Status report on H->ZZ analyses and H->invisible analysis at CEPC

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Status of H→ZZ analysis

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Introduction to HZZ channel

・ Since the state has 3 Z bosons, there are multiple combinations of final products.

・ Final states having ($\mu^+\mu^-$, jj, $\nu\nu$) are promising channels, owing to its clear signature. On the other hand, its low statistics could limit the final precision. (i.e., full-hadronic decay mode)

・This presentation summarizes the results from channels with the decay product combination of ($\mu\mu$, jj, $\nu\nu$) . Comparison of the cut-based analysis and the BDT-applied result will be presented.

Table : Promising decay product combinations

Z / ZZ*				
e^+e^-	$\nu\nu$jj	jj$\nu\nu$		
$\mu^+\mu^-$	$\nu\nu$jj	jj$\nu\nu$		jjjj
$\nu\nu$	e^+e^- jj	jje^+e^-	$\mu^+\mu^-$ jj	jj$\mu^+\mu^-$
jj	e^+e^- $\nu\nu$	$\nu\nu e^+e^-$	$\mu^+\mu^-$ $\nu\nu$	$\nu\nu$ $\mu^+\mu^-$

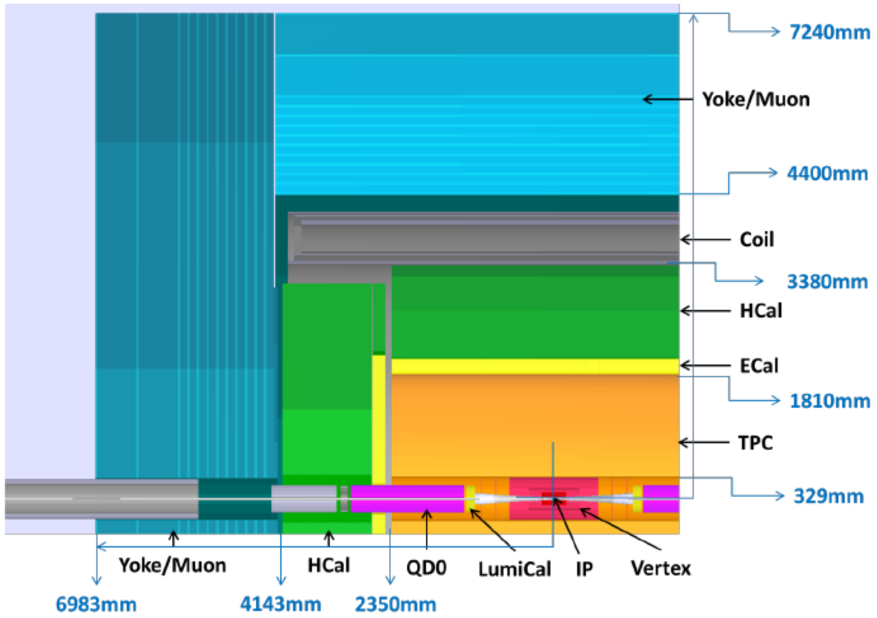
Monte Carlo Simulation

- CEPC_v4 (240GeV, 3T) configuration

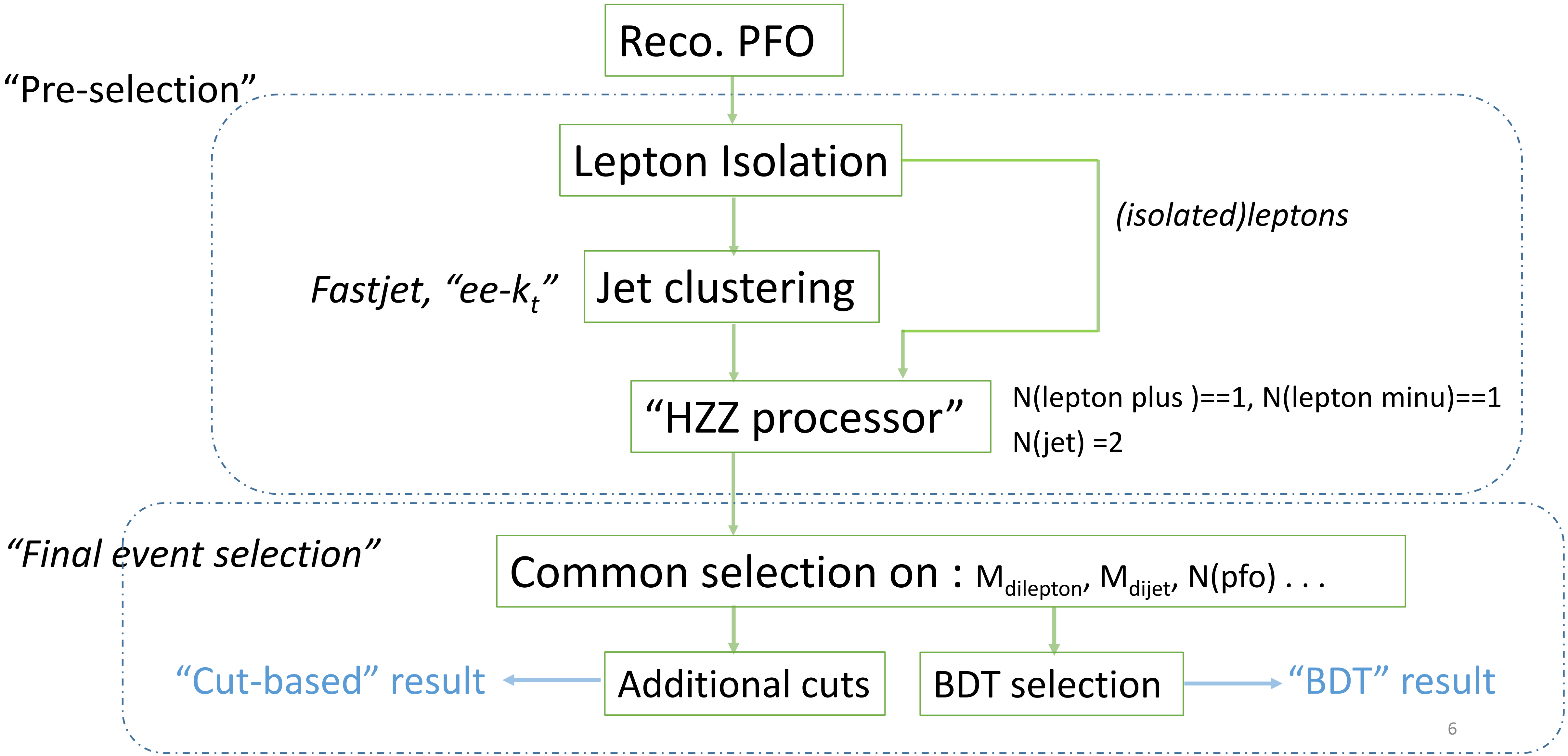
- Generator: Whizard 1.95
  (with ISR, L=5.6 ab^{-1}, M_{higgs}=125 GeV)

- Simulation :
  Geant4 and Mokka with ISR and bremsstrahlung effects

- Reconstruction:
  Marlin and ArborPFA

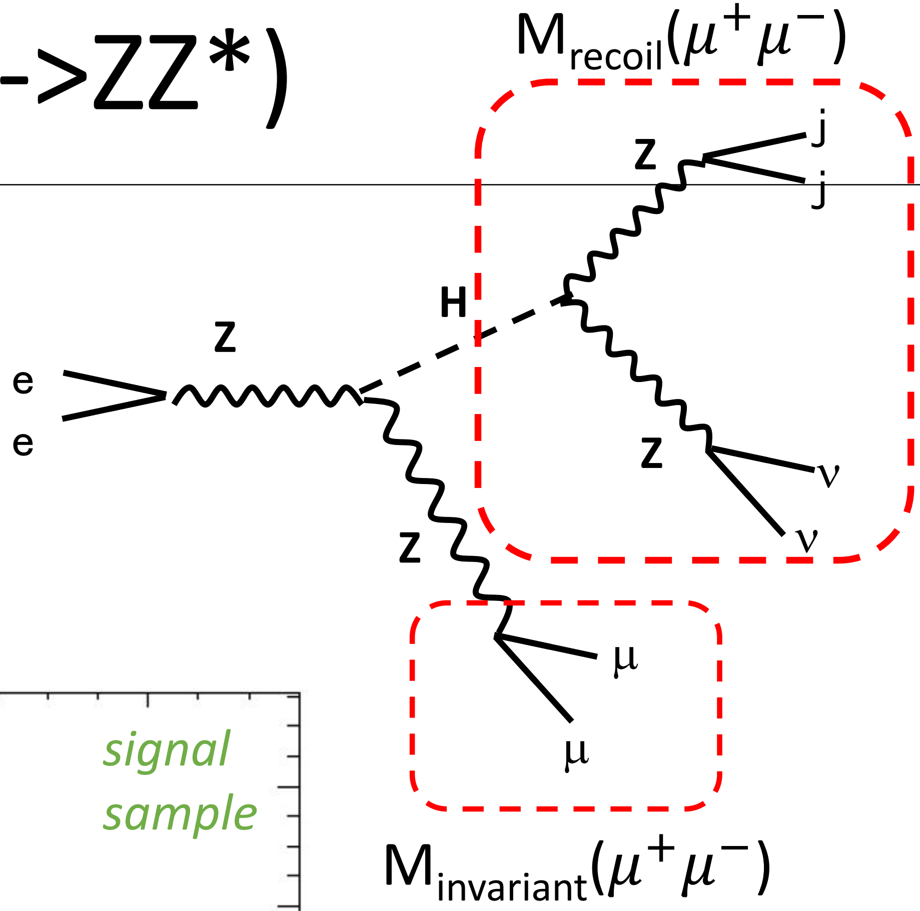


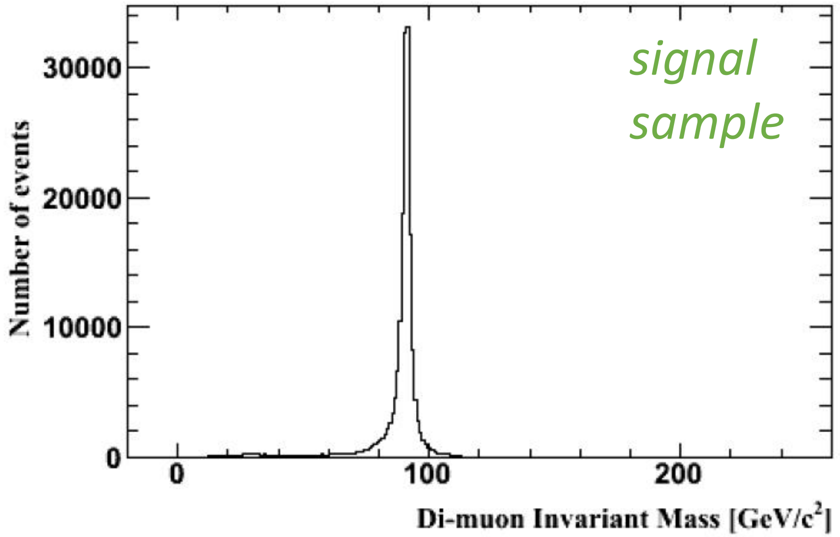
Analysis flow chart



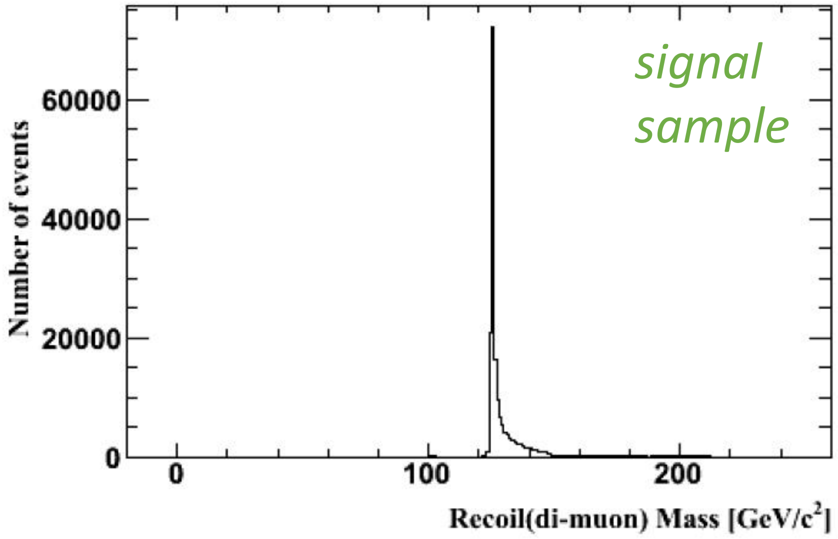
Signature of $Z(\to\mu^+\mu^-)H(\to ZZ^*)$

Identify two muons from initial Z boson
using invariant & recoil mass as usual





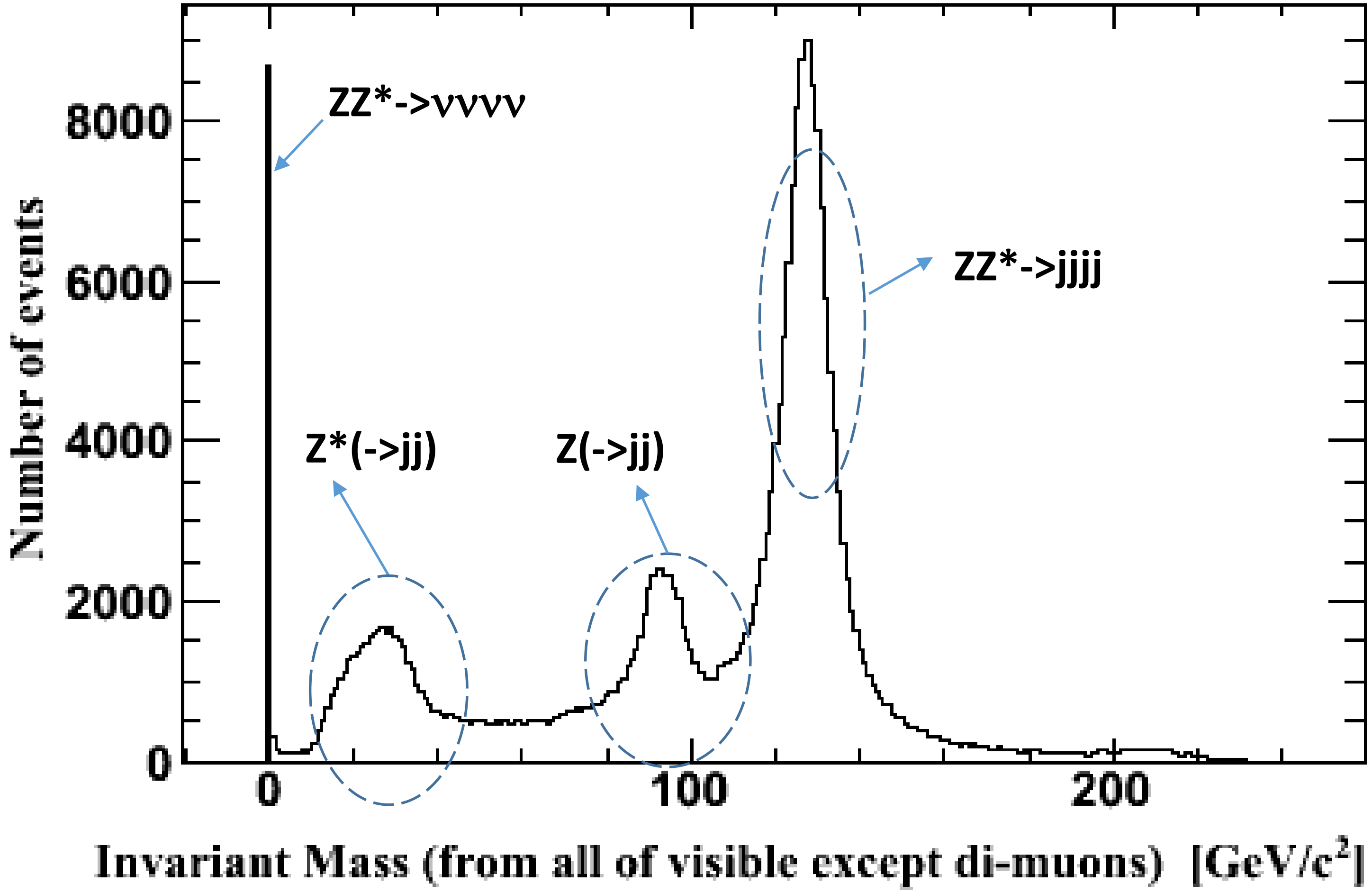
$M_{Invatiant}(\mu^+\mu^-)$



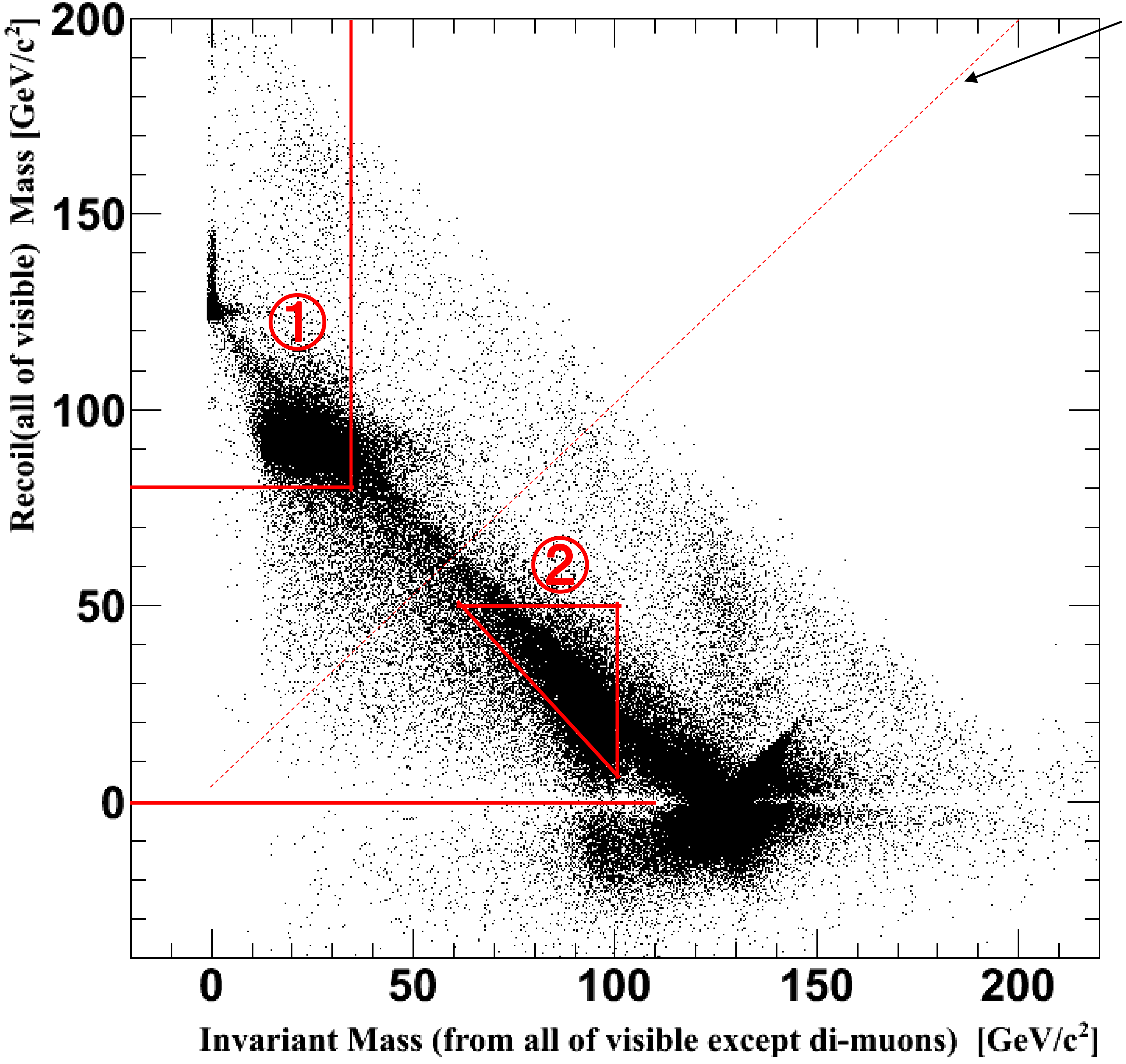
$M_{Recoil}(\mu^+\mu^-)$

Signature of Z(->$\mu^+\mu^-$)H(->ZZ*)

Distribution of invariant mass except two muons clearly shows each decay mode.



Jet clustering
N(jet)=2

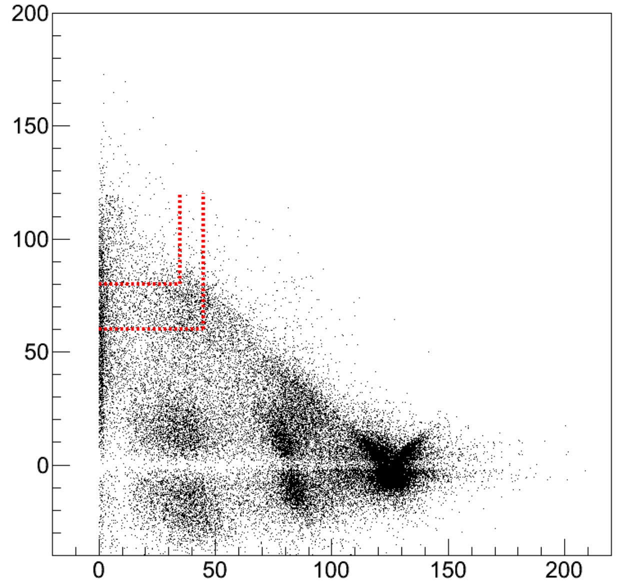


Missing Mass (Z->νν) = Dijet Mass (Z->jj)

Two regions are defined and separately analyzed

Region ① : H→ZZ*(Z→νν, Z*→qq)

Region ② : H→ZZ*(Z→qq, Z*→νν)



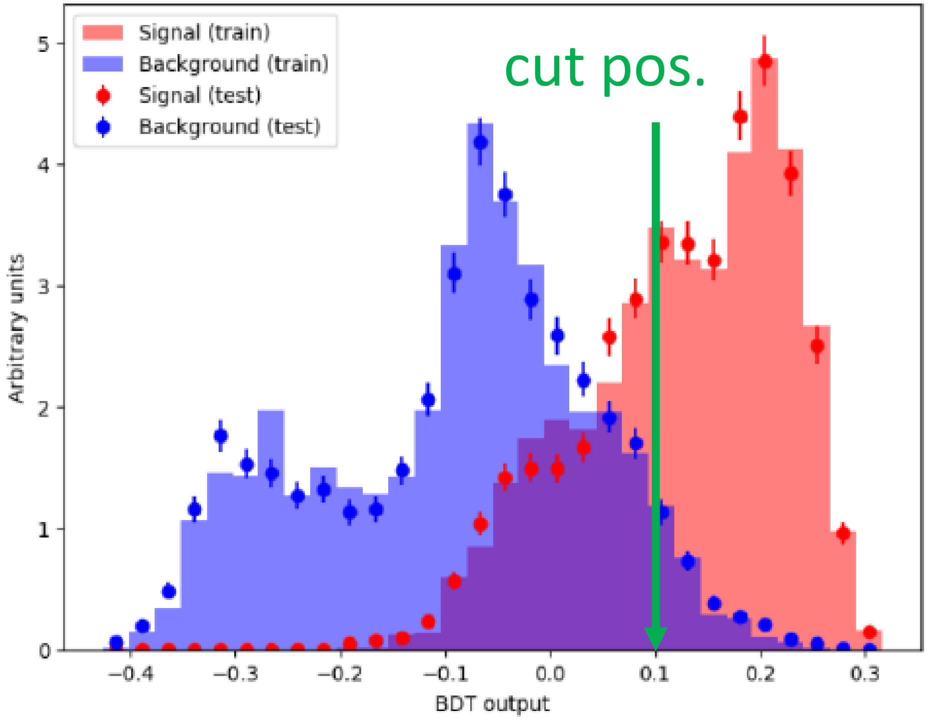
Example. Z(–>μμ)H(->WW*)
after pre-selection

BDT result

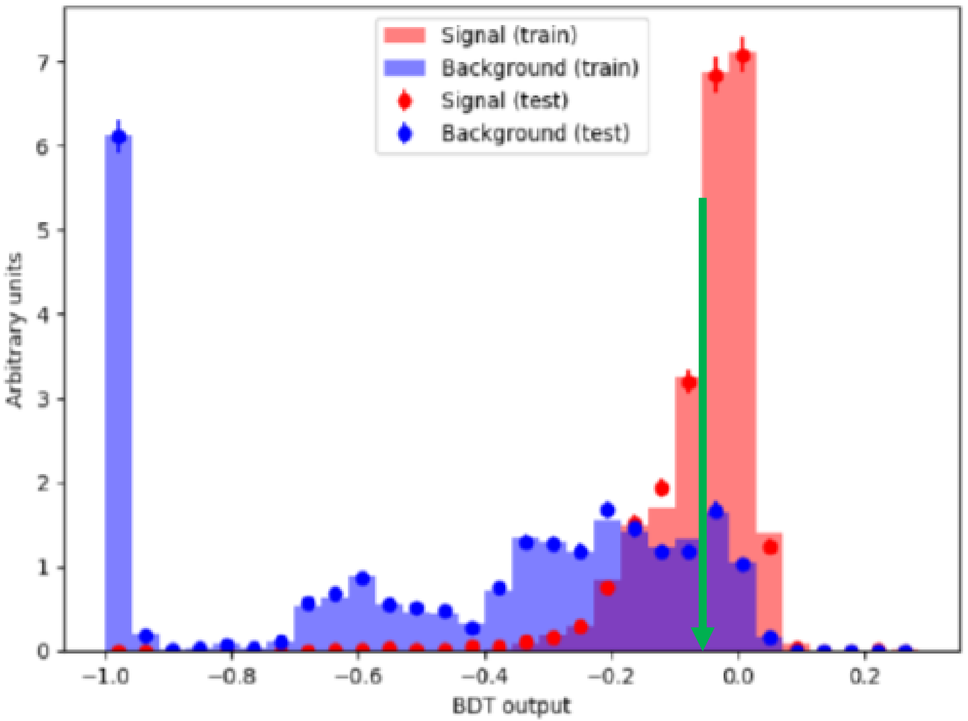
Variables used in the BDT

$P_{\text{all visible}}$	$E_{\text{leading-jet}}$	$\text{Cos}(\theta)$
$Pt_{\text{all visible}}$	$E_{\text{sub-leading-jet}}$	($\text{RecoilM}_{\text{dimuon}}$)
M_{dijet}	N(pfo)	($M_{\text{all visible}}$)
M_{dimuon}	$\text{Angle}_{\text{(dijet-dimuon)}}$	

$Z(\rightarrow\mu\mu)H(Z\rightarrow\nu\nu, Z^*\rightarrow qq)$



$Z(\rightarrow\mu\mu)H(Z\rightarrow qq, Z^*\rightarrow\nu\nu)$



Cut Flow: Z(→μμ)H(Z→νν, Z*→qq)

Cut-based

Cut	Signal	ZH background	2f background	4f background
Expected	1000	1140511	801811977	107203890
$Pre-selection$	616	30524	481301	515955
$Signal\ or\ not$	211	30307	481301	515955
$M_{missing} > M_{dijet}$	107	1605	115175	28838
M_{dimuon}	95	726	73813	6836
M^{rec}_{dimuon}	95	707	7894	1360
$N(pfo)$	94	336	3271	574
$Pt_{visible}$	89	312	342	168
$Angle_{min}$	85	298	283	139
$M_{missing}\ and\ M_{dijet}$	62	80	254	46
$Single\ Jet$	54	67	0	9

further cuts

At the end

$$\frac{\sqrt{S+B}}{S} = 0.21$$

Same cut procedures

BDT

Cut	Signal	ZH background	2f background	4f background
$Expected$	1000	1140511	801811977	107203890
$Pre-selection$	616	30494	480828	515426
$Signal\ or\ not$	211	30282	480828	515426
$M_{missing} > M_{dijet}$	107	1608	115062	28811
M_{dimuon}	95	725	73741	6833
M^{rec}_{dimuon}	95	706	7886	1359
$N(pfo)$	94	336	3268	574
$Pt_{visible}$	89	312	342	168
$BDT\ score$	57	22	14	9

BDT

$$\frac{\sqrt{S+B}}{S} = 0.18$$

Cut Flow: $Z(\rightarrow\mu\mu)H(Z\rightarrow qq, Z^*\rightarrow\nu\nu)$

Cut-based

Cut	Signal	ZH background	2f background	4f background
Expected	1000	1140511	801811977	107203890
$Pre-selection$	616	30524	481301	515955
$Signal\ or\ not$	211	30307	481301	515955
$M_{missing} > M_{dijet}$	103	28701	366125	487117
M_{dimuon}	92	22495	215657	239256
M_{dimuon}^{rec}	92	22401	17380	20630
$N(pfo)$	89	16776	321	16319
$Pt_{visible}$	74	4345	59	1273
$Angle_{min}$	71	4186	59	1216
$M_{missing}\ and\ M_{dijet}$	47	866	0	276
$Single\ Jet$	42	716	0	260

$$\frac{\sqrt{S+B}}{S} = 0.76$$

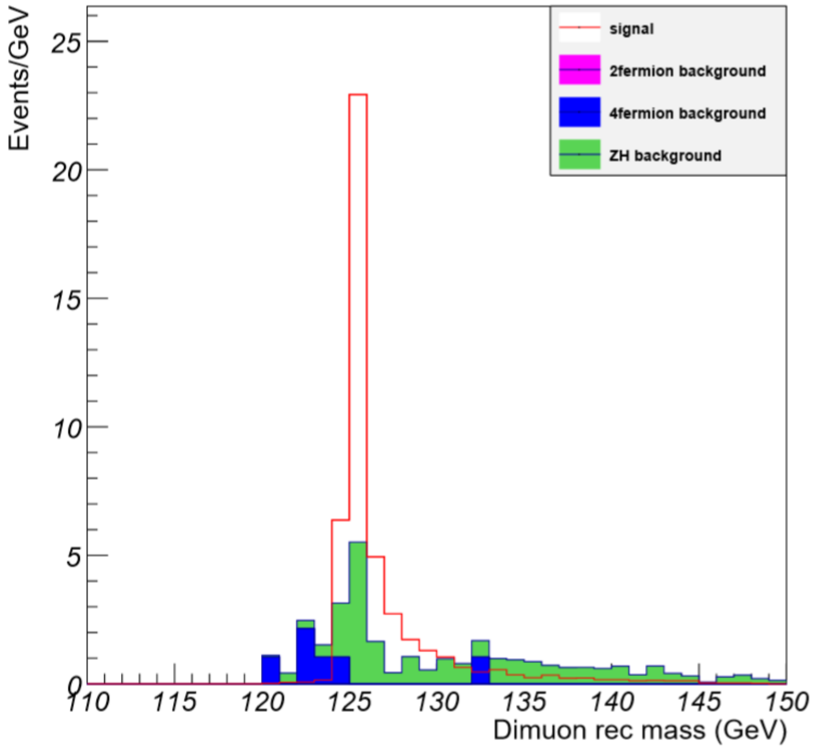
BDT

Cut	Signal	ZH background	2f background	4f background
$Expected$	1000	1140511	801811977	107203890
$Pre-selection$	616	30494	480828	515426
$Signal\ or\ not$	211	30282	480828	515426
$M_{missing} > M_{dijet}$	103	28674	365766	486615
M_{dimuon}	92	22473	215445	239023
M_{dimuon}^{rec}	92	22379	17363	20611
$N(pfo)$	89	16760	321	16304
$Pt_{visible}$	74	4341	59	1273
$BDT\ score$	45	573	0	260

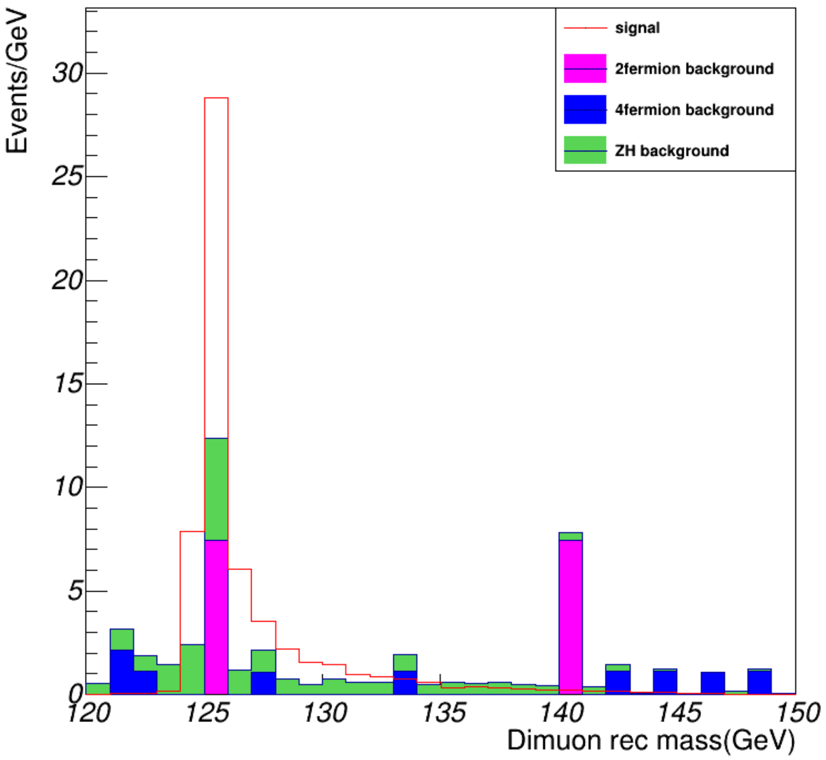
$$\frac{\sqrt{S+B}}{S} = 0.66$$

Recoil Mass(μμ) distribution: Z(→μμ)H(Z→νν, Z*→qq)

- **Cut based results**



- **BDT results**



Major backgrounds (Cut based)

name	scale	final
e2e2h_ww	0.08176	8
nnh_zz	0.06832	12
zz_l0taumu	1.04040	5

Major backgrounds (BDT)

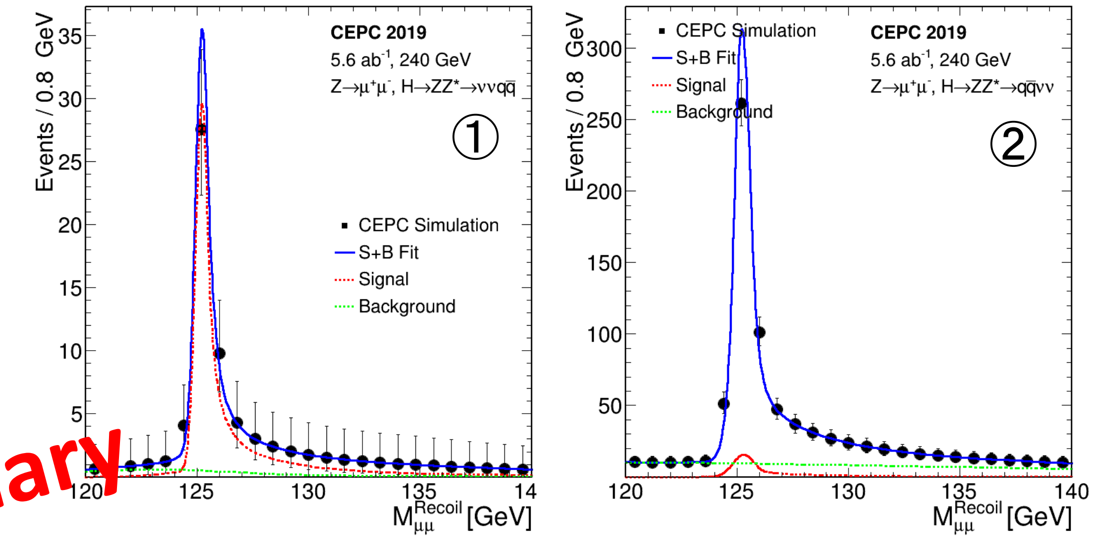
name	scale	final
e2e2h_ww	0.08176	7
nnh_zz	0.06832	12
e2e2	7.46579	14

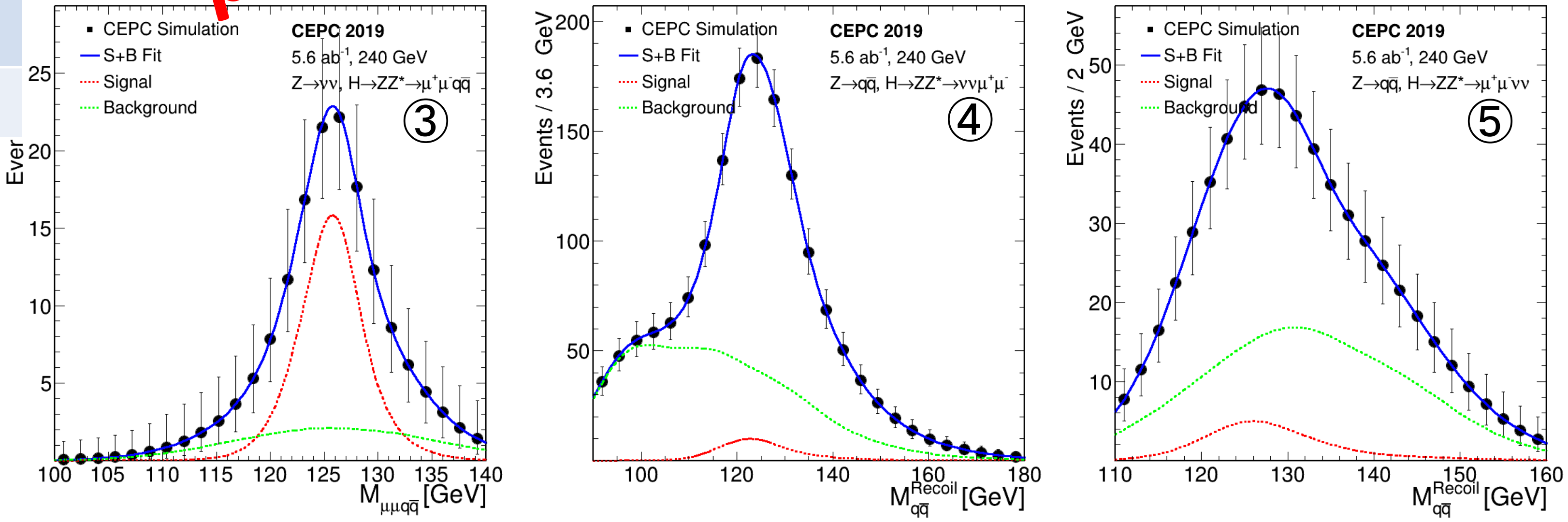
Preliminary results of signal fitting

Fitting procedure is performed on
the distributions from "cut-based" results.

Channel	Precision
① Z(→μμ)H(Z→νν, Z*→qq)	17.8 %
② Z(→μμ)H(Z→qq, Z*→νν)	71.5 %
③ Z(→νν)H(ZZ*→μμ, qq)	15.4 %
④ Z(→qq)H(Z→νν, Z*→μμ)	66.5 %
⑤ Z(→qq)H(Z→μμ, Z*→νν)	54.3 %
All combined	9.44 %

Note that the number is obtained from the fitting and different from those in previous tables.





An investigation about probing anomalous coupling of HZZ vertex along with the HZZ analysis

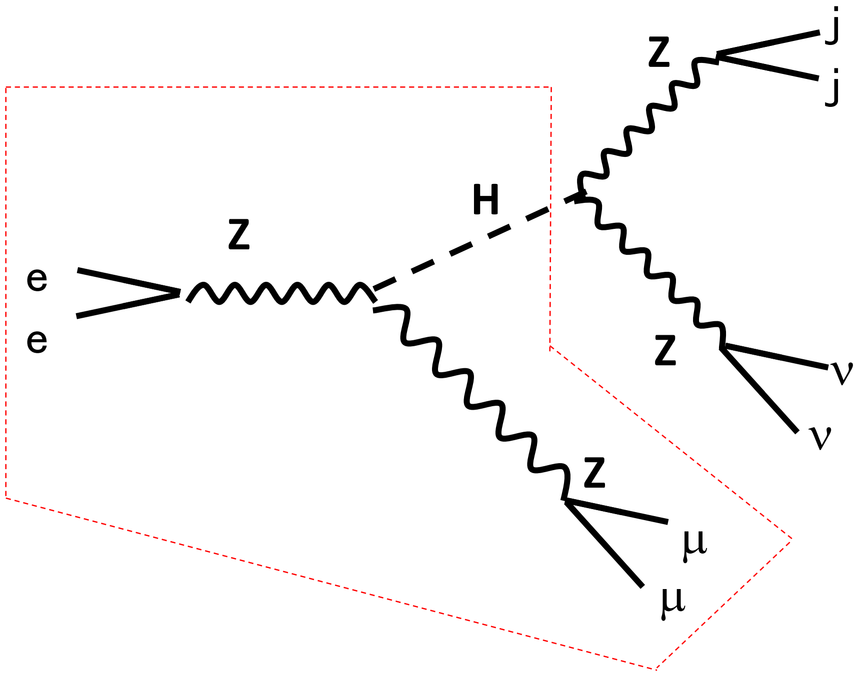
Motivation

-- To probe the anomalous couplings on HZZ vertex,
differential observables are used and compared with EFT models.

-- Reaction of ee/pp->$Z(l^+l^-)H(bb)$ is the process discussed in many places,
not only its simple picture but also the statistics and S/N.

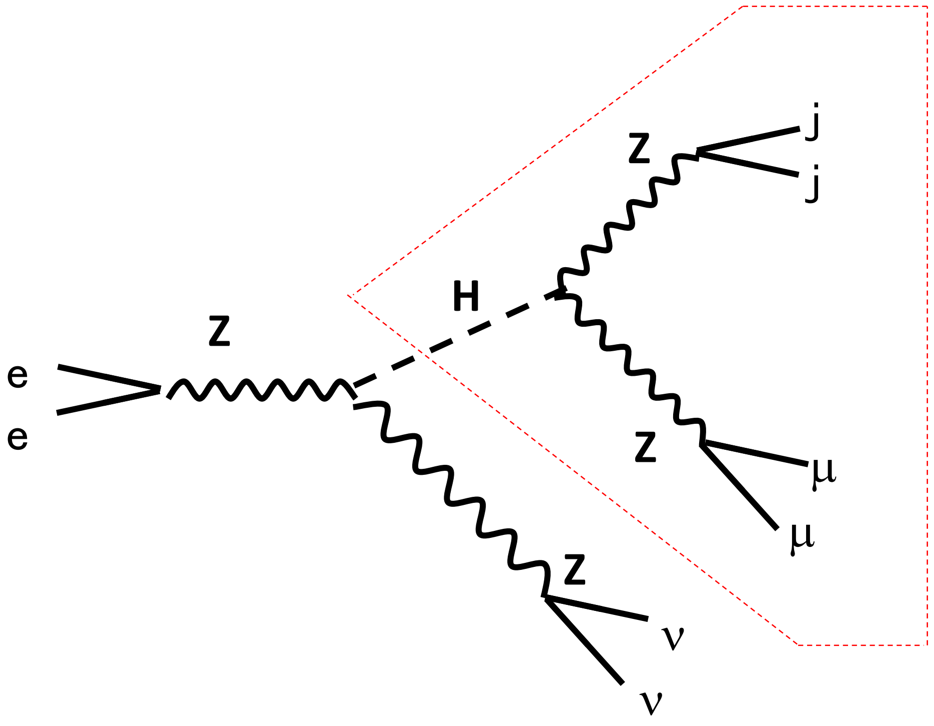
Question is, can we explore it through the framework shown in previous pages ?

Case1: $Z(\mu^+\mu^-)H(ZZ^*\text{->}\nu\nu, jj)$



- Much lower statistics than H->bb

Case2: $Z(\nu\nu)H(ZZ^*\text{->}\mu\mu, jj)$



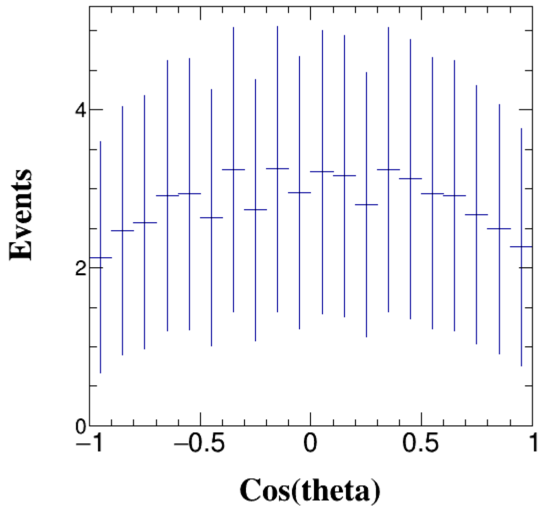
- One of motivation to use HZZ channel, √s is also different

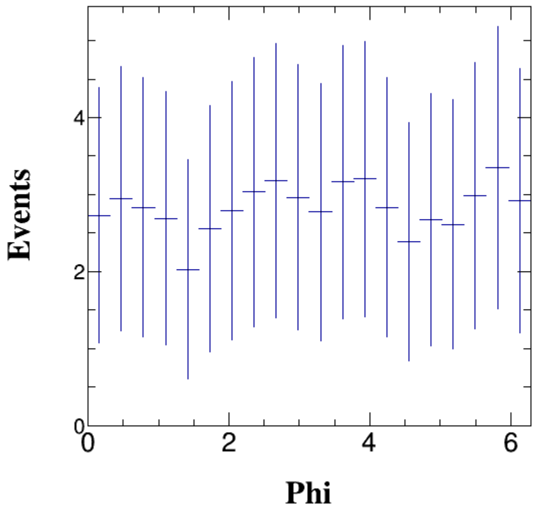
Case 1 has been chosen (because of rather simple kinematics) as a first trial and shown here.

Differential observables

- Analysis process of Z($\mu^+\mu^-$)H(ZZ*->$\nu\nu$, jj) is applied on the signal Z($\mu^+\mu^-$)H(ZZ*) sample.
- Background is not considered this time

cos(Θ) | ϕ





(h->)ZZ for this case

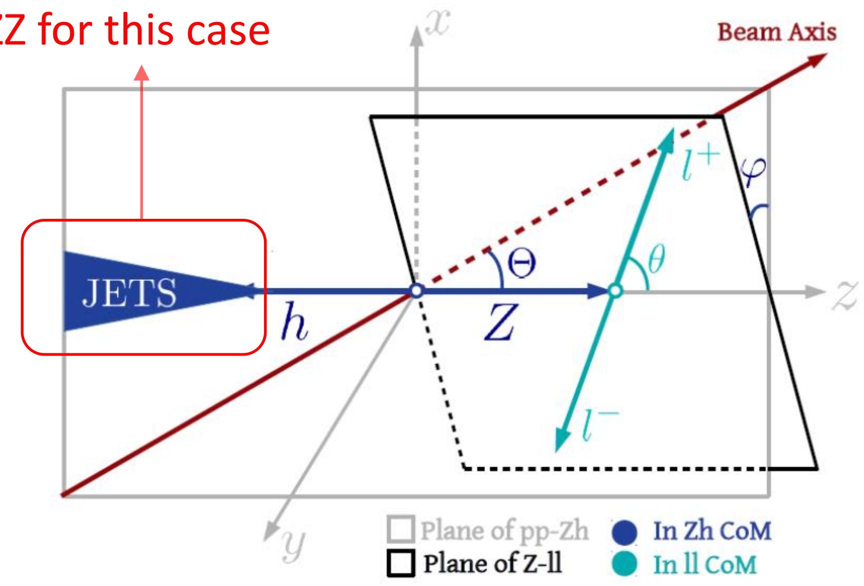


Diagram showing the angles used here.
(from the ref. shown in next page)

Variables are defined as usual and is shown in left figure.

EFT model

-- We have referred :

"Resolving the tensor structure of the higgs coupling to Z-bosons via Higgs-strahlung", Shankha Banerjee, Rick S. Gupta, Joey Y. Reiness and Michael Spannowsky, arXiv:1905.02728

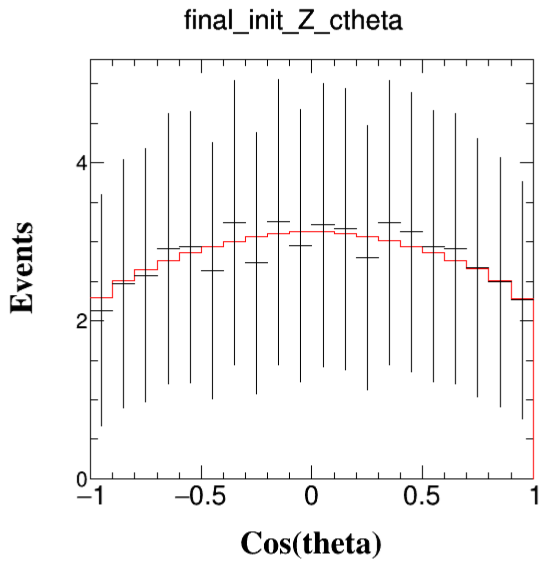
$$\Delta\mathcal{L}_6^{hZ\bar{f}f} \supset \delta\hat{g}^h_{ZZ}\,\frac{2m_Z^2}{v}h\frac{Z^\mu Z_\mu}{2} + \sum_f g^h_{Zf}\,\frac{h}{v}Z_\mu\bar{f}\gamma^\mu f$$
$$+\,\kappa_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}.$$

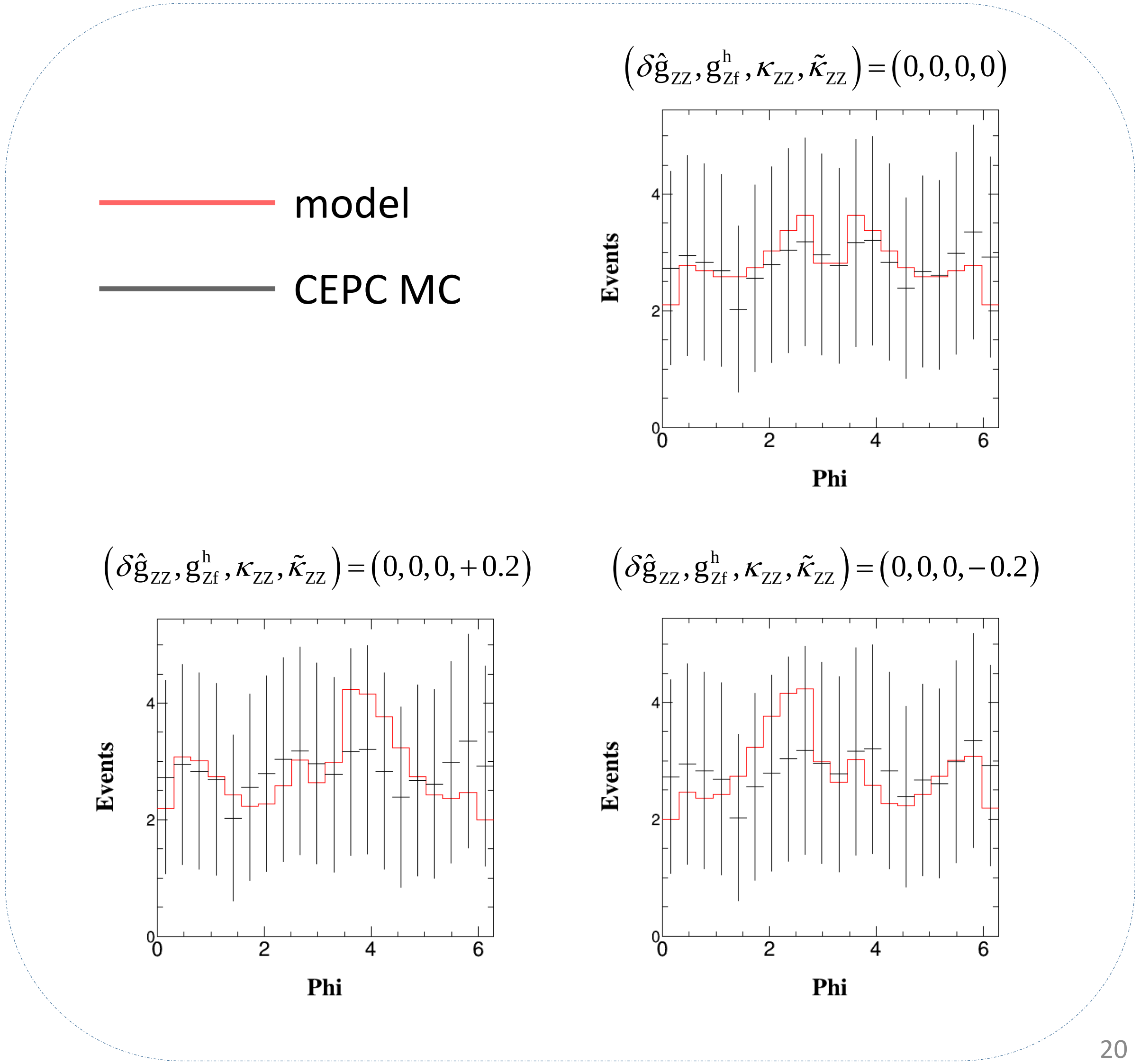
-- Amplitude is given in analytical form at first order (√s/Mz), and we have tried to reproduce the differential observables based on the formula.

-- Application to our analysis with this approximation would be an issue.

EFT model

-- Normalization factor is obtinned from the fitting of the analysis result with the model_{SM}





Comment

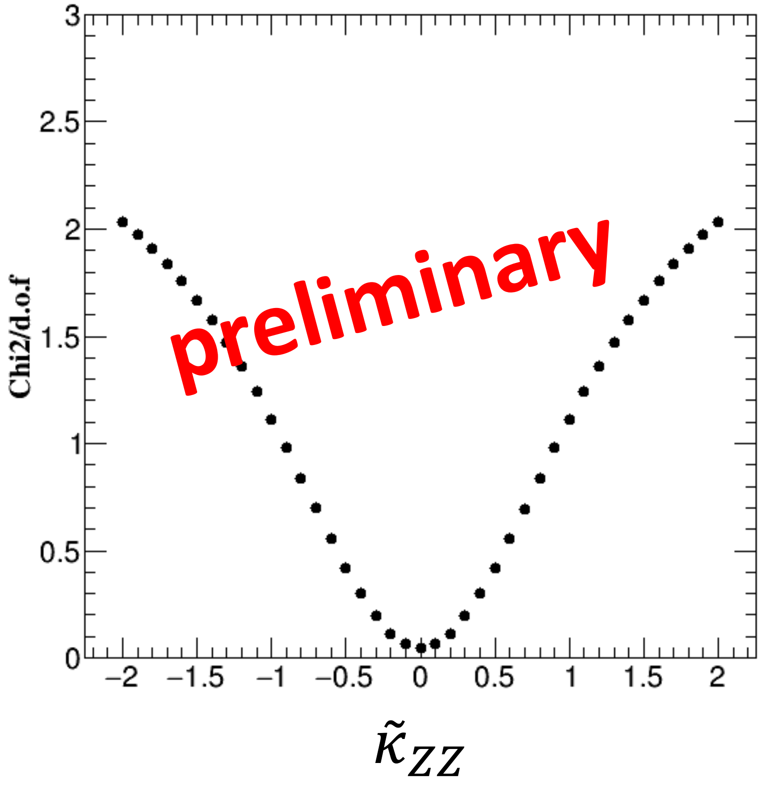
・The lower statistics might lead poorer limitation on the anomalous couplings

Further steps would be . . .

・Need to include background.

・Try to open the HZZ side. (Case2)

・Further Argument/consideration about the applicability (of this method) is necessary



Status of Higgs invisible analysis

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Institute of High Energy Physics

Please refer following link for the details :

https://indico.ihep.ac.cn/event/9832/session/9/contribution/17/material/slides/0.pdf

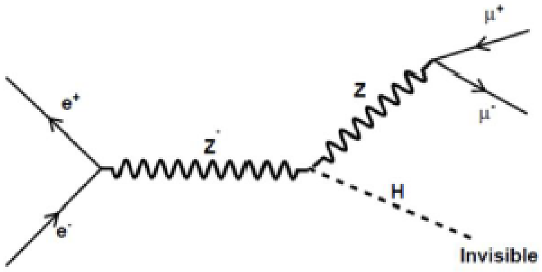
"The study of Higgs invisible decay" , Y. Tan, CEPC Physics WS@PKU (2019)

Motivation

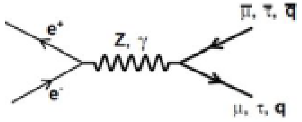
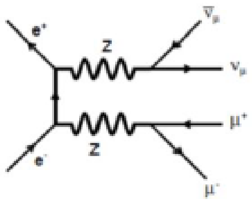
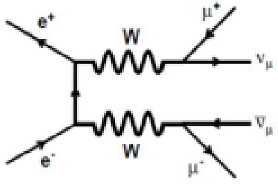
- The Higgs decay invisible in SM is via four neutrino, with BR=0.106%.
- Many new physics models predict a significant branching ratio of Higgs to invisible.
- ATLAS upper limit ~25%,CMS upper limit~ 24% for BR(Higgs->inv) at 95% C.L.
- Higgs invisible decay is a sensitive probe for new physics.
- The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

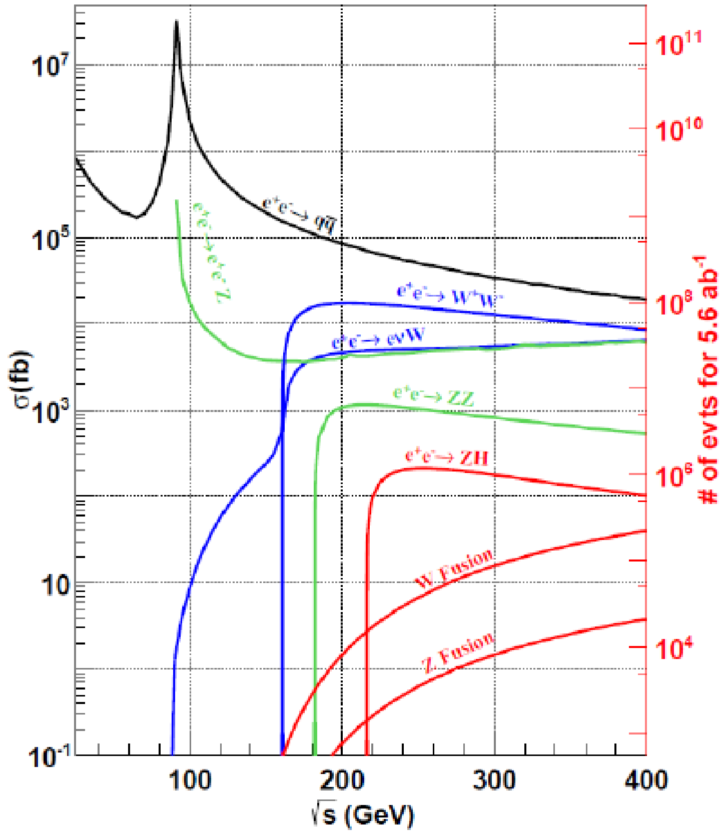
The sample of signal and background in Higgs->invisible:

- 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:



Cross section of major SM processes

Higgs->invisible State:

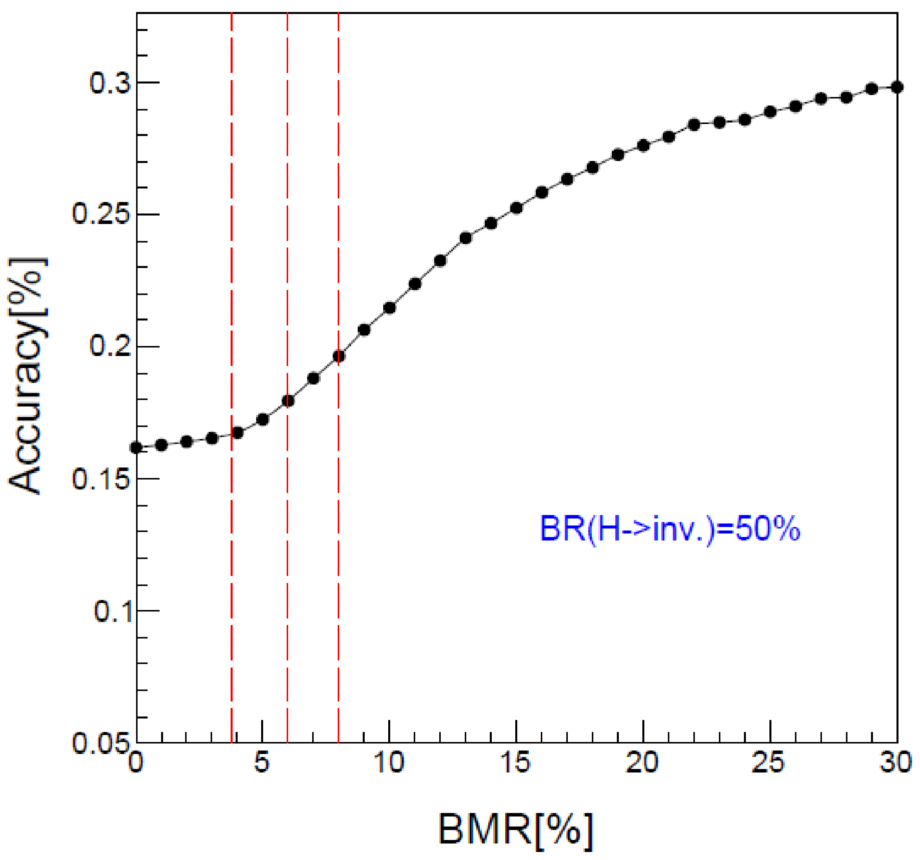
- Get the expected precision on the measurement of σ(ZH)/BR(H->inv) and the 95% confidence-level (CL) upper limit on BR(H->inv) from a CEPC dataset of 5.6 ab^{-1}

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

Higgs->invisible State:

- Add the BMR part of Higss->invisible
- qqH dominants the precision and rely on recoil mass to separate the ZZ bkg
- Essential for qqH analysis, especially H->non jet final state



- If the BMR degrades from 4% to 6%/8%: the higgs invisible measurement degrades by 11%/17%.(Under assuming BR(H->inv)=50%)

Summary

- ➢ Progress Status on HZZ analysis
  - We have analyzed 3 combinations of Z boson decays
  - Comparison of BDT-based/Cut-based analysis has been performed on each channel, for the first time.
  - An exploration has been done on the application of the EFT model
- ➢ Next step
  - Further optimization on event selection

- ➢ Progress Status on Higgs invisible decay analysis
  - U.L. on B.R. of the invisible decay of Higgs boson is obtained as 0.194%
  - Dependence on the BMR has been studied

Thank you very much !

Backup

Data samples

- Signal

  $Z(\to\mu\mu)H(ZZ^*\to\nu\nu, qq)$: /cefs/data/DstData/CEPC240/CEPC_v4/higgs/E240.Pe2e2h_zz.e0.p0.whizard195/

  $Z(\to\nu\nu)H(ZZ^*\to\mu\mu, qq)$: /cefs/data/DstData/CEPC240/CEPC_v4/higgs/E240.Pnnh_zz.e0.p0.whizard195/

  $Z(\to qq)H(ZZ^*\to\mu\mu, \nu\nu)$: /cefs/data/DstData/CEPC240/CEPC_v4/higgs/E240.Pqqh_zz.e0.p0.whizard195/

- Background (stored under /cefs/data/DstData/CEPC240/CEPC_V4/)

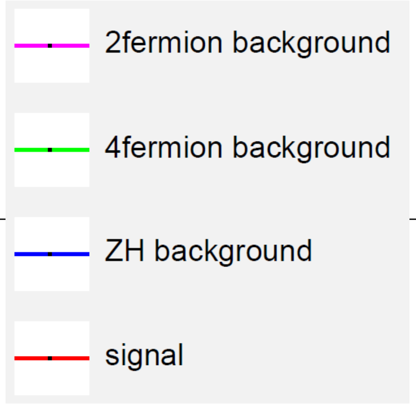
  - "2 fermions" (bhabha, e2e2, e3e3, qq, nn)

  - "4 fermions" (zz_h0, zz_sl0, zz_l04, ww_h0,,,,)

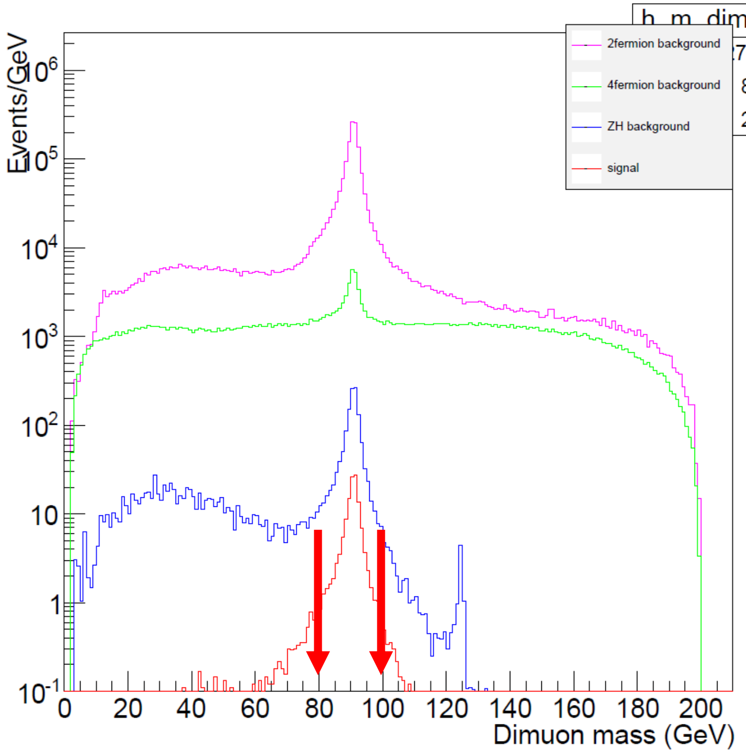
  - "ZH" (==other Higgs decays) (qqh_**, e1e1h_**, e2e2h_**, e3e3h_**, nnh_**)

Please refer the details at http://cepcsoft.ihep.ac.cn/guides/Generation/docs/ExistingSamples/

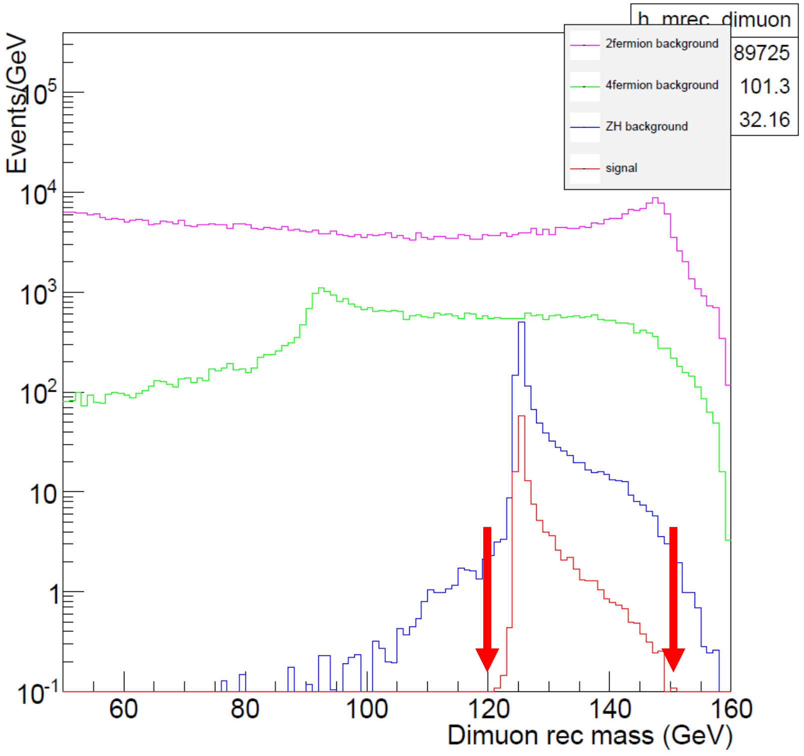
Distributions - I.



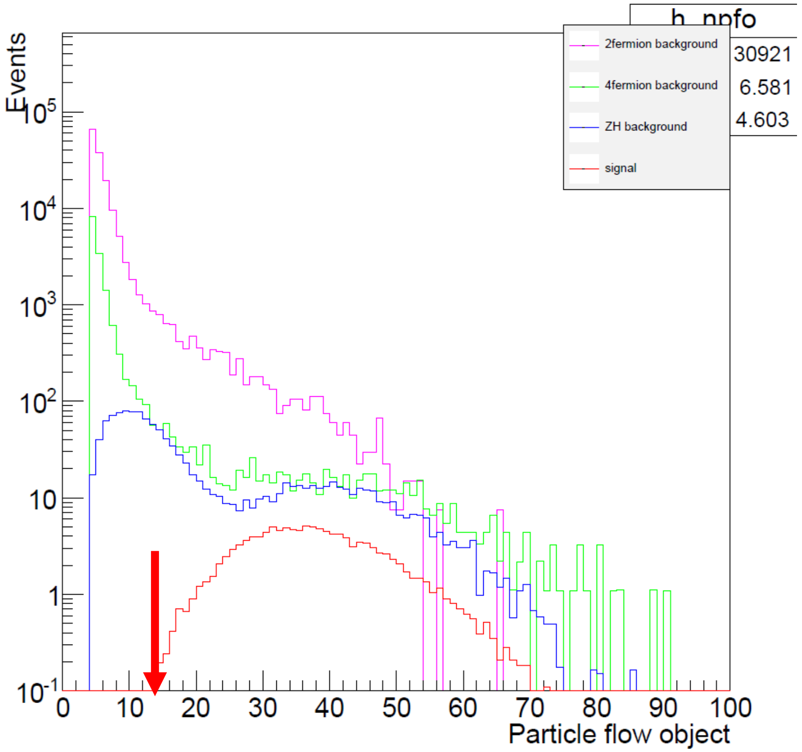
$M_{invariant}(\mu\mu)$



$M_{recoil}(\mu\mu)$

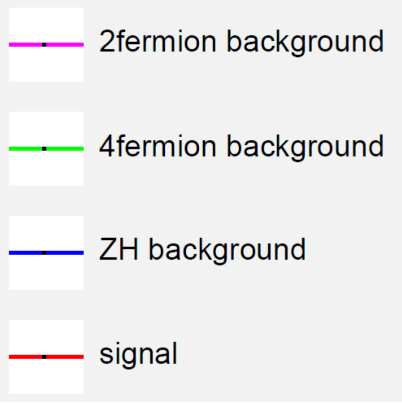


N(pfo)

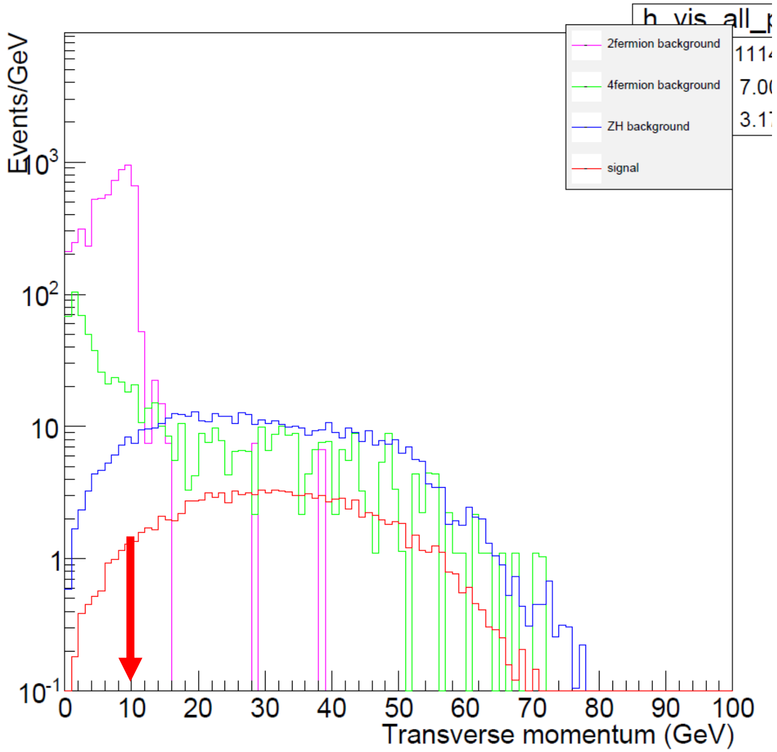


$Z(\rightarrow\mu\mu)H(Z\rightarrow\nu\nu, Z^*\rightarrow qq)$

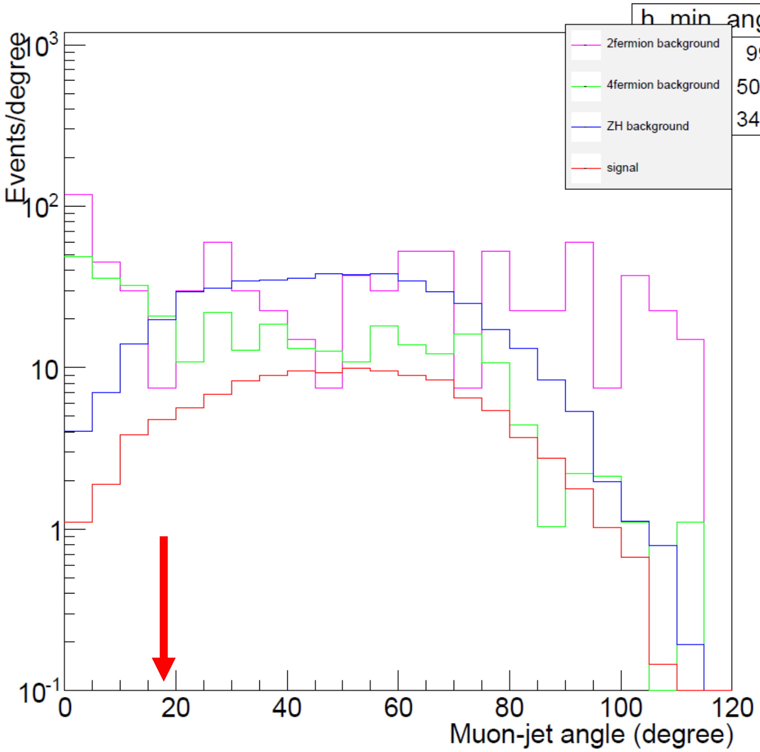
Distributions - II.



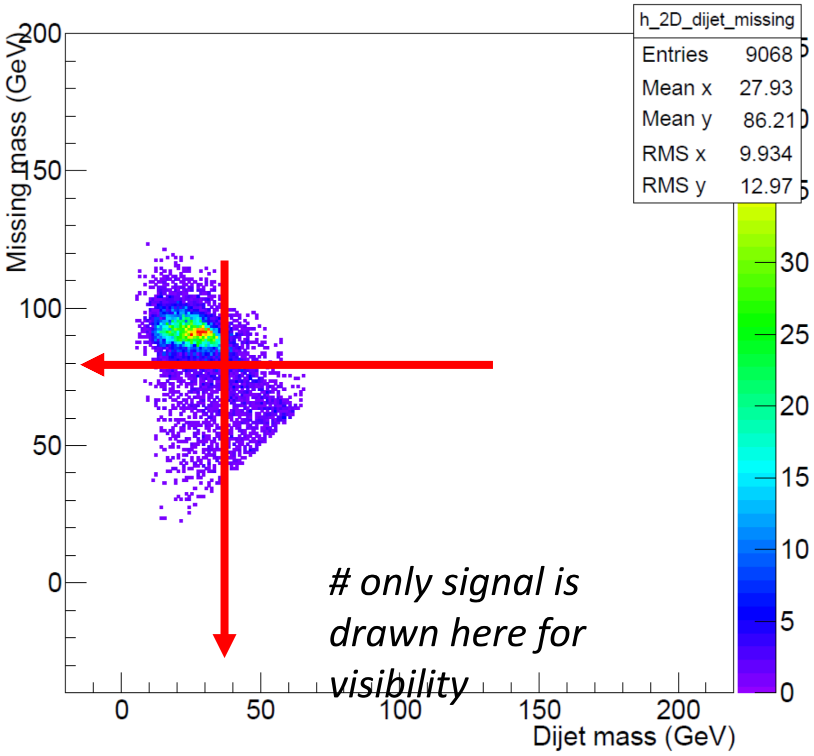
Pt(visible all)



Min. angle (lepton⇔jet)



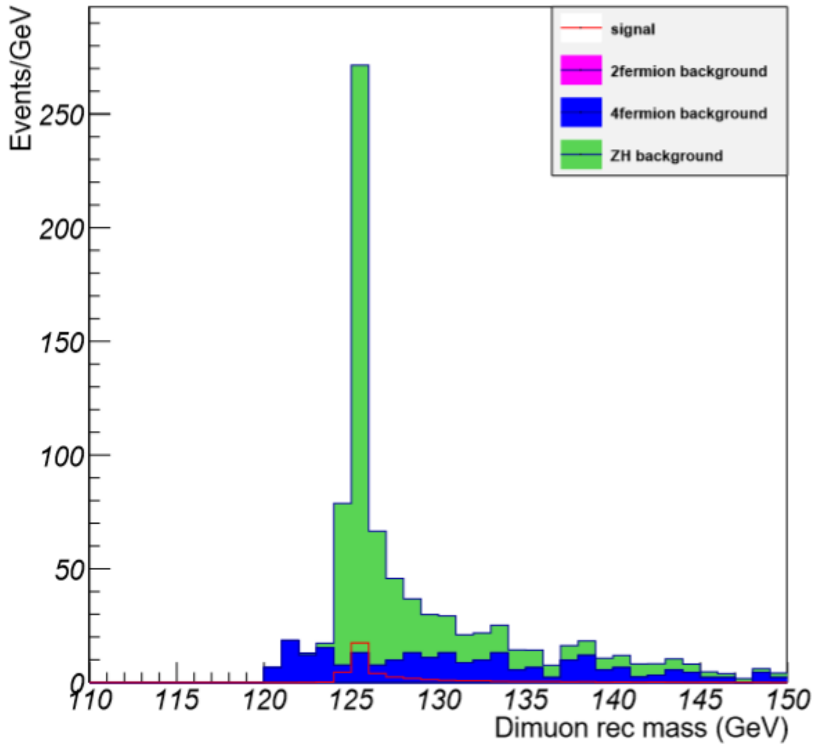
Missing Mass vs Di-jet Mass



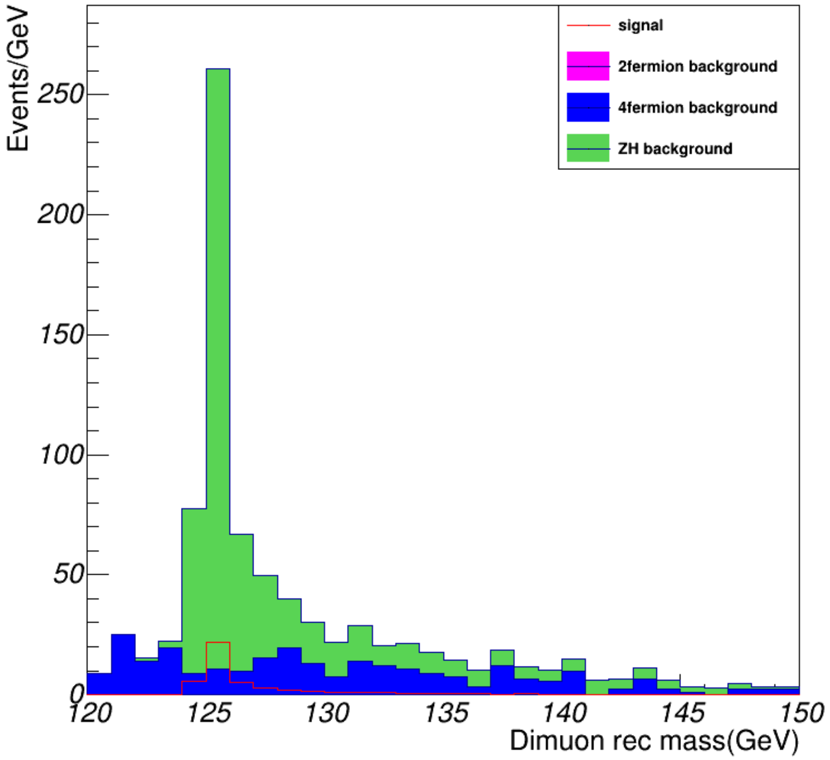
$Z(\rightarrow\mu\mu)H(Z\rightarrow\nu\nu, Z^{*}\rightarrow qq)$

Recoil Mass(μμ) distribution: Z(→μμ)H(Z→qq, Z*→νν)

➢ **Cut based results**



➢ **BDT results**



Major backgrounds (Cut based)

name	scale	final
e2e2h_bb	0.21896	352
e2e2h_ww	0.08176	196
qqh_zz	0.20216	21
zz_sl0mu_up	1.09032	53
zz_sl0mu_down	1.08025	171

Major backgrounds (BDT)

name	scale	final
e2e2h_bb	0.21896	299
e2e2h_ww	0.08176	217
qqh_e3e3	0.4844	11
qqh_zz	0.20216	33
zz_sl0mu_up	1.09032	45
zz_sl0mu_down	1.08025	198

Cut Flow: Z(→νν)H(ZZ*→μμ, qq)

Cut-based

further cuts

Same cut procedures

Cut	Signal	ZH background	2f background	4f background
Raw events	6844	1140511	801811977	107203890
$Pre-selection$	238	30494	480828	515425
$Signal\ or\ not$	226	30268	480828	515425
$N(pfo)$	198	10580	61902	268709
$115GeV < M_{visible} < 135GeV$	175	450	9694	6533
$\|cos\theta\| < 0.9$	126	328	132	414
$130GeV < M^{rec}_{dimuon} < 220GeV$	123	285	125	366
$43GeV < P_{visible} < 60GeV$	109	157	6	105
$10GeV < M_{dijet} < 100GeV$	106	150	6	100
$E_{leading\ jet}$	99	122	0	54
$E_{subleading\ jet}$	97	116	0	46
$Angle_{\mu j}$	92	103	0	34
$13GeV < M_{dimuon} < 100GeV$	92	100	0	33
$cos\ \theta_{visible}$	92	100	0	33
$80GeV < M^{rec}_{visible} < 107GeV$	87	89	0	30
$not\ 120GeV < M^{rec}_{dimuon} < 130GeV$	75	65	0	30
$not\ 120GeV < M^{rec}_{dijet} < 130GeV$	71	46	0	26

At the end

$$\frac{\sqrt{S+B}}{S} = 0.17$$

BDT

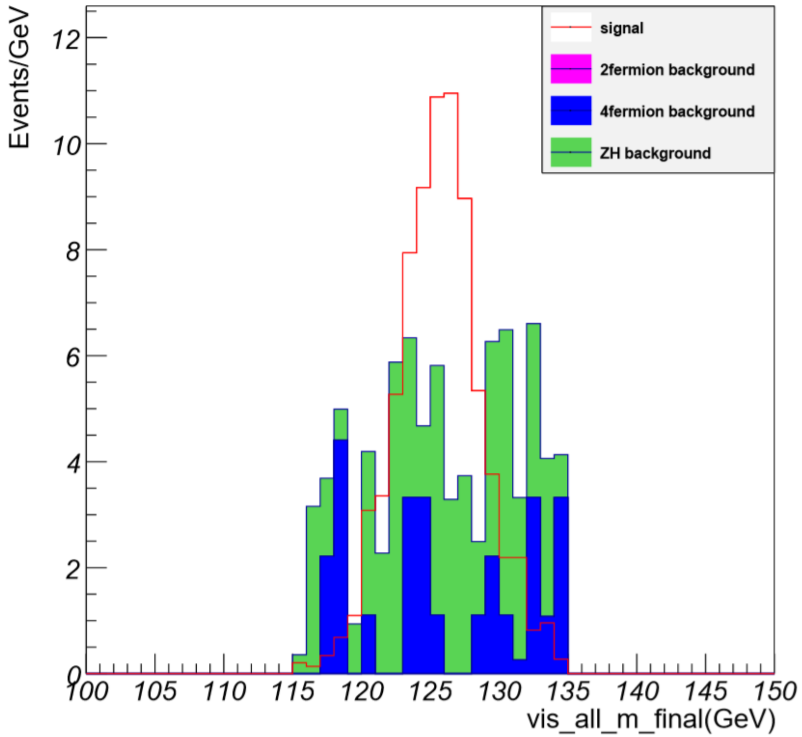
Cut	Signal	ZH background	2f background	4f background
$Expected$	6844	1140511	801811977	107203890
$Pre-selection$	238	30494	480828	515426
$Signal\ or\ not$	226	30268	480828	515426
$N(pfo)$	226	29861	152634	444220
$M_{visible}$	201	710	15429	10306
$cos\ \theta$	144	510	367	831
$BDT\ score$	81	43	0	18

BDT

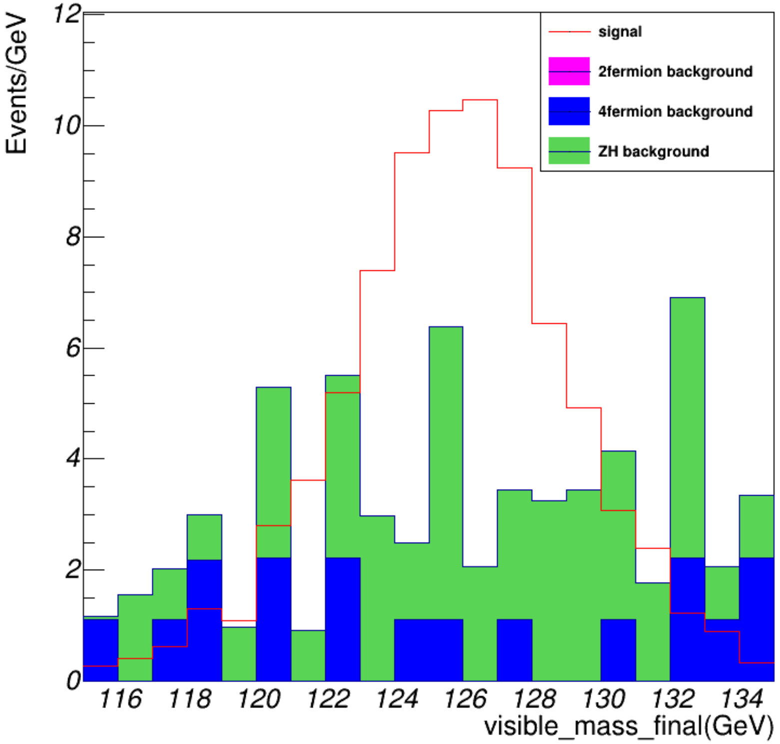
$$\frac{\sqrt{S+B}}{S} = 0.15$$

Higgs Invariant mass distribution: Z(→νν)H(ZZ*→μμ, qq)

➢ **Cut based results**



➢ **BDT results**



Major backgrounds (Cut based)

name	scale	final
e2e2h_ww	0.08176	6
e3e3h_ww	0.0812	6
qqh_e3e3	0.4844	6
qqh_ww	1.6464	24
zz_sl0tau_down	1.10887	7
ww_sl0muq	1.10890	9
ww_sl0tauq	1.10899	6

Major backgrounds (BDT)

name	scale	final
qqh_e3e3	0.4844	13
qqh_ww	1.6464	14
qqh_zz	0.20216	6
zz_sl0tau_down	1.10887	7

Cut Flow: Z(→qq)H(Z→νν, Z*→μμ)

Cut-based

cut	signal	zh background	2f background	4f background
Raw events	20254	1140511	801811977	107203890
$Pre-selection$	826	30494	480828	515425
$Signal\ or\ not$	203	30271	480828	515425
$M_{missing} > M_{dimuon}$	94	3167	18606	40769
$N(pfo)$	91	2502	2050	15114
$M_{visible}$	90	2220	557	6573
$cos\ theta$	72	1797	59	2156
M^{rec}_{dimuon}	70	1506	14	1942
$P_{visible}$	69	1459	14	1843
M_{dijet}	67	1207	0	1526
$E_{leading}$	67	1191	0	1203
$E_{subleading}$	67	1186	0	1119
$Angle_{\mu j}$	67	1165	0	1003
M_{dimuon}	67	1105	0	970
$cos\theta_{visible}$	64	1048	0	850
$M^{rec}_{visible}$	64	973	0	817
$Pt_{visible}$	63	962	0	775
$not\ \mu^+\mu^- HZZ$	63	962	0	775
$not\ \nu\nu HZZ$	56	884	0	744

At the end

$$\frac{\sqrt{S+B}}{S} = 0.73$$

BDT

Cut	Signal	ZH background	2f background	4f background
$Expected$	20254	1140511	801811977	107203890
$Pre-selection$	826	30494	480828	515426
$Signal\ or\ not$	203	30291	480828	515426
$M_{missing} > M_{dimuon}$	94	3179	18606	40770
$N(pfo)$	91	2502	2050	15115
M_{dijet}	85	1793	14	6178
$cos\ \theta$	67	1439	0	2175
$M_{visible}$	67	1345	0	1476
$BDT\ score$	46	358	0	226

$$\frac{\sqrt{S+B}}{S} = 0.55$$

Cut Flow: Z(→qq)H(Z→μμ, Z*→νν)

Cut-based

cut	signal	zh background	2f background	4f background
Expected	20254	1140511	801811977	107203890
$Pre-selection$	826	30494	480828	515425
$Signal\ or\ not$	203	30271	480828	515425
$M_{dimuon} > M_{missing}$	108	27103	462222	474656
$N(pfo)$	106	21479	27891	332167
$M_{visible}$	102	5496	2277	46449
$cos\theta$	82	4051	0	13096
M^{rec}_{dimuon}	77	3492	0	2617
$P_{visible}$	77	3461	0	2507
M_{dijet}	75	2795	0	1841
$E_{leading\ jet}$	74	2584	0	1466
$E_{subleading\ jet}$	73	2544	0	1397
$Angle_{\mu j}$	68	2157	0	963
M_{dimuon}	66	1832	0	772
$cos\theta_{visible}$	64	1734	0	570
$M^{rec}_{visible}$	50	844	0	395
$Pt_{visible}$	49	822	0	369
$not\ \mu^+\mu^- HZZ$	44	335	0	324
$not\ \nu\nu HZZ$	44	335	0	324

At the end

$$\frac{\sqrt{S+B}}{S} = 0.60$$

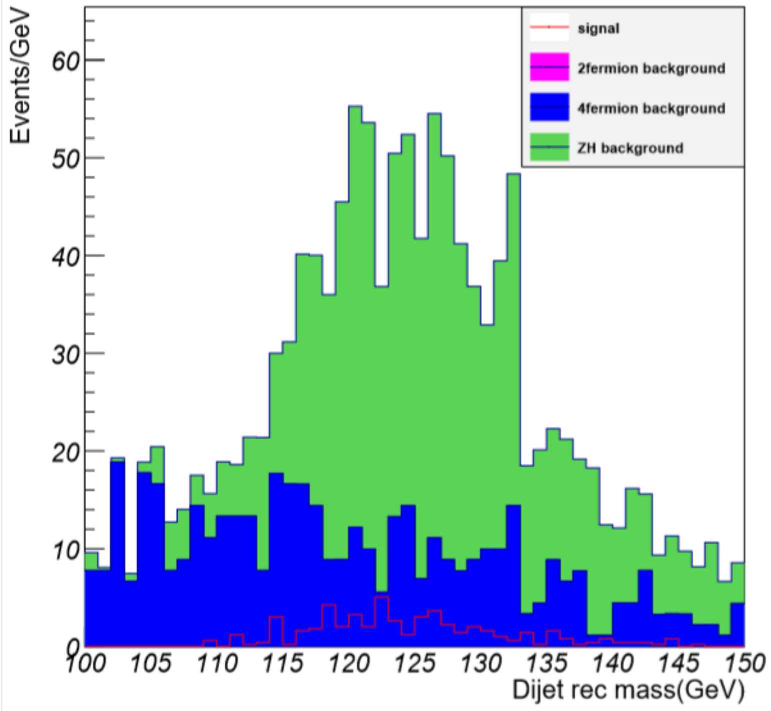
BDT

Cut	Signal	ZH background	2f background	4f background
$Expected$	20254	1140511	801811977	107203890
$Pre-selection$	826	30494	480828	515426
$Signal\ or\ not$	203	30291	480828	515426
$M_{missing} > M_{dimuon}$	108	27112	462222	474656
$N(pfo)$	106	21480	27891	332167
M_{dijet}	103	4833	141	265478
$cos\ \theta$	80	3576	7	156098
$M_{visible}$	77	2913	0	8750
$BDT\ score$	38	166	0	140

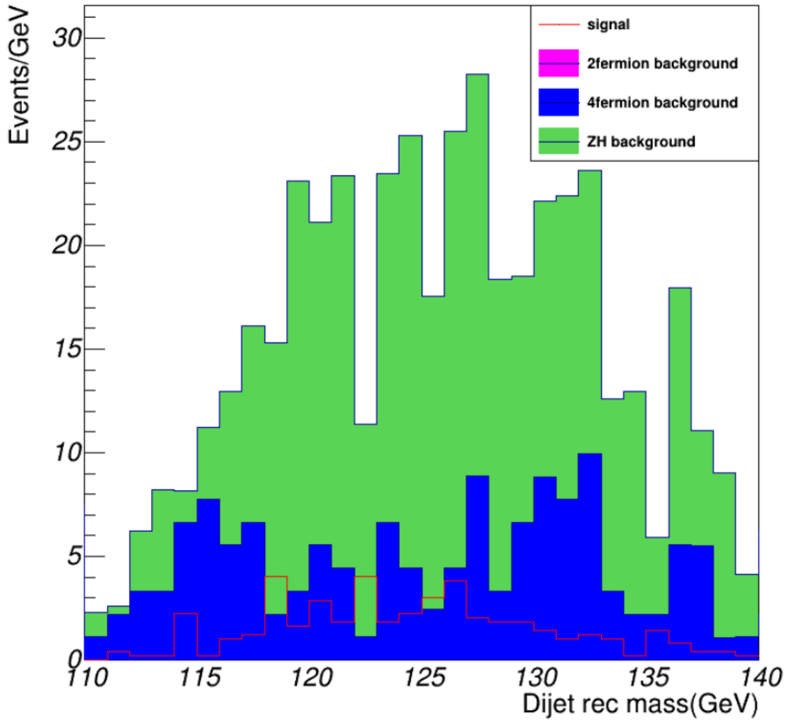
$$\frac{\sqrt{S+B}}{S} = 0.49$$

Recoil Mass(qq) distribution: Z(→qq)H(Z→νν, Z*→μμ)

➢ **Cut based results**



➢ **BDT results**



Major backgrounds (Cut based)

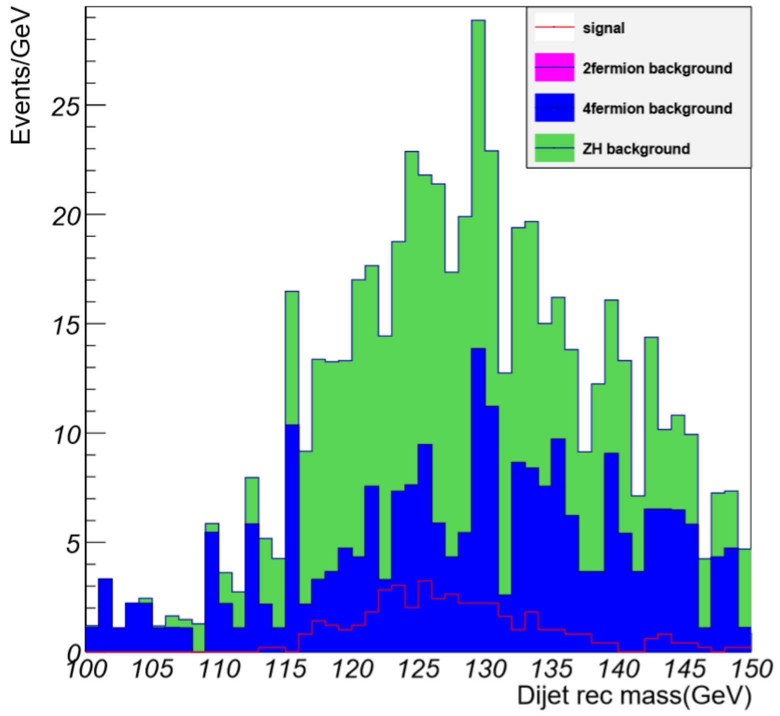
name	scale	final
e2e2h_bb	0.21896	56
e2e2h_ww	0.08176	20
e3e3h_bb	0.21784	26
e3e3h_ww	0.0812	32
nnh_zz	0.06832	32
qqh_e3e3	0.4844	299
qqh_ww	1.6464	395
zz_sl0mu_down	1.08025	16
zz_sl0tau_up	1.10880	262
zz_sl0tau_down	1.10887	412
ww_sl0muq	1.10890	14
ww_sl0tauq	1.10899	15

Major backgrounds (BDT)

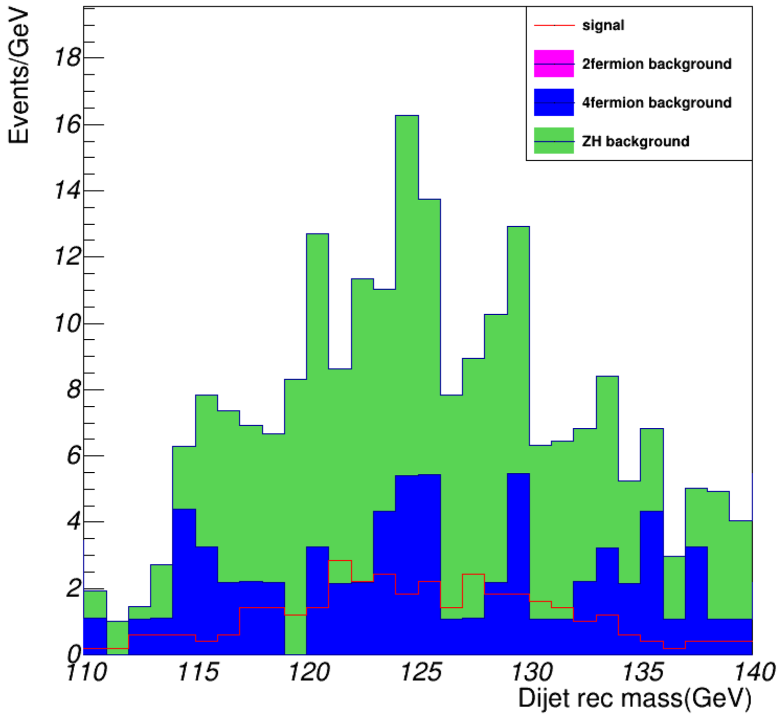
name	scale	final
e3e3h_bb	0.21784	13
e3e3h_ww	0.0812	12
nnh_zz	0.06832	32
qqh_e3e3	0.4844	199
qqh_ww	1.6464	85
zz_sl0tau_up	1.10880	69
zz_sl0tau_down	1.10887	140

Recoil Mass(qq) distribution: Z(→qq)H(Z→μμ, Z*→νν)

➢ **Cut based results**



➢ **BDT results**



Major backgrounds (Cut based)

name	scale	final
e2e2h_bb	0.21896	156
e2e2h_ww	0.08176	72
e2e2h_zz	0.01002	11
qqh_e3e3	0.4844	46
qqh_ww	1.6464	32
zz_sl0mu_up	1.49649	40
zz_sl0mu_down	1.08025	186
zz_sl0tau_up	5.8184	23
zz_sl0tau_down	1.10887	29

Major backgrounds (BDT)

name	scale	final
e2e2h_bb	0.21896	47
e2e2h_ww	0.08176	22
qqh_e3e3	0.4844	76
qqh_ww	1.6464	13
zz_sl0mu_down	1.0802	54
zz_sl0tau_up	1.10880	24
zz_sl0tau_down	1.10887	49