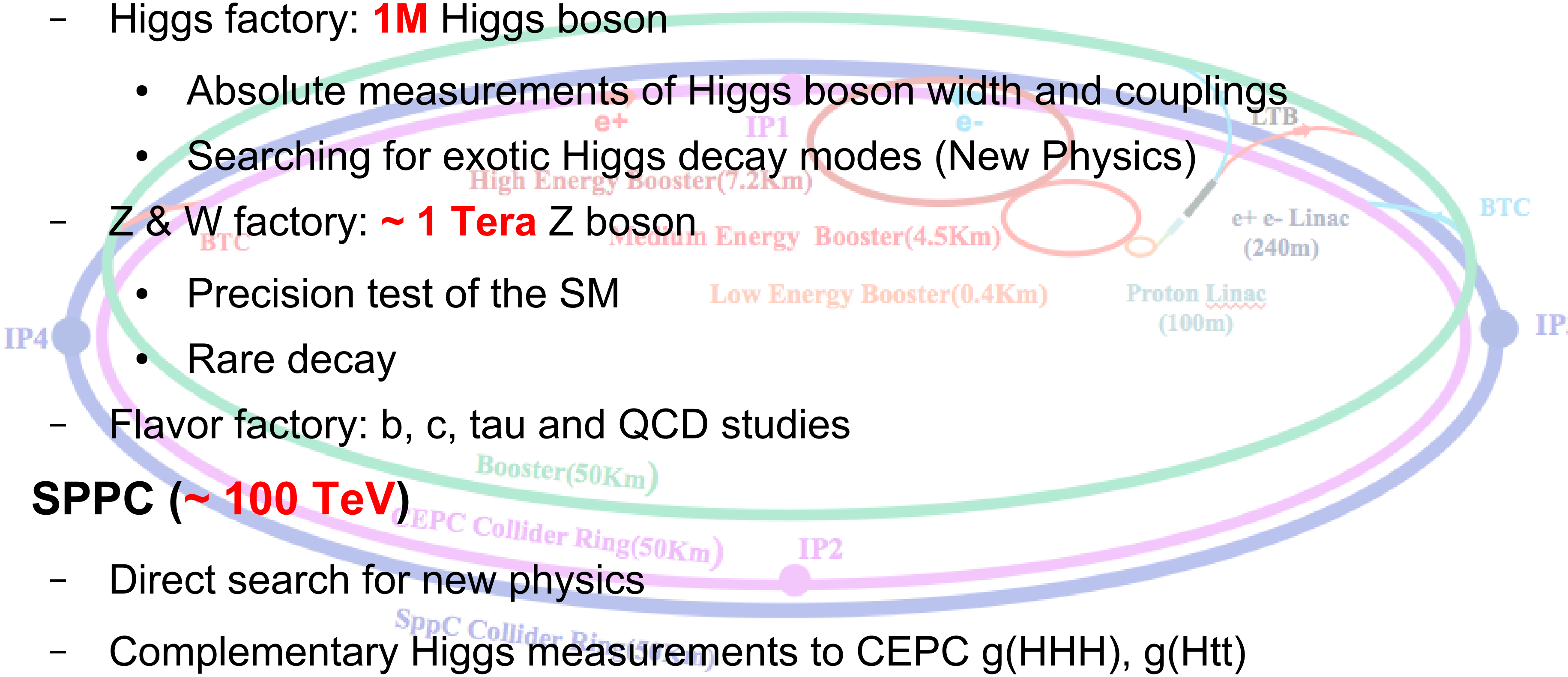
Progress on CEPC Higgs measurement & Performance studies

Manqi Ruan

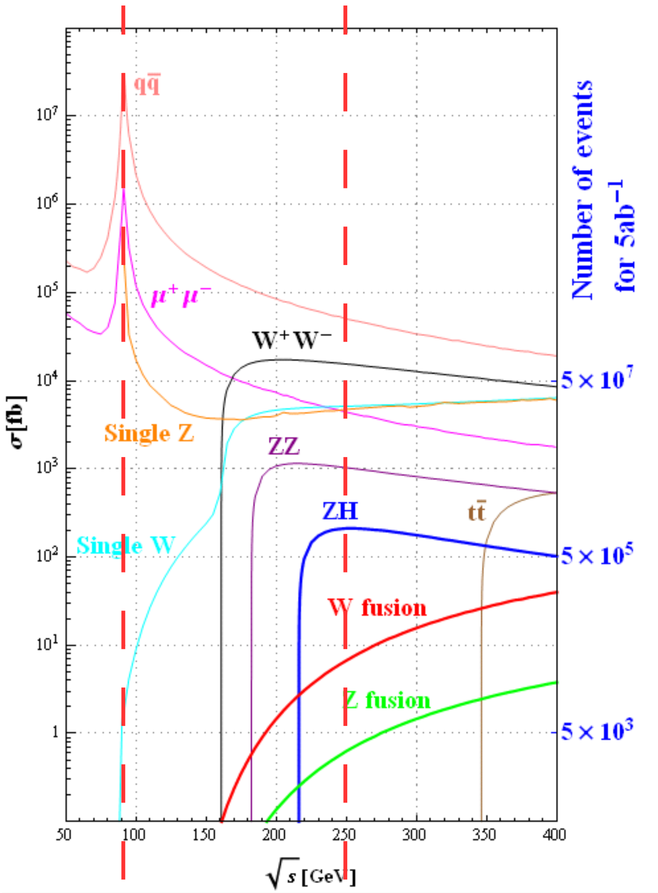
Key figures of the CEPC-SPPC

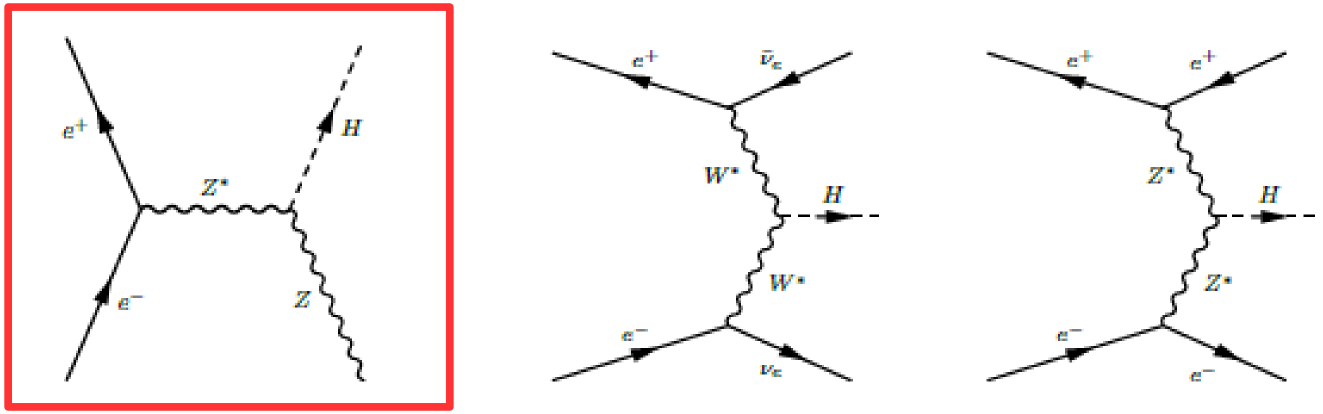
- **Tunnel ~ 100 km**
- **CEPC (90 – 250 GeV)**
  - Higgs factory: **1M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **~ 1 Tera** Z boson
    - Precision test of the SM
    - Rare decay
  - Flavor factory: b, c, tau and QCD studies
- **SPPC (~ 100 TeV)**
  - Direct search for new physics
  - Complementary Higgs measurements to CEPC g(HHH), g(Htt)
  - ...
- **Heavy ion, e-p collision...**



Complementary

Higgs @ CEPC



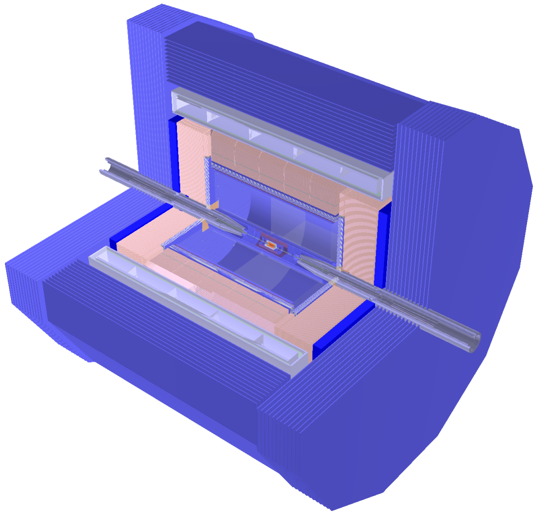


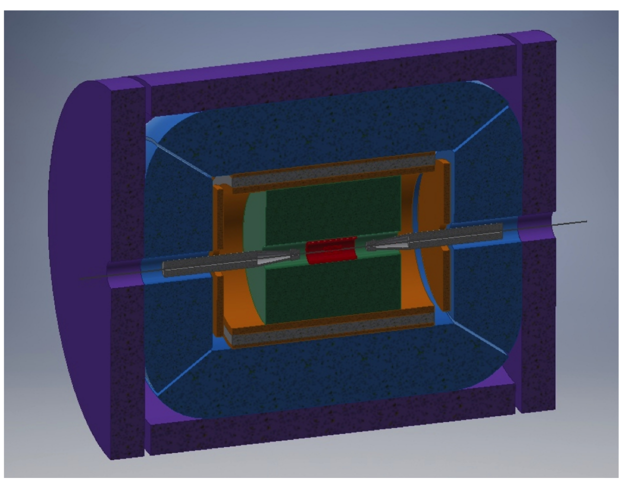
Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6

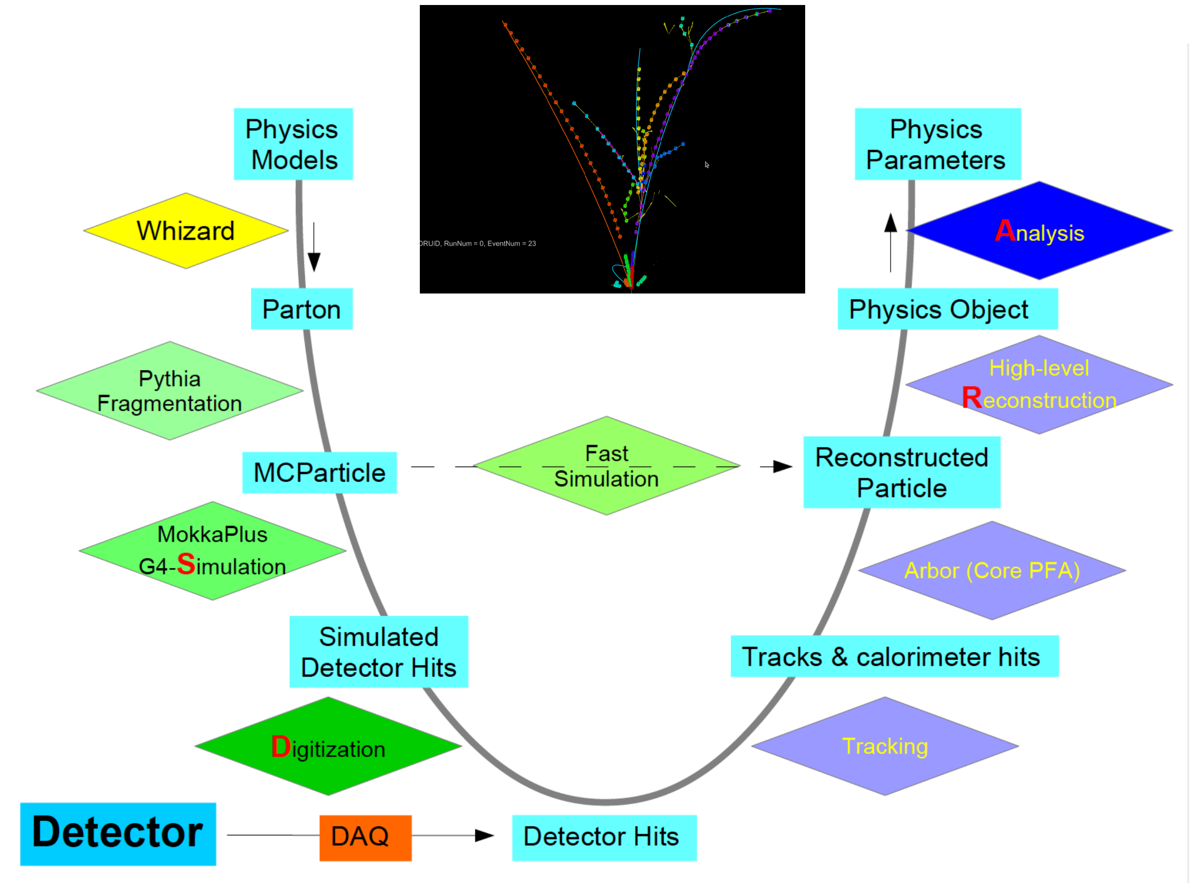
Observables: Higgs mass, CP, σ(ZH), event rates (σ(ZH, vvH)*Br(H→X)), Diff. distributions

Derive: Absolute Higgs width, branching ratios, couplings

Detector & Software

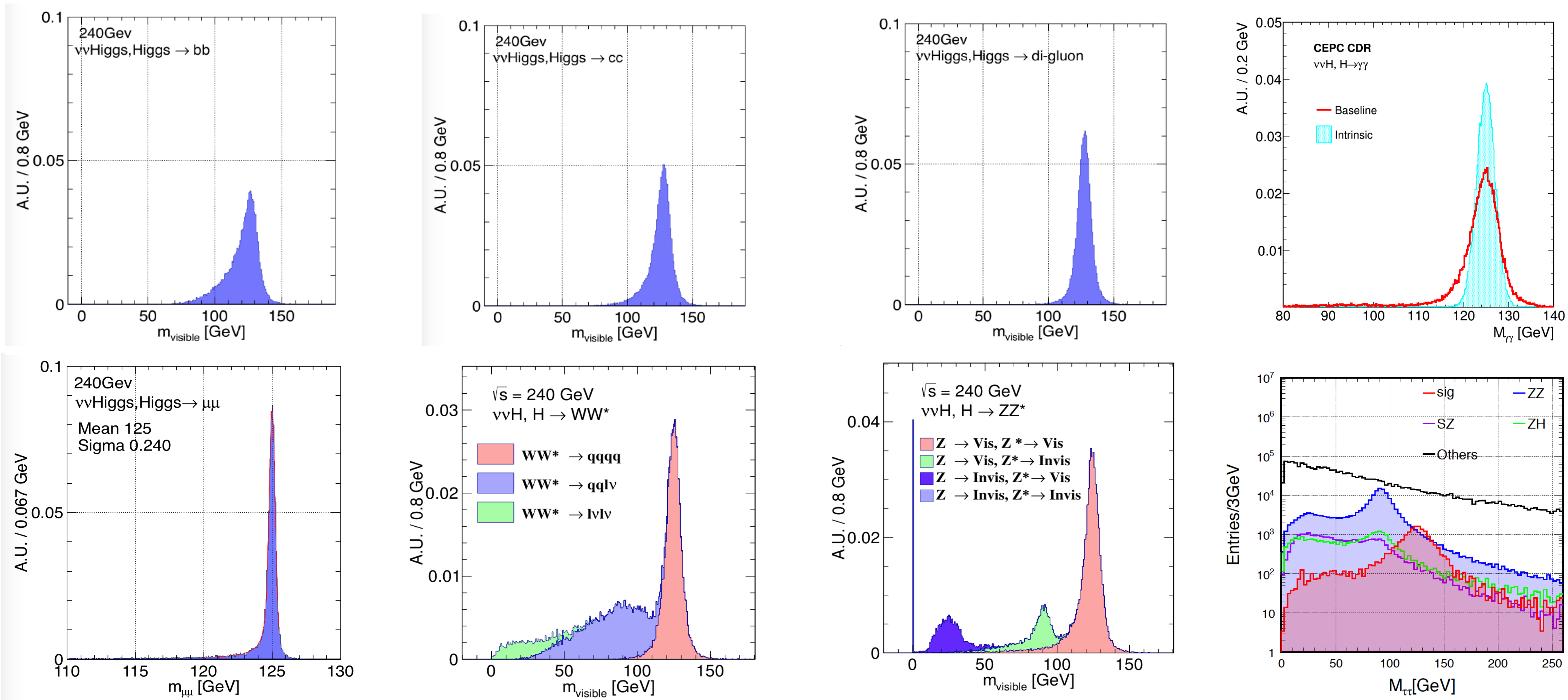






Full simulation reconstruction Chain functional, iterating/validation with hardware studies

Reconstructed Higgs Signatures



Clear Higgs Signature in all SM decay modes

Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level

Right corner: di-tau mass distribution at qqH events using collinear approximation

Higgs white paper delivered

Chinese Physics C Vol. 43, No. 4 (2019) 043002

Precision Higgs physics at the CEPC*

Fenfen An(安芬芬)[4,23] Yu Bai(白羽)[9] Chunhui Chen(陈春晖)[23] Xin Chen(陈新)[5] Zhenxing Chen(陈振兴)[3]
Joao Guimaraes da Costa[4] Zhenwei Cui(崔振崴)[3] Yaquan Fang(方亚泉)[4,6,34;1)] Chengdong Fu(付成栋)[4]
Jun Gao(高俊)[10] Yanyan Gao(高艳彦)[22] Yuanning Gao(高原宁)[3] Shaofeng Ge(葛韶锋)[15,29]
Jiayin Gu(顾嘉荫)[13;2)] Fangyi Guo(郭方毅)[1,4] Jun Guo(郭军)[10] Tao Han(韩涛)[5,31] Shuang Han(韩爽)[4]
Hongjian He(何红建)[11,10] Xianke He(何显柯)[10] Xiaogang He(何小刚)[11,10,20] Jifeng Hu(胡继峰)[10]
Shih-Chieh Hsu(徐士杰)[32] Shan Jin(金山)[8] Maoqiang Jing(荆茂强)[4,7] Susmita Jyotishmati[33] Ryuta Kiuchi[4]
Chia-Ming Kuo(郭家铭)[21] Peizhu Lai(赖培筑)[21] Boyang Li(李博扬)[5] Congqiao Li(李聪乔)[3] Gang Li(李刚)[4,34;3)]
Haifeng Li(李海峰)[12] Liang Li(李亮)[10] Shu Li(李数)[11,10] Tong Li(李通)[12] Qiang Li(李强)[3] Hao Liang(梁浩)[4]
Zhijun Liang(梁志均)[4] Libo Liao(廖立波)[4] Bo Liu(刘波)[4,23] Jianbei Liu(刘建北)[1] Tao Liu(刘涛)[14]
Zhen Liu(刘真)[26,30;4)] Xinchou Lou(娄辛丑)[4,6,33,34] Lianliang Ma(马连良)[12] Bruce Mellado[17,18] Xin Mo(莫欣)[4]
Mila Pandurovic[16] Jianming Qian(钱剑明)[24;5)] Zhuoni Qian(钱卓妮)[19] Nikolaos Rompotis[22]
Manqi Ruan(阮曼奇)[4;6)] Alex Schuy[32] Lianyou Shan(单连友)[4] Jingyuan Shi(史静远)[9] Xin Shi(史欣)[4]
Shufang Su(苏淑芳)[25] Dayong Wang(王大勇)[3] Jin Wang(王锦)[4] Liantao Wang(王连涛)[27;7)]
Yifang Wang(王贻芳)[4,6] Yuqian Wei(魏彧骞)[4] Yue Xu(许悦)[5] Haijun Yang(杨海军)[10,11] Ying Yang(杨迎)[4]
Weiming Yao(姚为民)[28] Dan Yu(于丹)[4] Kaili Zhang(张凯栗)[4,6;8)] Zhaoru Zhang(张照茹)[4]
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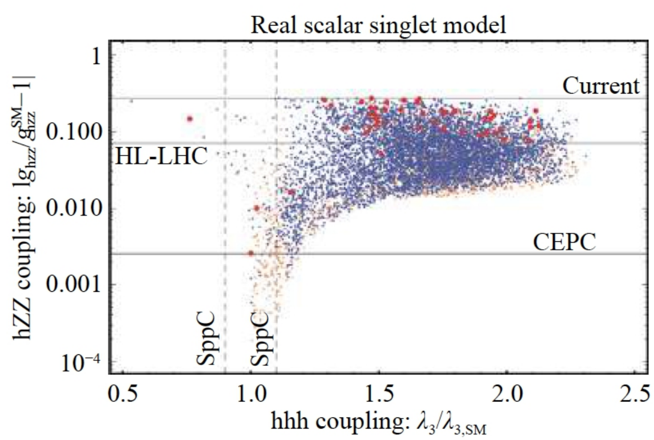
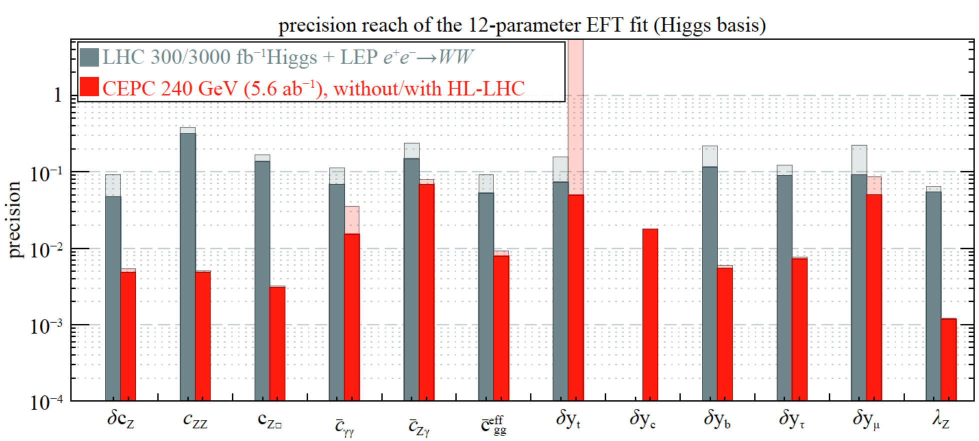
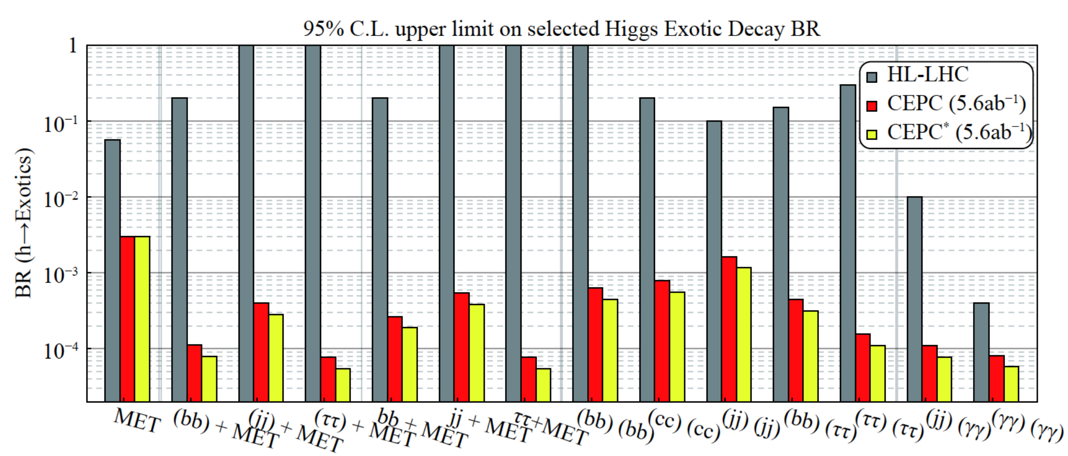






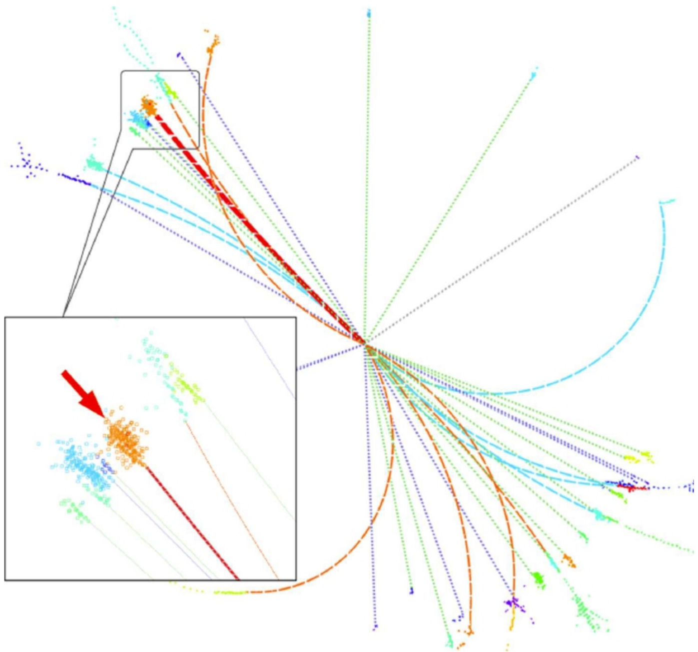
- *g(HXX), g(HHH), Br(H→exo)*

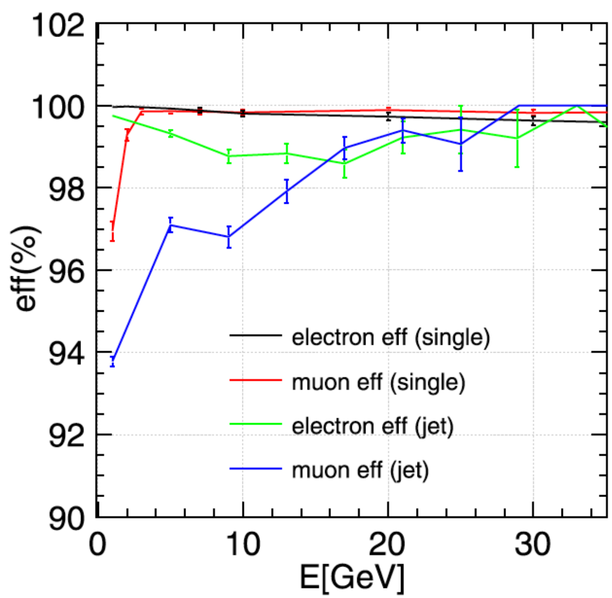
Recent Highlights

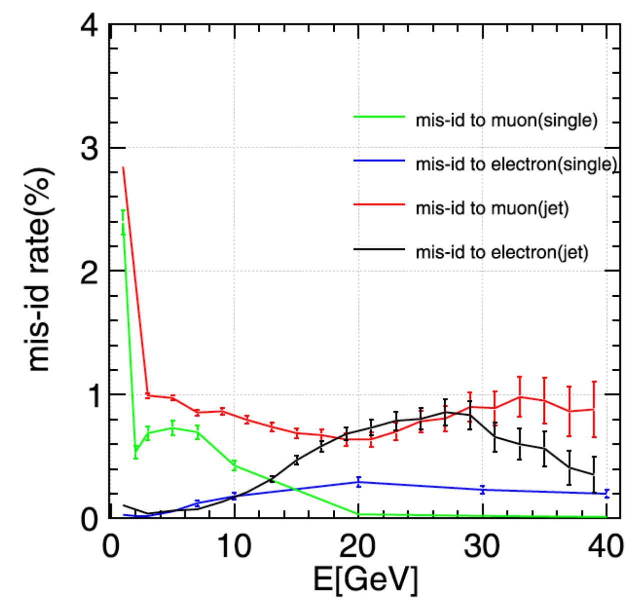
- Performance
  - Jet lepton
  - Tau
  - Jet Charge

- Physics
  - Operation at top threshold
  - $H \to bb$, cc, gg

Jet lepton @ Z->bb

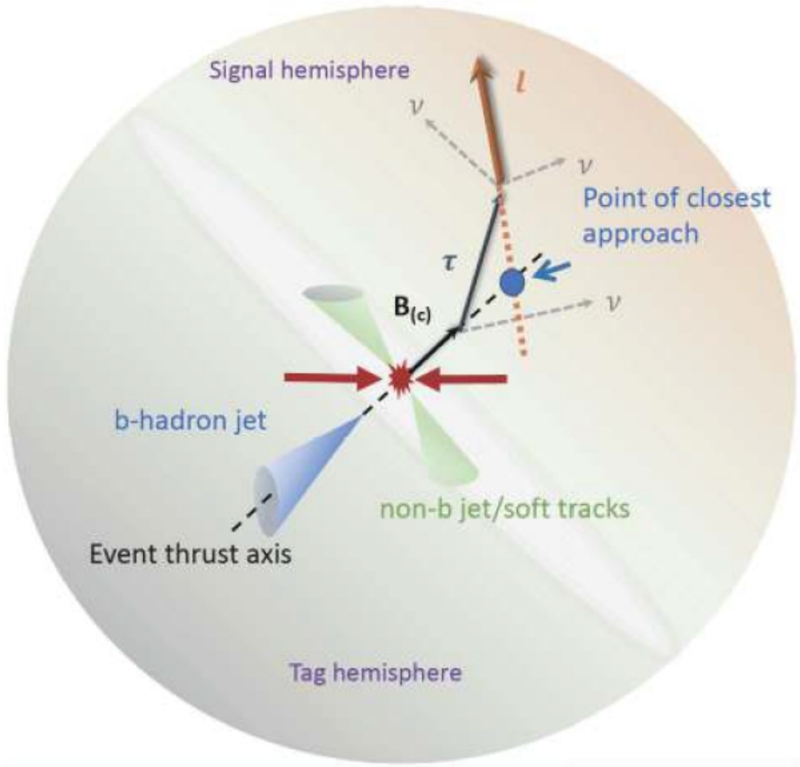


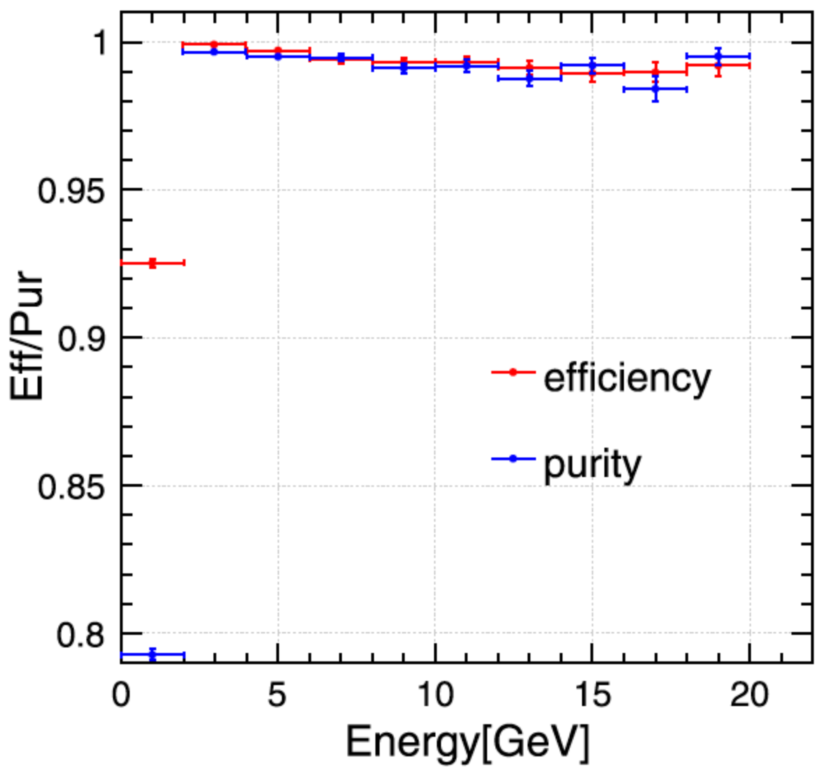




- Marginal Degrading (2021 JINST P06013)
  - Efficiency reduced up to 3% (muon @ low energy); mis-id increased to ~ 1%

At physics benchmark of Bc→τν→eνν





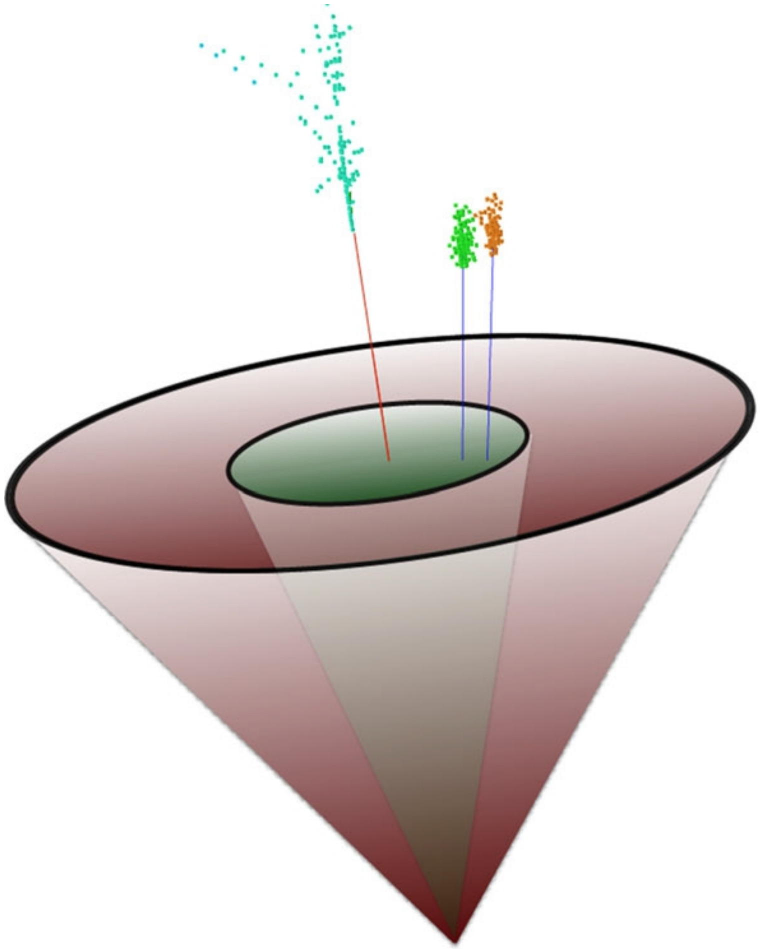
- No significant degrading due to Lepton id

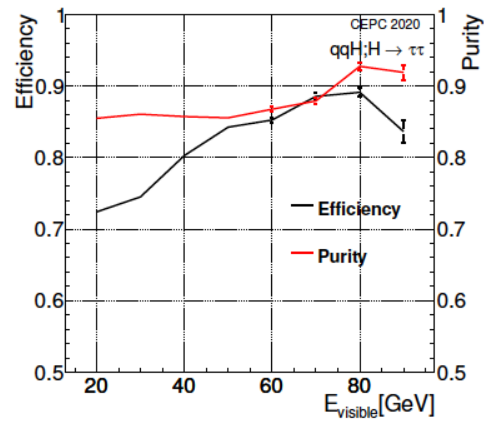
PAPER • **OPEN ACCESS**

Analysis of $B_c \to \tau\nu_\tau$ at CEPC *

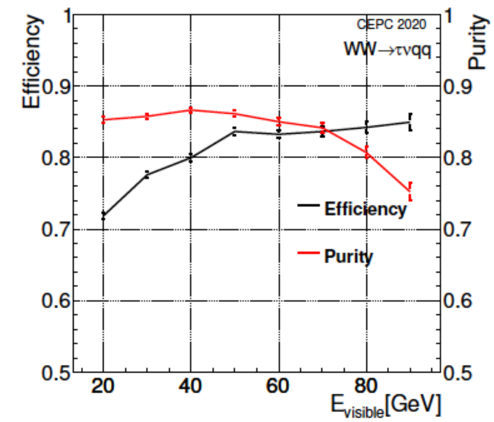
To cite this article: Taifan Zheng *et al* 2021 *Chinese Phys. C* **45** 023001

Tau reconstruction: Taurus

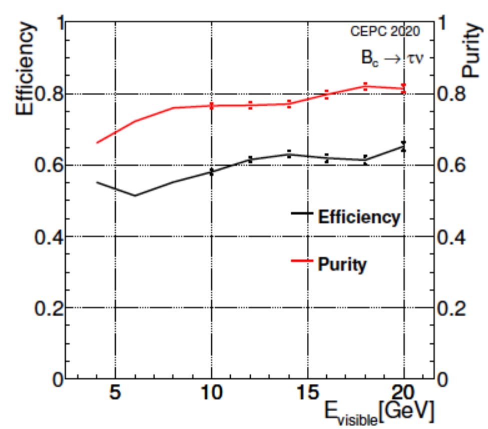




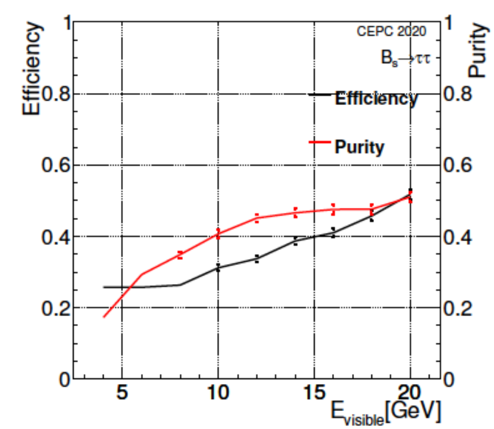
(a) $Z \to qq, H \to \tau\tau$, overall efficiency 80%, overall purity 86%



(b) $WW \to \tau\nu qq$, overall efficiency 79%, overall purity 85%

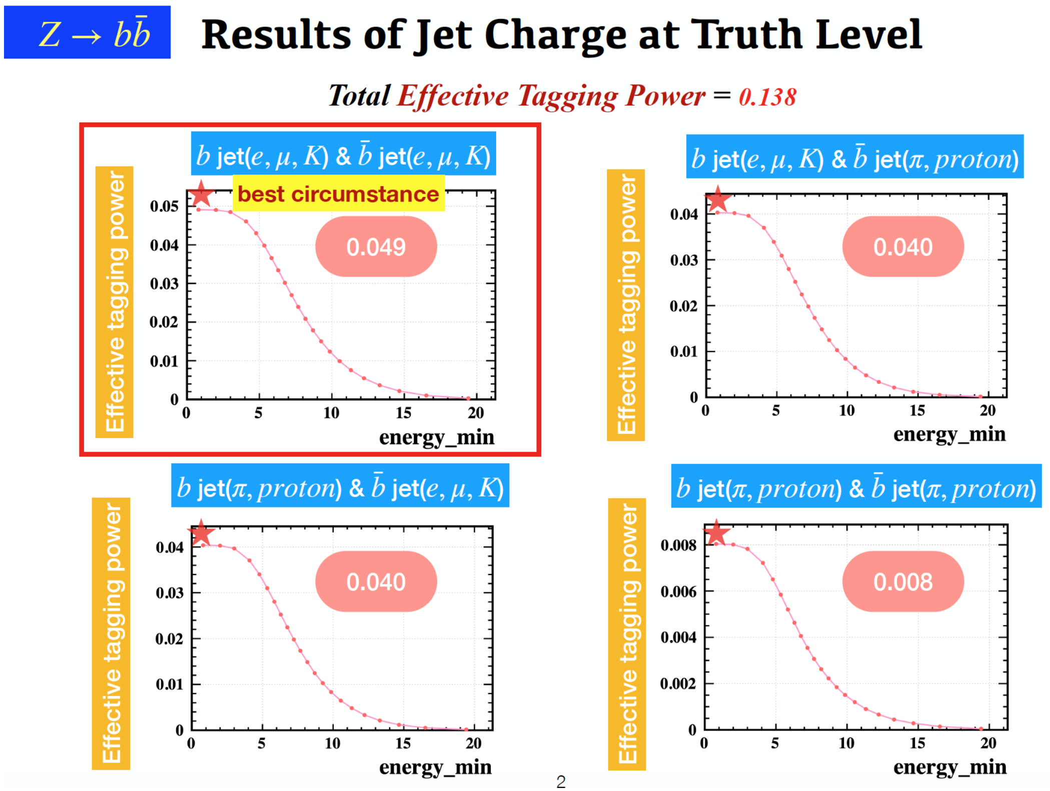


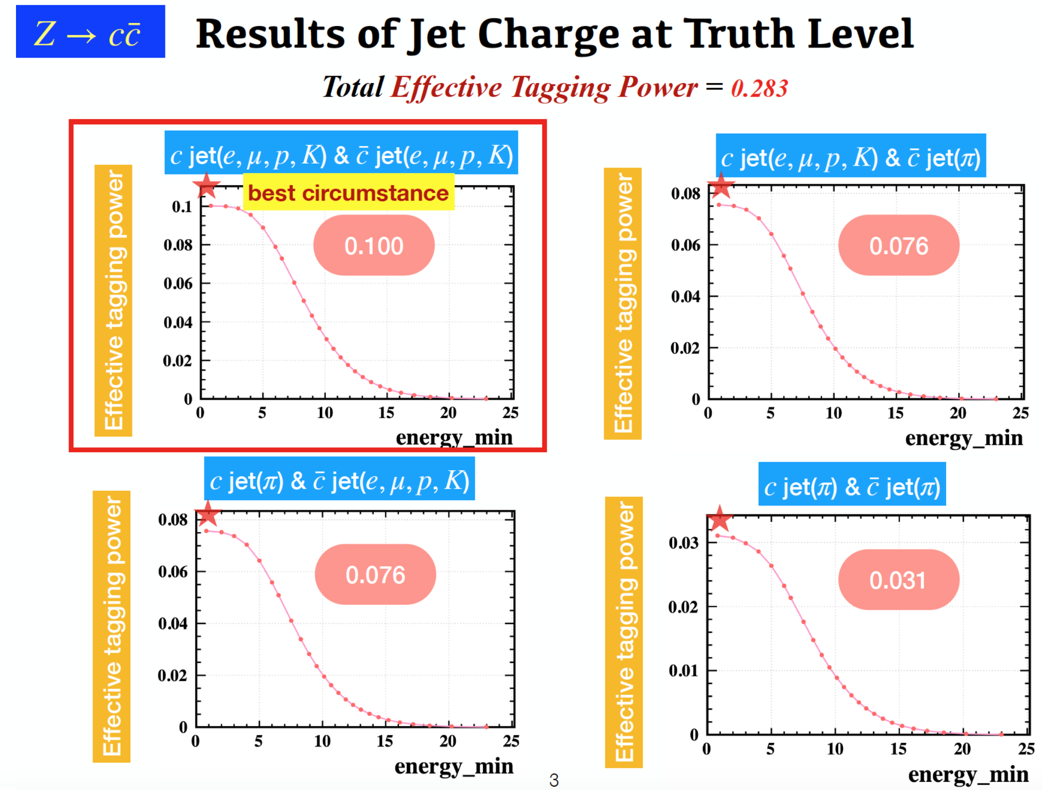
(c) $Z \to b\bar{b}, B_c \to \tau\nu$, overall efficiency 57%, overall purity 74%



(d) $Z \to b\bar{b}, B_s \to \tau\tau$, overall efficiency 32%, overall purity 33%

Jet Charge measurement





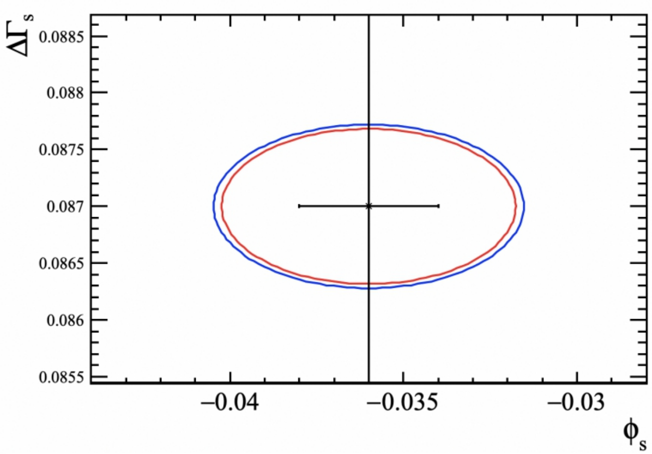
- Via leading charged particle type of each jet: effective tagging power (eff*$(1-2\Omega)^2$) = 14%/28% for inclusive Z→bb/Z→cc event
- Dependence on the heavy flavor hadron type & usage of other information: processing

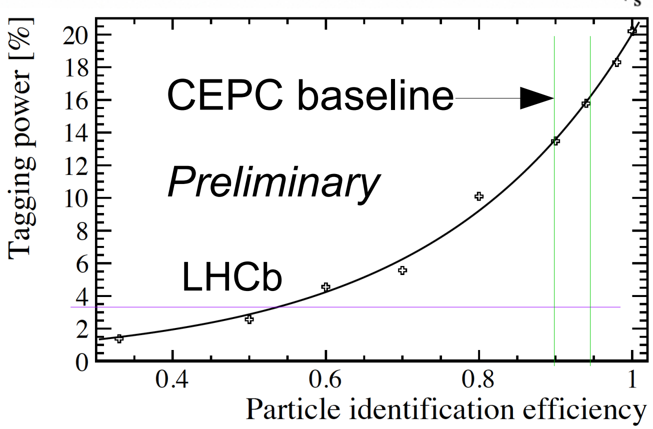
CP measurement with Bs->J/psi Phi... & requires good Pid!

$\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H, \phi_s = -2\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$

SM: small CPV phase ϕ_s

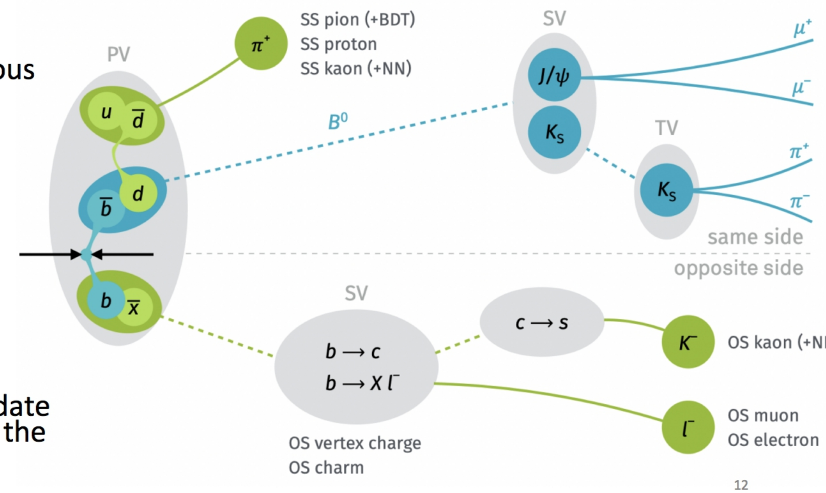
Contributions from physics beyond the SM could lead to much larger values of ϕ_s.





Flavour tagging power

- LHCb: 3~4%
- CEPC: 15% (Previous estimation)
- B factory: ~30%
- For Bs:
  - OS lepton
  - OS kaon
  - SS kaon
- A naïve algorithm developed to validate the robustness of the estimation

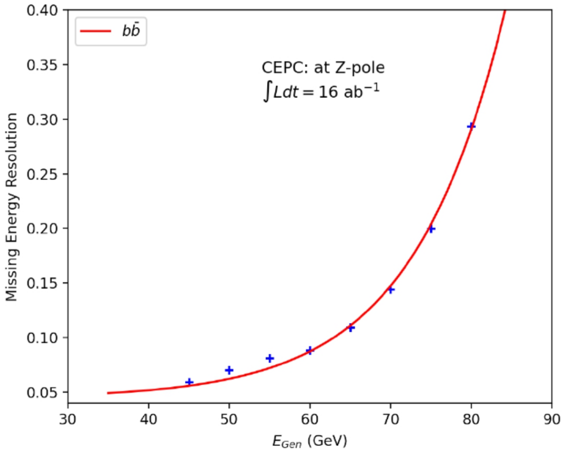


- With a decent Pid, the effective tagging power on jet Charge can be 5-6 times better than LHCb, which can compensate the statistic difference between LHCb & CEPC.
- Strong motivation to higher Luminosity at Z pole

Baseline Detector Performance for flavor physics

- Acceptance: |cos(θ)| < 0.99
- Tracks:
  - Pt threshold, ~ 100 MeV
  - δp/p ~ o(0.1%)
- Photons:
  - Energy threshold, ~ 100 MeV
  - δE/E: 3 – 15%/sqrt(E)
- Pi-Kaon separation: 3-sigma (requirement)
- Pi-0: rec. eff*purity @ Z→qq > 60% @ 5GeV
- B-tagging: eff*purity @ Z→qq: 70%
- C-tagging: eff*purity @ Z→qq: 40%
- Jet charge: eff*$(1-2\omega)^2$ ~ 15%/30% @ Z→bb/cc

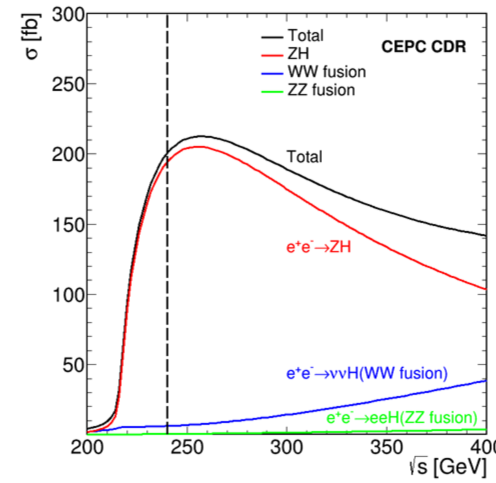
- Lepton inside jets: eff*purity @ Z→qq ~ 90% (energy > 3 GeV): slight degrading in jet
- Tau: eff*purity @ WW→tauvqq: 70%, mis id from jet fragments ~ o(1%)
- Reconstruction of simple combinations: Ks/Lambda/D with all tracks @ Z→qq: 60/75 – 80/85%
- BMR: 3.7%
- Missing Energy: Consistent with BMR.

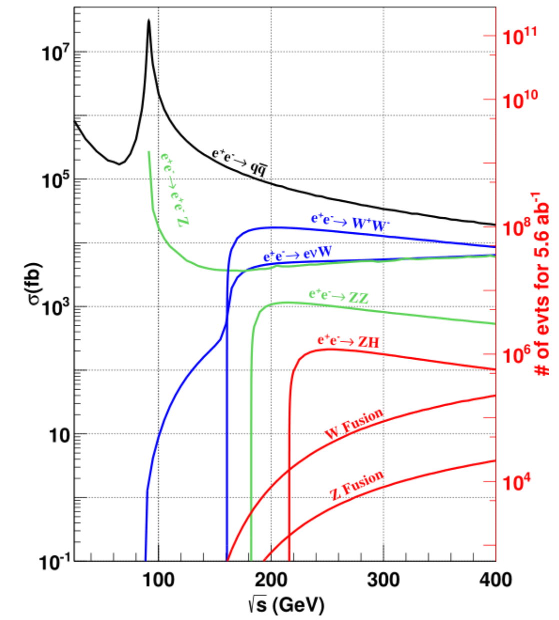


Upgrade option: 360 GeV operation

fb	240	350	360	365	360/240
ZH	196.9	133.3	126.6	123.0	-36%
WW fusion	6.2	26.7	29.61	31.1	+377%
ZZ fusion	0.5	2.55	2.80	2.91	+460%
Total	203.6		159.0		
Total Events	1.14M		0.32M		

pb	240	350	360	365	360/240
$ee(\gamma)$	930	336	325	319	-65%
$\mu\mu(\gamma)$	5.3	2.2	2.1	2.1	-60%
$qq(\gamma)$	54.1	24.7	23.2	22.8	-57%
WW	16.7	10.4	10.0	9.81	-40%
ZZ	1.1	0.66	0.63	0.62	-43%
tt	\	0.155	0.317	0.369	
sZ	4.54	5.72	5.78	5.83	+27%
sW	5.09	5.89	6.00	6.04	+18%

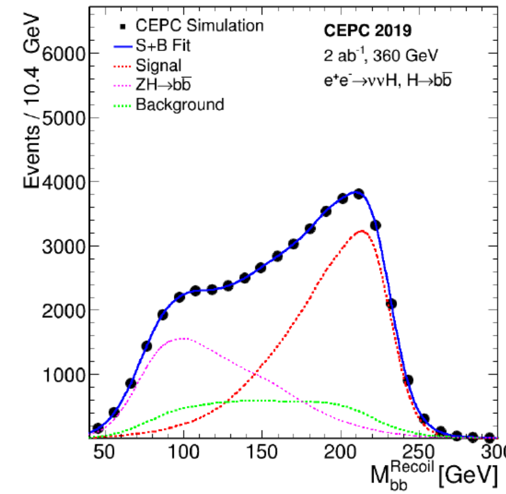


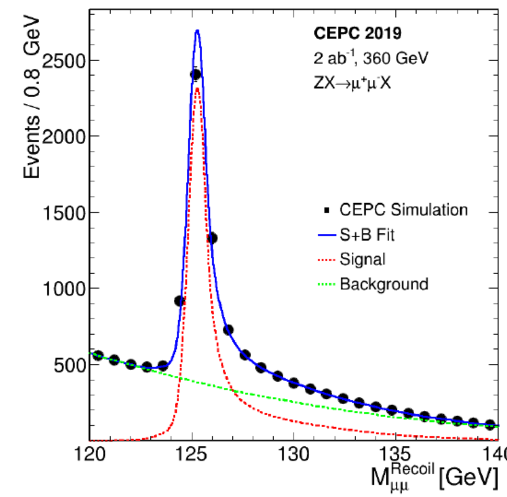


Upgrade option: 360 GeV operation

Results

	240GeV, 5.6ab^{-1}	360GeV, 2ab^{-1}	
	ZH	ZH	ννH
any	**0.50%**	**1%**	****
$\mathrm{H} \rightarrow \mathrm{bb}$	**0.27%**	**0.63%**	**0.76%**
$\mathrm{H} \rightarrow \mathrm{cc}$	**3.3%**	**6.2%**	**11%**
$\mathrm{H} \rightarrow \mathrm{gg}$	**1.3%**	**2.4%**	**3.2%**
$\mathrm{H} \rightarrow \mathrm{WW}$	**1.0%**	**2.0%**	**3.1%**
$\mathrm{H} \rightarrow \mathrm{ZZ}$	**7.9%**	**14%**	**15%**
$\mathrm{H} \rightarrow \tau\tau$	**0.8%**	**1.5%**	**3%**
$\mathrm{H} \rightarrow \gamma\gamma$	**5.7%**	**8%**	**11%**
$\mathrm{H} \rightarrow \mu\mu$	**12%**	**29%**	**40%**
$\mathrm{Br_{upper}(H \rightarrow inv.)}$	**0.2%**	****	****
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow Z\gamma)$	**16%**	**25%**	****
Width	**2.8%**	**1.4%**	





Measurement of H→bb, cc, gg

- llH: published result

- **Preliminary analyses** on vvH & qqH based on Full Sim
  - Anticipated accuracies at CEPC baseline
  - Optimization study
    - Flavor Tagging @ vvH & qqH
    - Color Singlet identification @ qqH

llH

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

Yu Bai(白羽)[1;1)] Chun-Hui Chen(陈春晖)[2;2)] Ya-Quan Fang(方亚泉)[3;3)] Gang Li(李刚)[3;4)]
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Bo-Yang Lan(兰博扬)[1] Zhan-Feng Liu(刘站峰)[1]

[1]School of Physics, Southeast University, Nanjing 210096, China
[2]Department of Physics and Astronomy, Iowa State University, Ames 50011-3160, USA
[3]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[4]School of physics and astronomy, the University of Manchester, Oxford Rd, M13 9PL, UK
[5]Department of Physics, College of Sciences, Northeastern University, Shenyang 110004, China
[6]School of Cyber Science and Engineering, Southeast University, Nanjing 210096, China

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

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

vvH

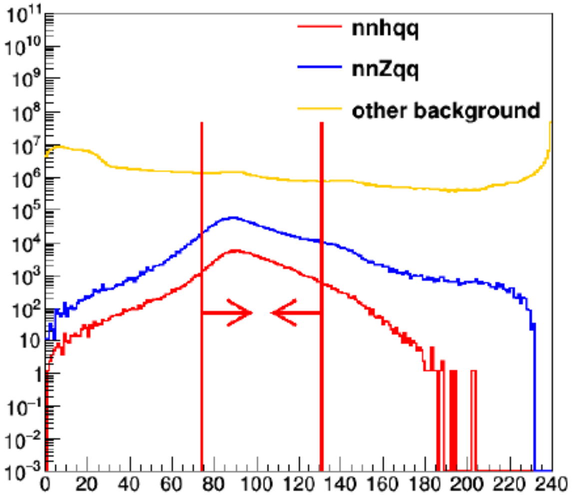
- Tag H→qq

	$\nu\nu Hq\bar{q}$	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

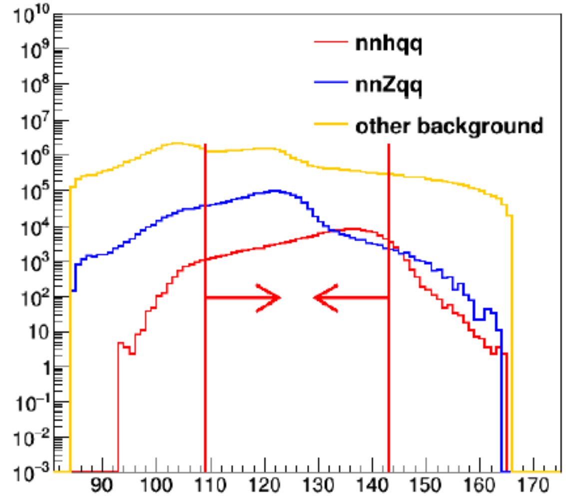
- Separate the H→bb, cc, gg & background using Flavor Tagging, etc

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

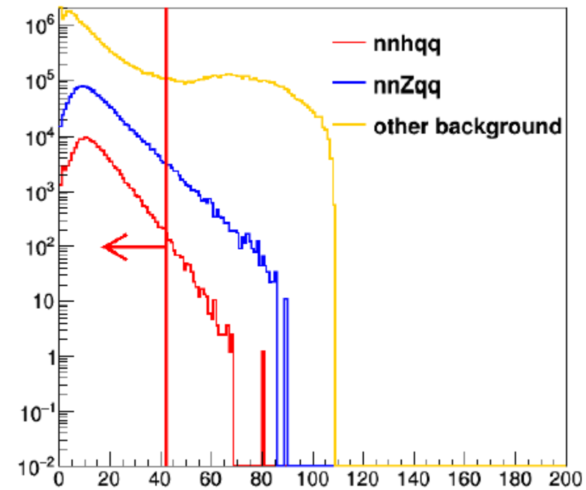
Variables & Cut to tag $\nu\nu H$, $H \rightarrow qq$



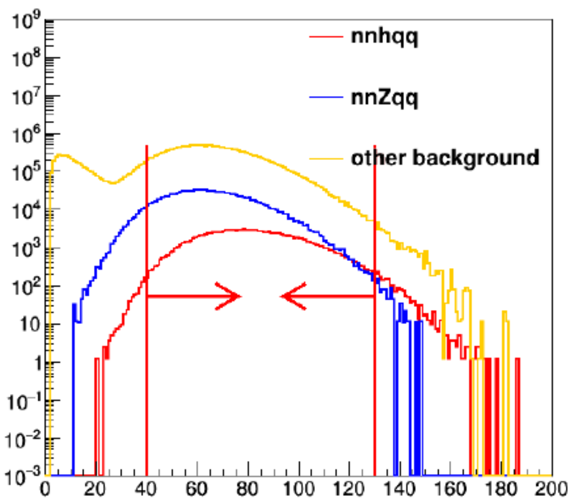
74 < recoil mass < 131



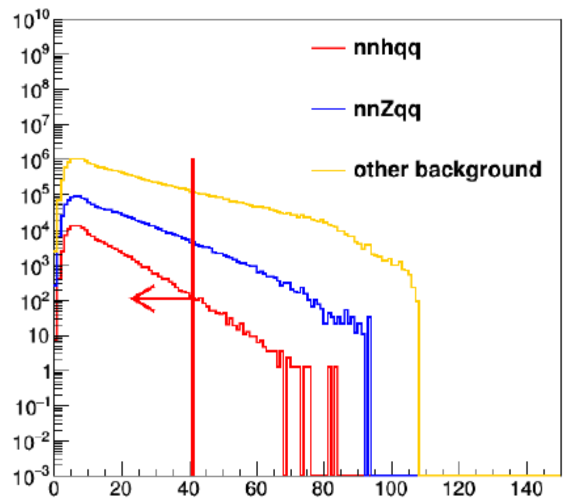
109 < visible energy < 143



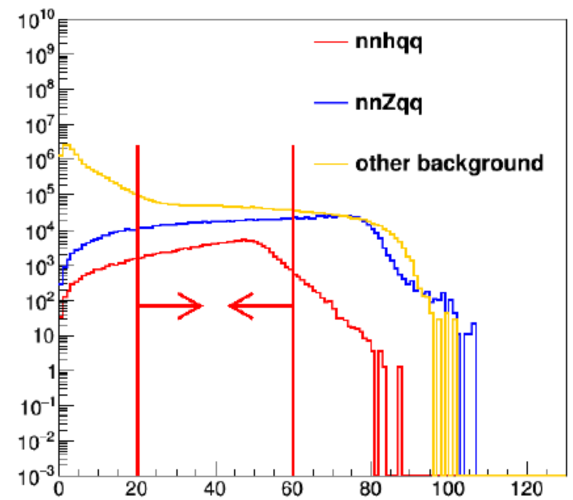
leading lepton energy < 42



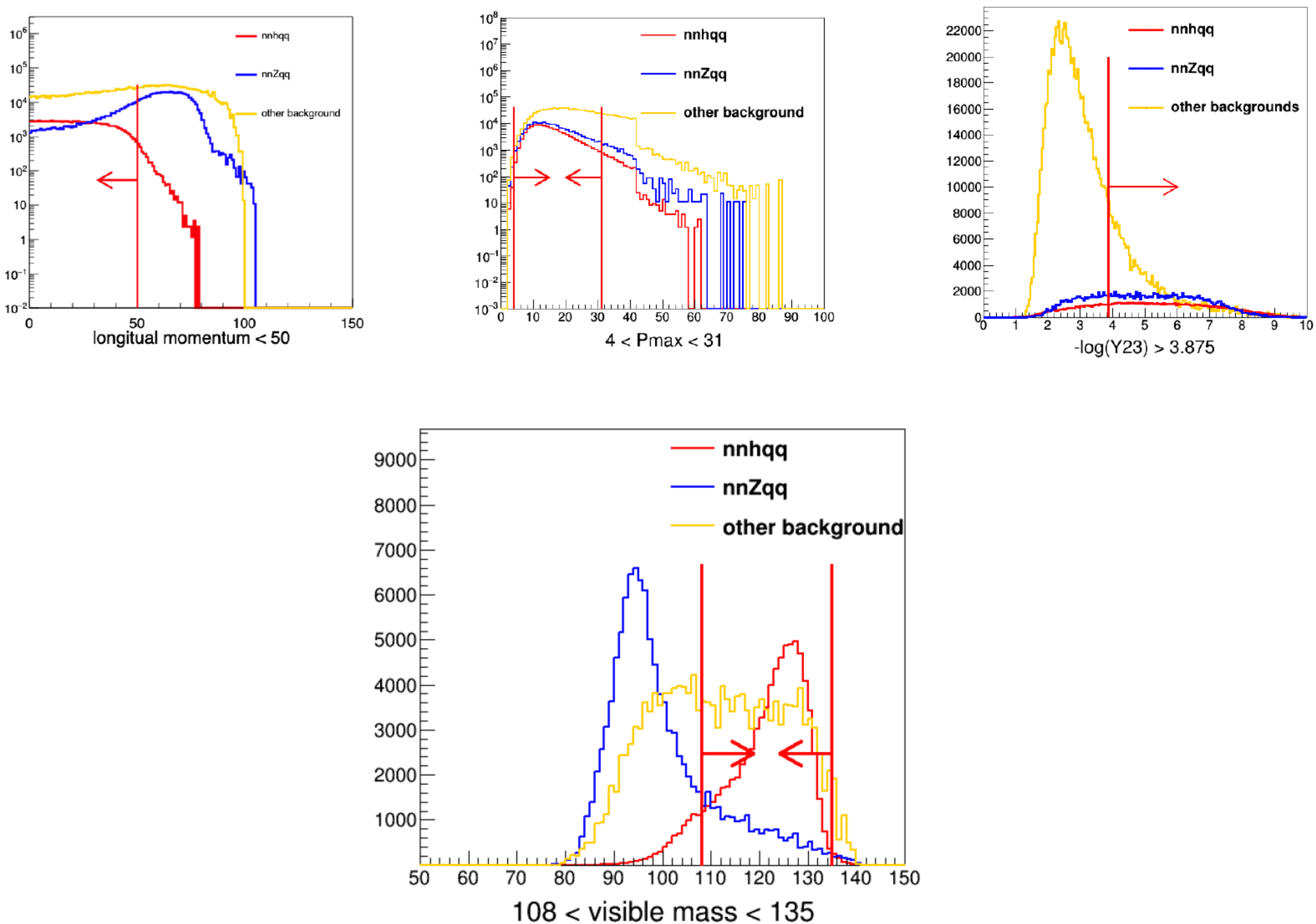
40 < multiplicity < 130



leading neutral energy < 41



20 < transverse momentum < 60


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

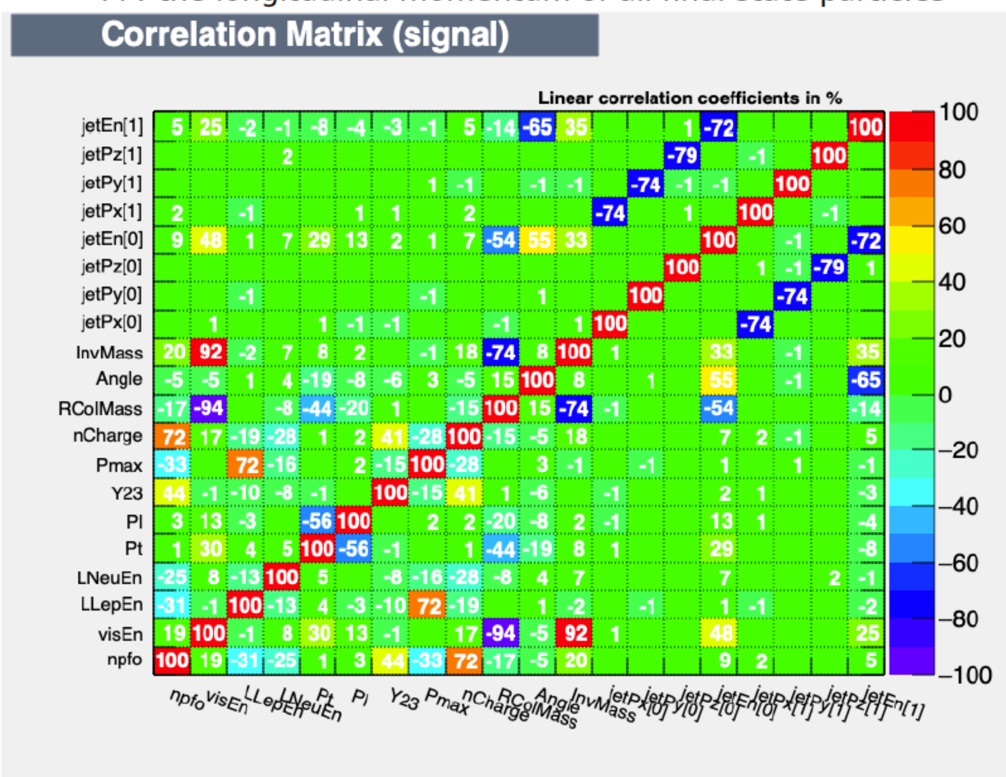
BDT for selecting $\nu\nu Hq\bar{q}$

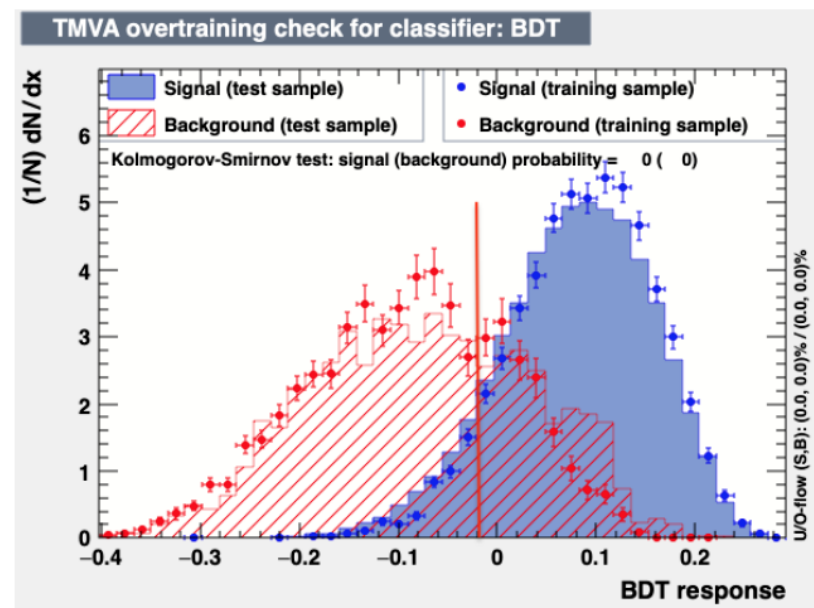
input variables :

Relative accuracy: 0.58 → 0.47

The remaining events are forced into 2-jets using ee-kt

- 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





Flavor Tagging Migration Matrix

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

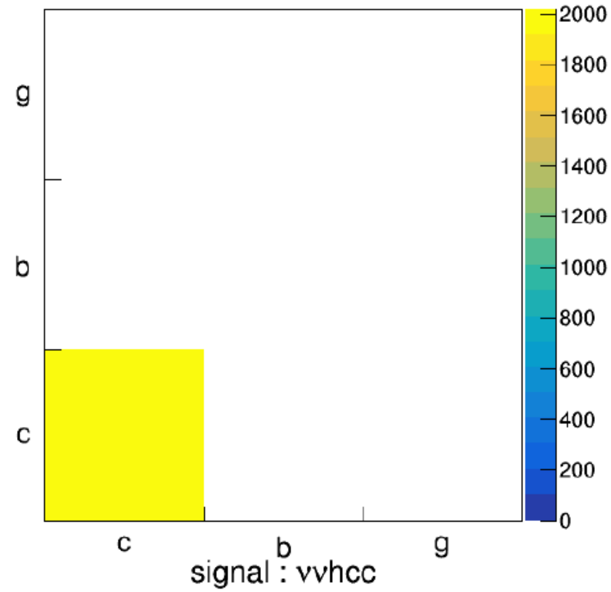
perfect flavor tagging

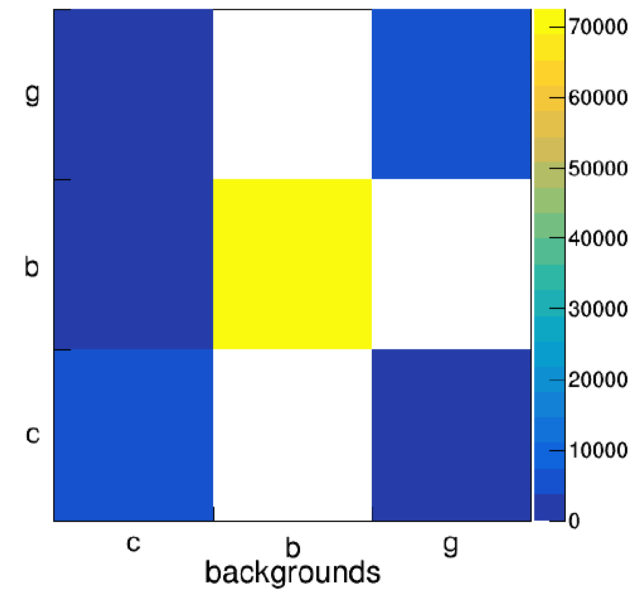
	c	b	udsg
udsg	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
b	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
c	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$

non flavor tagging

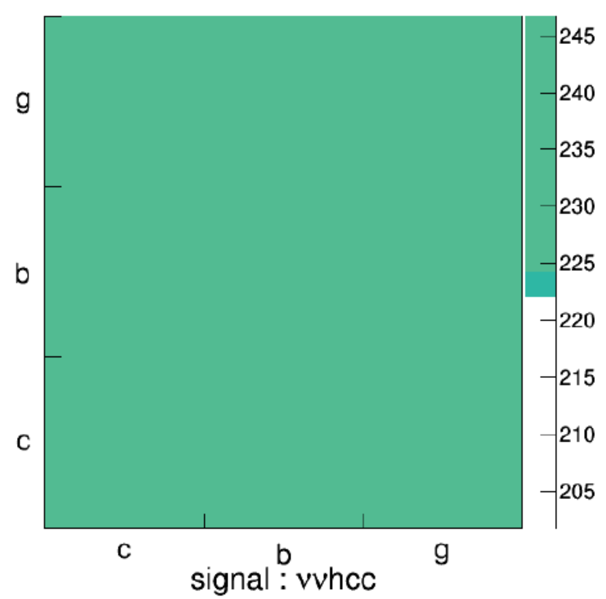
see $\nu\nu Hc\bar{c}$ as signal, and other samples as bkg

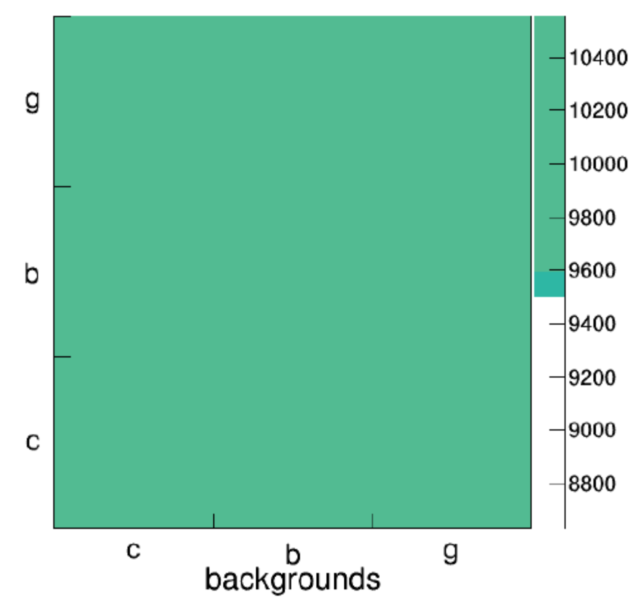
perfect flavor tagging



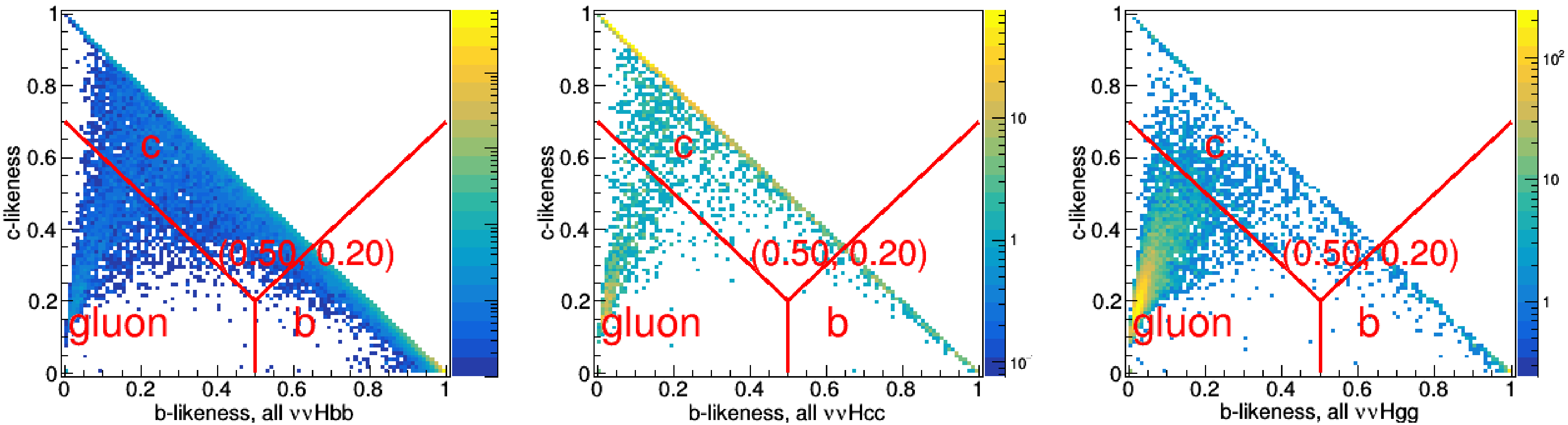


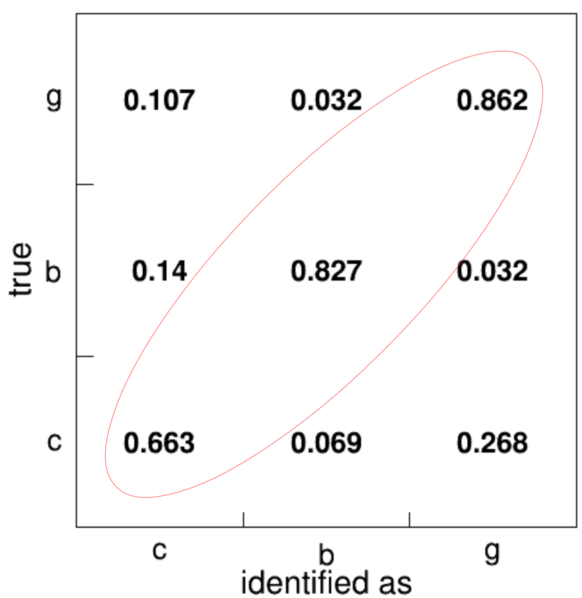
non flavor tagging





Identify Jet Flavor Using LCFIPlus



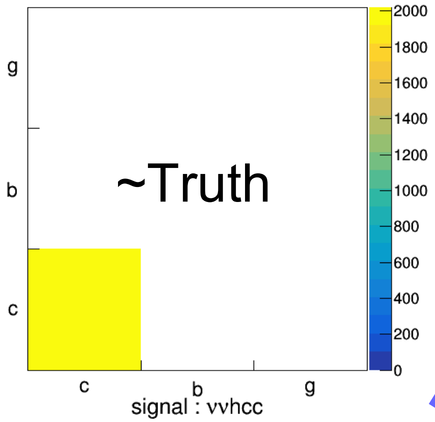


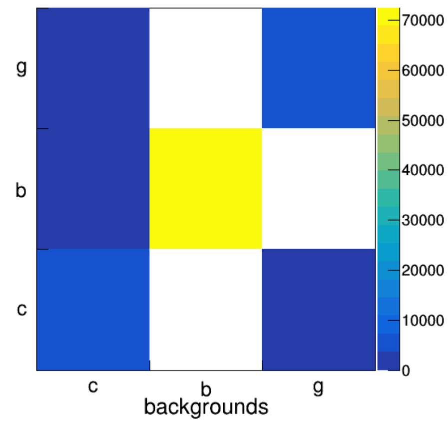
Vorking point selection:

laximize the trace of Migration Matrix (Diagonal terms)

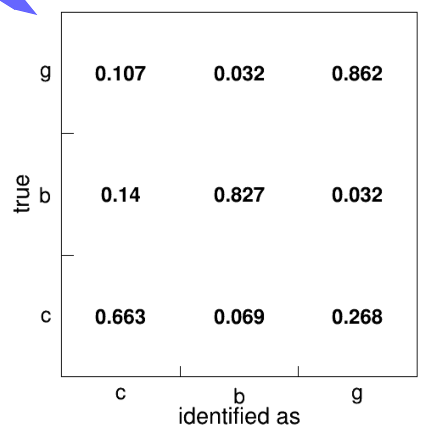
*)ptimizing Working Point for each decay modes independently
eads to percentage level improvement for H→cc/gg*

~Truth

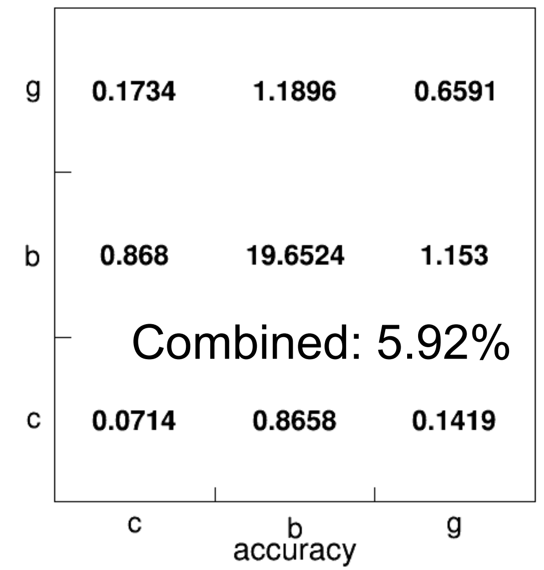




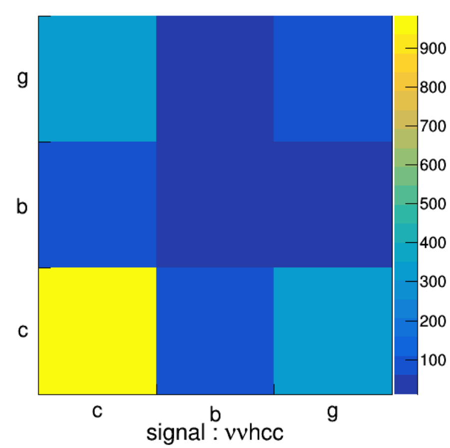
Migration Matrix

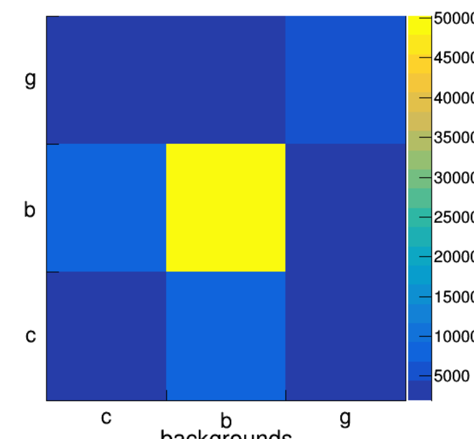


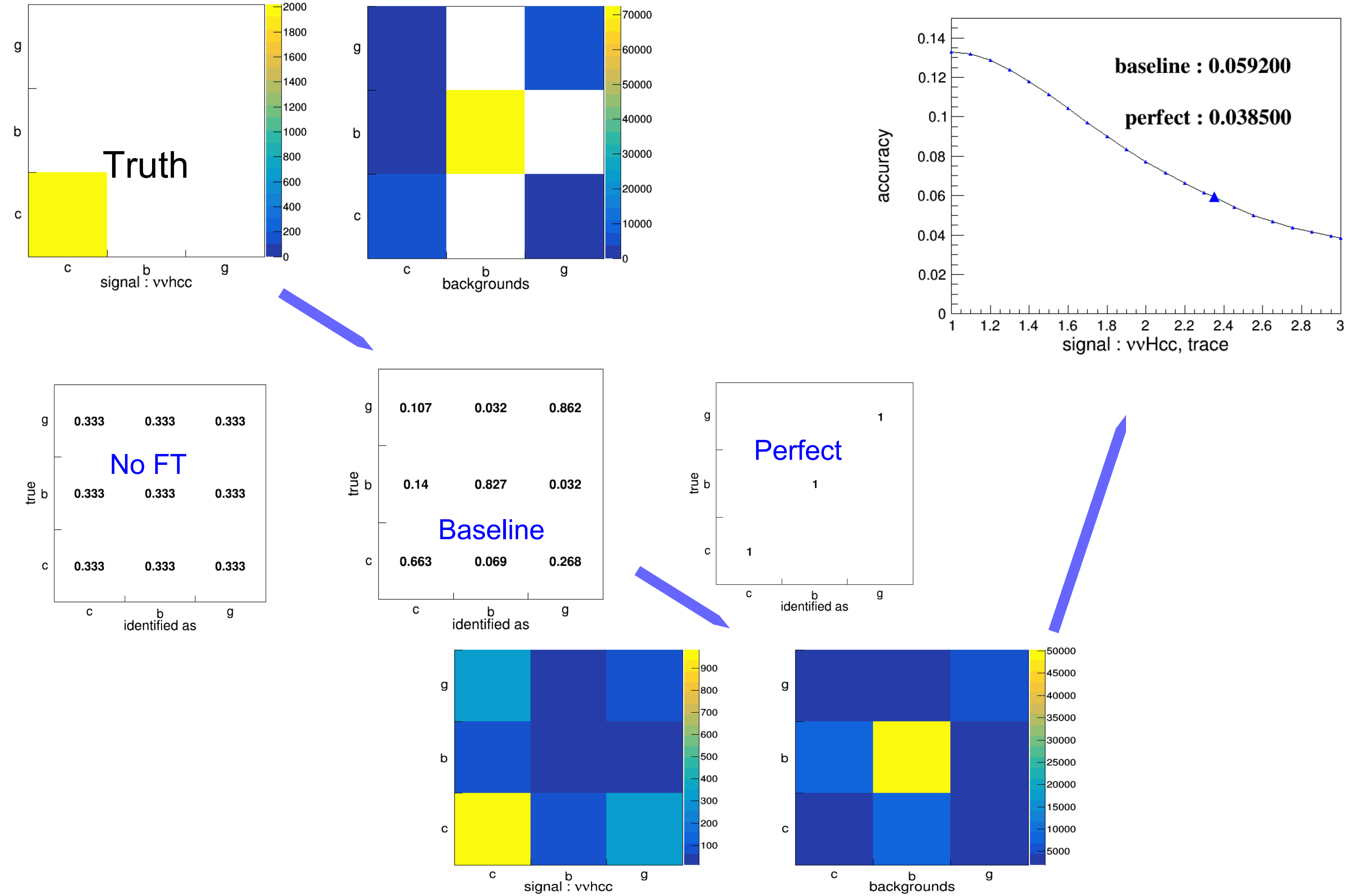
Per Bin Accuracy



~ reconstructed one

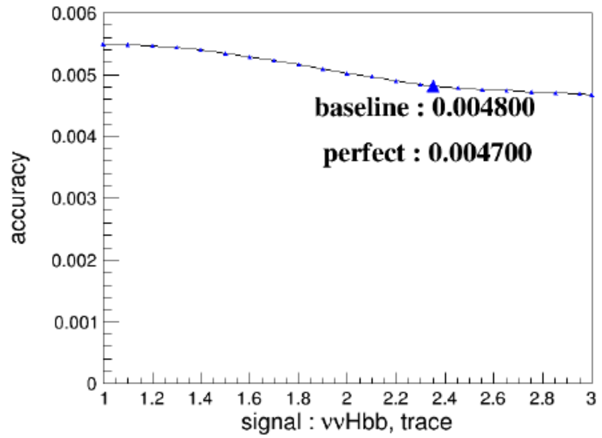


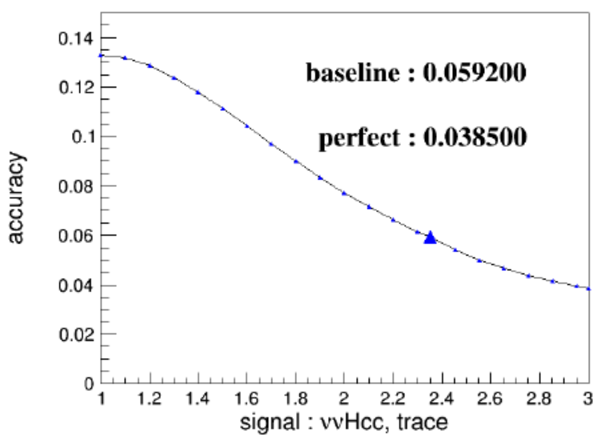


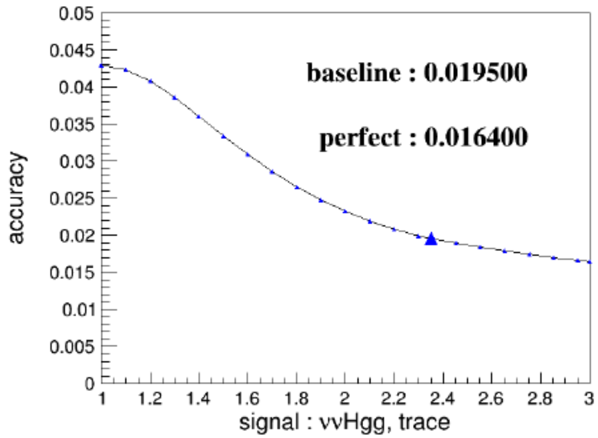


Interpolation: $temp\ matrix = \frac{x - trace_I}{trace_T - trace_I} \cdot (T - I) + I \quad (trace_I \leq x \leq trace_T)$

H→bb, cc, gg: dependence between accuracy & FT performance







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

Margin to improve up to ~50%...

qqH

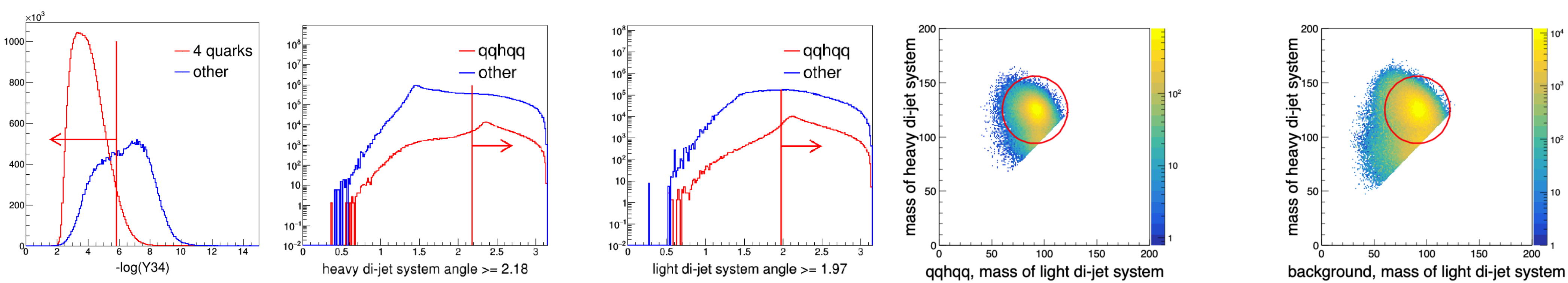
- Tag H→qq:

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.

- Distinguish the H→bb, cc, gg & background events using Flavor Tagging information
  - Using BDT information

Tag qqH, H→qq

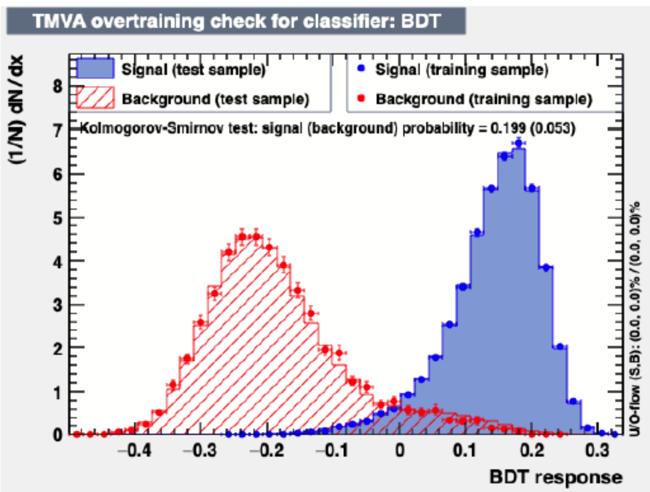
	qqHqq	2f	SW	SZ	WW	ZZ	Mixed	ZH	total bkg	$\frac{\sqrt{S+B}}{S}$ (%)
total	527488	8.01*E*8	1.95*E*7	9.07*E*6	5.08*E*7	6.39*E*6	2.18*E*7	613008	9.09*E*8	5.71
multiplicity	527488	3.04*E*8	1.46*E*7	3.37*E*6	4.85*E*7	6.00*E*6	1.81*E*7	577930	3.95*E*8	3.77
LLepEn	527036	2,98*E*8	6.76*E*6	2.44*E*6	3.93*E*7	5.40*E*6	1.79*E*7	531411	3.71*E*8	3.65
visEn	510731	1.21*E*8	1.29*E*6	551105	2.14*E*7	3.06*E*6	1.71*E*7	180571	1.65*E*8	2.52
LNeuEn	509623	5.68*E*7	716161	168030	2.04*E*7	2.93*E*6	1.65*E*7	176387	9,77*E*7	1.94
thrust	460535	7.81*E*6	473732	132126	1.88*E*7	2.60*E*6	1.54*E*7	167863	4.54*E*7	1.47
$-log(Y_{34})$	451468	4.90*E*6	181432	119836	1.74*E*7	2.40*E*6	1.45*E*7	165961	3.97*E*7	1.48
HJetA	326207	2.83*E*6	110156	58613	4.54*E*6	870276	3.74*E*6	96560.3	1.22*E*7	1.08
ZJetA	279030	1.37*E*6	33491	37101	2.39*E*6	496611	2.00*E*6	74005	6.41*E*6	0.93
ZHA	274530	1.32*E*6	17026	33847	2.28*E*6	468340	1.91*E*6	69620	6.10*E*6	0.92
circleqq	268271	1.20*E*6	10193	31567	2.13*E*6	424514	1.79*E*6	65434	5.65*E*6	0.907



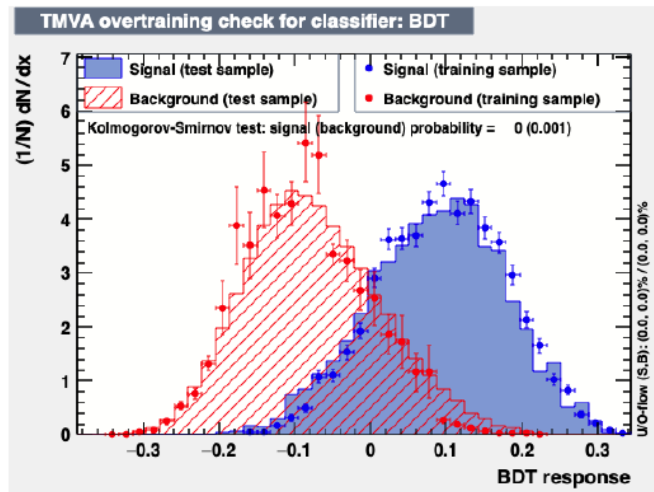
Relative Accuracy on qqH, H→qq: 0.9%

Finally, finding $qqH(H \to b\bar{b}, c\bar{c}, gg)$ from $ZH(Z \to q\bar{q}, H \to q\bar{q})$ with BDT.

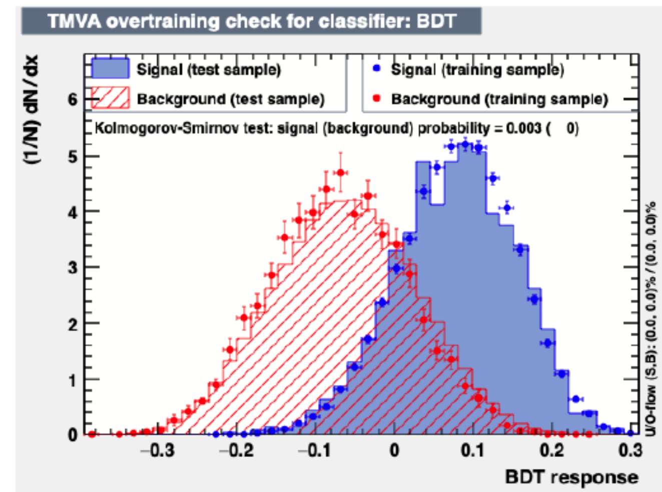
- number of final state particles
- visible energy of final state particles
- leading lepton energy, leading neutral energy
- thrust, Y34
- heavy di-jet angle, light di-jet angle
- the invariant mass of light di-jet system
- the invariant mass of heavy di-jet system
- the b/c-likeness of four jets
- four momentum of four jets



qqhbb



qqhcc



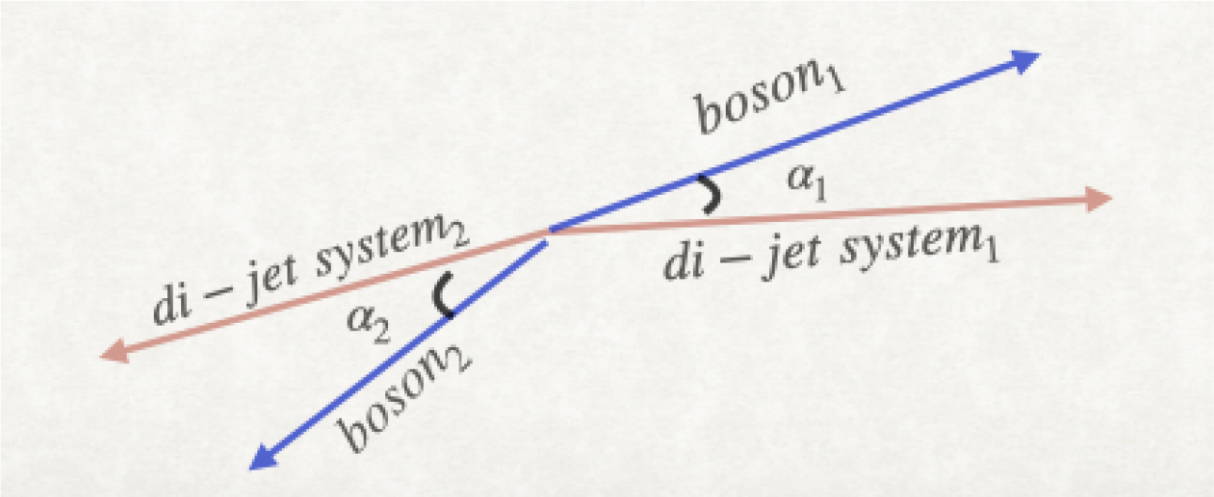
qqhgg

	signal	2f	SW	SZ	WW	ZZ	Mixed	ZH	total bkg	$\frac{\sqrt{S+B}}{S}$ (%)
qqhbb	174201	89168.9	0	67	3596	54373	4094	11264	162566	0.33
qqhcc	5084	76291	10	165	38838	21343	61524	15895	214068	9.2
qqhgg	19564	181982	0	0	140735	50184	134015	41995	548920	3.85

Optimization: CSI & Flavor Tagging

color singlet identification

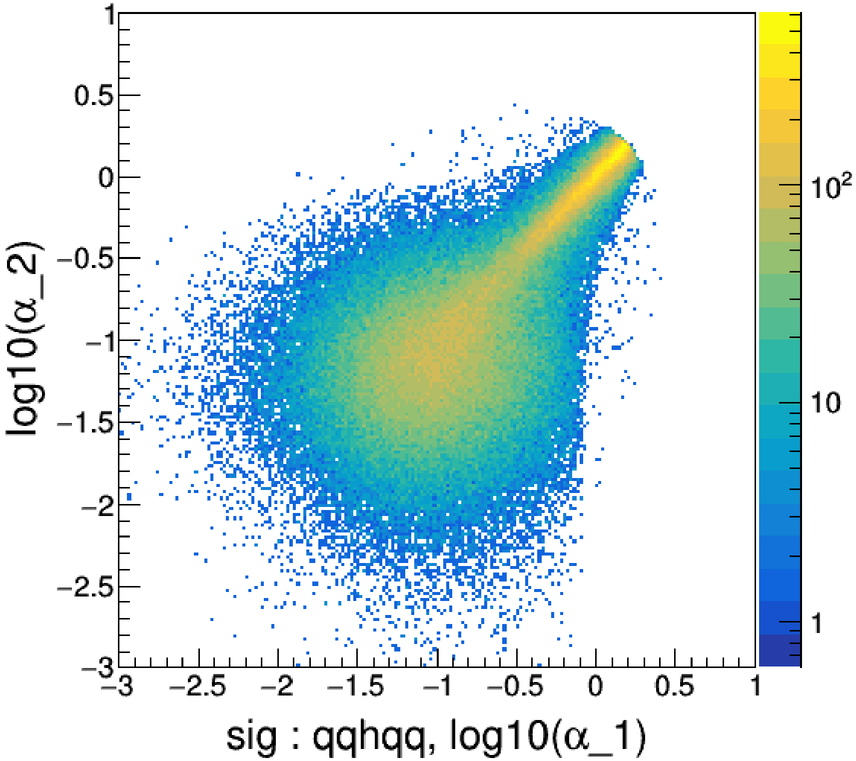
For di-boson event, there are two MC truth bosons and two di-jet systems, the variable $\alpha_i = angle(di-jet\ system_i, truth\ boson_i), (i = 1, 2)$ is used to characterize the performance of jet clustering and jet matching.

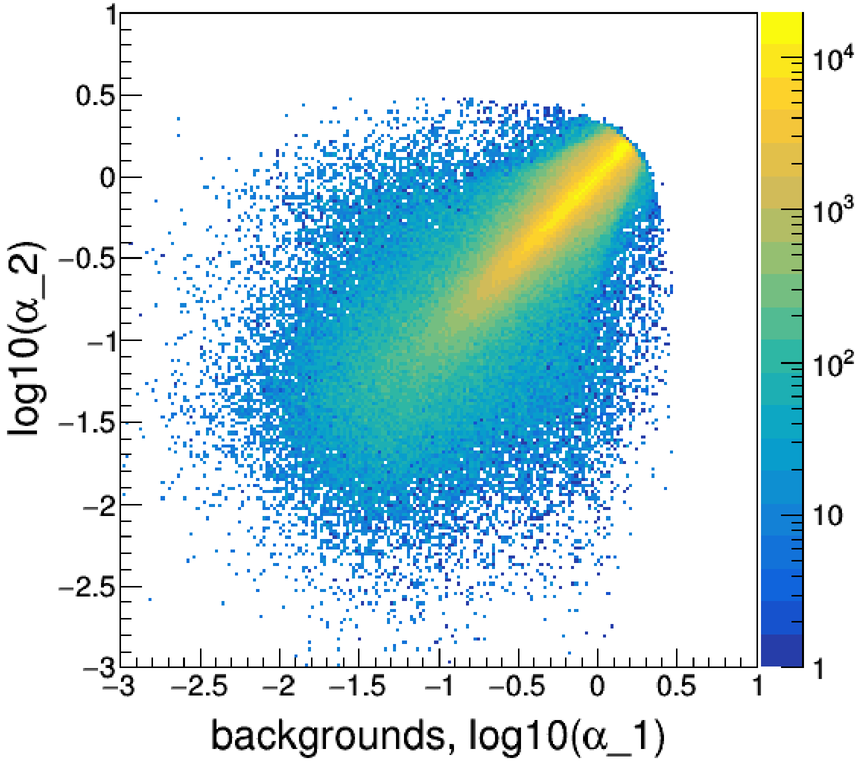


the α variable is just a cheated variable used to characterize the performance of color singlet identification

- Diagnosis method developed in EPJC...

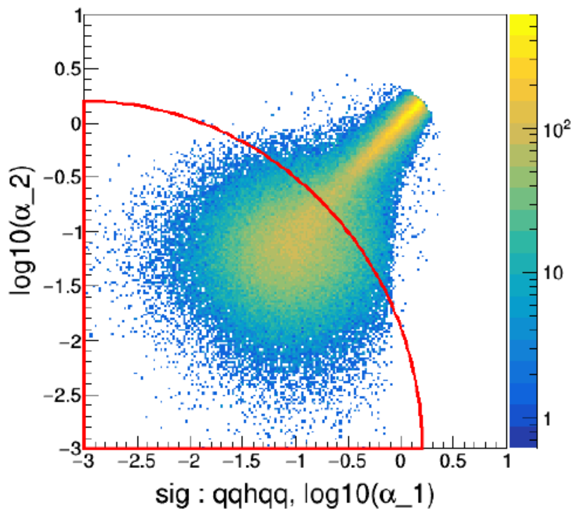
Distribution of alphas: Signal & Background

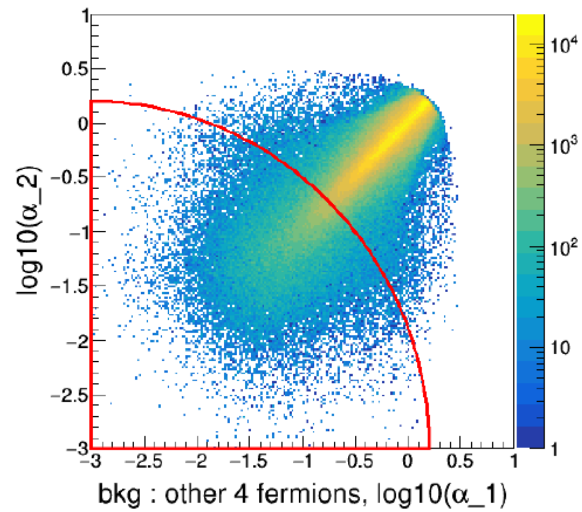


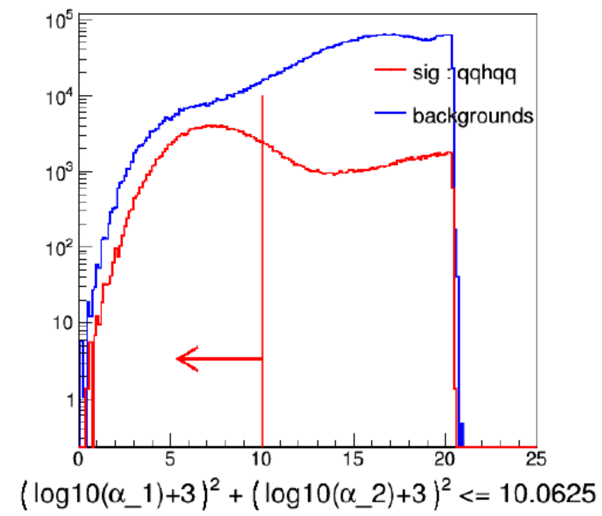


Observation: backgrounds tends to have large alphas – large jet confusion, induced by the Kinematics requirement in event selection

If we know the CSI performance...





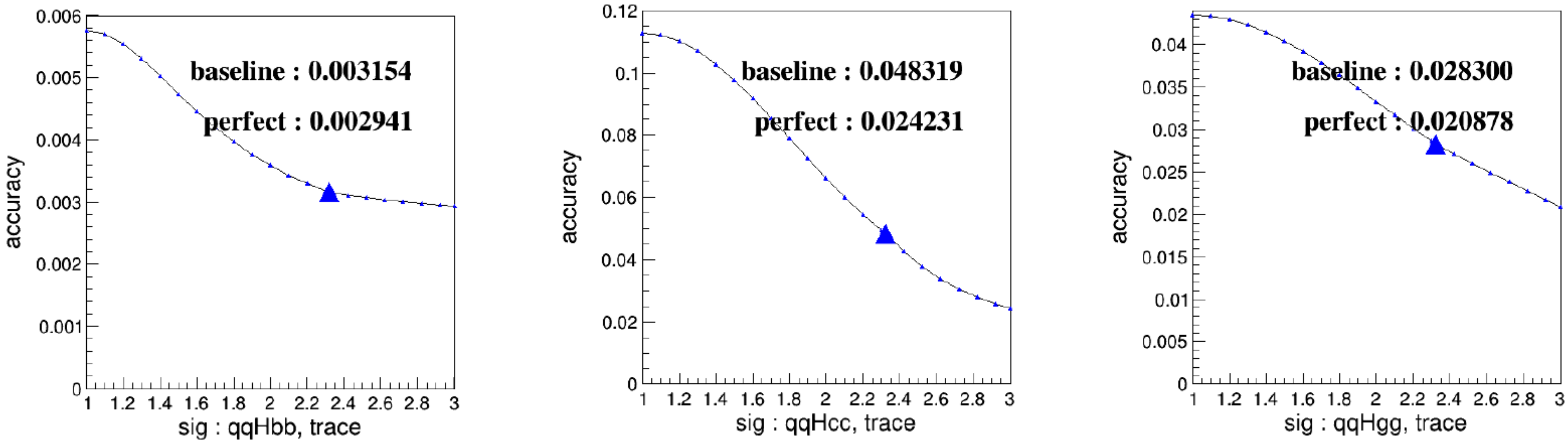


the red curve : $(log10(\alpha_1)+3)^2 + (log10(\alpha_2)+3)^2 <= 3.2^2$ used to select events with good color singlet identification

	qqhbb	qqhcc	qqhgg	background
after circle	219360	10430.5	31469.7	5.65E6
after alpha	132697	6776.48	17570	593172

α detail : https://link.springer.com/article/10.1140/epjc/s10052-019-6719-2

the variation of $qqHq\bar{q}$ measurement accuracy with trace



qqhbb qqhcc qqhgg

relative accuracy (%)	$qqHb\bar{b}$	$qqHc\bar{c}$	$qqHgg$
BDT	0.33	9.2	3.85
alpha & cut based flavor tagging	0.31	4.83	2.83
alpha & perfect flavor tagging	0.29	2.42	2.08

Summary

- CEPC Higgs White paper published in 2019: quantifies the core physics potential
- Performance: quantify requirements & baseline performance
- 360 GeV Higgs operation (2 ab^{-1})
  - Provides 30% more Higgs, improve the Higgs width measurement by ~ 2 times
  - Significant impact on top, etc
- $H\rightarrow qq$ analyses
  - Accuracies at Baseline: 0.26/4.3/1.6% for $H\rightarrow bb/cc/gg$
  - Optimization study
    - CSI: essential: quantify its performance already boost the accuracy on $H\rightarrow cc$ by 2 times.
    - Flavor Tagging: up to 50%/2 times ($H\rightarrow cc$ @ vvH/qqH)
  - Plan:
    - Develop better CSI, from quantify the CSI with reconstructable information.
    - Promote better Flavor tagging

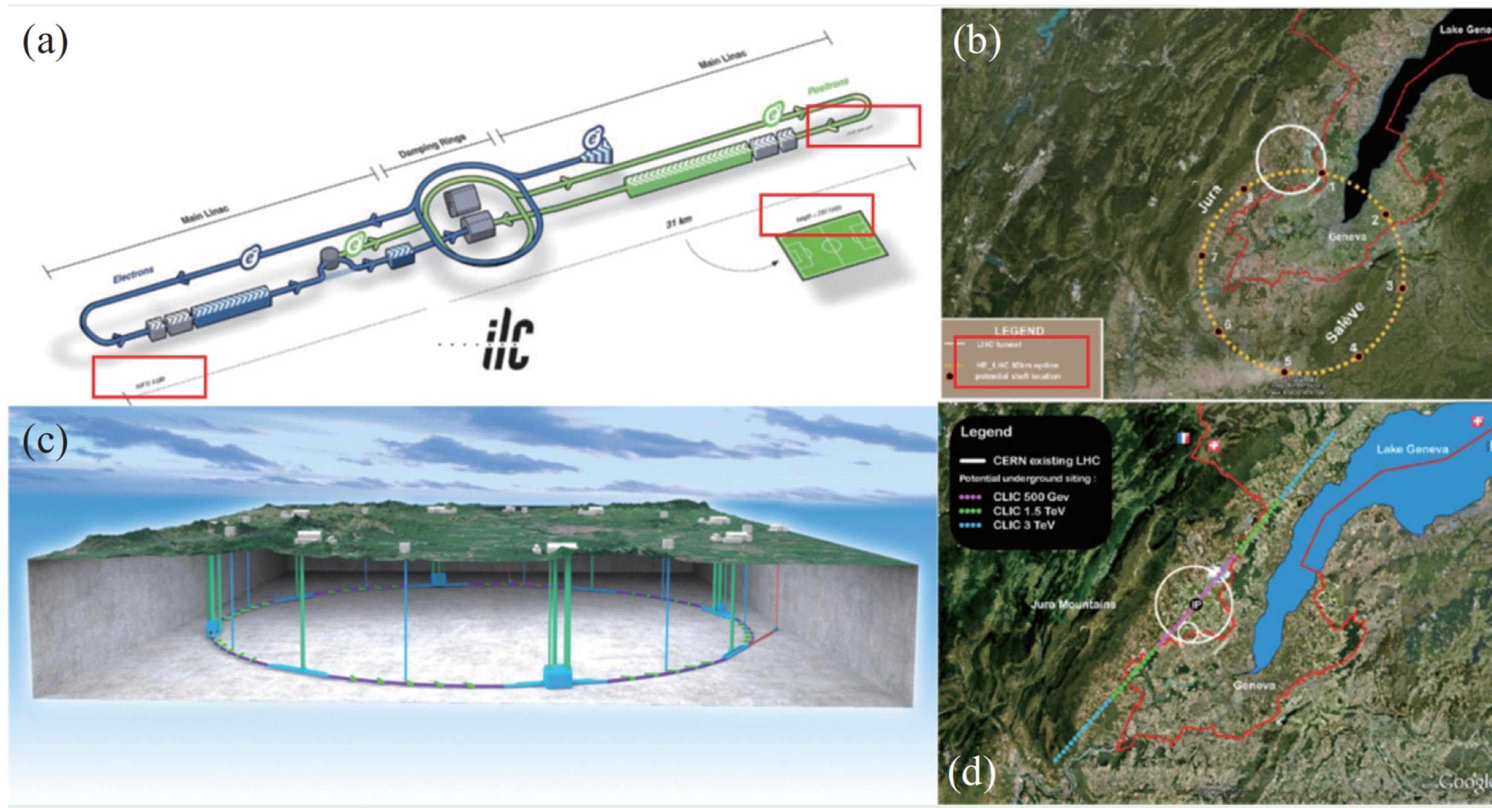
Back up

Electron Positron Higgs factories

High-priority future initiatives

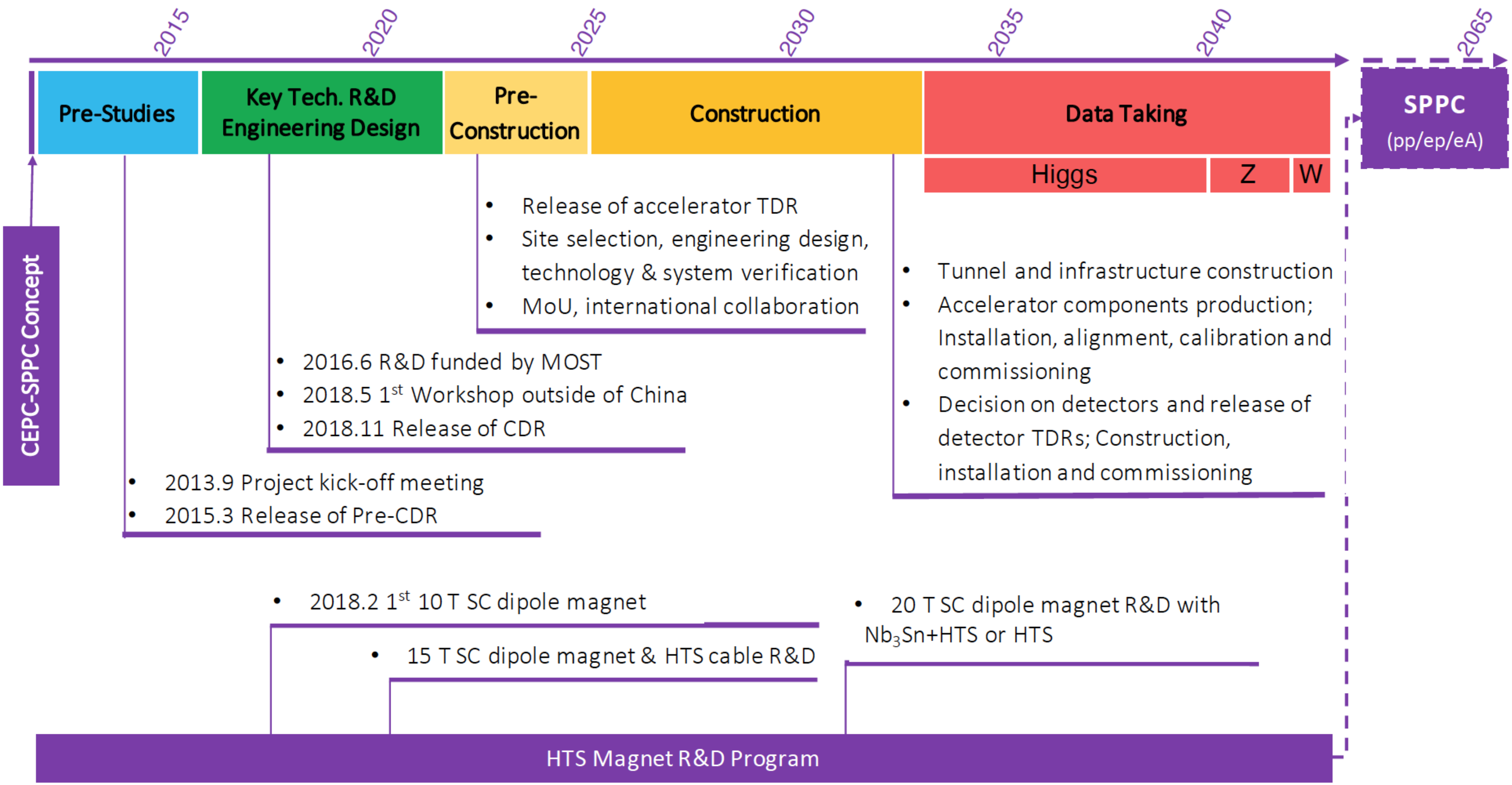
An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

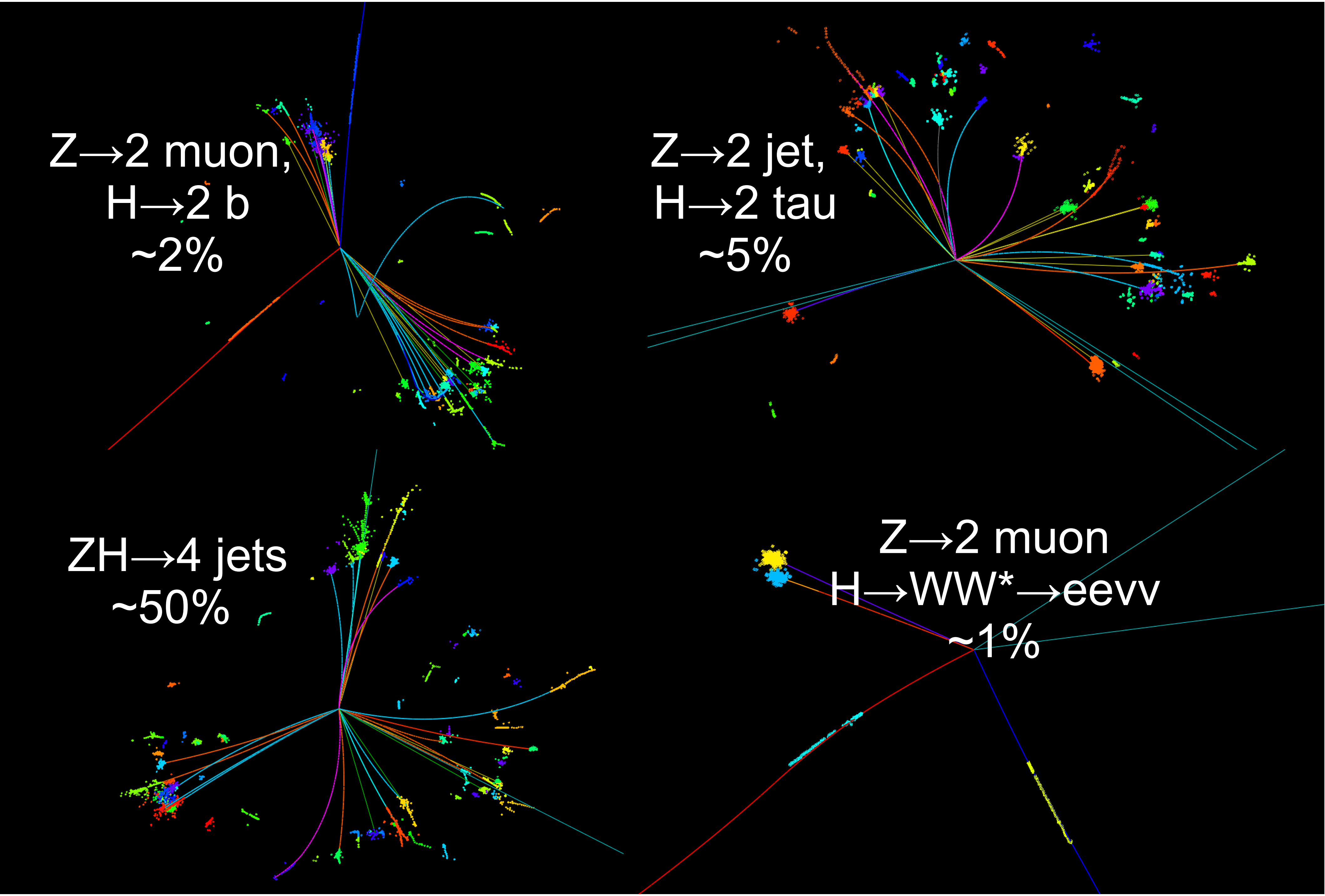
ILC (a):	TDR @ 2013
FCC (b):	CDR @ 2019
CEPC (c):	CDR @ 2018
CLIC (d):	CDR @ 2013



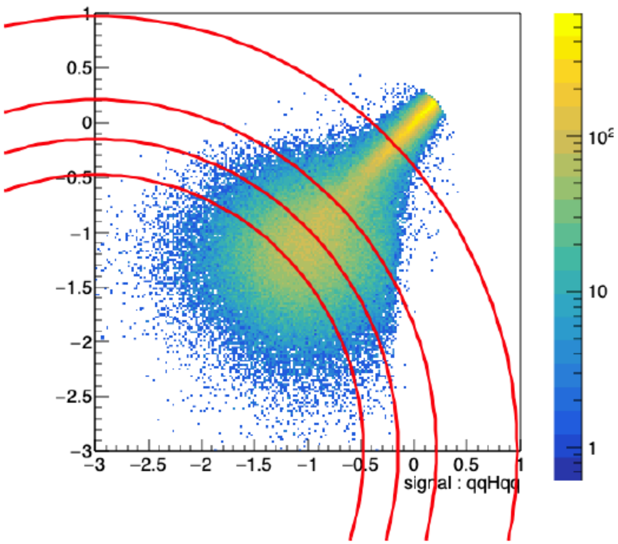
Timeline

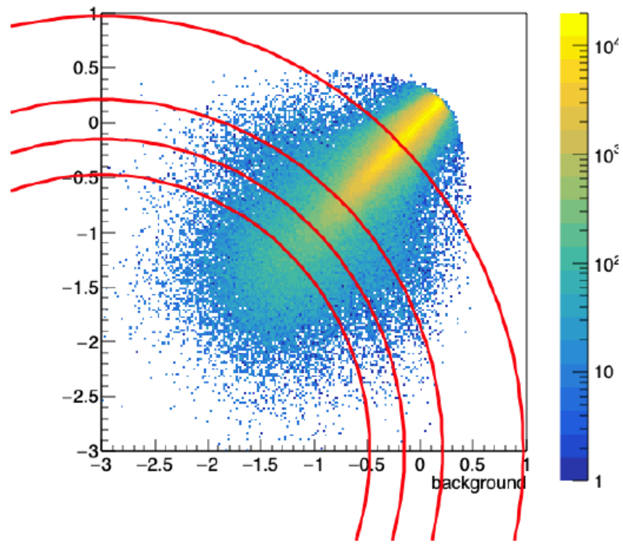
CEPC Project Timeline

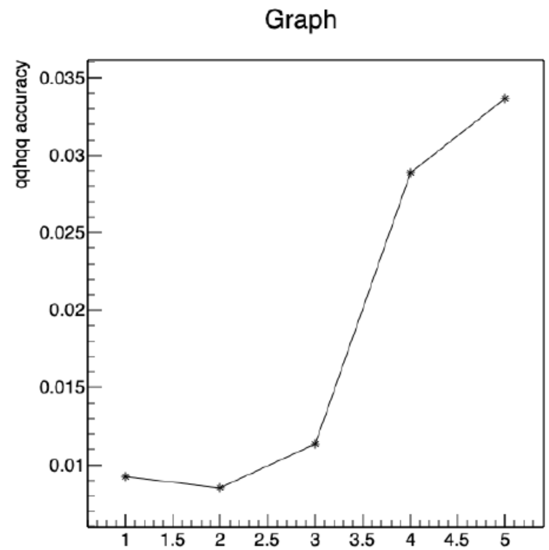



Z→2 muon,
H→2 b
~2%
Z→2 jet,
H→2 tau
~5%
ZH→4 jets
~50%
Z→2 muon
H→WW*→eevv
~1%

If we know the alphas...







Four red curve correspond to $log10(\alpha_1)$ = 2.525, 2.85, 3.21 and 3.97, respectively.

	bin_1	bin_2	bin_3	bin_4	bin_5
qqhqq	51245	52607	51244	51013	50954
bkg	171825	148041	287875	2.13E6	2.89E6
accuracy	0.92%	0.85%	1.14%	2.89%	3.37%

1/5 the data leads to the same accuracy on qqH, H->qq in total

Combination

Current

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%
$Z \to q\bar{q}$	0.33%	9.20%	3.85%
$Z \to \nu\bar{\nu}$	0.47%	5.95%	1.92%
combination	0.26%	4.31%	1.61%

White paper

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%

- Current,