Update on the Higgs Invisible Measurement

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Outline

- Motivation
- MC Simulation and sample
- Event selection of three channels
- The upper limit and BMR
- Summary

Motivation

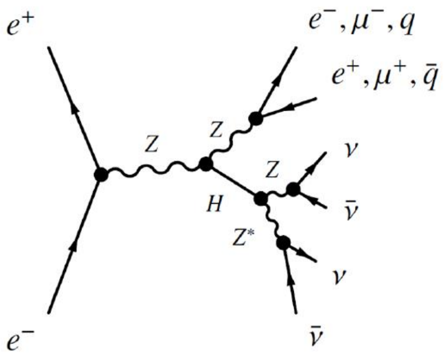
- The Higgs decay invisible in SM is via four neutrino, with BR=0.106%.
- Many new physics models predict a significant branching ratio of Higgs to invisible.
- ATLAS upper limit ~26%,CMS upper limit~ 19% for BR(Higgs->inv) at 95% C.L.
- The upper limit of BR(Higgs->inv) will be two orders of magnitude smaller on CEPC
- Higgs invisible decay is a sensitive probe for new physics.

Monte Carlo Simulation

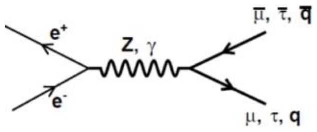
- CEPC_V4($\sqrt{s}$~240GeV, Solenoidal field~3T)
- Run about 7 years and produce a total of 1 million Higgs bosons
- Generator: Whizard 1.95 (with ISR, Lumi 5.6 ab^{-1}, M_H=125GeV)
- All Higgs boson signal samples and part of the leading background samples are processed with Geant4. The rest of backgrounds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

Data sample

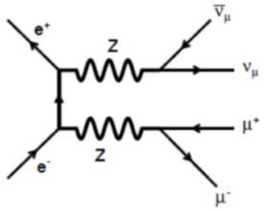
- The signal channels:
  ZH(Z->$\mu^+\mu^-$,H->invisible),ZH(Z->e^+e^-,H->invisible), ZH(Z->qq,H>invisible)

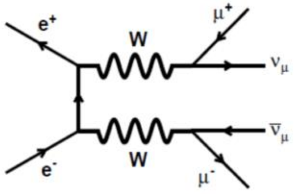


- The background channels:
  - Two fermion

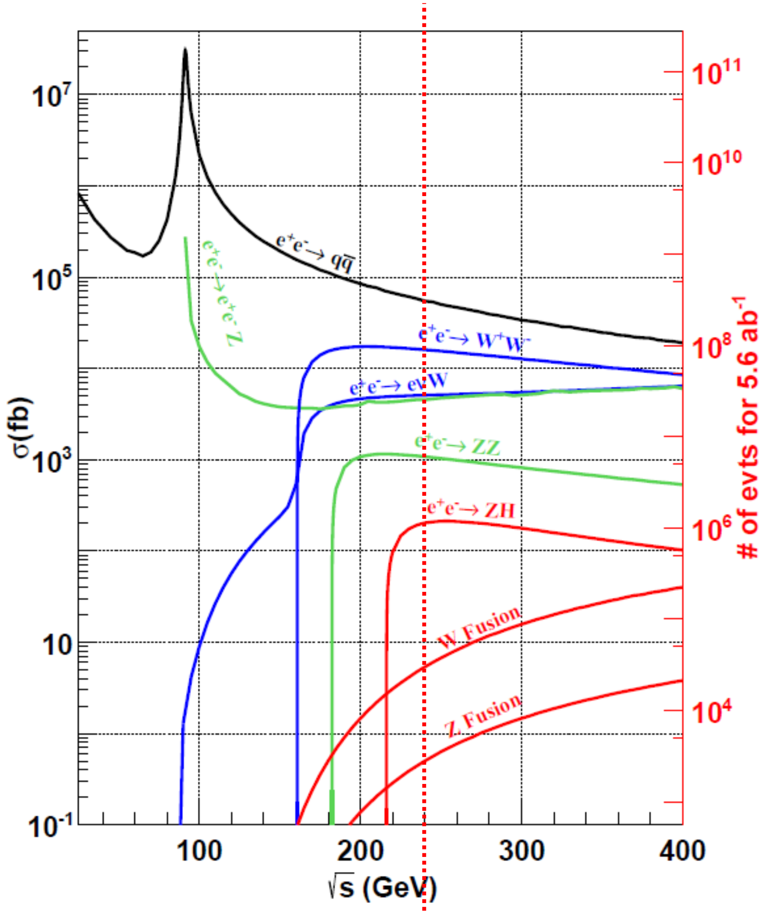


  - Four fermion



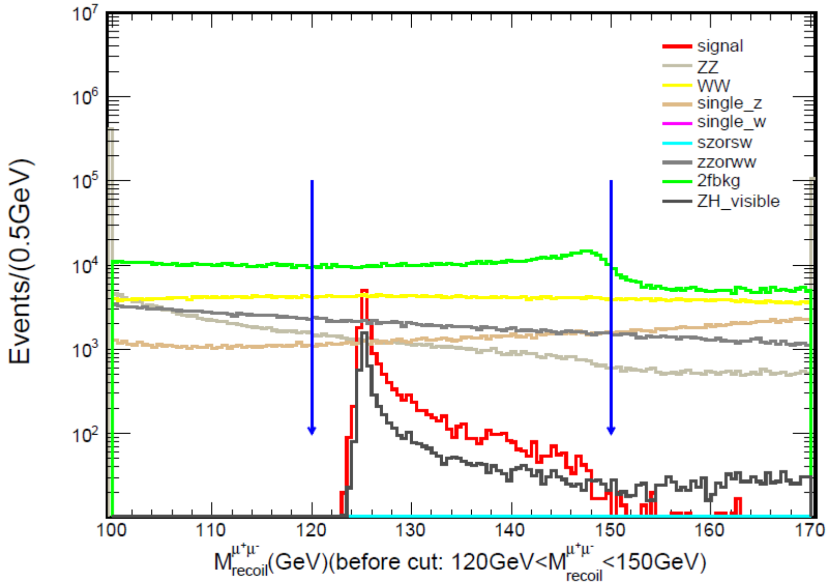


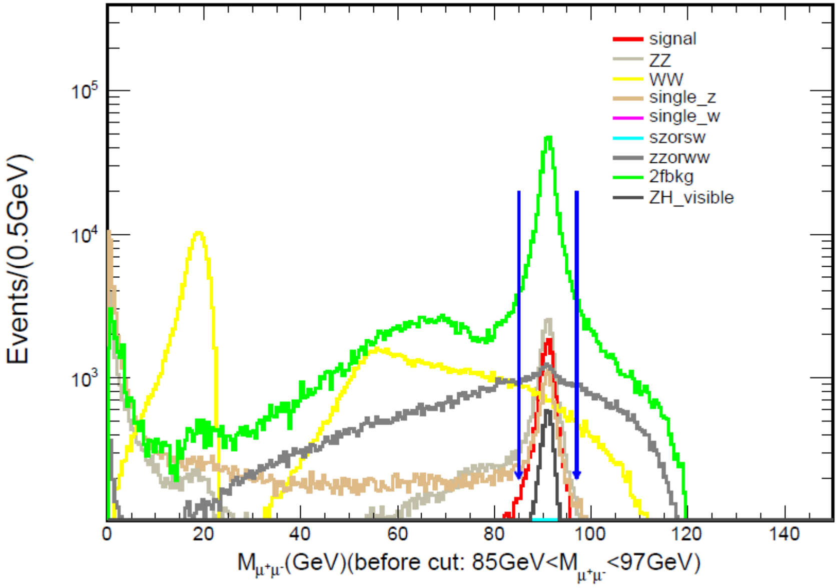
  - Sample details:
    https://gitlab.com/cepc/memo/sample-c4



Cross section of major SM processes

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



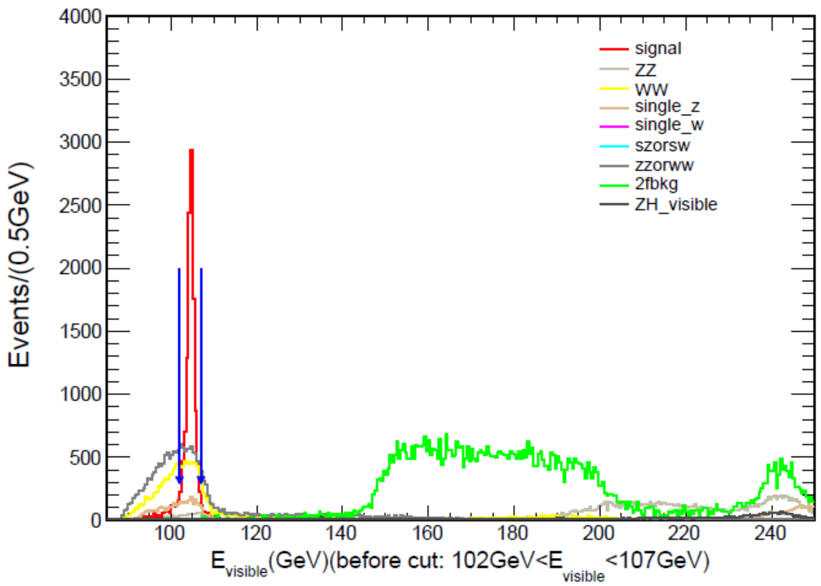


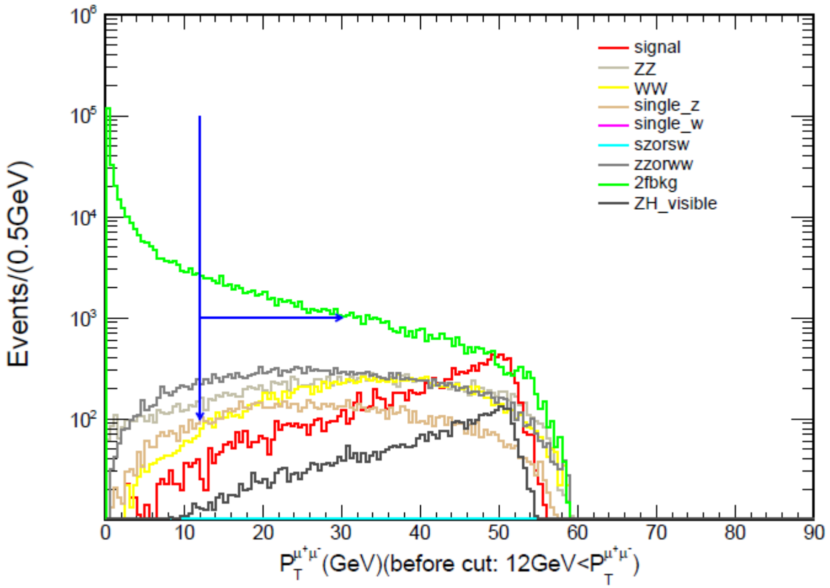
- $N_{\mu^+} = 1, N_{\mu^-} = 1$
- 85GeV<$M_{\mu^+\mu^-}$<97GeV
  - $M_{\mu^+\mu^-}$ is the mass of Z boson about 91.2GeV
- 120GeV<$M_{recoil}^{\mu^+\mu^-}$<150GeV
  - $M_{recoil}^{\mu^+\mu^-}$ is the mass of Higgs about 125GeV

$$(M_{rec}^{\mu^+\mu^-/e^+e^-})^2 = (\sqrt{s} - E_{\mu^+\mu^-/e^+e^-})^2 - P^2_{\mu^+\mu^-/e^+e^-} \quad (3)$$

$$M_Z^2 = E^2_{\mu^+\mu^-/e^+e^-} - P^2_{\mu^+\mu^-/e^+e^-} \quad (4)$$

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





- 102GeV< $E_{visible/\mu^+\mu^-}$<107GeV
  - M^2_{Higgs}=$(\sqrt{s} - E_{\mu^+\mu^-})^2 - P^2_{\mu^+\mu^-}$
  - From the formula, $E_{visible/\mu^+\mu^-}$ is around [91GeV,115GeV]

- $\Delta\phi_{\mu^+\mu^-}$<175°,12GeV< $P_t^{\mu^+\mu^-}$
  - In order to suppress 2 fermion background

The cut flow of $\mu\mu$H_inv

The accuracy under BR=50%

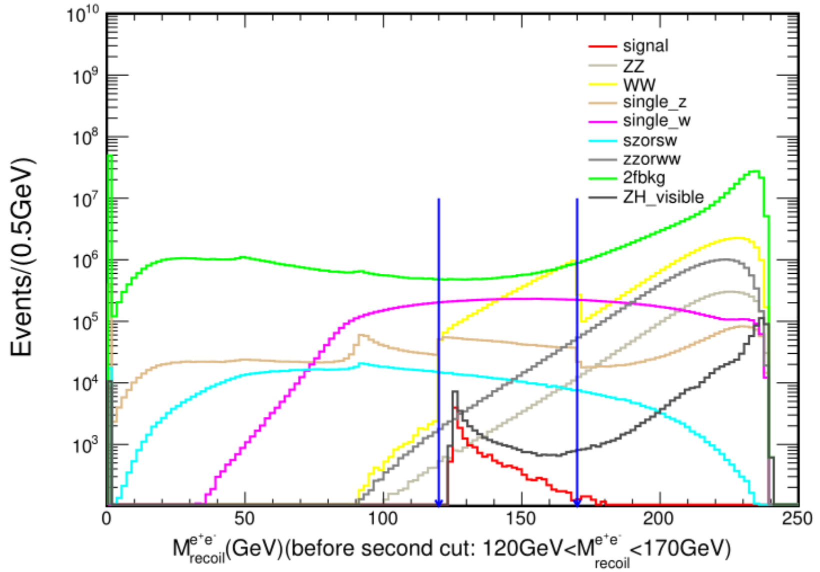
Process	$\mu^+\mu^- H\_inv$	2f	single_w	single_z	szorsw	zz	ww	zzorww	ZH	total_bkg	$\frac{\sqrt{S+B}}{S}$
Total generated	18956	801152072	19517400	9072951	1397088	6389430	50826214	20440840	1140495	909936490	159.13 %
$N_{\mu^+} = 1, N_{\mu^-} = 1$	16851	22737312	36122	723397	0	702041	1255610	1223595	59978	26738055	30.70 %
$120GeV < M^{\mu^+\mu^-}_{Recoil} < 150GeV$	16431	652616	24	81165	0	62389	250796	112141	5680	1164811	6.61 %
$85GeV < M_{\mu^+\mu^-} < 97GeV$	13957	381054	0	10576	0	20850	16718	24417	4485	458100	4.92 %
$12GeV < P_t^{\mu^+\mu^-}$	13522	92197	0	9333	0	18253	15903	21061	4324	161071	3.09 %
$\Delta\phi < 175^\circ$	12990	72196	0	8754	0	17023	14768	20230	4136	137107	2.98 %
102GeV<Visible Energy<107GeV	11365	61	0	1455	0	483	4378	5434	9	11820	1.34 %
$\frac{E_{\mu^+\mu^-}}{P_{\mu^+\mu^-}} < 2.4$	11216	26	0	1343	0	439	3502	4088	5	9403	1.28 %
$ReM_{visdtau} > 230GeV$	11143	26	0	1338	0	436	66	52	4	1922	1.03 %
Efficiency	58.78 %	0.00 %	0.00 %	0.01 %	0.00 %	0.01 %	0.00 %	0.00 %	0.00 %	0.00 %	

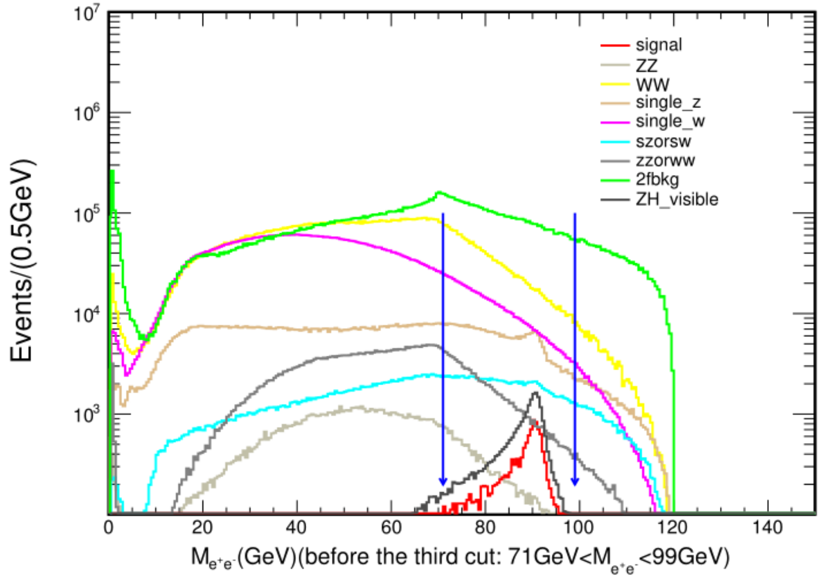
The main remain backgrounds:

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

The remain backgrounds are similar to signal($\upsilon_e, \bar{\upsilon}_e, \mu^+, \mu^-$).

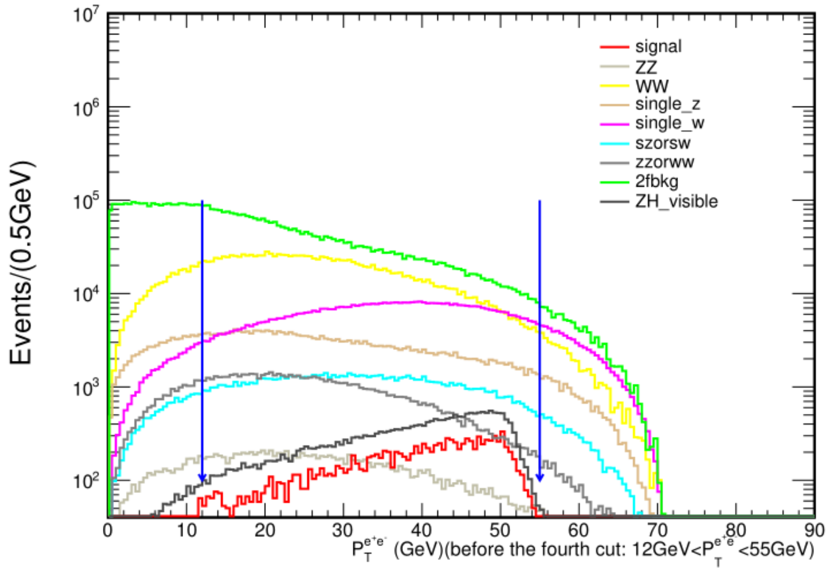
Event selection of ZH(Z->e^+e^-,H->invisible) : Suppose BR(H->inv)= 50%

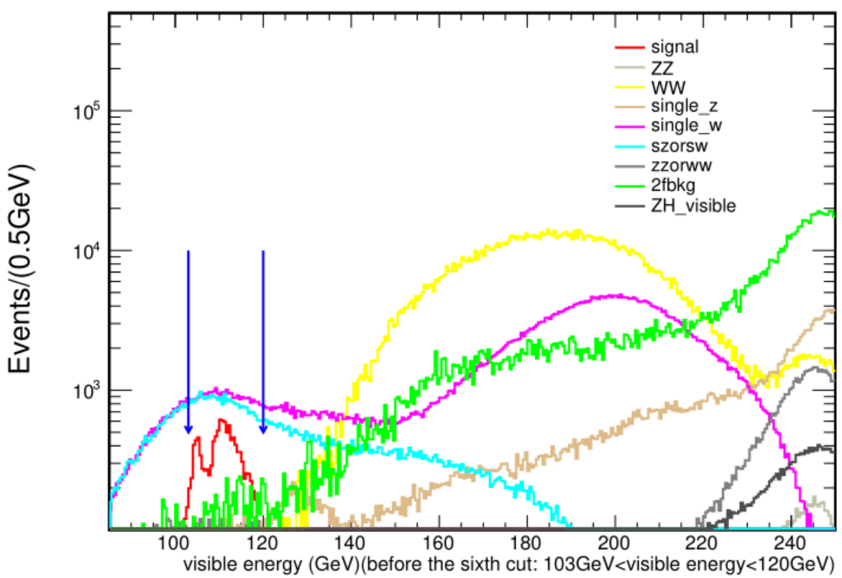




- 120GeV<$M^{e^+e^-}_{recoil}$<170GeV
  - $M^{\mu^+\mu^-}_{recoil}$ is the mass of Higgs about 125GeV
- 71GeV<$M_{e^+e^-}$<99GeV
  - $M_{\mu^+\mu^-}$ is the mass of Z boson about 91.2GeV

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

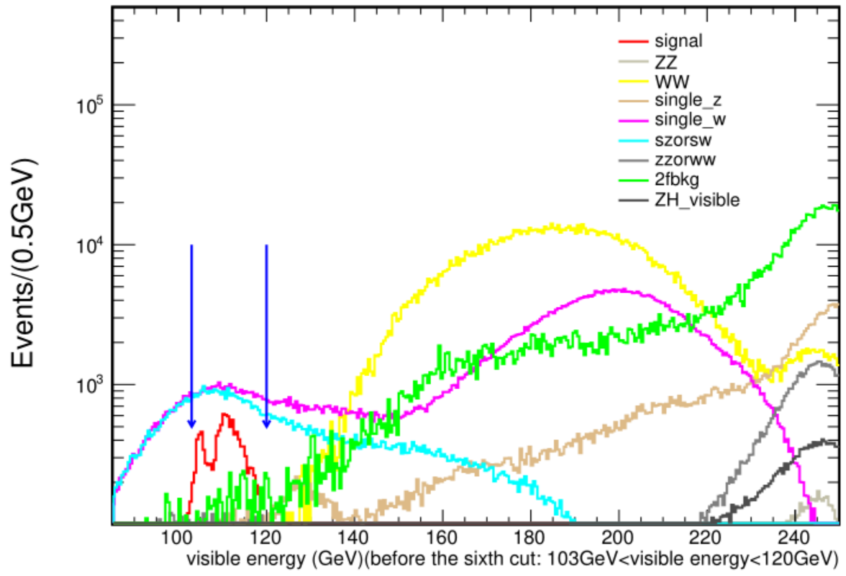




- $\Delta\phi_{e^+e^-}$<176°, 12GeV<$P_t^{\mu^+\mu^-}$<55GeV
  - In order to suppress 2 fermion background
- 103GeV<$E_{visible}$<120GeV
- Impact_Tau< 0.0011
  - Impact_Tau is related with secondary vertex
  - This can parameter distinguish between tau and e,μ

Explain the two peaks

- When electron generate a nearby photon.
- The electron and photon will reconstruct into one cluster.
- The track energy of the cluster is the electron - the photon.
- The energy of cluster energy subtract track energy (photon) will become a neutral particle, will appear in the reconstruction algorithm
- Due to the large energy of the cluster, the energy of these neutral particles will be zero or large value, which corresponds to the neutral particle is identified and unidentified.
- This will lead to two peaks at the distribution.



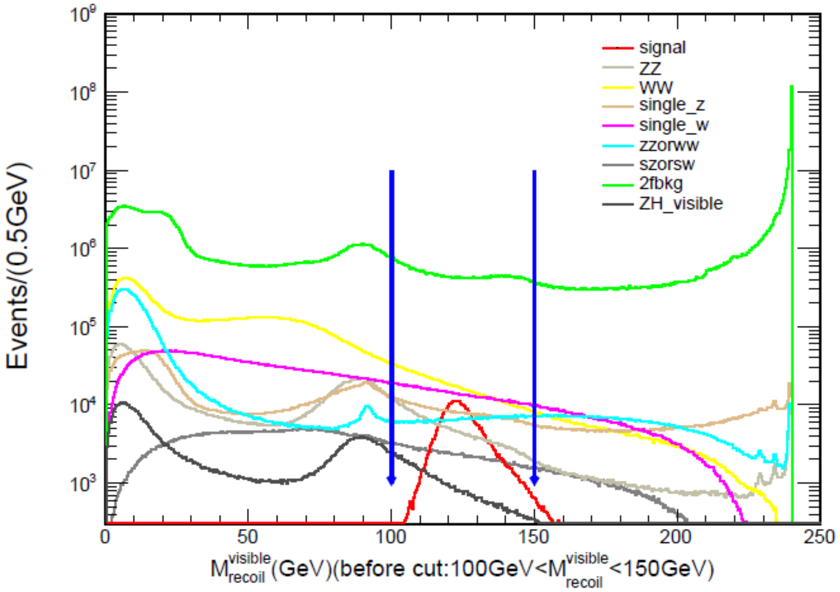
The cut flow of eeH_inv

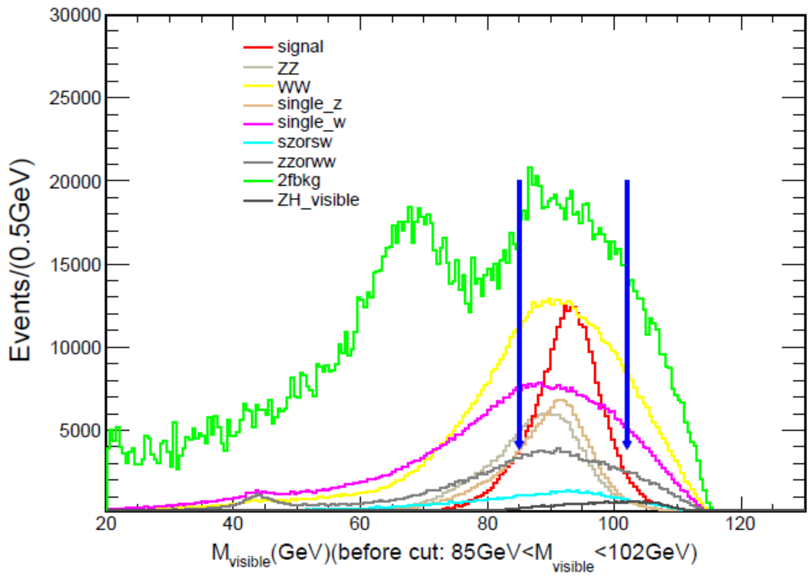
Process	eeH_invi	2f	single_w	single_z	szorsw	zz	ww	zzorww	ZH	total_bkg	$\frac{\sqrt{S+B}}{S}$
Total generated	19712	801152072	19517400	9072951	1397088	6389430	50826214	20440840	1140495	909936490	153.03 %
$N_{e^+} = 1, N_{e^-} = 1$	18405	389959503	15669806	4931933	1236440	5816250	47812974	18467237	679473	484573616	119.61 %
$120GeV < M_{recoil} < 170GeV$	16726	16124629	6286116	1272240	313037	100041	9972681	423152	35389	34527285	35.14 %
$71GeV < M_{e^+e^-} < 99GeV$	13677	5382788	647494	324692	113529	15001	1823446	92463	26188	8425601	21.24 %
$12GeV < P_t^{e^+e^-} < 55GeV$	13134	3476906	558026	259411	98570	12533	1584475	79506	25162	6094589	18.82 %
$\Delta\phi < 176^{\circ}$	12566	1230398	516751	238434	94468	10493	1435540	71282	24246	3621612	15.17 %
$103GeV < VisibleEnergy < 120GeV$	11618	4609	30665	3348	27463	56	570	3430	131	70272	2.46 %
$1.8 < \frac{E_{e^+e^-}}{P_{e^+e^-}} < 2.4$	9654	1085	14179	1705	12209	10	215	1127	61	30591	2.08 %
$ReM\_visdtau > 220$ and Impact_Tau<0.0011	8641	442	1281	1354	10244	0	19	39	26	13405	1.72 %
Efficiency	43.84 %	0.00 %	0.01 %	0.01 %	0.73 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	

The main remain backgrounds:

- szeorsw_l0l($e^+, e^-, \upsilon_e, \bar{\upsilon}_e$) 10244(76%)
- sze_l0nunu($e^+, e^-, \upsilon_{\mu,\tau}, \bar{\upsilon}_{\mu,\tau}$) 1276(10%)

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





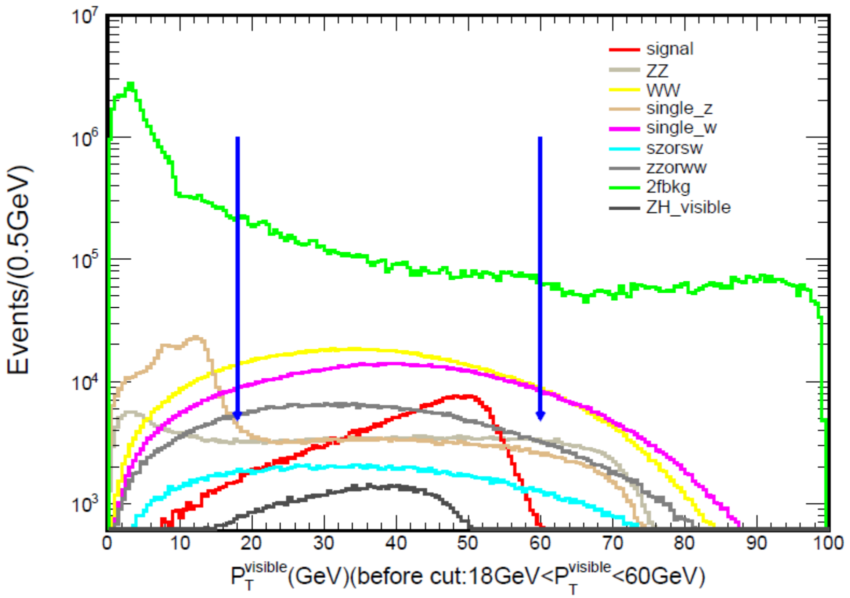
- 100GeV< $M_{recoil}^{visible}$ <150GeV
  - $M_{recoil}^{visible}$ is the mass of Higgs about 125GeV

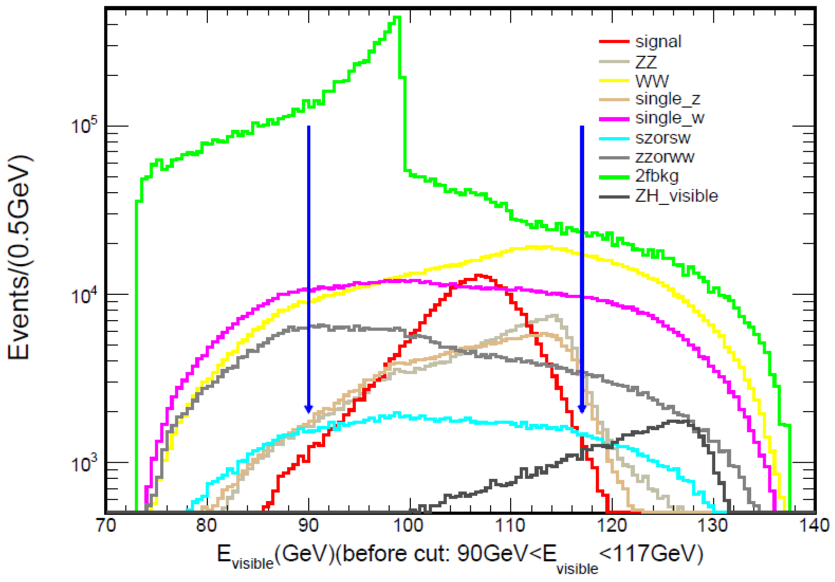
$$(M_{rec}^{visible})^2 = (\sqrt{s} - E_{visible})^2 - P_{visible}^2$$

$$M_{visible}^2 = E_{visible}^2 - P_{visible}^2$$

- 85GeV< $M_{visible}$ <102GeV
  - $M_{visible}$ is the mass of Z boson about 91.2GeV

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





- $\Delta\phi_{dijet}$<175°, 18GeV<$P_t^{visible}$<60GeV
  - In order to suppress 2 fermion background
- 90GeV< visible energy <117GeV
- $N_{IsoMuon} = 0, N_{IsoElectron} = 0$
  - 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_visible	total_bkg	$\frac{\sqrt{S+B}}{S}$
Total generated	383068	801152072	19517400	9072952	1397088	6389429	50826213	20440840	1140496	909936490	7.88 %
100GeV$< M_{recolil}^{visible} <$150GeV	369001	47294921	1388874	822725	229216	507558	1752824	658200	97384	52751702	1.98 %
18GeV$< P_T^{visible} <$60GeV	335572	9165308	1000761	269323	152273	282624	1294263	462027	79965	12706544	1.08 %
90GeV$<E_{visible}<$117GeV	319558	5748711	595694	223044	92958	231050	785389	272515	33705	7983066	0.90 %
85GeV$< M_{visible} <$102GeV	268930	605788	238190	148842	39280	135635	392275	113043	18282	1691335	0.52 %
$\Delta\phi_{dijet} < 175^\circ$	259553	390075	230271	141490	38358	129130	379928	109734	17393	1436379	0.50 %
30GeV$< P_{visible} <$58GeV	242860	241508	148607	69450	24392	46800	226881	74780	13465	845883	0.43 %
$N_{neutral} > 15$	242341	18081	22594	64324	149	44338	128425	8616	11852	298379	0.30 %
$N_{IsoMuon} = 0, N_{IsoElectron} = 0$	231374	8423	9604	60645	28	41536	76617	6447	9219	212519	0.29 %
Efficiency	60.40 %	0.00 %	0.05 %	0.67 %	0.00 %	0.65 %	0.15 %	0.03 %	0.81 %	0.02 %	

Before version： N_neutral>15, N_electron<7.

Due to the version of background and signal data are different and the number of electrons is affected by the reconstruction version, I change the signal version and remove the cut of N_electron<7.

Old version:

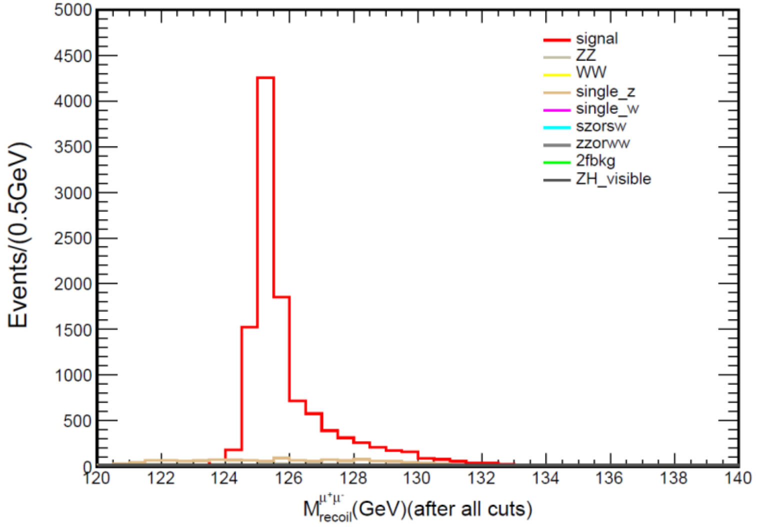
$P_{visible} < 58GeV$	209722	139241	109114	51235	16966	34630	158955	44160	10161	564462	0.420 %
$N_{neural} > 15, N_{electron} < 7$	207426	6617	10326	12539	116	9172	35114	5813	3343	83040	0.260 %
$N_{IsoMuon} = 0, N_{IsoElectron} = 0$	206299	1656	3214	11818	22	8513	16819	4362	2433	48837	0.245 %
effectiveness	53.854 %	0.000 %	0.016 %	0.130 %	0.002 %	0.133 %	0.033 %	0.021 %	0.213 %	0.005 %	

$\frac{\sqrt{S+B}}{B}$: 0.25% -> 0.29%

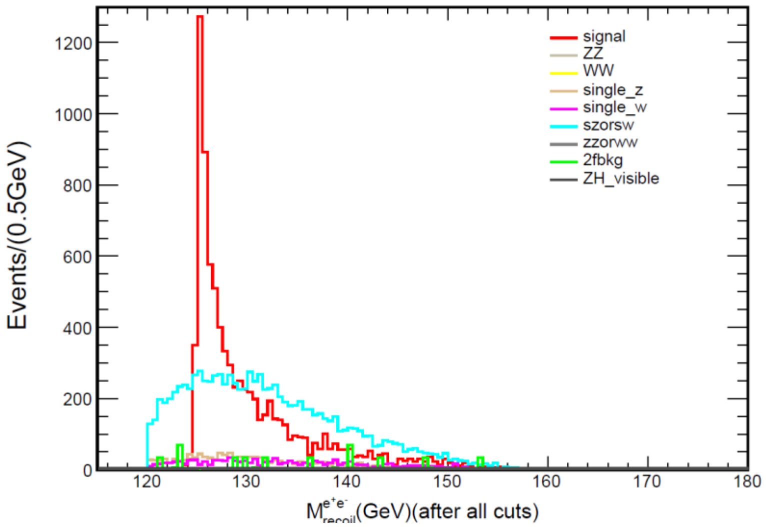
The main remain backgrounds in qqH_inv:

- nu_l, nu_l,q,q: 65151 (43%)
- tau,nu,up,down: 46126 (31%)

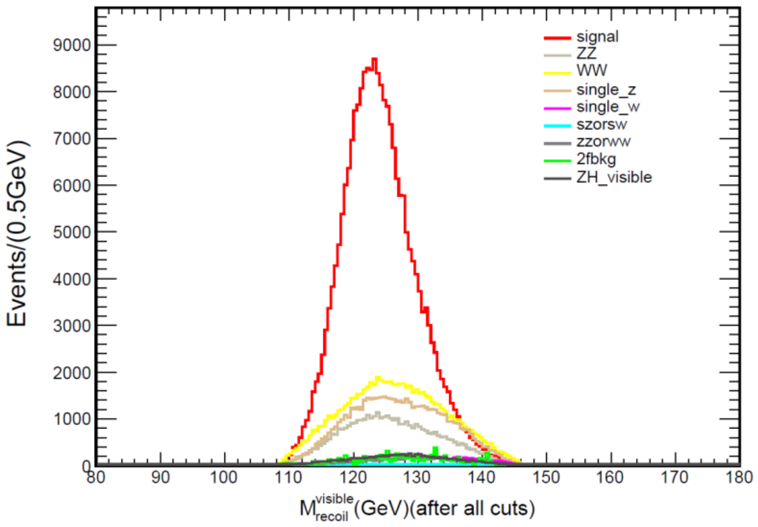
The distribution of recoil mass after cut flow:



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



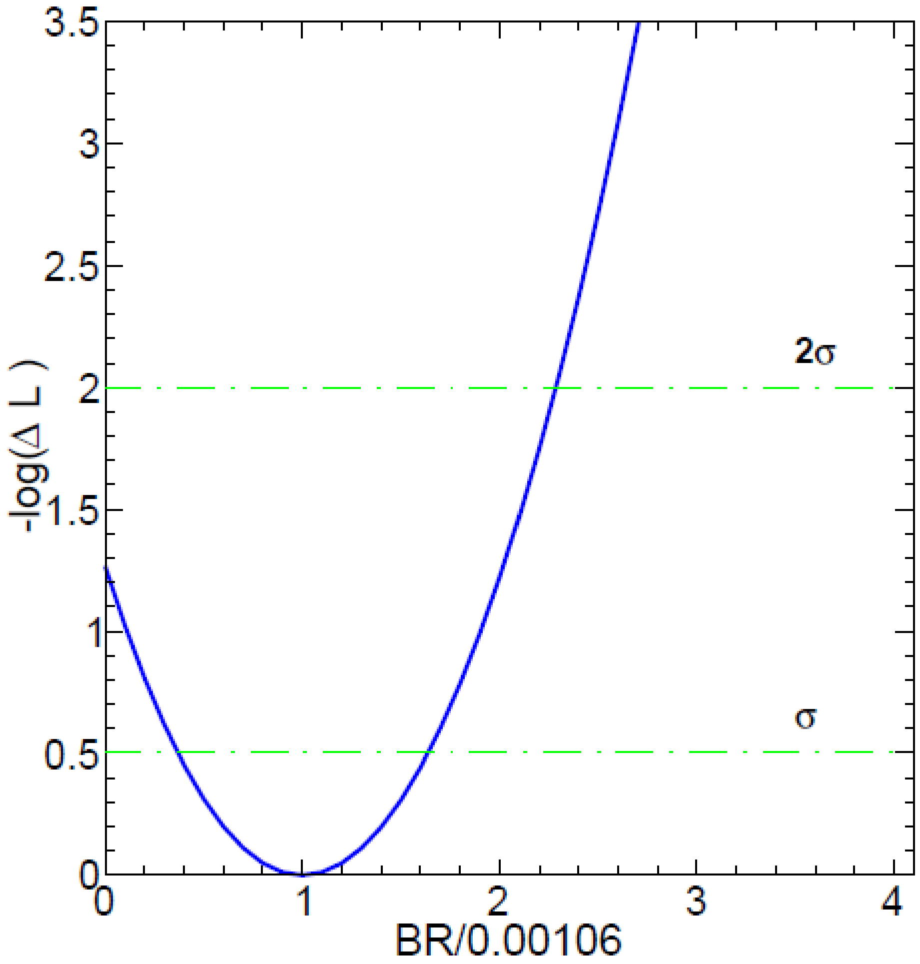
ZH(Z->e^+e^-,H->invisible)



ZH(Z->qq,H->invisible)

The upper limit – Likelihood Scan

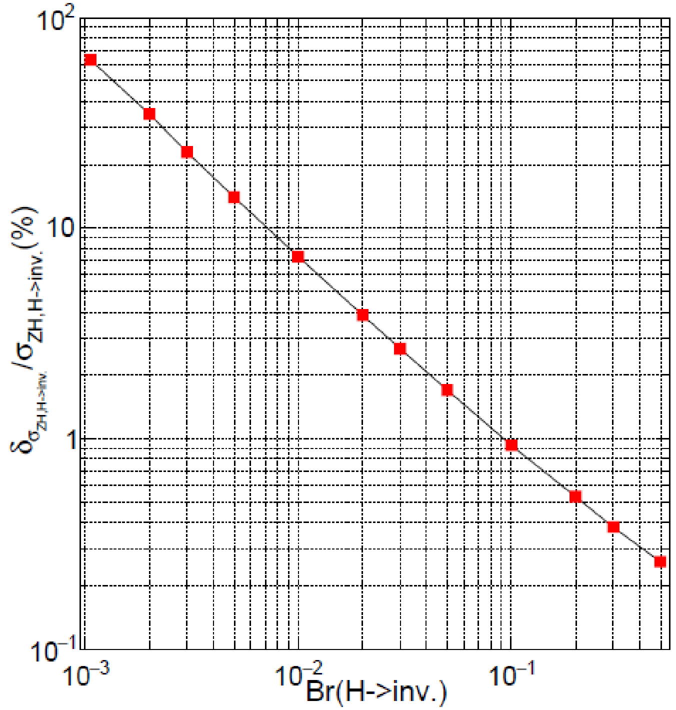
- Method: $\mu S + B$
- Fitting data: get the value and error of μ
- This picture is the likelihood scan result for the combination of three channels, where the green dash line label out the location of 68%/95% confidence level (-log(ΔL)=0.5/2).



The upper limit under different BR(H->inv.)

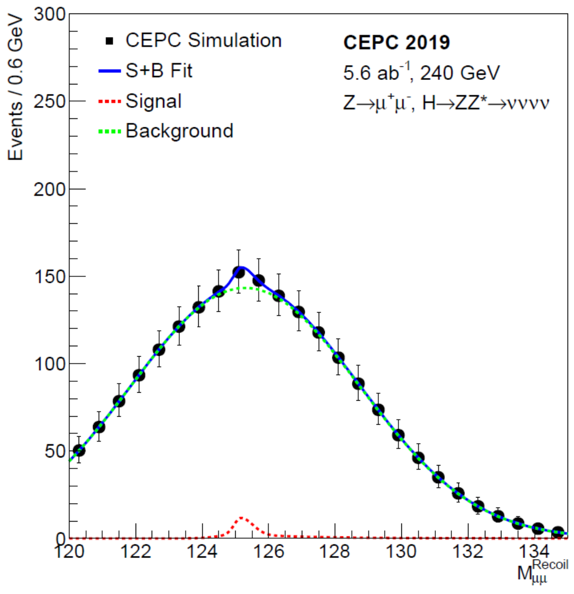
- The precision of the cross section of Higgs decay to invisible final states $\frac{\delta_{\sigma_{ZH,H\to inv.}}}{\sigma_{ZH,H\to inv.}}$ versus BR(H->inv.)
- The BR(H->inv.) is larger, and the precision is higher.
- When BR(H->inv.) = 50%, $\frac{\delta_{\sigma_{ZH,H\to inv.}}}{\sigma_{ZH,H\to inv.}}$=0.26%
- When BR(H->inv.)=0.106%, $\frac{\delta_{\sigma_{ZH,H\to inv.}}}{\sigma_{ZH,H\to inv.}}$=63%

Statistical error of fitting

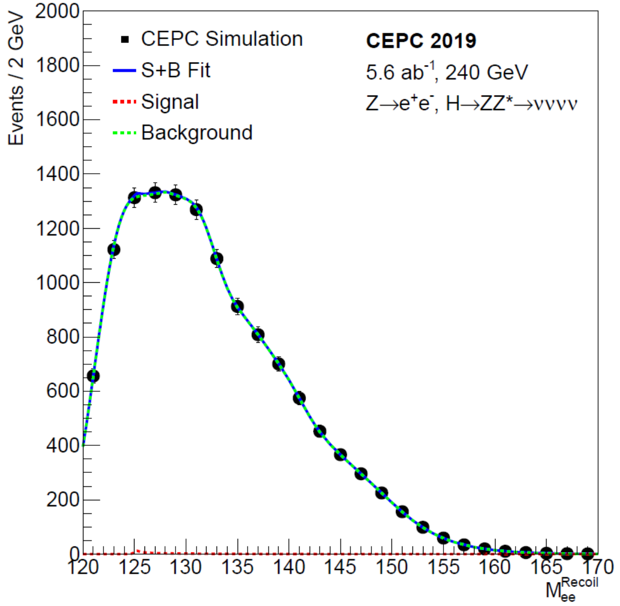


The result of fitting (Set BR(H->inv)=0.106%(SM))

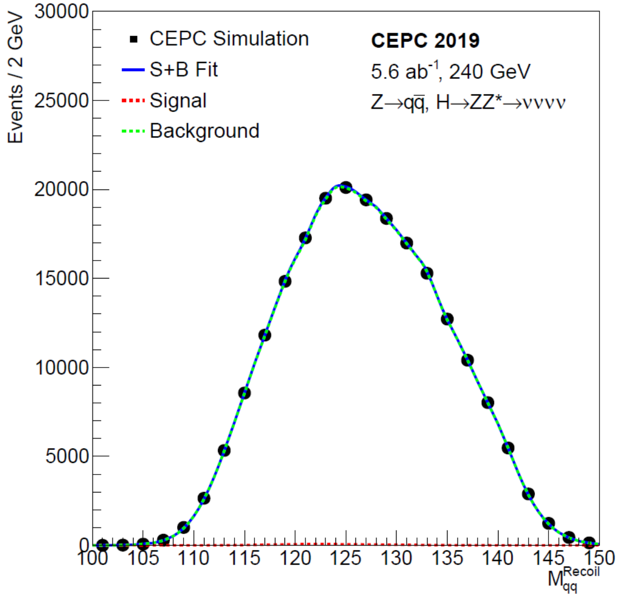
- The statistical error of the branching ratio can be obtained by fitting



ZH(Z->$\mu^+\mu^-$,H->invisible)
error: $\sigma_{H\to inv}$=0.10%



ZH(Z->e^+e^-,H->invisible)
error: $\sigma_{H\to inv}$=0.43%



ZH(Z->qq,H->invisible)
error: $\sigma_{H\to inv}$=0.09%

Combine result

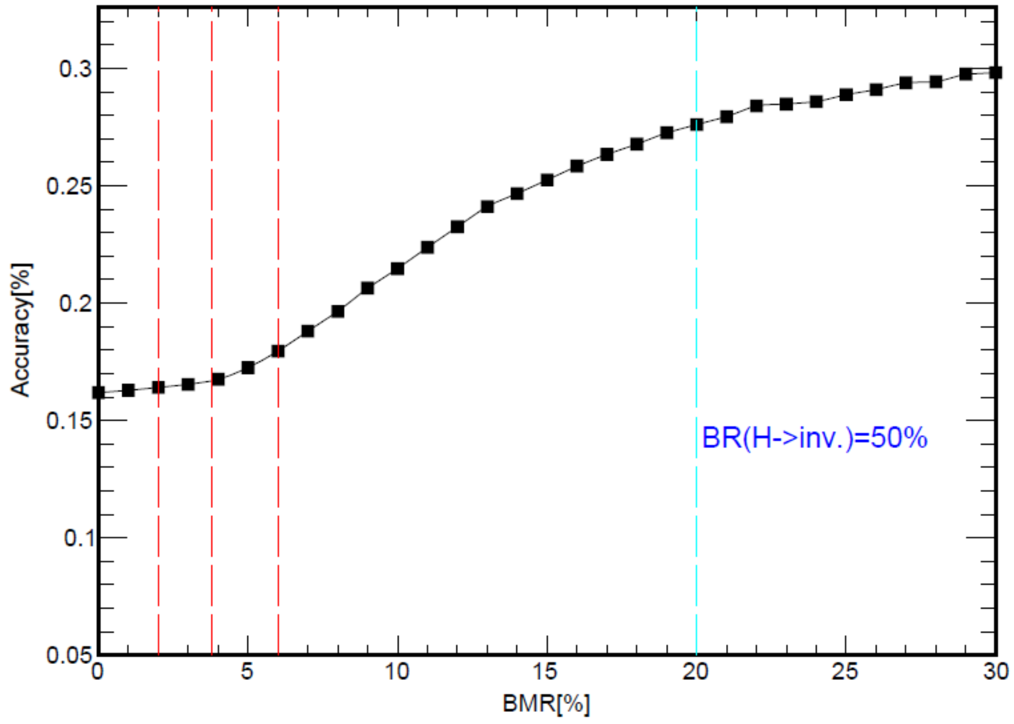
- This table is the expected precision on the measurement of σ(ZH)×BR(H->inv) and the 95% confidence-level (CL) upper limit on BR(H->inv) from a CEPC dataset of 5.6 ab^{-1}

ZH final state studied	Relative precision on $\sigma(ZH)\times$BR	Upper limit on BR (H→inv.)
Z→ e^+e^-, H→inv.	403%	0.96%
Z→ $\mu^+\mu^-$, H→inv.	98%	0.31%
Z→ $q\overline{q}$, H→inv.	85%	0.29%
Combination	63%	0.24%

- The combined branching ratio is measure as 0.106%±0.067% and the upper limit at 95% confidence level is estimated to be 0.24%.

The BMR of Higgs->invisible

- BMR(Boson mass resolution) of Higss->invisible under BR(H->inv.)=50%
- qqH dominants the precision & rely on recoil mass to separate the ZZ(Z->qq,Z->inv.) bkg
- Essential for qqH analysis, especially H->non jet final state



- If the BMR improves/degrades from 4% to 2%/6%: the Higgs invisible measurement improves/degrades by 2%/11%

Summary

Status：

- Further optimized the event flow and increased its reliability
- Add the precision of cross section of Higgs decay invisible part at different branching ratio
- Add the dependence of accuracy versus BMR
- Update the new result 95%UL. Br(H->inv.)=0.24%

Next Plan:

- Complete the paper of Higgs invisible decay
- May consider the affect of some system uncertainties

Thanks a lot