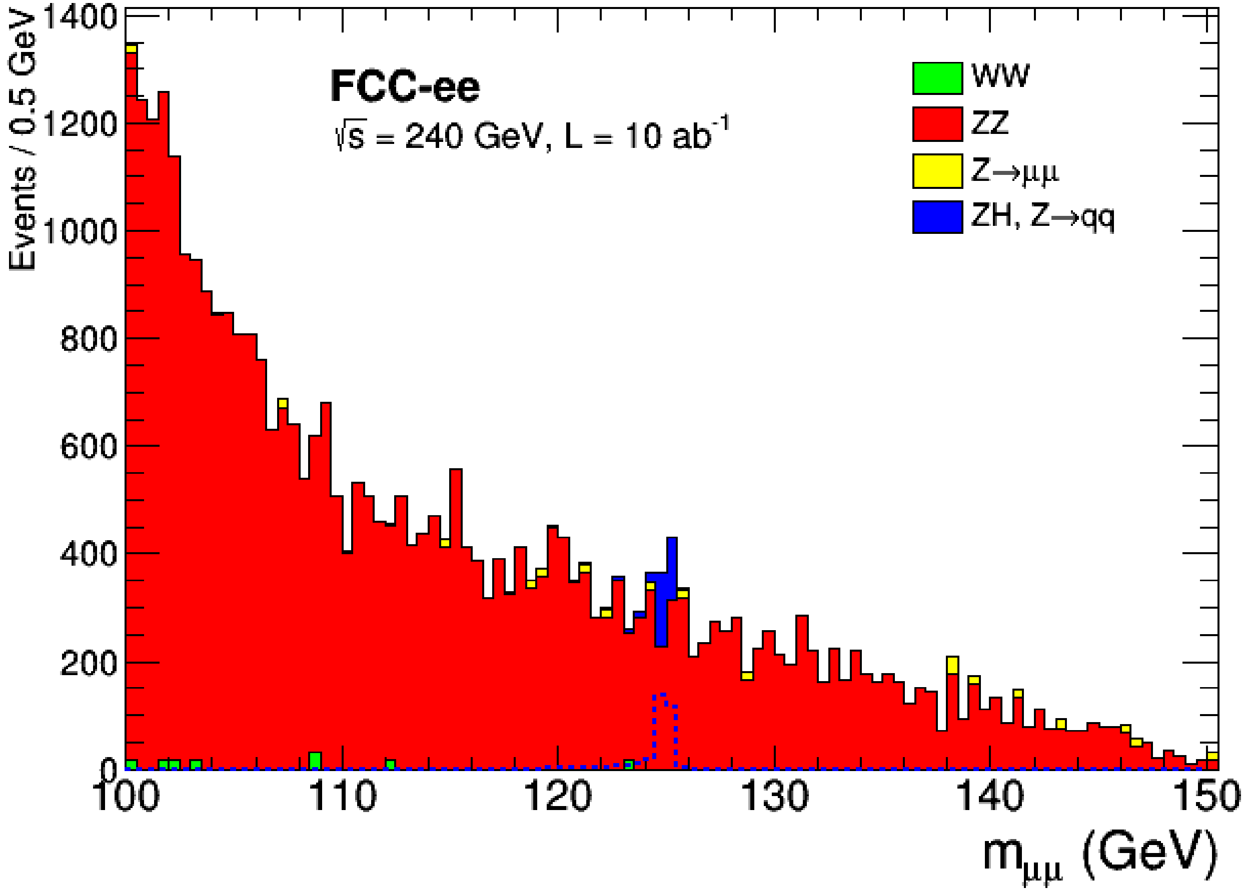
$$N_{new} = \sum K(x_i)\, N_i$$

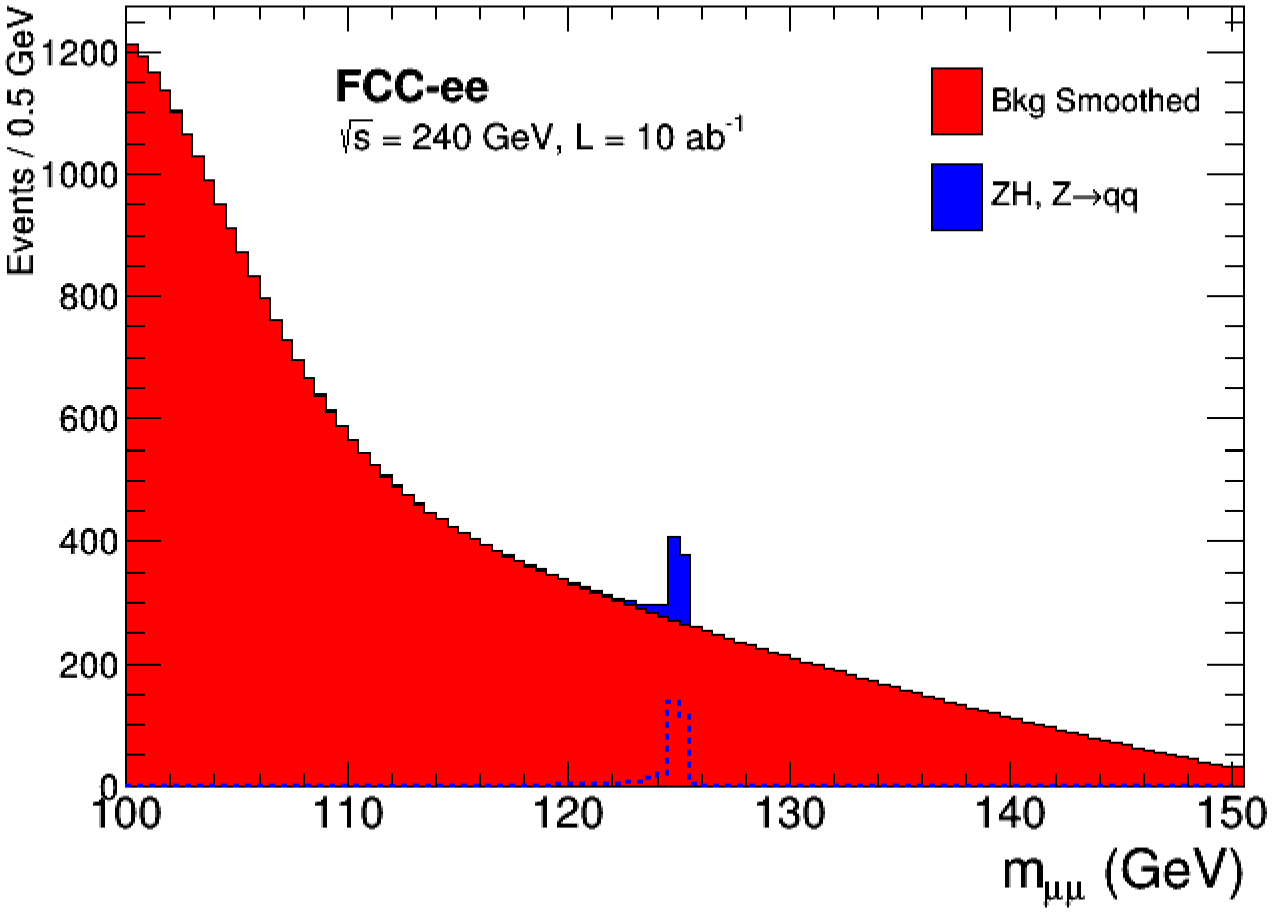
- This is repeated for each bin.

Kernel Smoothing of $Z \rightarrow qq$ channel

A smoothness factor of 5 was chosen

- Using HistFitter to perform a loglikelihood fit, to find the uncertainty on the signal strength constant.
- $\boldsymbol{\Delta\mu = 10.9\%}$

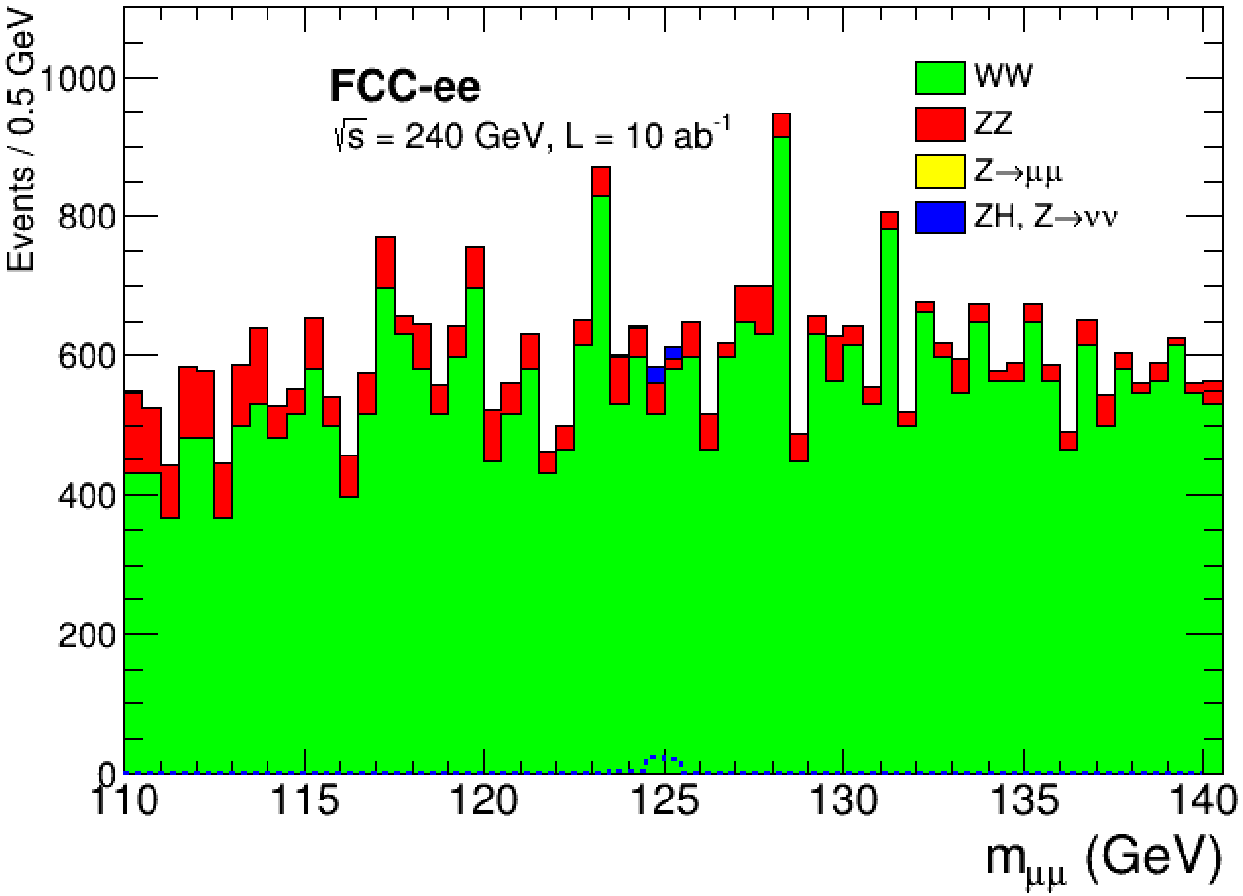


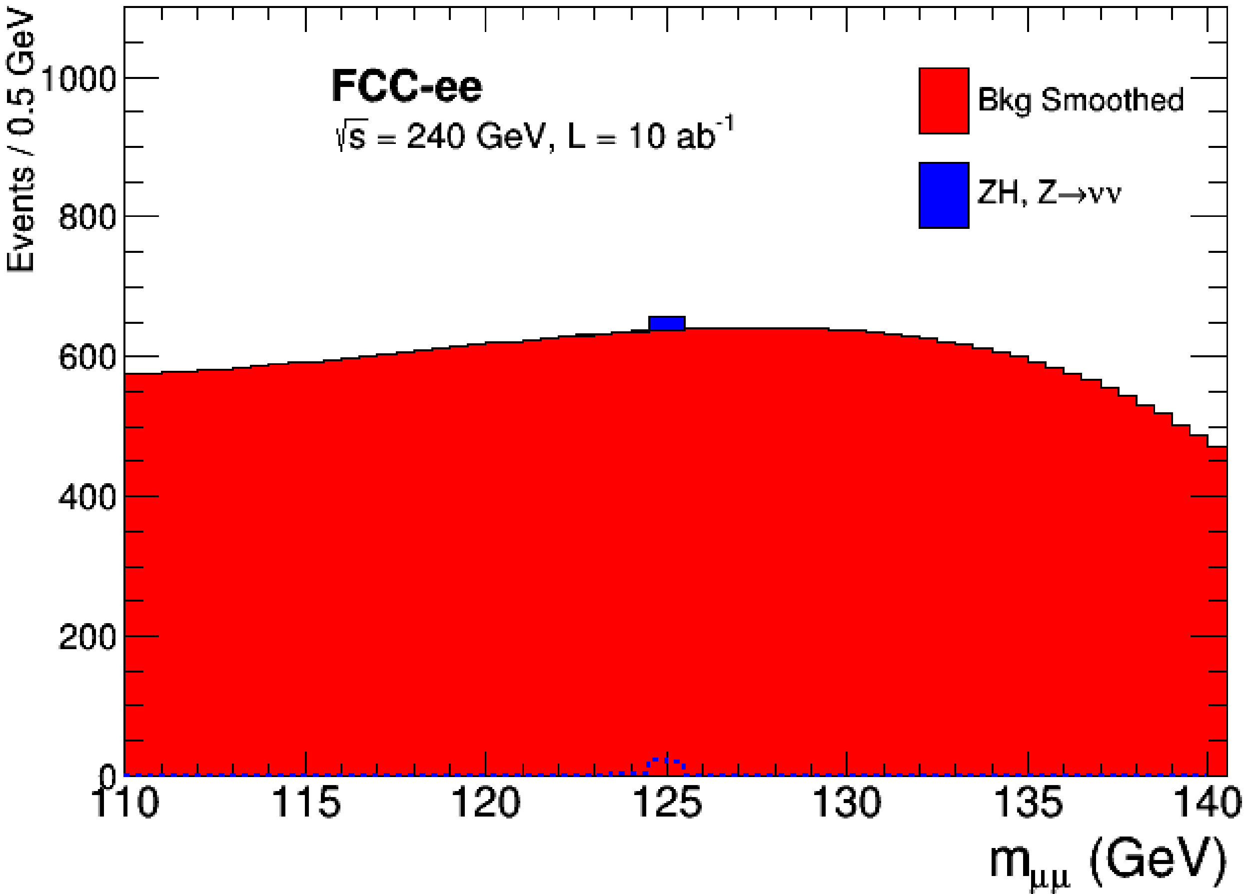


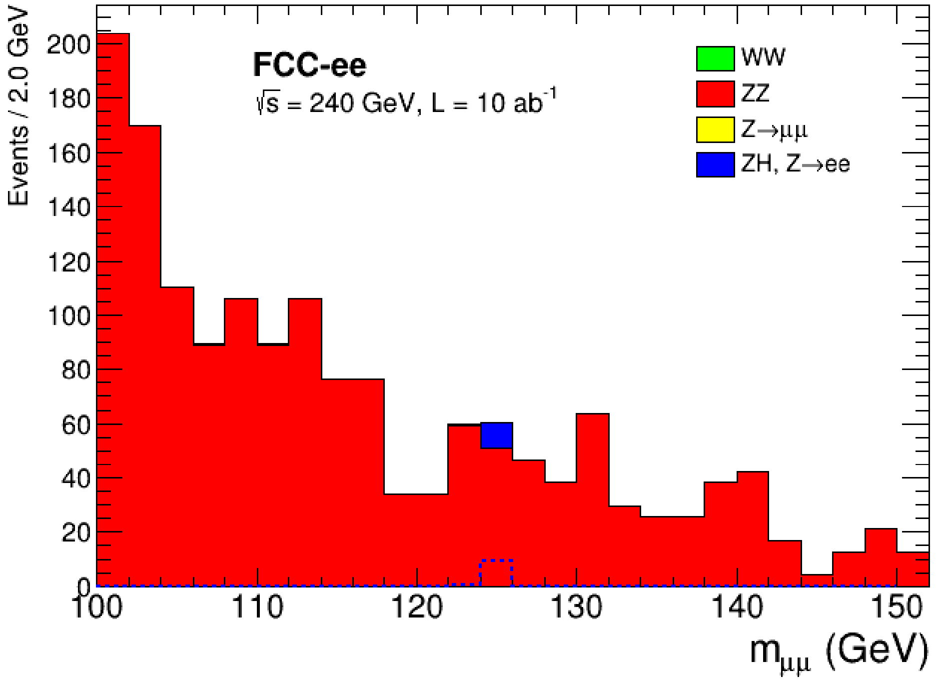
Invariant mass plot $Z \to \nu\nu$

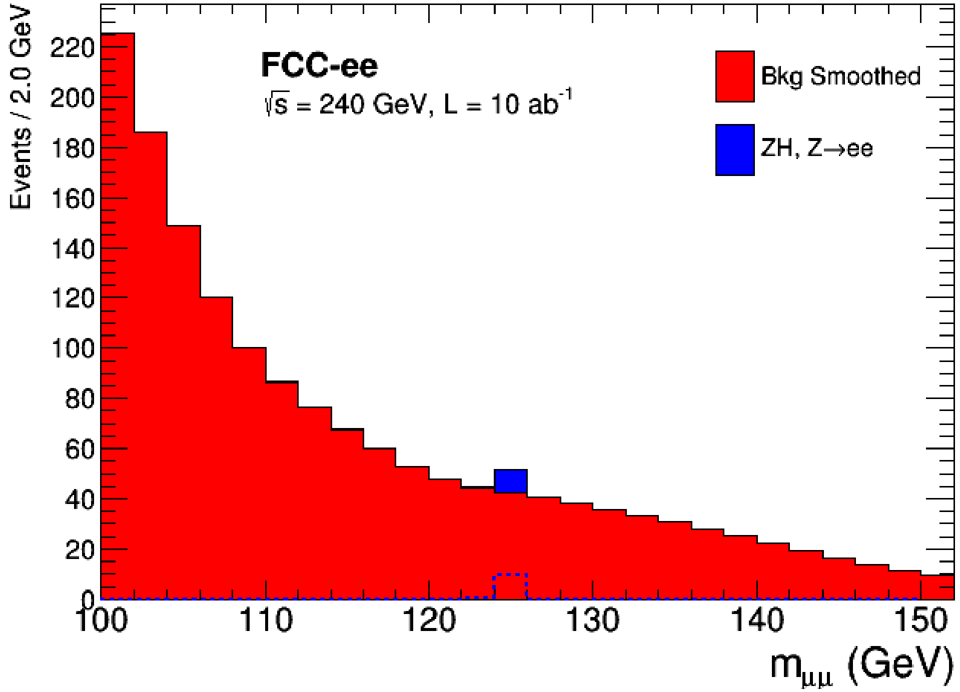
- $\Delta\mu = 92.8\%$

- Large background from the WW resulting in a large uncertainty.



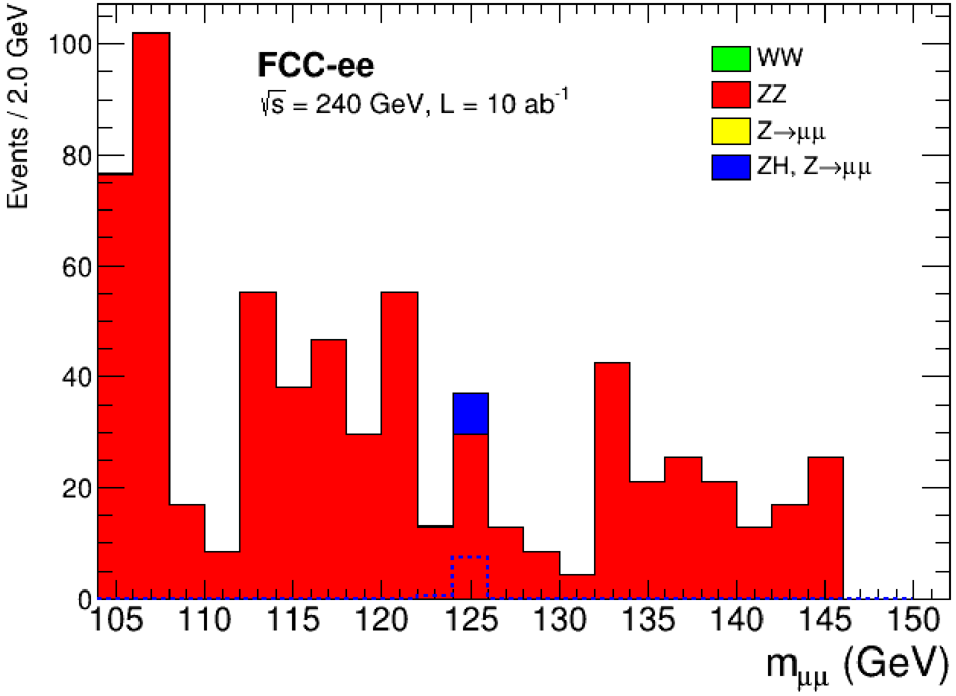


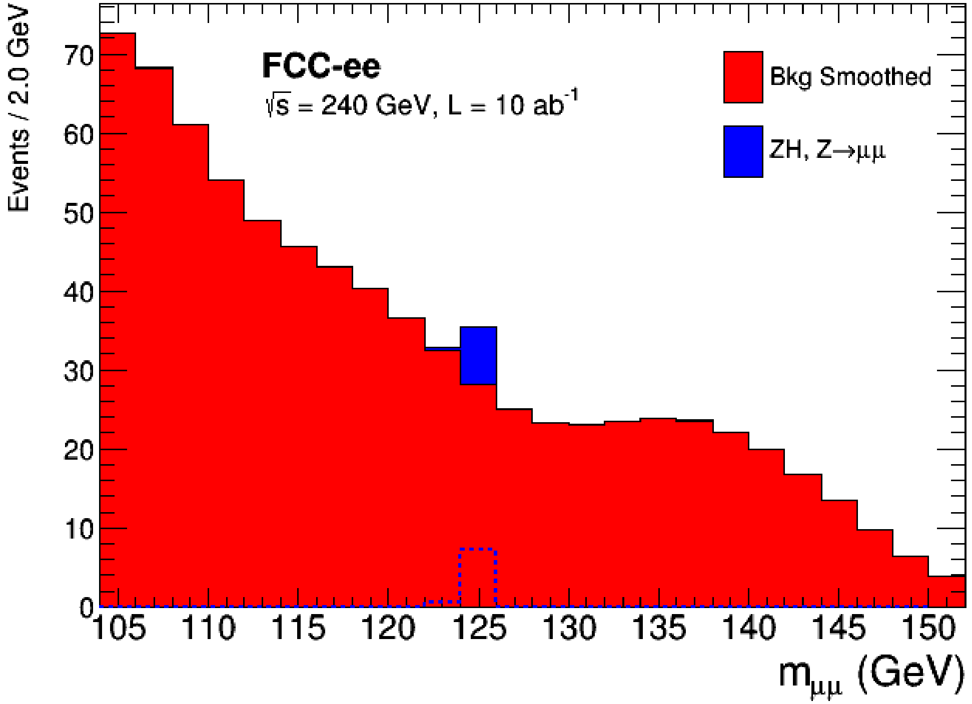




$Z \rightarrow ee$

$\boldsymbol{\Delta\mu = 77.3\%}$





$Z \rightarrow \mu\mu$

$\boldsymbol{\Delta\mu = 88.2\%}$

Both suffer from small number of events due to low branching fraction

Combining all channels

Combining all channels results in an uncertainty of 10.9%.

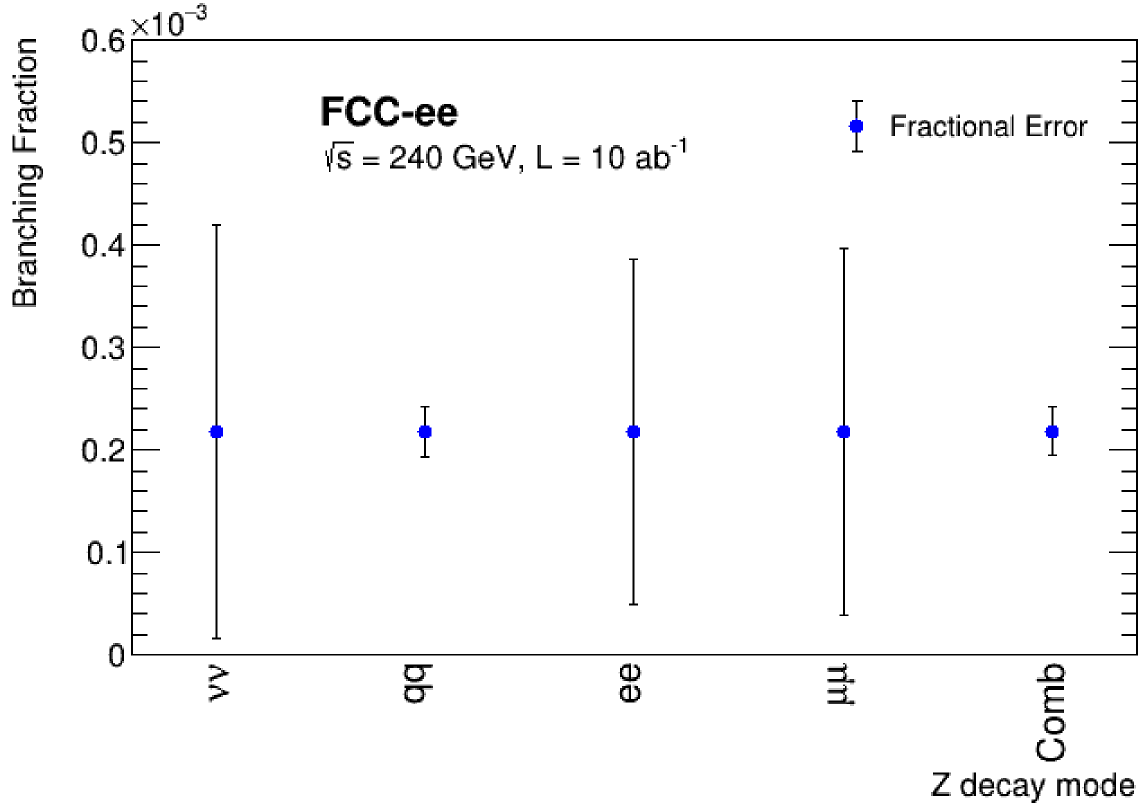
Comparing this to other measurements:

- M. Ruan found an uncertainty of 13%. However, used samples based on CMS detector
  [IHCEP_HiggsMeasurementAtCC_Modi_3 (cern.ch)]
- A.Freitas and others found an uncertainty of 12% from projected intrinsic and parametric uncertainties
  https://arxiv.org/pdf/1906.05379.pdf

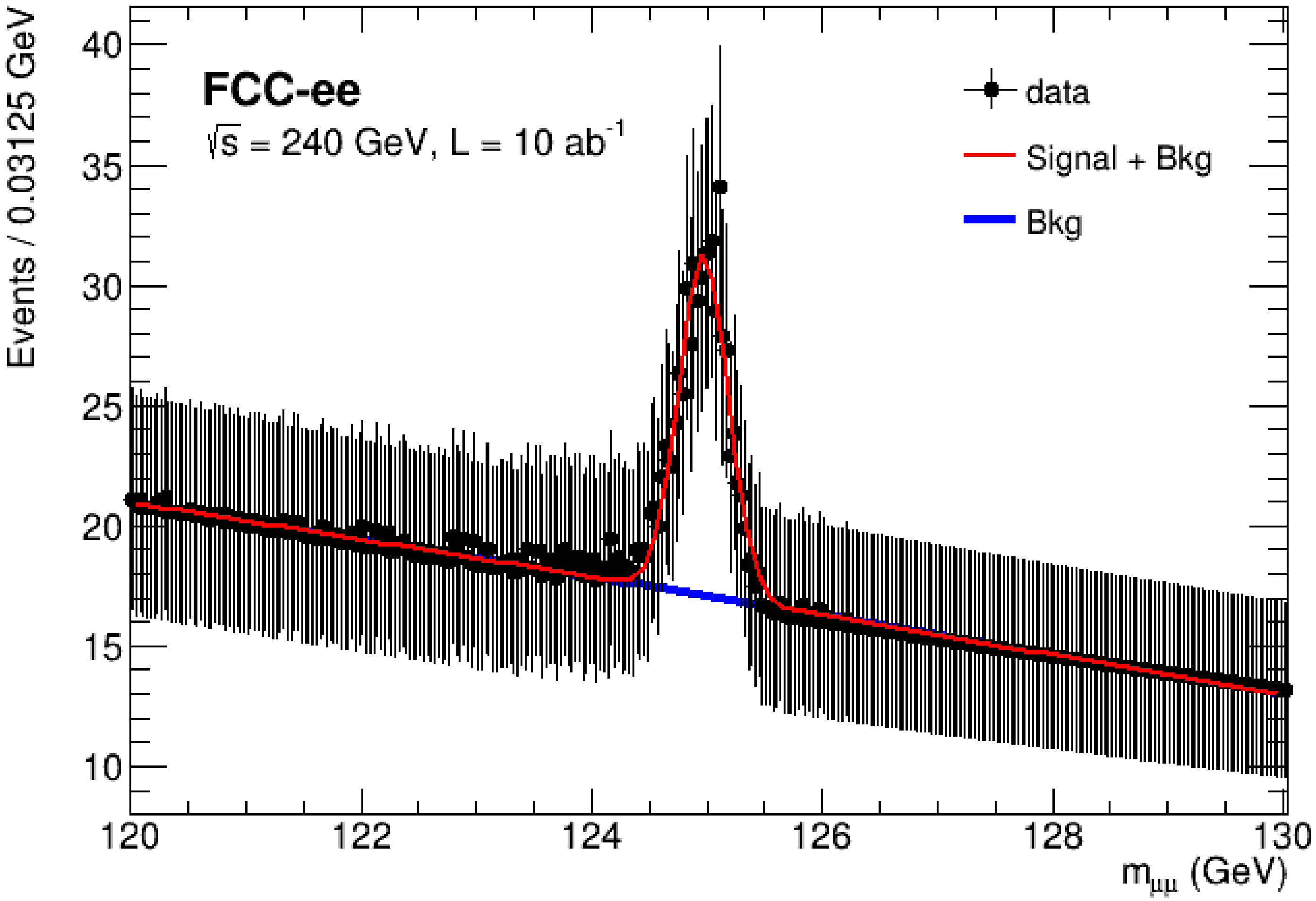
Expectations for the Higgs to muons at HL-LHC

- ATLAS expects uncertainty of 15 to 13%
- CMS expects uncertainty of 13 to 10%

1902.00134.pdf (arxiv.org)



Precision mass can be measured to in $\mathrm{H} \rightarrow \mu\mu$



- A polynomial + gaussian fit was used on the Z->qq channel to find the error on the centre of the gaussian.
- Uncertainty of 30 MeV
- Requires very small systematic errors.
- Other methods such as using the recoil mass have better precision. P.Azzurri and other predict an uncertainty of 6 MeV, including other channels can improve this to 2-3 MeV. These results are for the integrated luminosity of $5ab^{-1}$ so will improve for $10ab^{-1}$.

2106.15438.pdf (arxiv.org)

Conclusion

- Combining 4 channels results in the possible uncertainty on the Higgs to muons branching fraction to be 10.9%.

- The precision the mass in the Higgs to muons channel is 30 MeV.