Higgs→bb/cc/gg measurement at the CEPC and corresponding optimization study

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Motivation

- The measurement of $Higgs \to b\bar{b}/c\bar{c}/gg$ signal strength is important for Higgs coupling studies.
- The flavor tagging performance and color singlet identification has significant impact on the measurement accuracy.

Contents

- The relative accuracy of signal strength measurement of $\nu\nu H(H \to b\bar{b}, c\bar{c}, gg)$.
  - key performance : flavor tagging
- The relative accuracy of signal strength measurement of $qqH(H \to b\bar{b}, c\bar{c}, gg)$.
  - key performance : flavor tagging
  - key performance : color singlet identification
- summary

Sample

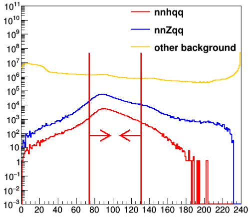
- all SM processes at CEPC ($\sqrt{s} = 240\,GeV$) with integrated luminosity of $5600\,fb^{-1}$

The analysis procedure can be divided into two steps:

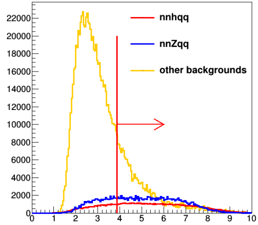
1. select signal events with cut flow
2. calculate the signal strength accuracy

The analysis process of $\nu\nu H$ channel.

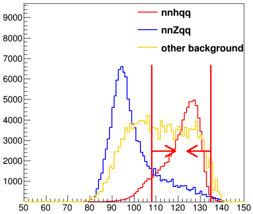
	$\nu\nu Hq\bar{q}/gg$	2f	SW	SZ	WW	ZZ	Mixed	ZH	$\frac{\sqrt{S+B}}{S}$ (%)
total	178890	8.01E8	1.95E7	9.07E6	5.08E7	6.39E6	2.18E7	961606	16.86
recoilMass (GeV) $\in(74, 131)$	157822	5.11E7	2.17E6	1.38E6	4.78E6	1.30E6	1.08E6	74991	4.99
visEn (GeV) $\in(109, 143)$	142918	2.37E7	1.35E6	8.81E5	3.60E6	1.03E6	6.29E5	50989	3.92
leadLepEn (GeV) $\in(0, 42)$	141926	2.08E7	3.65E5	7.24E5	2.81E6	9.72E5	1.34E5	46963	3.59
multiplicity $\in(40, 130)$	139545	1.66E7	2.36E5	5.24E5	2.62E6	9.07E5	4977	42751	3.29
leadNeuEn (GeV) $\in(0, 41)$	138653	1.46E7	2.24E5	4.72E5	2.49E6	8.69E5	4552	42303	3.12
Pt (GeV) $\in(20, 60)$	121212	248715	1.56E5	2.48E5	1.51E6	4.31E5	999	35453	1.37
Pl (GeV) $\in(0, 50)$	118109	52784	1.05E5	74936	7.30E5	1.13E5	847	34279	0.94
-log10(Y23) $\in(3.375, +\infty)$	96156	40861	26088	60349	2.25E5	82560	640	10691	0.76
InvMass (GeV) $\in(116, 134)$	71758	22200	11059	6308	77912	13680	248	6915	0.64
BDT $\in(-0.02, 1)$	60887	9140	266	2521	3761	3916	58	1897	0.47



74 < recoil mass < 131



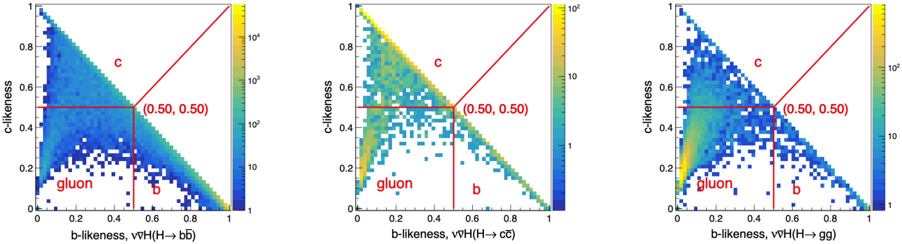
-log(Y23) > 3.875



108 < visible mass < 135

Optimized matrix

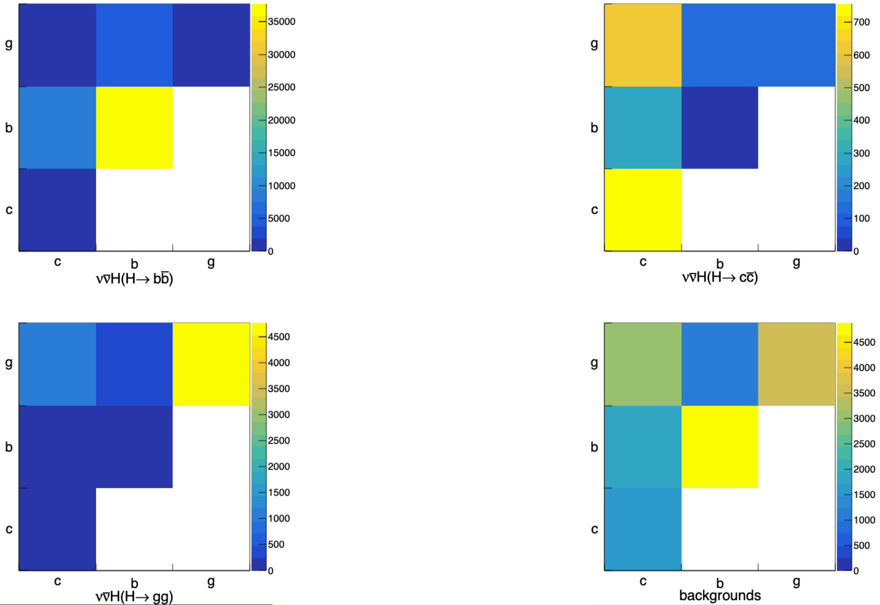
1. The b-likeness and c-likeness of two jets can be displaced in 2D graph.
2. The cut on b-likeness and c-likeness can be find to maximize the value of $eff(b \to b) + eff(c \to c) + eff(udsg \to udsg)$, the trace of flavor tagging matrix.



Optimized matrix :

true \ identified as	b	c	g
b	0.8675	0.0887	0.0437
c	0.1136	0.6263	0.2601
g	0.0411	0.1007	0.8582

events distribution based on optimized matrix :



$$-2\cdot log(\ell) = \sum_{i=1}^{i=6} \frac{[S_b\cdot N_{b,i} + S_c\cdot N_{c,i} + S_{light}\cdot N_{light,i} + N_{bkg,i} - N_i]^2}{N_i}$$

- S_b: the signal strength of $\nu\nu Hb\bar{b}$
- $N_{b,i}$: the event number of $\nu\nu Hb\bar{b}$ in *ith* bin
- N_i: the total event number in *i'th* bin of $\nu\nu Hb\bar{b}$, $\nu\nu H/c\bar{c}$, $\nu\nu Hgg$ and backgrounds
- $N_{bkg,i}$ is the expected event number in *ith* bin of backgrounds,
- similar for S_c, S_{light}, $N_{c,i}$, and $N_{light,i}$

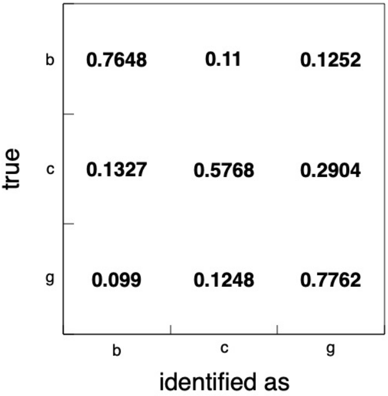
$$hessian\ matrix = \begin{bmatrix} \frac{\partial^2 log(\ell)}{\partial S_g \partial S_c} & \frac{\partial^2 log(\ell)}{\partial S_g \partial S_b} & \frac{\partial^2 log(\ell)}{\partial S_g \partial S_g} \\ \frac{\partial^2 log(\ell)}{\partial S_b \partial S_c} & \frac{\partial^2 log(\ell)}{\partial S_b \partial S_b} & \frac{\partial^2 log(\ell)}{\partial S_b \partial S_g} \\ \frac{\partial^2 log(\ell)}{\partial S_c \partial S_c} & \frac{\partial^2 log(\ell)}{\partial S_c \partial S_b} & \frac{\partial^2 log(\ell)}{\partial S_c \partial S_g} \end{bmatrix}$$

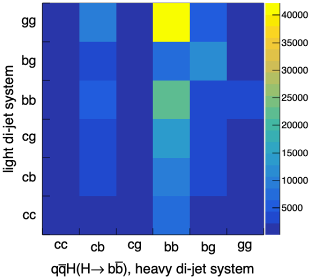
- The error covariance is obtained from the hessian matrix.
- The relative accuracy of signal strength is the square roots of the diagonal elements of the covariance matrix, it is 0.49%/5.75%/1.82% for $\nu\nu Hb\bar{b}/c\bar{c}/gg$.

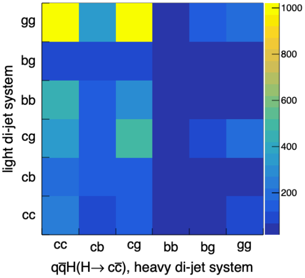
The analysis process of $q\bar{q}H$ channel.

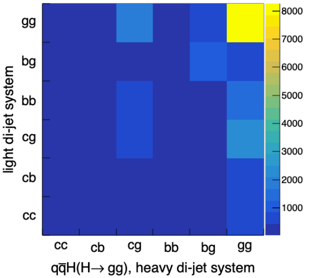
total	qqHqq/gg 527488	2f 8.01E8	SW 1.95E7	SZ 9.07E6	WW 5.08E7	ZZ 6.39E6	Mixed 2.18E7	ZH 613008	$\frac{\sqrt{S+B}}{S}$(%) 5.71
multiplicity $\in(27,+\infty)$	527488	3.04E8	1.46E7	3.37E6	4.85E7	6.00E6	1.81E7	577930	3.77
leadLepEn $\in(0,59)$	527036	2, 98E8	6.76E6	2.44E6	3.93E7	5.40E6	1.79E7	531411	3.65
visEn $\in(199,278)$	510731	1.21E8	1.29E6	551105	2.14E7	3.06E6	1.71E7	180571	2.52
leadNeuEn $\in(0,57)$	509623	5.68E7	716161	168030	2.04E7	2.93E6	1.65E7	176387	1.94
thrust $\in(0,0.86)$	460535	7.81E6	473732	132126	1.88E7	2.60E6	1.54E7	167863	1.47
$-log(Y_{34})$ $\in(0,5.8875)$	451468	4.90E6	181432	119836	1.74E7	2.40E6	1.45E7	165961	1.40
HiggsJetsA $\in(2.18,2\pi)$	326207	2.83E6	110156	58613	4.54E6	870276	3.74E6	96560	1.08
ZJetsA $\in(1.97,2\pi)$	279030	1.37E6	33491	37101	2.39E6	496611	2.00E6	74005	0.93
ZHiggsA $\in(2.32,2\pi)$	274530	1.32E6	17026	33847	2.28E6	468340	1.91E6	69620	0.92
circle	268271	1.20E6	10193	31567	2.13E6	424514	1.79E6	65434	0.90
BDT $\in(0.02,1)$	192278	378300	40	307	271436	141446	244126	30022	0.57

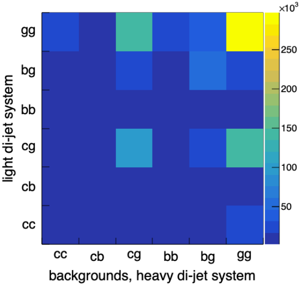
optimized matrix











The signal strength accuracy is 0.35%/7.74%/3.96% for $q\bar{q}Hb\bar{b}/c\bar{c}/gg$.

Z decay mode	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$
$Z \to e^+e^-$	1.57%	14.43%	10.31%
$Z \to \mu^+\mu^-$	1.06%	10.16%	5.23%
$Z \to q\bar{q}$	0.35%	7.74%	3.96%
$Z \to \nu\bar{\nu}$	0.49%	5.35%	1.77%
combination	0.27%	4.03%	1.56%

key performance : flavor tagging

$$M_{mig} = \frac{Tr_{mig} - Tr_{opt}}{Tr_{I} - Tr_{opt}} \cdot (M_{I} - M_{opt}) + M_{opt}, Tr_{mig} >= Tr_{opt}$$

$$M_{mig} = \frac{Tr_{mig} - Tr_{opt}}{Tr_{1/3} - Tr_{opt}} \cdot (M_{1/3} - M_{opt}) + M_{opt}, Tr_{mig} < Tr_{opt}$$

true / identified as

	b	c	g
b	1	0	0
c	0	1	0
g	0	0	1

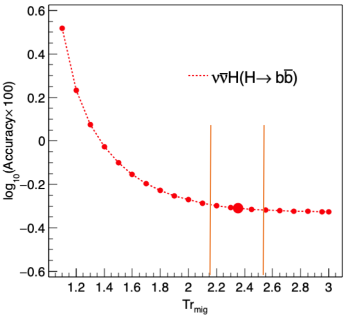
perfect

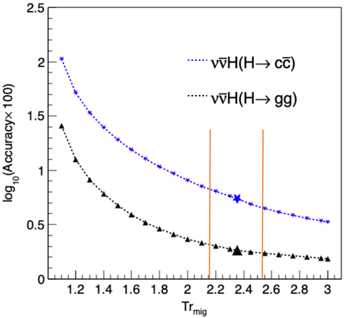
true / identified as

	b	c	g
b	1/3	1/3	1/3
c	1/3	1/3	1/3
g	1/3	1/3	1/3

none

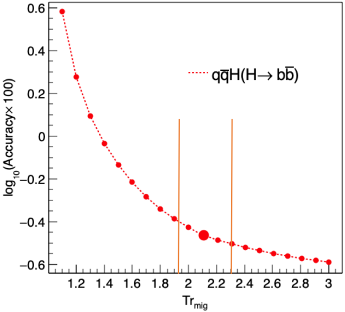
$\nu\bar{\nu}H$

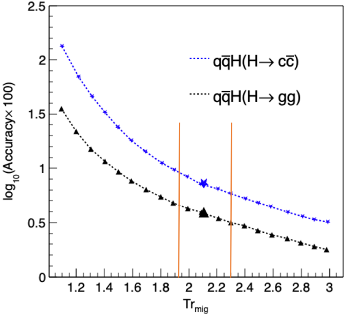




- The perfect flavor tagging performance can improve the $\nu\bar{\nu}H(H\to b\bar{b}/c\bar{c}/gg)$ signal strength accuracy by 2%/63%/13%.
- If the values of vertex detector parameters, including material budget, inner radius, and spatial resolution, is 0.5/2 times compared to the CEPC baseline, the Tr_{mig} will changes from 2.35 to 2.54/2.16 accordingly. The detail can be found in the following pages.

$q\bar{q}H$





- The perfect flavor tagging performance can improve the $\nu\bar{\nu}H(H \to b\bar{b}/c\bar{c}/gg)$ signal strength accuracy by 35%/122%/181%.
- If the values of vertex detector parameters is 0.5/2 times compared to the CEPC baseline, the Tr_{mig} will changes from 2.12 to 2.31/1.93 accordingly.

The dependency of flavor tagging performance on vertex detector design.

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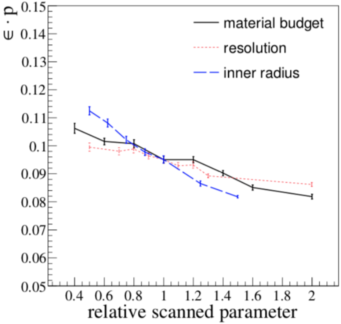
Table 1. The baseline design parameters of the CEPC vertex system.

	R(mm)	Z(mm)	single-point resolution(μm)	material budget
Layer 1	16	62.5	2.8	$0.15\%/X_0$
Layer 2	18	62.5	6	$0.15\%/X_0$
Layer 3	37	125.0	4	$0.15\%/X_0$
Layer 4	39	125.0	4	$0.15\%/X_0$
Layer 5	58	125.0	4	$0.15\%/X_0$
Layer 6	60	125.0	4	$0.15\%/X_0$



the right plot : the correlation between c-tagging efficiency times purity and vertex detector parameters

The dependency of Tr_{mig} on vertex detector parameters.

In $\nu\bar{\nu}H$ channel,

$$Tr_{mig} = 2.35 + 0.05 \cdot log_2 \frac{R^0_{material}}{R_{material}} + 0.04 \cdot log_2 \frac{R^0_{resolution}}{R_{resolution}} + 0.10 \cdot log_2 \frac{R^0_{radius}}{R_{radius}}.$$

$R^0_{material}$: the default material budget $R_{material}$: the modified material budget

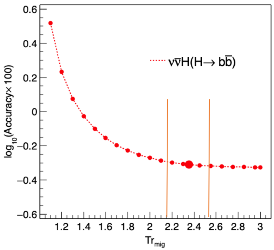
In $q\bar{q}H$ channel,

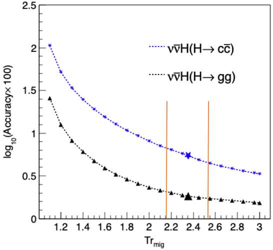
$$Tr_{mig} = 2.12 + 0.05 \cdot log_2 \frac{R^0_{material}}{R_{material}} + 0.04 \cdot log_2 \frac{R^0_{resolution}}{R_{resolution}} + 0.10 \cdot log_2 \frac{R^0_{radius}}{R_{radius}}.$$

Table 2. Reference geometries.

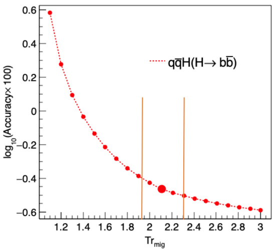
	Scenario A (Aggressive)	Scenario B (Baseline)	Scenario C (Conservative)
Material per layer/X_0	0.075	0.15	0.3
Spatial resolution/µm	1.4 - 3	2.8 - 6	5 - 10.7
R_{in}/mm	8	16	23
Tr_{mig} for $q\bar{q}H$	2.31	2.12	1.93
Tr_{mig} for $\nu\bar{\nu}H$	2.54	2.35	2.16

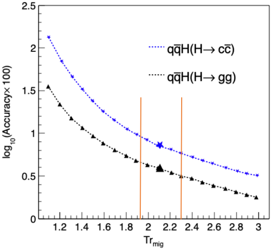
$\nu\bar{\nu}H$



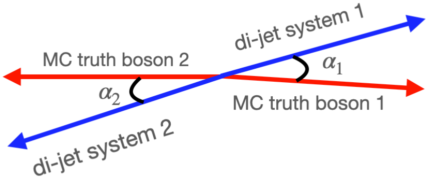


qqH



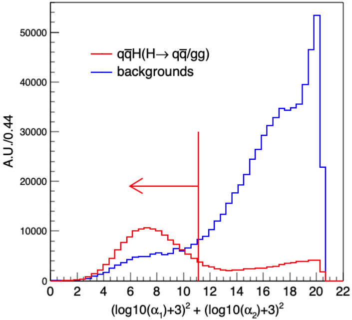


key performance : color singlet identification
(i.e. jet clustering and jet matching)



We use the angle between reconstructed boson and MC truth boson to evaluate the CSI performance.

note : The CSI evaluator in this report is just a demonstrator.



	$qqHb\bar{b}$	$qqHc\bar{c}$	$qqHgg$
w.o. alpha cut	0.35%	7.74%	3.96%
w.i. alpha cut	0.33%	4.37%	2.08%
improved by	6%	77%	90%

Summary :

- The total signal strength of $H \to b\bar{b}, c\bar{c}, gg$ can be measured to a relative accuracy of 0.27%/4.03%/1.56%, combining all four different channels of $\mu\mu H$, eeH, $\nu\nu H$ and qqH.

Z decay mode	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$
$Z \to e^+e^-$	1.57%	14.43%	10.31%
$Z \to \mu^+\mu^-$	1.06%	10.16%	5.23%
$Z \to q\bar{q}$	0.35%	7.74%	3.96%
$Z \to \nu\bar{\nu}$	0.49%	5.35%	1.77%
combination	0.27%	4.03%	1.56%

- The flavor tagging and color singlet identification (CSI) are the critical performances for these benchmarks. Their impact on the anticipated physics reach is evaluated.
  - for $\nu\nu H$ channel
    - The flavor tagging is critical for the $\nu\bar{\nu}H(H \to b\bar{b}/c\bar{c}/gg)$ measurement. Using an ideal flavor tagging, the anticipated accuracy could be improved by 2%/63%/13%.
  - for qqH channel
    - With perfect flavor tagging, the anticipated accuracy of $q\bar{q}H(H \to b\bar{b}/c\bar{c}/gg)$ could be improved by 35%/122%/181%.
    - If we can quantify the CSI performance and select the events with good CSI performance, the $q\bar{q}H(H \to b\bar{b}/c\bar{c}/gg)$ accuracy can be improved by 6%/77%/90%.
- A good color singlet identification, or even a reliable color singlet identification performance evaluator at reconstruction level, is highly appreciated.

https://arxiv.org/abs/2203.01469

Many thanks !

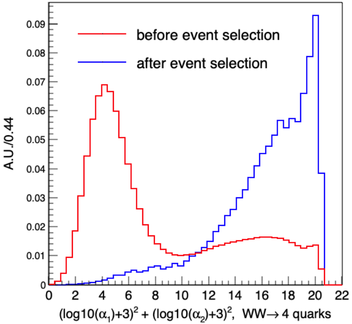
Back Up

systematic uncertainties

We categorize the leading systematic uncertainties into three groups:

- The first group includes the reconstructed energy/momentum scale of the physics objects, which are significantly smaller than the statistical uncertainties.
- The second group are those comparable to the statistical uncertainty, especially the integrated luminosity.
- The third group are those that can be significantly larger than the statistical uncertainty, including CSI and the jet configuration.

The detailed discussion can be found in `https://arxiv.org/abs/2203.01469`.



before event selection
after event selection
A.U./0.44
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0 2 4 6 8 10 12 14 16 18 20 22
(log10(α1)+3)2 + (log10(α2)+3)2, WW→ 4 quarks