Exotic Higgs Decay Research at CEPC

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Precision theory for precise measurements at LHC and future colliders
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Outline

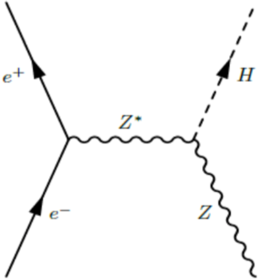
Introduction

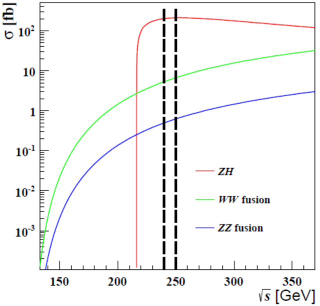
Motivation

- Current measurement of Higgs branching ratios at LHC allows for a significant fraction of invisible or exotic decay
- Searching for exotic decay is an important and straightforward way to distinguish SM-like Higgs boson from SM ones
- CEPC as a Higgs factory provides great opportunities for such searches
- Information of the Higgs can be obtained from the reconstructed Z-leptons via the recoil-mass method

Exotic Higgs decay at CEPC

- About 1 million Higgs events will be produced by CEPC
- The dominant Higgs production process is via Higgsstrahlung(ZH) at CEPC





- By tagging the products of Z boson decay, the Higgs candidate can be reconstructed via: (recoil-mass method)

$$m_{rec}^2 = (\sqrt{s} - E_{ll})^2 - \mathbf{p}_{ll}^2 = s - 2\sqrt{s}E_{ll} + E_{ll}^2 - \mathbf{p}_{ll}^2$$
$$= s - 2\sqrt{s}(E_{l1} + E_{l2}) + m_{ll}^2$$

Plan and status

Channels

- $h \to MET$
- $h \to \tau\mu$
- $h \to R + X$
- $h \to RR$
- $h \to ZR$

- For each of the last three decay modes, we look into $R \to bb$, $R \to ll$ and $R \to \gamma\gamma$
- Scan over the mass of the light resonance R (and other mass parameters)
- An upper confident limit for the branching ratio for each channel at CEPC is desired

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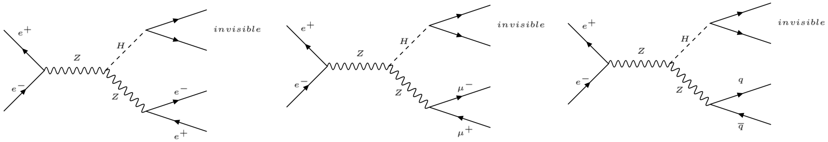
Analysis For Invisible Decay

Modelling

- ZH channel:
  - Same coupling of H to SM particles
  - Extra coupling of H to invisible particles
- Other SM decays unchanged
- Total ZH signal yield not changed for the total cross section of ZH is fixed
- Accuracy depends on $Br(H \to inv)$



Samples

- CM energy 250 GeV
- ZH signal on 3 channels: $Z \to ee$, $Z \to \mu\mu$ and $Z \to qq$
- Signal: full-simulated with Mokka v08-03 and reconstructed with Arbor v3_1
- Background: fast-simulated with momentum resolution and detection efficiency parameterized for different particle types
- Integrated luminosity: 5 ab^{-1}

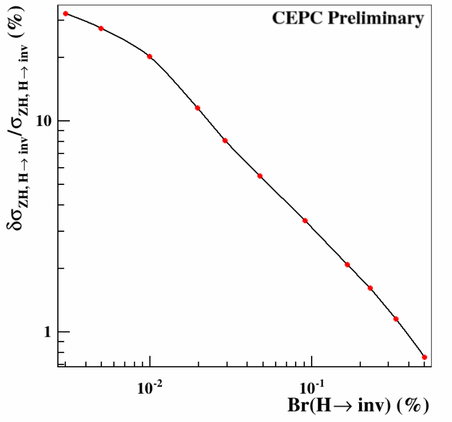
Measurement via $\mu\mu$

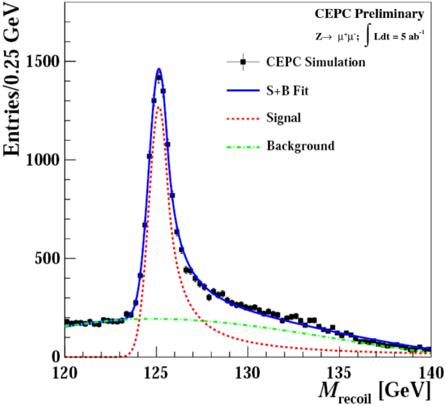
Cut flow:

	ZH	ZZ	WW	ZZorWW	Single Z	Z(2f)
Total	35247	5347053	44180832	17801222	7809747	418595861
$N_{\mu+}$>=1, $N_{\mu-}$>=1	95.73%	11.95%	0.65%	3.92%	9.75%	1.64%
120GeV/c^2<M_{rec}<150GeV/c^2	93.19%	1.71%	0.23%	0.70%	1.93%	0.17%
80GeV/c^2<$M_{\mu+\mu-}$<100GeV/c^2	85.47%	0.68%	0.06%	0.22%	0.22%	0.10%
P_{TZ}>20GeV/c	80.22%	0.57%	0.06%	0.17%	0.16%	0.02%
|φμ+-φμ-|<175	77.76%	0.51%	0.05%	0.17%	0.15%	0.01%
BDT cut	65.48%	0.26%	0.01%	0.05%	0.06%	0.01%
120GeV/c^2<M_{rec}<140GeV/c^2	65.33%	0.26%	0.01%	0.05%	0.06%	0.01%

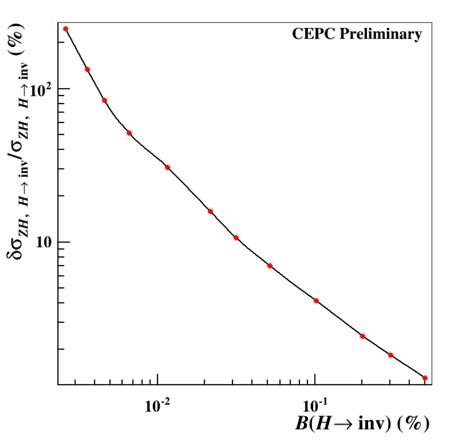
The cross section of SM ZH is fixed
Varied fractions of Higgs invisible decay are combined with the SM sample

$Br(H \to inv) = 50\%$
$\delta\sigma_{ZH,H\to inv}/\sigma_{ZH,H\to inv} = 1.16\%$



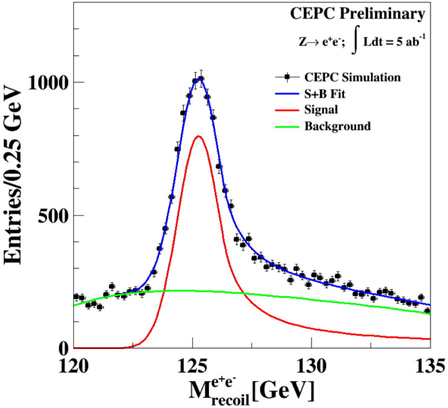


Measurement via ee

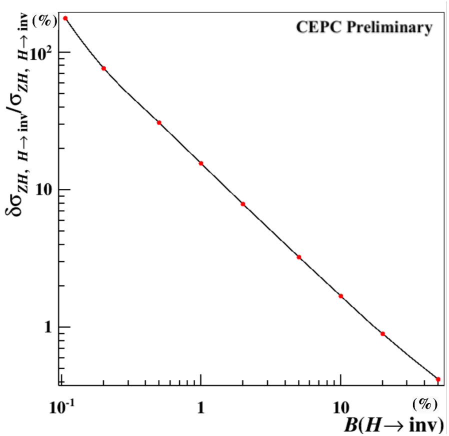


$Br(H \to inv) = 50\%$

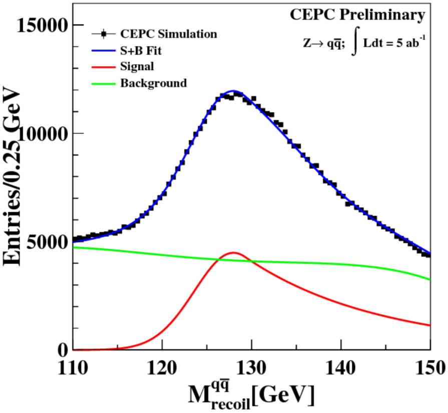
$\delta\sigma_{ZH,H\to inv}/\sigma_{ZH,H\to inv} = 1.31\%$



Measurement via qq

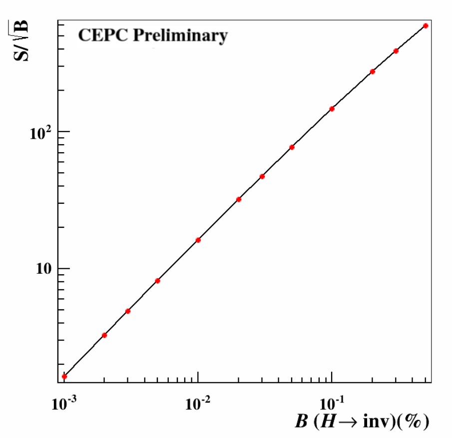


$$Br(H \to inv) = 50\%$$
$$\delta\sigma_{ZH,H\to inv}/\sigma_{ZH,H\to inv} = 0.42\%$$



Upper limit of $Br(H \to inv)$

Measurement on qq channel:



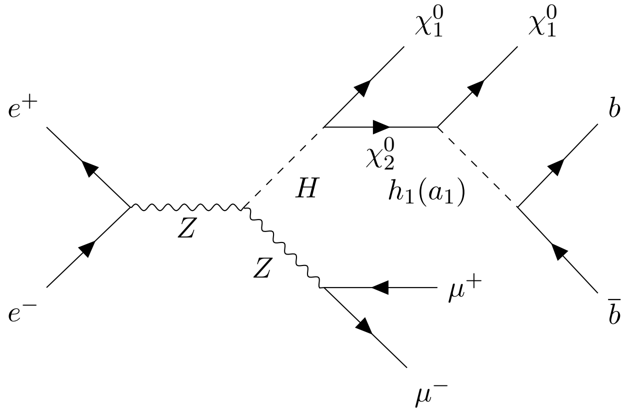
Upper confident limit of $Br(H \to inv)$ at 95% confidence level:

- qq: 1.25×10^{-3}
- ee: 1.8×10^{-2}
- $\mu\mu$: 1.2×10^{-2}

Conclusion: Combining all three channels, the limit of $Br(H \to inv)$ on CEPC detector is 1.24×10^{-3}

Analysis For Semi-invisible Decay

Signal for semi-invisible channel



χ_1^0 and χ_2^0 are the lightest and second lightest neutralinos respectively. h_1 is a scalar or pseudo-scalar. (χ_1^0 invisible or decaying invisibly)
Vary the mass parameters: $M_{\chi_1^0}$, $M_{\chi_2^0}$ and M_{h_1} (e.g. $M_{\chi_1^0} = 0$, $M_{\chi_2^0} = 80\,\mathrm{GeV}$ and $M_{h_1} = 45\,\mathrm{GeV}$)

Signal for semi-invisible channel

- Only consider $Z \to \mu^+\mu^-$
- (Will perform the same analysis for $Z \to e^+e^-$ channel afterwards)
- For a set of values of $M_{\chi_1^0}$, $M_{\chi_2^0}$ and M_{h_1}, 10000 events are generated
- CM energy 250 GeV, Higgs mass 125 GeV
- Generated by MadGraph(ver 2.3.2) using NMSSM model without ISR
- Full simulated with Mokka (v08-03, with model CEPC_v1) and reconstructed with Arbor (v3_KD)

Backgrounds

- Looking for events with 2 jets and 2 isolated muons
- Generated by Whizard (ver 1.95) and simulated with Mokka v08-03 and reconstructed with Arbor v3_KD)
- All background events are normalized to the integrated luminosity of 5 ab^{-1}

- ZZ backgrounds:
  - Leptonic decays: $ZZ \to 4l$
  - Semi-leptonic: $ZZ \to 2l + 2f$
- ZH background: $ZH \to \mu\mu bb$

Cut flow

- FSClasser: Pre-selection for 2 isolated muons + 2 jets, including M_{ll} cut 81.18 GeV $< M_{ll} <$ 101.18 GeV
- Recoil mass: 110 GeV $< M_{reco} <$ 140 GeV
- B likeness: at least one jet with b likeness larger than 0.9
- Missing energy: $E_{missing} >$ 20 GeV
- Invariant mass of the di-jet: M_{jj} cut depends on mass parameters

Cuts	No cut	FSClasser	M_{reco}	b likeness	$E_{missing}$	M_{jj}
Signal	10000	8420	8356	8356	6514	6482
ZH background	35849	28002	25874	13783	2399	19
ZZ background	3004042	280140	39700	5957	3639	69

A typical cut flow for $M_{\chi_1^0} = 0$, $M_{\chi_2^0} = 80\,\mathrm{GeV}$ and $M_{h_1} = 45\,\mathrm{GeV}$

Parameters for scan

Fix $M_{\chi_1^0} = 0$

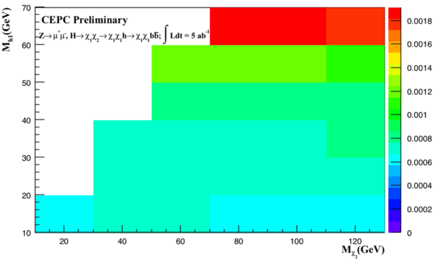
- 10 GeV $< M_{h_1} <$ 70 GeV (15, 25, 35, 45, 55, 65 GeV)
- 10 GeV $< M_{\chi_2^0} <$ 125 GeV (20, 40, 60, 80, 100, 120 GeV)

Fix $M_{h_1} = 30\,\mathrm{GeV}$

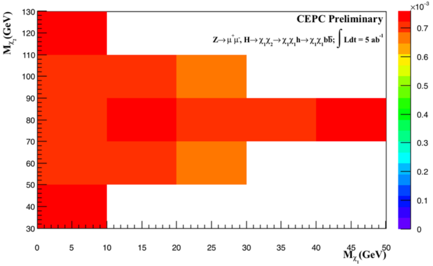
- 0 GeV $< M_{\chi_1^0} <$ 60 GeV (5, 15, 25, 35, 45, 55 GeV)
- 10 GeV $< M_{\chi_2^0} <$ 125 GeV (20, 40, 60, 80, 100, 120 GeV)

Results of scan

Distribution of upper confident limit at 2-σ significance of $Br(H \to semi-invisible)/Br(H \to b\bar{b})$



Fixing $M_{\chi_1^0} = 0$



Fixing $M_{h_1} = 30\,\text{GeV}$

Results of scan

- The most important parameter: M_{h_1}
- The significance reduces as M_{h_1} gets higher (close to Z pole), and thus lowering the sensitivity and giving a higher branching ratio limit (although b tagging is more accurate for high M_{h_1})
- $M_{\chi_1^0}$ and $M_{\chi_2^0}$ mainly affect $E_{missing}$, which is a low-efficient cut

Conclusion: the upper limit for branching ratio at 95% confidence level varies with the mass parameters within the range 6×10^{-4} to 1.9×10^{-3}

Summary

Summay

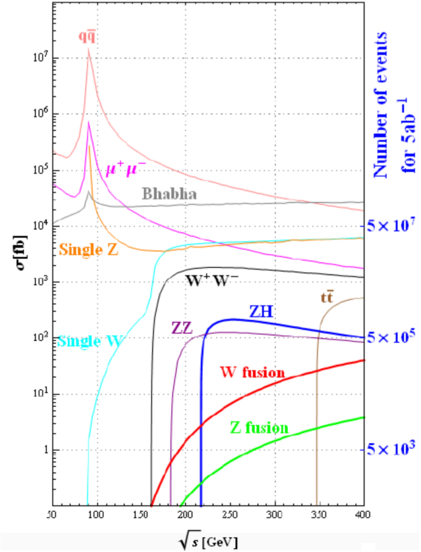
- Full-simulated signal samples are analyzed using the recoil-mass method
- For the invisible and semi-invisible channels, the upper confident limits for the branching ratio that CEPC could detect are given

- Will finish other channels ($R \to ll$ and $R \to \gamma\gamma$) of the semi-invisible decay
- We have started analysis for $h \to \tau\mu$, $h \to RR$ and $h \to ZR$ channels

Thank You!

Backup

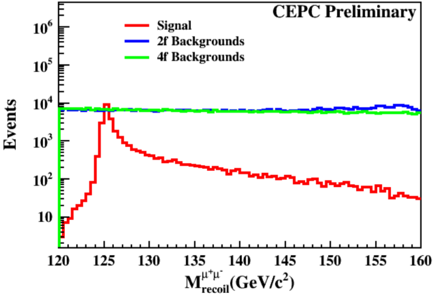
Rates of SM processes



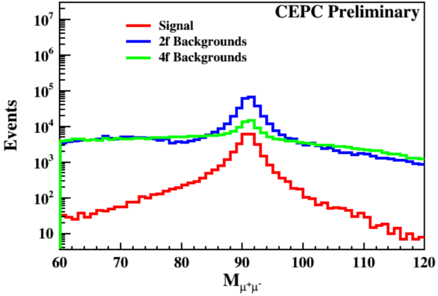
Measurement for invisible channel via $\mu\mu$

(plots normalized to max bin height)

1. At least one pair of $\mu^+\mu^-$ is reconstructed
2. Recoil mass of $\mu^+\mu^-$: $120\ \mathrm{GeV} < M^{reco}_{\mu^+\mu^-} < 150\ \mathrm{GeV}$
3. Invariant mass of $\mu^+\mu^-$: $80\ \mathrm{GeV} < M_{\mu^+\mu^-} < 100\ \mathrm{GeV}$



Based on (1)

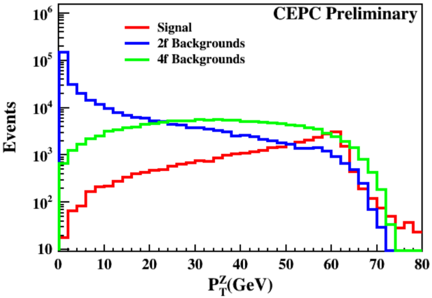


Based on (1)(2)

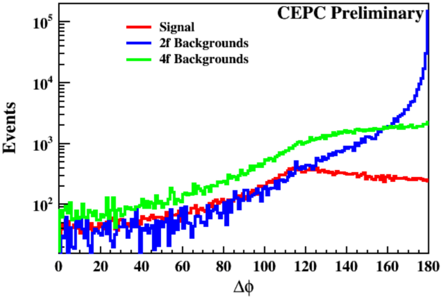
Measurement for invisible channel via $\mu\mu$

(plots normalized to max bin height)

4. Transverse momentum of Z boson candidate: $P_T^Z > 20\,\mathrm{GeV}$
5. The angle between two μ^+ and μ^-: $\Delta\Phi < 175°$



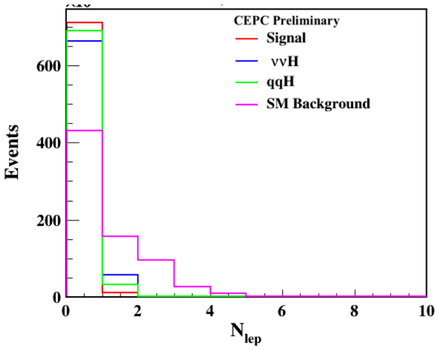
Based on (1)(2)(3)

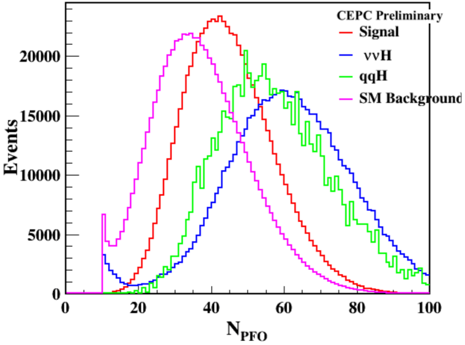


Based on (1)(2)(3)(4)

(plots normalized to signal event number) Pre-selection:

- Inclusive 2 jets
- $N_{PFO} > 10$
- $M_{vis} < 130\,\mathrm{GeV}/c^2$

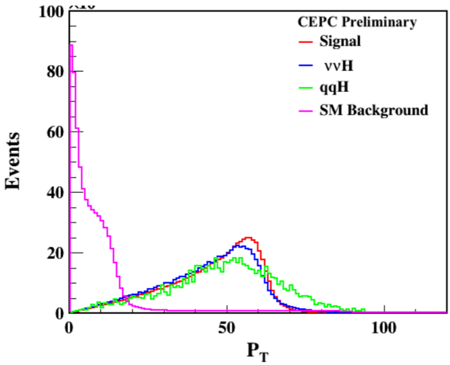


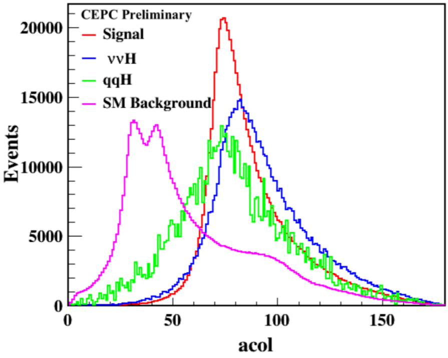


Measurement for invisible channel via qq

(plots normalized to signal event number)

- Transverse momentum of Z boson candidate: $P_T^Z > 20\,\mathrm{GeV}$
- The angle between two jets: $acol > 50^\circ$

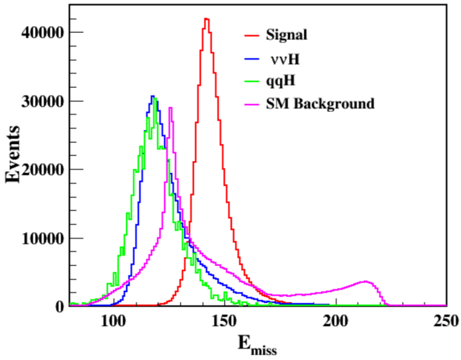


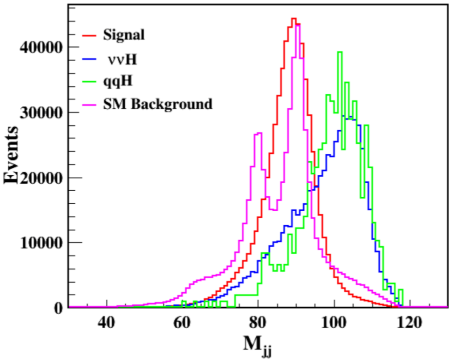


Measurement for invisible channel via qq

(plots normalized to signal event number)

- Missing energy: $130\,\mathrm{GeV} < E_{miss} < 170\,\mathrm{GeV}$
- The invariant mass of two jets: $75\,\mathrm{GeV} < M_{jj} < 100\,\mathrm{GeV}$





Measurement for invisible channel via qq

Cut flow:

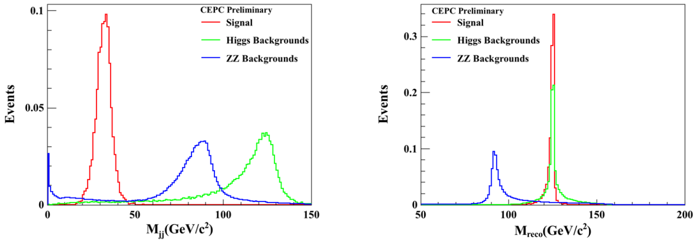
	Signal	qqH	vvH	SM BKG
Pre-cut	721232	8435	205822	69071903
N_{lep}=0	710648	5738	188928	41315384
15< N_{PFO} < 85	708747	5464	171283	39890767
P_T>20GeV/c	658280	5086	157211	3547505
Acol > 50	650532	4423	153950	1735168
130 GeV < E_{miss} < 170 GeV	629616	668	38430	620395
75 GeV < M_{jj} < 100 GeV	571924	317	19503	484991
110 GeV < M_{reco} < 150 GeV	550989	287	16322	336582

Measurement for invisible channel via ee

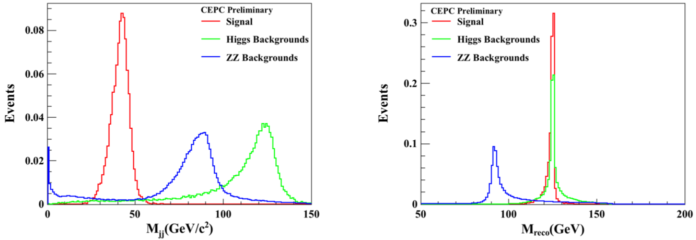
Cut flow:

	ZH	ZZ	WW	ZZorWW	Z	W	ZorW	Z(2f)
total	35247	5436373	44181064	17799208	7808854	17020374	1246802	418598154
N_{e+}>=1, N_{e-}>=1 $\cos\theta_{e+}$>-0.9,$\cos\theta_{e-}$<0.9	28010	13615	16266	20105	574212	222811	626516	6594087
$120GeV/c^2<M_{rec}<160GeV/c^2$	26437	903	1428	3667	122997	82943	156757	1204575
$80GeV/c^2<M_{e+e-}<100GeV/c^2$	22958	118	220	1497	45438	25050	53851	414026
P_{TZ}>20GeV/c	21574	85	166	1056	36414	22252	43108	263375
|φe+-φe-|<175	20908	64	157	986	33909	20613	41468	206862
BDT cut	14614	4	9	68	10961	3512	10085	37160

Semi-invisible decay



$M_{\chi_1^0} = 0,\ M_{\chi_2^0} = 80\,\mathrm{GeV}$ and $M_{h_1} = 35\,\mathrm{GeV}$



$M_{\chi_1^0} = 0,\ M_{\chi_2^0} = 100\,\mathrm{GeV}$ and $M_{h_1} = 45\,\mathrm{GeV}$