First look at Higgs’ width uncertainty in H(ZZ*) final state

(FCC-ee simulations)

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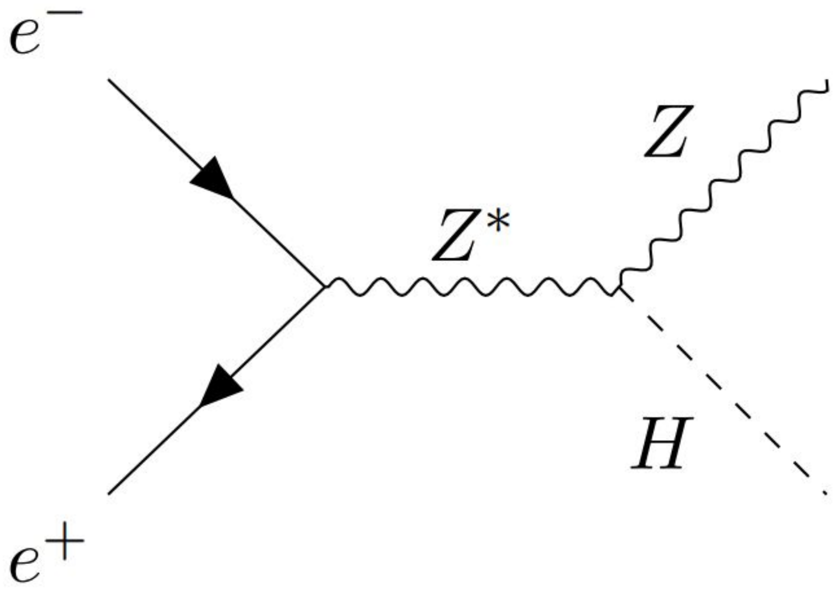
Reminder : Higgs factory for $\sqrt{s} = 240\mathrm{GeV}$



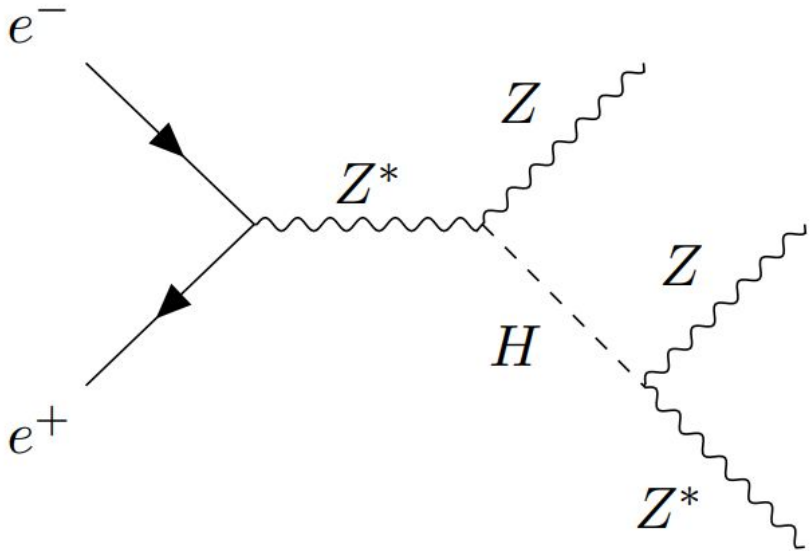
$$\mathrm{N}_{\text{expected ZH events}} \sim 10^6$$

for a luminosity of 5 ab^{-1}
at FCC-ee

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

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

Specific decay of the Higgs : H(ZZ*)



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

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

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

Link between Higgs' width and ZH,ZZZ cross section

Higgs' width measurement and its uncertainty

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

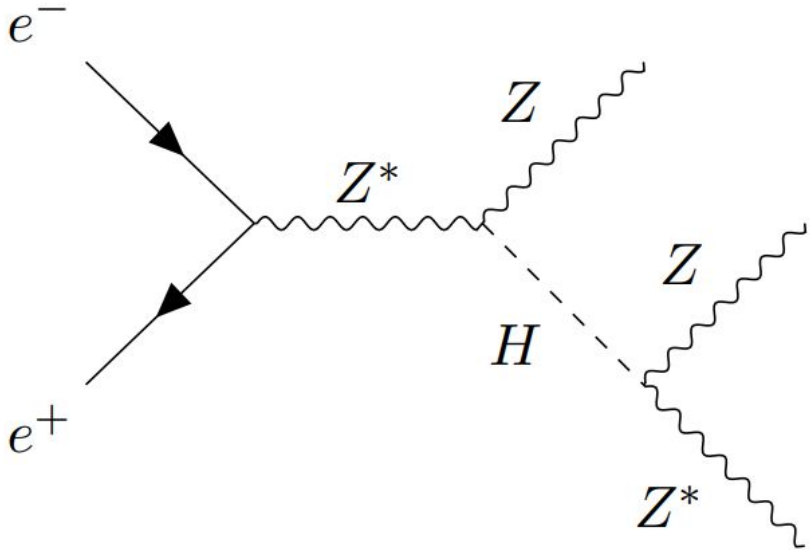
$$\frac{\delta\sigma_{ZH}}{\sigma_{ZH}} \sim 0.1\%$$

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

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

ZH(ZZ*) - Different final states

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



- Fully **hadronic** final states => more statistics but **complicated combinatorics**
- Fully **leptonic** => **fewer** statistics
- **Mixes** of leptons and/or neutrinos and/or jets => better **balance**

Choice →

3 (so far) combinations of a pair of leptons, pair of jets and pair of neutrinos

Plan

I - Mixed final states with a pair of neutrinos/leptons/jets

1 - Common features and background processes

2 - Details of the analysis on ZH,Z(ll)Z(vv)Z*(jj) final state

3 - Overview on ZH, Z(ll)Z(jj)Z*(vv)

4 - Overview on ZH, Z(vv)Z(ll)Z*(jj)

5 - Fit and uncertainty on the Higgs width

II - Influence of degradation of neutral hadrons energy resolution

I - Mixed final states

1 - *Common features* and **corresponding analysis steps before any selections**

- *Pair of (high momentum) leptons* coming from one on shell Z

  => selection of leptons with **25<p<80GeV**, and filter to have a **preselection** of events having only **one leptonic Z candidate**, reconstructed by taking the lepton pair with the dilepton mass closest to the Z mass (**resonance builder** function)

- *Pair of 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**

- *Pair of neutrinos*

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

1 - Backgrounds for ZH(ZZ*)

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

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

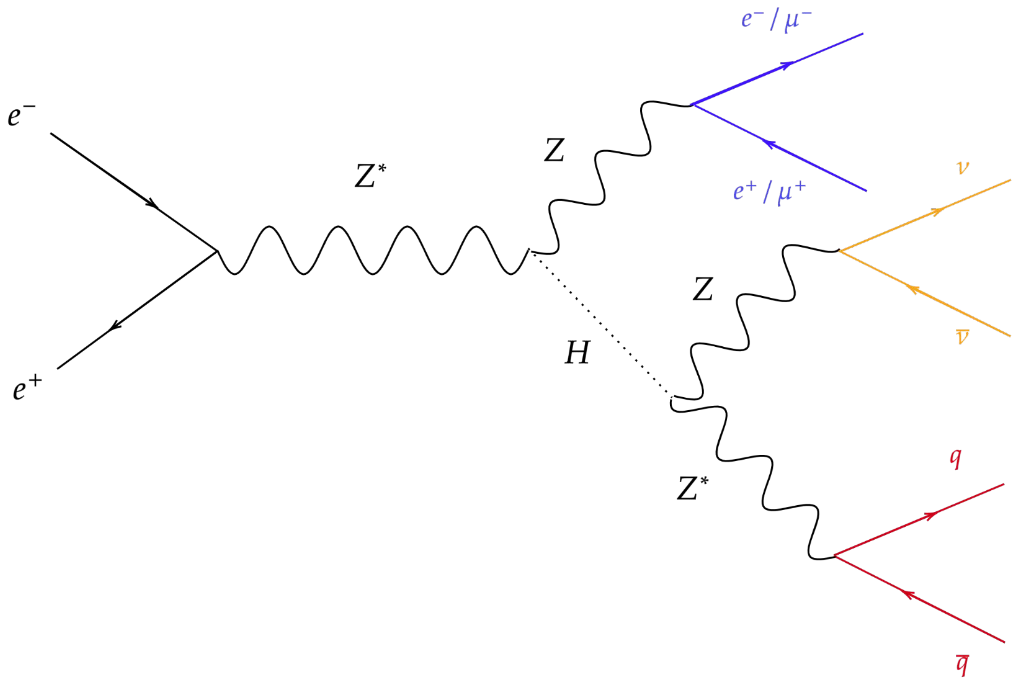
Recap : main steps of the analysis

- **Common preselection** (*stages 1 and 2* of fccanalysis framework, same for the three channels)
- **Selections**, specific to each channel (*final)*
- Generation of **histograms** and plots (*final and plots*)
- **Fit** with COMBINE

Ready to look at the three channels :
- details on ZH, Z(ll)Z(vv)Z*(jj) channel
- overview of the two others
- Combine result for the three channels together

2 - ZH, Z(ll)Z(vv)Z*(jj) final state

2 - ZH, Z(ll)Z(vv)Z*(jj) Feynman diagram and **signature**



Signature :

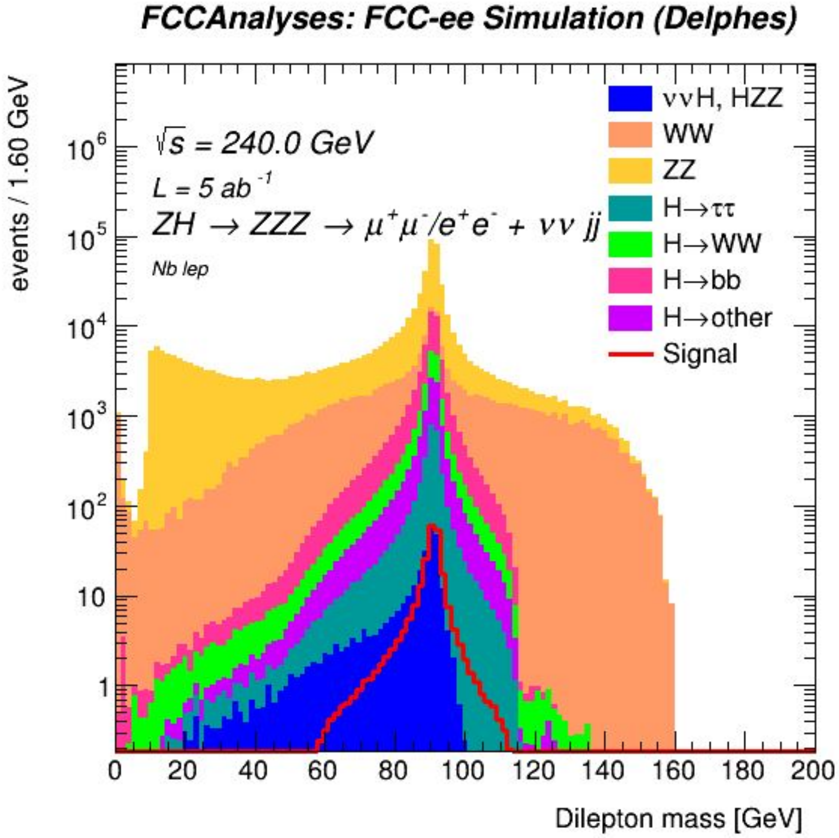
- dilepton mass around the Z mass
- leptonic recoil around Higgs mass
- high missing energy
- dijet mass around 30 GeV

Cut on **dilepton** mass

$$m_{ll} \in [70; 105]\mathrm{GeV}$$

Most reduced backgrounds :

- ZZ
- WW

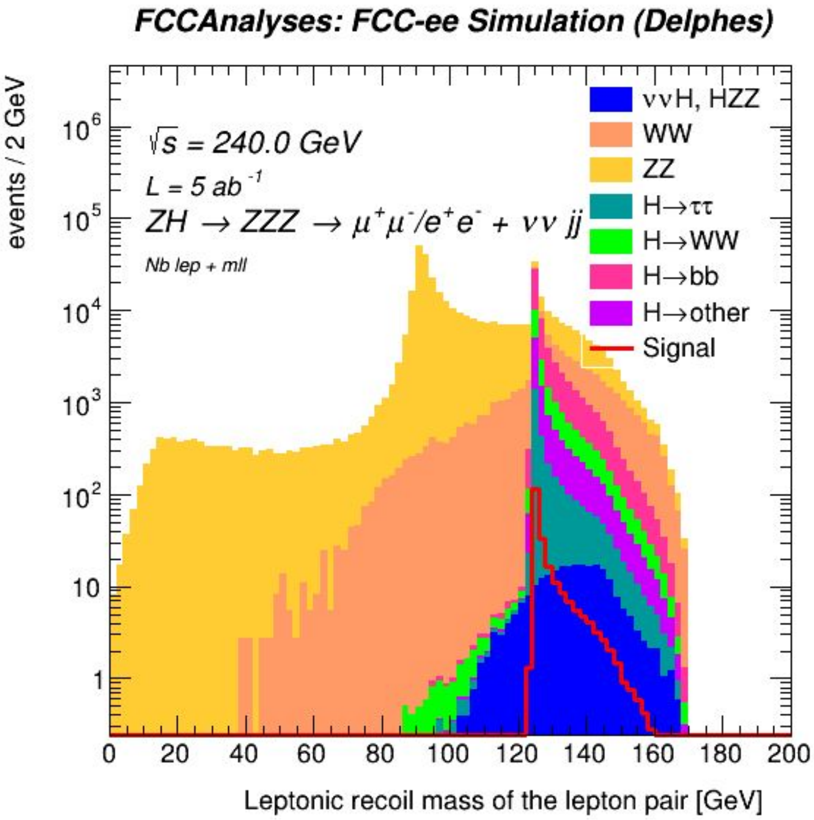


Cut on leptonic **recoil** mass

$$123 < m_{rec} < 130 \text{ GeV}$$

Most reduced backgrounds :

- ZZ
- WW

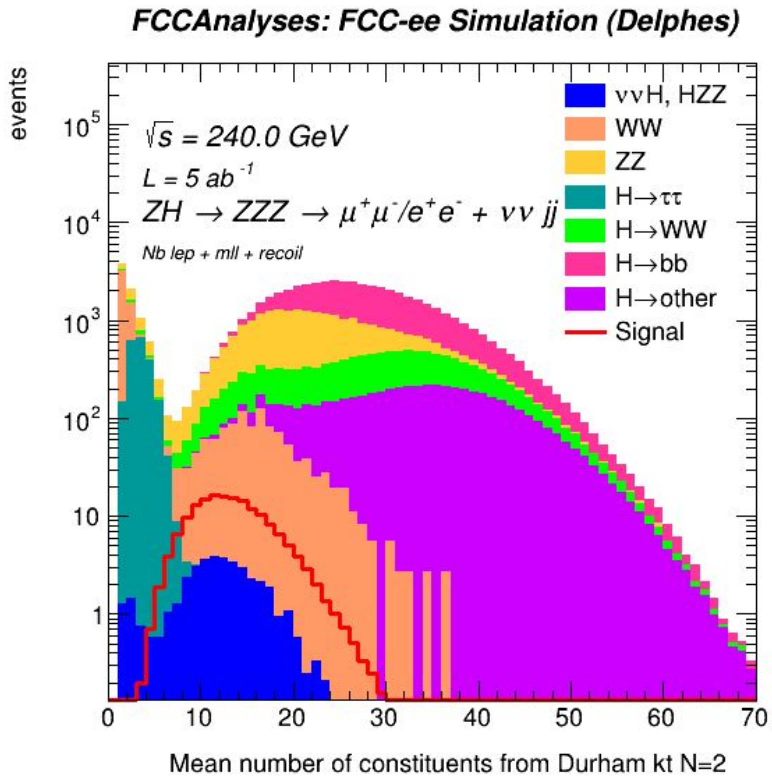


Cut on the **mean number of constituents per jet** reconstructed by Durham kt njets = 2

$$N^{\text{mean}}_{\text{constituents per jet}} > 7$$

Most reduced backgrounds :

- **Htautau**
- (WW*)

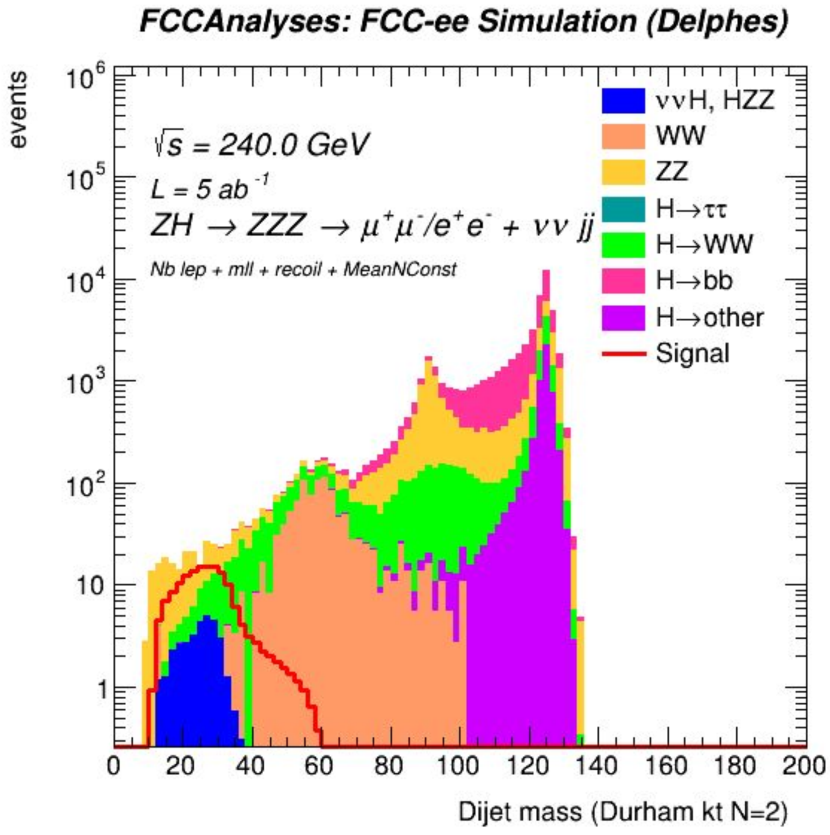


Cut on the **dijet** mass

$$10 < m_{jj} < 45 \text{ GeV}$$

Most reduced backgrounds :

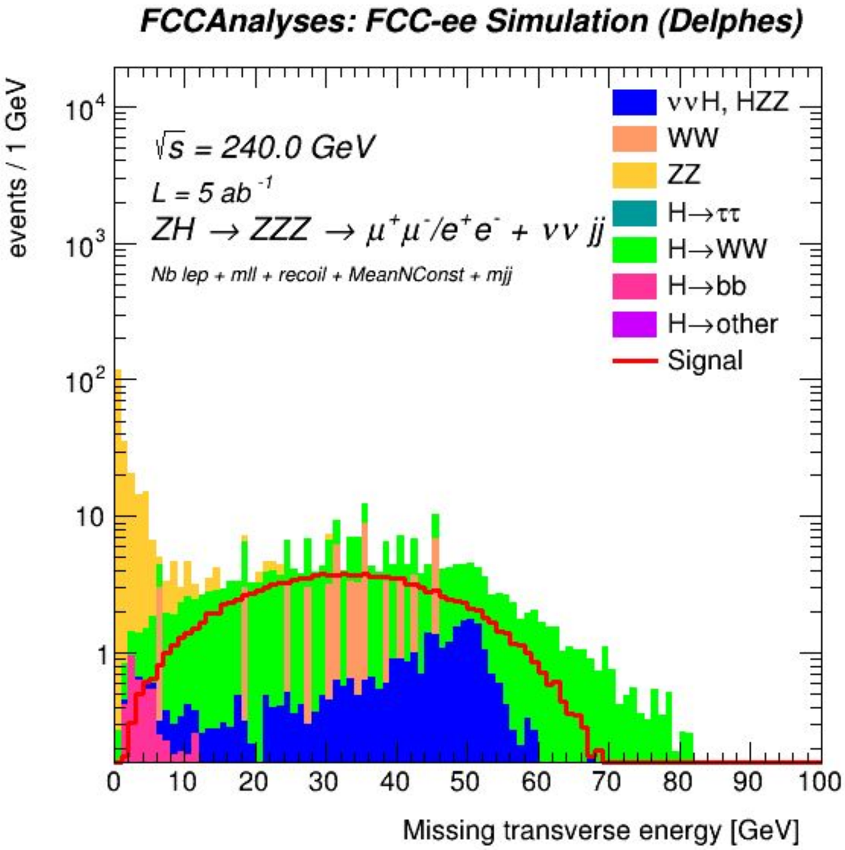
- **H(qq)**
- **ZZ**
- WW



Cut on the **missing transverse energy**

$$E_T^{miss} > 8 \text{ GeV}$$

Most reduced background :
- ZZ



2 - ZH, Z(ll)Z(νν)Z*(jj) - **Cutflow**

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)

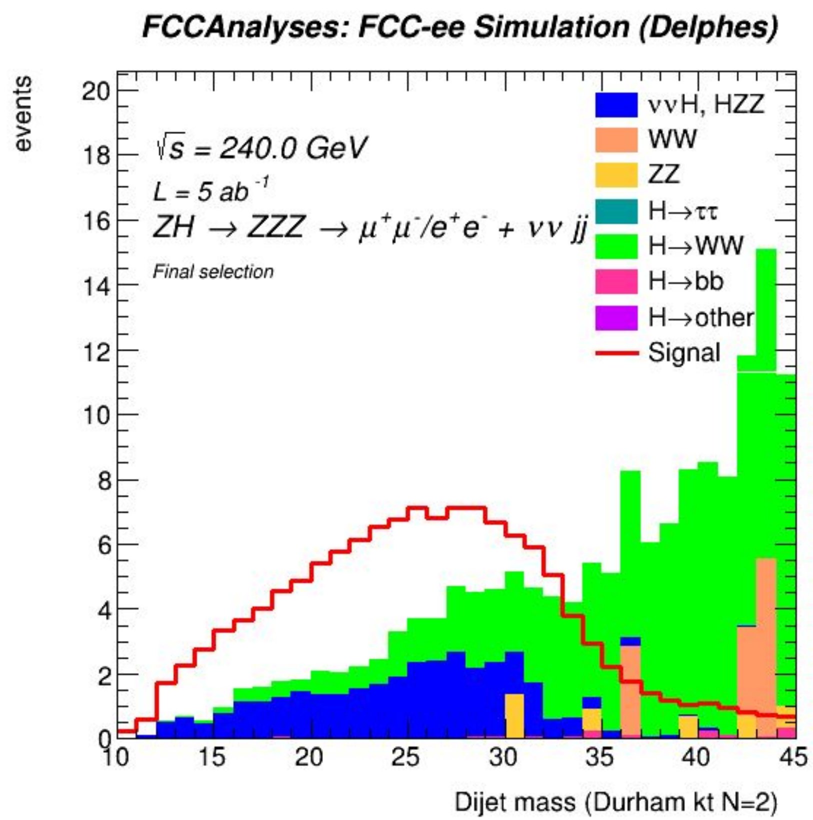
$$S = 129 \qquad \frac{S}{\sqrt{B}} \sim 11.7 \qquad \frac{S}{B} \sim 1.06$$

$$S_{\text{efficiency}} \sim 0.56$$

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

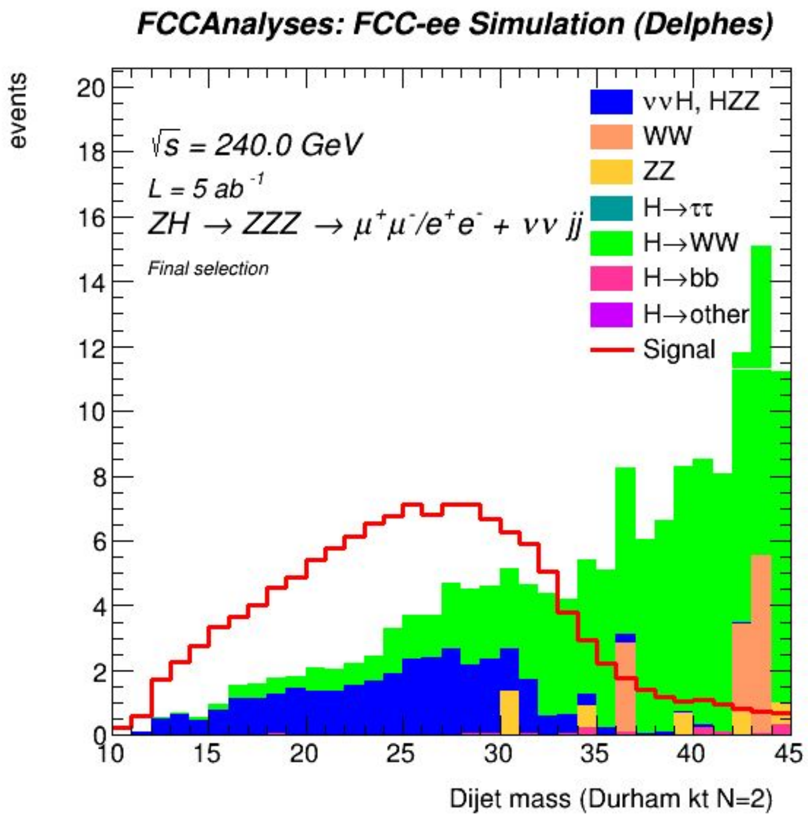
Correct S/B and still half of the events left

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



Dominant background after selections : ZH,H(WW*)
=> remaining H(WW*) events :
$H(WW^* \to \tau\nu_\tau jj)$
with low momentum tau lepton

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



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

COMBINE

$$r = 1 \pm 0.090$$

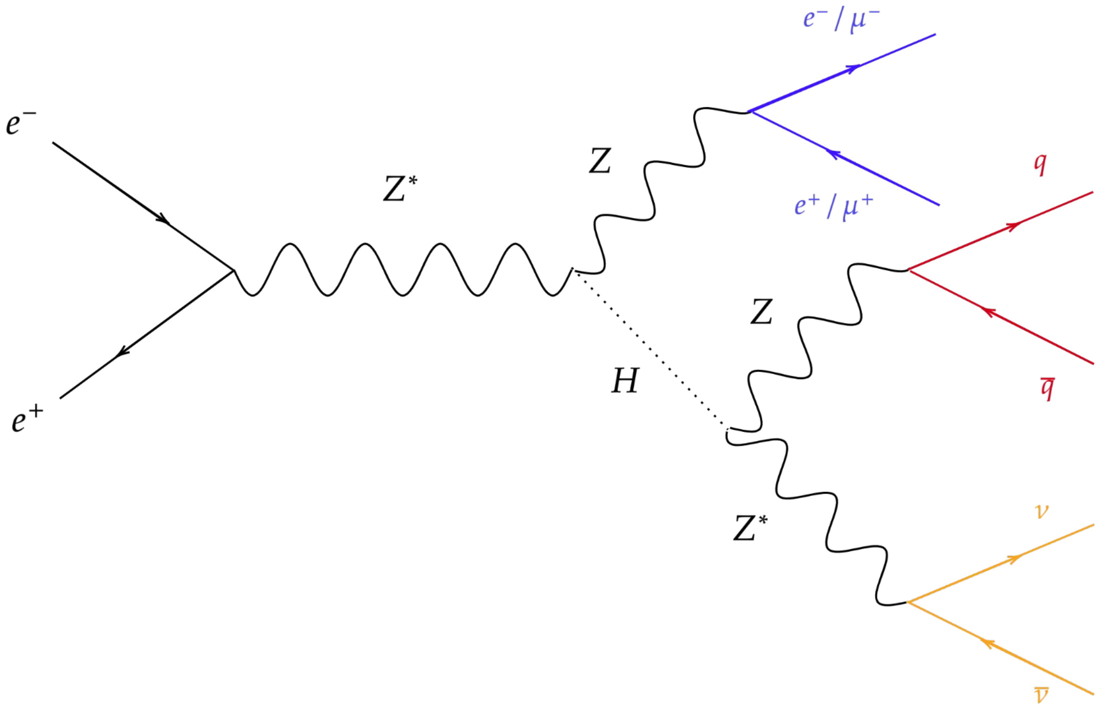
$\sim 9\%$ uncertainty

Included systematics :

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

3 - ZH, Z(ll)Z(jj)Z*(vv) final state

3 - ZH, Z(ll)Z(jj)Z*(vv) Feynman diagram and **signature**

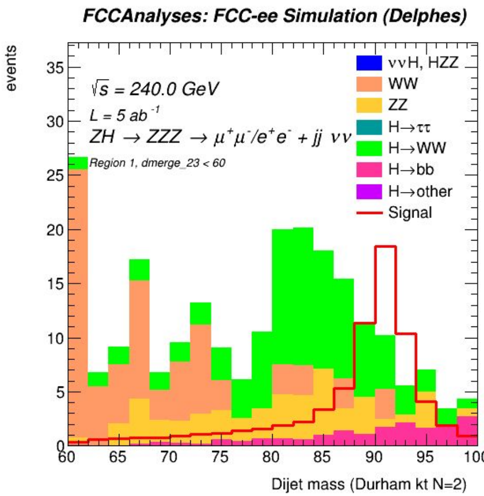


Signature :

- dilepton mass around the Z mass
- leptonic recoil around Higgs mass
- dijet mass around the Z mass
- missing energy around 30 GeV

3 - Fit result on the dijet mass for the 2 regions of ZH, Z(ll)Z(jj)Z*(νν)

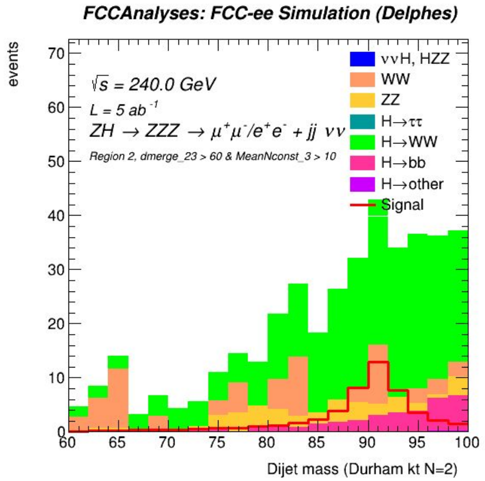
Fit results *(uncertainty on H(ZZ*) cross section)*



COMBINE

$$r = 1 \pm 0.17$$

$\sim 17\%$ uncertainty

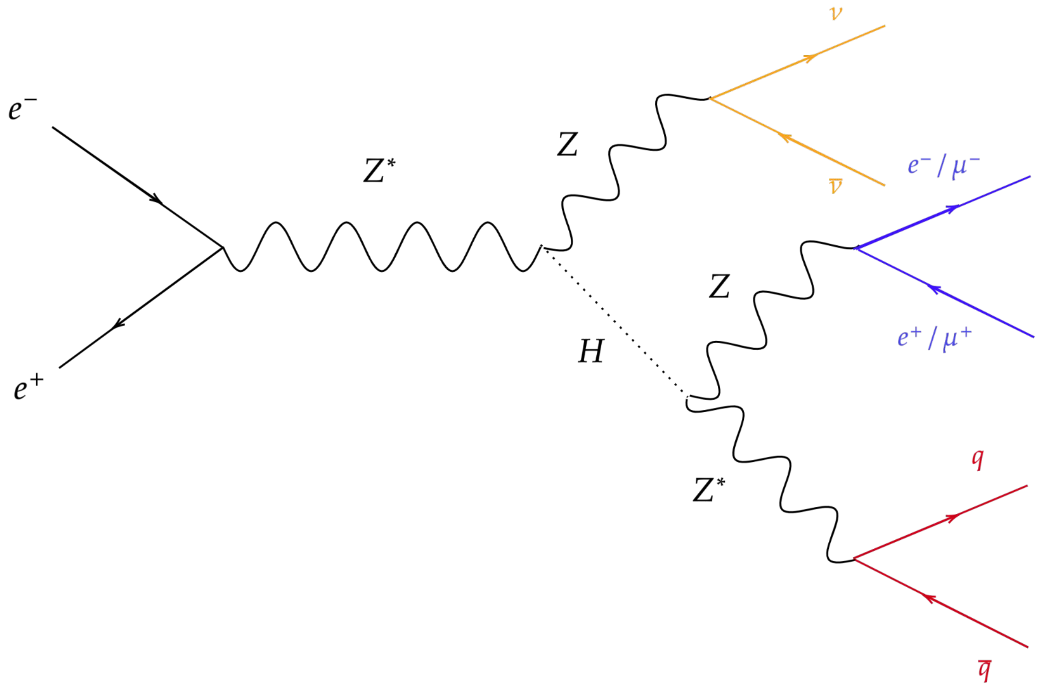


Included systematics :

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

4 - ZH, $Z(\nu\nu)Z(ll)Z^*(jj)$ final state

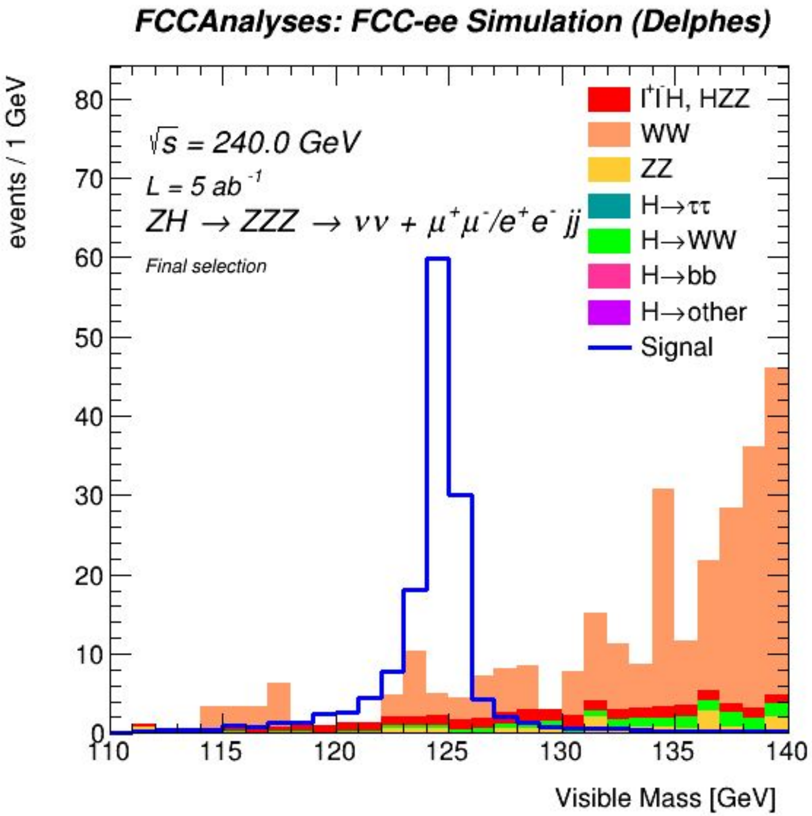
4 - ZH, Z(νν)Z(ll)Z*(jj) Feynman diagram and **signature**



Signature :

- high missing energy
- visible mass around the Higgs mass
- dilepton mass around the Z mass
- dijet mass around 30 GeV

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



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

COMBINE

$$r = 1 \pm 0.087$$

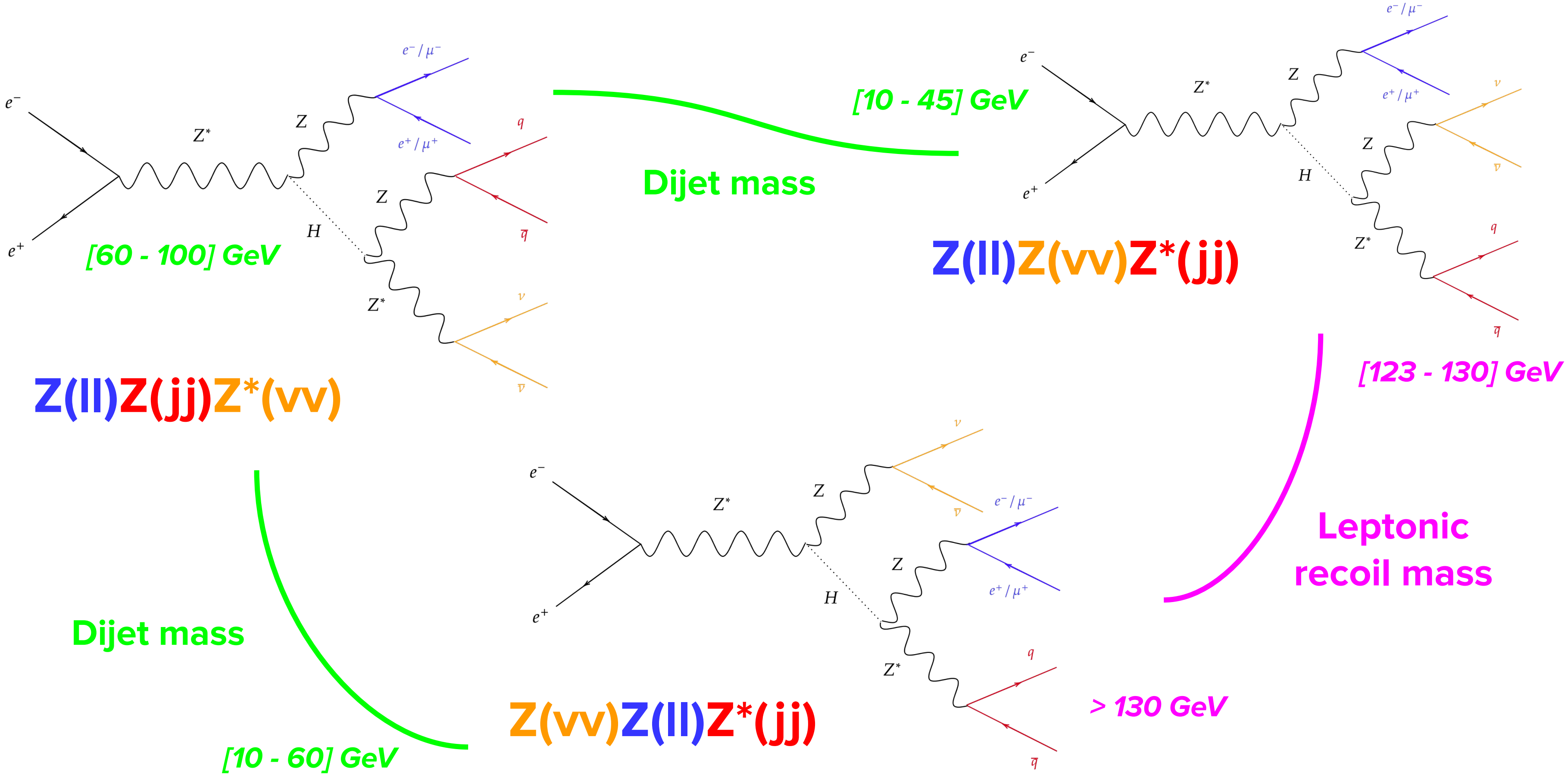
$\sim 8.7\%$ uncertainty

Included systematics :

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

5 - Complete fit and Higgs width uncertainty

5 - Orthogonality of selections



5 - Fit with the 3 channels

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

$\sim 17\%$

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

$\sim 9\%$

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

$\sim 8.7\%$

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

COMBINE

$$r = 1 \pm 0.066$$

Included systematics :

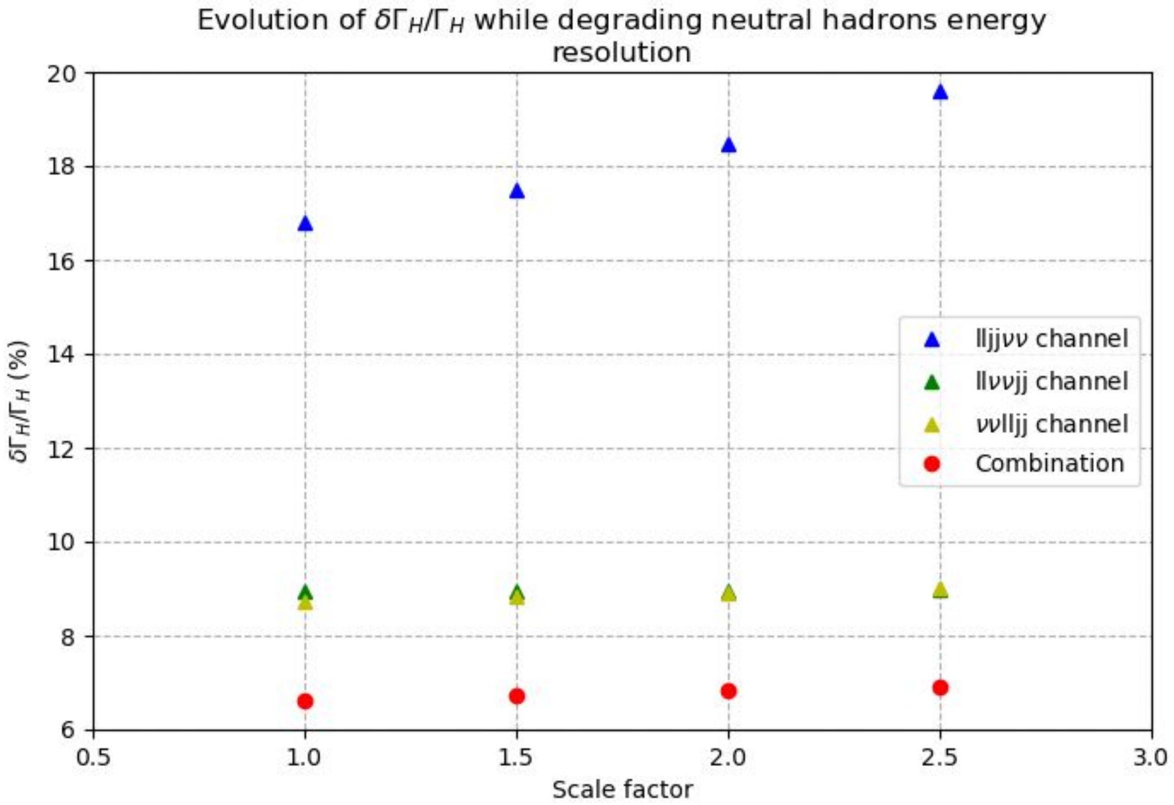
- H(WW*) normalisation : 5%
- ZZ normalisation : 10%

So far, final result for the width uncertainty :

$$\frac{\delta\sigma_{ZH(ZZ^*)}}{\sigma_{ZH(ZZ^*)}} \sim \frac{\delta\Gamma_H}{\Gamma_H} \sim 6.6\%$$

II - Degradation of neutral hadrons energy resolution

Influence of **neutral hadron energy resolution** (1)

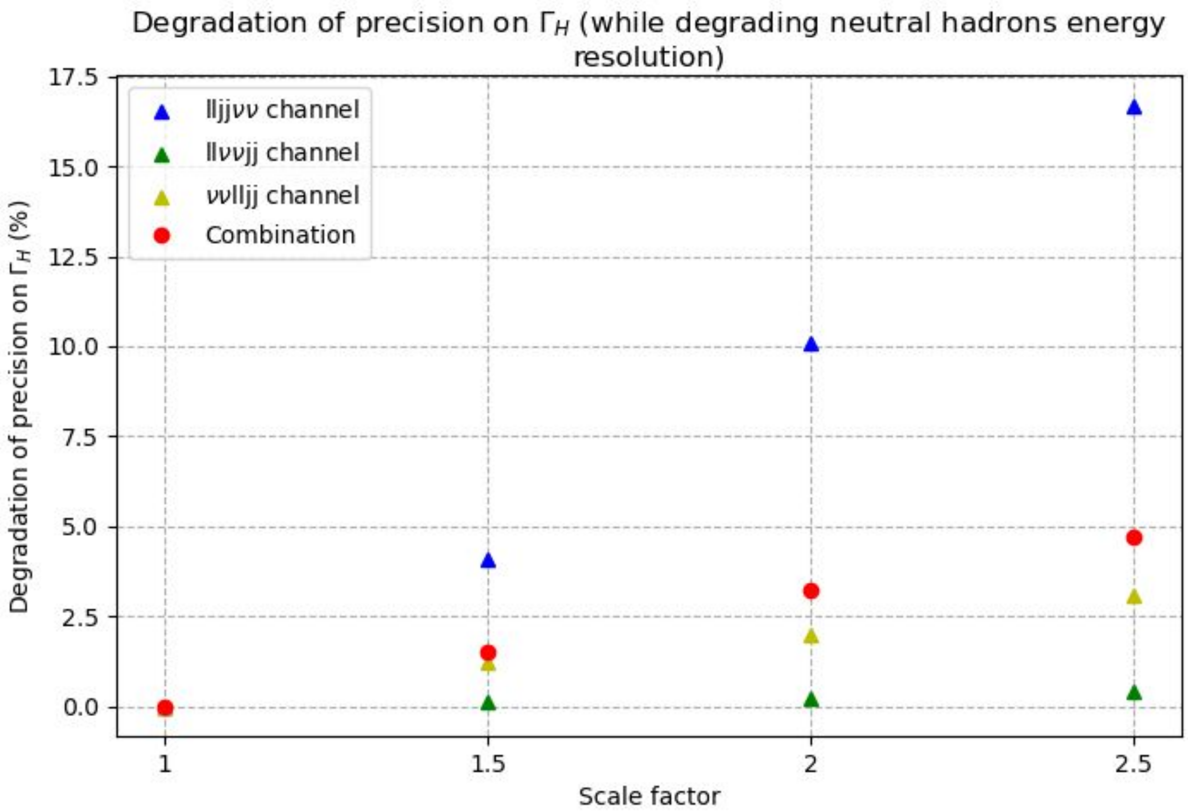


IDEA concept detector

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** (2)



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 !**

Conclusion

- A bit more than **6%** uncertainty on the Higgs' width with 3 mixed channels
- **Low impact of neutral hadron energy resolution** on Higgs' width measurement
- Study of H(4j) final state => hard to handle but really interesting case

What could be coming next ?

- Adding other mixed channel
- Optimising selections with a BDT
- Trying other H(4j) channels

Backup

1 - Exclusive Durham kt algorithm for jet reconstruction

=> Principle : *going backwards in the history/evolution of the jets*

Can be used specifically in electron-positron colliders where there is no pile-up

Steps followed by the algorithm in **njets mode** :

- Compute dij for each pair of particles

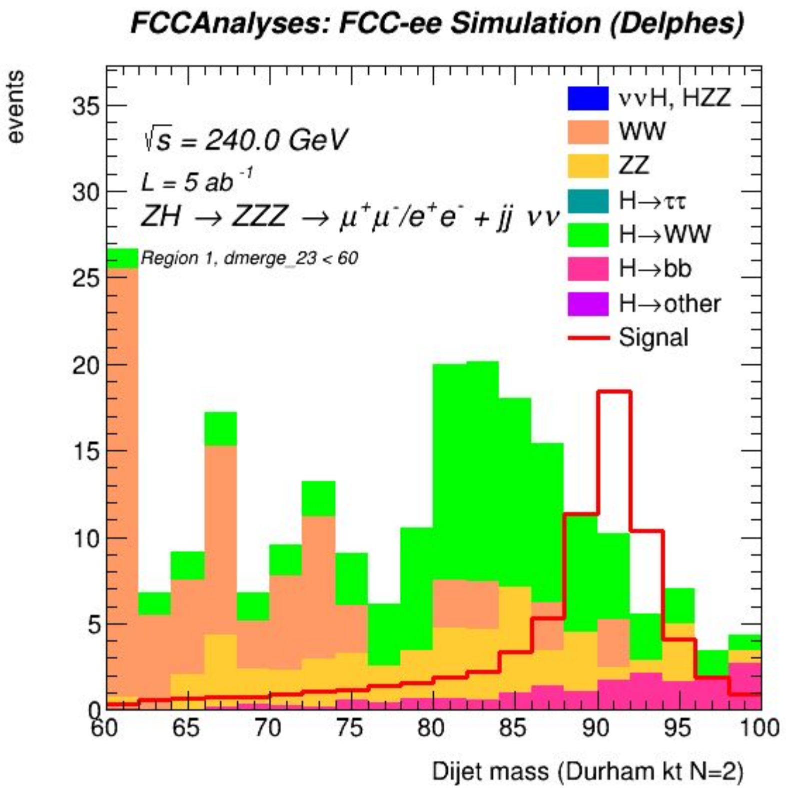
$$d_{ij} = 2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})$$

- Recombine the pair ij having the smallest dij
- Compute again dij for each pair (the ij pair from the previous step counts now as one particle, one jet)
- Stops when every particle has been clustered in one of the njets

3 - ZH, Z(ll)Z(jj)Z*(vv) - Cutflow

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
$\|cos(\theta_{miss})\| < 0.93$	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

3 - ZH, Z(ll)Z(jj)Z*(vv) REGION 1 - Recap after selection



$$S = 69$$

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

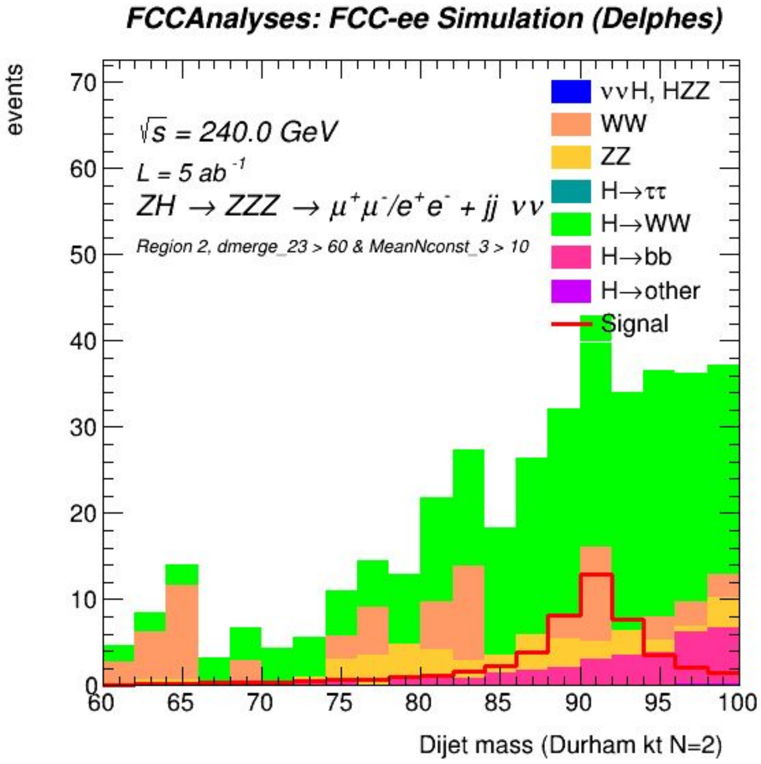
$$\frac{S}{B} \sim 0.303$$

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

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

=> Region enriched in signal, cut on d23 used to reduce H(WW*)
=> remaining H(WW*) events : $H(WW^* \to jj\tau\nu_\tau)$ with low momentum tau lepton

3 - ZH, Z(ll)Z(jj)Z*(vv) REGION 2 - Recap after selection



$$S = 49$$

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

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

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

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

=> Region 2 : not very good S/B ratios, but useful to perform the fit combined with the enriched region

4 - ZH, Z(νν)Z(ll)Z*(jj) final state - **Cutflow**

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

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

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

Not optimal here because of the large cut on the dilepton mass => but useful to have more statistics and a better fit

Higgs in 4 jets final state

Difference in the **analysis steps before any selections**

- *Pair of (high momentum) leptons* coming from one on shell Z

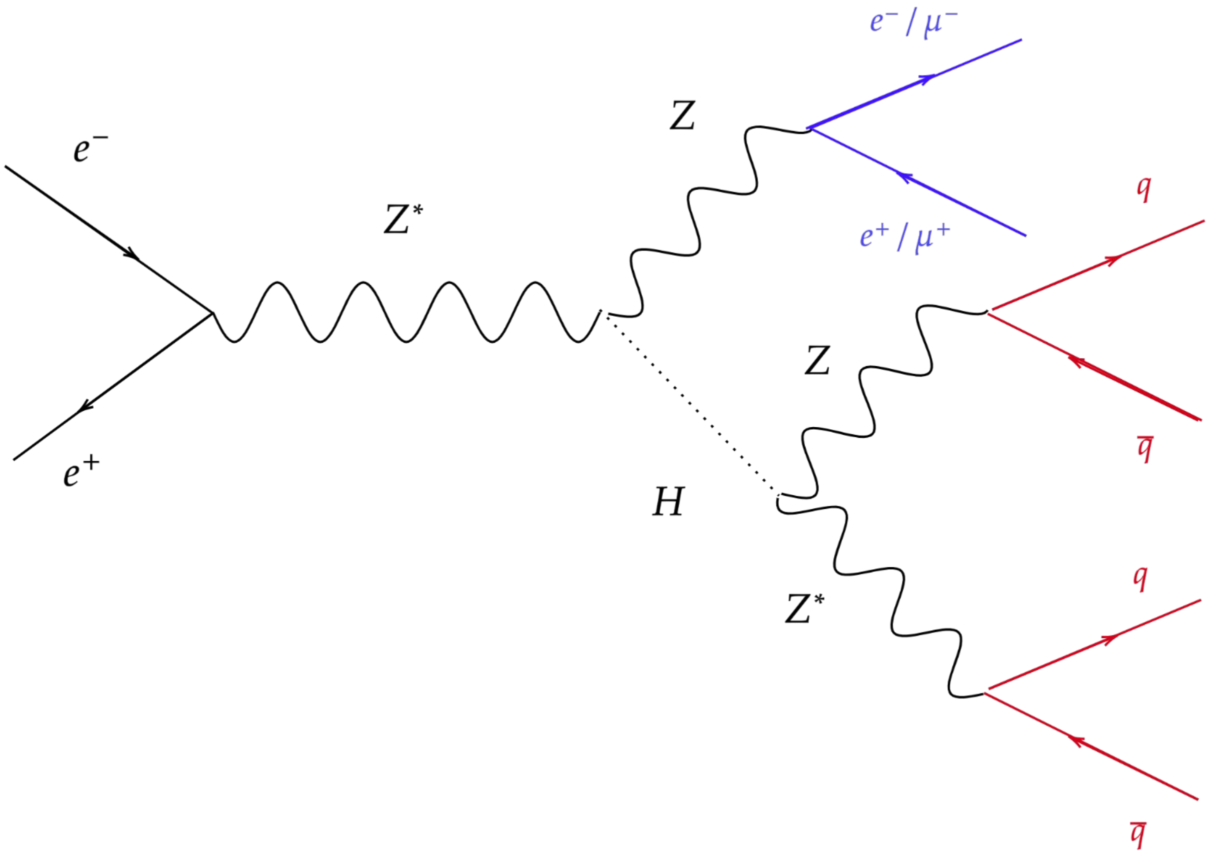
  => selection of leptons with **25<p<80GeV**, and filter to have a **preselection** of events having only **one leptonic Z candidate**, reconstructed by taking the lepton pair with the dilepton mass closest to the Z mass (**resonance builder** function)

- *Pair of 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 = 4**

  => Function (resonance builder) **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

ZH, Z(ll)Z(jj)Z*(jj) final state - Feynman diagram and **signature**



Signature :

- leptonic mass around the Z mass
- leptonic recoil around Higgs mass
- A pair of jets with a dijet mass around the Z mass
- The invariant mass of the 4 jets around the Higgs mass
- No missing energy

ZH, Z(ll)Z(jj)Z*(jj) - **Cutflow**

Number of events for L = $5ab^{-1}$								
Selection	H(ZZ)	ZZ	WW	H(WW)	H(bb)	H(cc)	H(gg)	H(other)
No cut (one Z(ll))	801	419933	17753	12648	36443	1808	5119	2821
$N_{\text{selected leptons}} = 2$	798	408700	17515	9784	34786	1791	5115	2320
$81 < m_{ll} < 101$ GeV	717	260722	3558	8734	31289	1611	4602	2058
$124 < m_{rec} < 140$ GeV	680	23358	1775	8279	29683	1530	4368	1945
$E_T^{miss} < 13$ GeV	664	22045	73	5824	25797	1460	4348	634
$p_{\text{z, miss}} < 15$ GeV	659	16314	49	5651	25255	1443	4321	566
$110 < m_{jjjj} < 138$ GeV	638	9051	8	5205	22927	1392	4259	208
$d_{34} > 60$	535	2840	8	4604	3930	231	2003	23

Number of signal events left after selections :

$S = 535$

$$\frac{S}{\sqrt{B}} \sim 4.58$$

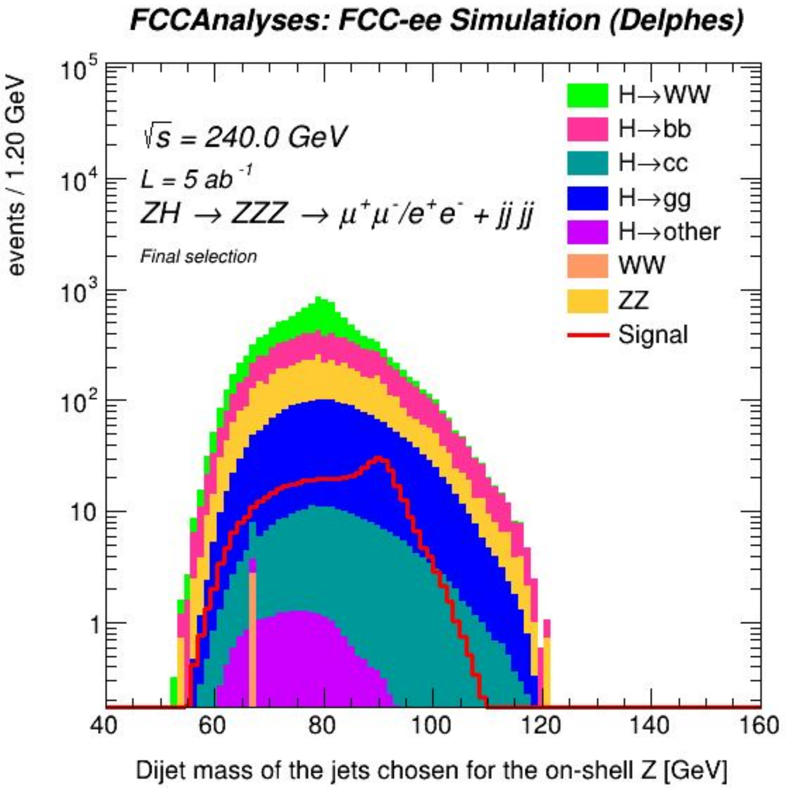
$$\frac{S}{B} \sim 0.039$$

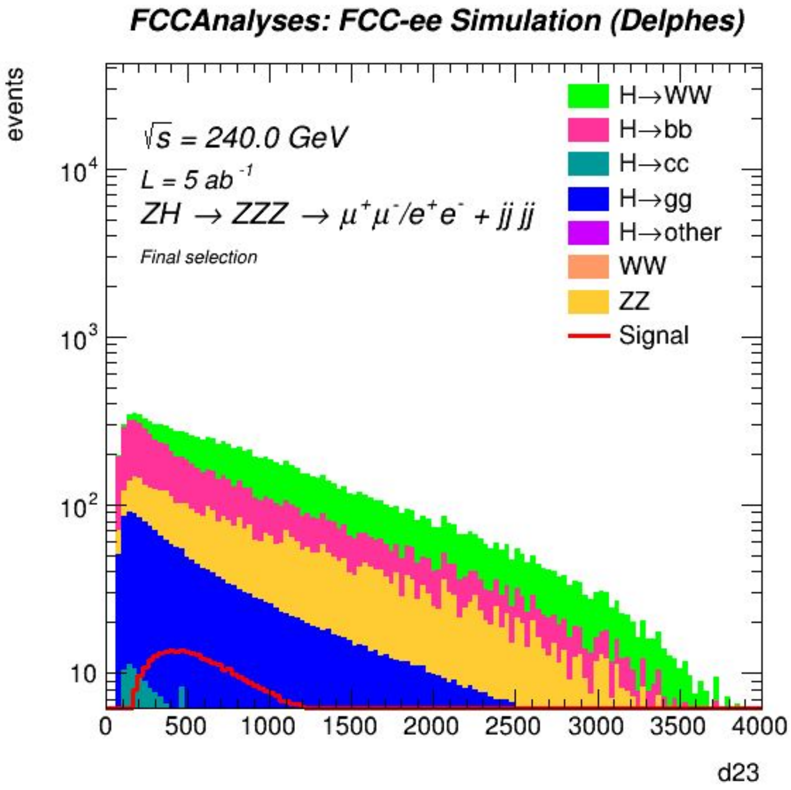
$$S_{\text{efficiency}} \sim 0.67$$

$$B_{\text{efficiency}} \sim 0.027$$

Bad signal over background ratio
? => why is it hard to get a better one ?

Plots after selections





Problem 1 : confusion between jets constituents for signal

Kinematic constraints => Higgs, and its decay (the two Zs) is almost **not boosted**

Particles from the 4 jets are mixed

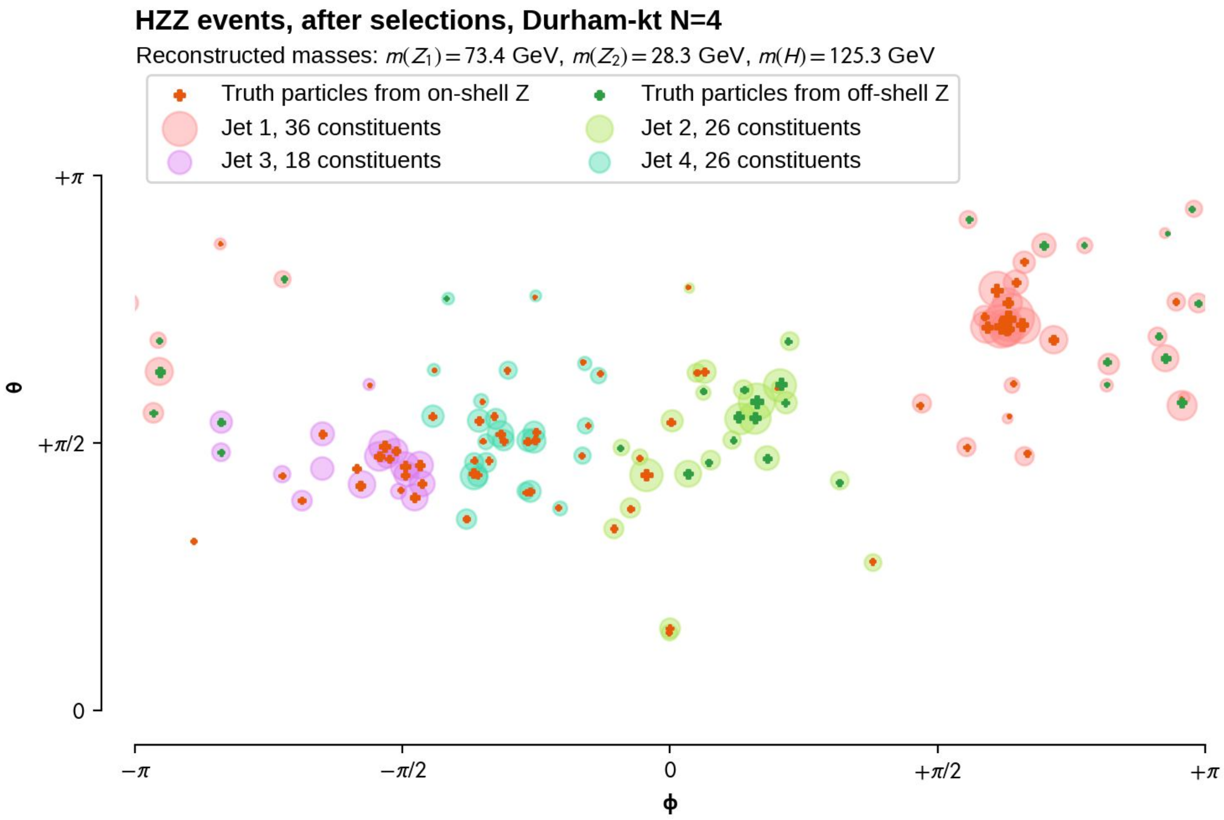
=> **Confusion** even at **truth** level for signal

Jet algorithm **struggles** to **reconstruct** the 4 **jets correctly**, and so the Zs

Bad dijet mass resolution

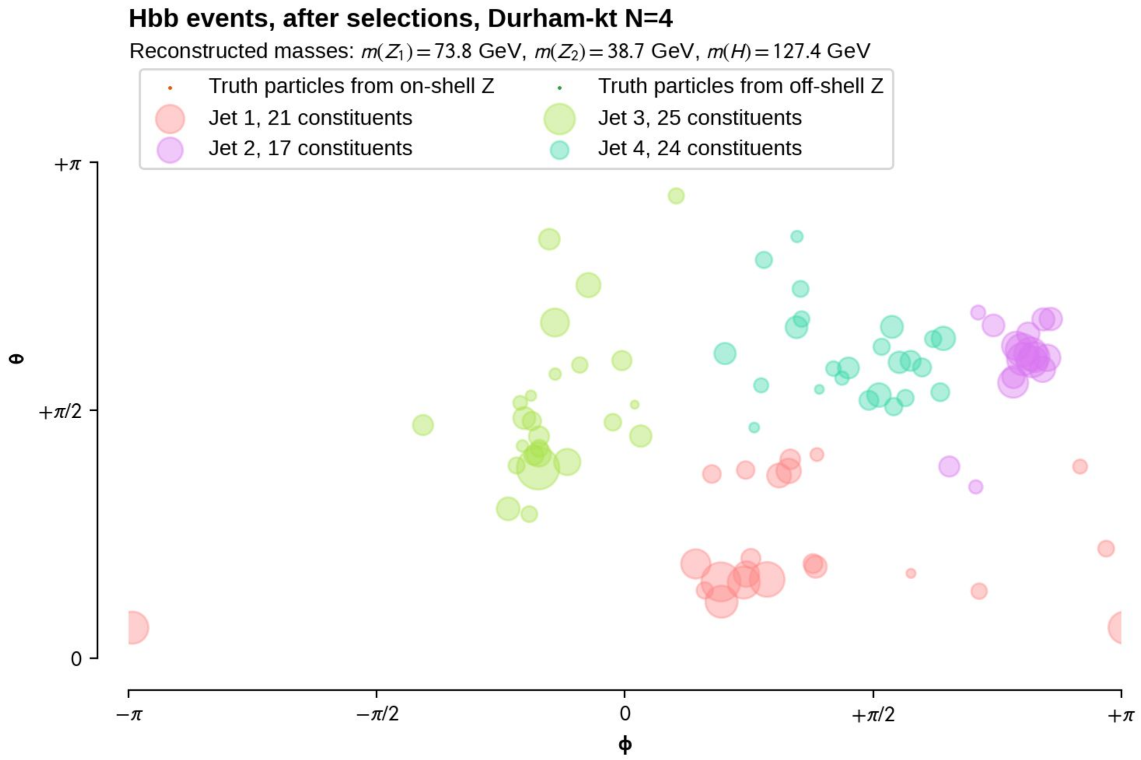
=> hard to reduce **H(WW*)** background (expected to be the dominant one after selections)

Confusion of the particles from the 2 Zs at the truth-level for signal



Bad association (of the jet algorithm) between the truth particles of the Zs and the reconstructed jets constituents

Problem 2 : H(qq) background with 4-jets topology



Around **50 times** more H(bb) events than signal events (H(4j)) before cuts

After selection, still a lot of H(bb) events, having a **4 jets-events topology** (signal topology)

Conclusion on $Z(ll)Z(jj)Z^{*}(jj)$

Bad dijet mass **resolution** for signal (because of confusion) makes it hard to reduce **$H(WW^{*})$** background

Still a lot of **H(qq)** background after selections because of their **4-jets topology**

Bad S/B ratio