FUTURE CIRCULAR COLLIDER

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U.S. DEPARTMENT OF ENERGY

Z(cc)H at FCC-ee

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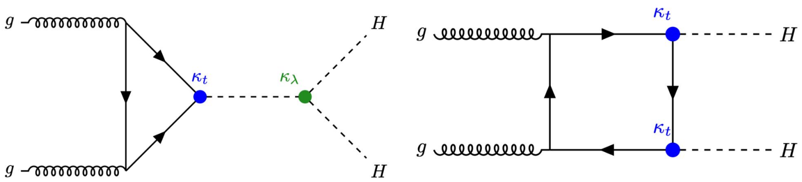
Introduction: Higgs self-coupling

- We want a **precise** measurement of **Higgs self-coupling**:
  - Fundamental test of **SM**
  - Use to search for variety of **BSM** physics

- Current estimated precision at HL-LHC: **~50%** (conservative) w/ Higgs pair production



- Estimated precision at FCC-hh: **~5%**

collider	single-H	HH	combined
HL-LHC	100-200%	50%	**50%**
$CEPC_{240}$	49%	–	49%
ILC_{250}	49%	–	49%
ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
* FCC-hh	-	5%	**5%**

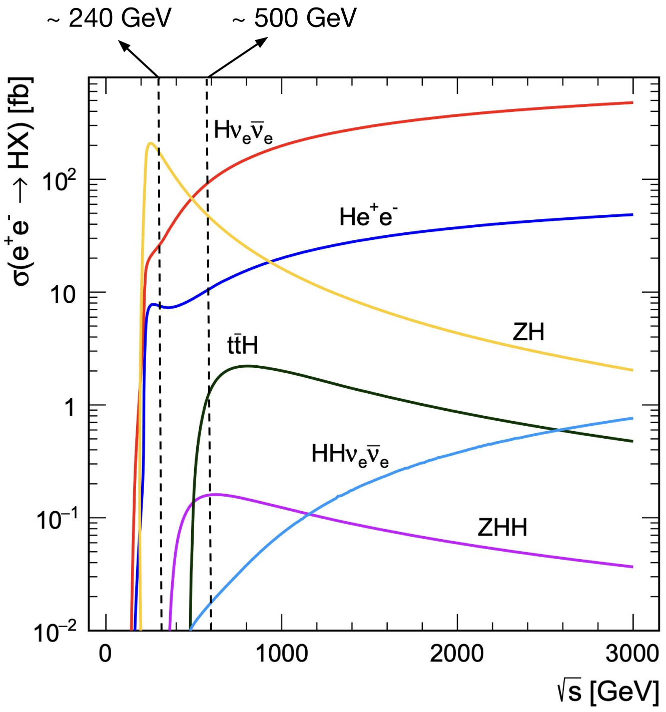
These values are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.

Sally Dawson, Caterina Vernieri @ LHC Higgs Working Group, December 3, 2021

* arXiv:2004.03505 2.9-5.5% depending on the systematic assumptions

Introduction: Self-coupling at FCC-ee

- HH production turns on at an e^+e^- collider:
  - **~500 GeV** for **ZHH**
  - Even higher for **HH$\nu\nu$**
- Center-of-mass energy at FCC-ee is **too low** (240 - 365 GeV) to produce **pairs of Higgs bosons** directly
- However, we have **indirect** sensitivity to the Higgs self-coupling from higher order contributions to **ZH** (main production mode), **VBF-H** production, and Higgs branching ratios



σ vs. √s, including HH

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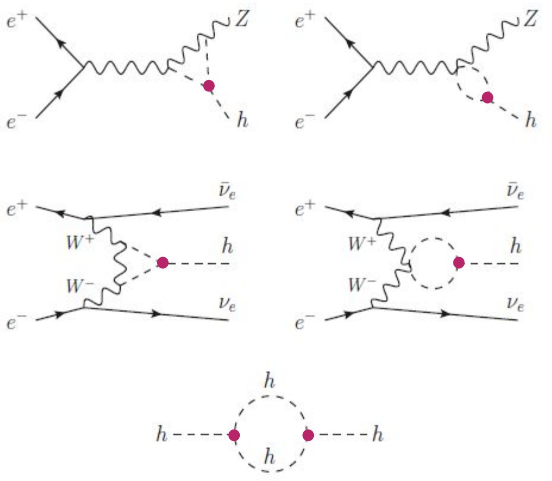
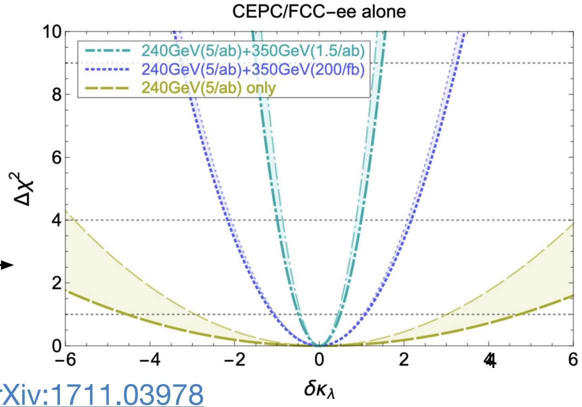
How to measure the Higgs self-coupling at the FCC-ee?

- The self-coupling measurement depends on measurements of Higgs production cross sections and decays to other particles.
- The κ analysis is expected to reach **~20%** accuracy [arXiv:1905.03764], while the global effective field theory fit will reach **~30%** [arXiv:1711.03978] (in combination with HL-LHC projections!)
- **The ZH cross section (240 GeV run) is most sensitive to changes in the self-coupling**
  - 365 GeV run is crucial for reducing uncertainties!





arXiv:1711.03978

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Z(cc)H study

Z(cc)H motivation

- Can we make a better ZH cross section measurement with exclusive ZH studies?
- **We propose a Z(cc)H study**
  - Few(er) existing studies with ZH→hadronic
  - Excellent test-case for c-tagging improvements (see George's talk) - unlikely to suffer from combinatoric problems with (rare) H(cc) decays
- Longer-term plans
  - Use results to aid in detector optimization studies ("what kind of detector will we need to enable this measurement?")
  - Combination with on-going studies in other Higgs channels for final self-coupling constraint
- This is our first time thinking about lepton colliders - lots to learn!

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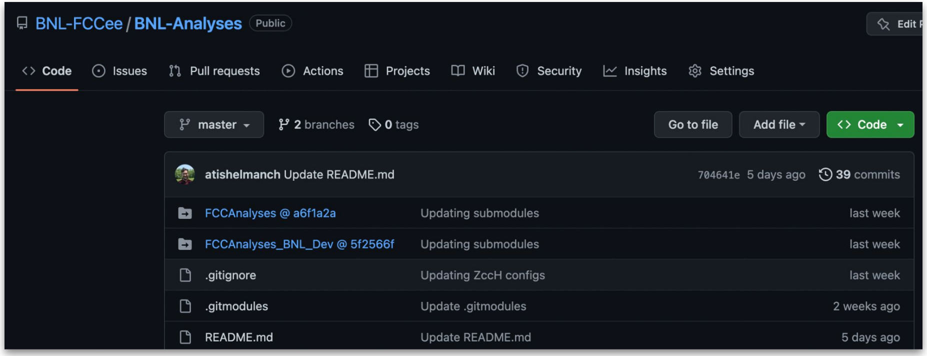
Kinematic study: Setup

- Using FCCAnalyses framework
- Analysis configuration files defined in BNL-FCCee GitHub organization
  - ZccH_stage1.py
  - ZccH_final.py
  - ZccH_plots.py
- Using samples from **Winter 2023** campaign:
  - Produced by **Louis Portalès**
  - $\sqrt{s}$ = 240 GeV
  - WHIZARD event generator
  - Delphes simulation of **IDEA** detector
  - Signal: Z(cc)H(exclusive)
  - Background: WW, ZZ, qq



BNL-Analyses

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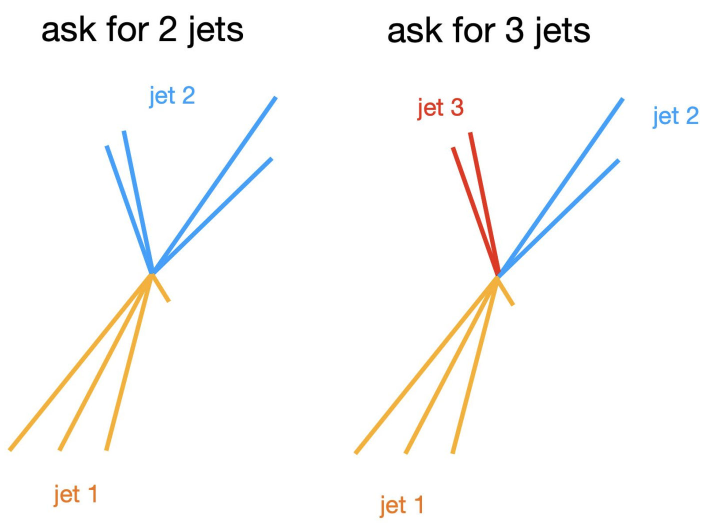
Kinematic study: Re-clustering

- Inclusive vs. exclusive jet clustering
  - **Inclusive**: define size of jets "I want all the jets with some particular ΔR"
  - **Exclusive**: define number of jets to be clustered "I want three jets"
- Using **exclusive jet re-clustering** - Require **four** jets per event [targeting Z(cc)H(hadrons)]
- For more jet details, see this excellent talk:
  - [27 June 2022 - FCC Physics performance meeting], Matteo Cacciari, Gavin Salam and Gregory Soyez



Same event,
two interpretations!

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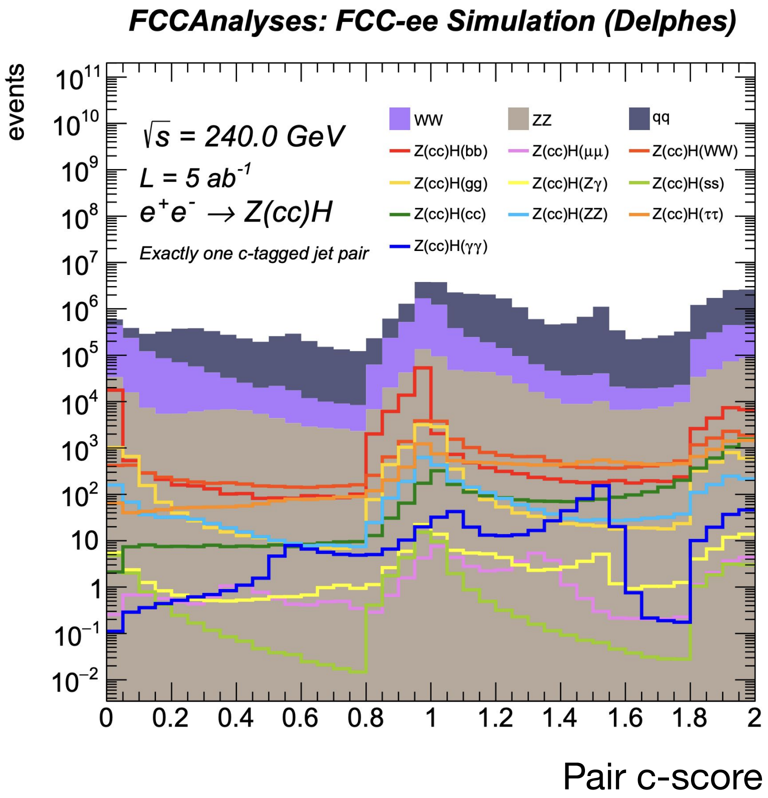
Kinematic study: Jet pair c-score

- Each jet has a c-score assigned
  - "How charm-like is this jet?" from 0 (not-charm-like) to 1 (charm-like)
- "**Pair c-score**": Sum the two c-scores for each of <u>6 **jet pairs**</u> in the event:
  - Range: [0, 2]
- Peaks at **2** for events with cc-like jet pairs (expected from Z(cc))
- Peak around **1** indicates:
  - One jet tagged **c-like**
  - Other jet tagged as **not-c-like**



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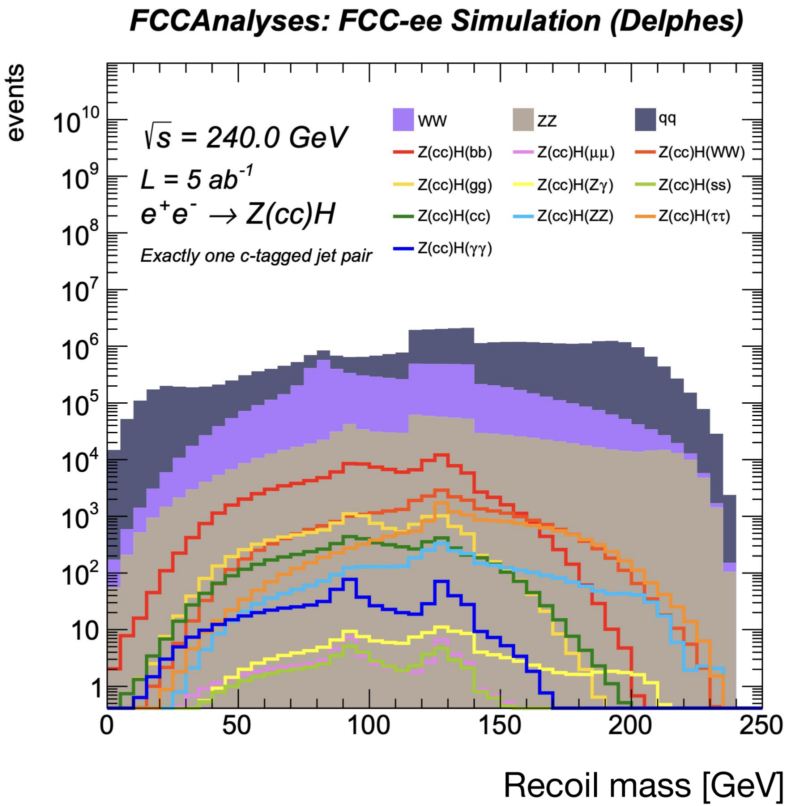
Kinematic study: Recoil mass

- Events with:
  - **Exactly** one dijet pair with **c score** > 1.8
  - **Exactly** one dijet pair with recoil mass 115 - 140 GeV (remember, still **6 entries** per event)

- Z(cc)H(bb) has highest yield signal peak around 125 GeV

- Z(cc)H(γγ) and Z(cc)H(ττ) peaks are sharp, but lower yield.

- Interestingly, see WW sample peak around 80 GeV
  - Tagging W from W(hadhad)W(X) process?



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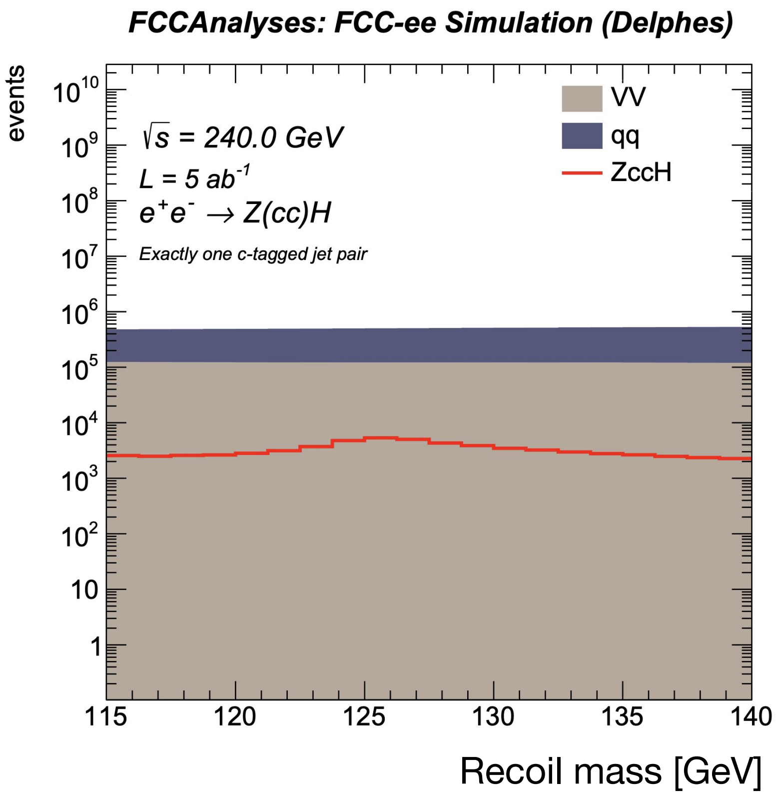
Kinematic study: Higgs mass

- **Same selections, zoom into higgs mass window**
- **Discernable peak** at the **Higgs mass** from **Z(cc)H**, but very **high background** yield.
- Backgrounds have **non-peaking** structure, can remove with further selections:
    - Require jet pair mass in **Z window** (Reduce W→hadrons background)
    - Add **lepton** and **missing energy** rejection
      (reduce leptonic VV background)



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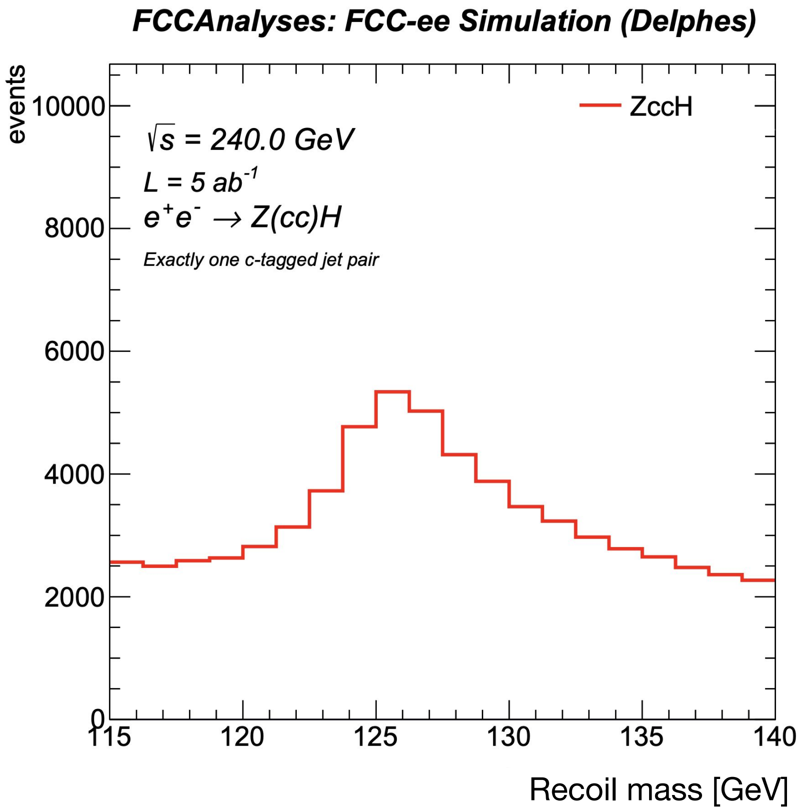
Kinematic study: Signal Higgs mass

- **Same selections**
- **Signal only** to look at **shape**
- Lots of incorrectly reconstructed **mass values** - motivates improved Z(cc) **pairing** strategy



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Summary

- **The Higgs self-coupling can be measured indirectly at the FCC-ee, hopefully with higher precision than at the HL-LHC**
  - This measurement depends on precise measurements of the Higgs cross sections and branching ratios, using data from runs at several center-of-mass energies
- We are interested in studying ZH→hadronic, starting with Z(cc)H
- We'd love to collaborate with [you]! You can reach us at:
  - elizabeth.brost@cern.ch
  - abraham.tishelman.charny@cern.ch

Backup

What precision do we *need* on the Higgs self-coupling?

- **Is 50% enough?**
  - Depends which models you would like to study
- **Motivates future colliders**
  - “**The goal for future machines beyond the HL-LHC should be to probe the Higgs potential quantitatively. This requires at least gold quality precision for the self-coupling parameter.** … achievable … at the highest energy lepton machines (ILC_{1000} or $CLIC_{3000}$) and hadron machines (FCC-hh)”

- **Bronze (100%):** sensitive to models with the largest new physics effects
- **Silver (25-50%):** can exclude a physical hypothesis with realistic deviations in the Higgs self-coupling
- **Gold (5-10%):** sensitive to a broad class of loop diagram effects… could complement measurements on new particles that could be discovered at the HL-LHC.
- **Platinum (1%):** sensitive to typical quantum corrections to the Higgs self-coupling generated by loop diagrams.

HH White Paper 2018 arXiv:1910.00012

Samples

- **Winter 2023 campaign:**
  - [Link]
  - 240 GeV, WHIZARD event generator
  - Delphes simulation of IDEA detector

Process	Z(cc)H(bb)	Z(cc)H(WW)	Z(cc)H(gg)	Z(cc)H($\tau\tau$)	Z(cc)H(cc)	Z(cc)H(ZZ)	Z(cc)H(γγ)	Z(cc)H(Zγ)	Z(cc)H(ss)	Z(cc)H(μμ)		Z/γ*→qq	WW	ZZ
σ*Γ **[pb]**	0.01359	0.005023	0.001911	0.001464	0.0006747	0.0006164	5.298e-05	3.578e-05	5.607e-06	5.079e-06		52.6539	16.4385	1.35899
σ*Γ / σ*Γ[Z(cc)H(bb)]	1	0.36961	0.140618	0.1077	0.04965	0.04536	3.90E-03	2.63E-03	4.13E-04	3.74E-04		3874.46	1210	100
Events generated	200,000	1,200,000	400,000	400,000	400,000	1,200,000	400,000	400,000	300,000	400,000		100,559,248	373,375,386	56,162,093

- Total expected **Z(cc)H** events with lumi = 5 ab^{-1}: **116,892**
- Total expected **qq/WW/ZZ** events with lumi = 5 ab^{-1}: **352,256,950**
- Try to use **recoil** mass of **Higgs peak** to separate Signal and background.

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Signal yields

- Total yield with No Selections **matches expected number:** 116,891.83
- Highest weighted yields **(scaling to be verified)**:
  - Z(cc)H(bb) when tagging a **cc pair**, w/ recoil mass near Higgs peak
- Tagging a c pair with recoil mass near Higgs has ~ **13.6 - 42**% efficiency

	No Selection	Exactly 4 jets	Ex one jet pair B tagged, near Higgs window	Ex one jet pair C tagged, near Higgs window
Z(cc)H(WW)	25115.000 ± 3.317	25115.000 ± 22.927	12.034 ± 0.502	4897.320 ± 10.124
Z(cc)H(gg)	9555.000 ± 2.335	9555.000 ± 15.108	16.697 ± 0.632	2125.581 ± 7.126
Z(cc)H(Zγ)	178.900 ± 0.006	178.900 ± 0.283	3.945 ± 0.042	24.364 ± 0.104
Z(cc)H(ss)	28.035 ± 0.000	28.035 ± 0.051	0.001 ± 0.000	8.977 ± 0.029
Z(cc)H($\mu\mu$)	25.395 ± 0.000	25.395 ± 0.040	0.008 ± 0.001	10.422 ± 0.026
Z(cc)H(ZZ)	3082.000 ± 0.143	3082.000 ± 2.813	80.838 ± 0.456	579.139 ± 1.220
Z(cc)H($\tau\tau$)	7320.000 ± 1.566	7320.000 ± 11.574	3.916 ± 0.268	2539.271 ± 6.817
Z(cc)H($\gamma\gamma$)	264.900 ± 0.011	264.900 ± 0.419	0.003 ± 0.001	112.203 ± 0.273
Z(cc)H(cc)	3373.500 ± 0.490	3373.500 ± 5.334	0.152 ± 0.036	972.082 ± 2.863
Z(cc)H(bb)	67950.000 ± 88.563	67950.000 ± 151.941	9201.789 ± 55.913	20429.167 ± 83.312

	Z(cc)H(WW)	Z(cc)H(gg)	Z(cc)H(Zγ)	Z(cc)H(ss)	Z(cc)H($\mu\mu$)	Z(cc)H(ZZ)	Z(cc)H($\tau\tau$)	Z(cc)H($\gamma\gamma$)	Z(cc)H(cc)	Z(cc)H(bb)
No Selection	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Exactly 4 jets	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Ex one jet pair B tagged, near Higgs window	0.000	0.002	0.022	0.000	0.000	0.026	0.001	0.000	0.000	0.135
Ex one jet pair C tagged, near Higgs window	0.195	0.222	0.136	0.320	0.410	0.188	0.347	0.424	0.288	0.301

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Background yields

- Total yield with no selection matches expectation:
  - **352,256,950**

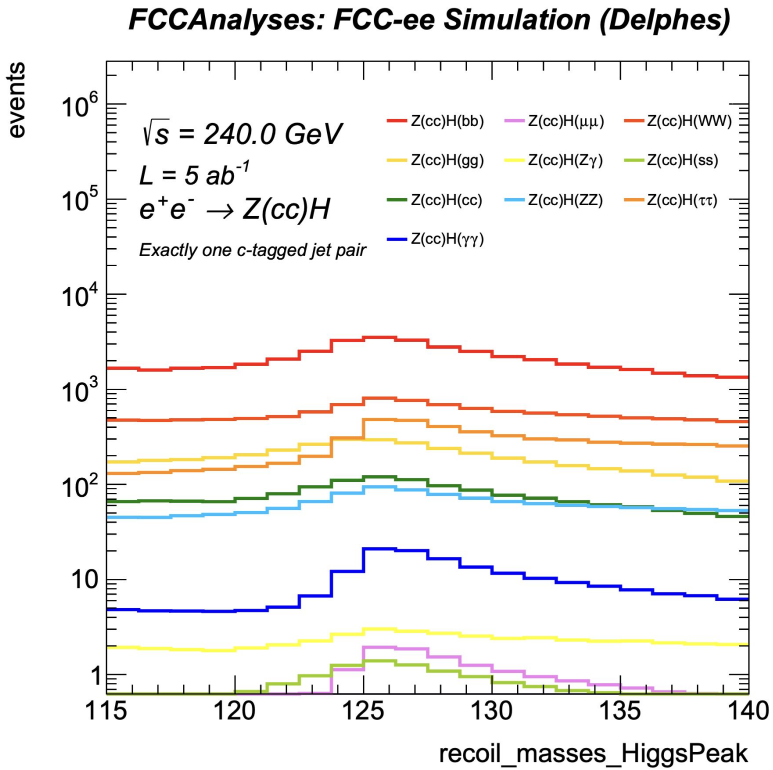
	No Selection	Exactly 4 jets	Ex one jet pair B tagged, near Higgs window	Ex one jet pair C tagged, near Higgs window
qq	263269500.000 ± 42479.442	261805416.364 ± 26180.539	6554221.233 ± 4142.379	4757393.459 ± 3529.180
WW	82192500.000 ± 2002.707	75993087.167 ± 4097.205	13484.571 ± 54.578	1134011.005 ± 500.506
ZZ	6794950.000 ± 315.381	6311147.022 ± 873.827	285306.970 ± 185.792	158321.758 ± 138.402

	WW	ZZ	qq
No Selection	1.0	1.0	1.0
Exactly 4 jets	0.925	0.929	0.994
Ex one jet pair B tagged, near Higgs window	0.000	0.042	0.025
Ex one jet pair C tagged, near Higgs window	0.014	0.023	0.018

- Requiring a c-tagged jet pair with a recoil mass near the Higgs removes ~ **77% - 86**% of background, but there are **large yields** left.

Kinematic study: Signal Higgs mass

- See peaks from **other final states**
- Consistently see Z(cc)H(bb) with highest yield
- Other final states sub-dominant, but peak around 125 GeV.
- Can explore **channel dependent** kl effects



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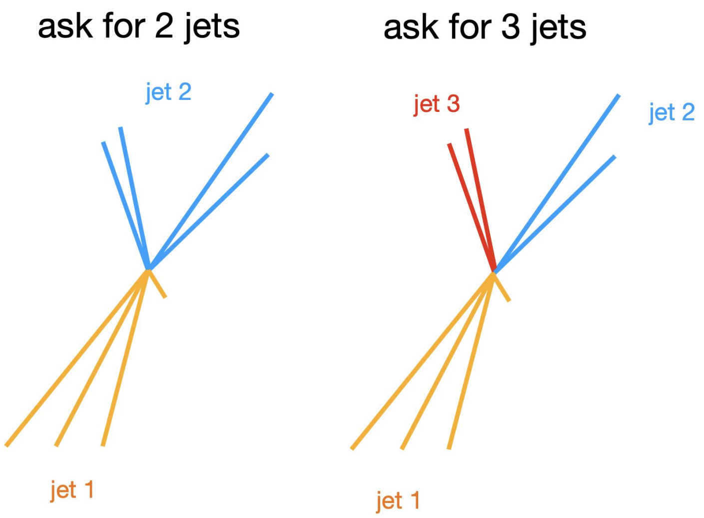
Kinematic study: Re-clustering

- Using **exclusive jet re-clustering** - Require **four** jets per event
  - [6 March 2023 - FCC Higgs performance meeting], Jan Eysermans, Emmanuel Perez, Michele Selvaggi



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