Higgs width measurement at FCC-ee in the ZH,H(ZZ*) final state

FUTURE CIRCULAR COLLIDER

Inès Combes (IJCLab, Orsay)
05-11-2024, FCC Workshop Venice

Higgs width and its LHC/FCC-ee measurement methods

For a 125 GeV Higgs boson :

$$\Gamma_H \sim 4.1\,\mathrm{MeV}$$

Standard Model prediction

Essential property of the Higgs boson
=> directly linked to its decays so potentially to **new physics**!

Width of the order of **MeV** => **impossible** via direct measurement through **lineshape**

(HL-)LHC
proton-proton

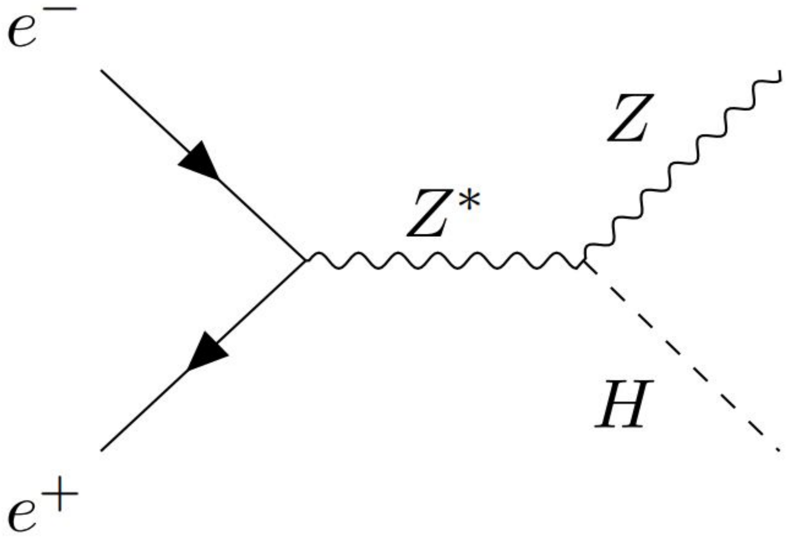
Model-dependent measurement
(theoretical assumptions)

In e+e-, energy involved in the collision (initial state) is known!

FCC-ee
electron-positron

Model-independent measurement

Higgs factory (ZH) at $\sqrt{s} = 240$ GeV



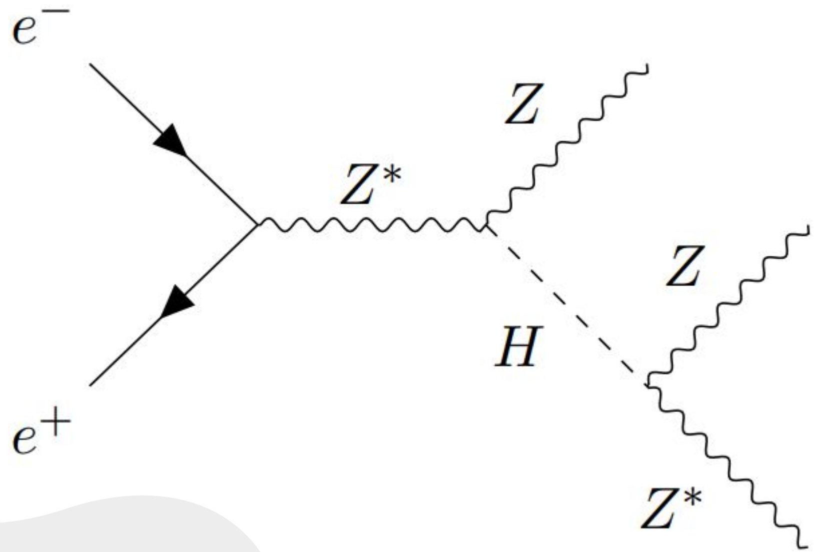
$$\mathrm{N}_{\text{expected ZH events}} \sim 10^6$$

for a luminosity of 5 ab^{-1} for the ZH run in these studies

$$\sigma_{\mathrm{ZH}} \propto \mathrm{g}_Z^2$$

=> **direct** measurement of ZH cross section in electron-positron collider (initial energy known so access to **recoil mass**)

Specific decay of the Higgs : H(ZZ*)



- $\mathrm{BR}(H \to ZZ^*) \sim 2.64\%$

$$\mathrm{N}_{\text{expected } ZH(ZZ^*) \text{ events}} \sim 25000$$

- $$\sigma_{ZH(ZZ^*)} \propto \frac{\mathrm{g}_Z^4}{\Gamma_H}$$

Link between Higgs' width and ZH,ZZZ cross section

Higgs' width measurement and its uncertainty

$$\Gamma_H \propto \frac{\sigma^2_{ZH}}{\sigma_{ZH(ZZ^*)}}$$

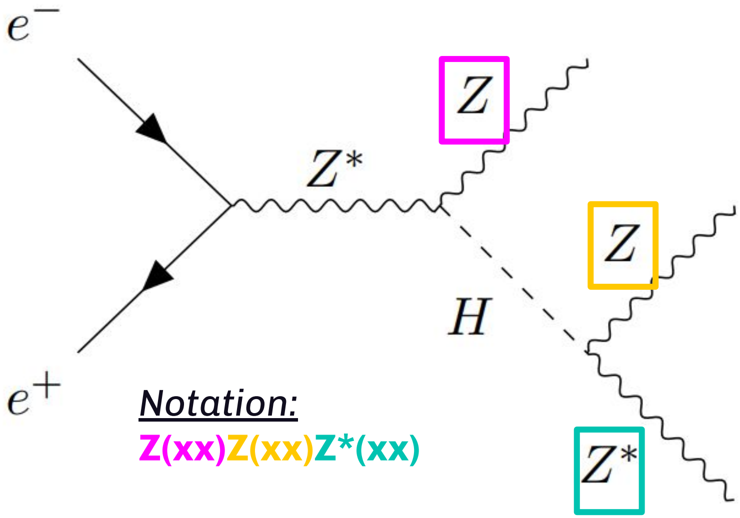
$$\frac{\delta\sigma_{ZH}}{\sigma_{ZH}} \sim 0.1\%$$

$$\frac{\delta\sigma_{ZH(ZZ^*)}}{\sigma_{ZH(ZZ^*)}} > 1\%$$

the uncertainty on the width is the one on the ZH(ZZ*) cross section in first approximation

ZH(ZZ*) - Different final states

$$\mathrm{BR}(Z \to \mathrm{ee}/\mu\mu) \sim 6.7\%$$
$$\mathrm{BR}(Z \to \mathrm{qq}) \sim 70\%$$
$$\mathrm{BR}(Z \to \nu\nu) \sim 20\%$$



Notation:
Z(xx)Z(xx)Z*(xx)

What has been studied so far?

- **4 leptons** final states (all combinations with either vv or jj)
- Mixed final states (3 combinations of **ll+jj+vv**)
- One **4 jets** final state (challenging)

Outline

01

Common features

Object reconstruction, samples, backgrounds

02

4l + X *final states*

Cut-based analysis, and combination

03

ll+jj+vv *final states*

Cut based analysis and BDT-based analysis, and combination

04

Impact of systematics

Background normalisation and neutral hadron energy resolution

05

Challenging channels

Encountered challenges for some 4l and 4j channels

01

Common features in analyses

Common object reconstruction

- *Pair of (high momentum) leptons* coming from on-shell or off-shell Z(s)

  => For on-shell Z(s), pair(s) of same flavor and opposite sign leptons both passing the selection **25<p<80GeV** reconstructed by taking the lepton pair with the dilepton mass closest to the Z mass. In the 4l case, if the other Z is off-shell, remaining same flavor and opposite sign leptons with **p>5GeV**.

  => Preselection to select the right number of leptonic Z depending on the considered channel

- *Jets* (coming from either the on shell or off shell Z of the Higgs)

  => Jet reconstruction with **Durham-kt** algorithm in the FCC Analysis framework, njets mode with **njets = 2** (or 4 in 4j case). Hadronic Zs reconstructed picking the pair of jets with the dijet mass closest to the **Z mass** (and building its 4-vector) , and building the off-shell Z from the leftover jets.

- *Neutrinos*

  => extraction of missing energy, missing transverse energy, missing z-momentum

Backgrounds for ZH(ZZ*) and samples

Most abundant
- ZZ
- WW
- ZH with all other Higgs' decays :

$H \to \gamma Z$
$H \to l^+ l^-$
$H \to q\bar{q}$
$H \to gg$
$H \to \gamma\gamma$
$H \to WW$

Expected number of signal and background (in this study for 5ab-1):

Number of events for $L = 5ab^{-1}$						
H(ZZ)	ZZ	WW	H(WW)	H(bb)	$H(\tau\tau)$	H(other)
$\sim 26\ 400$	$\sim 6.8\ 10^6$	$\sim 82\ 10^6$	$\sim 215\ 000$	$\sim 577\ 000$	$\sim 63\ 200$	$\sim 90\ 000$

Samples:
FCC-ee winter2023 production with IDEA Delphes datacard
ZH: Whizard+Pythia6
ZZ/WW: Pythia8

02

4 leptons (4l + X) final states

Work done by **Hind Taibi** *(with Marco Delmastro and Olivier Arnaez, LAPP, Annecy)*
Note: every figure in this part is taken from her work

Hind's internship presentation

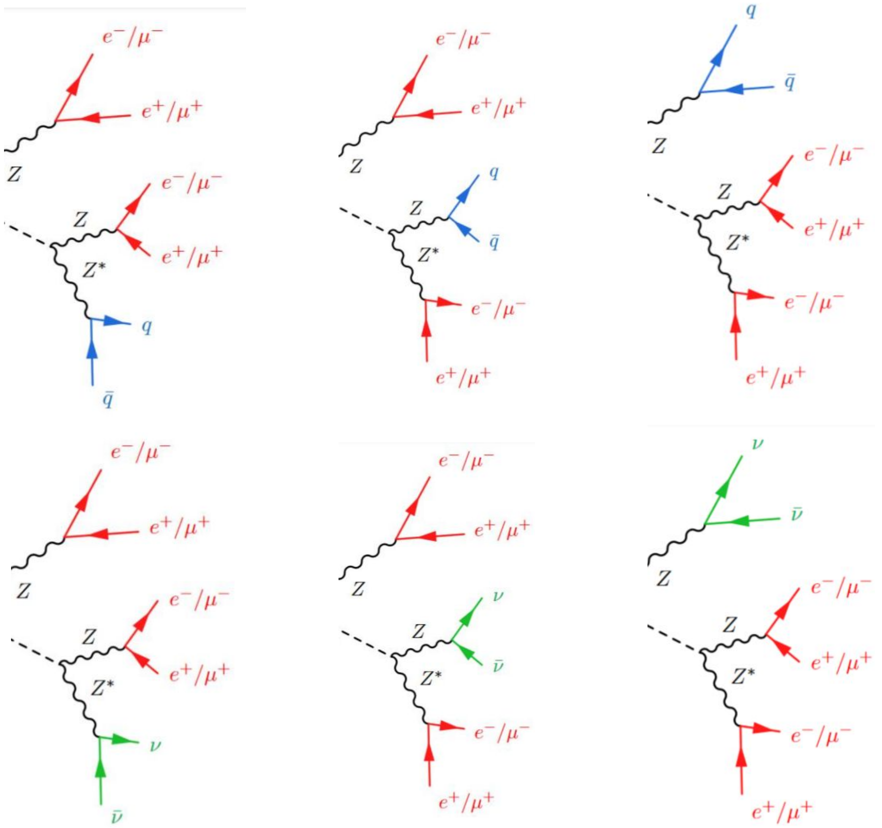
+ Few points on a similar new studies done in the **Bari** group!

Final states and analysis strategy

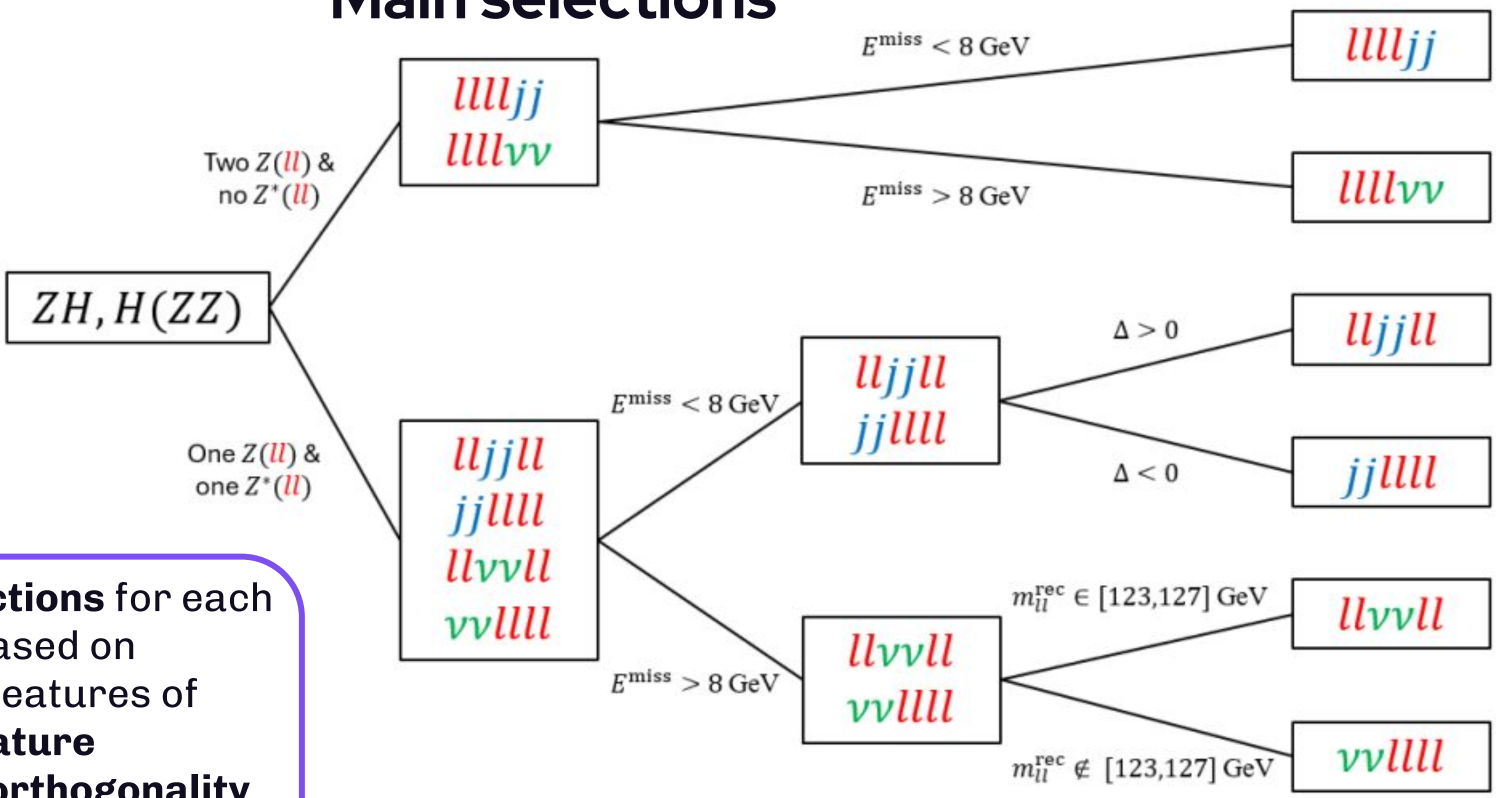
Consider **every (6)** possible combinations of 4 leptons + either vv or jj

Analysis/results:
=> cut-based
using recoil mass, dilepton mass, missing energy, ...

Uncertainties obtained with individual fits and **combination of 4** out the 6 channels



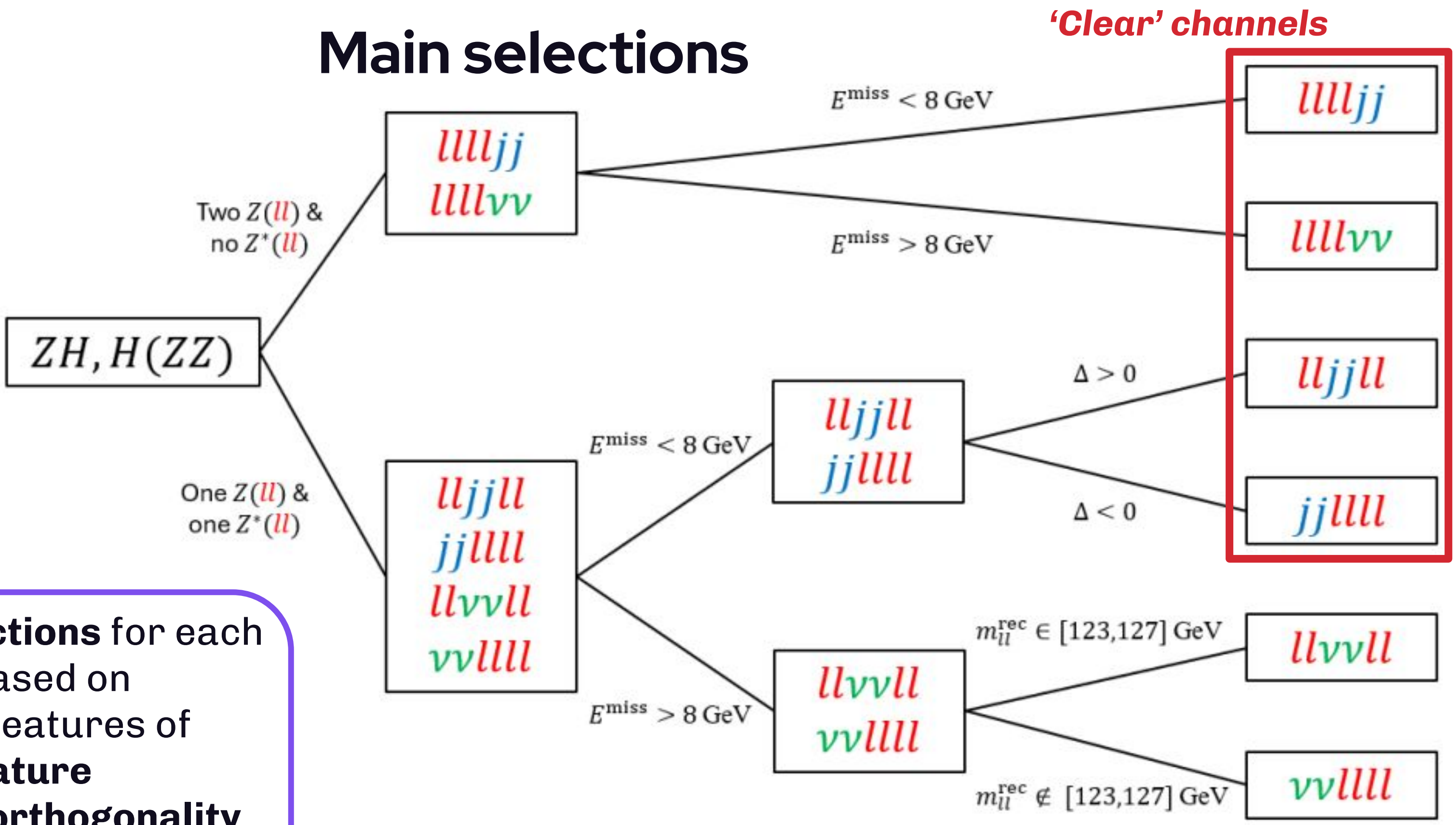
Main selections



- **First selections** for each channel based on essential features of their **signature**
- Ensuring **orthogonality** between channels for the **combined** fit

with $\Delta = |125\ \mathrm{GeV} - m_{jj}^{\mathrm{rec}}| - |125\ \mathrm{GeV} - m_{ll}^{\mathrm{rec}}|$

Main selections



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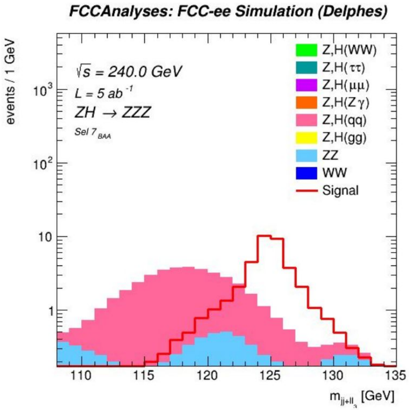
- Ensuring **orthogonality** between channels for the **combined** fit

with $\Delta = |125 \text{ GeV} - m_{jj}^{\text{rec}}| - |125 \text{ GeV} - m_{ll}^{\text{rec}}|$

4 clear channels – variables used for their fit

Channel	S/B	$S/\sqrt{B}$
$Z_1(ll)Z_2(ll)Z_3(jj)$	~ 1.5	~ 7.9
$Z_1(ll)Z_2(jj)Z_3(ll)$	~ 0.95	~ 6.2
$Z_1(jj)Z_2(ll)Z_3(ll)$	~ 3.1	~ 10.9
$Z_1(\nu\nu)Z_2(ll)Z_3(ll)$	~ 0.75	~ 2.9

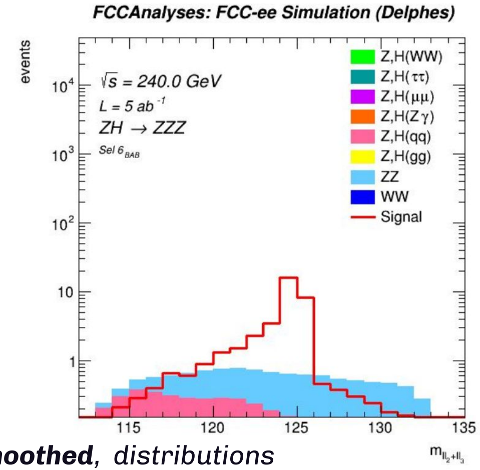


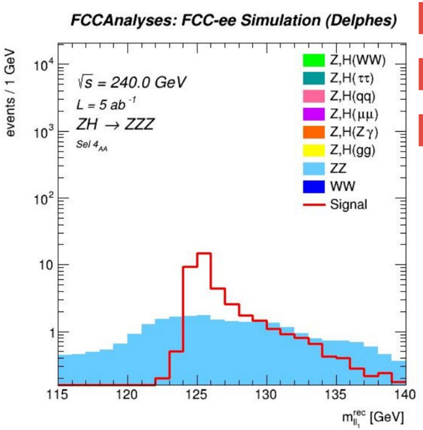
Z(ll)Z(jj)Z*(ll)

Mass of the jet pair and the off-shell Z lepton pair (cutflow)

Mass of the 2 lepton pairs (cutflow)

Z(jj)Z(ll)Z*(ll)



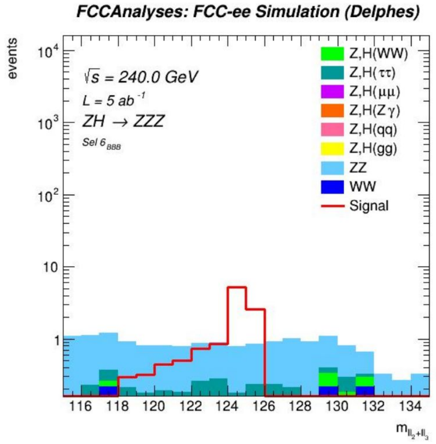


Z(ll)Z(ll)Z*(jj)

Recoil mass of the first Z lepton pair (cutflow)

Mass of the 2 lepton pairs (cutflow)

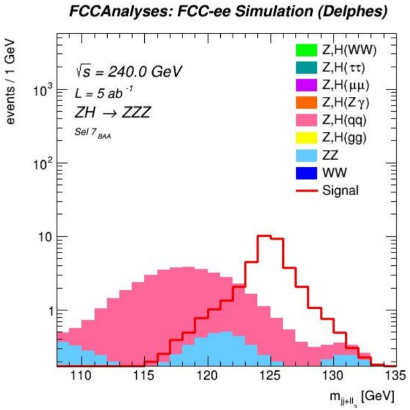
Z(νν)Z(ll)Z*(ll)



Note: *these distributions are* ***smoothed****, distributions before smoothing are shown in backup*

4 clear channels – variables used for their fit

Reach a good S/B with kinematic selection analyses!
(Without using BDT!)



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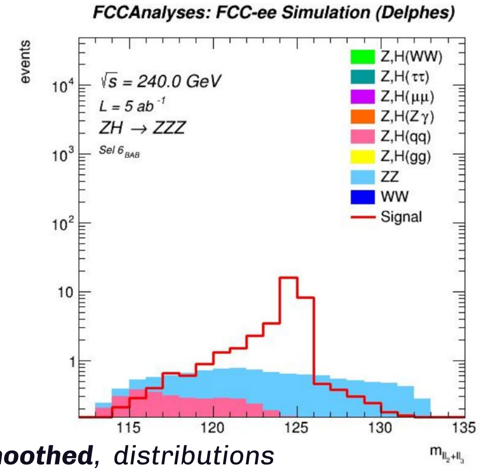

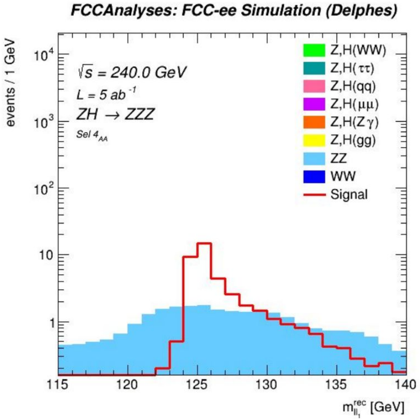

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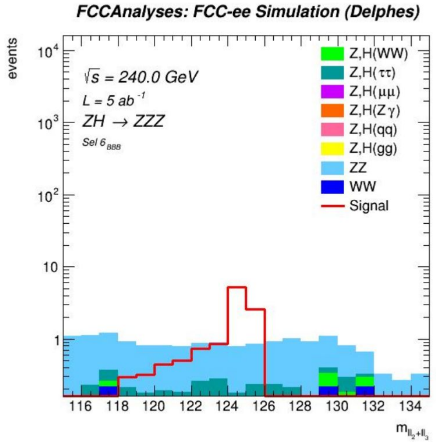


Note: *these distributions are* ***smoothed****, distributions before smoothing are shown in backup*

Fits and combination

Z(ll)Z(jj)Z*(ll)

$\sim 18\%$

Z(jj)Z(ll)Z*(ll)

$\sim 17\%$

Z(ll)Z(ll)Z*(jj)

$\sim 18\%$

Z(vv)Z(ll)Z*(ll)

$\sim 36\%$

Fit results *(uncertainty on H(ZZ*) cross section)*

COMBINE

Final result for the width uncertainty using kinematic selections:

$$r = 1 \pm 0.101$$

$$\frac{\delta\sigma_{ZH(ZZ^*)}}{\sigma_{ZH(ZZ^*)}} \sim \frac{\delta\Gamma_H}{\Gamma_H} \sim 10.1\%$$

Included systematics :

- For jjllll and lljjll only: H(qq) normalisation : 10%
- ZZ normalisation : 10%

In yellow, differences with Hind's work

Alternative 4l studies

Z(jj)Z(ll)Z*(ll)
Z(vv)Z(ll)Z*(ll)

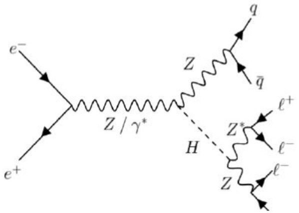
By: Yehia Mahmoud and Nicola De Filippis in collaboration with Michela Selvaggi and Jan Eysermans

H(ZZ*) -> (4l) channel Two channels studied: Z(jj)H(4l) and Z(vv) H(4l)

Samples:

Produced by WHIZARD+PYTHIA for event generation and Delphes (IDEA detector card) for detector simulation. FCCee Winter 2023 Samples. Events produced at $\sqrt{s}$ = 240 GeV and L = 10.8 ab^{-1}. Hind=>5ab-1

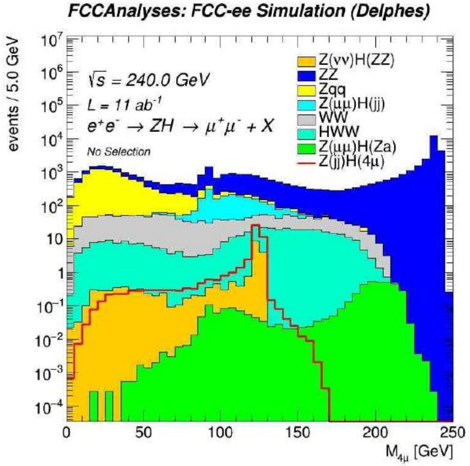
Backround -> ZZ/ WW/ Zqq/ HWW/ Hjj/ HZa Hind=> no Zqq, all ZH,H(xx)



Lepton Selection criteria (Same for hadronic and invisible channels):

- First pair of leptons (From On-shell Z)
  - Oppositely charged leptons
  - The pair which minimises $|M_{ll} - M_Z|$
- Second Pair of leptons (From off-shell Z)
  - Oppositely charged leptons
  - Highest momentum oppositely charged pair of the remaining

- Additional cut for 2e2mu: On-shell Z mass > 60 GeV. This is to remove contribution from Off-Shell Z leptons.



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Alternative 4l studies

Z(jj)Z(ll)Z*(ll)
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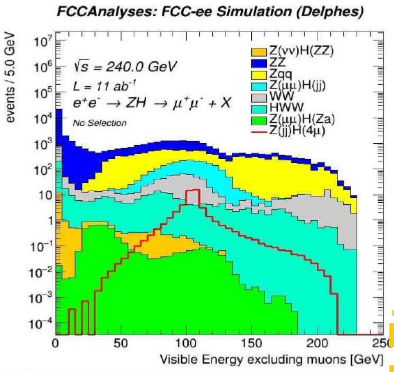
H(ZZ*) -> (4l) channel Two channels studied: Z(jj)H(4l) and Z(vv) H(4l)



WARNING: analyses involve some differences in the lumi and backgrounds

Analysis cuts:

- Momentum of the softest lepton of the reconstructed 4 lepton:
  P_{min} > 5 GeV.
- Missing momentum cut:
  P_{miss} < 40 GeV for Z(jj), P_{miss} > 100 GeV for Z(vv)
- Visible energy of all the reconstructed particles excluding the 4 leptons
  E_{vis} > 30 GeV
- Invariant mass of dimuon pair from the Off-shell Z*
  10 < M_{Z^*} < 65 GeV
- Invariant mass of the 4 leptons:
  124 < M_{4l} < 125.5 GeV

Channel	Signal yield	Total Bckg	s/√(s+b)	S/B combining all types of leptons together:	Hind's S/B:
Z(jj)H(4μ)	26	3	4.82	~4	~3.1
Z(jj)H(4e)	19	8	3.6		
Z(jj)H(2e2μ)	20	5	4.0		
Z(vv)H(4μ)	9	4	2.496	~2.44	~0.75
Z(vv)H(4e)	6	2	2.12		
Z(vv)H(2e2μ)	7	3	2.21		

Work ongoing in Bari, interesting results upcoming!

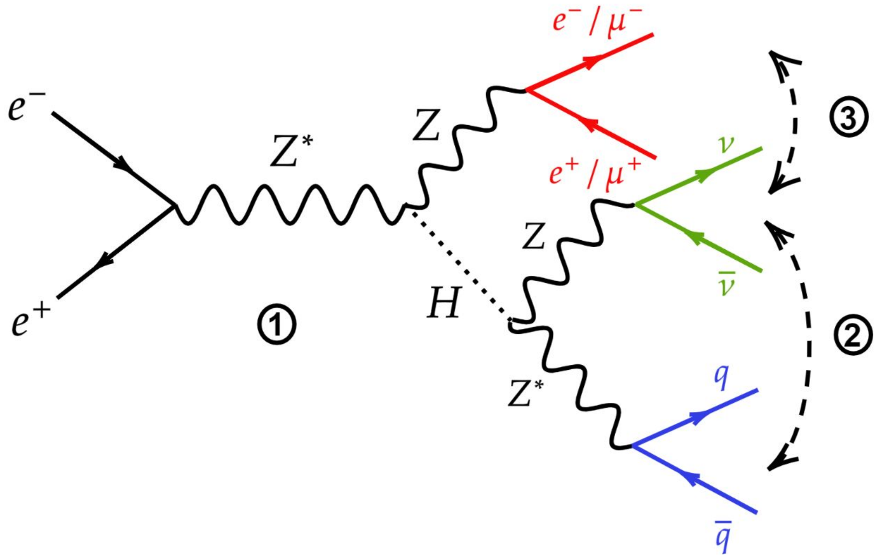
03

Mixed (vv+ll+jj) final states

Work done in IJCLab (Paris) with Nicolas Morange

Presentation at Higgs/Top performance meeting (24.07.2023, Paris)
FCC Note written in 09.23

Mixed channels signature and analysis strategy



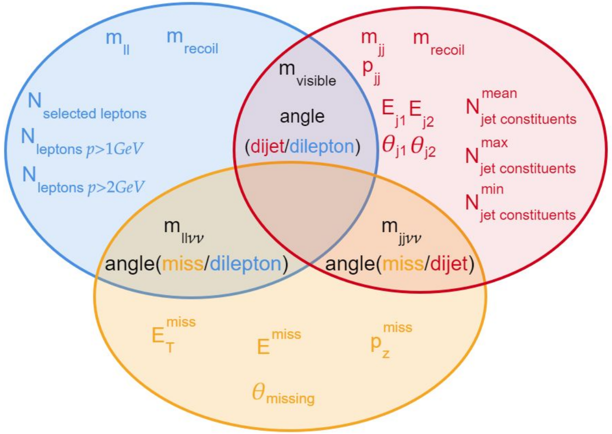
Study of 3 combinations of **ll+vv+jj**

2 types of analyses/results:

- Cut-based (backup, from this slide)
- **BDT**

Uncertainties obtained with individual fits and **combination**

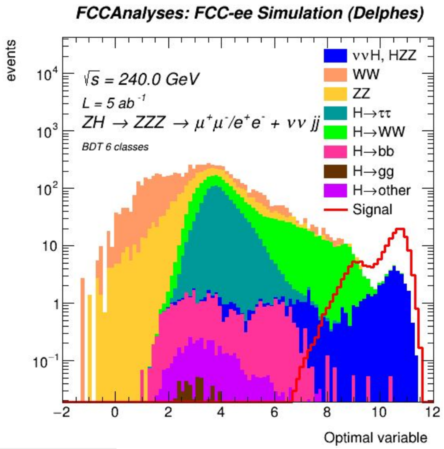
3 mixed channels



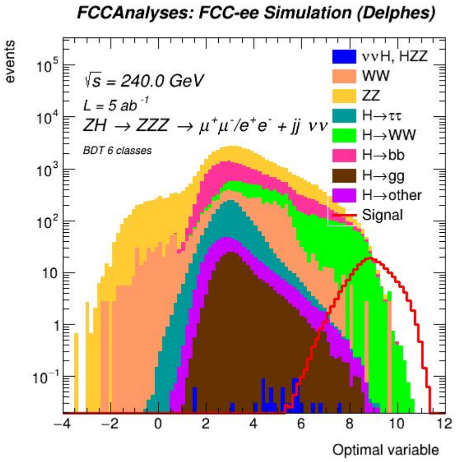
Boosted decision tree classification:

- Trained on 6 classes (signal, ZZ, WW, ZH(WW), ZH(bb), ZH(tautau))
- Variables shown on the diagram on the right
- Output: optimal variables for S and B separation (likelihood ratio)

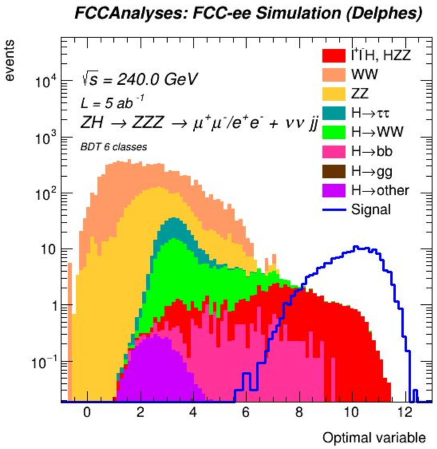
Z(ll)Z(vv)Z*(jj)



Z(ll)Z(jj)Z*(vv)



Z(vv)Z(ll)Z*(jj)



Fits and combination

Z(ll)Z(vv)Z*(jj)

$\sim 7.4\%$

Z(ll)Z(jj)Z*(vv)

$\sim 10.7\%$

Z(vv)Z(ll)Z*(jj)

$\sim 6.9\%$

Fit results *(uncertainty on H(ZZ*) cross section)*

COMBINE

$$r = 1 \pm 0.046$$

Final result for the width uncertainty using BDT:

$$\frac{\delta\sigma_{ZH(ZZ^*)}}{\sigma_{ZH(ZZ^*)}} \sim \frac{\delta\Gamma_H}{\Gamma_H} \sim 4.6\%$$

Cut-based analysis

$\sim 6.6\%$

30% better with BDT!

Included systematics :

- H(WW*) normalisation : 5%
- ZZ normalisation : 10%

04

Impact of systematics

Influence of background normalisation

Leptonic (4l) channels

Included systematics :

- For jjllll and lljjll only: H(qq) normalisation 10%
- ZZ normalisation : 10%

Channel	δ_μ^{stat}	δ_μ^{tot}
$Z_1(ll)Z_2(ll)Z_3(jj)$	$+0.191$ -0.173	$+0.193$ -0.176
$Z_1(ll)Z_2(jj)Z_3(ll)$	$+0.191$ -0.173	$+0.193$ -0.174
$Z_1(jj)Z_2(ll)Z_3(ll)$	$+0.186$ -0.168	$+0.187$ -0.168
$Z_1(\nu\nu)Z_2(ll)Z_3(ll)$	$+0.393$ -0.327	$+0.394$ -0.329
Combination	$+0.103$ -0.097	$+0.104$ -0.098

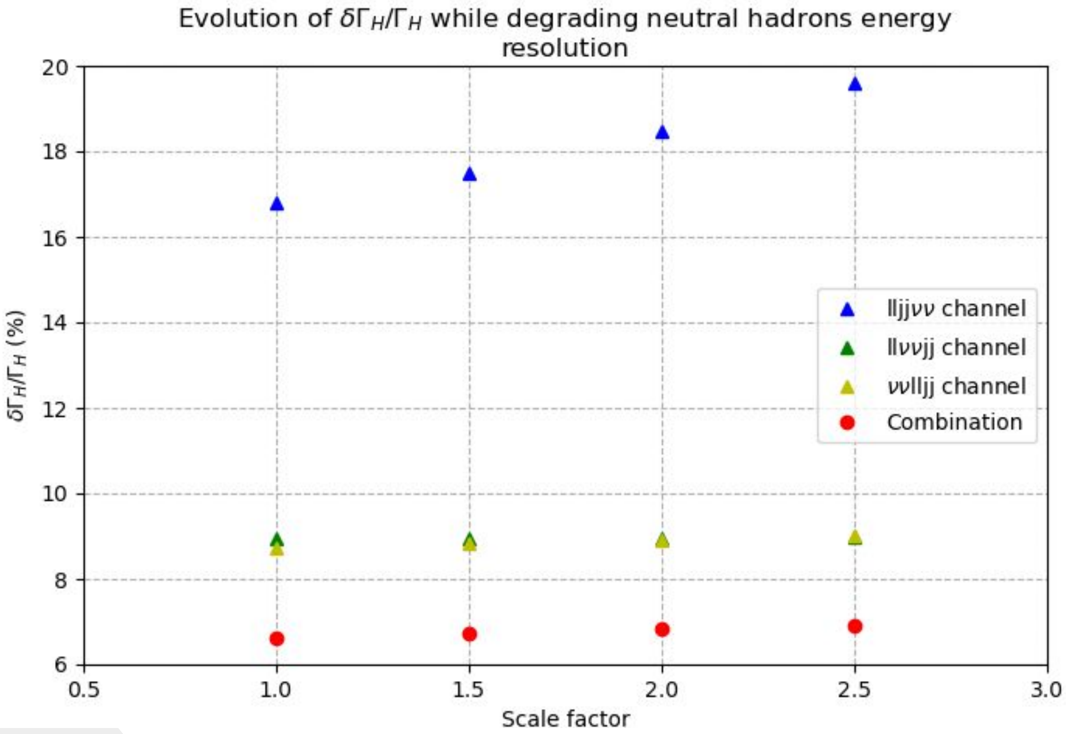
Mixed channels

Uncertainty in $\Gamma_H(\%)$	
Total	4.6%
Statistics	4.5%
H(WW*) normalisation (5%)	0.8%
ZZ normalisation (10%)	0.2%
WW normalisation (10%)	0.1%

In both studies, uncertainties dominated by **statistics**

Influence of neutral hadron energy resolution

Study on mixed channels containing one pair of jets -> **expecting similar** behavior **for 4-leptons** channels since at most one jet pair too

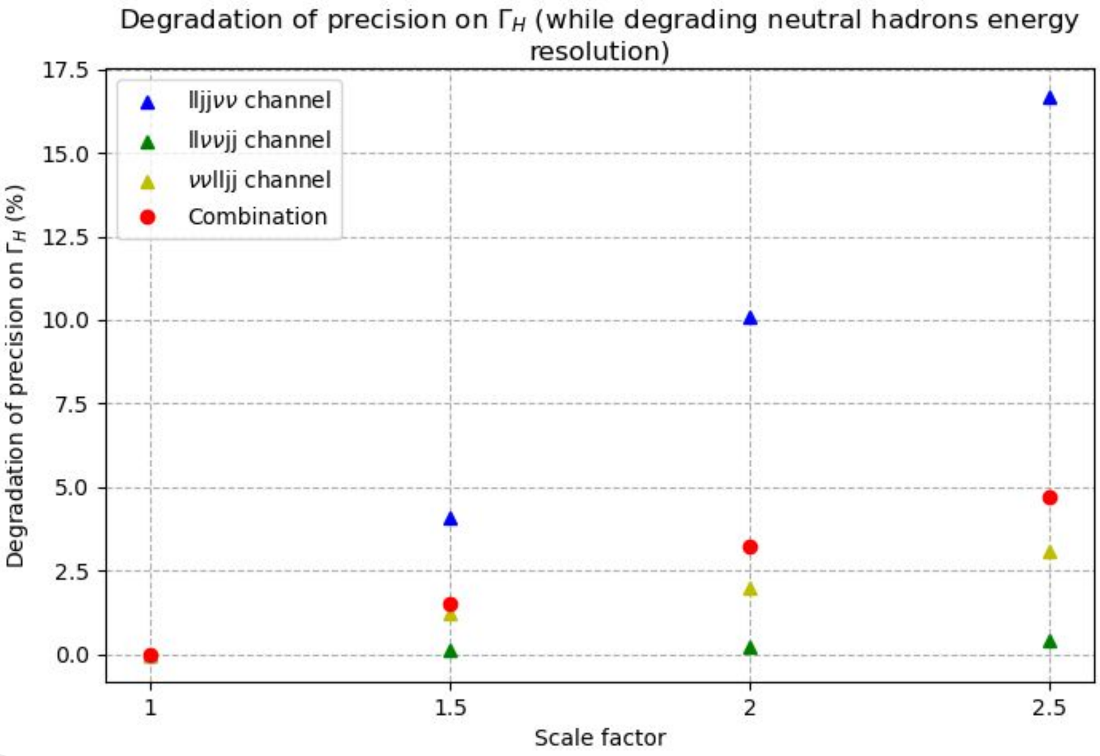


IDEA concept detector

Neutral hadron energy resolution : $\frac{30\%}{\sqrt{E}}$

Small influence of degradation on Higgs' width uncertainty ! (combination, red dots)

Influence of neutral hadron energy resolution



Loss of 5% in precision for the combination for a scale factor of 2.5

↓

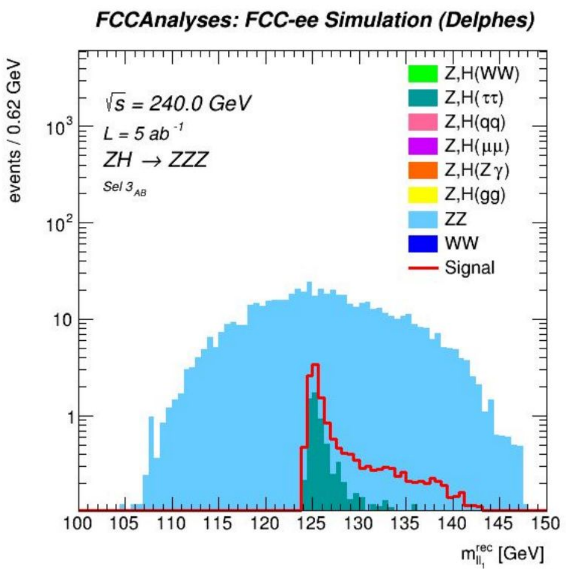
Neutral hadron energy resolution does **not** have **a big effect on Higgs' width measurement !**

05

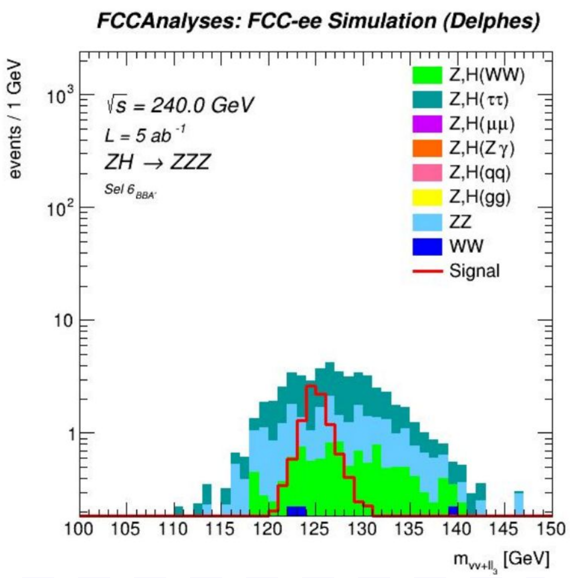
Encountered challenges

Encountered difficulties in 4l channels

Z(ll)Z(ll)Z*(vv)



Z(ll)Z(vv)Z*(ll)



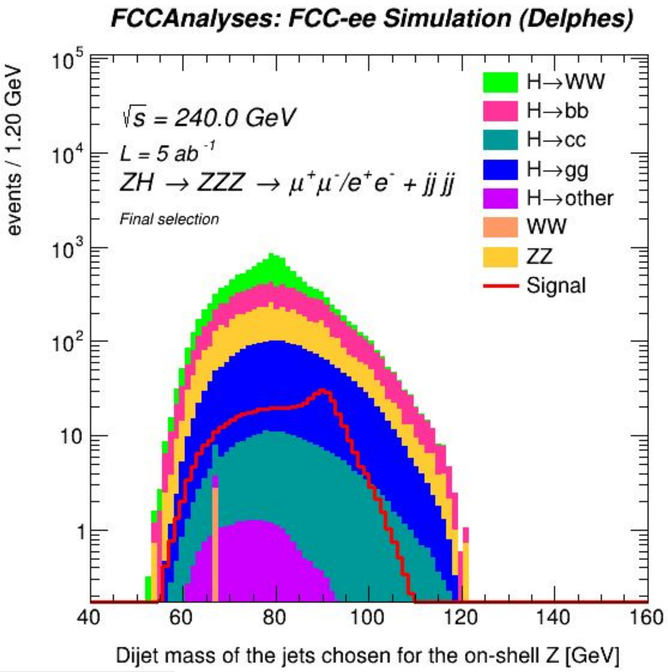
S/B not as good as the 4 other 4l channels

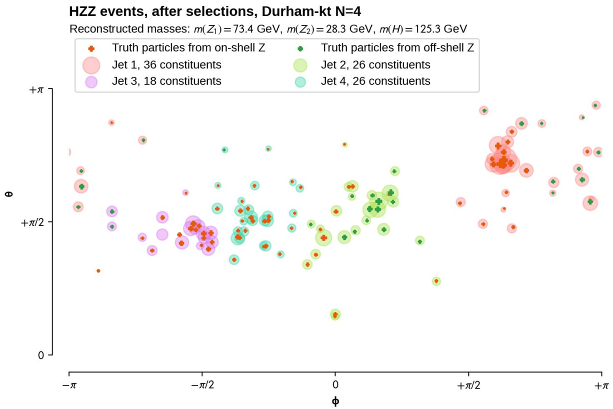
=> Contamination mostly coming from ZZ and ZH,H->tautau

- Tau tagging would help reduce the H->tautau background
- Use of a BDT could give a good separation as it is seen in the 4j channel (next slides)

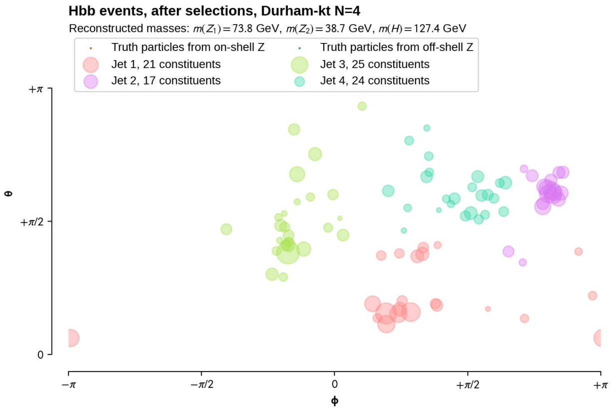
Encountered difficulties in a 4j channel: Z(ll)Z(jj)Z*(jj)

Difficult to reach a good S/B with kinematic selections for this channel



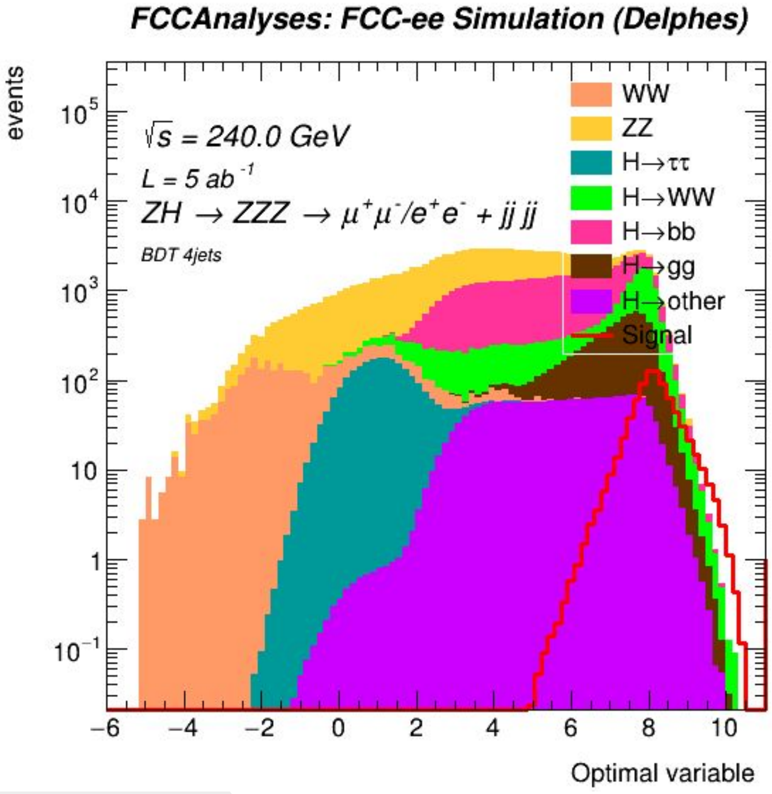


Confusion between components during jet reconstruction for signal



H(bb) events with **4-jets topology**, irreducible background

Encountered difficulties in a 4j channel: Z(ll)Z(jj)Z*(jj)



With a BDT analysis:

Fit results *(uncertainty on H(ZZ*) cross section)*

COMBINE

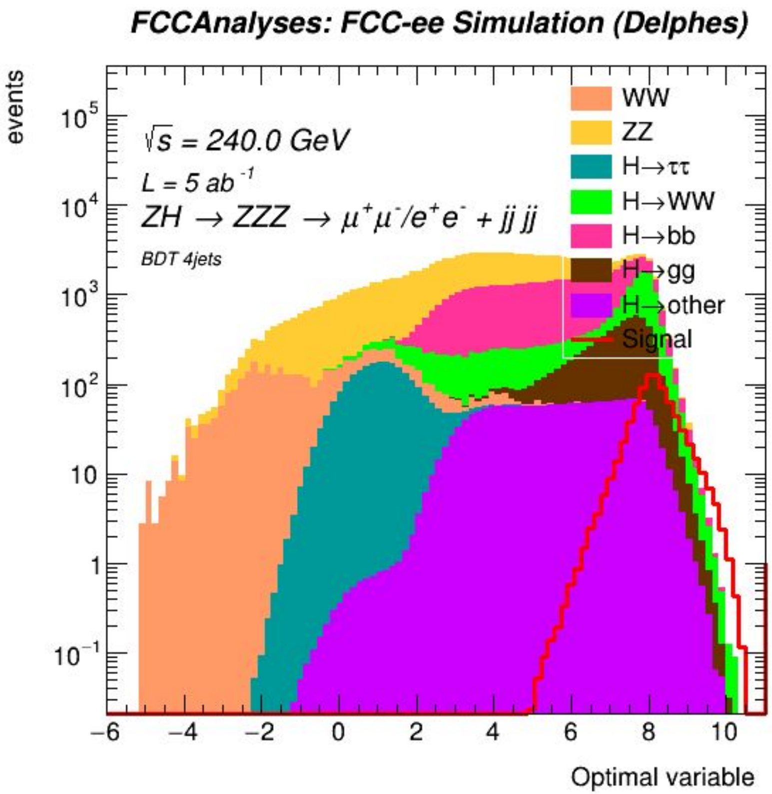
$$r = 1 \pm 0.124$$

$\sim 12.4\%$ uncertainty

=> Even if there is confusion, still a good channel that could give a contribution of the **same order** of the 4-leptons one to a full **combination**!

Would still benefit from **flavour tagging** for reducing H->bb and tau tagging for H->tautau

Encountered difficulties in a 4j channel: Z(ll)Z(jj)Z*(jj)



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COMBINE

$$r = 1 \pm 0.124$$

$$\sim 12.4\% \text{ uncertainty}$$

An interesting other 4j channel could be **Z(jj)Z(jj)Z*(ll)** where the 4 jets come from on-shell Z => more collimated so less confusion would be expected between the components!

Conclusion

- Higgs width uncertainty estimation : **10.1 %** for 4-leptons channels.
- Higgs width uncertainty estimation : **4.6 %** for mixed channels using BDT.
- Overall, **4%** is easily reachable (naive combination)!
- **Low** impact of **neutral hadron energy resolution** on Higgs' width measurement (analysis without BDT)
- **Low** impact of **background normalisation systematics** on Higgs' width measurement
- ***Ongoing***: **4-leptons** channels in the group in Bari!

*What could be coming **next** ?*

- Combining them all
- Adding other mixed channel, 4j, or others!
- Implementing BDT for 4l channels, especially for the ones not used yet in the combination
- Flavour tagging implementation to reduce H->qq backgrounds
- Tau tagging implementation to reduce H->tautau background

Conclusion

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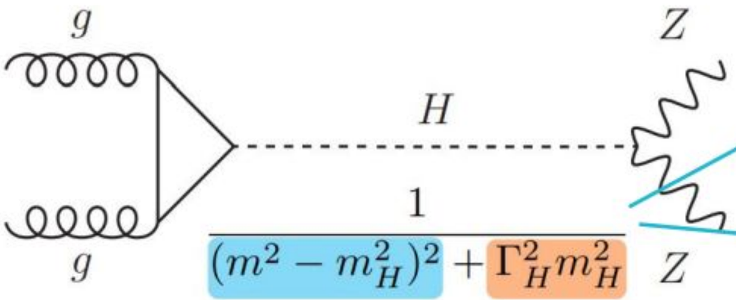
- Flavour tagging implementation to reduce H->qq backgrounds
- Tau tagging implementation to reduce H->tautau background

A sensitivity of around 1-2% seems at reach combining these efforts and new ideas!

Backup

Measurement method of the width at the LHC

- Indirect measurement at the LHC: off-shell Higgs production
  - Assumptions ! No Q^2 dependence of the Higgs couplings, as in the SM



$$\frac{1}{(m^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}$$

$$\sigma^{\text{on-shell}}_{vv\to H\to 4\ell} \propto \frac{g^2_{\text{gluon}} g^2_V}{\Gamma_H}$$

$$\sigma^{\text{off-shell}}_{vv\to H\to 4\ell} \propto g^2_{\text{gluon}} g^2_V$$

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma}{\Gamma_{\text{SM}}}$$

~2.5 MeV precision !

From Nicolas Morange's slides

Backup for 4l channels

Common selections for Z(ll)Z(ll)Z*(xx) (2 on-shell Zs)

	Signal	Background							
Selection	$Z,H(ZZ^*)$	$Z,H(WW)$	$Z,H(\mu\mu)$	$Z,H(qq)$	$Z,H(\tau\tau)$	$Z,H(Z\gamma)$	$Z,H(gg)$	ZZ	WW
Two $Z(ll)$ & no $Z^*(ll)$ (Sel 0_A)	113.6 ±0.5	181 ±2	7.56 ±0.01	25 ±1	59.4 ±0.6	5.76 ±0.03	0.007 ±0.007	12196 ±38	47 ±3
Sel 0_A + $m_{ll_{1,2}} \in [80, 110]$ GeV (Sel 1_A)	65.2 ±0.4	1.0 ±0.1	0.538 ±0.003	0 $\pm\delta < 1$	8.7 ±0.2	4.63 ±0.02	0 $\pm\delta < 0.007$	6286 ±28	0 $\pm\delta < 3$
Sel 1_A + $E^{\text{miss}} < 8$ GeV (Sel 2_{AA})	46.1 ±0.3	0.02 ±0.02	0.498 ±0.003	0 $\pm\delta < 1$	0.52 ±0.05	4.34 ±0.02	0 $\pm\delta < 0.007$	4817 ±24	0 $\pm\delta < 3$
Sel 1_A + $E^{\text{miss}} > 8$ GeV (Sel 2_{AB})	19.1 ±0.2	1.0 ±0.1	0.0399 ±0.0009	0 $\pm\delta < 1$	8.2 ±0.2	0.289 ±0.006	0 $\pm\delta < 0.007$	1468 ±13	0 $\pm\delta < 3$

Cutflow for Z(ll)Z(ll)Z*(jj)

	Signal	Background							
Selection	$Z, H(ZZ^*)$	$Z, H(WW)$	$Z, H(\mu\mu)$	$Z, H(qq)$	$Z, H(\tau\tau)$	$Z, H(Z\gamma)$	$Z, H(gg)$	ZZ	WW
Two $Z(ll)$ & no $Z^*(ll)$ (Sel 0_A)	113.6 ± 0.5	181 ± 2	7.56 ± 0.01	25 ± 1	59.4 ± 0.6	5.76 ± 0.03	0.007 ± 0.007	12196 ± 38	47 ± 3
Sel 0_A + $m_{ll_{1,2}} \in [80, 110]$ GeV (Sel 1_A)	65.2 ± 0.4	1.0 ± 0.1	0.538 ± 0.003	0 $\pm\delta < 1$	8.7 ± 0.2	4.63 ± 0.02	0 $\pm\delta < 0.007$	6286 ± 28	0 $\pm\delta < 3$
Sel 1_A + $E^{\text{miss}} < 8$ GeV (Sel 2_{AA})	46.1 ± 0.3	0.02 ± 0.02	0.498 ± 0.003	0 $\pm\delta < 1$	0.52 ± 0.05	4.34 ± 0.02	0 $\pm\delta < 0.007$	4817 ± 24	0 $\pm\delta < 3$
Sel 1_A + $E^{\text{miss}} > 8$ GeV (Sel 2_{AB})	19.1 ± 0.2	1.0 ± 0.1	0.0399 $\pm$0.00[illegible]	0 $\pm\delta < 1$	8.2 ± 0.2	0.289 ± 0.006	0 $\pm\delta < 0.007$	1468 ± 13	0 $\pm\delta < 3$
Sel 2_{AA} + $E^{\gamma} < 20$ GeV (Sel 3_{AA})	45.1 ± 0.3	0.02 ± 0.02	0.204 ± 0.002	0 $\pm < 1$	0.43 ± 0.05	0.135 ± 0.004	0 $\pm\delta < 0.007$	3539 ± 21	0 $\delta < 3$
Sel 3_{AA} + $m^{\text{rec}}_{ll_2+\gamma} > 115$ GeV (Sel 4_{AA})	41.3 ± 0.3	0.02 ± 0.02	0.0160 ± 0.0005	0 $\pm\delta < 1$	0.32 ± 0.04	0.030 ± 0.002	0 $\pm\delta < 0.007$	29 ± 2	0 $\pm\delta < 3$

Cutflow for Z(ll)Z(ll)Z*(vv)

Selection	Signal	Background							
	$Z,H(ZZ^*)$	$Z,H(WW)$	$Z,H(\mu\mu)$	$Z,H(qq)$	$Z,H(\tau\tau)$	$Z,H(Z\gamma)$	$Z,H(gg)$	ZZ	WW
Two $Z(ll)$ & no $Z^*(ll)$ (Sel 0_A)	113.6 ±0.5	181 ±2	7.56 ±0.01	25 ±1	59.4 ±0.6	5.76 ±0.03	0.007 ±0.007	12196 ±38	47 ±3
Sel 0_A + $m_{ll_{1,2}} \in [80, 110]$ GeV (Sel 1_A)	65.2 ±0.4	1.0 ±0.1	0.538 ±0.003	0 $\pm\delta < 1$	8.7 ±0.2	4.63 ±0.02	0 $\pm\delta < 0.007$	6286 ±28	0 $\pm\delta < 3$
Sel 1_A + $E^{\text{miss}} < 8$ GeV (Sel 2_{AA})	46.1 ±0.3	0.02 ±0.02	0.498 ±0.003	0 $\pm\delta < 1$	0.52 ±0.05	4.34 ±0.02	0 $\pm\delta < 0.007$	4817 ±24	0 $\pm\delta < 3$
Sel 1_A + $E^{\text{miss}} > 8$ GeV (Sel 2_{AB})	19.1 ±0.2	1.0 ±0.1	0.0399 ±0.0009	0 $\pm\delta < 1$	8.2 ±0.2	0.289 ±0.006	0 $\pm\delta < 0.007$	1468 ±13	0 $\pm\delta < 3$
Sel 2_{AB} + $m^{\text{rec}}_{ll_2} \in [125, 150]$ GeV (Sel 3_{AB})	16.1 ±0.2	0.7 ±0.1	0.0267 ±0.0007	0 $\pm\delta < 1$	6.8 ±0.2	0.264 ±0.006	0 $\pm\delta < 0.007$	577 ±8	0 $\pm\delta < 3$

Common selections for Z(ll)Z(xx)Z*(ll) or Z(xx)Z(ll)Z*(ll) *(1 on-shell Z, 1 off-shell Z)*

	Signal	Background							
Selection	$Z, H(ZZ^*)$	$Z, H(WW)$	$Z, H(\mu\mu)$	$Z, H(qq)$	$Z, H(\tau\tau)$	$Z, H(Z\gamma)$	$Z, H(gg)$	ZZ	WW
One $Z(ll)$ & one $Z^*(ll)$ (Sel 0_B)	206.8 ±0.8	270 ±2	5.97 ±0.01	951 ±7	130.5 ±0.8	1.17 ±0.01	5.1 ±0.2	28340 ±59	846 ±14
Sel 0_B + $m_{ll} \in [80, 110]$ GeV (Sel 1_B)	173.4 ±0.7	246 ±2	5.27 ±0.01	866 ±6	118.6 ±0.8	1.06 ±0.01	4.7 ±0.2	15680 ±44	257 ±8
Sel 1_B + $m_{ll_3} \in [10, 40]$ GeV (Sel 2_B)	158.2 ±0.7	187 ±2	0.0288 ±0.0007	462 ±4	76.4 ±0.6	0.337 ±0.007	0.77 ±0.07	3097 ±19	12 ±2
Sel 2_B + $E^{\text{miss}} < 8$ GeV (Sel 3_{BA})	96.4 ±0.5	1.4 ±0.2	0.0268 ±0.0007	155 ±2	0.19 ±0.03	0.152 ±0.005	0.32 ±0.05	1412 ±13	0 $\pm\delta < 2$
Sel 2_B + $E^{\text{miss}} > 8$ GeV (Sel 3_{BB})	61.8 ±0.4	186 ±2	0.0020 ±0.0002	307 ±4	76.2 ±0.6	0.185 ±0.005	0.45 ±0.06	1685 ±14	12 ±2

Cutflow for Z(ll)Z(jj)Z*(ll)

	Signal	Background							
Selection	$Z, H(ZZ^*)$	$Z, H(WW)$	$Z, H(\mu\mu)$	$Z, H(qq)$	$Z, H(\tau\tau)$	$Z, H(Z\gamma)$	$Z, H(gg)$	ZZ	WW
One $Z(ll)$ & one $Z^*(ll)$ (Sel 0_B)	206.8 $\pm$0.8	270 $\pm$2	5.97 $\pm$0.01	951 $\pm$7	130.5 $\pm$0.8	1.17 $\pm$0.01	5.1 $\pm$0.2	28340 $\pm$59	846 $\pm$14
Sel 0_B + $m_{ll} \in [80, 110]$ GeV (Sel 1_B)	173.4 $\pm$0.7	246 $\pm$2	5.27 $\pm$0.01	866 $\pm$6	118.6 $\pm$0.8	1.06 $\pm$0.01	4.7 $\pm$0.2	15680 $\pm$44	257 $\pm$8
Sel 1_B + $m_{ll_3} \in [10, 40]$ GeV (Sel 2_B)	158.2 $\pm$0.7	187 $\pm$2	0.0288 $\pm$0.0007	462 $\pm$4	76.4 $\pm$0.6	0.337 $\pm$0.007	0.77 $\pm$0.07	3097 $\pm$19	12 $\pm$2
Sel 2_B + $E^{\text{miss}} < 8$ GeV (Sel 3_{BA})	96.4 $\pm$0.5	1.4 $\pm$0.2	0.0268 $\pm$0.0007	155 $\pm$2	0.19 $\pm$0.03	0.152 $\pm$0.005	0.32 $\pm$0.05	1412 $\pm$13	0 $\pm\delta < 2$
Sel 2_B + $E^{\text{miss}} > 8$ GeV (Sel 3_{BB})	61.8 $\pm$0.4	186 $\pm$2	0.0020 $\pm$0.00[illegible]	307 $\pm$4	76.2 $\pm$0.6	0.185 $\pm$0.005	0.45 $\pm$0.06	1685 $\pm$14	12 $\pm$2
Sel 3_{BA} + $\Delta > 0$ (Sel 4_{BAA})	51.5 $\pm$0.4	1.3 $\pm$0.2	0.0248 $\pm$0.0007	137 $\pm$2	0.19 $\pm$0.03	0.127 $\pm$0.004	0.21 $\pm$0.04	741 $\pm$9	0 $\pm\delta < 2$
Sel 4_{BAA} + $m_{jj} \in [80, 110]$ GeV (Sel 5_{BAA})	44.8 $\pm$0.3	0.30 $\pm$0.07	0.0005 $\pm$0.0001	101 $\pm$2	0.011 $\pm$0.008	0.064 $\pm$0.003	0.20 $\pm$0.04	23 $\pm$2	0 $\pm\delta < 2$
Sel 5_{BAA} + $m^{\text{rec}}_{ll_3} \in [190, 215]$ GeV (Sel 6_{BAA})	40.6 $\pm$0.3	0.07 $\pm$0.04	0.0005 $\pm$0.0001	40 $\pm$1	0.005 $\pm$0.005	0.024 $\pm$0.002	0.04 $\pm$0.02	10 $\pm$1	0 $\pm\delta < 2$
Sel 6_{BAA} + $m^{\text{rec}}_{jj+ll_3} \in [80, 110]$ GeV (Sel 7_{BAA})	40.1 $\pm$0.3	0.07 $\pm$0.03	0.0005 $\pm$0.0001	34 $\pm$1	0.005 $\pm$0.005	0.022 $\pm$0.002	0.04 $\pm$0.02	8 $\pm$1	0 $\pm\delta < 2$

Cutflow for Z(jj)Z(ll)Z*(ll)

	Signal	Background							
Selection	$Z,H(ZZ^*)$	$Z,H(WW)$	$Z,H(\mu\mu)$	$Z,H(qq)$	$Z,H(\tau\tau)$	$Z,H(Z\gamma)$	$Z,H(gg)$	ZZ	WW
One $Z(ll)$ & one $Z^*(ll)$ (Sel 0_B)	206.8 $\pm$0.8	270 $\pm$2	5.97 $\pm$0.01	951 $\pm$7	130.5 $\pm$0.8	1.17 $\pm$0.01	5.1 $\pm$0.2	28340 $\pm$59	846 $\pm$14
Sel 0_B + $m_{ll} \in [80, 110]$ GeV (Sel 1_B)	173.4 $\pm$0.7	246 $\pm$2	5.27 $\pm$0.01	866 $\pm$6	118.6 $\pm$0.8	1.06 $\pm$0.01	4.7 $\pm$0.2	15680 $\pm$44	257 $\pm$8
Sel 1_B + $m_{ll_3} \in [10, 40]$ GeV (Sel 2_B)	158.2 $\pm$0.7	187 $\pm$2	0.0288 $\pm$0.0007	462 $\pm$4	76.4 $\pm$0.6	0.337 $\pm$0.007	0.77 $\pm$0.07	3097 $\pm$19	12 $\pm$2
Sel 2_B + $E^{\text{miss}} < 8$ GeV (Sel 3_{BA})	96.4 $\pm$0.5	1.4 $\pm$0.2	0.0268 $\pm$0.0007	155 $\pm$2	0.19 $\pm$0.03	0.152 $\pm$0.005	0.32 $\pm$0.05	1412 $\pm$13	0 $\pm\delta < 2$
Sel 2_B + $E^{\text{miss}} > 8$ GeV (Sel 3_{BB})	61.8 $\pm$0.4	186 $\pm$2	0.0020 $\pm$0.[illegible]	307 $\pm$4	76.2 $\pm$0.6	0.185 $\pm$0.005	0.45 $\pm$0.06	1685 $\pm$14	12 $\pm$2
Sel 3_{BA} + $\Delta < 0$ (Sel 4_{BAB})	44.9 $\pm$0.4	0.11 $\pm$0.05	0.0020 $\pm$0.0002	18.3 $\pm$0.8	0 $\pm\delta < 0.03$	0.024 $\pm$0.002	0.11 $\pm$0.03	663 $\pm$9	0 $\pm\delta < 2$
Sel 4_{BAB} + $m_{jj} \in [80, 110]$ GeV (Sel 5_{BAB})	42.4 $\pm$0.4	0.11 $\pm$0.05	2.8 10^{-4} $\pm$0.8 10^{-4}	16.0 $\pm$0.8	0 $\pm\delta < 0.03$	0.017 $\pm$0.002	0.09 $\pm$0.03	87 $\pm$3	0 $\pm\delta < 2$
Sel 5_{BAB} + $m^{\text{rec}}_{ll_3} \in [195, 215]$ GeV (Sel 6_{BAB})	38.3 $\pm$0.4	0.02 $\pm$0.02	1.2 10^{-4} $\pm$0.5 10^{-4}	4.4 $\pm$0.4	0 $\pm\delta < 0.03$	0.006 $\pm$0.001	0.02 $\pm$0.01	9 $\pm$1	0 $\pm\delta < 2$

Cutflow for Z(ll)Z(vv)Z*(ll)

	Signal	Background							
Selection	$Z, H(ZZ^*)$	$Z, H(WW)$	$Z, H(\mu\mu)$	$Z, H(qq)$	$Z, H(\tau\tau)$	$Z, H(Z\gamma)$	$Z, H(gg)$	ZZ	WW
One $Z(ll)$ & one $Z^*(ll)$ (Sel 0_B)	206.8 $\pm$0.8	270 $\pm$2	5.97 $\pm$0.01	951 $\pm$7	130.5 $\pm$0.8	1.17 $\pm$0.01	5.1 $\pm$0.2	28340 $\pm$59	846 $\pm$14
Sel 0_B + $m_{ll} \in [80, 110]$ GeV (Sel 1_B)	173.4 $\pm$0.7	246 $\pm$2	5.27 $\pm$0.01	866 $\pm$6	118.6 $\pm$0.8	1.06 $\pm$0.01	4.7 $\pm$0.2	15680 $\pm$44	257 $\pm$8
Sel 1_B + $m_{ll_3} \in [10, 40]$ GeV (Sel 2_B)	158.2 $\pm$0.7	187 $\pm$2	0.0288 $\pm$0.0007	462 $\pm$4	76.4 $\pm$0.6	0.337 $\pm$0.007	0.77 $\pm$0.07	3097 $\pm$19	12 $\pm$2
Sel 2_B + $E^{\text{miss}} < 8$ GeV (Sel 3_{BA})	96.4 $\pm$0.5	1.4 $\pm$0.2	0.0268 $\pm$0.0007	155 $\pm$2	0.19 $\pm$0.03	0.152 $\pm$0.005	0.32 $\pm$0.05	1412 $\pm$13	0 $\pm\delta < 2$
Sel 2_B + $E^{\text{miss}} > 8$ GeV (Sel 3_{BB})	61.8 $\pm$0.4	186 $\pm$2	0.0020 $\pm$0.0002	307 $\pm$4	76.2 $\pm$0.6	0.185 $\pm$0.005	0.45 $\pm$0.06	1685 $\pm$14	12 $\pm$2

+

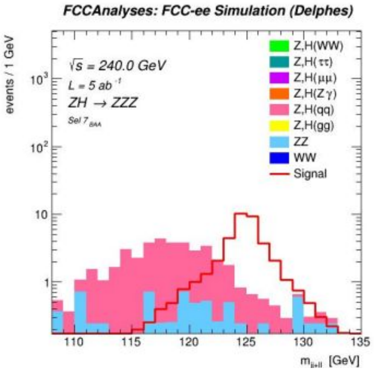
Sel 3_{BB} + $m_{ll}^{\text{rec}} \in [123, 127]$ GeV (Sel 4_{BBA})	20.3 $\pm$0.42	119 $\pm$1	$2\ 10^{-5}$ $\pm 2\ 10^{-5}$	195 $\pm$3	49.0 $\pm$0.5	0.114 $\pm$0.004	0.29 $\pm$0.05	84 $\pm$3	1.1 $\pm$0.5

Cutflow for Z(vv)Z(ll)Z*(ll)

	Signal	Background							
Selection	$Z,H(ZZ^*)$	$Z,H(WW)$	$Z,H(\mu\mu)$	$Z,H(qq)$	$Z,H(\tau\tau)$	$Z,H(Z\gamma)$	$Z,H(gg)$	ZZ	WW
One $Z(ll)$ & one $Z^*(ll)$ (Sel 0_B)	206.8 ±0.8	270 ±2	5.97 ±0.01	951 ±7	130.5 ±0.8	1.17 ±0.01	5.1 ±0.2	28340 ±59	846 ±14
Sel 0_B + $m_{ll} \in [80, 110]$ GeV (Sel 1_B)	173.4 ±0.7	246 ±2	5.27 ±0.01	866 ±6	118.6 ±0.8	1.06 ±0.01	4.7 ±0.2	15680 ±44	257 ±8
Sel 1_B + $m_{ll_3} \in [10, 40]$ GeV (Sel 2_B)	158.2 ±0.7	187 ±2	0.0288 ±0.0007	462 ±4	76.4 ±0.6	0.337 ±0.007	0.77 ±0.07	3097 ±19	12 ±2
Sel 2_B + $E^{\text{miss}} < 8$ GeV (Sel 3_{BA})	96.4 ±0.5	1.4 ±0.2	0.0268 ±0.0007	155 ±2	0.19 ±0.03	0.152 ±0.005	0.32 ±0.05	1412 ±13	0 $\pm\delta < 2$
Sel 2_B + $E^{\text{miss}} > 8$ GeV (Sel 3_{BB})	61.8 ±0.4	186 ±2	0.0020 ±0.0002	307 ±4	76.2 ±0.6	0.185 ±0.005	0.45 ±0.06	1685 ±14	12 ±2
Sel 3_{BB} + $m_{ll}^{\text{rec}} \notin [123, 127]$ GeV (Sel 4_{BBB})	38.1 ±0.4	67 ±1	0.0020 ±0.0002	112 ±2	27.2 ±0.4	0.070 ±0.003	0.16 ±0.03	1601 ±14	11 ±2
Sel 4_{BBB} + $E^{\text{miss}} \in [45, 55]$ GeV (Sel 5_{BBB})	12.3 ±0.2	12.9 ±0.5	0 $\pm\delta < 0.0002$	0.4 ±0.1	4.5 ±0.2	0.0040 ±0.0007	0 $\pm\delta < 0.03$	161 ±4	2.0 ±0.7
Sel 5_{BBB} + $m^{\text{vis}} < 135$ GeV (Sel 6_{BBB})	12.0 ±0.2	2.0 ±0.2	0 $\pm\delta < 0.0002$	0 $\pm\delta < 0.1$	3.1 ±0.1	0.0002 ±0.0001	0 $\pm\delta < 0.03$	13 ±1	0.7 ±0.4

4 clear channels – variables used for their fit

BEFORE SMOOTHING

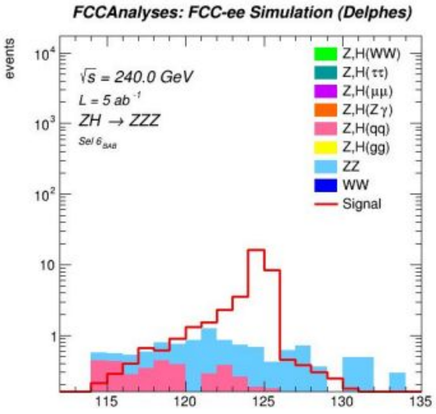


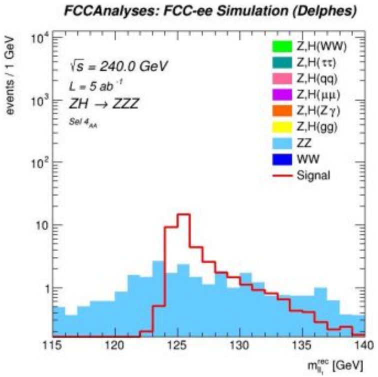
Z(ll)Z(jj)Z*(ll)

Mass of the jet pair and the off-shell Z lepton pair

Mass of the 2 lepton pairs

Z(jj)Z(ll)Z*(ll)



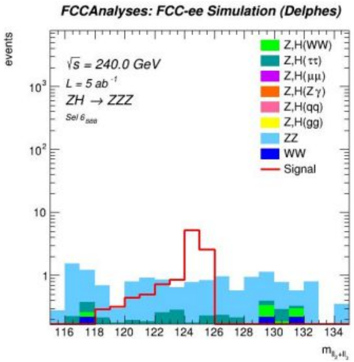


Z(ll)Z(ll)Z*(jj)

Recoil mass of the first Z lepton pair

Mass of the 2 lepton pairs

Z(vv)Z(ll)Z*(ll)



Smoothing is used to reduce statistical fluctuations of some backgrounds

Backup for mixed channels

3 mixed channels - BDT Preselections

Preselections before BDT:

Z(ll)Z(vv)Z*(jj)

- $55 < m_{ll} < 115\,\mathrm{GeV}$
- $120 < m_{\mathrm{rec}} < 130\,\mathrm{GeV}$
- $10 < m_{jj} < 60\,\mathrm{GeV}$
- $\mathrm{E}^{\mathrm{miss}} < 80\,\mathrm{GeV}$

Z(ll)Z(jj)Z*(vv)

- $55 < m_{ll} < 115\,\mathrm{GeV}$
- $120 < m_{\mathrm{rec}} < 170\,\mathrm{GeV}$
- $60 < m_{jj} < 120\,\mathrm{GeV}$
- $\mathrm{E}^{\mathrm{miss}} < 76\,\mathrm{GeV}$

Z(vv)Z(ll)Z*(jj)

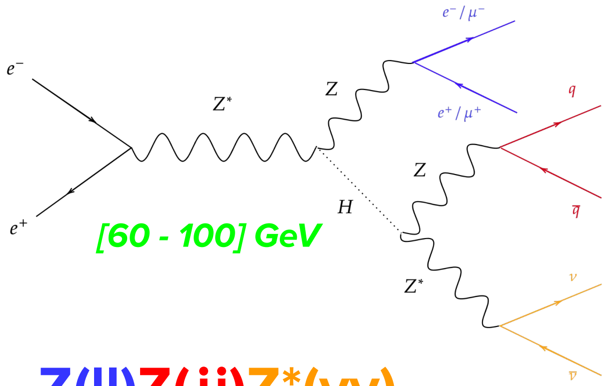
- $40 < m_{ll} < 100\,\mathrm{GeV}$
- $m_{\mathrm{rec}} > 130\,\mathrm{GeV}$
- $10 < m_{jj} < 60\,\mathrm{GeV}$
- $100 < m_{\mathrm{visible}} < 150\,\mathrm{GeV}$

Boosted decision tree classification:

- Trained on 6 classes (signal, ZZ, WW, ZH(WW), ZH(bb), ZH(tautau))
- Variables shown on the diagram on the right
- Output: optimal variables for S and B separation (likelihood ratio)

Orthogonality of selections for mixed channels

(for both cut-based and BDT analyses)

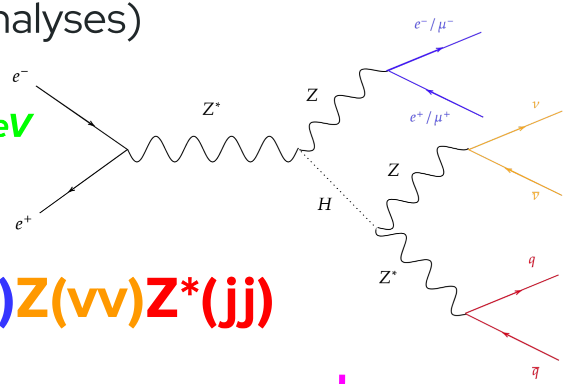


[60 - 100] GeV

Z(ll)Z(jj)Z*(vv)

Dijet mass

[10 - 45] GeV



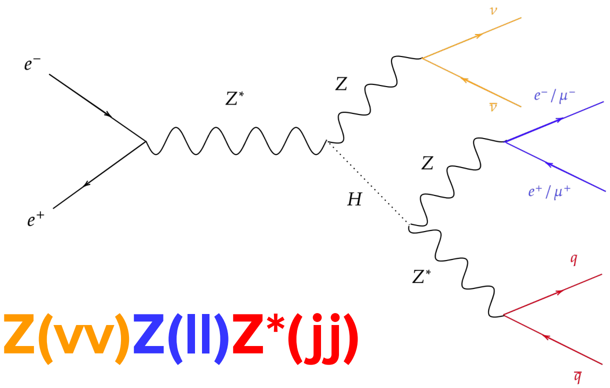
Z(ll)Z(vv)Z*(jj)

[123 - 130] GeV

Leptonic recoil mass

Dijet mass

[10 - 60] GeV



Z(vv)Z(ll)Z*(jj)

> 130 GeV

BDT Final output

Optimal variable to separate signal and background

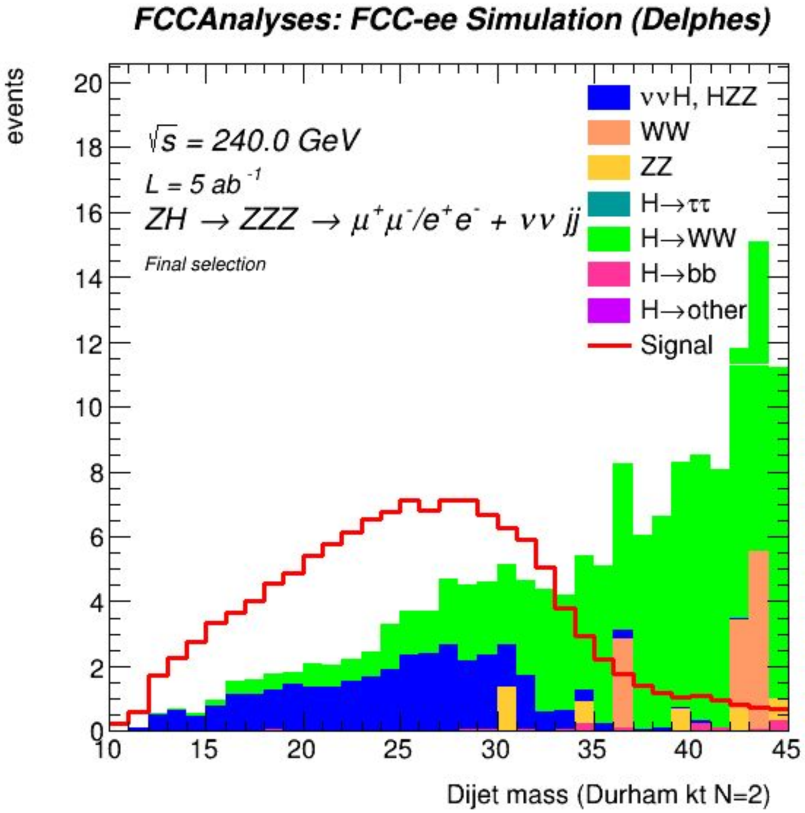
$$\frac{\mathrm{p_s}}{\sum_\mathrm{b} \mathrm{p_b}}$$

Combination of the BDT evaluated scores to obtain the optimal variable

BDT Final output

$$\log_{10}\left(\frac{\mathrm{p_s^{raw}}}{\sum_\mathrm{b} \frac{\sigma_\mathrm{b}\mathrm{p_b^{raw}}}{\mathrm{N_b^{raw}}}}\right)$$

ZH, Z(ll)Z(vv)Z*(jj) - Fit on dijet mass



Fit results *(uncertainty on H(ZZ*) cross section)*

COMBINE

$$r = 1 \pm 0.090$$

$\sim 9\%$ uncertainty

Included systematics :

- H(WW*) normalisation : 5%
- ZZ normalisation : 10%

ZH, Z(ll)Z(vv)Z*(jj) - Selections for cut-based

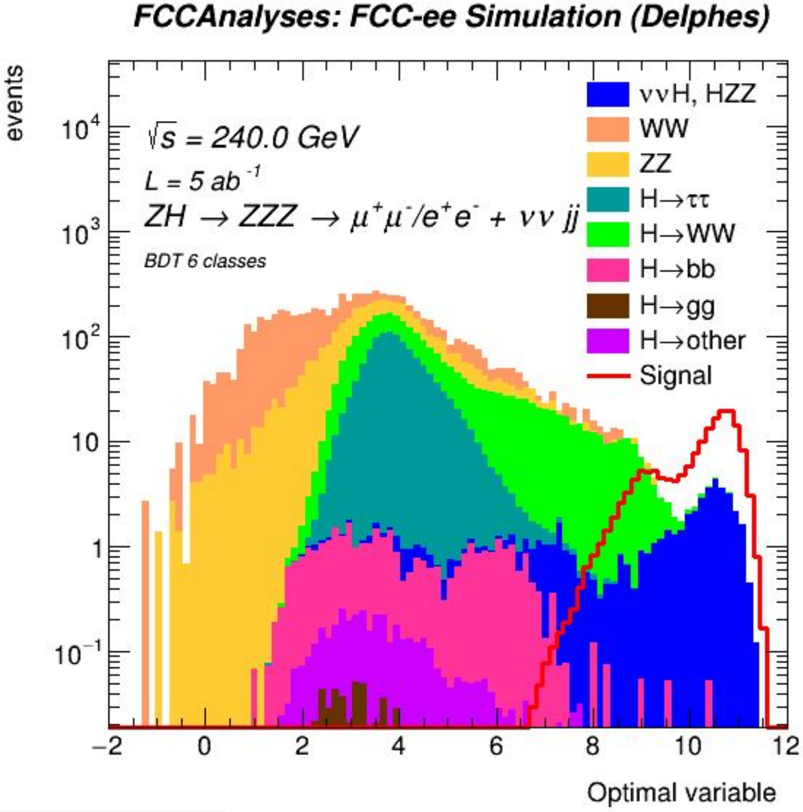
Number of events for L = $5ab^{-1}$							
Selection	H(ZZ)	ZZ	WW	H(WW)	H(bb)	H($\tau\tau$)	H(other)
No cut (one Z(ll))	229	450664	84592	13270	36466	3674	7114
$N_{\text{selected leptons}} = 2$	229	427481	84037	9942	34808	2806	7086
$70 < m_{ll} < 105$ GeV	221	303820	34760	9528	33580	2695	6842
$123 < m_{rec} < 130$ GeV	168	16552	5088	7204	25497	2023	5186
$N^{mean}_{\text{jet const Durham N=2}} > 7$	155	14955	1065	6930	25497	1	5127
$10 < m_{jj} < 45$ GeV	145	218	46	176	4	0	0
$E_T^{miss} > 8$ GeV	141	12	43	170	1	0	0
$p_{jj} < 40$ GeV	129	4	10	106	1	0	0

Most reduced background(s)

$$S = 129 \qquad \frac{S}{\sqrt{B}} \sim 11.7 \qquad \frac{S}{B} \sim 1.06$$

$$S_{\text{efficiency}} \sim 0.56$$
$$B_{\text{efficiency}} \sim 2.0\ 10^{-4}$$

ZH, Z(ll)Z(vv)Z*(jj) - Fit on BDT output



Fit results *(uncertainty on H(ZZ*) cross section)*

COMBINE

$$r = 1 \pm 0.074$$

$\sim 7.4\%$ uncertainty

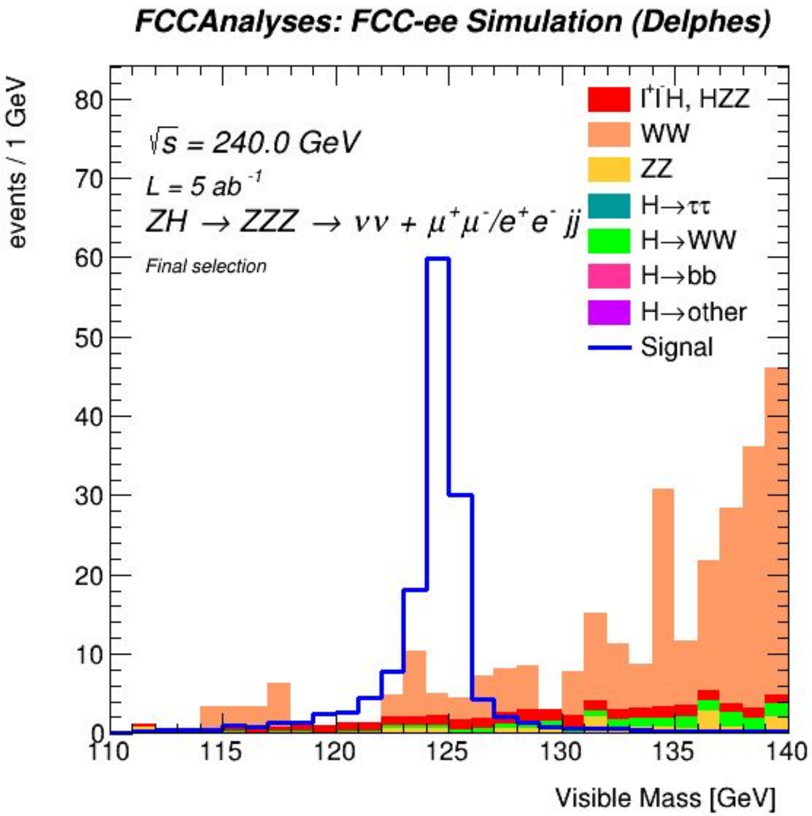
Cut-based

$\sim 9\%$

Included systematics :

- H(WW*) normalisation : 5%
- ZZ normalisation : 10%

ZH, Z(vv)Z(ll)Z*(jj) - Fit on visible mass



Fit results *(uncertainty on H(ZZ*) cross section)*

COMBINE

$$r = 1 \pm 0.087$$

$\sim 8.7\%$ uncertainty

Included systematics :

- H(WW*) normalisation : 5%
- ZZ normalisation : 10%

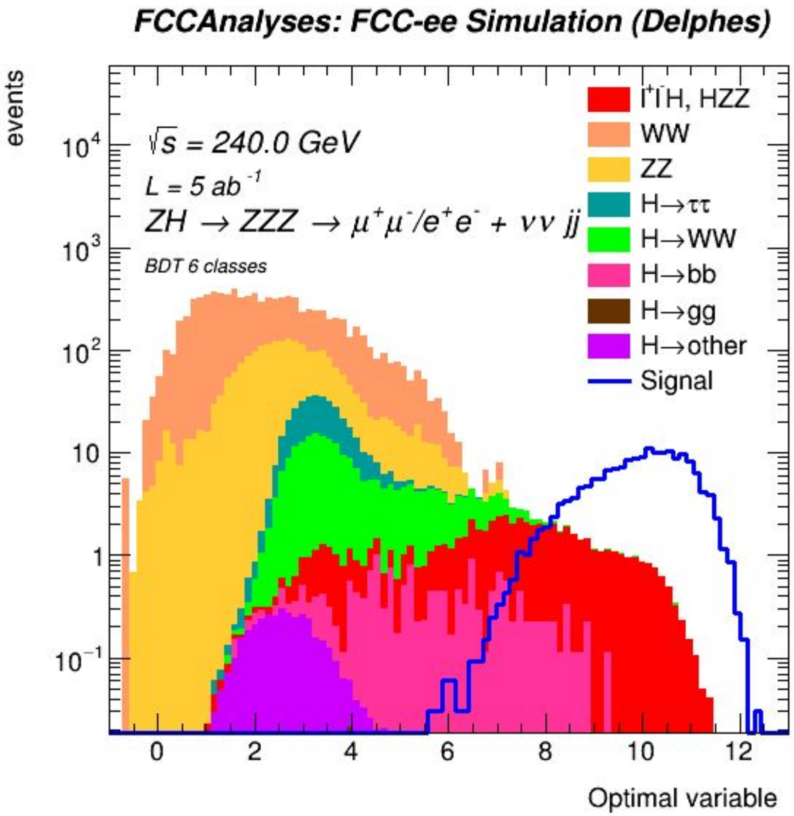
ZH, Z(vv)Z(ll)Z*(jj) - Selections for cut-based

Number of events for L = 5ab^{-1}							
Selection	H(ZZ)	ZZ	WW	H(WW)	H(bb)	H($\tau\tau$)	H(other)
No cut (one Z(ll))	245	450664	84592	13270	36466	3674	7114
$N_{\text{selected leptons}} = 2$	245	427481	84037	9942	34808	2806	7086
$25 < E^{miss} < 75$ GeV	236	51853	62778	2424	2074	1678	84
$110 < m_{vis} < 140$ GeV	234	3170	19185	235	235	360	8
$10 < m_{jj} < 60$ GeV	232	2254	5577	202	10	341	4
$N^{mean}_{\text{jet const Durham N=2}} > 5$	228	183	1447	66	10	0	0
$70 < m_{ll} < 100$ GeV	206	120	238	62	2	0	0
$E_T^{miss} > 10$ GeV	202	23	238	61	1	0	0
$m_{rec} > 130$ GeV	143	14	227	17	0	0	0

$$S = 143 \qquad \frac{S}{\sqrt{B}} \sim 8.90 \qquad \frac{S}{B} \sim 0.55$$

$$S_{\text{efficiency}} \sim 0.58$$
$$B_{\text{efficiency}} \sim 4.3\ 10^{-3}$$

ZH, Z(vv)Z(ll)Z*(jj) Fit on BDT output



Fit results *(uncertainty on H(ZZ*) cross section)*

COMBINE

Cut-based

$\sim 8.7\%$

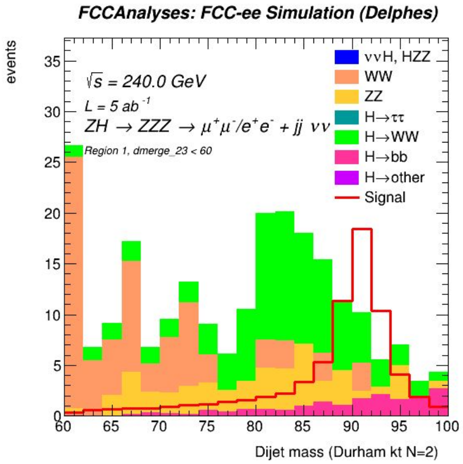
$$r = 1 \pm 0.069$$

$\sim 6.9\%$ uncertainty

Included systematics :

- H(WW*) normalisation : 5%
- ZZ normalisation : 10%

ZH, Z(ll)Z(jj)Z*(vv) - Fit on dijet mass in 2 regions

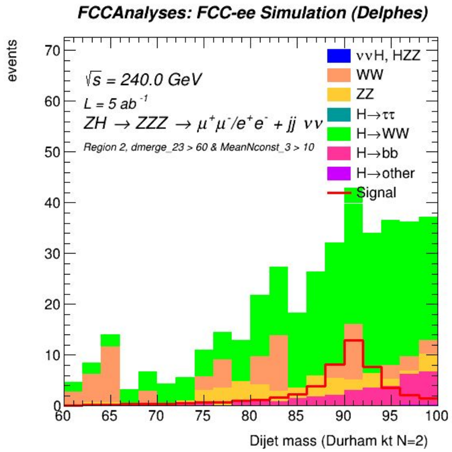


Fit results *(uncertainty on H(ZZ*) cross section)*

COMBINE

$$r = 1 \pm 0.17$$

$\sim 17\%$ uncertainty



Included systematics :

- H(WW*) normalisation : 5%
- ZZ normalisation : 10%

ZH, Z(ll)Z(jj)Z*(vv) - Selections for cut-based

Number of events for $L = 5ab^{-1}$							
Selection	H(ZZ)	ZZ	WW	H(WW)	H(bb)	$H(\tau\tau)$	H(other)
No cut (one Z(ll))	237	450664	84592	13270	36466	3674	7114
$N_{\text{selected leptons}} = 2$	236	427481	84037	9942	34808	2806	7086
$81 < m_{ll} < 101$ GeV	213	271292	20160	8857	31289	2500	6370
$124 < m_{rec} < 138$ GeV	198	22026	6981	8224	29088	2318	5922
$N^{mean}_{\text{jet const Durham N=2}} > 8$	197	19907	1315	7880	29087	0	5848
$60 < m_{jj} < 100$ GeV	178	9192	617	1655	2474	0	58
$\lvert cos(\theta_{miss})\rvert < 0.93$	165	688	604	1515	2090	0	26
min angle miss/jet > 0.4	156	580	576	1420	577	0	6
$N_{\text{leptons with } p>2} = 2$	132	145	499	612	52	0	0
$5 < E^{miss} < 45$ GeV	126	100	296	537	51	0	0
$d_{12} > 2000$	121	86	184	448	48	0	0
Region 1 : $d_{23} < 60$	69	46	76	89	17	0	0
Region 2 : $d_{23} > 60$ and $N^{mean}_{\text{jet const Durham N=3}} > 10$	49	37	68	260	31	0	0

ZH, Z(ll)Z(jj)Z*(vv) - Selections for cut-based

Region 1 (signal-enriched)

$$S = 69$$

$$\frac{S}{\sqrt{B}} \sim 4.57$$

$$\frac{S}{B} \sim 0.303$$

$$S_{\text{efficiency}} \sim 0.29$$

$$B_{\text{efficiency}} \sim 3.8\ 10^{-4}$$

Region 2

$$S = 49$$

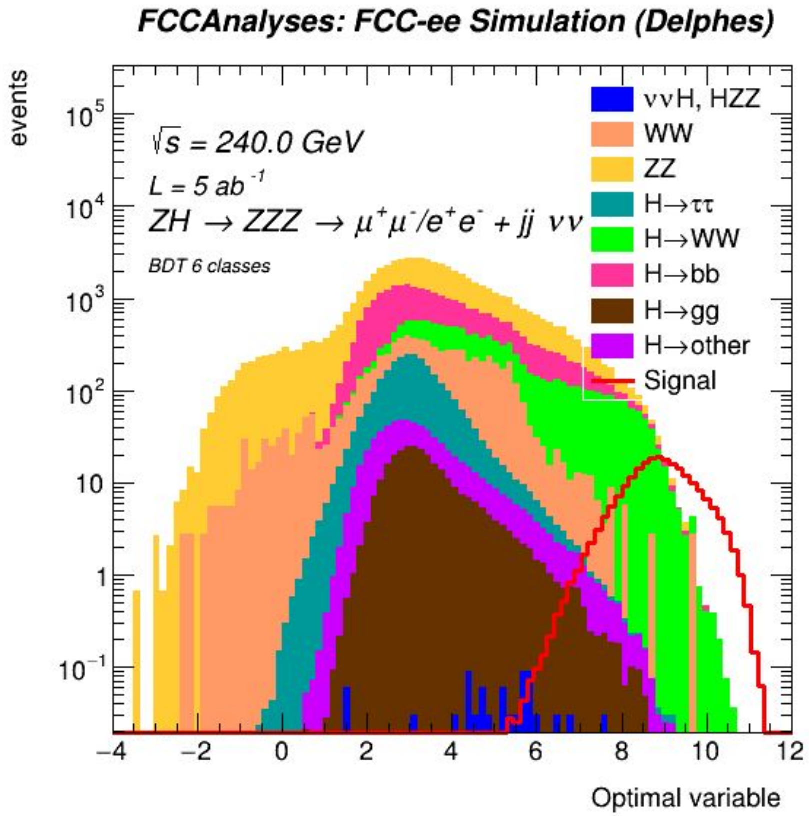
$$\frac{S}{\sqrt{B}} \sim 2.46$$

$$\frac{S}{B} \sim 0.124$$

$$S_{\text{efficiency}} \sim 0.21$$

$$B_{\text{efficiency}} \sim 6.6\ 10^{-4}$$

ZH, Z(ll)Z(jj)Z*(vv) Fit on BDT output



Fit results *(uncertainty on H(ZZ*) cross section)*

COMBINE

$$r = 1 \pm 0.107$$

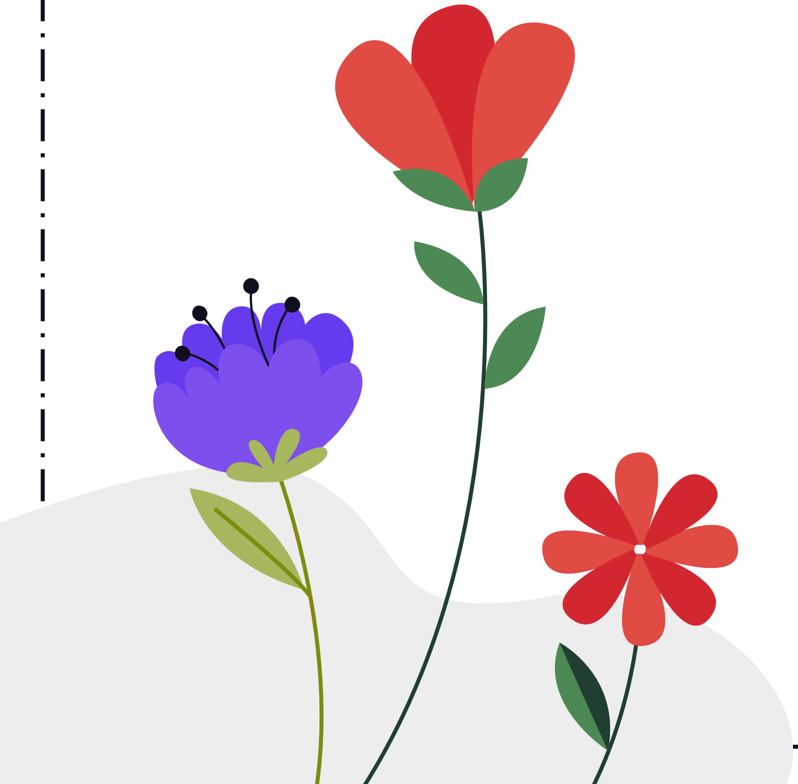
$\sim 10.7\%$ uncertainty

Cut-based

$\sim 17\%$

Included systematics :

- H(WW*) normalisation : 5%
- ZZ normalisation : 10%



Thanks!

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