The study of Higgs invisible decay

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Outline

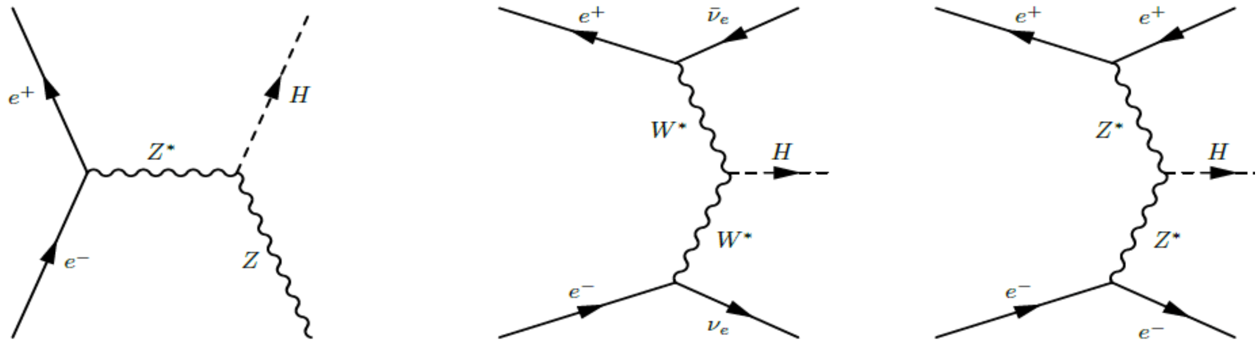
- Motivation
- MC Simulation and sample
- Event selection of three channels
- The fit and combine result
- Summary

Motivation

- The Higgs decay invisible in SM is via four neutrino, with BR=0.106%.
- Many new physics models predict a significant branching ratio of Higgs to invisible.
- ATLAS upper limit ~25%,CMS upper limit~ 24% for BR(Higgs->inv) at 95% C.L.
- Higgs invisible decay is a sensitive probe for new physics.
- The upper limit of BR(Higgs->inv) will be two orders of magnitude smaller on CEPC

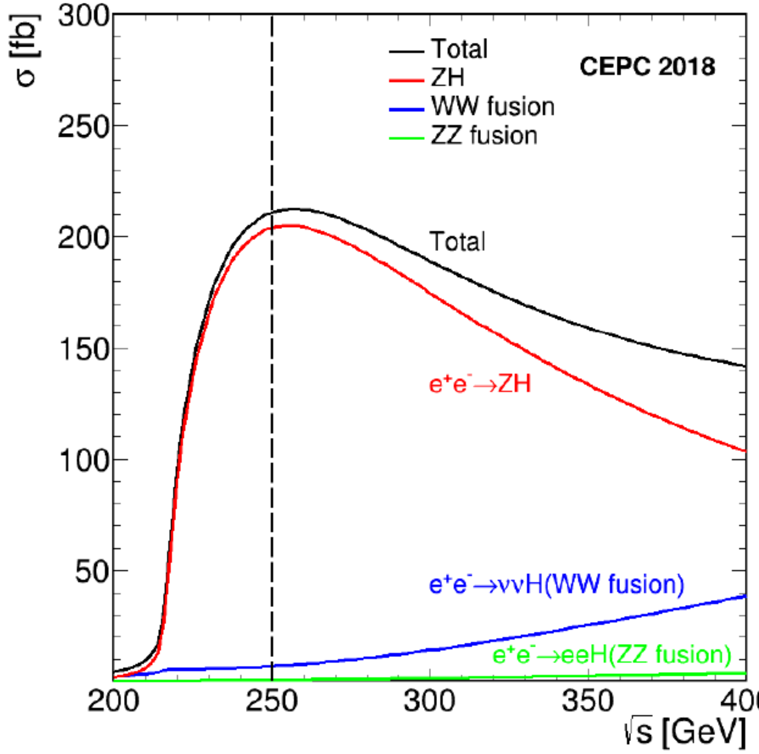
Higgs On CEPC

- The Higgs bosons are produced via Higgsstrahlung(ZH),WW fusion and ZZ fusion at CEPC



- ZH is the dominant Higgs production process
- By tagging the products of Z boson decay, the Higgs candidate can be reconstructed via

$$m_{\rm rec}^2 = (\sqrt{s} - E_{\ell\ell})^2 - \mathbf{p}_{\ell\ell}^2 = s - 2\sqrt{s}E_{\ell\ell} + E_{\ell\ell}^2 - \mathbf{p}_{\ell\ell}^2$$
$$= s - 2\sqrt{s}\,(E_{\ell 1} + E_{\ell 2}) + m_{\ell\ell}^2\,,$$



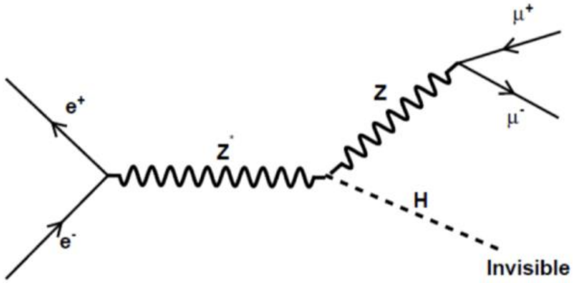
Production cross sections of Higgs

Monte Carlo Simulation

- CEPC_V4($\sqrt{s}$~240GeV, Solenoidal field~3T)
- Run about 7 years and produce a total of 1 million Higgs bosons
- Generator: Whizard 1.95 (with ISR, Lumi 5.6 ab^{-1}, M_H=125GeV)
- All Higgs boson signal samples and part of the leading background samples are processed with Geant4. The rest of backgrounds are simulated with fast simulation.

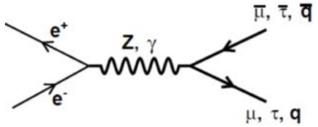
The sample of signal and background in Higgs->invisible:

- The signal channels:
  ZH(Z->$\mu^+\mu^-$,H->invisible),ZH(Z->e^+e^-,H->invisible), ZH(Z->qq,H>invisible)

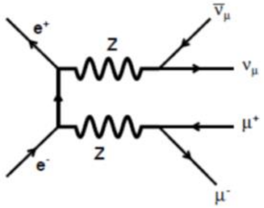


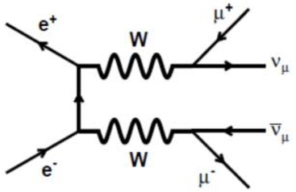
- The background channels:

  - Two fermions

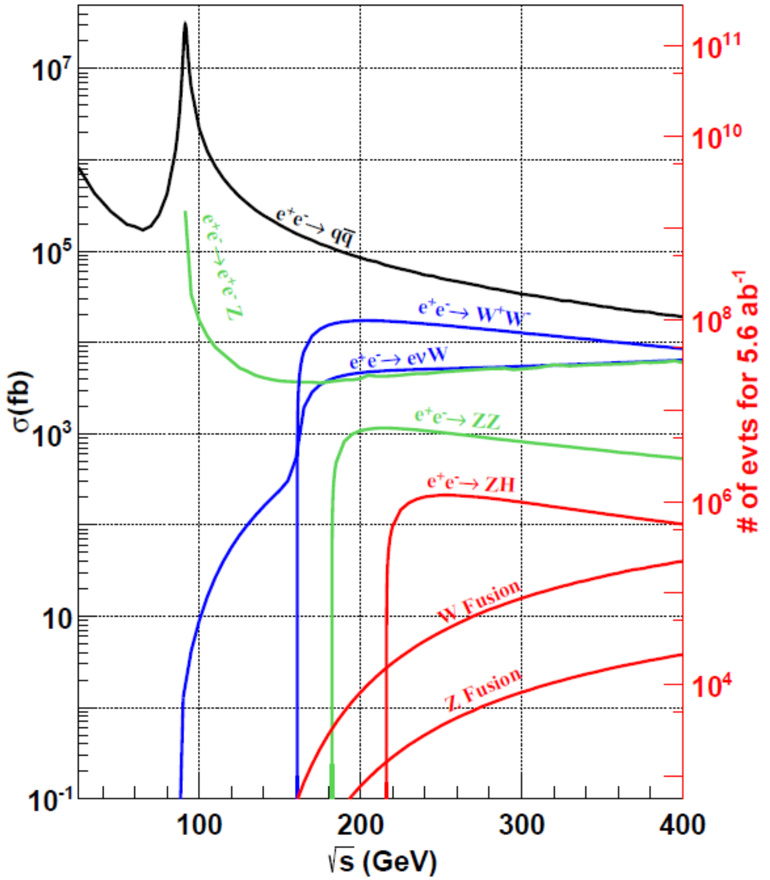


  - Four fermions





  - Sample details:
    https://gitlab.com/cepc/memo/sample-c4



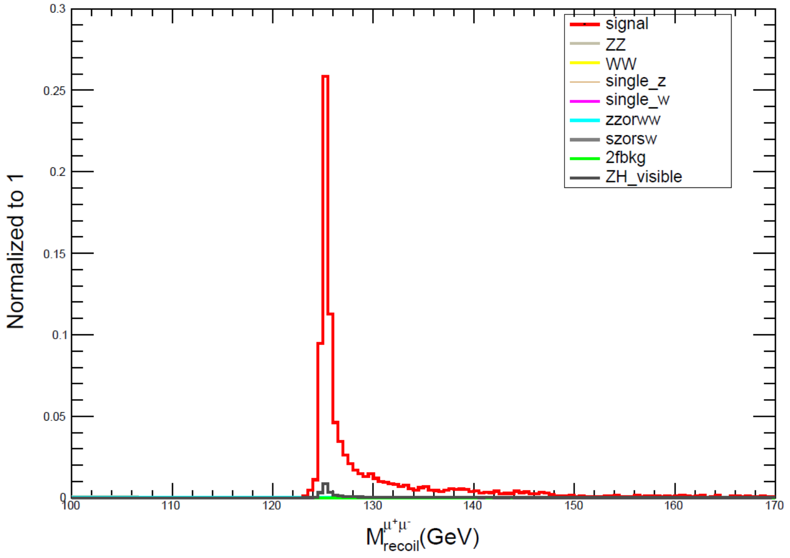
Cross section of major SM processes

The event selection of ZH(Z->$\mu^+\mu^-$,H->invisible)

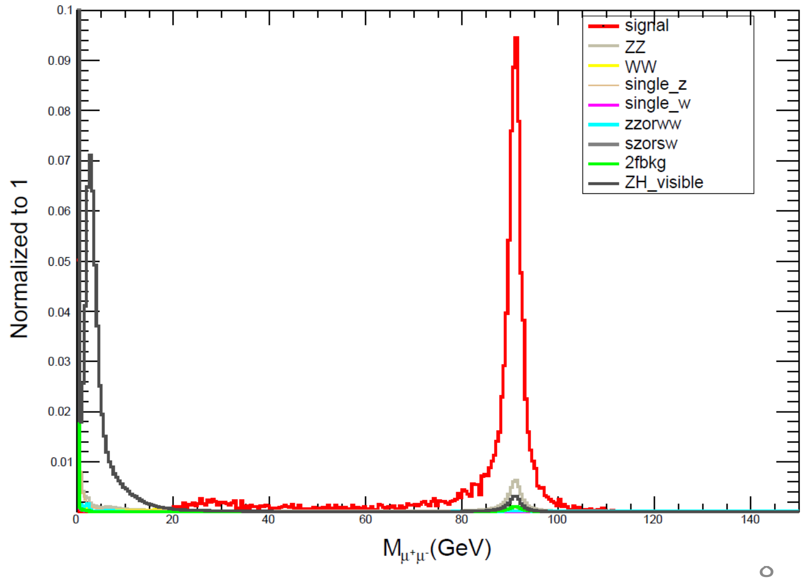
Event selection: Suppose BR(H->inv)= 50%. ZH(Z->$\mu^+\mu^-$,H->invisible)

1.General cut and raw data distribution :

Raw data



- $N_{\mu^+} = 1, N_{\mu^-} = 1$
- 120GeV<$M_{recoil}^{\mu^+\mu^-}$<150GeV
  - $M_{recoil}^{\mu^+\mu^-}$ is the mass of Higgs about 125GeV
- 85GeV<$M_{\mu^+\mu^-}$<97GeV
  - $M_{\mu^+\mu^-}$ is the mass of Z boson about 91.2GeV

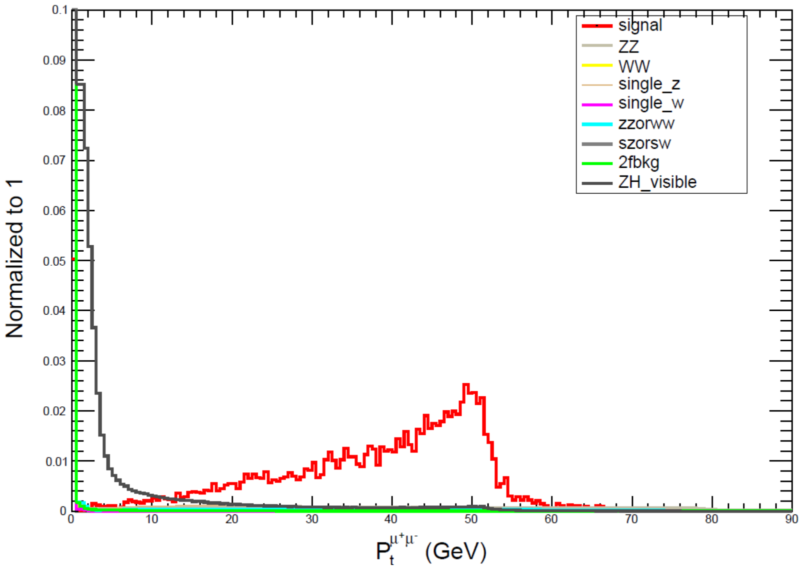


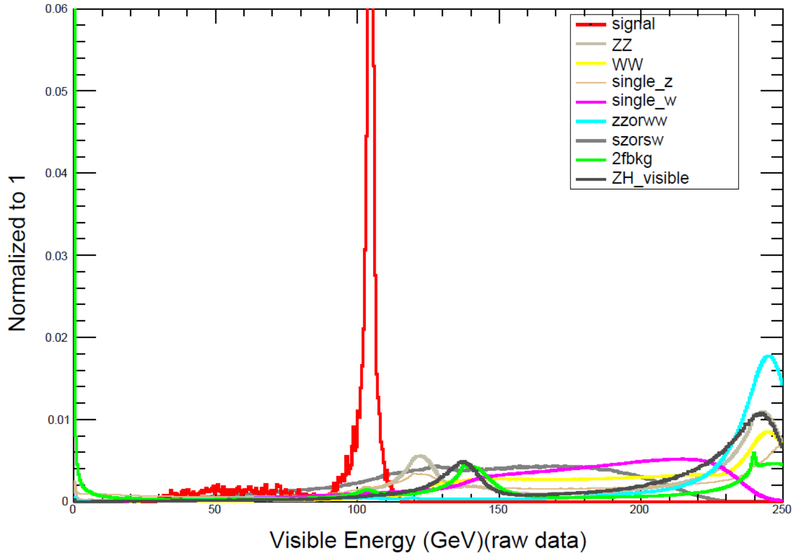
Event selection: Suppose BR(H->inv)= 50%. ZH(Z->$\mu^+\mu^-$,H->invisible)

1.General cut and raw data distribution：

- $\Delta\phi_{\mu^+\mu^-}$<175°,12GeV< $P_t^{\mu^+\mu^-}$
    - In order to suppress 2 fermion background
- 102GeV< $E_{visible}$<107GeV
    - M_{Higgs}^2=$(\sqrt{s} - E_{\mu^+\mu^-})^2$−$P_{\mu^+\mu^-}^2$
    - From the formula, $E_{visible}$ is around [91GeV,115GeV]

Raw data

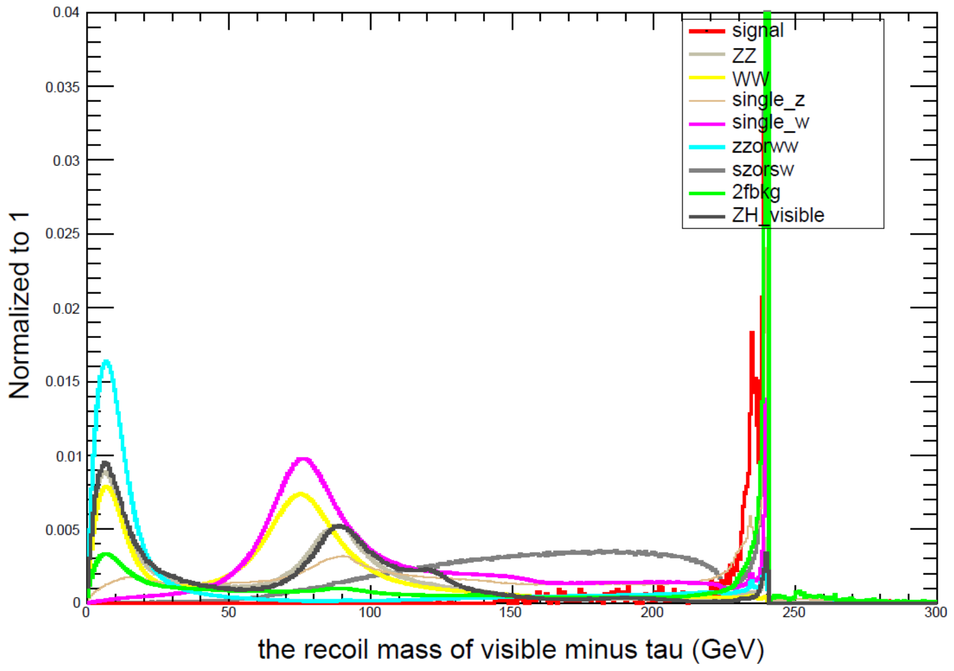




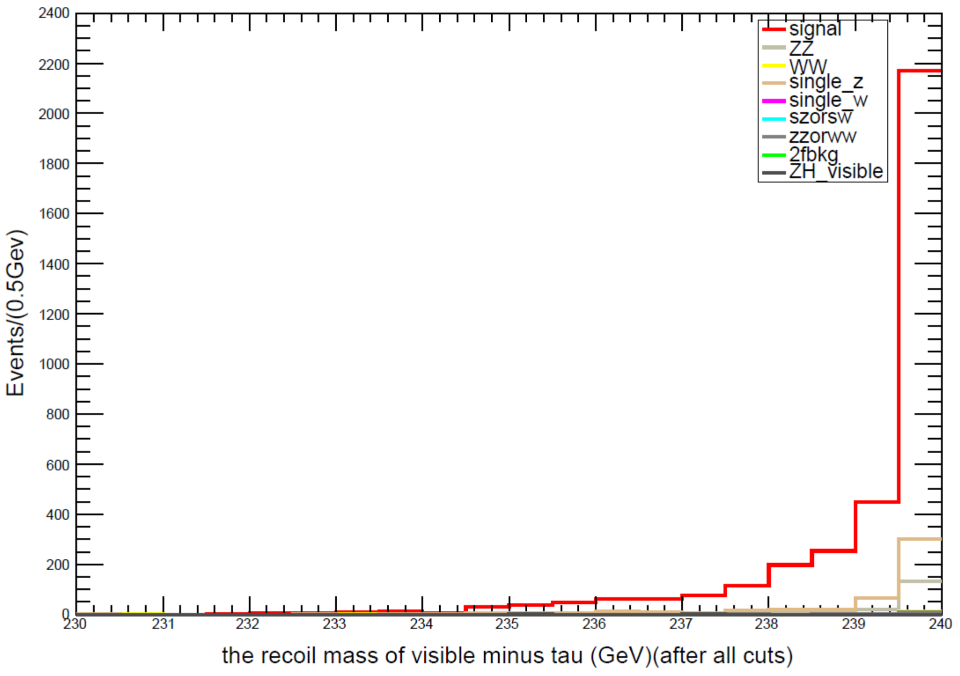
Event selection: Suppose BR(H->inv)= 50%. ZH(Z->$\mu^+\mu^-$,H->invisible)

2. Special cut

- The recoil mass of visible minus candidate tau >230GeV (Use Dan Yu's tau information) .
  - This cut can suppress the backgrounds which include tau and quarks



Before all cuts



After all cuts

The cut flow of $\mu\mu$H_inv

The precision under BR=50%

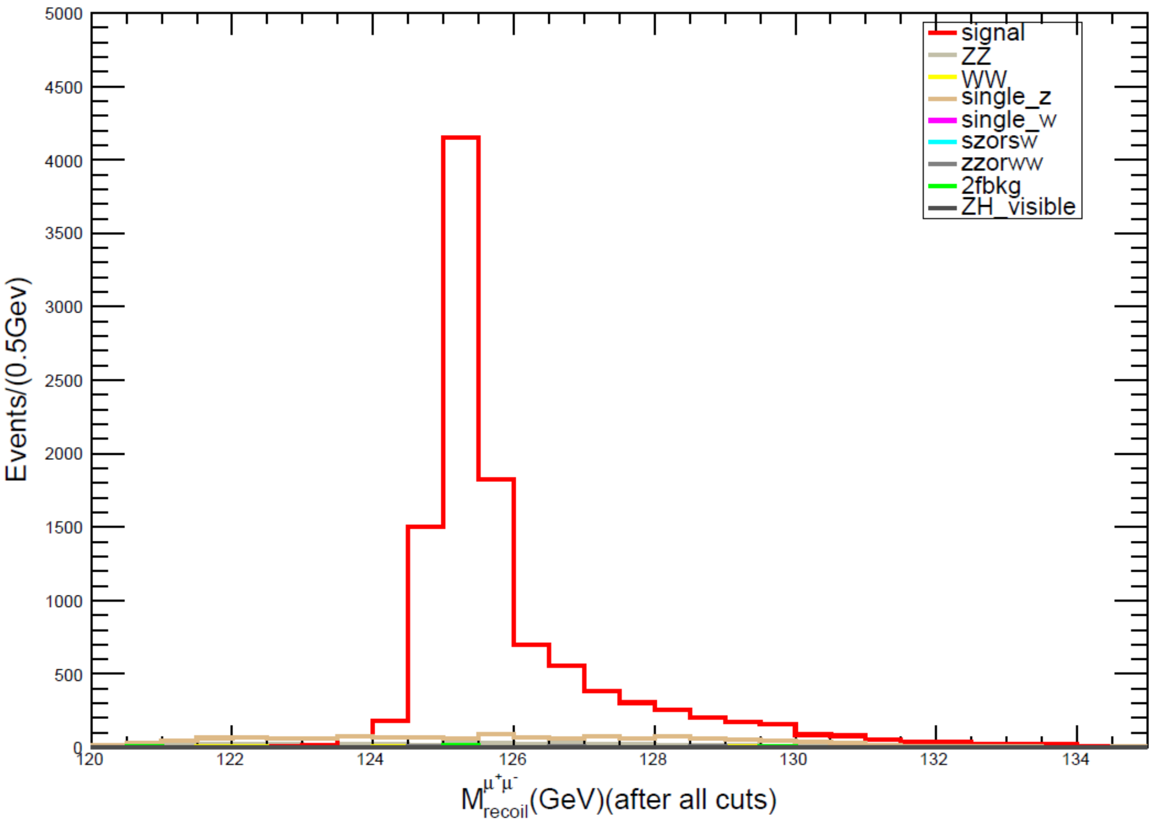
Process	$\mu^+\mu^- H\_inv$	2f	single_w	single_z	szorsw	zz	ww	zzorww	ZH	total_bkg	$\frac{\sqrt{S+B}}{S}$
Total generate	18956	801152072	19517400	9072951	1397088	6389430	50826214	20440840	1140495	909936490	159.134 %
$N_{\mu^+} = 1, N_{\mu^-} = 1$	17993	22737312	36122	723397	0	702041	1255610	1223579	59978	26738039	28.748 %
$120GeV < M_{Recoil} < 150GeV$	16200	652653	24	100432	0	62459	250815	112141	5707	1184231	6.763 %
$85GeV < M_{\mu^+\mu^-} < 97GeV$	13659	381054	0	10736	0	20851	16718	24417	4491	458267	5.029 %
$12GeV < P_t^{\mu^+\mu^-}$	13233	92197	0	9480	0	18254	15903	21061	4328	161223	3.156 %
$\Delta\phi < 175°$	12699	72196	0	8892	0	17024	14768	20230	4140	137250	3.049 %
$102GeV < VisibleEnergy < 107GeV$	11118	61	0	1455	0	483	4378	5434	9	11820	1.362 %
$\frac{E}{P} < 2.4$	10985	26	0	1343	0	439	3502	4088	5	9403	1.300 %
$ReM_{visdtau} > 230GeV$	10915	26	0	1338	0	436	66	52	4	1922	1.038 %
effectiveness	57.581 %	0.000 %	0.000 %	0.015 %	0.000 %	0.007 %	0.000 %	0.000 %	0.000 %	0.000 %	

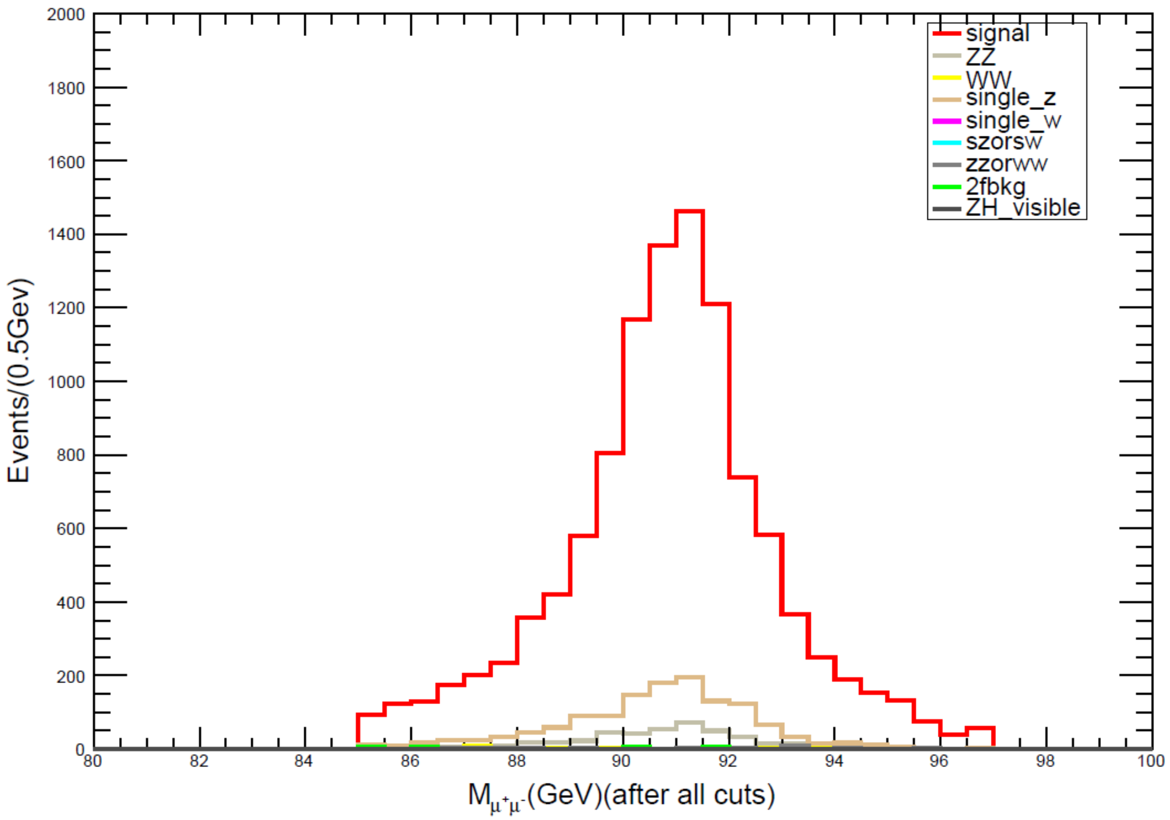
The main remain backgrounds:

- sznu_l0mumu($\upsilon_e, \bar{\upsilon}_e, \mu^+, \mu^-$) 1338(70%)
- ZZ_l0mumu($\upsilon_\tau, \bar{\upsilon}_\tau, \mu^+, \mu^-$) 434(23%)

Event selection: Suppose BR(H->inv)= 50%. ZH(Z->$\mu^+\mu^-$,H->invisible)

The distribution after all cuts:





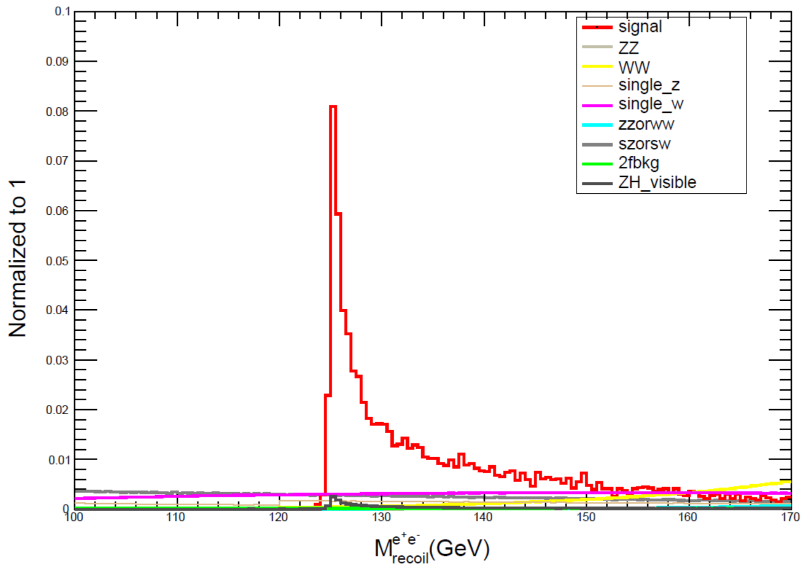
The event selection of ZH(Z->e^+e^-,H->invisible)

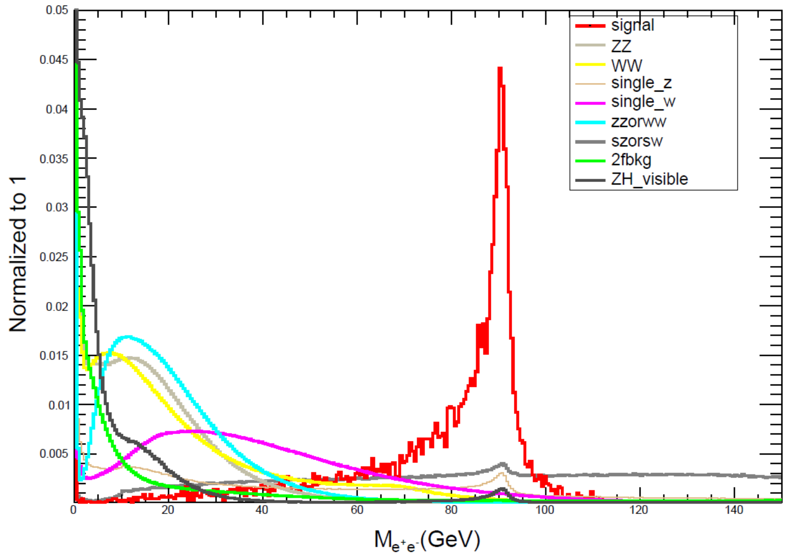
Event selection: Suppose BR(H->inv)= 50%. ZH(Z->e^+e^-,H->invisible)

Cuts and raw data distribution:

- $N_{e^+} \geq 1, N_{e^-} \geq 1$
- 120GeV<$M_{recoil}^{e^+e^-}$<170GeV
  - $M_{recoil}^{\mu^+\mu^-}$ is the mass of Higgs about 125GeV
- 71GeV<$M_{e^+e^-}$<99GeV
  - $M_{\mu^+\mu^-}$ is the mass of Z boson about 91.2GeV

Raw data

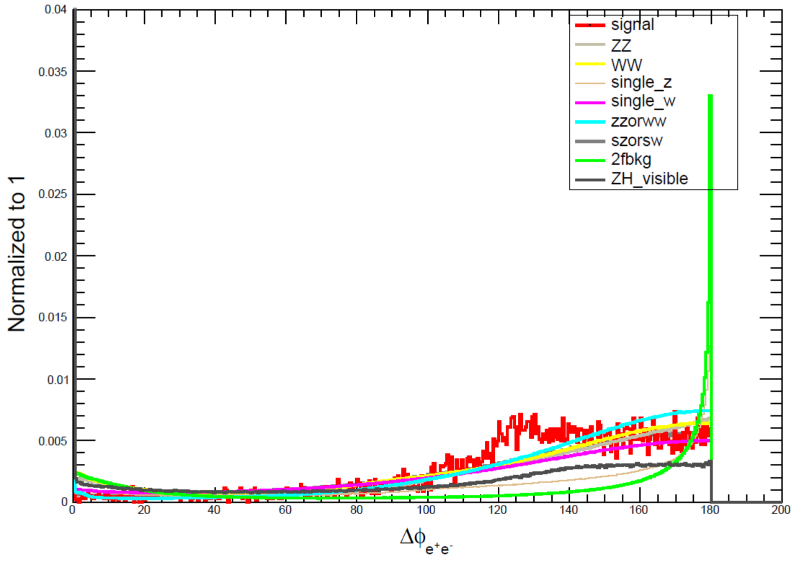




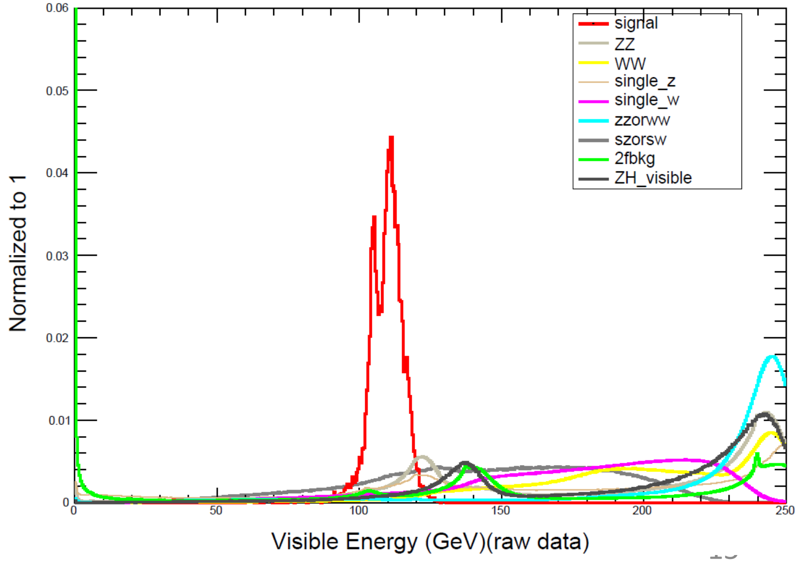
Event selection: Suppose BR(H->inv)= 50%. ZH(Z->e^+e^-,H->invisible)

Cuts and raw data distribution:

Raw data



- $\Delta\phi_{e^+e^-}$<176°, 12GeV<$P_t^{\mu^+\mu^-}$<55GeV
  - In order to suppress 2 fermion background
- 103GeV<$E_{visible}$<120GeV
- Impact_Tau< 0.0011
  - Impact_Tau is related with secondary vertex
  - This can parameter distinguish between tau and e,μ



The cut flow of eeH_inv

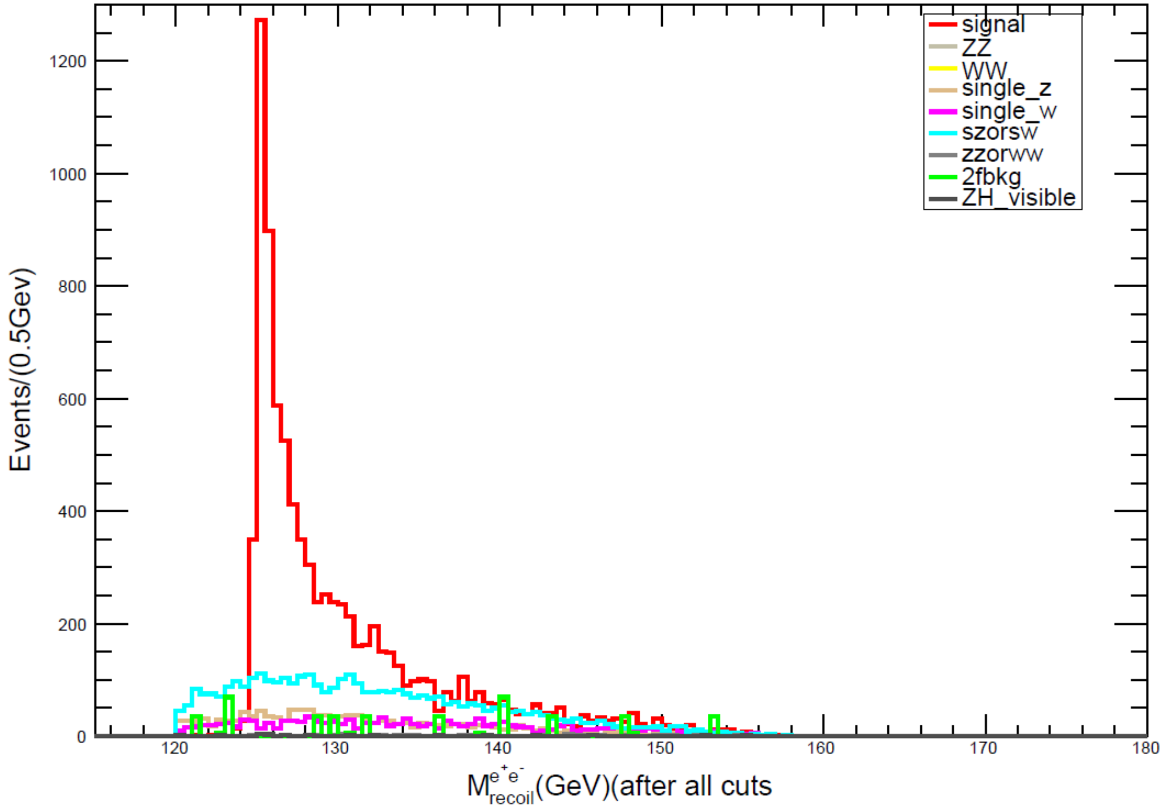
Process	eeh_invi	2f	single_w	single_z	szorsw	zz	ww	zzorww	ZH	total_bkg	$\frac{\sqrt{S+B}}{S}$
Total generate	19712	801152072	19517400	9072951	1397088	6389430	50826214	20440840	1140495	909936490	153.031 %
$N_{e^+} \geq 1, N_{e^-} \geq 1$	18405	389959503	15669806	4792268	1238220	5816250	47424558	18467259	679473	484047337	119.541 %
$120GeV < M_{recoil} < 170GeV$	16726	16148345	6286116	751321	315184	102752	1055871	423261	35469	25118319	29.974 %
$71GeV < M_{e^+e^-} < 99GeV$	13677	5382811	647494	206632	114041	15051	185249	92483	26217	6669978	18.902 %
$12GeV < P_t^{e^+e^-} < 55GeV$	13134	3476921	558026	160656	98938	12574	160275	79518	25187	4572095	16.304 %
$\Delta\phi < 176°$	12566	1230405	516751	145144	94820	10531	144468	71295	24271	2237685	11.938 %
$103GeV < VisibleEnergy < 120GeV$	11618	4609	30665	3342	27273	56	157	3430	131	69663	2.454 %
$1.8 < \frac{E_{e^+e^-}}{P_{e^+e^-}} < 2.4$	9654	1085	14179	1702	12160	10	46	1127	61	30370	2.072 %
$ReM_{visdtau} > 220$ and Impact_Tau<0.0011	8641	442	1281	1354	3881	0	1	39	26	7024	1.448 %
effectiveness	43.836 %	0.000 %	0.007 %	0.015 %	0.278 %	0.000 %	0.000 %	0.000 %	0.002 %	0.001 %	

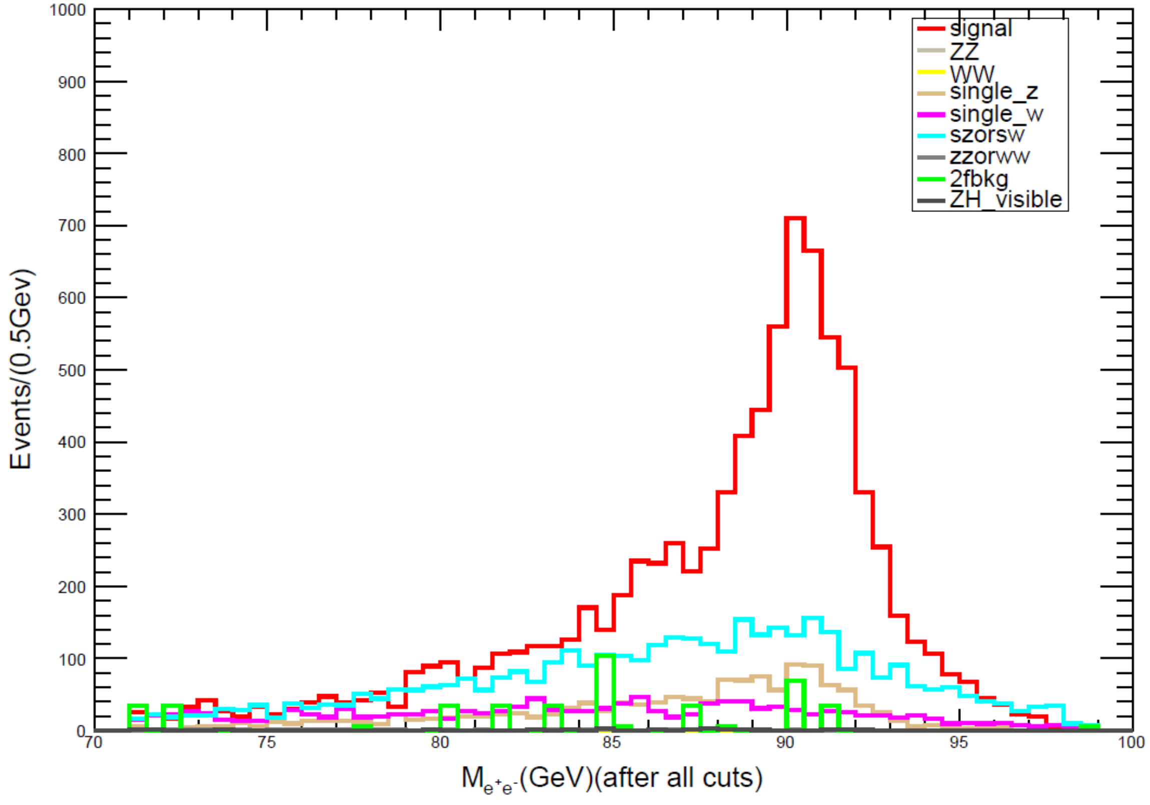
The main remain backgrounds:

- szeorsw_l0l($e^+, e^-, \upsilon_e, \bar{\upsilon}_e$) 3881(55%)
- sze_l0nunu($e^+, e^-, \upsilon_{\mu,\tau}, \bar{\upsilon}_{\mu,\tau}$) 1276(18%)
- sw_l0tau($e, \upsilon_e, \tau, \upsilon_{\mu,\tau}$) 1255(18%)

Event selection: Suppose BR(H->inv)= 50%. ZH(Z->e^+e^-,H->invisible)

The distribution after all cuts:





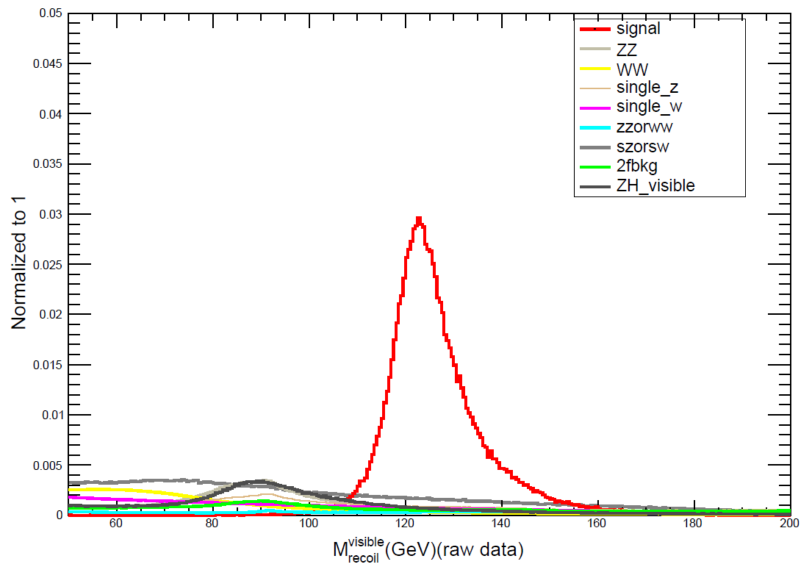
The event selection of ZH(Z->qq,H->invisible)

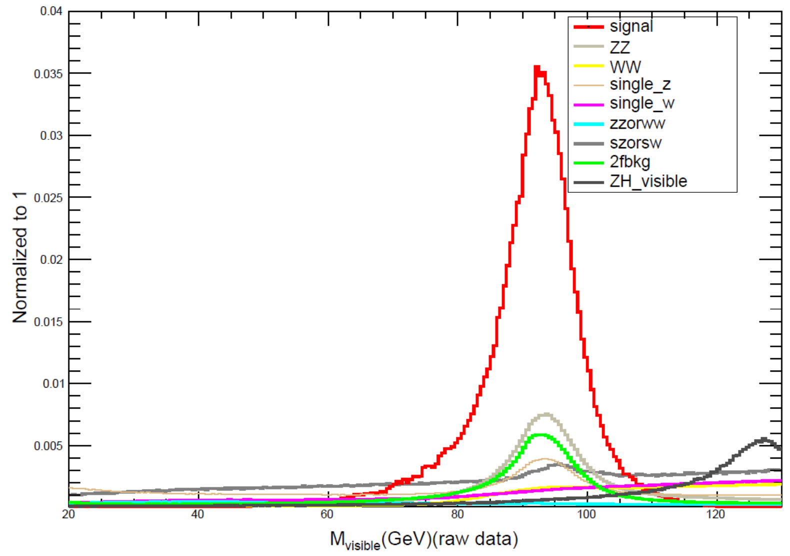
Event selection: Suppose BR(H->inv)= 50%. ZH(Z->qq,H->invisible)

Cuts and raw data distribution:

Raw data

- $N_{neutral} > 15$
  - qq will generate many particles
- 100GeV<$M_{recoil}^{visible}$<150GeV
  - $M_{recoil}^{visible}$ is the mass of Higgs about 125GeV
- 85GeV<$M_{visible}$<102GeV
  - $M_{visible}$ is the mass of Z boson about 91.2GeV



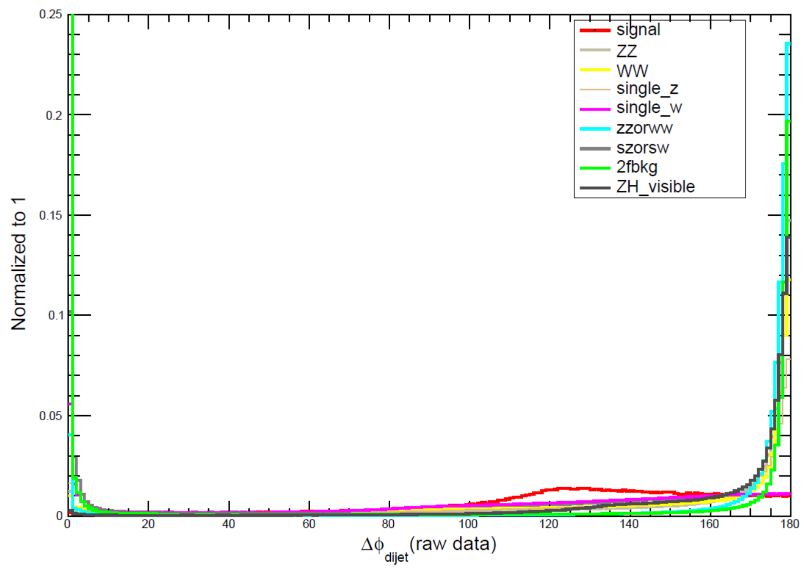


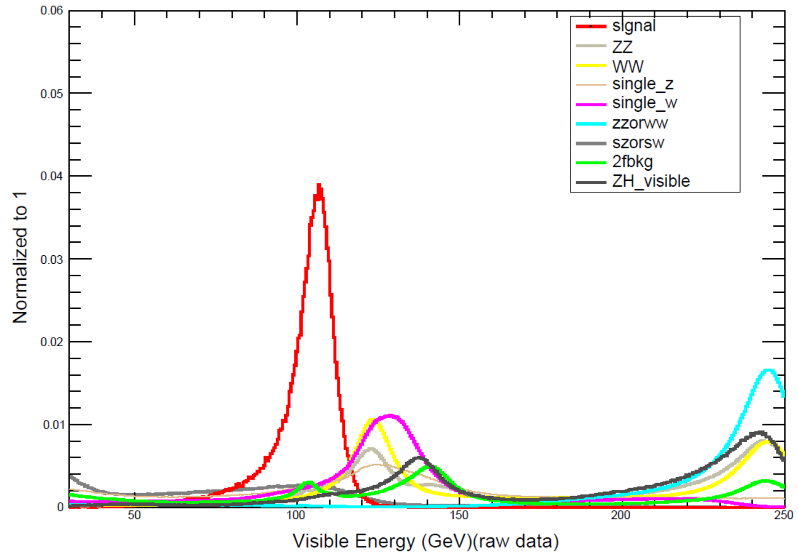
Event selection: Suppose BR(H->inv)= 50%. ZH(Z->qq,H->invisible)

Cuts and raw data distribution:

Raw data

- $\Delta\phi_{dijet}$<175°, 30GeV<$P_t^{visible}$<60GeV
  - In order to suppress 2 fermion background
- 90GeV<$E_{visible}$<117GeV
- $\mathrm{N_{IsoMuon}} = 0, \mathrm{N_{IsoElectron}} = 0$
  - Isolate package only record isolated particles





The cut flow of qqH_inv

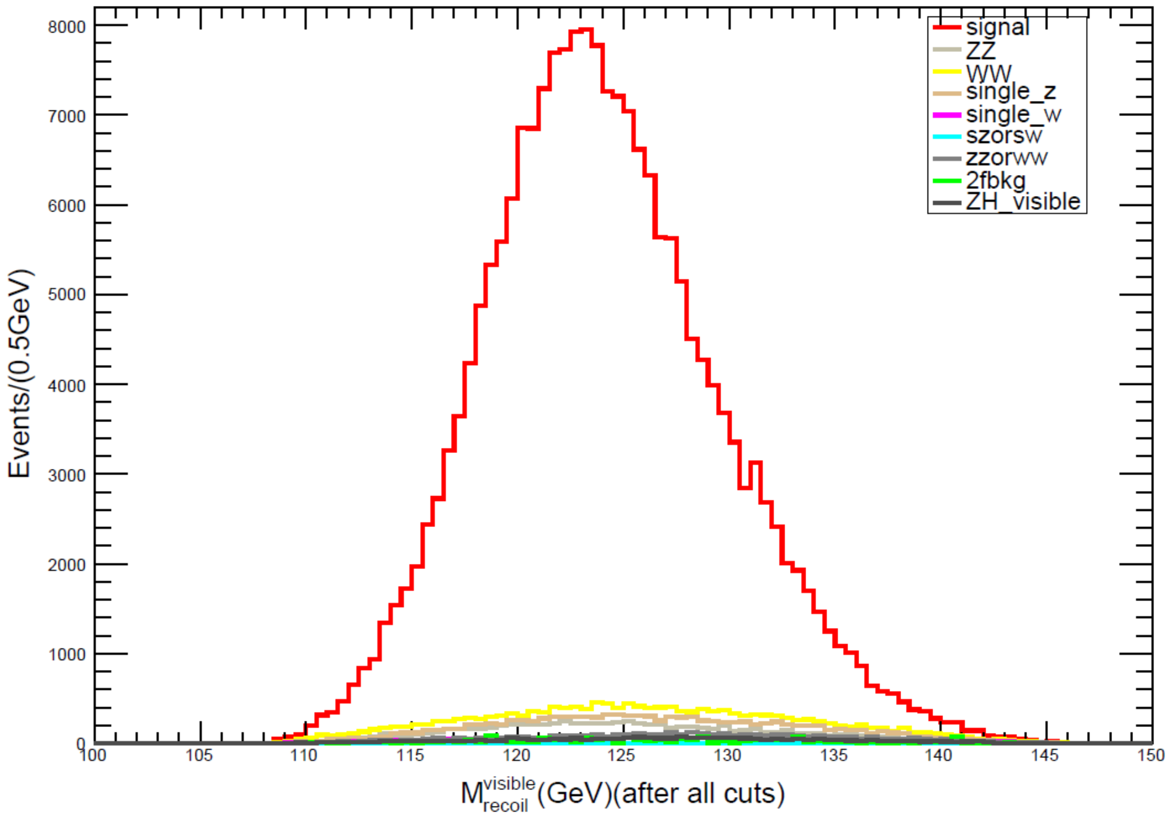
Process	qqH_inv	2f	single_w	single_z	szorsw	zz	ww	zzorww	ZH	total_bkg	$\frac{\sqrt{S+B}}{S}$
Total generate	383068	801152072	19517400	9072951	1397088	6389430	50826214	20440840	1140495	909936490	7.876 %
$100GeV < M_{recolil}^{visible} < 150GeV$	368367	34602867	1342725	818614	225883	503588	1666338	518251	96885	39775151	1.720 %
$30GeV < P_t^{visible} < 60GeV$	280799	2532942	718721	186863	104495	203426	853612	247154	55983	4903196	0.811 %
90GeV<Visible Energy<117GeV	268711	1545260	432951	158180	64932	169826	528936	145922	22807	3068814	0.680 %
$85GeV < M_{visible} < 102GeV$	227114	301096	168343	107155	26193	101355	265697	58251	12417	1040507	0.496 %
$\Delta\phi_{dijet} < 175°$	220612	194003	163303	103004	25731	97518	258678	56622	11908	910767	0.482 %
$P_{visible} < 58GeV$	209722	139241	109114	51235	16966	34630	158955	44160	10161	564462	0.420 %
$N_{neutral} > 15, N_{electron} < 7$	207426	6617	10326	12539	116	9172	35114	5813	3343	83040	0.260 %
$N_{IsoMuon} = 0, N_{IsoElectron} = 0$	206299	1656	3214	11818	22	8513	16819	4362	2433	48837	0.245 %
effectiveness	53.854 %	0.000 %	0.016 %	0.130 %	0.002 %	0.133 %	0.033 %	0.021 %	0.213 %	0.005 %	

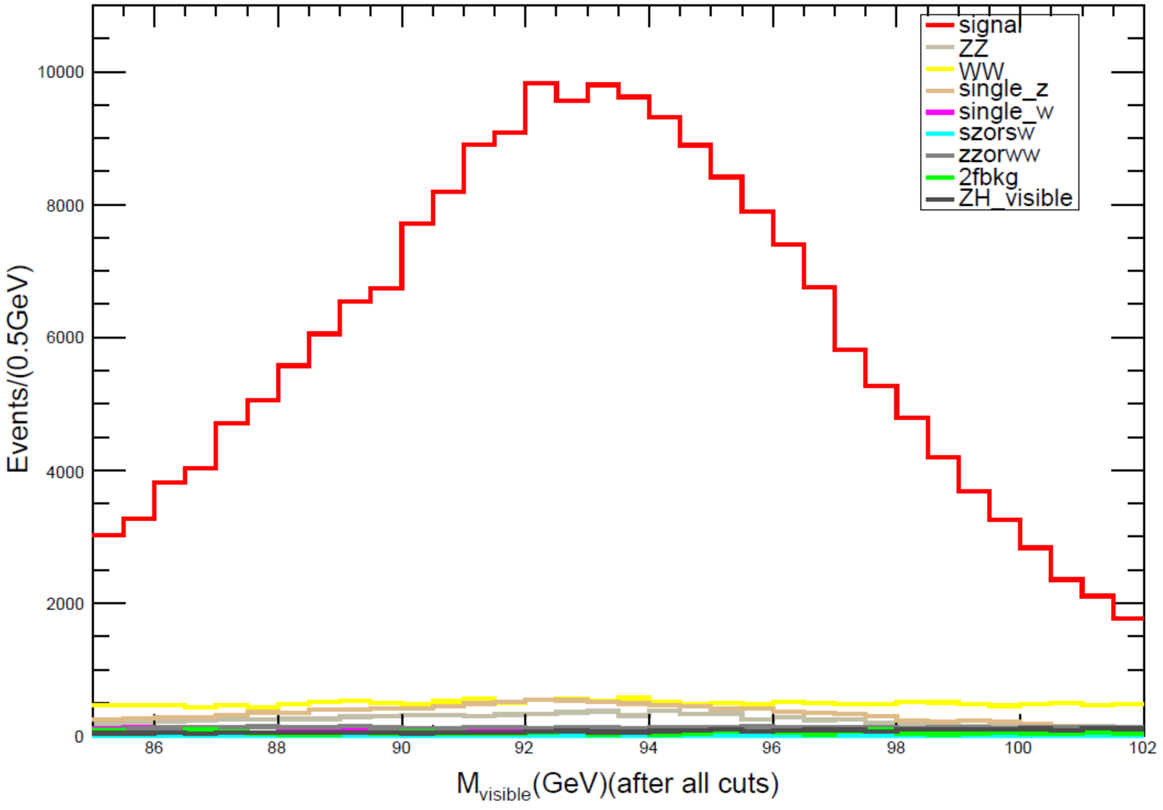
The main remain backgrounds:

- ww_sl0tauq(tau,nu,up,down) 14577(30%)
- sznu_sl0nu_down(nu_e, nu_e,down,down) 7828(16%)
- zz_sl0nu_down($nu_{\mu,\tau}$, $nu_{\mu,\tau}$,up,up) 5619(12%)

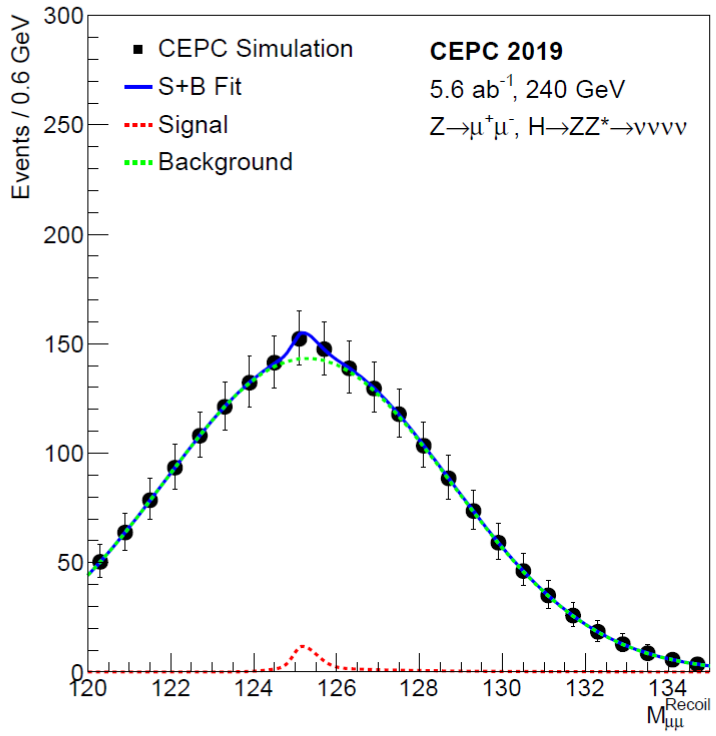
Event selection: Suppose BR(H->inv)= 50%. ZH(Z->qq,H->invisible)

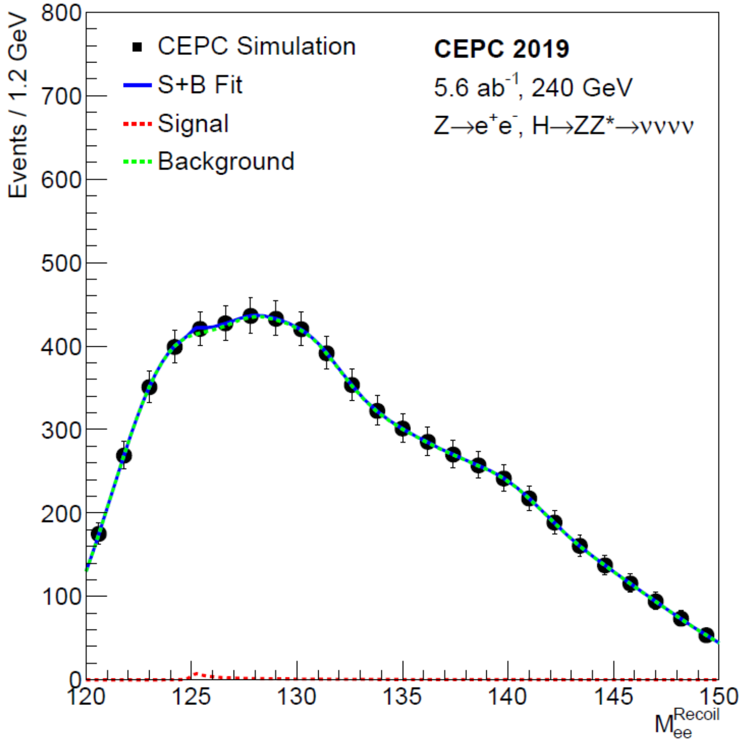
The distribution after all cuts:

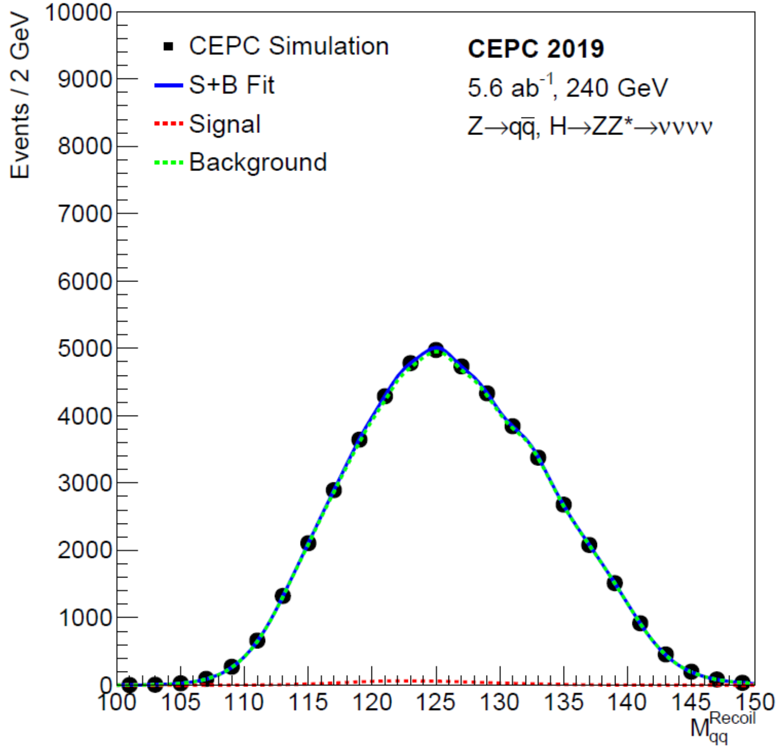




The result of fitting (Now set BR(H->inv)=0.106%(SM))





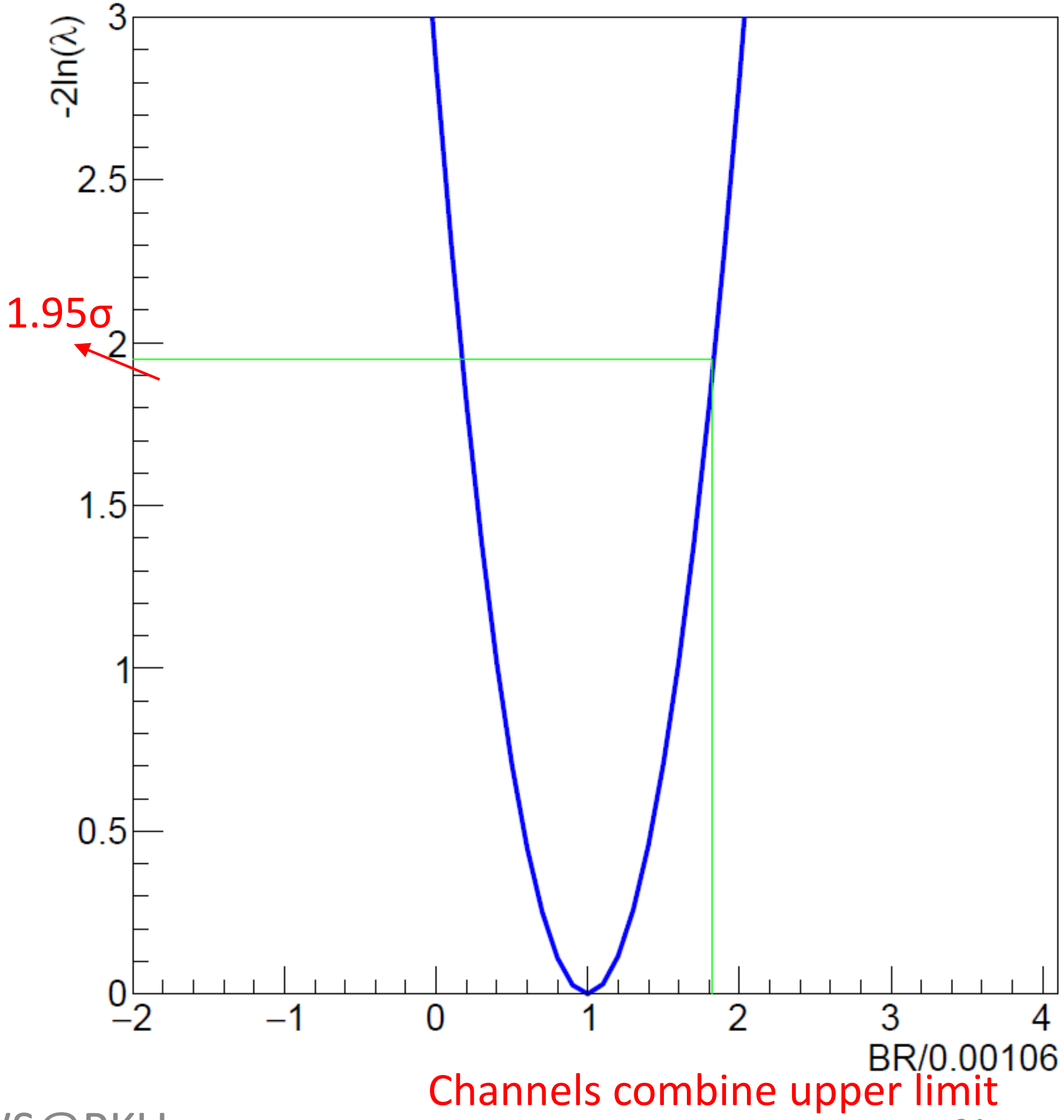


ZH(Z->$\mu^+\mu^-$,H->invisible) ZH(Z->e^+e^-,H->invisible) ZH(Z->qq,H->invisible)

- The statistical error of the branching ratio can be obtained by fitting.

Likelihood Scan

- Likelihood scan can get the upper limit of each channel or combine result.
- This picture is likelihood scan for the combination of three channels, where the green projective line label out the location of 95% confidence level (1.95σ).



Combine result

- This table is the expected precision on the measurement of σ(ZH)/BR(H->inv) and the 95% confidence-level (CL) upper limit on BR(H->inv) from a CEPC dataset of 5.6 ab^{-1}

ZH final state studied	Relative precision on $\sigma(ZH)/BR$	Upper limit on $BR(H \rightarrow inv)$
$Z \rightarrow e^+e^-$, H$\rightarrow$ inv	301%	0.698%
$Z \rightarrow \mu^+\mu^-$, H$\rightarrow$inv	105%	0.329%
$Z \rightarrow q\bar{q}$, H$\rightarrow$inv	46%	0.204%
Combination	42%	0.194%

- The combined branching ratio is measure as 0.106%$\pm$0.045% and the upper limit at 95% confidence level is estimated to be 0.194%.

Summary

- Based on a full simulated Higgs sample of 5.6 ab^{-1}, the branching ration precision of Higgs invisible decay under different channels are presented.
  - Assume BR(H->inv)=50% to select signal.
  - Assume BR(H->inv)=0.106% to get precision and upper limit of each channel.
- Next, summarize the work, solve the problems and begin to write draft.

Thanks a lot

Backup

Question:

ZH final state studied	Relative precision on $\sigma(ZH)/BR$	Upper limit on $BR(H \to inv)$
$Z \to e^+e^-$, H→ inv	301%	0.698%
$Z \to \mu^+\mu^-$, H→inv	105%	0.329%
$Z \to q\bar{q}$, H→inv	46%	0.204%
Combination	42%	0.194%

Why is the result of qq channel so good?

Comparison of the two versions cuts:

Moxin's cuts(CEPC-v1)
total generated
$\mathrm{N_{Lep}} \leq 1,\ \mathrm{N_{trks}} \leq 40,\ 10 < \mathrm{N_{clus}} < 90$
$20\mathrm{GeV} < P_t^{q\bar{q}} < 70\mathrm{GeV}$
$\lvert P_z^{q\bar{q}} \rvert < 70\mathrm{GeV}$
$-0.9 < \cos\theta_{q\bar{q}} < -0.2$
$90\mathrm{GeV} < VisibleEnergy < 130\mathrm{GeV}$
$80\mathrm{GeV} < M_{q\bar{q}} < 105\mathrm{GeV}$
BDT cut
fit window

My cuts(CEPC-v4)
Total generate
$100GeV < M_{recolil}^{visible} < 150GeV$
$30GeV < P_t^{visible} < 60GeV$
90GeV<Visible Energy<117GeV
$85GeV < M_{visible} < 102GeV$
$\Delta\phi_{dijet} < 175°$
$P_{visible} < 58GeV$
$N_{neural} > 15, N_{electron} < 7$
$N_{IsoMuon} = 0, N_{IsoElectron} = 0$
effectiveness

Reason:

1. Use visible system instead of jet information
2. The range of cut is smaller
3. Use some very special cuts. Eg. The number of electron and the number of isolated lepton.

Table 3: The alias for particles

$uq : u, \bar{u}$	$up : u, \bar{u}, c, \bar{c}$	$nu_e : \nu_e, \overline{\nu}_e$
$dq : d, \bar{d}$	$down : d, \bar{d}, s, \bar{s}, b, \bar{b}$	$nu_\mu : \nu_\mu, \overline{\nu}_\mu$
$cq : c, \bar{c}$	$e : e^-, e^+$	$nu_\tau : \nu_\tau, \overline{\nu}_\tau$
$sq : s, \bar{s}$	$mu : \mu^-, \mu^+$	$nu_{\mu,\tau} : \nu_{\mu,\tau}, \overline{\nu}_{\mu,\tau}$
$bq : b, \bar{b}$	$tau : \tau^-, \tau^+$	$nu : \nu_{e,\mu,\tau}, \overline{\nu}_{e,\mu,\tau}$
$f : e^-, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, u, d, c, s, b$		q:u,d,c,s,b

Abbreviation	Process	Final states	X-sections(fb)	Events expected
single_w	sw_l0*mu*	e,nu_e,mu,$nu_{\mu,\tau}$	436.70	2445520
	sw_l0tau	e,nu_e,tau,$nu_{\mu,\tau}$	435.93	2441208
	sw_sl0qq	e,nu_e,up,down	2612.62	14630672
single_z	sze_l0e	uncertain:e^-, e^+, e^-, e^+	78.49	439544
	sze_l0*mu*	e^-, e^+, μ^-, μ^+	845.81	4736536
	sze_l0nunu	$e^-, e^+, \nu_{\mu,\tau}, \overline{\nu}_{\mu,\tau}$	28.94	162064
	sze_l0tau	e^-, e^+, τ^-, τ^+	147.28	824767
	sze_sl0*dd*	e,e,down,down	125.83	704648
	sze_sl0uu	e,e,up,up	190.21	1065176
	sznu_l0mumu	$\nu_e, \overline{\nu}_e, \mu^-, \mu^+$	43.42	243152
	sznu_l0tautau	$\nu_e, \overline{\nu}_e, \tau^-, \tau^+$	14.57	81592
	sznu_sl0nu_down	$\nu_e, \overline{\nu}_e, down, down$	90.03	504168
	sznu_sl0nu_up	$\nu_e, \overline{\nu}_e, up, up$	55.59	311304
zorw	szeorsw_l0l	$e^-, e^+, \nu_e, \overline{\nu}_e$	249.48	1397088
WW	ww_h0ccbs	cq,cq,bq,sq	5.89	32984
	ww_h0ccds	cq,cq,dq,sq,	170.18	953008
	ww_h0cuxx	cq,uq,down,down	3478.89	19481784
	ww_h0uubd	uq,uq,bq,dq	0.05	280
	ww_h0uusd	uq,uq,sq,dq	170.45	954519
	ww_l0ll	mu, tau, nu_μ, nu_τ	403.66	2260496
	ww_sl0muq	mu,nu,up,down	2423.43	13571207

	ww_sl0muq	mu,nu,up,down	2423.43	13571207
	ww_sl0tauq	tau,nu,up,down	2423.56	13571936
ZZ	zz_h0 cc _nots	cq,cq,(dq,bq),(dq,bq)	98.97	554232
	zz_h0dtdt	down,down,down,down	233.46	1307376
	zz_h0utut	up,up,up,up	85.68	479808
	zz_h0uu_notd	uq,uq,(sq,bq),(sq,bq)	98.56	551936
	zz_l04 mu	$\mu^-, \mu^+, \mu^-, \mu^+$	15.56	87136
	zz_l04tau	$\tau^-, \tau^+, \tau^-, \tau^+$	4.61	25816
	zz_l0mumu	$\nu_\tau, \bar{\nu}_\tau, \mu^-, \mu^+$	19.38	108528
	zz_l0taumu	$\tau^-, \tau^+, \mu^-, \mu^+$	18.65	104440
	zz_l0tautau	$\nu_\mu, \bar{\nu}_\mu, \tau^-, \tau^+$	9.61	53816
	zz_sl0 mu _down	mu,mu,down,down	136.14	762383
	zz_sl0 mu _up	mu,mu,up,up	87.39	489383
	zz_sl0nu_down	$nu_{\mu,\tau}, nu_{\mu,\tau}, down, down$	139.71	782376
	zz_sl0nu_up	$nu_{\mu,\tau}, nu_{\mu,\tau}, up, up$	84.38	472528
	zz_sl0tau_down	tau,tau,down,down	67.31	376936
	zz_sl0tau_up	tau,tau,up,up	41.56	232736
zzorww	zzorww_h0cscs	cq,sq,cq,sq	1607.55	9002280
	zzorww_h0udud	uq,dq,uq,dq	1610.32	9017792
	zzorww_l0mumu	mu, mu, nu_μ, nu_μ	221.10	1238160
	zzorww_l0tautau	$tau, tau, nu_\tau, nu_\tau$	211.18	1182608