The $Higgs \to b\bar{b}, c\bar{c}, gg$ measuremnet at CEPC & corresponding optimization studies

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IHEP

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Motivation

- The g(Hcc), the second generation fermion Yukawa coupling, is one of the most important benchmark at CEPC, and its measurement strongly depend on the Higgs branching ratio measurement accuracy.
- It is very important to estimate the measurement accuracy of Higgs branching ratio to verify the Higgs mechanism.

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 ($\sqrt{s} = 240GeV$) with integrated luminosity of $5600fb^{-1}$

$llH(H \rightarrow b\bar{b}, H \rightarrow c\bar{c}, H \rightarrow gg)$ *accuracy measurement* at CEPC ($\sqrt{s} = 250\ GeV$ with integrated luminosity $5000fb^{-1}$)

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Measurements of decay branching fractions of $H \rightarrow b\bar{b}/c\bar{c}/gg$ in associated $(e^+e^-/\mu^+\mu^-)H$ production at the CEPC*

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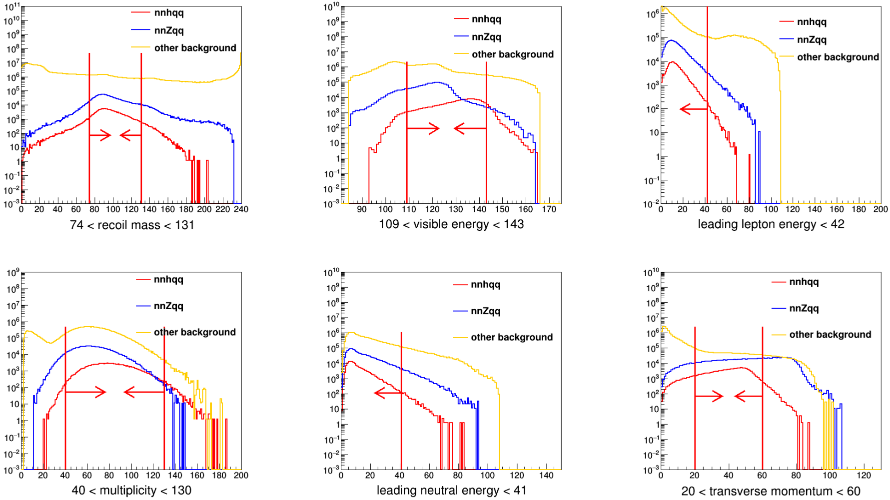
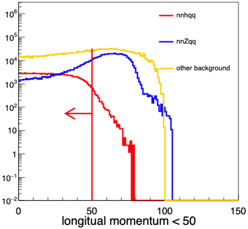
	$\mu^+\mu^-H$			e^+e^-H		
	$H \rightarrow b\bar{b}$	$H \rightarrow c\bar{c}$	$H \rightarrow gg$	$H \rightarrow b\bar{b}$	$H \rightarrow c\bar{c}$	$H \rightarrow gg$
accuracy	1.1%	10.5%	5.4%	1.6%	14.7%	10.5%

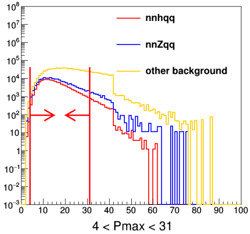
for the detail : `https://arxiv.org/abs/1905.12903v2`

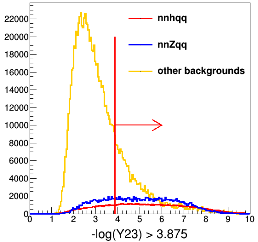
$\nu\nu H(H \rightarrow b\bar{b}, H \rightarrow c\bar{c}, H \rightarrow gg)$ *accuracy measurement*

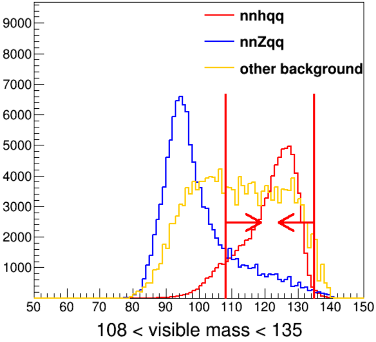
The following cuts were used to identify $\nu\nu Hq\bar{q}/gg$.




nnhqq
nnZqq
other background
longitual momentum < 50


nnhqq
nnZqq
other background
4 < Pmax < 31

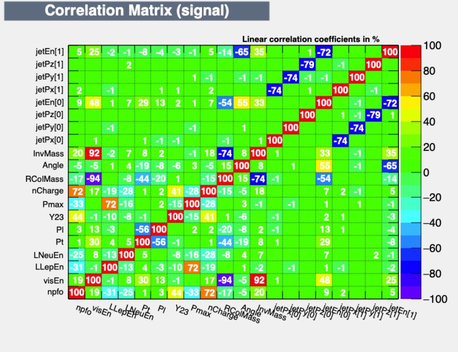

nnhqq
nnZqq
other backgrounds
-log(Y23) > 3.875

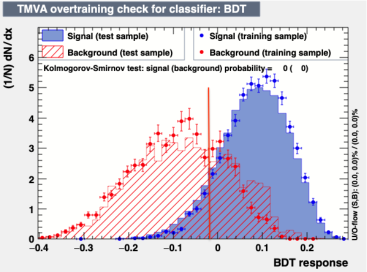

nnhqq
nnZqq
other background
108 < visible mass < 135

BDT for selecting $\nu\nu Hq\bar{q}$

input variables :

- recoilMass : the recoil mass of final state particles
- visEn : visible energy of final state particles
- Npfo : number of final state particles
- leadLepEn : leading lepton energy,
- leadNeuEn : leading neutral energy
- Pt : the transverse momentum of all final state particles
- Pl : the longitudinal momentum of all final state particles
- Pmax : the maximum transverse momentum among final state particles
- Y23
- InvMass : visible mass
- num_charge : number of charge particles
- Angle : the angle between two jets
- 4 momentum of two jets





The full cut chain shown in the following table.

	$\nu\nu Hq\bar{q}$	2f	SW	SZ	WW	ZZ	Mixed	ZH	total bkg	$\frac{\sqrt{S+B}}{S}$ (%)
total	178890	8.01E8	1.95E7	9.07E6	5.08E7	6.39E6	2.18E7	961606	9.10E8	16.86
recoilMass	157822	5.11E7	2.17E6	1.38E6	4.78E6	1.30E6	1.08E6	74991	6.19E7	4.99
visEn	142918	2.37E7	1.35E6	8.81E5	3.60E6	1.03E6	6.29E5	50989	3.13E7	3.92
leadLepEn	141926	2.08E7	3.65E5	7.24E5	2.81E6	9.72E5	1.34E5	46963	2.59E7	3.59
Npfo	139545	1.66E7	2.36E5	5.24E5	2.62E6	9.07E5	4977	42751	2.09E7	3.29
leadNeuEn	138653	1.46E7	2.24E5	4.72E5	2.49E6	8.69E5	4552	42303	1.86E7	3.12
Pt	121212	248715	1.56E5	2.48E5	1.51E6	4.31E5	999	35453	2.63E6	1.37
Pl	118109	53308	1.08E5	74936	729604	1.14E5	789	34279	1.11E6	0.94
Pmax	113413	47319	51976	69548	577336	104827	491	31833	883331	0.88
Y23	82647	33350	8682	49159	110365	64962	334	5159	272015	0.72
InvMass	72094	24801	3860	7036	47765	13235	213	3632	100546	0.58
BDT	64656	12867	315	3149	6081	4859	102	1810	29187	0.47

	$\nu\nu Hb\bar{b}$	$\nu\nu Hc\bar{c}$	$\nu\nu Hgg$	backgrounds
before BDT	61375	2892	7784	100546
after BDT	55257	2283	7087	29187

cut based flavor tagging

introduce the flavor tagging performance matrix :

eff \ to / true	c	b	udsg
udsg	udsg to c	udsg to b	udsg to udsg
b	b to c	b to b	b to udsg
c	c to c	c to b	c to udsg

to : identified as

c to c : the ratio of c jet identified as c

	c	b	udsg
udsg	0	0	1
b	0	1	0
c	1	0	0

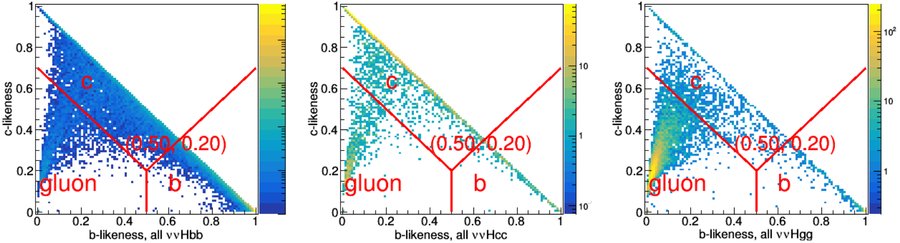
perfect flavor tagging

	c	b	udsg
udsg	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
b	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
c	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$

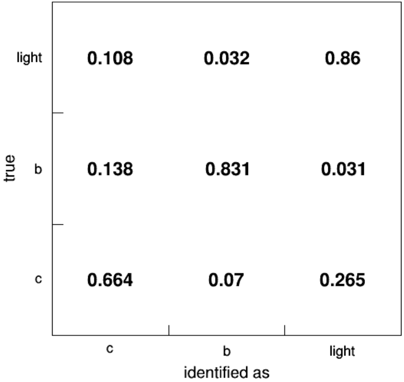
non flavor tagging

Optimized matrix

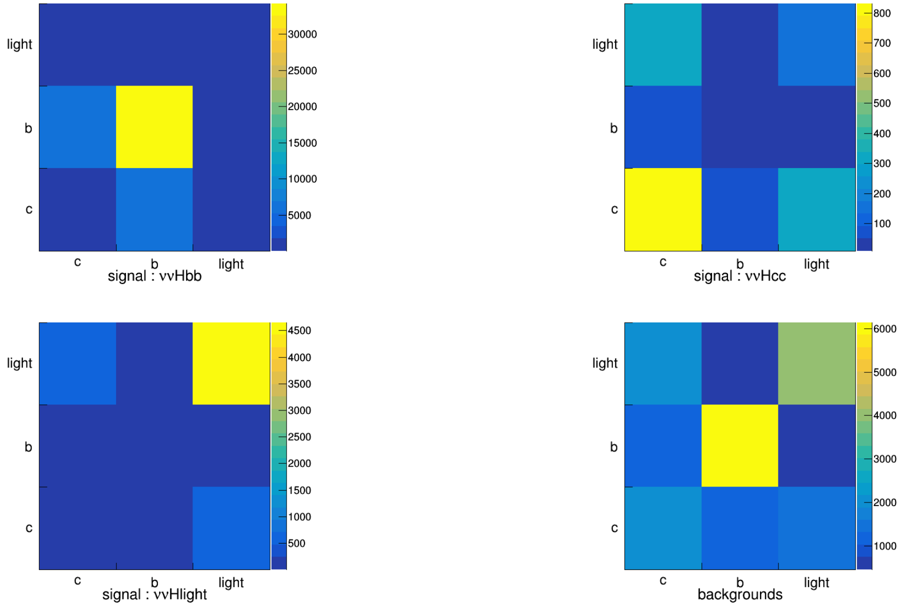
1. The b-likeness and c-likeness of two jets can be displaced in 2D graph.
2. The cut on b-likeness and c-likeness can be find to maximize the value of $eff(b \to b) + eff(c \to c) + eff(udsg \to udsg)$, the trace of flavor tagging matrix.



Optimized matrix :



events distribution based on optimized matrix :



$$-2 \cdot log(\ell) = \sum_{i=1}^{i=9} \frac{[S_b \cdot N_{b,i} + S_c \cdot N_{c,i} + S_{light} \cdot N_{light,i} + N_{bkg,i} - N_i]^2}{N_i}$$

- 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, tt is 0.50%/6.43%/2.00% for $\nu\nu Hb\bar{b}/c\bar{c}/gg$.

key performance : flavor tagging

changing flavor tagging performance :

$$non\ flavor\ tagging \rightarrow perfect\ flavor\ tagging$$

the changing procedure of flavor tagging performance matrix :

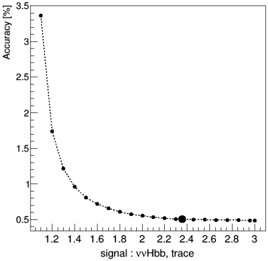
$$temp\ matrix = \frac{x - trace_I}{trace_T - trace_I} \cdot (T - I) + I \qquad (trace_I \leq x \leq trace_T)$$

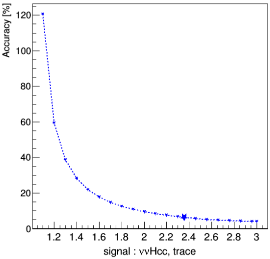
T : matrix with perfect flavor tagging

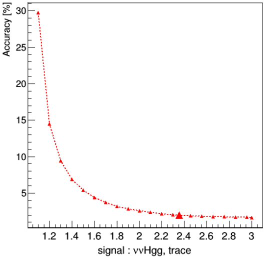
I : matrix with non flavor tagging

$trace_I, trace_T$: the trace of matrix I and T

The x value and flavor tagging performance matrix have a one to one relation.





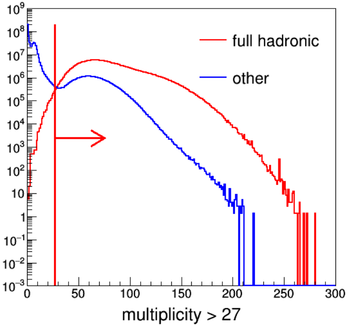


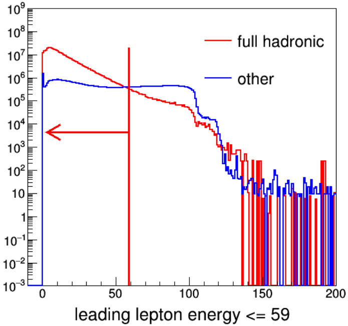
relative accuracy (%)	$\nu\nu Hb\bar{b}$	$\nu\nu Hc\bar{c}$	$\nu\nu Hgg$
cut based flavor tagging	0.50	6.43	2.00
perfect flavor tagging	0.49	4.05	1.67

$qqH(H \to b\bar{b}, H \to c\bar{c}, H \to gg)$ accuracy measurement

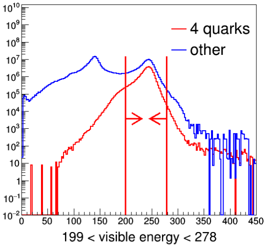
1. Finding the full hadronic samples from all samples.
2. Finding 4-quark samples from the full hadronic samples.
3. Finding $ZH(Z \to q\bar{q}, H \to q\bar{q})$ from 4-quark samples.

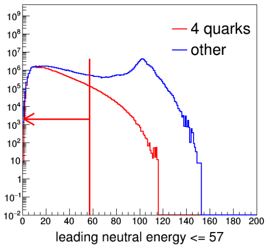
Firstly, finding the full hadronic samples from all samples.

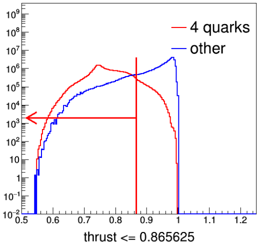


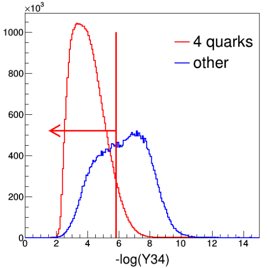


Secondly, finding 4-quark samples from the full hadronic samples.



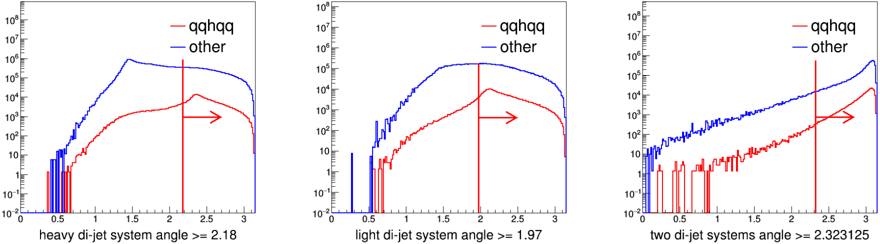




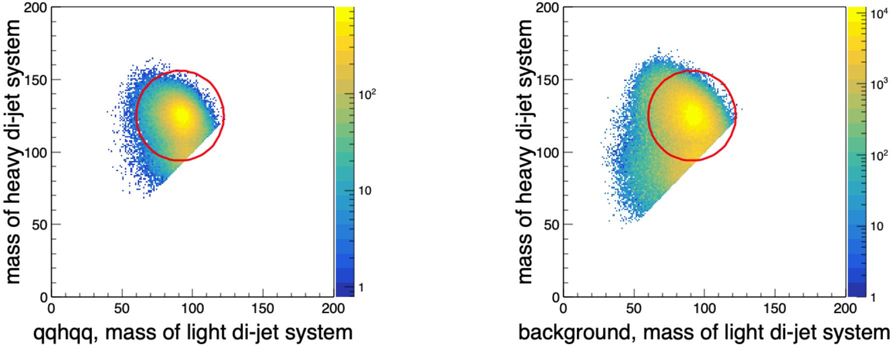


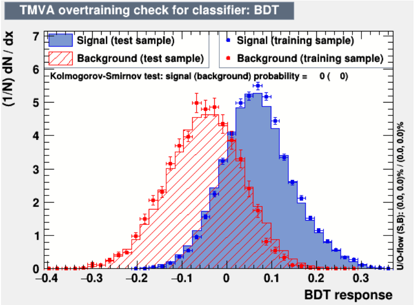
Thirdly, finding $ZH(Z \to q\bar{q}, H \to q\bar{q})$ from 4-quark samples.

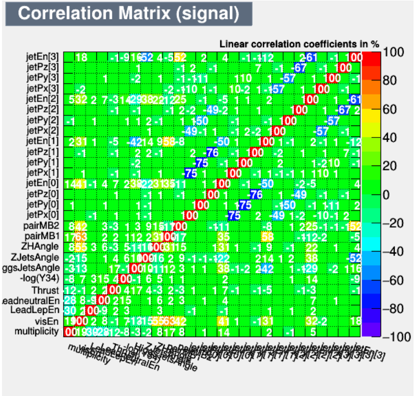
After finding 4-quark samples, the method of maximize $\chi^2 = \frac{(M_{12}-M_{B1})^2}{\sigma_{B1}^2} + \frac{(M_{34}-M_{B2})^2}{\sigma_{B2}^2}$ can be used to pair four jets into two di-jet systems.



Then a circle can be used to find ZH events.







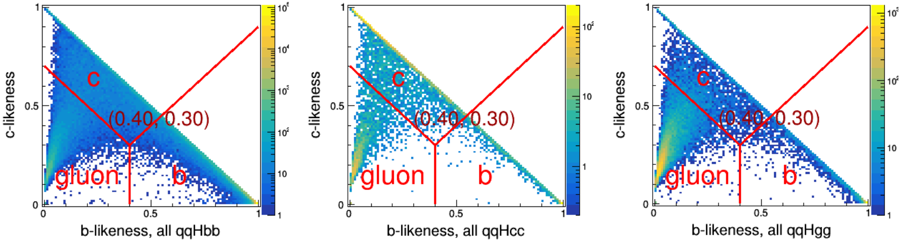
	qqHqq	2f	SW	SZ	WW	ZZ	Mixed	ZH	total bkg	$\frac{\sqrt{S+B}}{S}$ (%)
circleqq	268271	1.20E6	10193	31567	2.13*E*6	424514	1.79E6	65434	5.65*E*6	0.907
BDT	187425	405026	80	404	333924	140340	295986	27768	1.20E6	0.608

	$qqHb\bar{b}$	$qqHc\bar{c}$	$qqHgg$	backgrounds
before BDT	225482	10670	31973	5.65E6
after BDT	160802	6435	22890	1.20E6

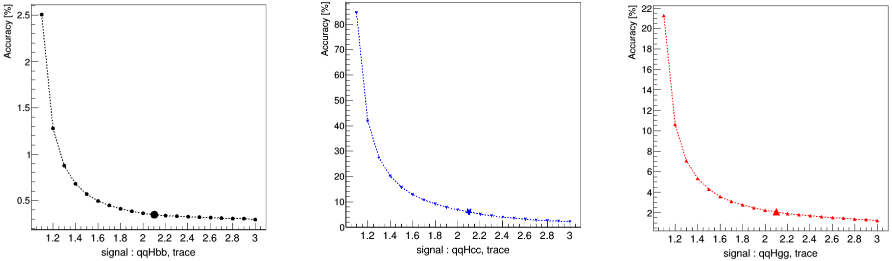
the cut chain of first three stages shown in the following table :

	qqHqq	2f	SW	SZ	WW	ZZ	Mixed	ZH	total bkg	$\frac{\sqrt{S+B}}{S}$ (%
total	527488	8.01E8	1.95E7	9.07E6	5.08E7	6.39E6	2.18E7	613008	9.09E8	5.71
multiplicity	527488	3.04E8	1.46E7	3.37E6	4.85E7	6.00E6	1.81E7	577930	3.95E8	3.77
LLepEn	527036	2,98E8	6.76E6	2.44E6	3.93E7	5.40E6	1.79E7	531411	3.71E8	3.65
visEn	510731	1.21E8	1.29E6	551105	2.14E7	3.06E6	1.71E7	180571	1.65E8	2.52
LNeuEn	509623	5.68E7	716161	168030	2.04E7	2.93E6	1.65E7	176387	9,77E7	1.94
thrust	460535	7.81E6	473732	132126	1.88E7	2.60E6	1.54E7	167863	4.54E7	1.47
$-log(Y_{34})$	451468	4.90E6	181432	119836	1.74E7	2.40E6	1.45E7	165961	3.97E7	1.48
HJetA	326207	2.83E6	110156	58613	4.54E6	870276	3.74E6	96560.3	1.22E7	1.08
ZJetA	279030	1.37E6	33491	37101	2.39E6	496611	2.00E6	74005	6.41E6	0.93
ZHA	274530	1.32E6	17026	33847	2.28E6	468340	1.91E6	69620	6.10E6	0.92
circleqq	268271	1.20E6	10193	31567	2.13E6	424514	1.79E6	65434	5.65E6	0.907
BDT	187425	405026	80	404	333924	140340	295986	27768	1.20E6	0.608

optimized matrix



true \ identified as	c	b	udsg
udsg	**0.1116**	**0.0867**	**0.8017**
b	**0.1139**	**0.778**	**0.108**
c	**0.6267**	**0.1018**	**0.2715**

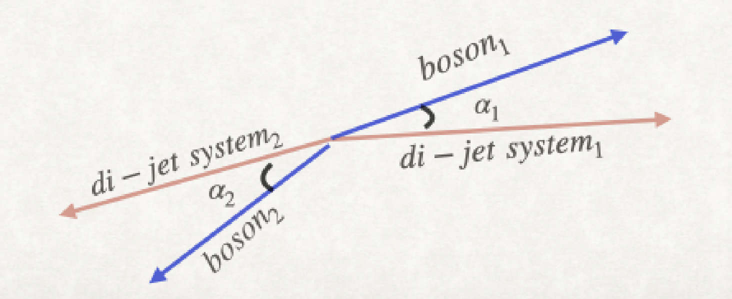


relative accuracy (%)	$qqHb\bar{b}$	$qqHc\bar{c}$	$qqHgg$
cut based flavor tagging	0.35	6.02	2.06
perfect flavor tagging	0.30	2.15	1.24

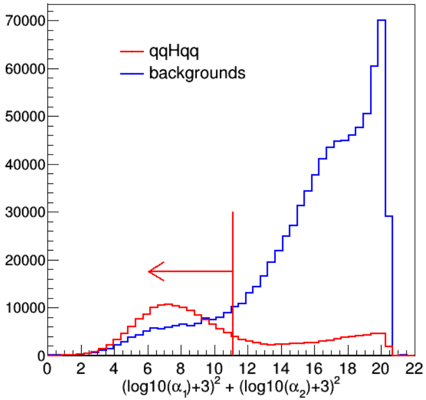
key performance : color singlet identification
(i.e. jet clustering and jet matching)

color singlet identification

For di-boson event, there are two MC truth bosons and two di-jet systems, the variable $\alpha_i = angle(di - jet\ system_i, truth\ boson_i), (i = 1, 2)$ is used to characterize the performance of jet clustering and jet matching.



the α variable is just a cheated variable used to characterize the performance of color singlet identification



	$qqHb\bar{b}$	$qqHc\bar{c}$	$qqHgg$
w.o. alpha cut	0.35%	6.02%	2.06%
w.i. alpha cut	0.37%	4.06%	1.49%

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%/3.91%/1.37%, combining all four different channels of $\mu\mu H$, eeH, $\nu\nu H$ and qqH.

Z decay mode	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$
$Z \to e^+e^-$	1.6%	14.7%	10.5%
$Z \to \mu^+\mu^-$	1.1%	10.5%	5.4%
$Z \to q\bar{q}$	0.35%	6.02%	2.06%
$Z \to \nu\bar{\nu}$	0.50%	6.43%	2.00%
combination	0.27%	3.91%	1.37%

- 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 $H \to c\bar{c}$ measurement. Using an ideal flavor tagging, the anticipated accuracy could be improved by 58% (baseline/ideal : 6.43%/4.05%).
  - for qqH channel
    - With perfect flavor tagging, the anticipated accuracy of $qqHc\bar{c}$ could be improved by 180% (baseline/ideal : 6.02%/2.15%).
    - The CSI has great impact on $H \to c\bar{c}$ measurement. If we can quantify the CSI performance and select halve of the statistic, corresponding to good CSI, the $H \to c\bar{c}$ accuracy can be improved by 48% (baseline/good CIS : 6.02%/4.06%).
- A good color singlet identification, or even a reliable color singlet identification performance evaluator at reconstruction level, is highly appreciated.

Thanks !

Backup

Z decay mode	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$	scenario
CEPC	0.27%	3.91%	1.37%	240GeV, $5600fb^{-1}$
CEPC CDR	0.3%	3.1%	1.2%	240GeV, $5600fb^{-1}$
ILC	1.0%	6.02%	8.5%	250 GeV, $250fb^{-1}$
FCC	0.3%	2.2%	1.9%	240 GeV, $5000fb^{-1}$

ILC result

Eur. Phys. J. C (2013) 73:2343
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THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

A study of measurement precision of the Higgs boson branching ratios at the International Linear Collider

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Table 1 Summary of the $\nu\bar{\nu}H$ channel background reduction assuming $\mathscr{L} = 250$ fb^{-1} with $P(e^-, e^+) = (-0.8, +0.3)$

CM energy	250 GeV			350 GeV
Cut names	Condition	Sig.	Bkg.	Condition
Generated		19360	44827100	
Missing mass	$80 < M_{miss} < 140$ GeV	15466	6214050	$50 < M_{miss} < 240$ GeV
Transverse visible momentum	$20 < P_T < 70$ GeV	13727	549340	$10 < P_T < 140$ GeV
Longitudinal visible momentum	$P_L < 60$ GeV	13342	392401	$P_L < 130$ GeV
# of charged tracks	$N_{chd} > 10$	12936	374877	$N_{chd} > 10$
Maximum track momentum	$P_{max} < 30$ GeV	11743	205038	$P_{max} < 60$ GeV
Y_{23} value	$Y_{23} < 0.02$	7775	74439	$Y_{23} < 0.02$
Y_{12} value	$0.2 < Y_{12} < 0.8$	7438	62584	$0.2 < Y_{12} < 0.8$
Di-jet mass	$100 < M_{jj} < 130$ GeV	6691	19061	$100 < M_{jj} < 130$ GeV
Likelihood ratio	$LR > 0.165$	6293	10940	$LR > 0.395$
Significance (Efficiency)	$S/\sqrt{S+B}$	47.9 (32.5 %)		$S/\sqrt{S+B}$

Table 2 Summary of $q\bar{q}H$ channel background reduction assuming $\mathscr{L} = 250$ fb^{-1} with $P(e^-, e^+) = (-0.8, +0.3)$

CM energy	250 GeV			350 GeV
Cut names	Condition	Sig.	Bkg.	Condition
Generated		52507	45904900	
χ^2	$\chi^2 < 10$	32447	2608980	$\chi^2 < 10$
# of charged tracks	$N_{chd} > 4$	25281	1120950	$N_{chd} > 4$
Y_{34} value	$-\log(Y_{34}) > 2.7$	25065	1002125	$-\log(Y_{34}) > 2.7$
thrust	thrust < 0.9	24688	935950	thrust < 0.85
thrust angle	$\|\cos\theta_{thrust}\| < 0.9$	21892	696201	$\|\cos\theta_{thrust}\| < 0.9$
Higgs jets angle	$105° < \theta_H < 160°$	20062	622143	$70° < \theta_H < 120°$
Z di-jet mass	$80 < M_Z < 100$ GeV	16359	411863	$80 < M_Z < 100$ GeV
H di-jet mass	$105 < M_H < 130$ GeV	16359	411863	$105 < M_H < 130$ GeV
Likelihood ratio	$LR > 0.375$	13726	166807	$LR > 0.15$
Significance (Efficiency)	$S/\sqrt{S+B}$	32.3 (26.1 %)		$S/\sqrt{S+B}$

	Higgs Mass	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$
CEPC	125 GeV	57.7%	2.91%	8.57%
ILC	120 GeV	65.7%	3.6%	5.5%

	ILC	CEPC
luminosity	$250fb^{-1}$	$5600fb^{-1}$
polarization	*ep*(-80%+30%)	
cross-section		
total events		
Higgs Mass	120 GeV	125
$H \to b\bar{b}$	65.36%	57.9%
$H \to c\bar{c}$	3.244%	2.87%
$H \to gg$	8.409%	8.17%

$\nu\nu H$	ILC	CEPC
total events	$250fb^{-1}$	$5600fb^{-1}$
before BDT	*ep*(-80%+30%)	
after BDT		

FCCee result

Table 1.1. Relative statistical uncertainty on $\sigma_{\rm HZ} \times {\rm BR}({\rm H} \to {\rm XX})$ and $\sigma_{\nu\bar{\nu}{\rm H}} \times {\rm BR}({\rm H} \to {\rm XX})$, as expected from the FCC-ee data, obtained from a fast simulation of the CLD detector and consolidated with extrapolations from full simulations of similar linear-collider detectors (SiD and CLIC).

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma{\rm BR})/\sigma{\rm BR}$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
H $\to$ any	± 0.5		± 0.9	
H $\to$ b$\bar{\rm b}$	± 0.3	± 3.1	± 0.5	± 0.9
H $\to$ c$\bar{\rm c}$	± 2.2		± 6.5	± 10
H $\to$ gg	± 1.9		± 3.5	± 4.5
H $\to$ W$^+$W$^-$	± 1.2		± 2.6	± 3.0
H $\to$ ZZ	± 4.4		± 12	± 10
H $\to$ $\tau\tau$	± 0.9		± 1.8	± 8
H $\to$ $\gamma\gamma$	± 9.0		± 18	± 22
H $\to$ $\mu^+\mu^-$	± 19		± 40	
H $\to$ invisible	<0.3		<0.6	

Notes. All numbers indicate 68% CL intervals, except for the 95% CL sensitivity in the last line. The accuracies expected with 5 ab^{-1} at 240 GeV are given in the middle column, and those expected with 1.5 ab^{-1} at $\sqrt{s} = 365$ GeV are displayed in the last column.

CEPC CDR result

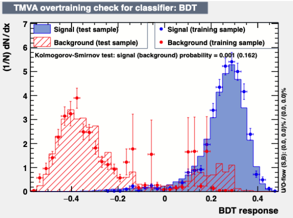
Table 6. Expected relative precision on $\sigma(ZH)\times\mathrm{BR}$ for the $H\to b\bar{b}, c\bar{c}$ and gg decays from a CEPC dataset of $5.6\,\mathrm{ab}^{-1}$.

Z decay mode	$H\to b\bar{b}$	$H\to c\bar{c}$	$H\to gg$
$Z\to e^+e^-$	1.3%	12.8%	6.8%
$Z\to \mu^+\mu^-$	1.0%	9.4%	4.9%
$Z\to q\bar{q}$	0.5%	10.6%	3.5%
$Z\to \nu\bar{\nu}$	0.4%	3.7%	1.4%
combination	0.3%	3.1%	1.2%

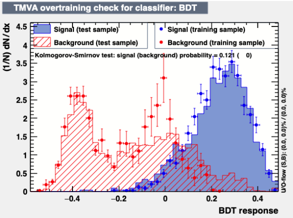
Z decay mode	$H\to b\bar{b}$	$H\to c\bar{c}$	$H\to gg$
$Z\to e^+e^-$	1.6%	14.7%	10.5%
$Z\to \mu^+\mu^-$	1.1%	10.5%	5.4%
$Z\to q\bar{q}$	0.34%	5.58%	1.91%
$Z\to \nu\bar{\nu}$	0.48%	5.92%	1.95%
combination	0.26%	3.67%	1.31%

The BDT was used to identify $\nu\nu H(H \to b\bar{b}, H \to c\bar{c}, H \to gg)$.

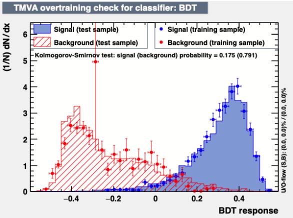
- # of final state particles
- visible energy of final state particles
- leading lepton energy, leading neutral energy
- thrust, Y23
- the transverse momentum of all final state particles
- the longitudinal momentum of all final state particles
- the maximum transverse momentum among final state particles
- the angle of two jets
- # of charge particles
- visible mass
- recoil mass of final state particles
- the b-likeness of each jet
- the b-likeness of each jet
- the energy difference of two hemispheres



$\nu\nu Hb\bar{b}$



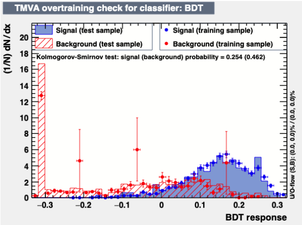
$\nu\nu Hc\bar{c}$



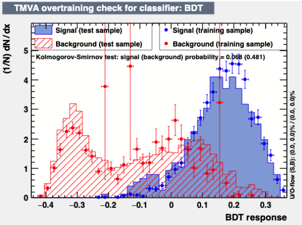
$\nu\nu Hgg$

	signal	2f	SW	SZ	WW	ZZ	Mixed	ZH	total bkg	$\frac{\sqrt{S+B}}{S}$ (%)
$\nu\nu Hc\bar{c}$	1868	5181	120	693	3578	1345	33	1467	12420	6.39
$\nu\nu Hb\bar{b}$	47928	7632	0	940	27	1478	0	305	10385	0.50
$\nu\nu Hg\bar{g}$	5568	726	210	1273	2222	1772	0	789	6995.22	2.01

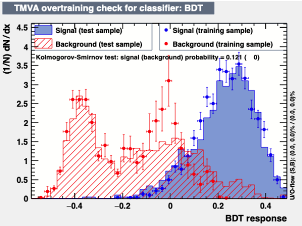
BDT with different input variables for $\nu\nu Hc\bar{c}$



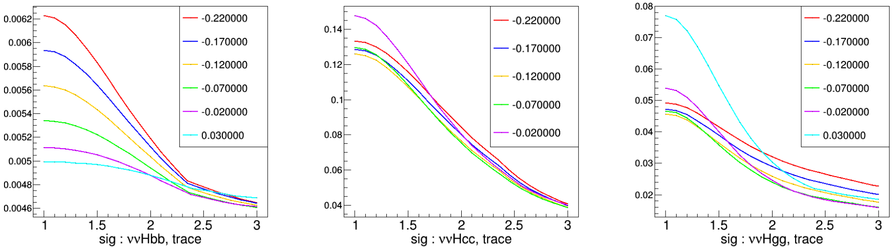
8.64% with only b/c-likeness



7.39% with b/c-likeness & jets 4-momentum



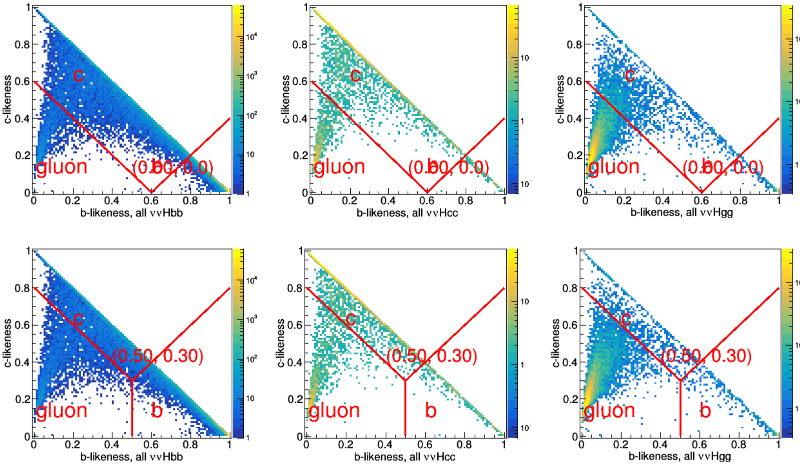
6.39% with b/c-likeness & jets 4-momentum & cut variables with different BDT cut value :



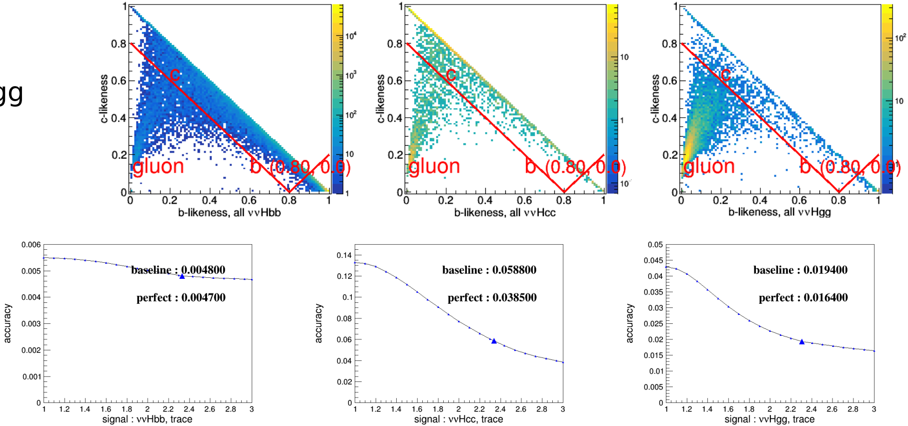
see relative accuracy as optimization target

bb

cc



gg



relative accuracy (%)		$\nu\nu Hb\bar{b}$	$\nu\nu Hc\bar{c}$	$\nu\nu Hgg$
trace as optimization target	cut based flavor tagging	0.48	5.92	1.95
	perfect flavor tagging	0.47	3.85	1.64
accuracy as optimization target	cut based flavor tagging	0.48	5.88	1.94
	perfect flavor tagging	0.47	3.85	1.64