Massachusetts Institute of Technology

Optimizing the Search for $H \rightarrow Z\gamma$ at the FCC-ee

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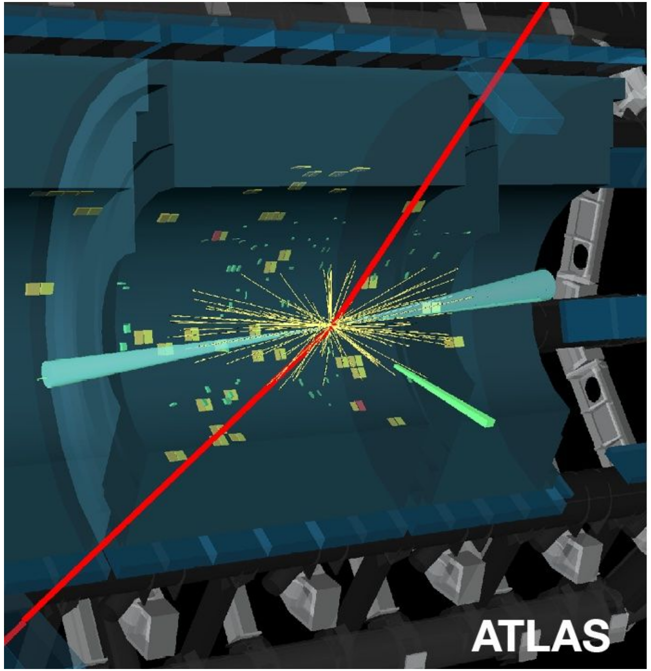
Outline

- Status of H $\rightarrow$ Zγ at the LHC
- Signal and Background Selection
- 2 Quark 2 Lepton Channel
- 4 Lepton Channel: Mass Reconstruction
- Kinematic Cuts: Histograms
- Cut Flow Analysis
- Conclusion

Status of H → Zγ

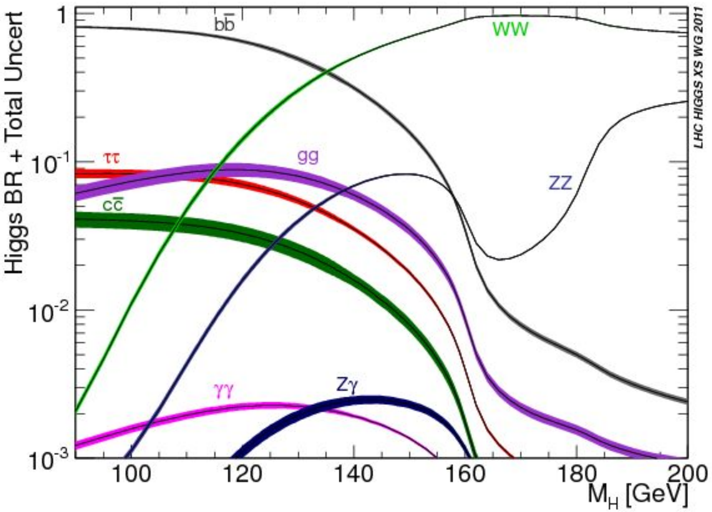
- Using data from LHC proton–proton collisions, ATLAS and CMS independently conducted searches for the decay H → Zγ → $\ell^+\ell^-$ γ at $\sqrt{s}$ = 7, 8, and 13 TeV
    - Search strategy: identify Z through its decays into pairs of electrons or muons
- May 2023: ATLAS-CMS collaboration announced first evidence of the H → Zγ decay (significance = 3.4 SD)



Candidate event from ATLAS for a Higgs decaying into a Z and a photon, with the Z decaying into 2 muons. (Image: CERN)

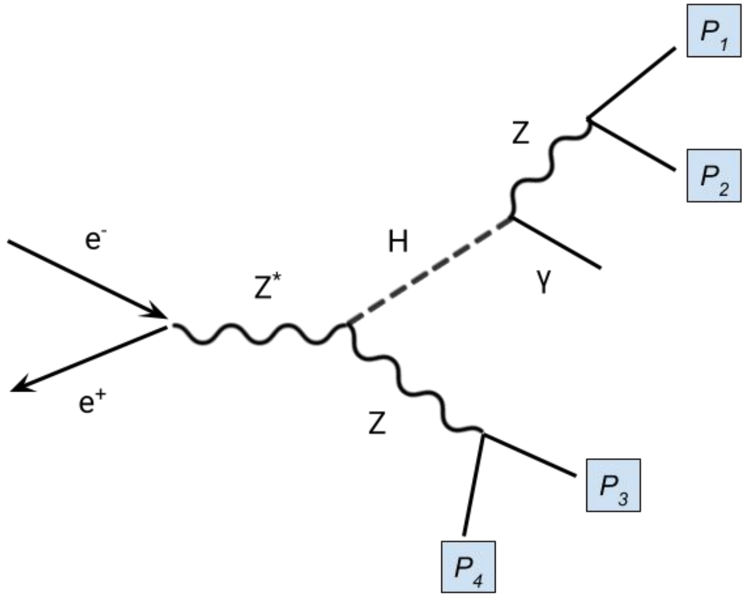
Future of $H \to Z\gamma$

- Sensitivity at LHC limited due to very low branching fraction of $H \to Z\gamma$
- FCC-ee could function as a Higgs factory, offering the opportunity to study rare Higgs decays such as $H \to Z\gamma$ with greater precision
- SM predicts that for Higgs with mass = 125 GeV, ~0.15% of Higgs will decay into $Z\gamma$
    - Studying $H \to Z\gamma$ pathway could offer insights into nature of Higgs boson and BSM physics



Branching fractions for Higgs boson

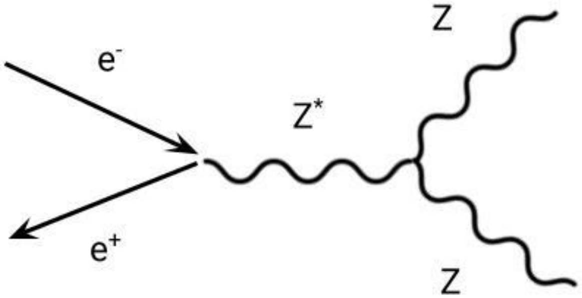
Signal Channels

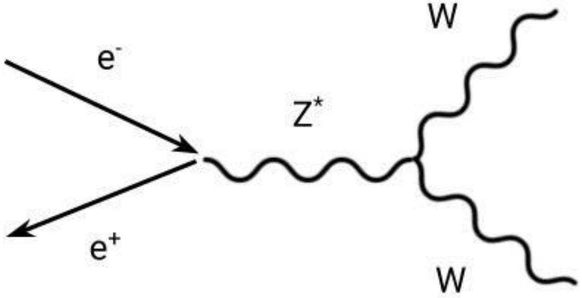


- Higgsstrahlung process in which Higgs decays into Z and a photon
- All processes studied at ECM of 240 GeV
- Channels determined based on the decay products of the two Z bosons:
  - 4 leptons
  - 2 quarks, 2 leptons
  - 4 quarks
  - Invisible (2q2nu, 2l2nu)
- Signal generator: Whizard

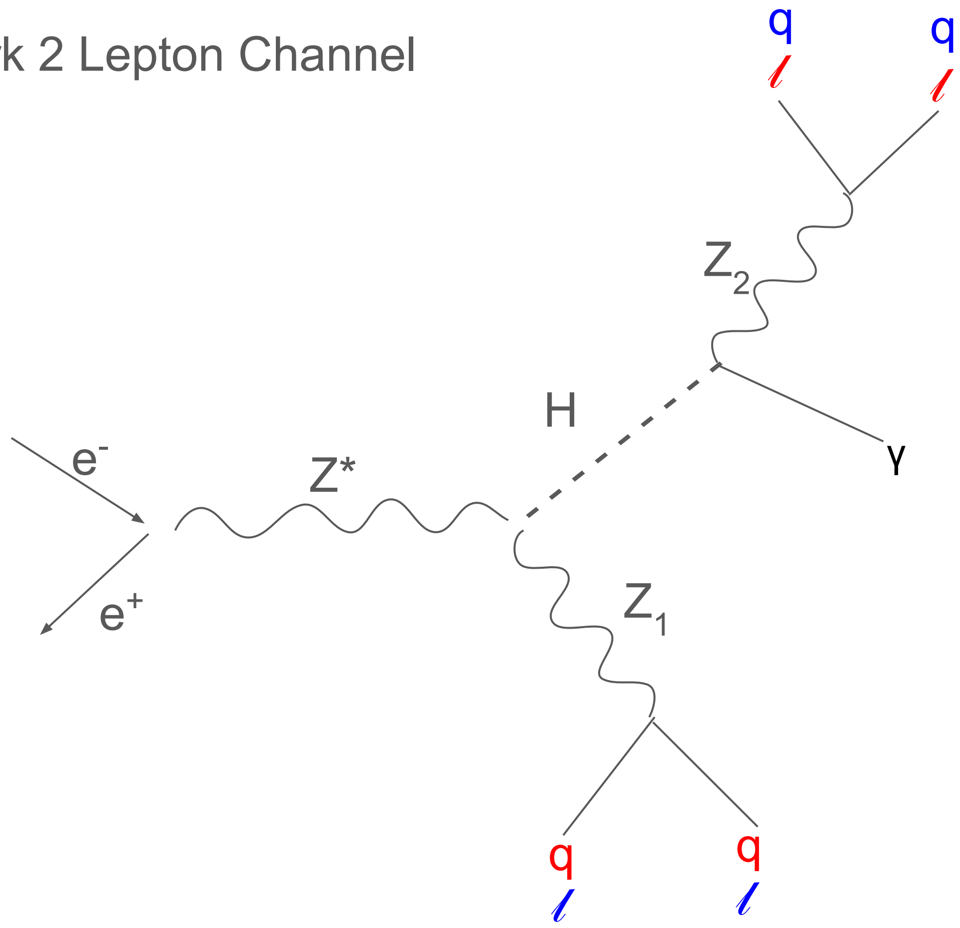
Backgrounds

- Primary backgrounds are diboson, with ZZ background dominant:
    - e +e → ZZ → *4l, 4q, 2l2q…*
    - e +e → WW → *4l, 4q, 2l2q…*
- *Additional backgrounds considered, but do not contribute:*
    - e +e → μμ
    - e +e → ττ
    - e +e → Z → qq
- Background generator: Pythia8





2 Quark 2 Lepton Channel

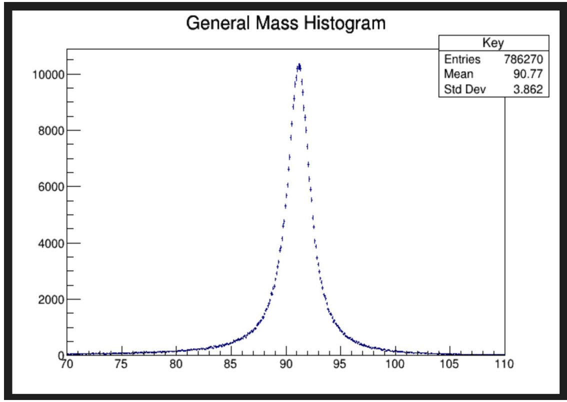


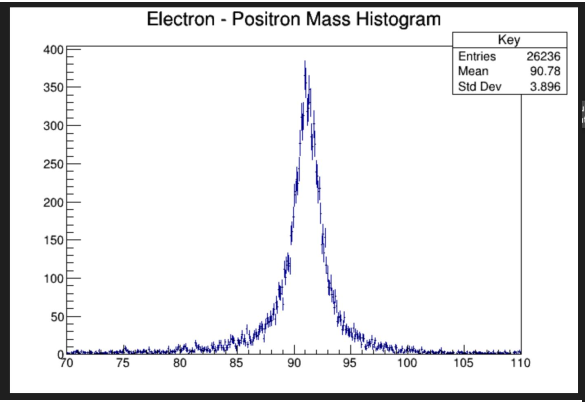
Only evaluating ee and mumu for leptons

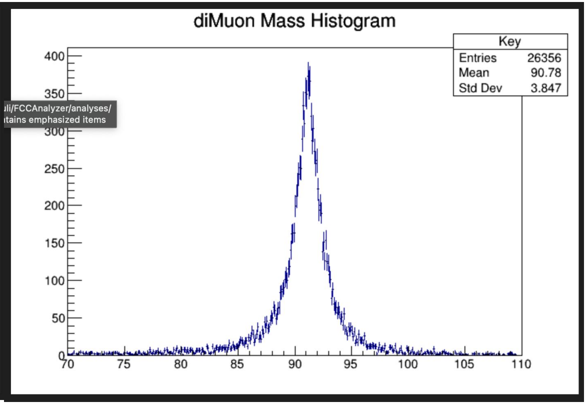
Reconstruction:

- Only consider events where two quarks and two leptons were produced.
- Reconstruct mass of Z_2 and Z_1
- Reconstruct mass of H based on Z_1 and energy of γ

Generator-Level







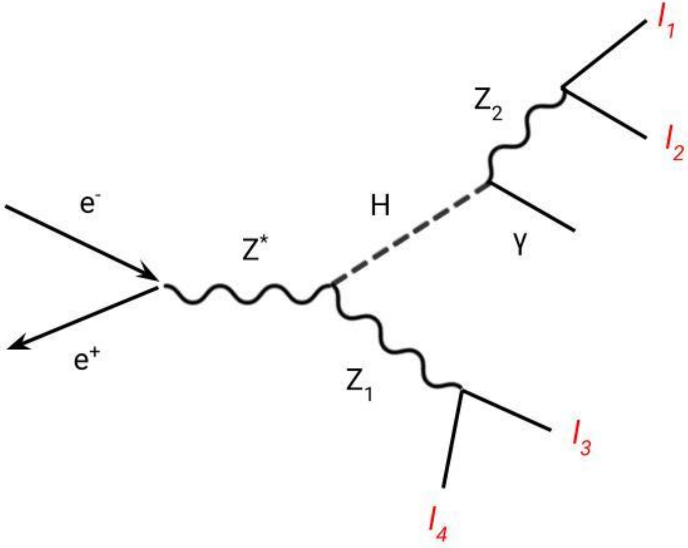
Histograms of the Z_1 decay product mass constructed from generator level information.

Does not prove much as all of the information regarding the Z boson was already available, instead we must attempt to reconstruct the mass of the Z boson based on its decay products.

Analysis future steps

- Plot all 2 lepton 2 quark events
- Find significant background events
    - Most significant are ZZ events
- Plot signal over background $(s/(s+b)^{1/2})$
- Make cuts while trying to optimize the amount of signal events

4-Lepton Channel



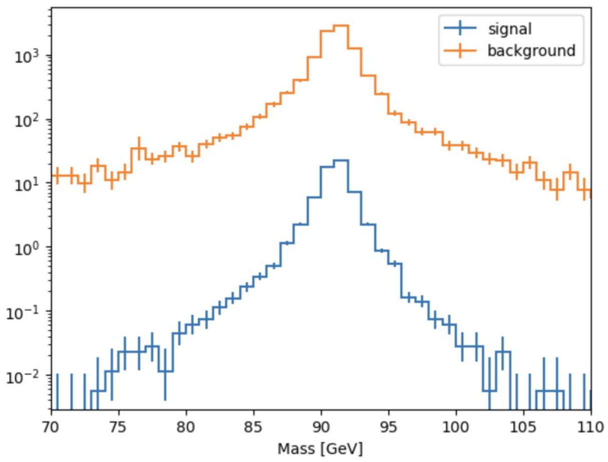
Only electrons and muons considered → 4 sub-channels: ee/μμ, μμ/ee, ee/ee, μμ/μμ

Reconstruction Process

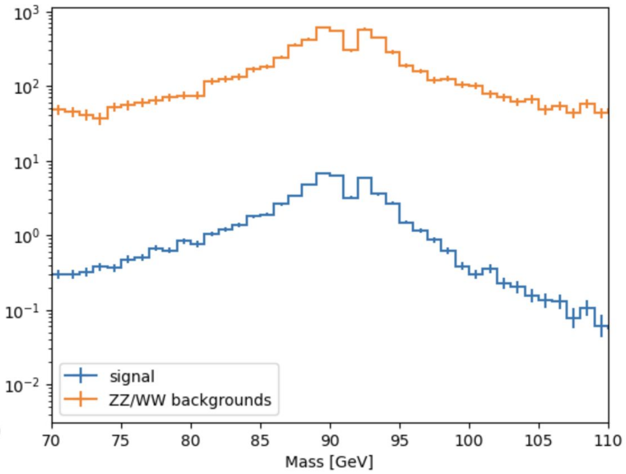
1. Initial selection for the number and type of final products (i.e. number of muons ≥ 4 in the 4 muon channel)
2. Construct resonance for Z_1 using relevant particles (i.e. 2 muons) with a mass of 91.2 GeV and recoil mass of 125 GeV
3. Reconstruct the Higgs using recoil of Z_1
4. Using remaining particles, find a second resonance to reconstruct Z_2 (decay product of the Higgs)

Initial Mass Reconstruction (μμ/μμ) Histograms

Z_1

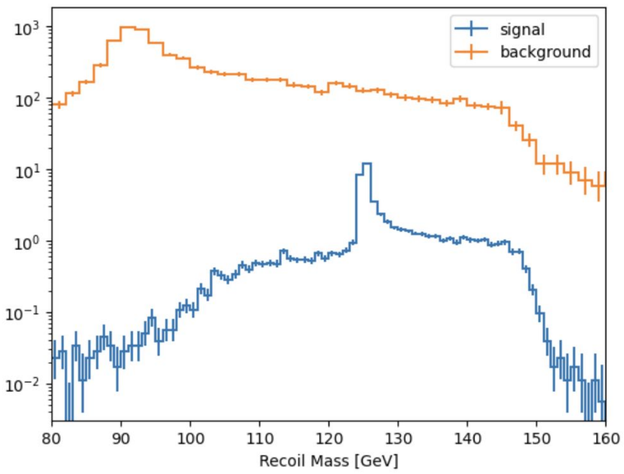


Z_2



Poor resolution for Z_2 suggests need for quality control in resonance building from the muons

Higgs



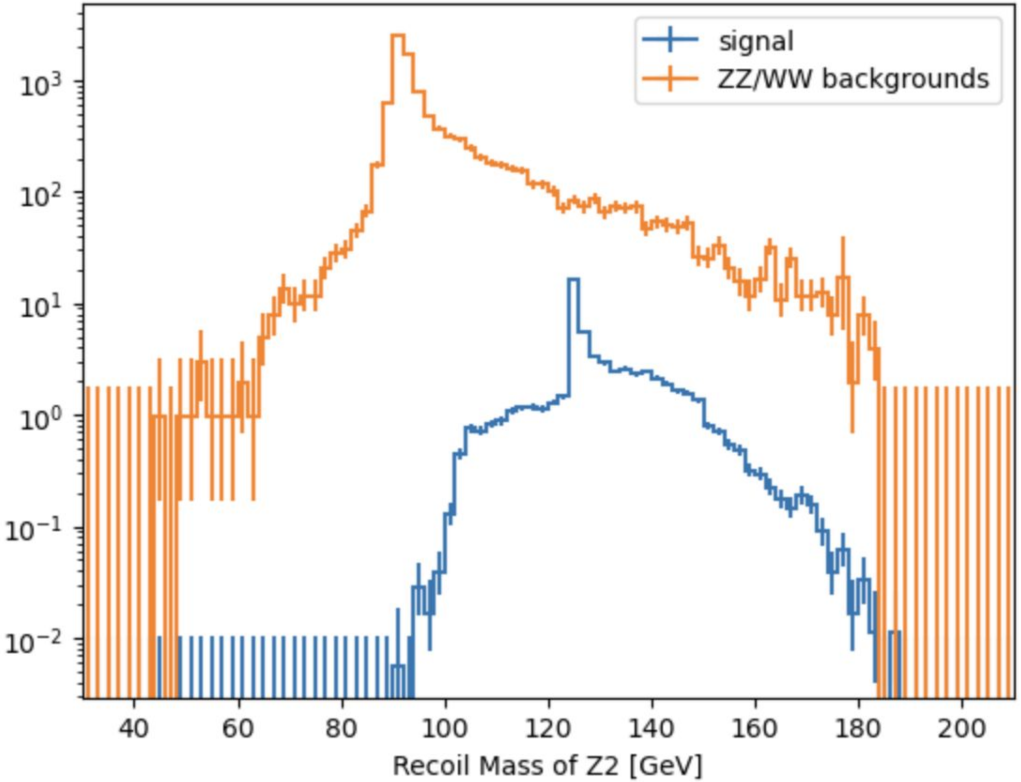
Background peaks around Z mass, likely due to e +e → ZZ process

Mass Reconstruction: Sub-channel Comparisons

	$Q = \frac{Nsig}{\sqrt{Nsig + Nbkg}}$		
	$80 < M_Z < 100$		$110 < M_H < 145$
Channel Z_1 leptons/Z_2 leptons	Z_1 (Higgs sister)	Z_2 (Higgs daughter)	Higgs
μμ/ee	0.477	0.503	1.250
ee/μμ	0.492	0.527	1.195
μμ/μμ	0.629	0.707	1.697
ee/ee	0.654	0.685	1.554

4 muon channel is the most sensitive

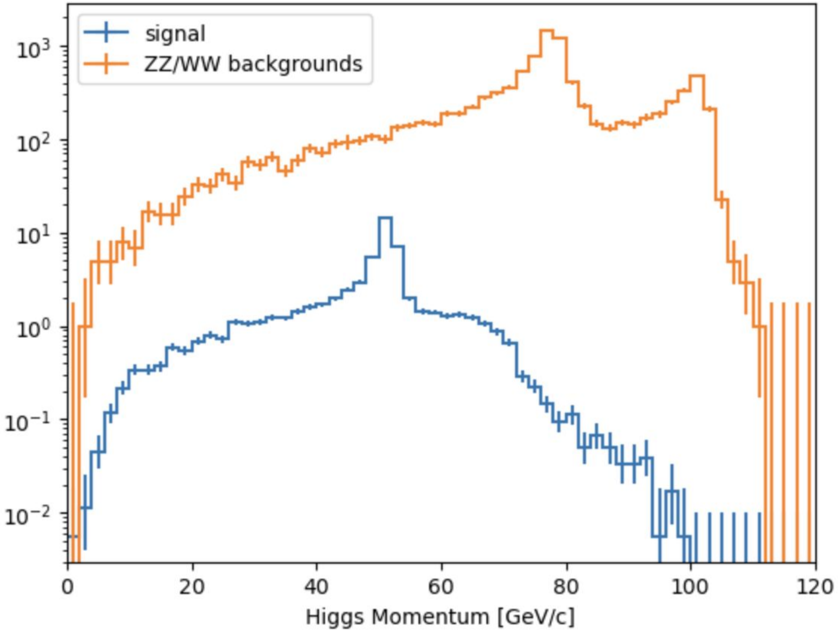
Z_2 Recoil Mass

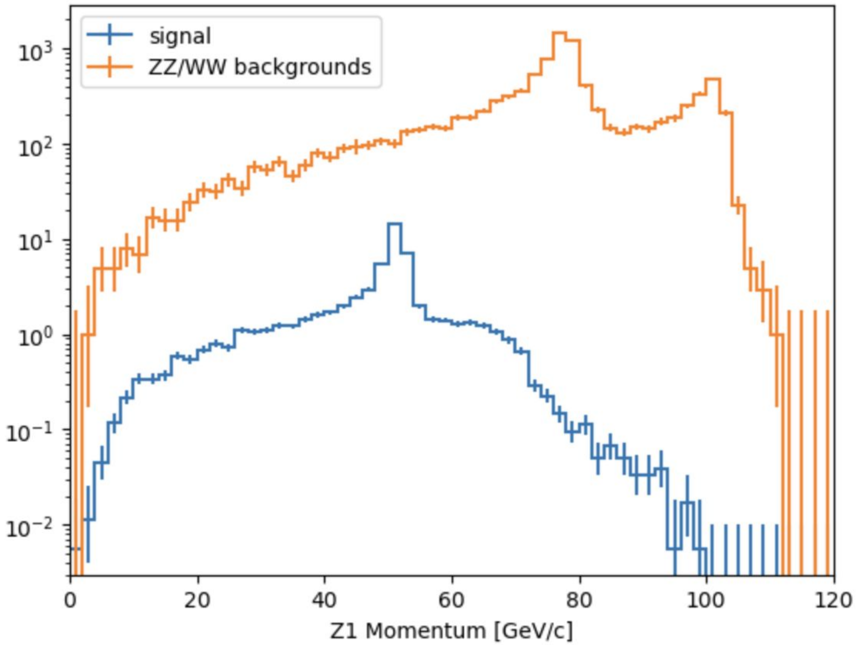


Cut: $100 < M_{recoil} < 165$

Background peaks around Z-mass (Z_1 in ZZ background)

Z_1 and Higgs Momentum

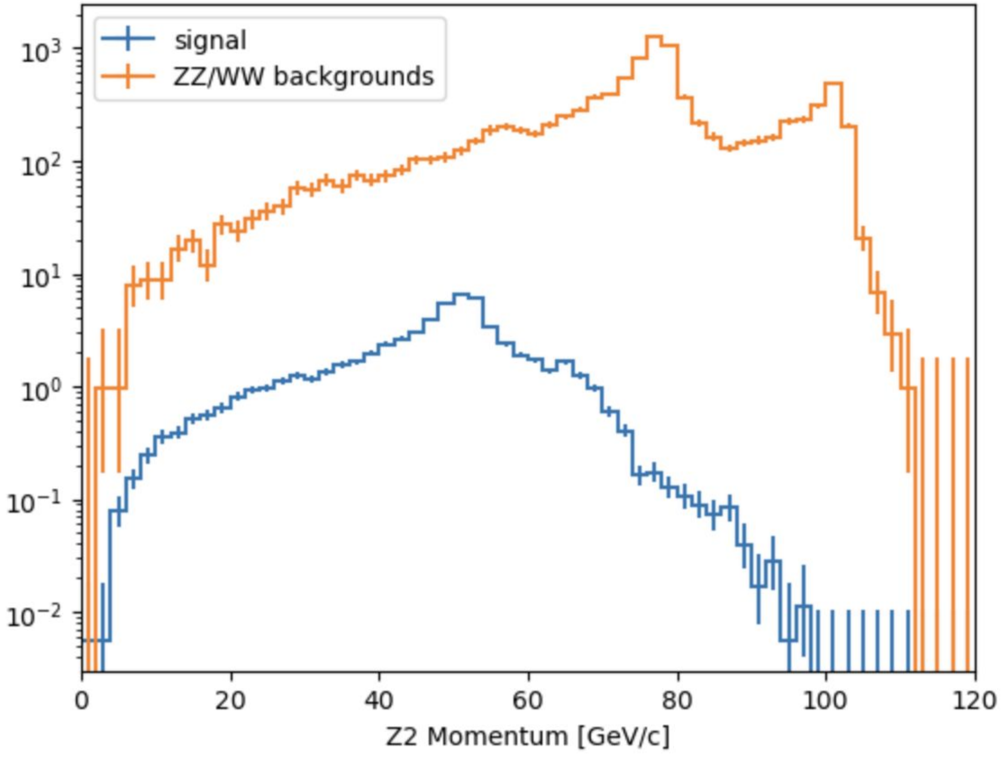




Higgs is constructed through recoil of Z_1 so momentum distributions are expected to be identical

Cut: $0 < p_Z < 75$

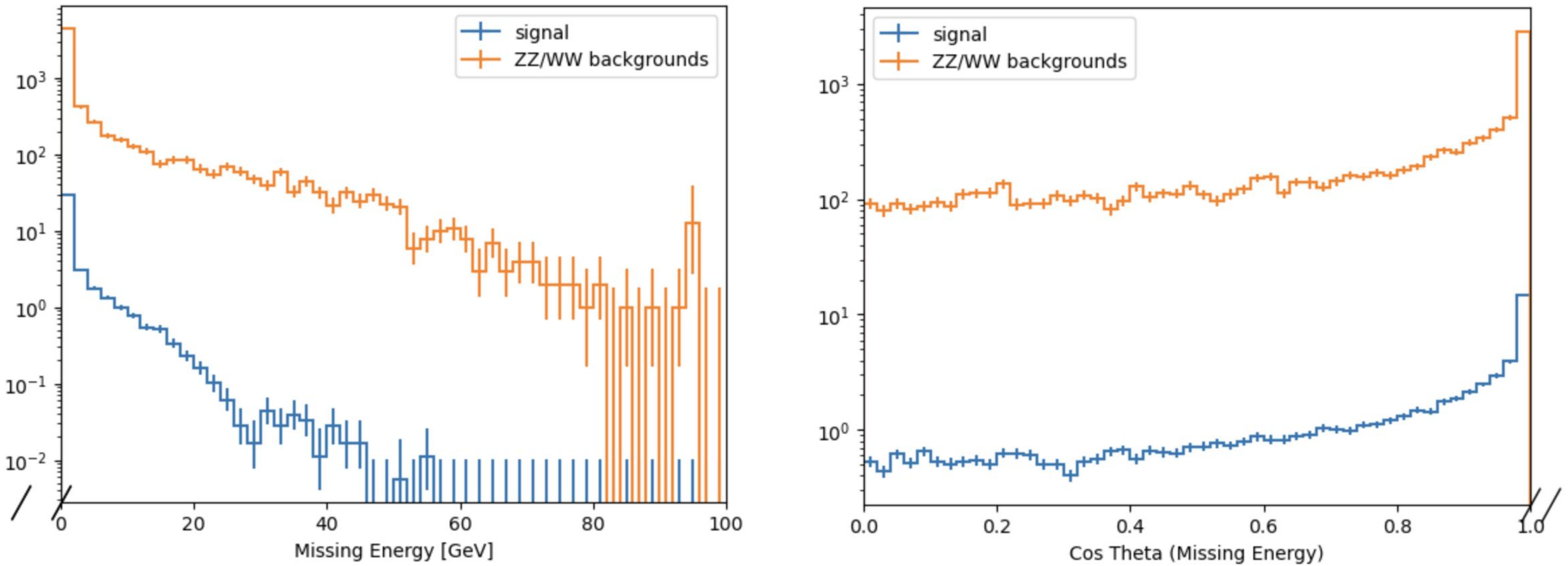
Z_2 Momentum



Momentum of Z_2

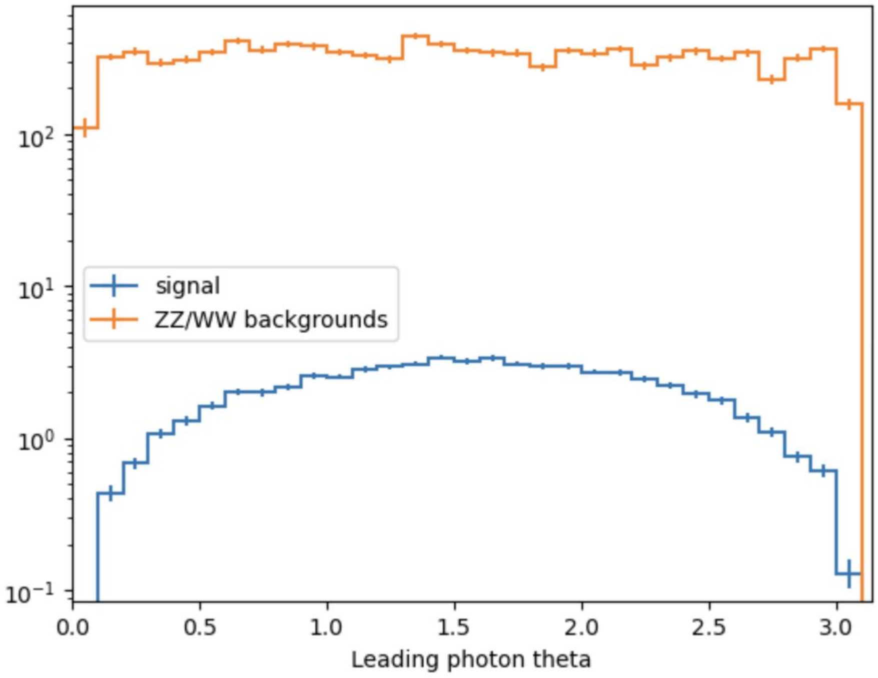
Cut: $0 < p_Z < 75$

Missing Energy and Cos(θ) of Missing Energy

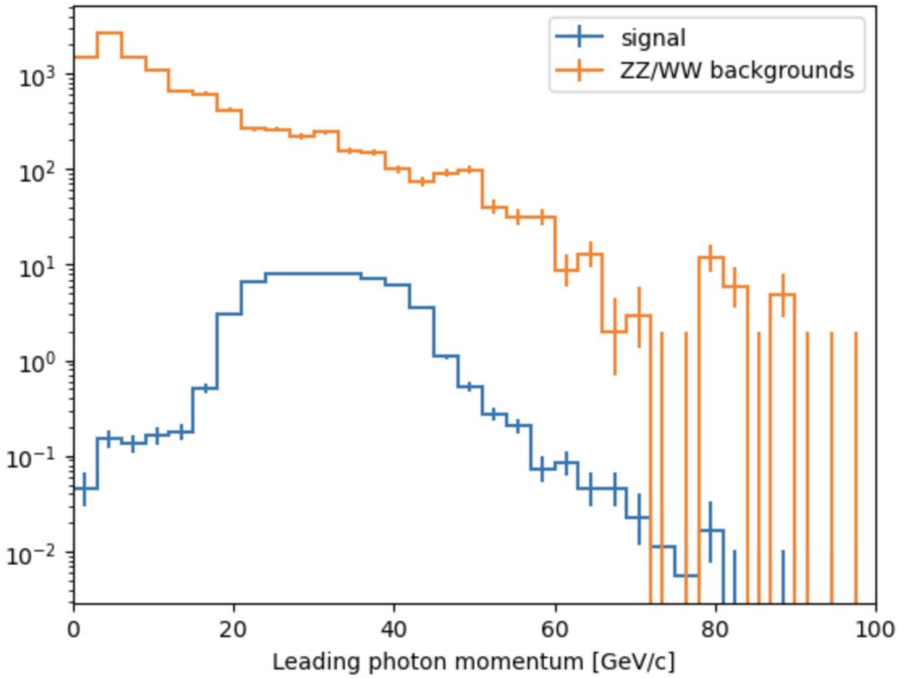


Cut: E_{miss} < 40

Leading Photon θ and Momentum



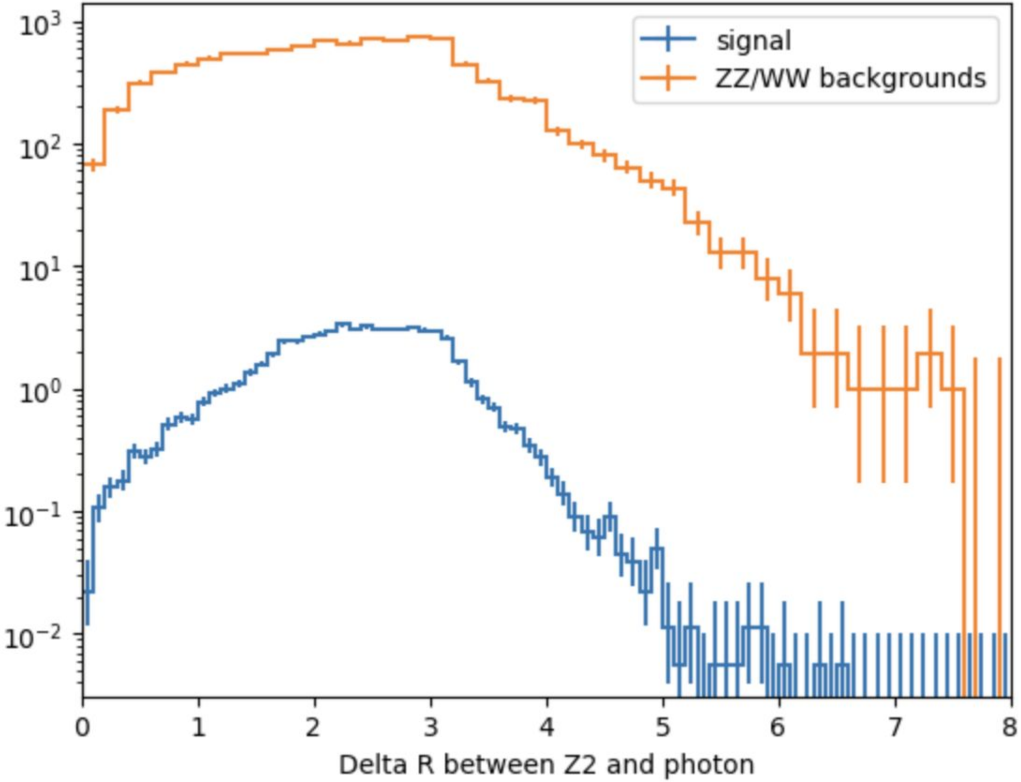
Cut: $0 < \theta_\gamma < 2.8$



Cut: $20 < p_\gamma < 50$

Peaks around ½ Higgs momentum

ΔR between Z_2 and Photon



Cut: 0 < ΔR < 4.5

Cuts

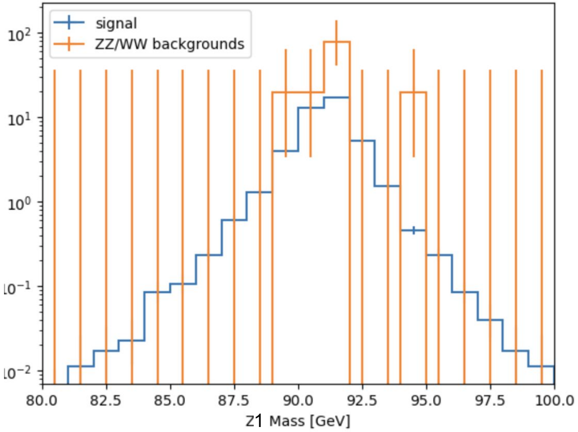
Variable	Condition	Signal Count	Signal % Selected	Background Count	Background % Selected	Q
No cuts		75		638729208		**0.00295**
Muon count	$N_\mu \geq 4$	62	100%	10126	100%	**0.615**
Z_1 mass	$80 < M_Z < 100$	62	100.0%	9581	94.6%	**0.629**
Z_2 mass	$80 < M_Z < 100$	51	82.2%	5237	51.7%	**0.707**
Higgs mass	$110 < M_H < 145$	46	74.2%	695	6.86%	**1.697**
Recoil mass of Z_2	$100 < M_{recoil} < 165$	46	74.2%	654	6.46%	**1.745**

Cuts (continued)

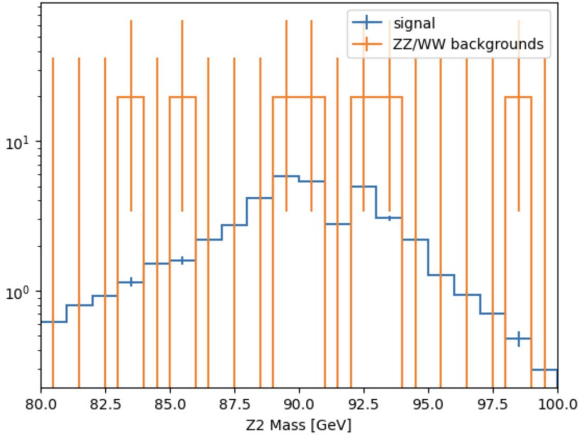
Variable	Condition	Signal Count	Signal % Selected	Background Count	Background % Selected	Q
Z_2 momentum	$0 < p_Z < 75$	46	74.2%	651	6.43%	**1.749**
Missing energy	$E_{miss} < 40$	46	74.2%	581	5.73%	**1.841**
Delta R between photon and Z_2	$0 < \Delta R < 4.5$	46	74.2%	570	5.62%	**1.851**
Photon theta	$0 < \theta_\gamma < 2.8$	45	72.5%	513	5.07%	**1.897**
Photon momentum	$20 < p_\gamma < 50$	44	70.9%	157	1.55%	**3.081**

Mass Reconstruction (μμ/μμ) Histograms After Cuts

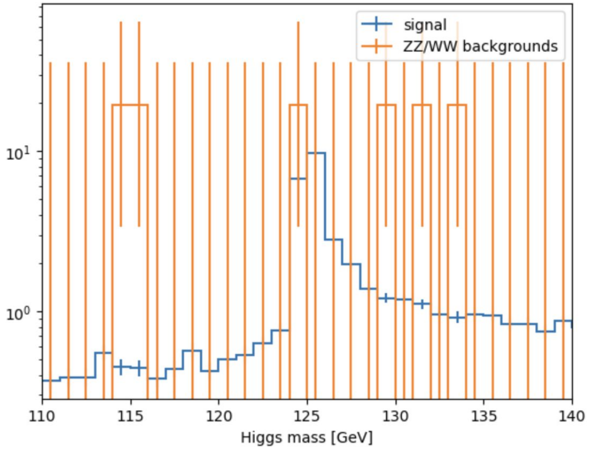
Z_1



Z_2



Higgs



4 Lepton Channel: Conclusion

- Separation between $H \rightarrow Z\gamma$ signal and diboson background can be significantly improved through kinematic cuts
- Potential next steps for 4 lepton channel:
    - Quality control checks (ΔR, momentum) on muons are needed to improve the resolution of the Z_2 mass
    - Application of boosted decision trees (BDTs) to further improve separation of signal from background
        - Helpful for variables that can't be separated visually like Cosθ (missing energy)
    - Consider kinematic cuts in other 4-lepton subcategories (ee/μμ, μμ/ee, ee/ee)
    - Consider tau particles in 4-lepton channel, rather than just muons and electrons
    - Use Combine to get an estimate of uncertainty on the $H \rightarrow Z\gamma$ coupling constant

Citations

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