Measurement of H->ZZ* at the CEPC

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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.

・This presentation summarizes the updated results from channels with the decay product combination of ($\mu\mu$, jj, $\nu\nu$)

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^- $\nu\nu$	$\nu\nu e^+e^-$	$\mu^+\mu^-$ $\nu\nu$	$\nu\nu$ $\mu^+\mu^-$

Higgs boson width and HZZ measurement

・ It is well known that the Higgs boson width and its precision can be deduced using the H->ZZ* precision using following relationship:

- $BR(H \to ZZ) = \Gamma(H \to ZZ)/\Gamma_H \propto g^2_{HZZ}/\Gamma_H$

- $\sigma(ZH) \propto g^2_{HZZ}$

$$\Rightarrow \quad \sigma(ZH) \times BR(H \to ZZ) \propto \frac{g^2_{HZZ} \times g^2_{HZZ}}{\Gamma_H}$$

・ Independent measurement of σ(ZH) × BR(HZZ) and σ(ZH)

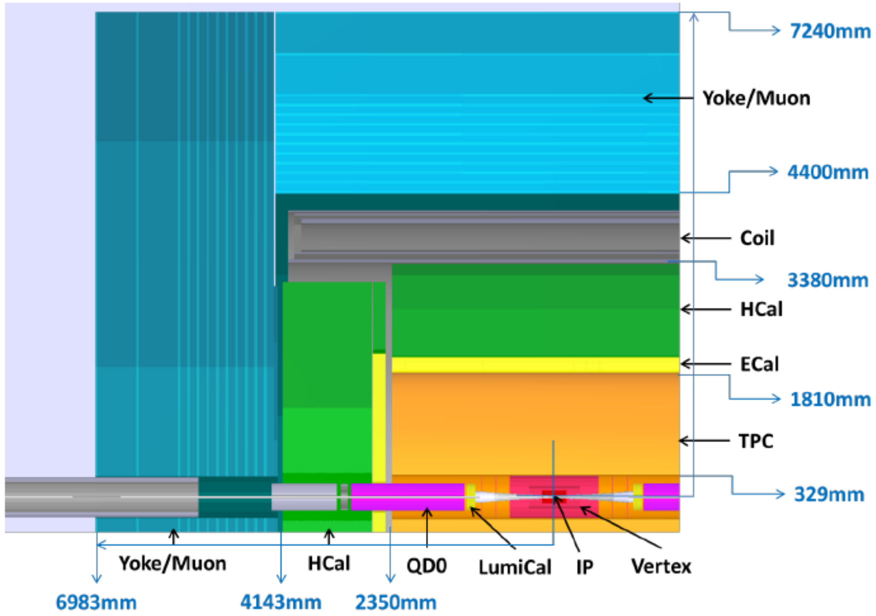
・ H->WW* measurement can do the same calculation and current study shows that H->WW* precision will dominate the Higgs width precision （please refer the CEPC white paper）

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



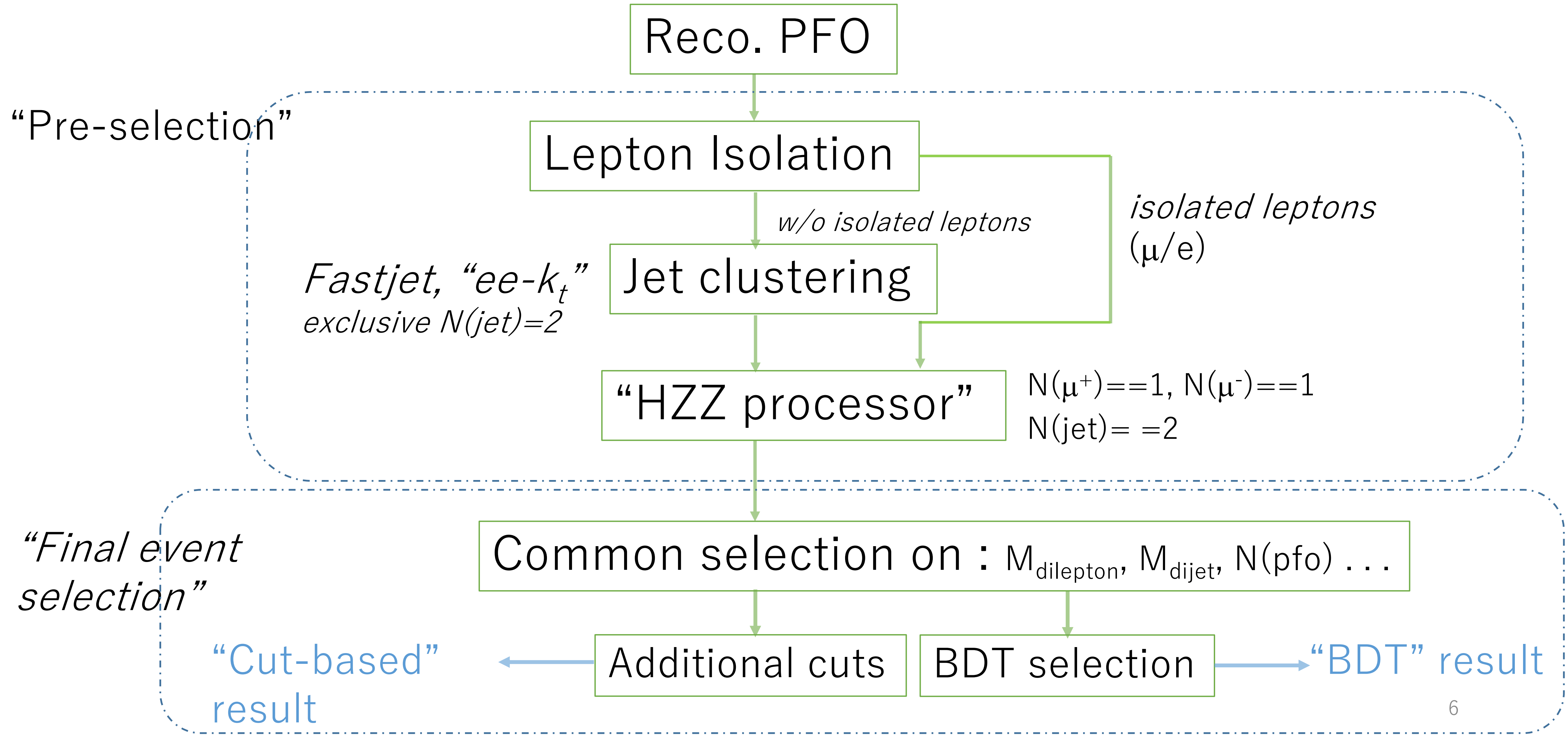
Signal Sample

-- $Z\to\mu\mu$, $H\to ZZ^*\to\nu\nu qq$

-- $Z\to\nu\nu$, $H\to ZZ^*\to\mu\mu qq$

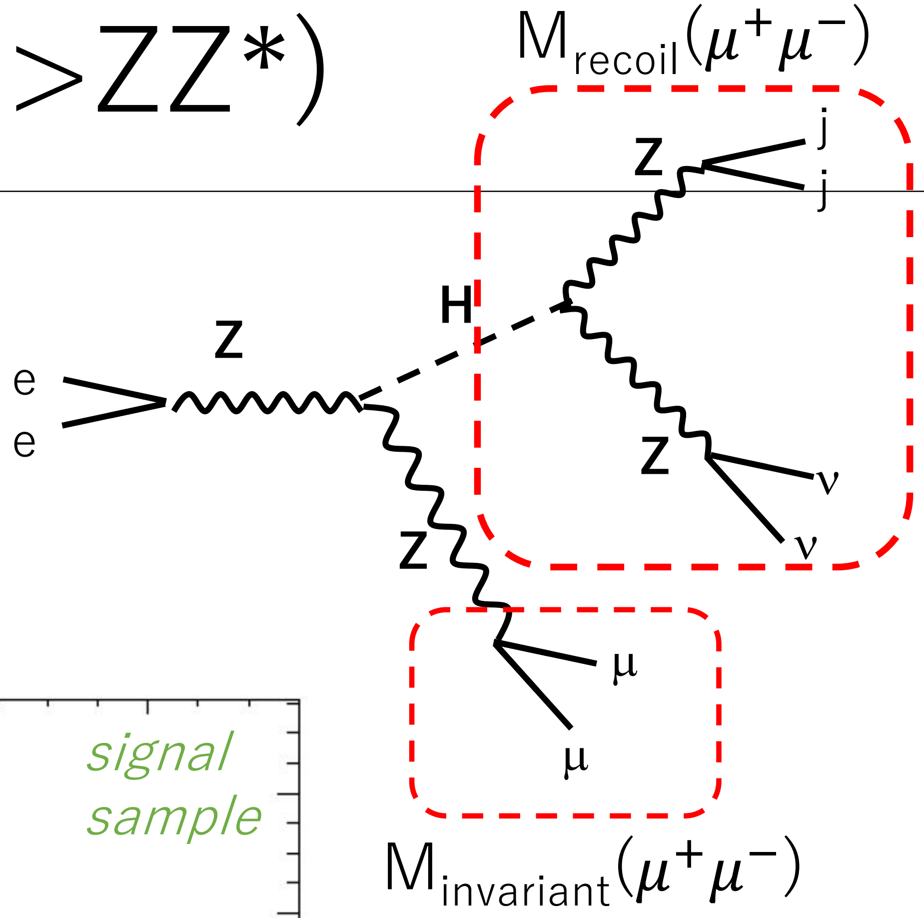
-- $Z\to qq$, $H\to ZZ^*\to\nu\nu\mu\mu$

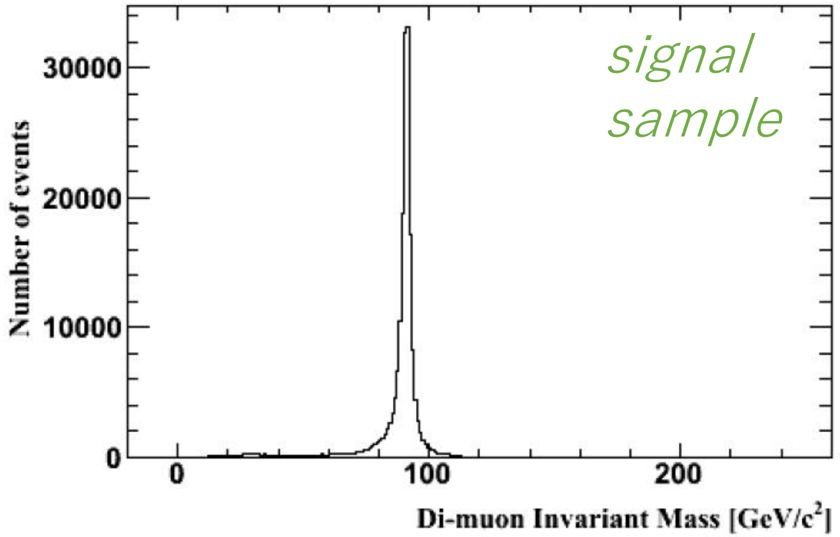
Analysis flow chart



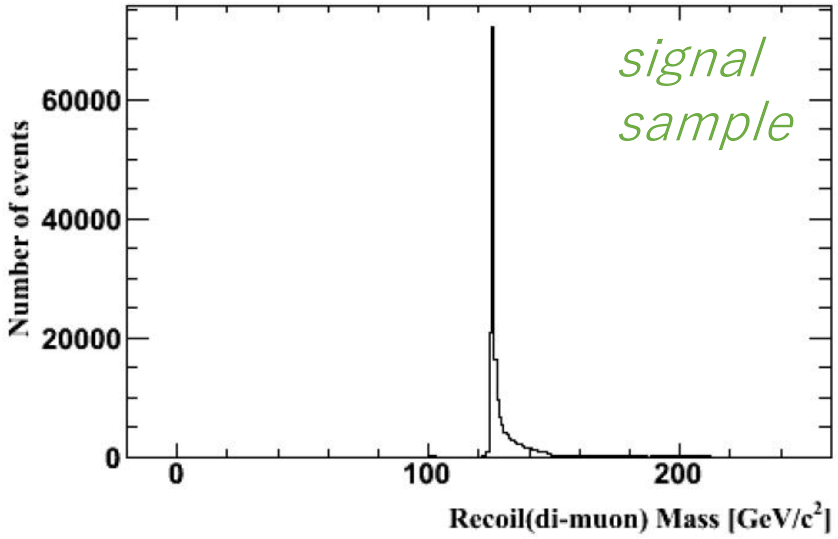
Signature of Z(->$\mu^+\mu^-$)H(->ZZ*)

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





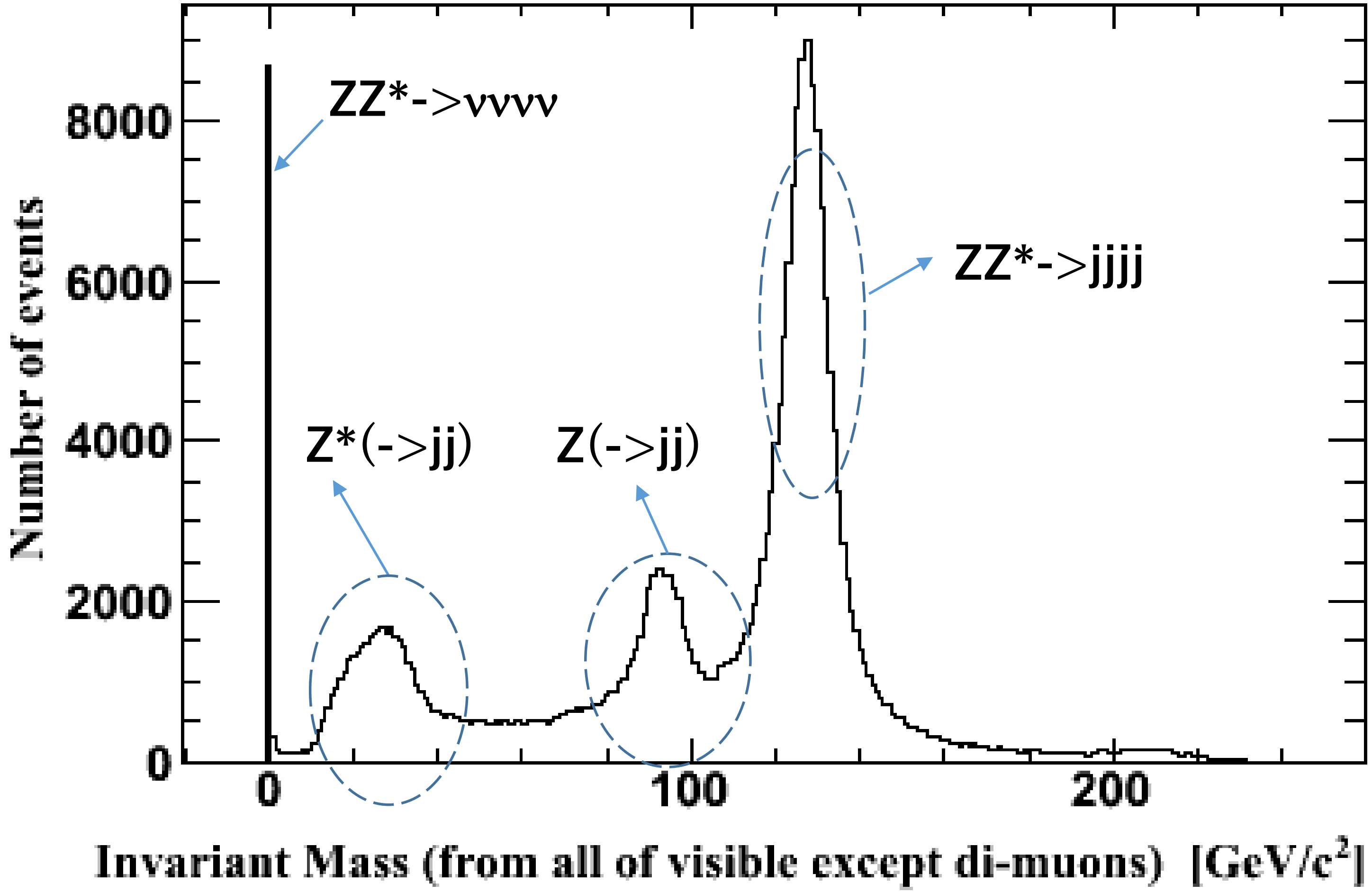
$M_{Invatiant}(\mu^+\mu^-)$



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

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

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



 # Jet clustering N(jet)=2

Note that above distribution is obtained by allowing ZZ*->4ν events to be saved, which are dropped normally in our analysis.

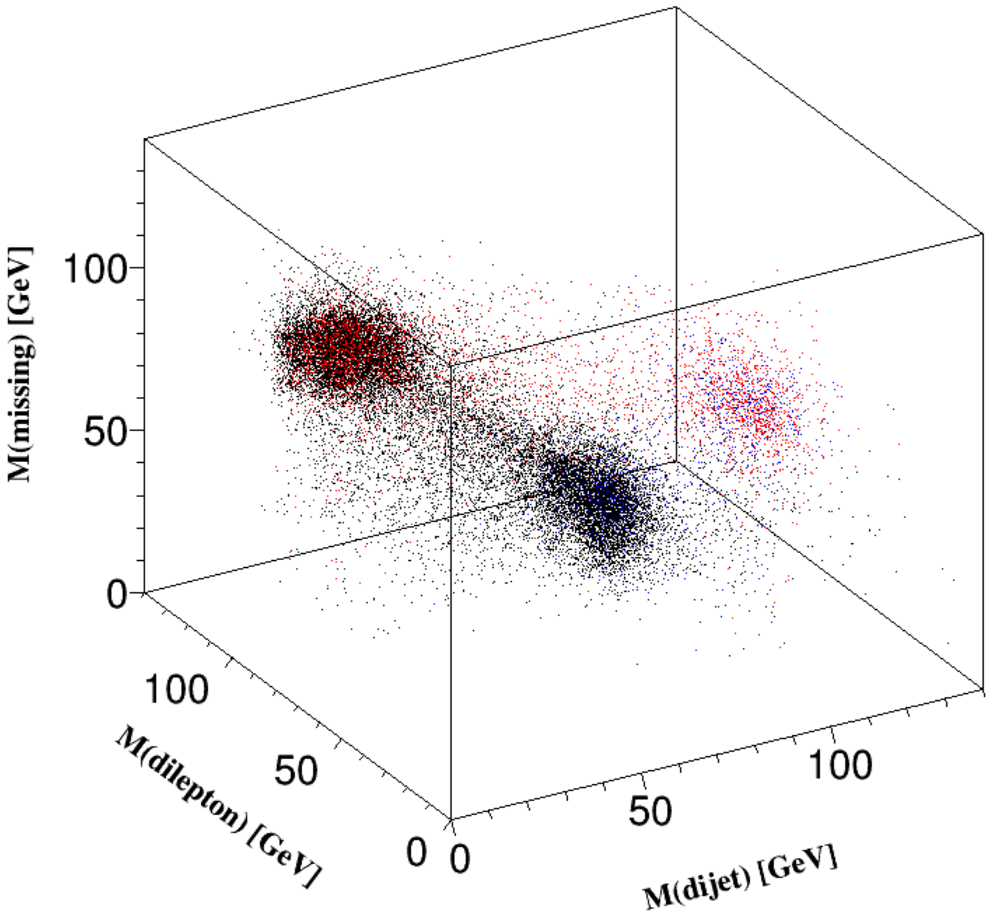
Distribution in $M_{\mu\mu}$-$M_{\nu\nu}$-M_{qq} space

ee→ZH→ZH(ZZ*)

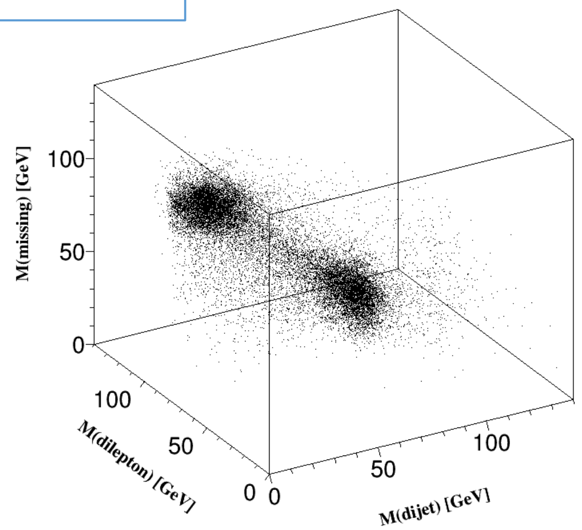
-- μμHννqq , ννHμμqq

-- ννHqqμμ , qqHννμμ

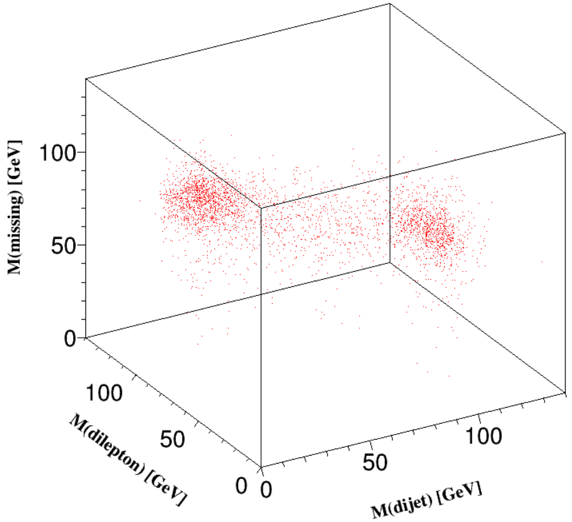
-- qqHμμνν , μμHqqνν



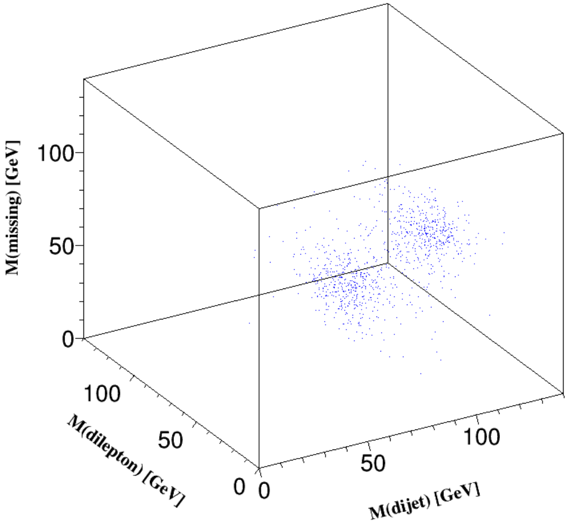
μμHZZ signal



ννHZZ signal

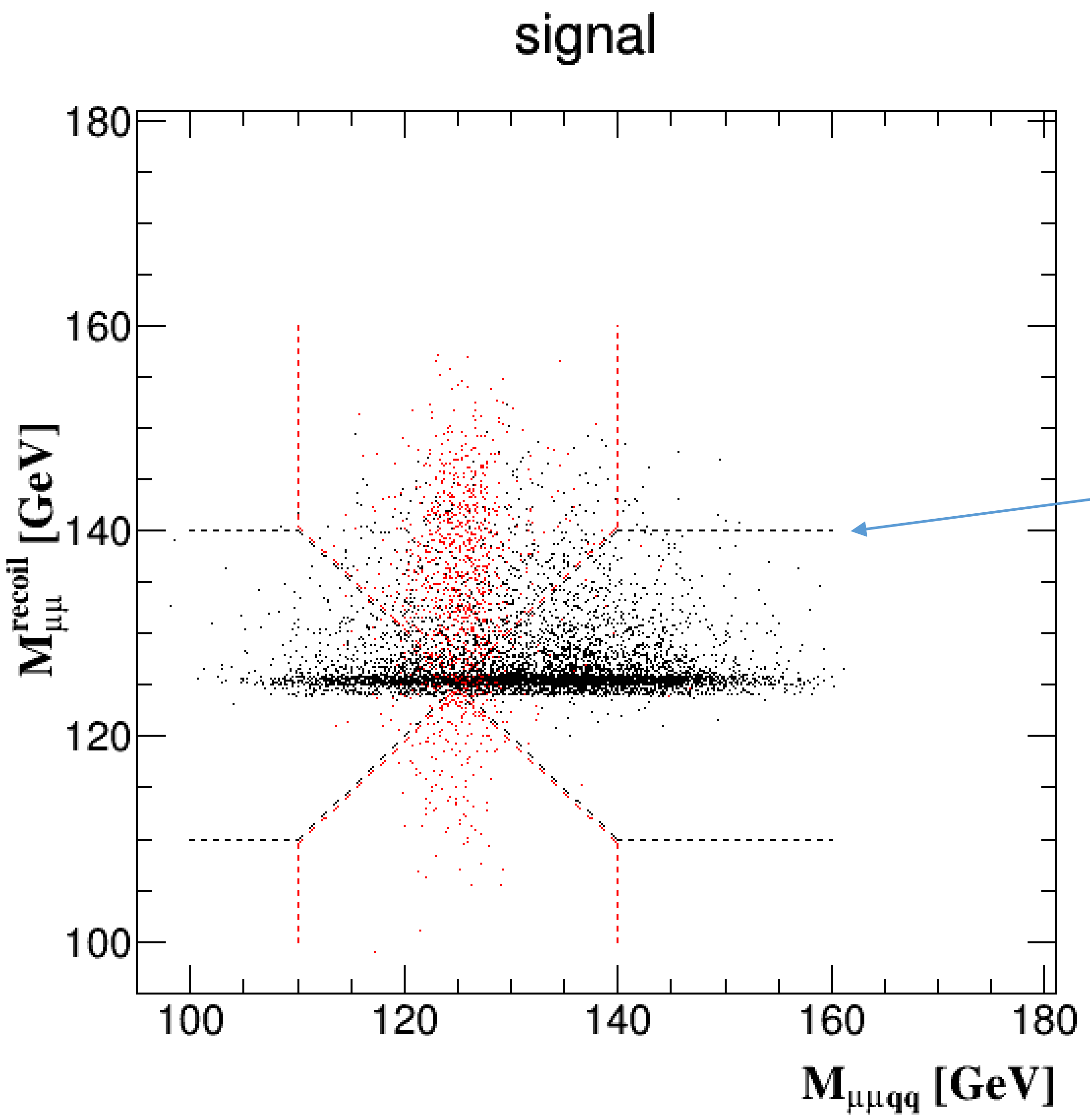


qqHZZ signal



Each signal shows 2 separate distribution in this kinematic phase space.

Separation on recoil mass distribution



・2D Recoil mass distribution shows overwrap of two signal channels

Black : Z→μμ, H→ZZ*→ννqq

Red : Z→νν, H→ZZ*→μμqq

・To make each category exclusive, in other words, no double counting of events, "separation" has been performed on the recoil mass distribution.

Overview table I. Cut-based analysis

Table 1 Overview of the requirements applied when selecting events (cut-based).

Pre-selections
$N(l) = 2$, where leptons(l) should pass the isolation criteria $N(\mu^+) = 1$, $N(\mu^-) = 1$ with $E(\mu^\pm) > 3$ GeV $N(jet) = 2$

Selection (Cut-based)	$\mu\mu$H$\nu\nu qq$	$\mu\mu$H$qq\nu\nu$	$\nu\nu$H$\mu\mu qq$	$\nu\nu$H$qq\mu\mu$	qqH$\nu\nu\mu\mu$	qqH$\mu\mu\nu\nu$
Mass order	$M_{\text{miss}} > M_{jj}$	$M_{\text{miss}} < M_{jj}$	$M_{\mu\mu} > M_{jj}$	$M_{\mu\mu} < M_{jj}$	$M_{\text{miss}} > M_{\mu\mu}$	$M_{\text{miss}} < M_{\mu\mu}$
$M_{\mu\mu}$ (GeV)	[80, 100]		[60, 100]	[10, 60]	[15, 55]	[75, 100]
M_{jj} (GeV)	[15, 60]	[60, 105]	[10, 55]	[60, 100]	[75, 105]	
M_{miss} (GeV)	[75, 105]	[10, 55]	[75, 110]		[70, 110]	[10, 50]
$M_{\mu\mu}^{\text{recoil}}$ (GeV)	[110, 140]		-	-	[175, 215]	[115, 155]
M_{vis} (GeV)	-	[175, 215]	[110, 140]		[115, 155]	[185, 215]
M_{jj}^{recoil} (GeV)	[185, 220]	-	-	-	[110, 140]	
N_{PFO}	[20, 90]	[30, 100]	[20, 60]	[30, 100]	[40, 95]	[40, 95]
$\lvert\cos\theta_{\text{vis}}\rvert$	< 0.95					
$\Delta\phi_{ZZ}$ (degree)	[60, 170]	[60, 170]	< 135	< 135	-	[120, 170]
Region masking	*not-$\nu\nu$HZZ & not-qqHZZ*		*not-$\mu\mu$HZZ & not-qqHZZ*		*not-$\nu\nu$HZZ & not-$\mu\mu$HZZ*	

Overview table II. BDT-based analysis

Table 3 Overview of the requirements applied when selecting events (BDT-based).

Pre-selections						
$N(l) = 2$, where leptons(l) should pass the isolation criteria $N(\mu^+) = 1$, $N(\mu^-) = 1$ with $E(\mu^\pm) > 3$ GeV $N(jet) = 2$						
Selection (MVA)	$\mu\mu$H$\nu\nu qq$	$\mu\mu$H$qq\nu\nu$	$\nu\nu$H$\mu\mu qq$	$\nu\nu$H$qq\mu\mu$	qqH$\nu\nu\mu\mu$	qqH$\mu\mu\nu\nu$
Mass order	$M_{\text{miss}} > M_{jj}$	$M_{\text{miss}} < M_{jj}$	$M_{\mu\mu} > M_{jj}$	$M_{\mu\mu} < M_{jj}$	$M_{\text{miss}} > M_{\mu\mu}$	$M_{\text{miss}} < M_{\mu\mu}$
$M_{\mu\mu}$ (GeV)	[80,100]		-	-	-	-
M_{jj} (GeV)	-	-	-	-	[75, 105]	
M_{miss} (GeV)	-	-	[75, 110]		-	-
$M_{\mu\mu}^{\text{recoil}}$ (GeV)	[110, 140]		-	-	-	-
M_{vis} (GeV)	-	-	[110, 140]		-	-
M_{jj}^{recoil} (GeV)	-	-	-	-	[110, 140]	
N_{PFO}	[20, 90]	[30, 100]	[20, 60]	[30, 100]	[40, 95]	[40, 95]
$\lvert\cos\theta_{\text{vis}}\rvert$	< 0.95					
Region masking	*not-$\nu\nu$HZZ & not-qqHZZ*		*not-$\mu\mu$HZZ & not-qqHZZ*		*not-$\nu\nu$HZZ & not-$\mu\mu$HZZ*	
BDT score	> 0.14	> 0.01	> -0.01	> -0.01	> -0.04	> -0.01

Number of expected events & efficiency

Table 2 Summary of the selection efficiency ϵ and the number of expected events $N_{evt.}$ for each category after the final event selection in the cut-based analysis..

(Cut-based)	$\mu\mu H\nu\nu qq$		$\mu\mu H qq\nu\nu$		$\nu\nu H\mu\mu qq$	
Process	ϵ [%]	$N_{evt.}$	ϵ [%]	$N_{evt.}$	ϵ [%]	$N_{evt.}$
Signal ("dominant")	38	53	36	50	54	76
Signal ("sub")	6	8	10	14	6	9
Higgs decays Bg.	$2.2\cdot10^{-3}$	25	$7.0\cdot10^{-2}$	794	$5.3\cdot10^{-4}$	6
SM four-fermion Bg.	$3.7\cdot10^{-6}$	4	$4.9\cdot10^{-4}$	520	$5.6\cdot10^{-6}$	6
SM two-fermion Bg.	0	0	0	0	0	0
	$\nu\nu H qq\mu\mu$		$qq H\nu\nu\mu\mu$		$qq H\mu\mu\nu\nu$	
Process	ϵ [%]	$N_{evt.}$	ϵ [%]	$N_{evt.}$	ϵ [%]	$N_{evt.}$
Signal ("dominant")	36	51	26	37	23	32
Signal ("sub")	8	11	7	10	4	6
Higgs decays Bg.	$1.0\cdot10^{-2}$	114	$2.4\cdot10^{-2}$	275	$1.4\cdot10^{-2}$	160
SM four-fermion Bg.	$4.3\cdot10^{-5}$	46	$1.5\cdot10^{-4}$	157	$1.8\cdot10^{-4}$	190
SM two-fermion Bg.	0	0	0	0	0	0

- Signal efficiency : 27 - 60 %

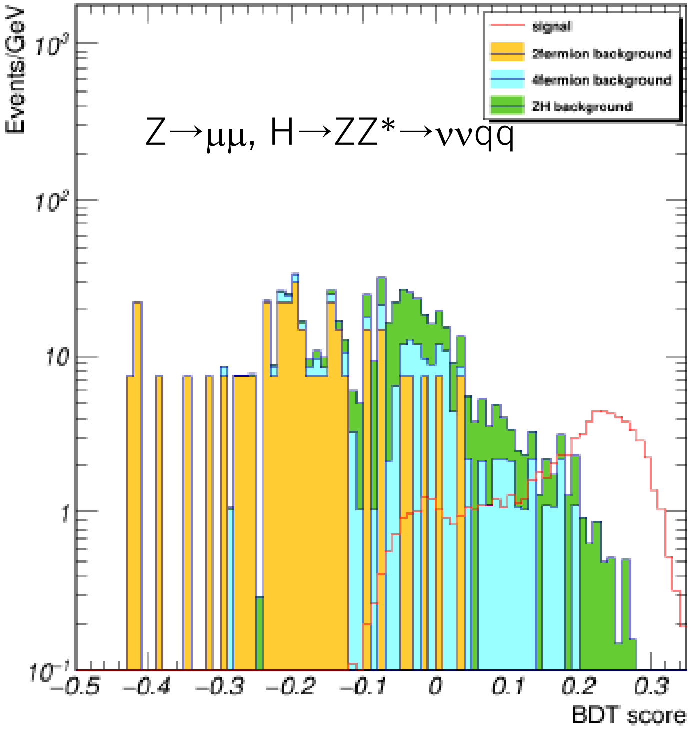
BDT analysis

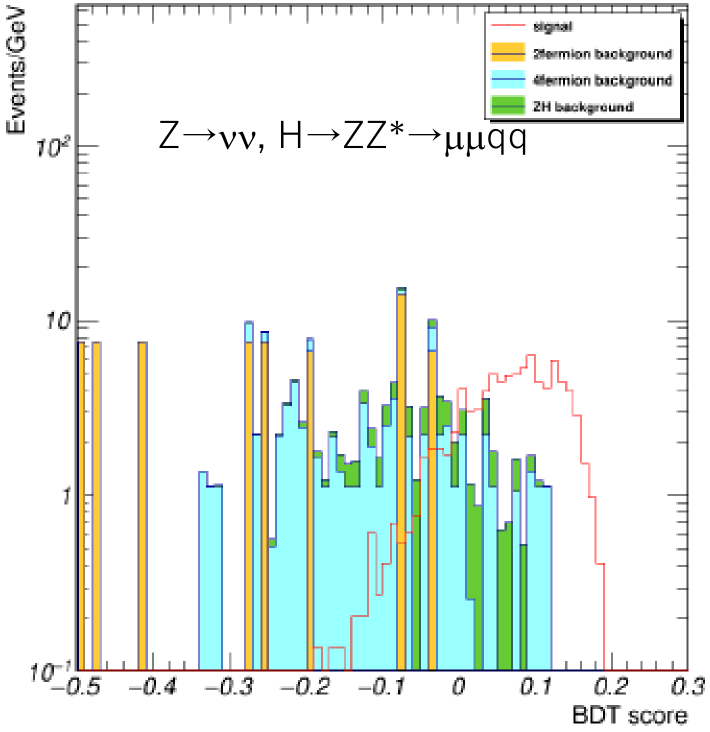
・ BDT training and cuts are applied after several simple cuts : M_{xx}, M^{recoil}_{xx}, N_{pfo}, $\cos\theta$, etc.

・ BDT cut position is optimized based on the measure, $S/\sqrt{(S+B)}$, which to be maximized.

Variables used in the BDT

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

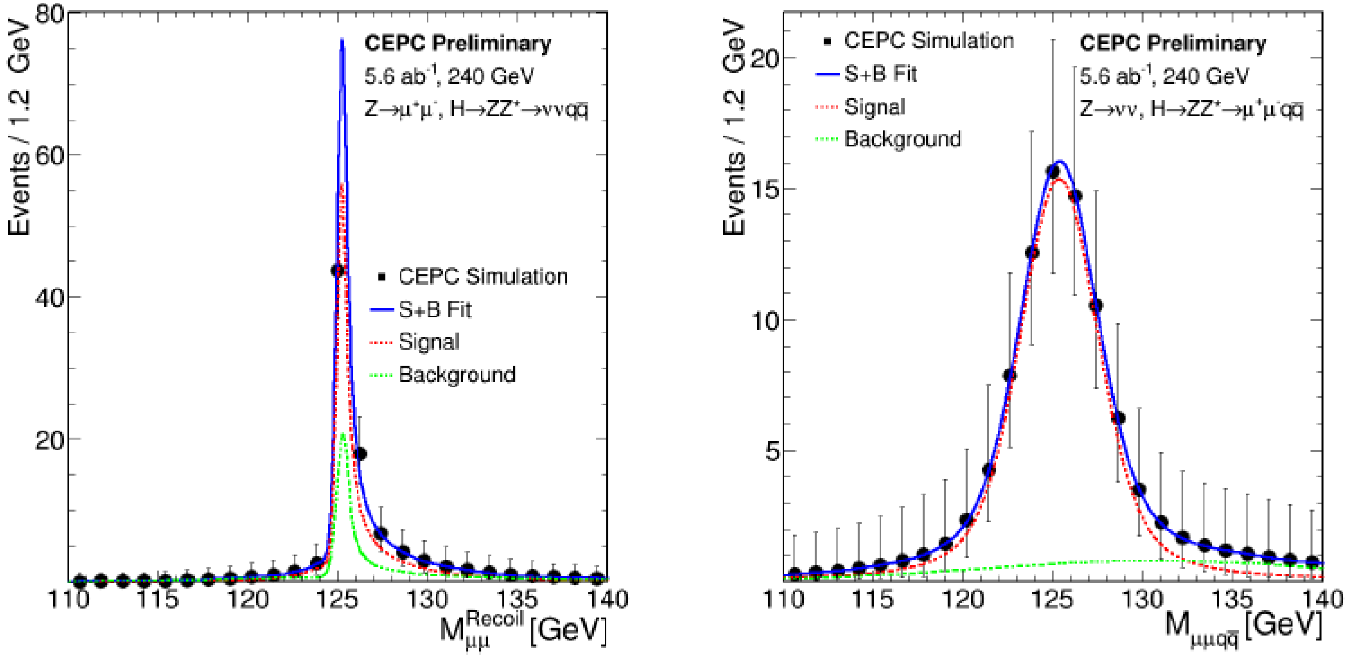




Obtained precision

Obtained uncertainty from each category. Both of cut-based and BDT-based results are shown together.

Category	$\frac{\Delta(\sigma \cdot BR)}{(\sigma \cdot BR)}$ [%] cut-based	BDT
$\mu\mu H\nu\nu qq^{cut/mva}$	15.5	13.6
$\mu\mu Hqq\nu\nu^{cut/mva}$	48.0	42.1
$\nu\nu H\mu\mu qq^{cut/mva}$	11.9	12.5
$\nu\nu Hqq\mu\mu^{cut/mva}$	23.5	20.5
$qqH\nu\nu\mu\mu^{cut/mva}$	45.3	37.0
$qqH\mu\mu\nu\nu^{cut/mva}$	52.4	44.4
Combined	8.34	7.89



Figs. Recoil mass distribution from two best categories.

H->ZZ* part in the CEPC white paper

$Z \to \mu\mu$, $H \to ZZ^* \to \nu\nu qq$

- $M_{\mu\mu}$: 80-100 GeV
- $M^{recoil}_{\mu\mu}$: 120-160 GeV
- M_{jj} : 10-38 GeV
- P_t : > 10 GeV

$Z \to \nu\nu$, $H \to ZZ^* \to l^+l^- qq$

- Visible Energy : < 180 GeV
- $M_{missing}$: 58-138 GeV
- Mass & pt cuts on lepton/jet pairs

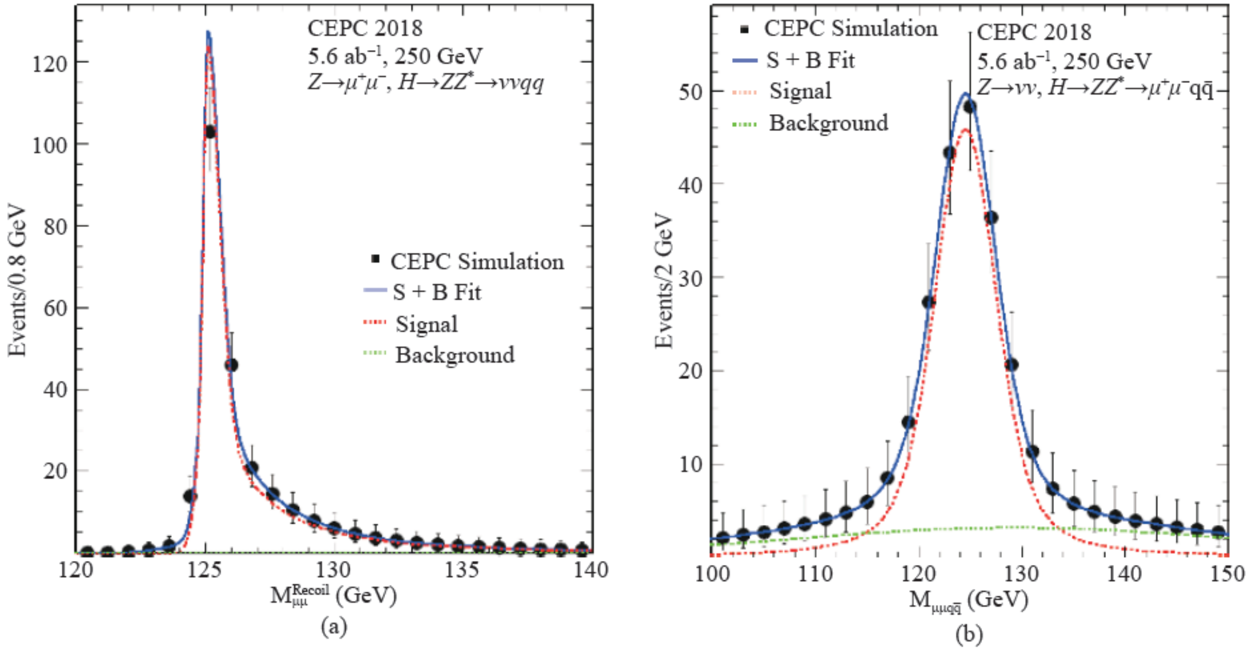


Table 8. Expected relative precision for the $\sigma(ZH)\times BR(H \to ZZ^*)$ measurement with an integrated luminosity 5.6 ab^{-1}.

ZH final state		precision
$Z \to \mu^+\mu^-$	$H \to ZZ^* \to \nu\bar{\nu}q\bar{q}$	7.2%
$Z \to \nu\bar{\nu}$	$H \to ZZ^* \to \ell^+\ell^- q\bar{q}$	7.9%
combination		4.9%

Comparison of results

	Precision from current analysis (cut-based)	Precision in the white paper#
$Z\to\mu\mu$, $H\to ZZ^*\to\nu\nu qq$	15.5%	7.2%
$Z\to\nu\nu$, $H\to ZZ^*\to\mu\mu qq$	11.9%	8.2%#
2 channels combined	9.43%	5.4%

7.9% in previous page is the combined results from $Z\to\nu\nu$, $H\to ZZ^*\to\mu\mu qq$ & $Z\to\nu\nu$, $H\to ZZ^*\to eeqq$ where the former precision of 8.2% is not separately shown in the white paper.

there are certain discrepancy here . . .

Comparison of final recoil mass

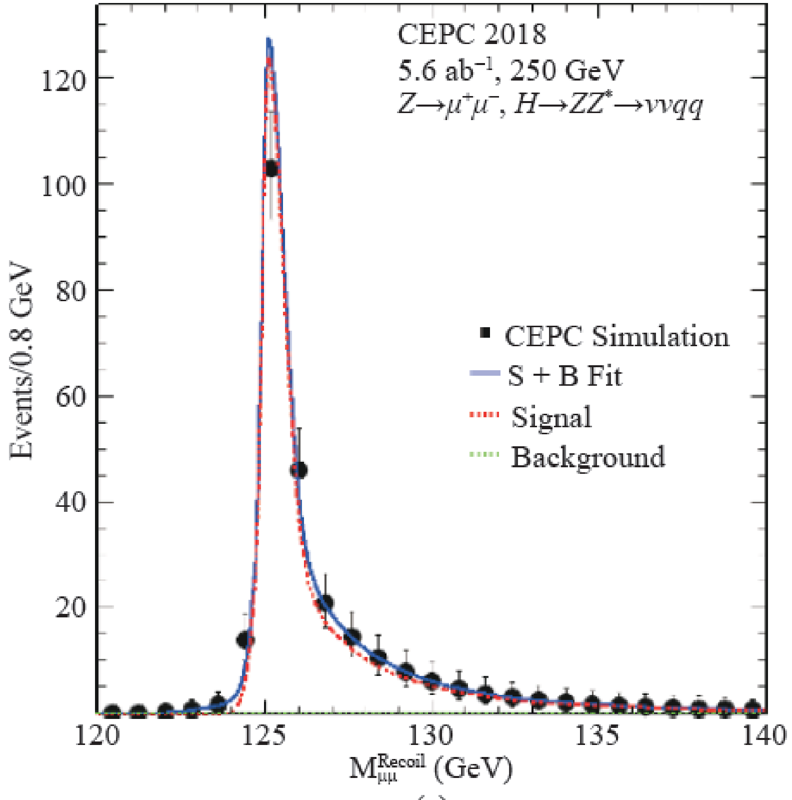
In comparison with the current analysis (left), the figure in the white paper (right) shows

Much larger signal events :

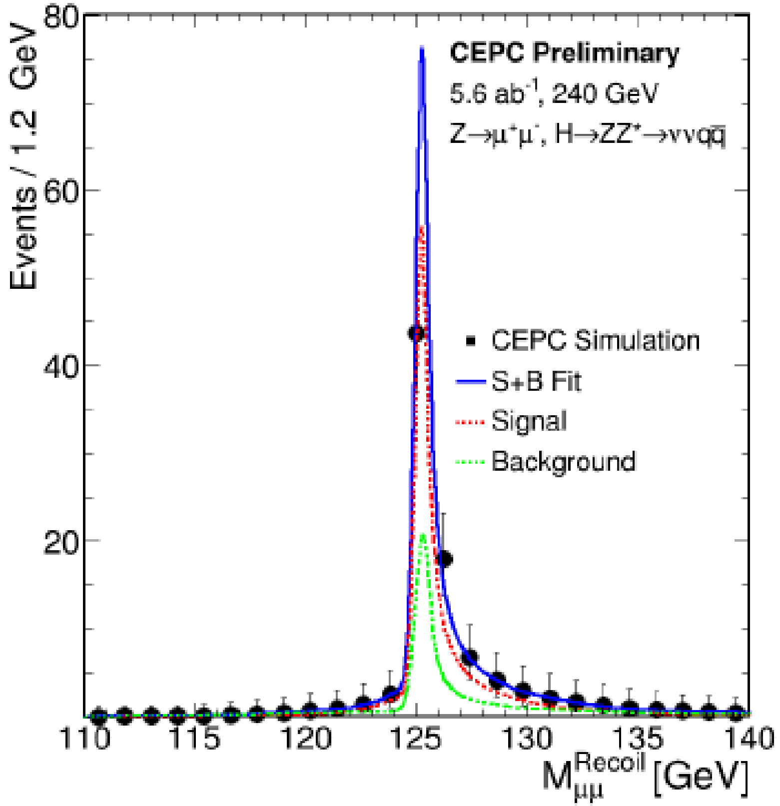
-- N(sig)~200 (old)

-- N(sig)~60 (current)

(smaller bg. events :)



(a)



Number of events ?

- Using following numbers,

  -- σ_{ZH}=204fb, L=5600 fb^{-1}, BR(H->ZZ) =2.64%, BR(Z->qq)=70%, BR(Z->$\nu\nu$)=70%, BR(Z->$\mu\mu$)=3.3%

  N($Z\rightarrow\mu\mu$, $H\rightarrow(Z\rightarrow\nu\nu, Z^*\rightarrow qq)$) = 139 events

  ⇩

  Number of signal of more than 200 is not what we expect,
  therefore, the possible scenarios would be,

1. The plot in the white paper is sum of 2 channel : $(Z\rightarrow\nu\nu, Z^*\rightarrow qq)$ + $(Z\rightarrow qq, Z^*\rightarrow\nu\nu)$ despite the requirement, M_{jj} : 10-38 GeV , is described.
2. Something wrong with the scaling in the old result

Ref: Situation of Z→μμ, H→(Z→qq,Z*→νν)

- Background components for Z→μμ, H→(Z→qq,Z*→νν) channel

  -- H→bb

  -- H→WW

  -- zz-sl0mu-up/down

There are huge background to this channel

N(sig) ~ 50 events

- Hard to bring the precision of this channel to the opposite one.

Remaining background components ("cut-based")

name	scale	final
e2e2h_bb	0.21896	457
e2e2h_cc	0.011032	6
e2e2h_e3e3	0.023968	6
e2e2h_gg	0.0326888819557	2
e2e2h_ww	0.08176	312
e2e2h_zz	0.010024	7
e3e3h_zz	0.009968099681	2
qqh_e3e3	0.4844	4
qqh_zz	0.20216	14
zz_sl0mu_up	1.09032214858	125
zz_sl0mu_down	1.08025726079	386
zz_sl0tau_down	1.10887174477	4
ww_sl0muq	1.2235862395	6

Other info. - 1

・Obtained precision in Yuqian's thesis is relatively close to current result.
(But the thesis is published in 2017)

表 5.2 H->ZZ*所有衰变末态中统计误差 >20%的衰变道的统计结果

	信号事例数	信号效率	统计误差
$e^+e^-\nu\nu jj$	65±8	50.1%	15.1%
$\mu^+\mu^-\nu\nu jj$	88±9	67.3%	12.0%
$\nu\nu e^+e^- jj$	43±7	27.6%	18.6%
$\nu\nu \mu^+\mu^- jj$	90±9	57.4%	11.4%
$\nu\nu jj \mu^+\mu^-$	77±8	49.7%	12.9%

・Root files to make the distribution in the white paper, lack the "weight" information, and weight=1 is assumed（info. from Kaili）

・Background samples might only include the one which has large yield.（info. from Kaili）

Other info. - 2

What is not in our analysis but is described in Yuqian’s thesis :

・FSR correction

・LCFIPlus （but no description of usage of tagging information in HZZ analysis is found）

[Short Summary]

Although our analysis has a room to improve, not easy to reach the level in the white paper.

A possible scenario is that the old result was obtained by including very limited number of background events/components.

H→ZZ* precision from the other future colliders

- ILC

  -- $\Delta(\sigma \cdot BR(HZZ))/\sigma \cdot BR(HZZ)$ = 18% with L=250 fb^{-1} at 250 GeV

  ⇨ it is corresponding to ~5% by scaling the number of ZH events to that of the CEPC

  -- Various HZZ final states are included in that estimation.

  "ILC Higgs White Paper" arXiv:1310.0763

- FCC-ee

  -- $\Delta(\sigma \cdot BR(HZZ))/\sigma \cdot BR(HZZ)$ = 4.4% with L=5 ab^{-1} at 240 GeV

  -- No specific information about the HZZ final states analyzed is obtained yet.

  Abada, A., Abbrescia, M., AbdusSalam, S.S. *et al.* FCC-ee: The Lepton Collider. *Eur. Phys. J. Spec. Top.* **228,** 261–623 (2019). https://doi.org/10.1140/epjst/e2019-900045-4

Summary

・ $H \rightarrow ZZ^*$ decay is analyzed on the final state, having 2μ, 2ν, and 2-jets.

・ The final precision is obtained as 8.3% from the cut-based analysis and 7.9% from the BDT-based analysis.

・ On the other hand, the past result in the white paper is ~5% which shows discrepancy, and we do not have clear conditions(s) to account this difference yet.

・ Any suggestions are welcome .

Thank you very much !