Measurement of $WW \text{fusion}, H \rightarrow b\bar{b}$ Cross-Section at CEPC

Hao Liang

CEPC Mini-workshop

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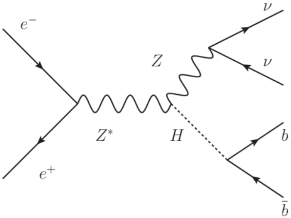
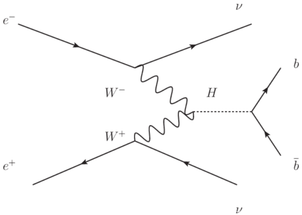
Contents

Motivation

- Two main channels for final states $\nu\nu H, H \to b\bar{b}$:



ZH



WW fusion

Motivation Cont'd

- Higgs width is strongly of interest for physicists.
- Impossible to be extracted from the line shape directly, because of the narrow Higgs decay width.
- Two methods of measuring Higgs width: First method is related to $\mathrm{Br}(H \to ZZ)$. The precision is 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 is related to $WW \mathrm{fusion}, H \to b\bar{b}$.

Motivation Cont'd

- $$\sigma_{ZH} = F_1 \cdot g_Z^2$$
$$\sigma_{ZH,H\to b\bar{b}} = F_2 \cdot g_z^2 g_b^2/\Gamma$$
$$\sigma_{ZH,H\to W^-W^+} = F_3 \cdot g_z^2 g_W^2/\Gamma$$
$$\sigma_{WW\mathrm{fusion},H\to b\bar{b}} = F_4 \cdot g_W^2 g_b^2/\Gamma$$

  Where F_i, $i = 1 ... 4$ are constant factors, which can be calculated in theory. The Higgs width, Γ, can sovled from above four equations:

$$\Gamma = \frac{F_2 F_3}{F_1^2 F_4} \cdot \frac{\sigma_{WW\mathrm{fusion},H\to b\bar{b}}\sigma_{ZH}^2}{\sigma_{ZH,H\to b\bar{b}}\sigma_{ZH,H\to W^-W^+}} = \Gamma_{\mathrm{SM}} \cdot \frac{\mu_{WW\mathrm{fusion},H\to b\bar{b}}\mu_{ZH}^2}{\mu_{ZH,H\to b\bar{b}}\mu_{ZH,H\to W^-W^+}} \quad (1)$$

  where the μ means the signal stress, which is the cross section normalized by SM prediction, and Γ_{SM} is the Higgs width predicted by SM, which is about 4 MeV.
- Independent to the Higgs decay models.
- The bottleneck: $WW\mathrm{fusion}, H \to b\bar{b}$

Monte Carlo Samples

- Higgs samples
  - 100k WW fusion events
  - 100k ZH events
  - Samples for interference between WW fusion and ZH can not be generated by current software
  - Assign weights corresponding to 5 ab^{-1}
  - Simulated and reconstructed for CEPC-v1 and CEPC-v4 respectively
- SM backgrounds samples
  - Integral luminosity: 5 ab^{-1}
  - 2fermions + 4 fermions
  - The pre-selections were applied for saving the computation time
  - Simulated and reconstructed for CEPC-v1 only, but used for both cases

Event Selection

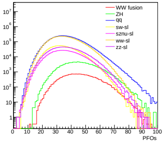
- Pre-Cuts for SM backgrounds

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

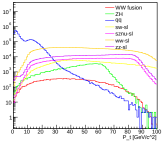
- Main backgrounds
  - $ZH, Z \to vv, H \to b\bar{b}$
  - $q\bar{q}$
  - Irreducible SM backgrounds: zz-sl, sznu-sl
  - Two b jets + single charged isolated lepton: ww-sl, sw-sl

Event Selection Cont'd

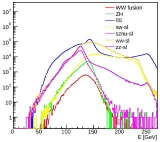
- CEPC v1



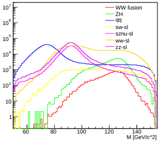
PFOs



P_T

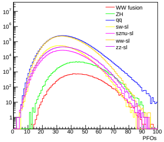


E_{vis}

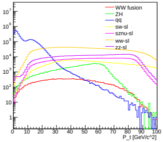


$M_{\rm vis}$

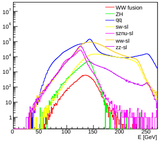
- CEPC v4



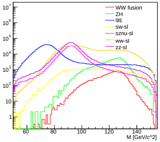
PFOs



P_T



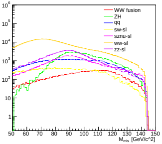
E_{vis}



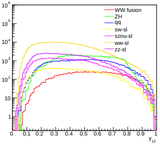
$M_{\rm vis}$

Event Selection Cont'd

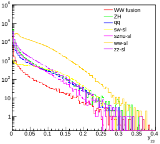
- CEPC v1



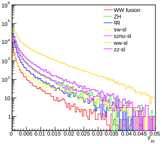
M_{recoil}



y_{12}

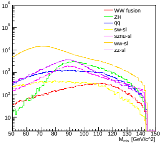


y_{23}

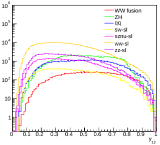


y_{34}

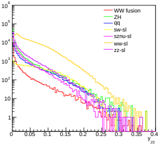
- CEPC v4



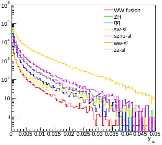
M_{recoil}



y_{12}



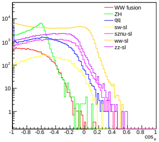
y_{23}



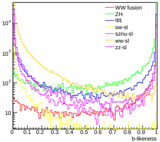
y_{34}

Event Selection Cont'd

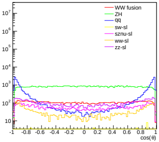
- CEPC v1



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

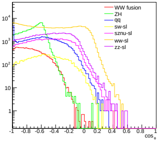


bb-likeness

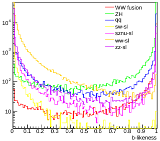


$\cos(\theta_z)$

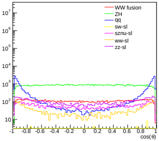
- CEPC v4



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



bb-likeness



$\cos(\theta_z)$

Event Selection Cont'd

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

Signal and Higgs Backgrounds

Cut	WW fusion (v1)	WW fusion (v4)	ZH (v1)	ZH (v4)
$N_{\mathrm{PFO}(E>0.4\mathrm{GeV})} > 20$	20102	19912	122403	122073
$105\mathrm{GeV} < E_{\mathrm{total}} < 155\mathrm{GeV}$	18181	17939	115656	114926
$P_T > 13\mathrm{GeV}/c$	16935	16694	112297	111663
Isolation lepton veto	14969	15463	106993	101951
$100 < M_{\mathrm{vis}} < 135$	13513	13929	97766	100289
$65 < M_{\mathrm{mis}} < 135$	13441	13846	96172	99750
y_{12}, y_{23}, y_{34}	11959	12251	85453	90976
$-0.98 < \cos(\theta_{2\mathrm{jets}}) < -0.4$	11158	11416	83308	88548
$bb - \mathrm{likeness} > 0.4$	10639	10916	79623	82597

Recoil Mass Reconstruction

- The number of WW fusion, $H \to b\bar{b}$ events extracted from the fitting of recoil mass
- Approach 1: 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.
- Approach 2: The energy is replaced with the one calculated from the momentum

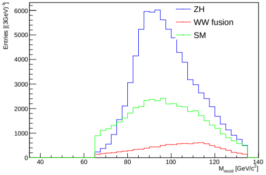
$$m_{\mathrm{recoil}} = \sqrt{(\sqrt{s} - \sqrt{m_H^2 + p_H^2})^2 - p_H^2}$$

- The approach 2 is expected to be better, because:

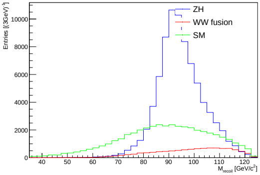
  (sensitivity of m_{recoil} to p_H) $\times$ (p_H resolusion) $<$ (sensitivity of m_{recoil} to E_H) $\times$ (E_H resolusion)

Recoil Mass Reconstruction Cont'd

CEPC-v1

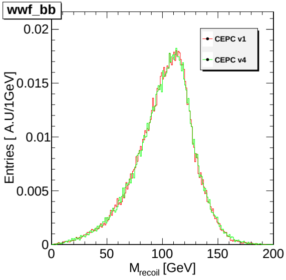


Approach 1: M_{recoil}

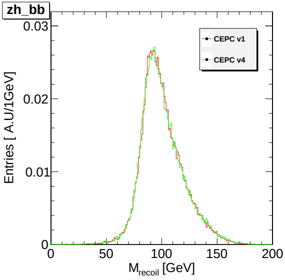


Approach 2: M_{recoil}

approach 2



WW fusion: M_{recoil}



ZH: M_{recoil}

Fit Model

- Methodology objective: as much realism as possible within acceptable analysis complexity
- SM backgrounds where assumed to be known very well, so the expected numbers of SM backgrounds events were fixed

Fit Model Cont'd

- Additional information of $ZH, Z \to \nu\nu, H \to b\bar{b}$ obtained from eeH, $\mu\mu H$, and qqH where $H \to b\bar{b}$.
  - Assumption 1: The uncertainties due to electroweak physics are assumed to be negligible.
  - Assumption 2: ZZ fusion contribution to eeH is negligible
  - Consequent: Three signal strengthes are proportional to the $ZH, Z \to \nu\nu, H \to b\bar{b}$
  - Assumption 3: The measurement correlation of signal strengthes of three channels are negligible
  - Conclusion: The external constraint of $ZH, Z \to \nu\nu, H \to b\bar{b}$:
    - $1/\sqrt{\left(\frac{1}{\sigma_{eeH,H\to b\bar{b}}}\right)^2 + \left(\frac{1}{\sigma_{\mu\mu H,H\to b\bar{b}}}\right)^2 + \left(\frac{1}{\sigma_{qqH,H\to b\bar{b}}}\right)^2}$
    - $1/\sqrt{\left(\frac{1}{1.2\%}\right)^2 + \left(\frac{1}{1.1\%}\right)^2 + \left(\frac{1}{0.4\%}\right)^2} = 0.375\%$
    - See Yu Bai's report for newest values.

Fit Model Cont'd

- Binned log likelihood constructed as

$$\log L = \log P(data; \mu_{WWF}, \mu_{ZH}) - 0.5 \left(\frac{\mu_{ZH} - 1}{0.375\%} \right)^2 \qquad (2)$$

$$\log P = \sum_i \log \mathrm{Poisson} \left(n_{i,data}; n_{i,\mathrm{bkg}} + n_{i,ZH}\mu_{ZH} + n_{i,WWF}\mu_{WWF} \right) \qquad (3)$$

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 $ZH, Z \to \nu\nu, H \to b\bar{b}$.

- The statistical uncertainty was determined via the hessian matrix at maximum point of the log likelihood

Result

- 2D-fit: recoil mass and θ

	CEPC-v1	CEPC-v4
Approach 1	3.8%	3.8%
Approach 2	3.1%	3.1%

In apporch 1, $m_{\mathrm{recoil}} = \sqrt{(\sqrt{s} - E_H)^2 - p_H^2}$. In approach 2, E_H is replaced with $\sqrt{p_H^2 + m_H^2}$

- 0.7% improvement by replacing E_H with $\sqrt{p_H^2 + m_H^2}$
- Compared to pre-CDR of CEPC, the method is more realistic, the result get a bit worse (pre-CDR: 2.8%).
- BTW: 0.1% (absolute) improvement for 2D fit compared to 1D-fit

Result for CEPC-v4 at 240GeV

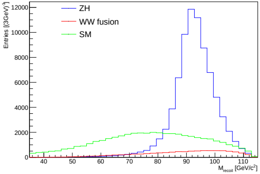
- Cross-section
  - Cross-section of *WW* fusion decreases by 20.4%
  - Cross-section of *ZH* decreases by 3%
  - Most SM backgrounds increase (by up to 10%)
- Events selection

Cut	WW (250 v1)	WW (250 v4)	WW (240 v4)	ZH (250 v1)	ZH (250 v4)	ZH (240 v4)
$N_{\mathrm{PFO}(E>0.4\mathrm{GeV})} > 20$	20102	19912	15859	122403	122073	116808
$105\mathrm{GeV} < E_{\mathrm{total}} < 155\mathrm{GeV}$	18181	17939	14496	115656	114926	109426
$P_T > 13\mathrm{GeV}/c$	16935	16694	13384	112297	111663	104818
Isolation lepton veto	14969	15463	13384	106993	101951	104818
$100 < M_{\mathrm{vis}} < 135$	13513	13929	12446	97766	100289	97293
$65 < M_{\mathrm{mis}} < 135$	13441	13846	11546	96172	99750	95080
y_{12}, y_{23}, y_{34}	11959	12251	10197	85453	90976	86269
$-0.98 < \cos(\theta_{\mathrm{2jets}}) < -0.4$	11158	11416	9594	83308	88548	83855
$bb - \mathrm{likeness} > 0.4$	10639	10916	9210	79623	82597	81283

- Events number *WW* fusion after events selection is 15.6% smaller compared to 240GeV

Result for CEPC-v4 at 240GeV

- Monte Carlo samples
  - SM backgrounds samples for CEPC-v1 at 250GeV reused for CEPC-v4 at 240GeV by assign weight
- Recoil Mass



M_{recoil}

- Fit Result

CEPC-v1 250	CEPC-v4 250	CEPC-v4 240
3.1%	3.1%	3.66%

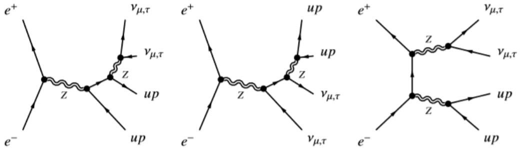
18% worse than the result at energy of 250GeV

Analysis strategy for 250 GeV still valid for energy of 240GeV

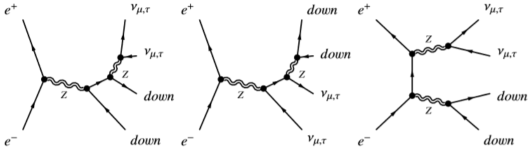
The statistics change is responsible for the degeneration

Thansks!

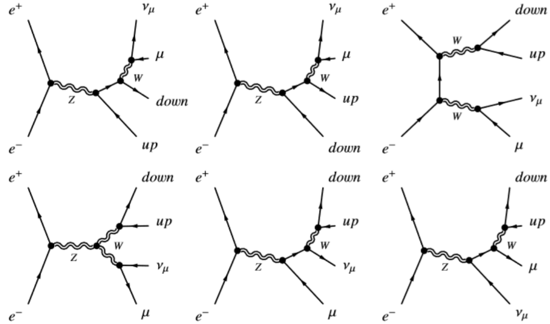
6.5 zz_sl0nu_up



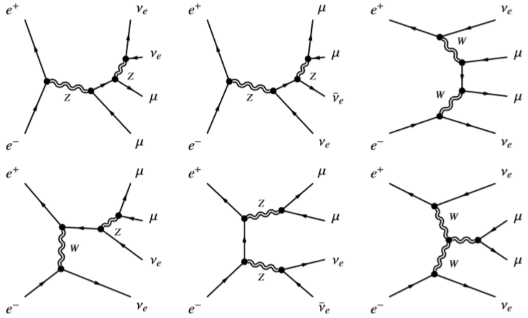
6.6 zz_sl0nu_down



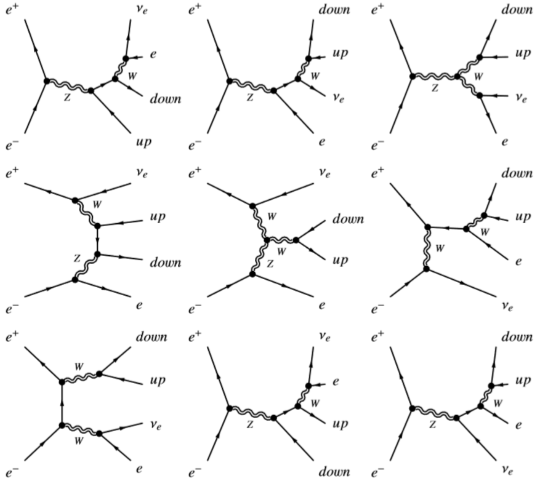
6.21 ww_sl0muq



6.33 sznu_l0mumu



6.39 sw_sl0qq



e^+ ν_e e W Z $down$ e^- up
e^+ $down$ up W Z ν_e e^- e
e^+ $down$ up Z W ν_e e^- e
e^+ ν_e W up Z $down$ e^- e
e^+ ν_e W $down$ W up Z e^- e
e^+ $down$ up W W e e^- ν_e
e^+ $down$ W up ν_e W e^- e
e^+ ν_e e W Z up e^- $down$
e^+ $down$ up W Z e e^- ν_e

Event Selection Cont'd

- bb-likeness: the likeness of a pair of b jets.

$$\mathrm{bb-likeness} = \frac{b_1 b_2}{(b_1 b_2) + (1 - b_1)(1 - b_2)}$$

where b_i is the b flavor likeness of the ith jet.

Recoil Mass Reconstruction Cont'd