WW Fusion, $H \to bb$ and Higgs Width measurement at CEPC

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Contents

Motivation

- Higgs width is strongly of interest for physicists.
  - Extraction for absolute coupling of Higgs
  - New physics in Higgs invisible decay
- Impossible to be extracted from the line shape directly
  - Mass resolution a few GeV $\gg$ Higgs width (4 MeV)
- Off-shell decay of Higgs at LHC
  - $\sigma_{H\to ZZ}/\sigma_{H\to ZZ} \propto 1/\Gamma$
  - Best result: $\approx$20 MeV
    - CMS arXiv:1605.02329v2
    - ATLAS arXiv:1808.01191v2
  - Only 4MeV predicted by SM
  - Far from precision measurement

Motivation Cont'd

Two methods at CEPC

- First method

$$\Gamma = \Gamma_{\mathrm{SM}} \cdot \frac{\mu_{ZH}}{\mathrm{Br}(H \to ZZ)/\mathrm{Br}_{\mathrm{SM}}(H \to ZZ)}$$

  - Limited by the statistics of $H \to ZZ$, due to the small $\mathrm{Br}(H \to ZZ)$, which is only 2.3% by the SM.

- Second method (Better)

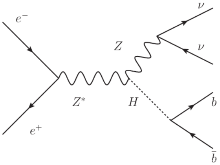
$$\Gamma = \Gamma_{\mathrm{SM}} \cdot \frac{\mu_{WW\mathrm{fusion}, H \to b\bar{b}}}{\left(\frac{\mathrm{Br}(H \to b\bar{b})\mathrm{Br}(H \to W^- W^+)}{\mathrm{Br}_{\mathrm{SM}}(H \to b\bar{b})\mathrm{Br}_{\mathrm{SM}}(H \to W^- W^+)}\right)}$$

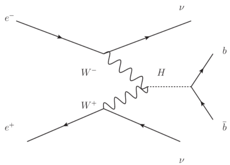
  - The bottleneck: $WW\mathrm{fusion}, H \to b\bar{b}$

- Focus: $WW\mathrm{fusion}, H \to b\bar{b}$

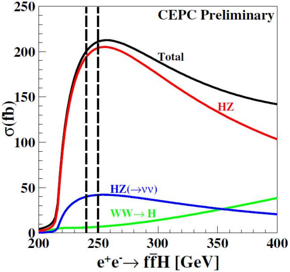
Motivation Cont'd

Two main channels for final states $\nu\nu H(b\bar{b})$ at CEPC:





ZH WW fusion



Monte Carlo Samples

- Higgs samples
  - $\sqrt{s} = 240\mathrm{GeV}$
  - 100k WW fusion, $H \to b\bar{b}$ events
  - 100k $ZH, Z \to \nu\nu, H \to b\bar{b}$ events
  - The interference can NOT be generated by current software
  - Weight assigned according to:
    - $\nu\nu H$ in total: Whizard2(Omega) 46.29fb
    - WW fusion take a fraction of 13%
    - ZH take a fraction of 87%
  - Simulated and reconstructed for CEPC-v4
- SM backgrounds samples
  - 2fermions + 4 fermions
- Result scaled to integral luminosity 5.6 ab^{-1}

Event Selection

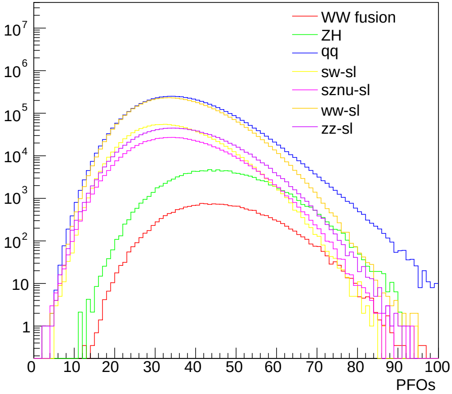
- Main backgrounds
  - Irreducible SM backgrounds:
    - $ZH, Z \to vv, H \to b\bar{b}$
    - 2fermions: $b\bar{b}$
    - 4fermions: double Z ($\nu\nu b\bar{b}$), Single Z ($\nu\nu b\bar{b}$)
  - 2jets + 1charged isolated lepton
    - ww-sl, sw-sl
- Pre-Cuts for SM backgrounds

Pre-cut	Cut on reconstructed variables
$60\mathrm{GeV}/c^2 < M_{\mathrm{mis}} < 225\mathrm{GeV}/c^2$	$65\mathrm{GeV}/c^2 < M_{\mathrm{mis}} < 135\mathrm{GeV}/c^2$
$50\mathrm{GeV}/c^2 < M_{\mathrm{vis}}$	$100\mathrm{GeV}/c^2 < M_{\mathrm{vis}} < 135\mathrm{GeV}/c^2$
$10\mathrm{GeV}/c < P_T < 100\mathrm{GeV}/c$	$13\mathrm{GeV}/c < P_T < 90\mathrm{GeV}/c$

Event Selection Cont'd

Selection for (semi-)hadronic final states:

- Cut on number of Objects

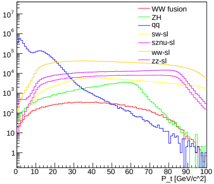


PFOs

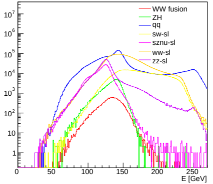
(Cut in order. Previous cuts applied before the each cut variable was plot)

Event Selection Cont'd

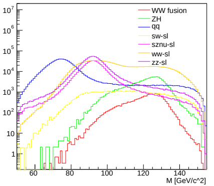
Selection according to the kinematic distribution:



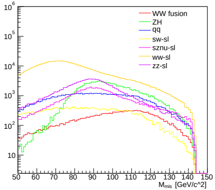
P_T



E_{vis}



M_{vis}

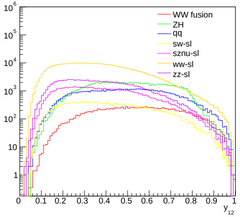


M_{recoil}

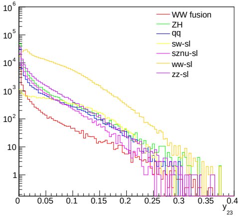
Event Selection Cont'd

Selection for di-jets events

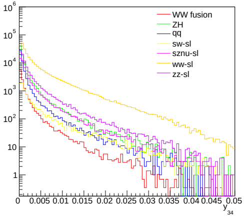
- Cut on output of clustering algorithm



y_{12}



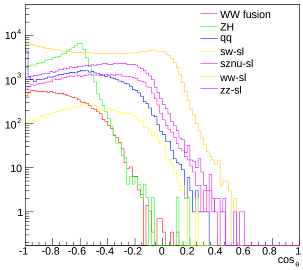
y_{23}



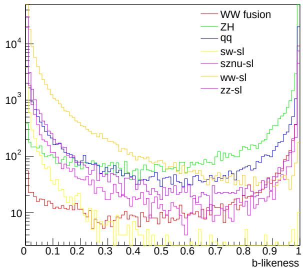
y_{34}

Event Selection Cont'd

Selection on the angle of di-jets and the flavor:



$\cos(\theta_{\mathrm{2jets}})$



bb-likeness

Event Selection Cont'd

Signal and Higgs Backgrounds

Cut	WW fusion	ZH
$N_{\mathrm{PFO}(E>0.4\mathrm{GeV})} > 20$	19912	122073
$105\mathrm{GeV} < E_{\mathrm{total}} < 155\mathrm{GeV}$	17939	114926
$P_T > 13\mathrm{GeV}/c$	16694	111663
Isolation lepton veto	15463	101951
$100 < M_{\mathrm{vis}} < 135$	13929	100289
$65 < M_{\mathrm{mis}} < 135$	13846	99750
y_{12}, y_{23}, y_{34}	12251	90976
$-0.98 < \cos(\theta_{2\mathrm{jets}}) < -0.4$	11416	88548
$bb - \mathrm{likeness} > 0.4$	10916	82597

Main SM backgrounds

Cut	$q\bar{q}$	sw-sl	sz-nu	ww-sl	zz-sl
Generated	250283714	13025535	744000	23788000	2581000
Pre-cut & reconstructed	5924182	1193000	658000	5208810	1112000
$N_{\mathrm{PFO}(E>0.4\mathrm{GeV})} > 20$	5717282	1138089	629242	5077296	1066096
$105\mathrm{GeV} < E_{\mathrm{total}} < 155\mathrm{GeV}$	3821137	356219	529778	2883329	911700
$P_T > 13\mathrm{GeV}/c$	826961	351546	520798	2799966	891644
Isolation lepton veto	792950	59642	488958	1376469	818336
$100 < M_{\mathrm{vis}} < 135$	76396	33928	70942	652630	127555
$65 < M_{\mathrm{mis}} < 135$	62586	19427	62508	446045	110631
$0.15 < y_{12} < 1$	61719	18517	58941	409226	103750
$y_{23} < 0.06$	54797	9651	53150	277300	92458
$y_{34} < 0.01$	53711	8629	50802	245424	87819
$-0.98 < \cos(\theta_{2\mathrm{jets}}) < -0.4$	37224	5809	31017	133305	50646
$bb - \mathrm{likeness} > 0.4$	25630	124	5745	3230	9764

However... note: numbers in above tables were normalized to $5\mathrm{ab}^{-1}$

Recoil Mass Reconstruction

- Number of WW fusion, $H \to b\bar{b}$ events mainly extracted from the recoil mass. The precision reconstruction of recoil mass is crutial.
- Raw method: The recoil mass is calculated by

$$m_{\mathrm{recoil}} = \sqrt{(\sqrt{s} - E_H)^2 - p_H^2}$$

  where E_H and p_H is reconstructed energy and momentum of Higgs, respectively.
- Refined method: The energy is replaced with the one calculated from the momentum

$$m_{\mathrm{recoil}} = \sqrt{(\sqrt{s} - \sqrt{m_H^2 + p_H^2})^2 - p_H^2}$$

- The refined method is refined, because:

  (sensitivity of m_{recoil} to p_H) $\times$ (p_H resolusion) $<$ (sensitivity of m_{recoil} to E_H) $\times$ (E_H resolusion)

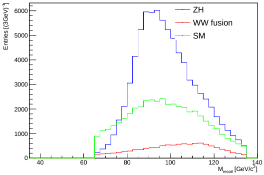
Recoil Mass Reconstruction Cont'd

The other methods of modifying the energies of jets tried:

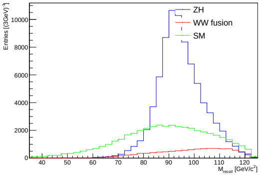
- Kinematic fit:
  Minimize the $\chi^2 = \sum_{i=1,2}(\frac{E_i - E_i^{reco}}{\delta_i(E)})^2$
  With constraint: $M_{2jets} = m_H(125\mathrm{GeV})$
- Global scaling:
  $E_{1(2)}$ were scaled with same factor to let
  $M_{2jets} = m_H(125\mathrm{GeV})$

Same results obtained as the previous refined method. No more detail showed in this report.

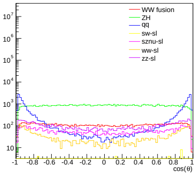
Signal and Background Character



Raw: M_{recoil}



Refined: M_{recoil}



$\cos(\theta_z)$

Fit Model

- Methodology objective: as much realism as possible within acceptable analysis complexity
- Additional information of $ZH, Z \to \nu\nu, H \to b\bar{b}$ obtained from eeH, $\mu\mu H$, and qqH where $H \to b\bar{b}$. Three signal strengthes are proportional to the $ZH, Z \to \nu\nu, H \to b\bar{b}$, by three assumptions:
  - 1: The uncertainties due to electroweak physics are assumed to be negligible.
  - 2: ZZ fusion contribution to eeH is negligible
  - 3: The correlations of signal strengthes of three channels are negligible
  - The additional constraint of $ZH, Z \to \nu\nu, H \to b\bar{b}$:
    $1/\sqrt{\left(\frac{1}{\sigma_{eeH,H\to b\bar{b}}}\right)^2 + \left(\frac{1}{\sigma_{\mu\mu H,H\to b\bar{b}}}\right)^2 + \left(\frac{1}{\sigma_{qqH,H\to b\bar{b}}}\right)^2}$
    $=1/\sqrt{\left(\frac{1}{1.32\%}\right)^2 + \left(\frac{1}{0.99\%}\right)^2 + \left(\frac{1}{0.46\%}\right)^2} = 0.39\%$

Higgs Boson Width

Numbers from Kaili's report

Channels Table(2018.11)

All scaled to 240 GeV, 5.6ab^{-1}

Signal Z	Signal H	Precision
H->qq		
ee	**bb**	**1.32%**
ee	cc	13.5%
ee	gg	7.22%
μμ	**bb**	**0.99%**
μμ	cc	9.54%
μμ	gg	5.01%
qq	**bb**	**0.46%**
qq	cc	11.1%
qq	gg	3.64%
νν	bb	0.39%
νν	cc	3.83%
νν	gg	1.47%
H->Invisible		
qq	ZZ(νννν)	232%
ee	ZZ(νννν)	370%
μμ	ZZ(νννν)	245%

Signal Z	Signal H	Precision
H->WW		
ee	lνlν	9.52%
ee	eνqq	4.56%
ee	μνqq	3.93%
μμ	lνlν	7.29%
μμ	eνqq	3.90%
μμ	μνqq	3.90%
νν	qqqq	1.90%
νν	eνqq	4.65%
νν	μνqq	4.14%
νν	lνlν	11.5%
qq	qqqq	1.75%
H->ZZ		
νν	μμqq	8.26%
νν	eeqq	40%
μμ	ννqq	7.32%
ZH bkg contribution		19.4%

Signal Z	Signal H	Precision
H→γγ, Zγ		
μμ+ττ	γγ	23.7%
νν	γγ	10.5%
qq	γγ	9.84%
νν	Zγ(qqγ)	15.7%
ννH(WW fusion)		
νν	bb	3.00%
H→μμ		
qq	μμ	17.1%
ee	μμ	
μμ	μμ	
νν	μμ	
H→ττ		
ee	ττ	2.75%
μμ	ττ	2.61%
qq	ττ	0.95%
νν	ττ	2.66%

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Fit Model Cont'd

- Binned log likelihood constructed as

$$\log L = \log P(data; \mu_{WWF}, \mu_{ZH}) - 0.5 \left(\frac{\mu_{ZH} - 1}{0.39\%} \right)^2 \quad (1)$$

$$\log P = \sum_i \log \mathrm{Poisson}\left(n_{i,data}; n_{i,\mathrm{bkg}} + n_{i,ZH}\mu_{ZH} + n_{i,WWF}\mu_{WWF}\right) \quad (2)$$

where $n_{i,data}$ is the events number in bin i; $n_{i,\mathrm{bkg}}$, $n_{i,ZH}$, $n_{i,WWF}$ the expected events number of backgrounds, $ZH, Z \to \nu\nu, H \to b\bar{b}$, and $WW\mathrm{fusion}, H \to b\bar{b}$ in bin i; Backgrounds means all backgrounds (SM backgrounds and Higgs backgrounds) except the $ZH, Z \to \nu\nu, H \to b\bar{b}$.

Result

- 1D-fit: recoil mass
- 2D-fit: recoil mass and θ

	$\mu_{WW\mathrm{fusion}}$ 1D	$\mu_{WW\mathrm{fusion}}$ 2D	μ_{ZH} 1D	μ_{ZH} 2D
Raw	3.9%	3.8%	0.33%	0.32%
Refined	3.1%	3.0%	0.30%	0.30%

- 0.1% improvement for 2D fit compared to 1D-fit.
- 0.8% improvement for refined recoil mass compared to raw recoil mass.
- Consistent with Kaili's result of κ framework.

Higgs width

- δ relative error
- fusion

$$\delta\Gamma_{fus} = \sqrt{\delta^2_{\sigma(fus,H\to bb)} + \delta^2_{\sigma(ZH,H\to bb)} + \delta^2_{\sigma(ZH,H\to WW)} + (2\delta_{\sigma(ZH)})^2}$$

$$= \sqrt{(3.0\%)^2 + (0.28\%)^2 + (1.0\%)^2 + (2\cdot 0.5\%)^2} = 3.3\%$$

- ZZ

$$\delta\Gamma_{ZZ} = \sqrt{\delta^2_{\sigma(ZH,H\to ZZ)} + (2\delta_{\sigma(ZH)})^2}$$

$$= \sqrt{(5.1\%) + (2\cdot 0.5\%)^2} = 5.2\%$$

- Combination:

$$\Gamma = 1/\sqrt{1/\Gamma^2_{ZZ} + 1/\Gamma^2_{\mathrm{fus}}} = 2.8\%$$

- See Kaili's form nubmers
- Consistent with Kaili's κ framework

Next work

Combined $WW\text{fusion}, H \to bb$ analysis with $ZH, Z \to \nu\nu, H \to bb$ analysis (Baiyu), to count on the correlations.

- $ZH, Z \to \nu\nu, H \to bb$ analysis were performed stand-alone.
- Cuts are optimized for each case.
- Fit on flavors tagging in ZH analysis.
- Fit on recoil mass and recoil polar angle in $WW\text{fusion}$ analysis.

Possible solution:

- divide data into 3 categories:
  - Data fall only in $ZH, H \to bb$ window.
  - Data fall only in $WW\text{fusion}, H \to bb$ window.
  - Data fall in both windows.
- Fit both recoil mass and flavor tagging for each category, then combine.
- Difficulty: High dimensional PDF construction.

Next work

Interference is still big ‘homework’.

- Inter. / WWfusion = 7%
- Not much effect on statistical error

Thanks!