Measurement of the Higgs width

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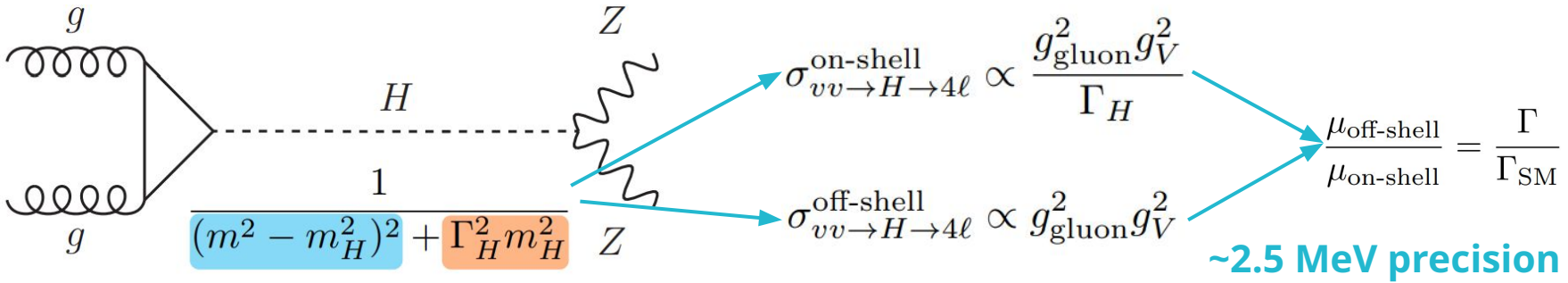
Introduction: Higgs width measurements

Higgs width in SM is $_{small}$: ~4 MeV

- No direct measurement through lineshape in final state possible
  - LHC: resolution ~2-3 GeV
  - FCC: should be better, but not by 3 orders of magnitude !

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

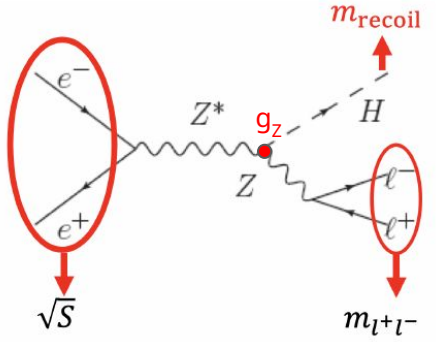


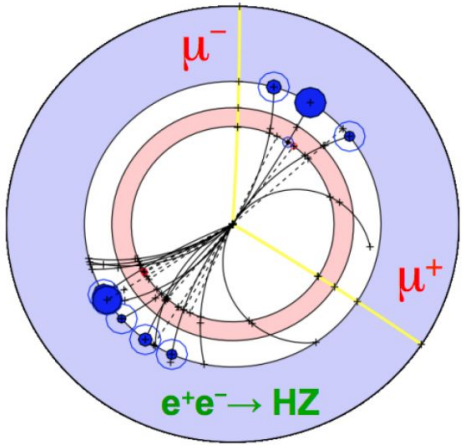
~2.5 MeV precision !

- **FCC-ee: total width measurement through couplings**

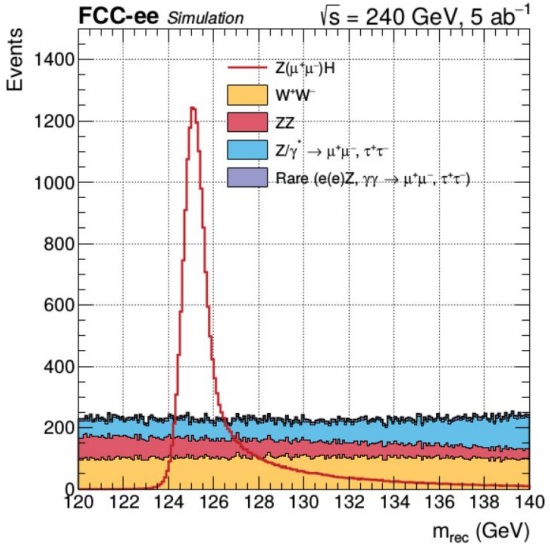
Higgs recoil analysis

The basis for many measurements at 240 Gev





$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$



Very clean peak to fit !

In interim report

- **Total ZH cross-section ⇒ absolute g_Z coupling**
- Higgs mass measurement
- Study of hadronic decays

Higgs width measurement

Not been studied in details in the past few years

	HL-LHC (*)	FCC-ee
$\delta\Gamma_H / \Gamma_H$ (%)	SM (**)	1.3
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	0.17
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	0.43
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	0.61
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	1.21
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	1.01
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	0.74
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–
$\delta g_{HHH} / g_{HHH}$ (%)	50	~40 (indirect)
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	< 1%

How do we get this ?

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

- Through ZH → ZZZ*
  - Most straightforward
  - Recoil analysis gives σ_{ZH} hence g_Z
  - Then ZZZ* gives BR(ZZ*) hence Γ_H
  - ~2-3% precision expected

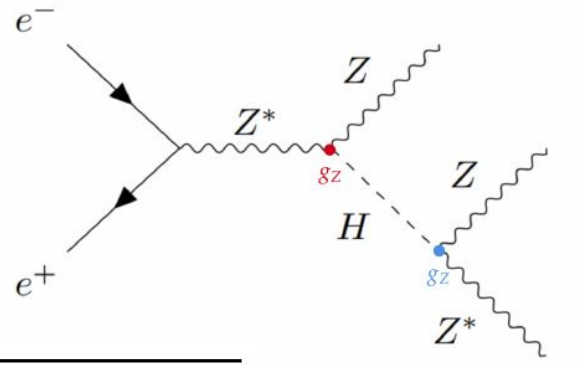
- Through VBF
  - A bit more convoluted
  - Combine ZH cross-section, BR(bb), BR(WW*) at 240 GeV, and WW→H→bb at 365 GeV
  - 1-2% precision expected

$$\frac{\sigma(ZH \to bb)\sigma(ZH \to WW^*)}{\sigma(\nu\nu H \to bb)\sigma(ZH)^2} \propto \Gamma_H$$

Higgs width through H→ZZ*: channels

3 Z in the final state: lots of fun !

- Many decay channels to study !
  - ll, νν, qq decays for each Z
  - Not always high statistics
- The 3 Z are not interchangeable:
  - "Recoil" Z vs "Higgs" Zs
  - H → ZZ*: on-shell vs off-shell Z



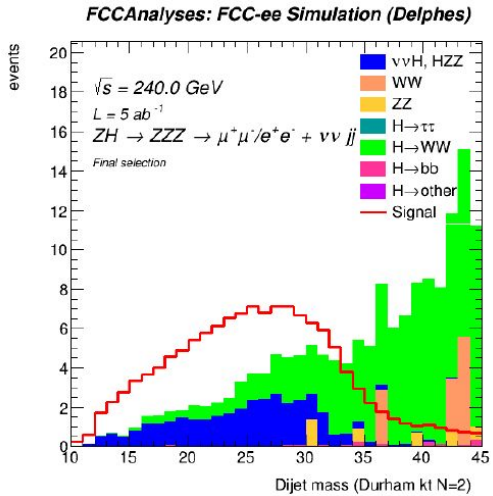
ZZZ^* decay type	Number of events for $L = 5\,ab^{-1}$	Z combinatorics (objects pairing)	Particle combinatorics (jets)
Fully hadronic	~ 9000	*hard+*	*hard+*
Fully leptonic	~ 8	*hard+*	*easy+*
Mixed channels	~ 1500	*easy+*	*easy*
2 leptons, 4 jets	~ 2600	*hard*	*hard*
2 jets, 4 leptons	~ 250	*hard*	*easy*

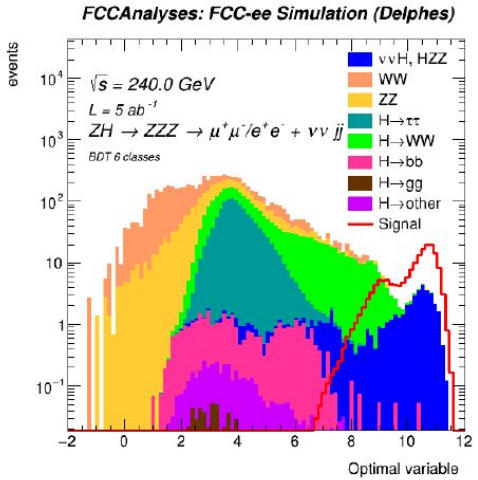
Reminder:
BR(H→ZZ*) = 2.6%

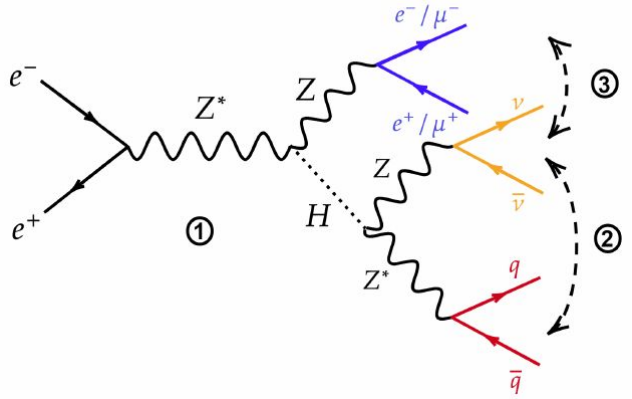
ZH→ZZZ*→llvvqq

Study of 3 of the "mixed" channels (Inès Combes internship, 2023)

- Fun final state: leptons, neutrinos, jets
  - 6 possible sub-channels
- Start by hand-crafting cuts to get used of the topology
- Then move to simple BDT to gain in precision

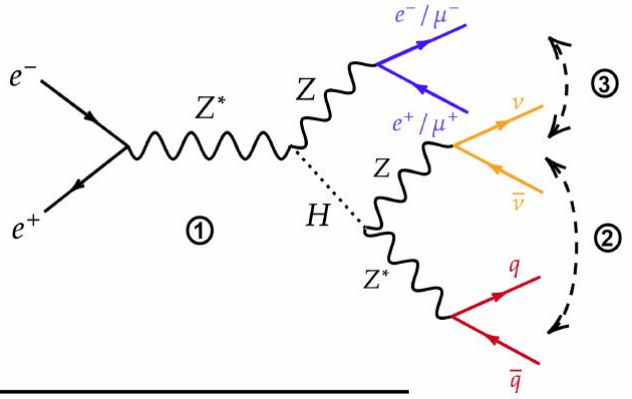






ZH→ZZZ*→llvvqq: signals and backgrounds

- Signal: H→ZZ*
  - Cuts optimised for each sub-channel independently (dis-regarding other HZZ events for optimisation)
  - Then orthogonality between channels implemented by simple cuts



- Backgrounds:
  - WW and ZZ
  - Other Higgs decays
  - Low BR(H→ZZ*) makes the analysis a bit challenging !

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

- Technical remarks:
  - Samples copied at IJCLab and processed on local server
    - Only fraction of ZZ and WW
  - Overall great experience with FCCAnalysis

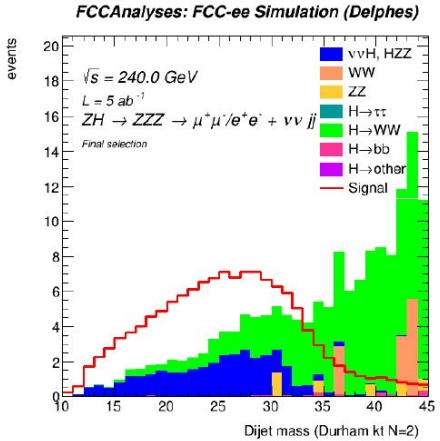
ZH→ZZZ*→llvvqq: Example channel llvvqq

Recoil Z→ll selection

Target Z*→qq

Number of events for $L = 5ab^{-1}$							
Selection	$H(ZZ)$	ZZ	WW	$H(WW)$	$H(bb)$	$H(\tau\tau)$	$H(\text{other})$
Preselection (one $Z(ll)$)	229	450 664	84 592	13 270	36 466	3674	7114
$N_{\text{selected leptons}} = 2$	229	427 481	84 037	9942	34 808	2806	7086
$70 < m_{ll} < 105$ GeV	221	303 820	34 760	9528	33 580	2695	6842
$123 < m_{\text{recoil}} < 130$ GeV	168	16 552	5088	7204	25 497	2023	5186
$N^{\text{mean}}_{\text{jet const Durham N=2}} > 7$	155	14 955	1065	6930	25 497	1	5127
$10 < m_{jj} < 45$ GeV	145	218	46	176	4	0	0
$E_T^{\text{miss}} > 8$ GeV	141	12	43	170	1	0	0
$p_{jj} < 40$ GeV	129	4	10	106	1	0	0

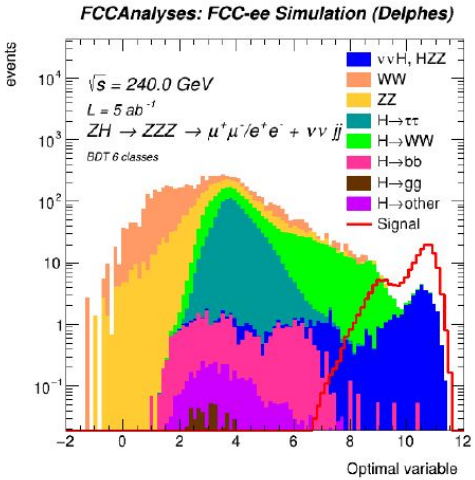
- Simple cut-based analysis already providing quite good results !
- Main background remaining: H→WW* with W→τν
  - Despite poor man's hadronic tau veto
  - Dedicated tau reconstruction algorithms would help a lot !
    - Would also allow to add Z→ττ channel !

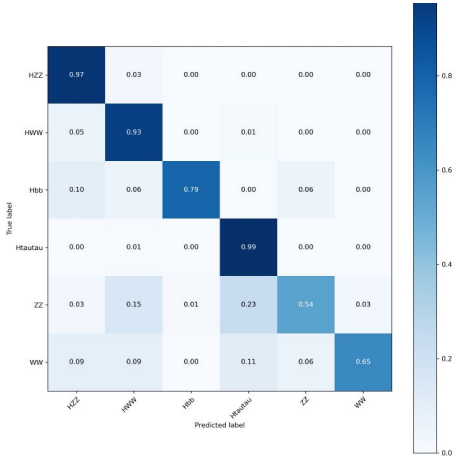


ZH→ZZZ*→llvvqq: going multivariate

- BDT architecture following example of H→hadrons classifier
  - Multiclass BDT using XGBoost (one output per signal / background)
  - Then combine outputs into an optimal discriminant for H→ZZ*

Leptonic variables	Jet variables	Neutrino variables	Mixed variables
m_{ll}	m_{jj}, p_{jj}	E^{miss}	m_{visible}
m_{recoil}	m_{recoil}	E_T^{miss}	$m_{ll\nu\nu}$
$N_{\text{selected leptons}}$	$E_{\text{j1}}, E_{\text{j2}}$	p_z^{miss}	$m_{jj\nu\nu}$
$N_{\text{leptons with } p>1}$	$\theta_{\text{j1}}, \theta_{\text{j2}}$	θ^{miss}	$\theta_{jj/ll}$
$N_{\text{leptons with } p>2}$	$N^{\text{mean}}_{\text{jet const}}$		$\theta_{ll/\nu\nu}$
	$N^{\text{min}}_{\text{jet const}}$		
	$N^{\text{max}}_{\text{jet const}}$		





- Significant gains over cut-based in all 3 sub-channels

ZH→ZZZ*→llvvqq: results

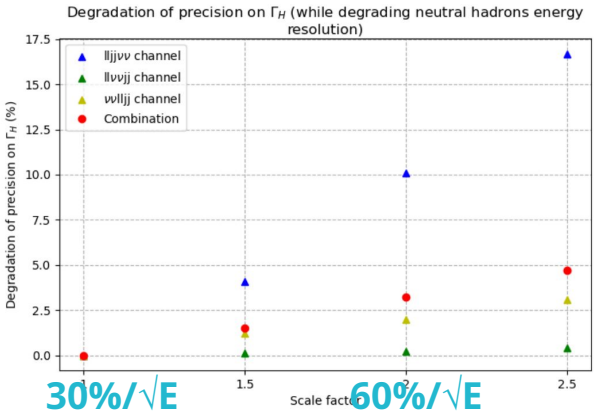
- 4.6% precision achievable with only these 3 sub-channels !

δΓ/Γ (%)	llvvqq	llqqvv	vvllqq	combination
Cut-based	9.0	17	8.7	6.6
BDT	7.4	10.7	6.9	4.6

- Fully dominated by stat. uncertainties

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

- Results robust wrt neutral hadron energy resolution



ZH→ZZZ*→llqqqq

Surprises on the path

- Started by looking at ZZ* → jets as larger BR
- Was meant to be a test bed for hadronic energy resolution:
  - Separation Z → jets from W → jets

Number of events for L = 5ab^{-1}								
Selection	$H(ZZ^*)$	ZZ	WW	$H(WW^*)$	$H(bb)$	$H(cc)$	$H(gg)$	$H(\text{other})$
Preselection (one $Z(ll)$)	801	419 933	17 753	12 648	36 443	1808	5119	2821
$N_{\text{selected leptons}} = 2$	798	408 700	17 515	9784	34 786	1791	5115	2320
$81 < m_{ll} < 101$ GeV	717	260 722	3558	8734	31 289	1611	4602	2058
$124 < m_{\text{recoil}} < 140$ GeV	680	23 358	1775	8279	29 683	1530	4368	1945
$E_T^{\text{miss}} < 13$ GeV	664	22 045	73	5824	25 797	1460	4348	634
$p_z^{\text{miss}} < 15$ GeV	659	16 314	49	5651	25 255	1443	4321	566
$110 < m_{jjjj} < 138$ GeV	638	9051	8	5205	22 927	1392	4259	208
$d_{34} > 60$	535	2840	8	4604	3930	231	2003	23

- First sets of cut reduces non-Higgs backgrounds a lot, but still small S/B
  - Next natural cuts should be on m_Z / m_{Z^*} …

ZH→ZZZ*→llqqqq

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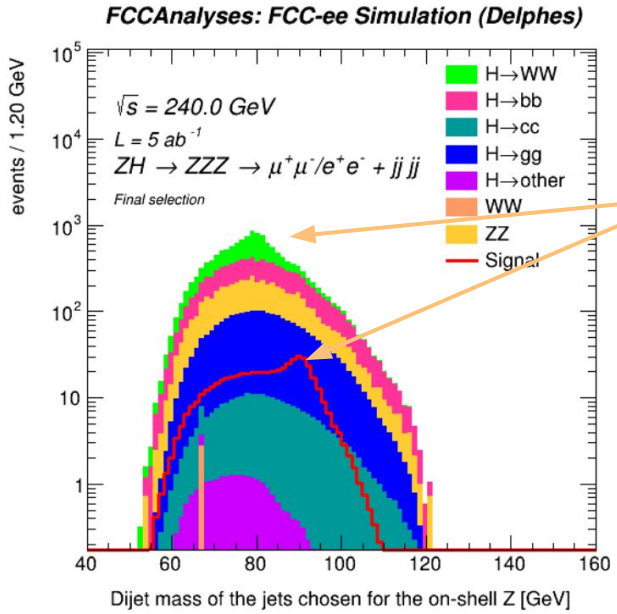

Very poor HZZ*/HWW* separation !

- Even assuming 30%/√E
- Why is the Z peak leaking so much ?

ZH→ZZZ*→llqqqq

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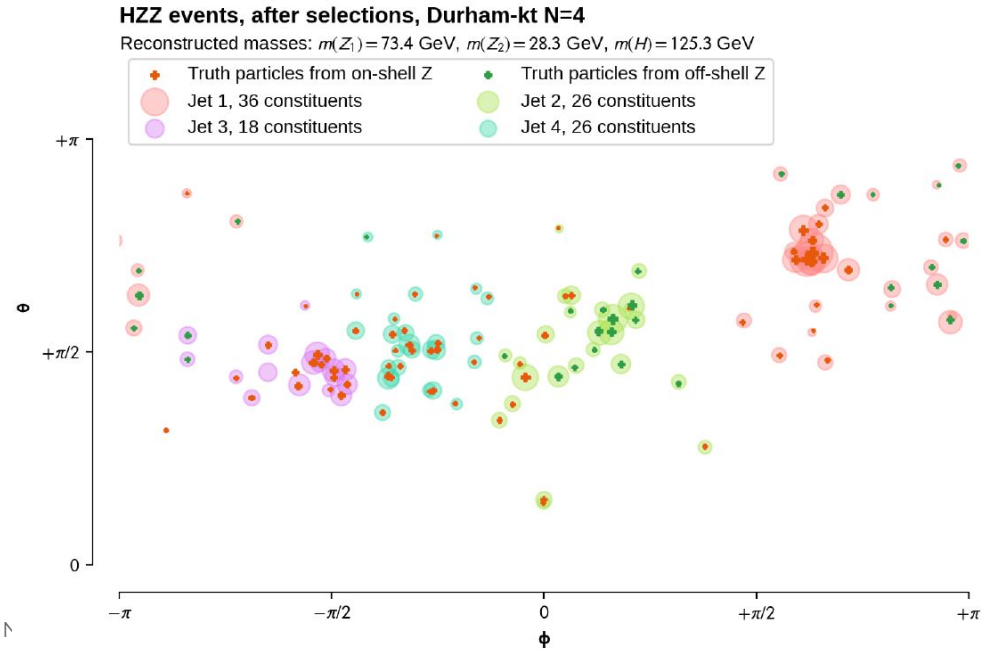
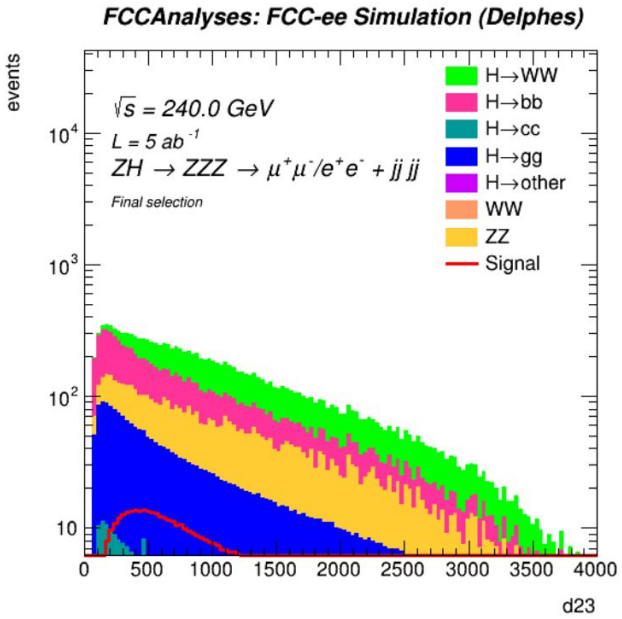
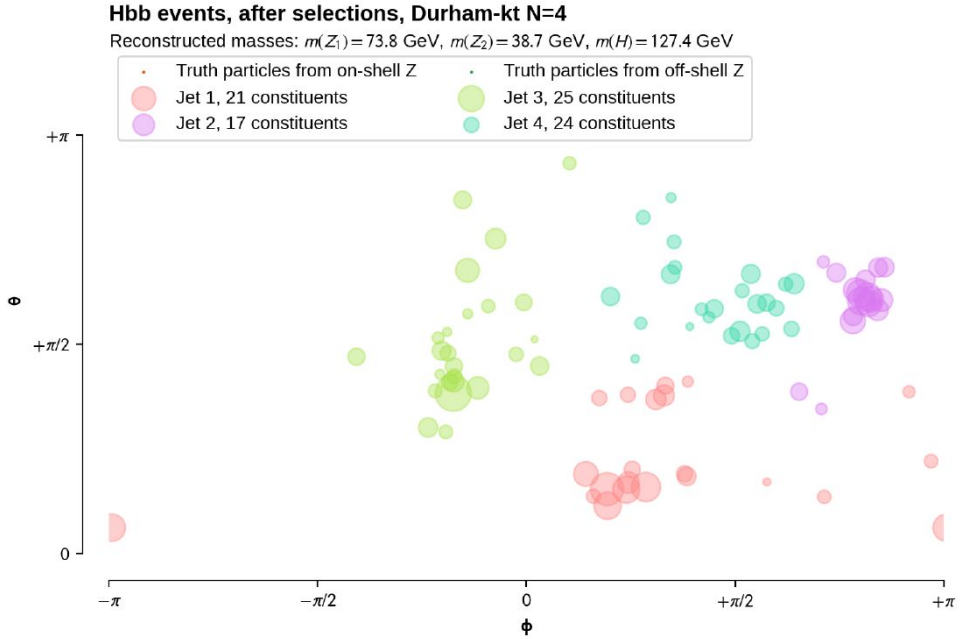


- Issue is **intrinsic**: particles from the decay of (low energy) Z and Z* are mixed in the theta/phi plane
  - seems very tough for any jet finding algorithm
- Excellent boson mass resolution (4% at 45 GeV for jets) is actually **irrelevant to separate H→ZZ*→jets from H→WW***

ZH→ZZZ*→llqqqq: further hiccups

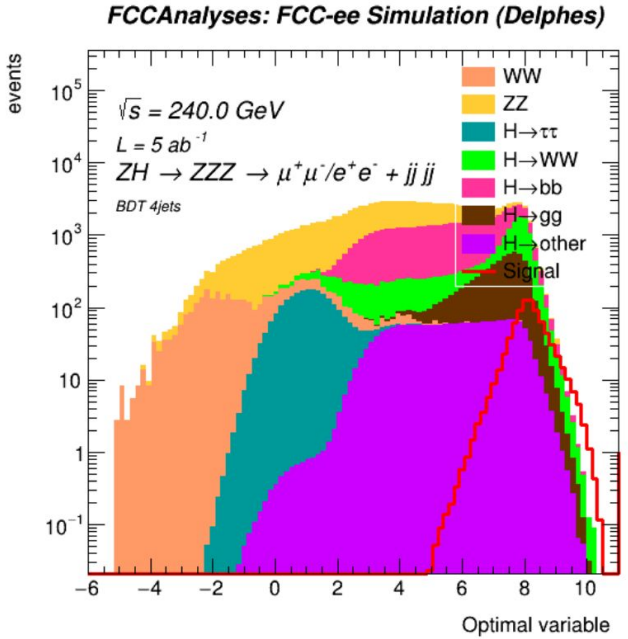
- Still large backgrounds from H→bb/cc/gg
- d-cuts indicate they are **4-jets like topologies**
- Checked on event displays that it's indeed the case





ZH→ZZZ*→llqqqq: hope for progress ?

- Implementation of BDT shows that there is still a lot to be gained in kinematics
  - Precision 12.4%
- Using flavour tagging to further classify the events should help
  - Esp. H→WW* and H→bb backgrounds will be in different categories
- Other sub-channels, esp. qqqqll, might be easier
  - No very low E jet
  - Low-mass lepton pair should be quite characteristic of Z*→ll
  - To be studied…



Prospects for H→ZZ* measurements

We need to study (almost) ALL channels to get to the maximum precision

- Study of llvvqq channels well advanced already
  - 3 sub-channels to add. Expected sensitivities similar to channels studied so far
- Addition of 4-lepton channels
  - Low stats, but should be basically background-free
  - Sensitivity ~5%
- Further investigation of the 4-jets channels
  - Clear possibilities to make them relevant in the combination
- Other channels ?
  - 6-jets seems extremely difficult
  - vvqqqq channels ?
- **2-3% precision on Γ_H from H→ZZ* measurement seems within reach !**

Higgs width: a great project for second part of feasibility study ?

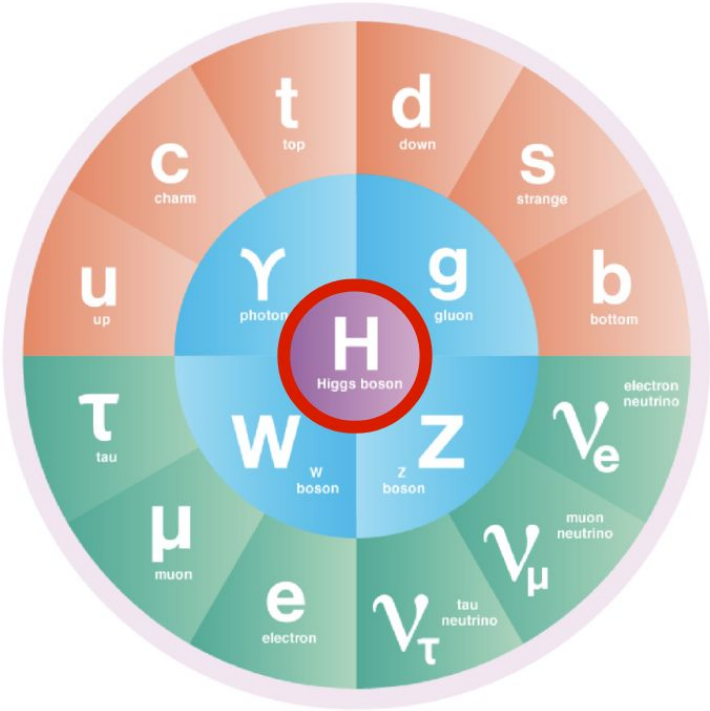
Higgs width measurement as a research project:

- Many final states to explore
  - Already with ZH → ZZZ*
  - And even more with the measurement using VBF events
  - The ultimate precision will come from the **combination of all of them !**
    - There is not a single channel that dominates the overall sensitivity

- Work for everyone
  - Many channels are **easily accessible for newcomers**: other “mixed” channels, 4 lepton channels…
  - Will benefit a lot from recent developments in e.g **flavour tagging**
  - Width measurement in VBF is a **whole new project** to explore
  - Add **tau-ID and tau reconstruction** would add quite a bit of stats, help to reduce backgrounds
    - and be beneficial to many other FCC analyses
  - Hard problems for experts to solve: ZZ → 4 jets reconstruction
  - Given the diversity of final states, a good match to help defining **detector requirements**

Conclusions

- Precise measurement of the Higgs total width (without assumptions) is one of the main goals of FCC-ee
  - Impossible to achieve at hadron colliders
- End result will be a combination of H→ZZ* measurement and of VBF cross-section
- Preliminary studies of H→ZZ* give confidence that expected precision can be met
  - Documented in FCC note
  - Would love to see new collaborators pickup from there and continue the study !



Backup

The FCC-ee Higgs dataset

Higgsstrahlung

- 1 million clean ZH events at 240 GeV
- (2 experiments)

Vector boson scattering

- Decent statistics (50k events) at 365 GeV
- Very complementary for many of the measurements