Physics Highlights at CEPC

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(IHEP)

HiggsPotential 2022
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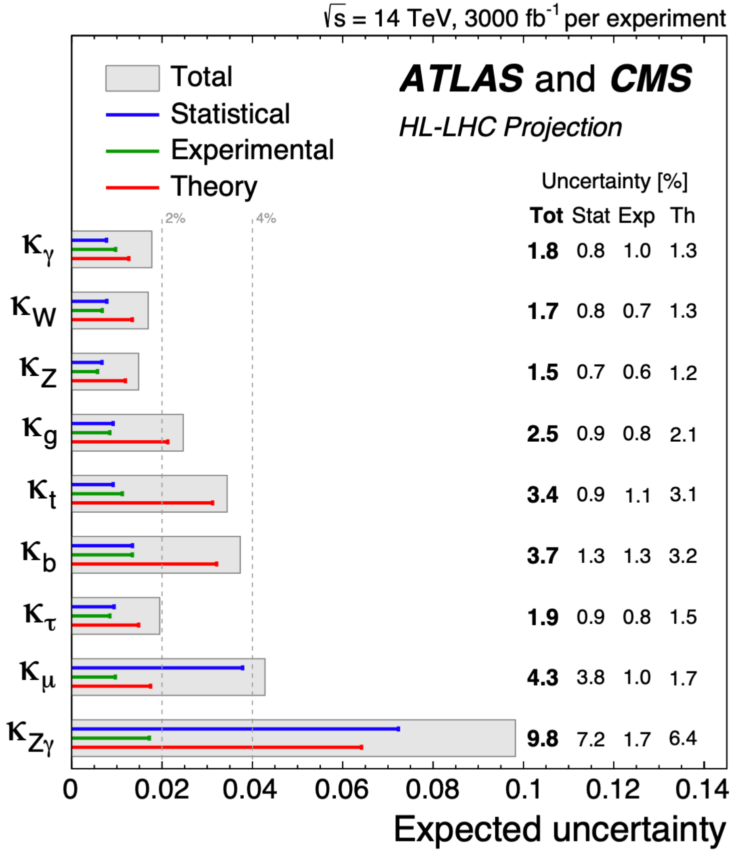
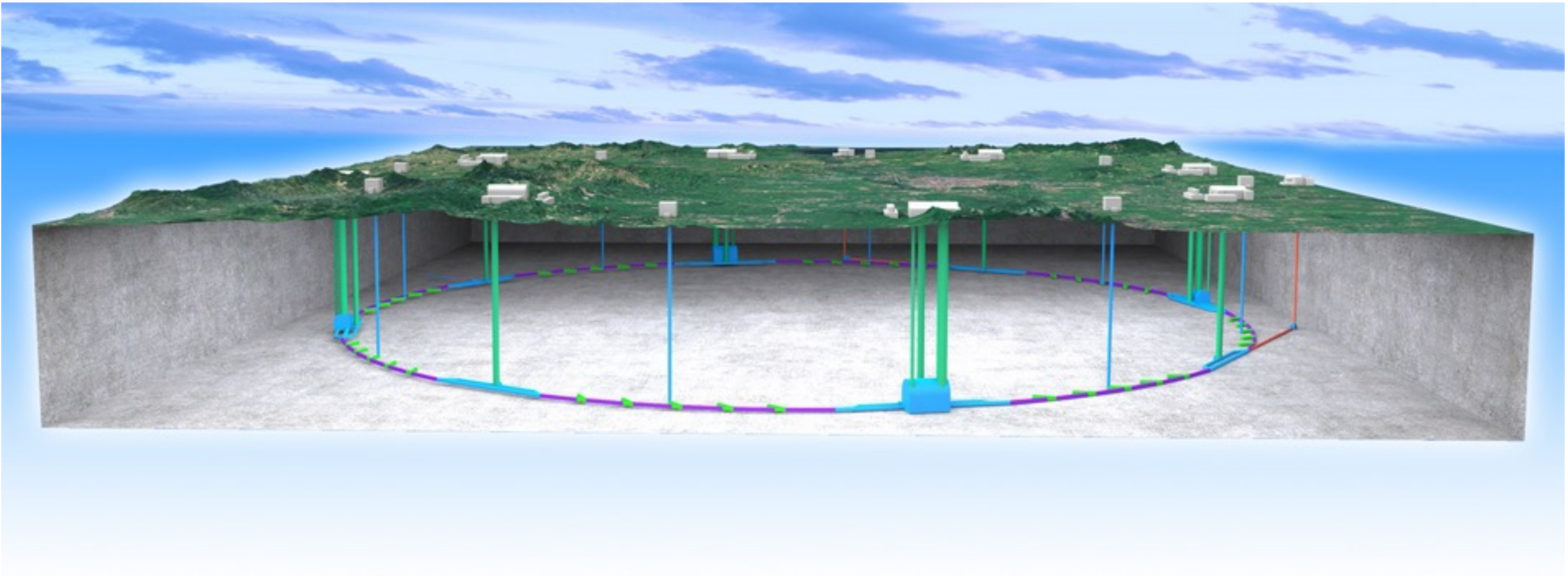
Why do we need e^+e^- collider?



- For HL-LHC (3000 fb^{-1}), the precisions of measurements of Higgs coupling parameters are not better than a few percent.
  - Theoretical uncertainties start to be the dominant one.
- If the new physics is at the sub-percent level, HL-LHC is not sensitive.
- Need e^+e^- machine to precisely measure Higgs property as well as explore new physics.

CEPC

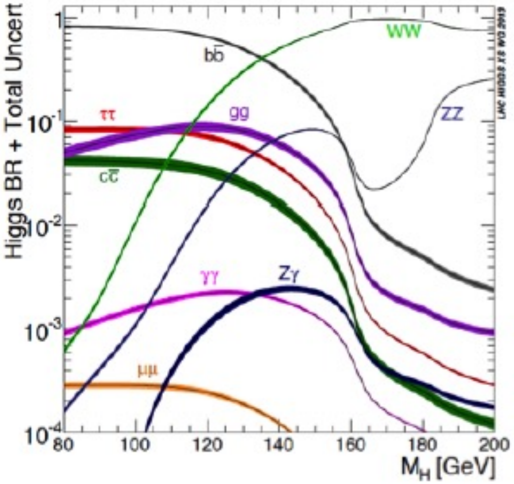
- Thanks to the low mass Higgs, CEPC+SPPC was proposed:
  - Circular e+e- collider(CEPC) has a higher luminosity
  - The tunnel can be re-used for Super proton-proton Collider(SppC), and AA, ep colliders in the far future:

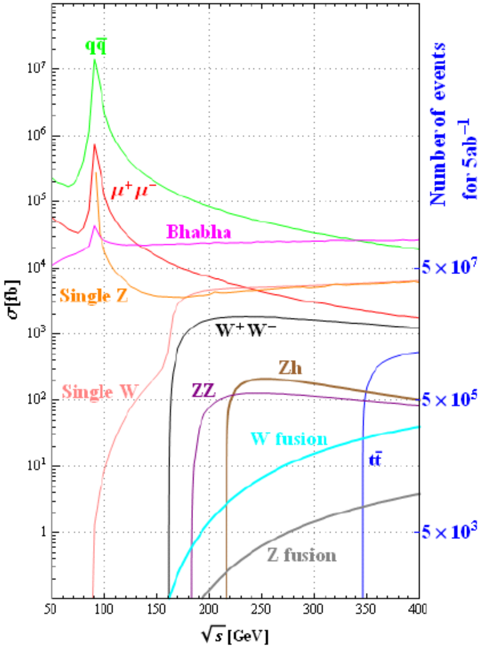


First in the world to have such a proposal, reported at HF2012 at Fermilab

Baseline: 100 km, 30 MW; Upgradable to 50 MW, High Lumi Z

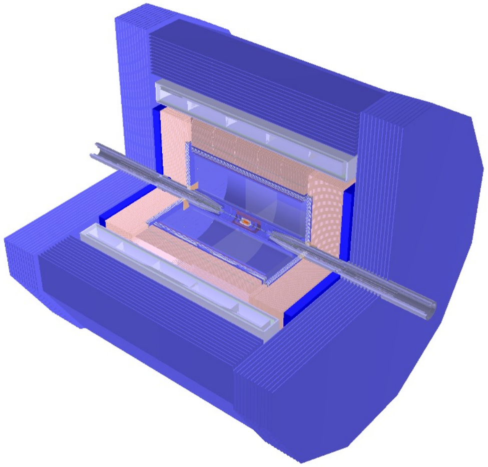
SM Higgs decay branching ratio, Bkg process

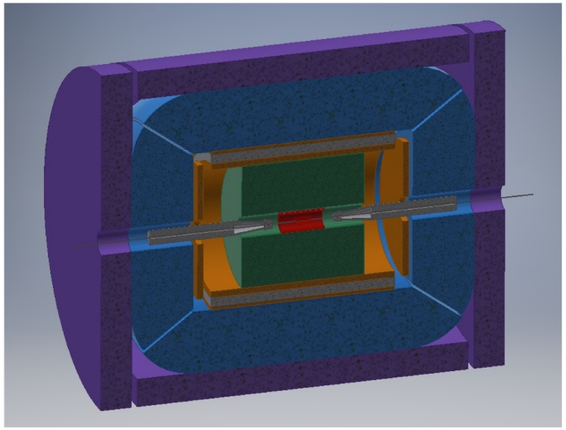


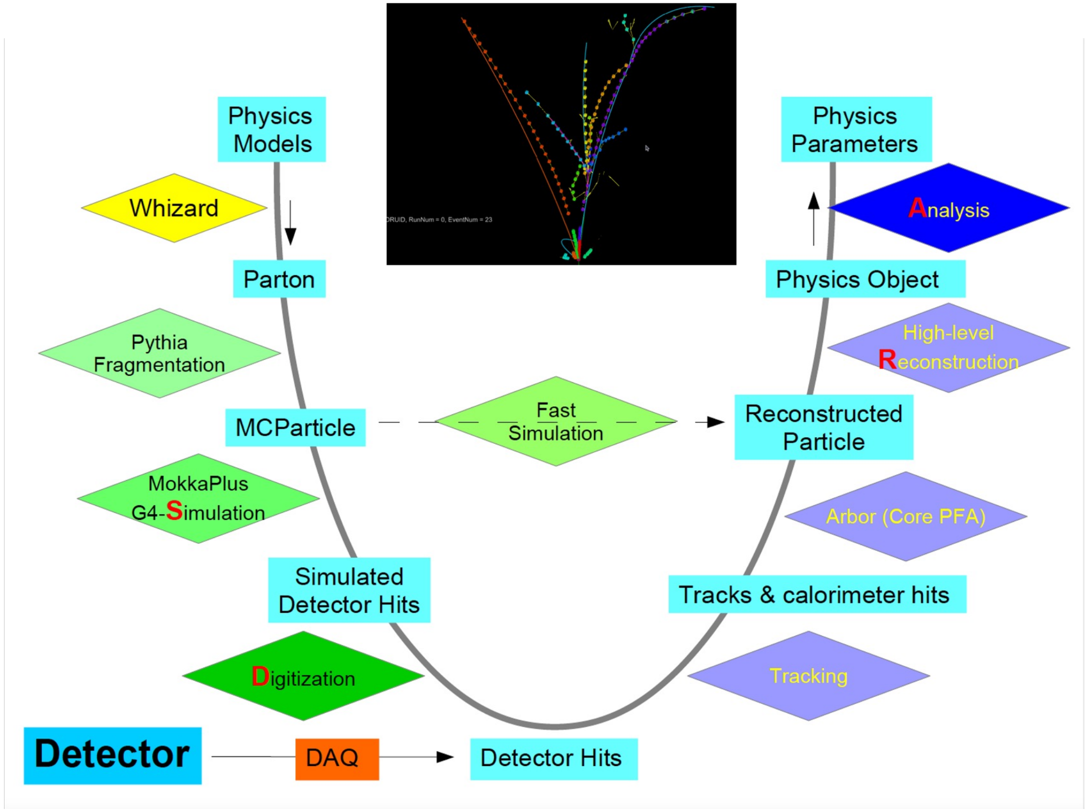


- ✓ e^+e^- collider provides a good opportunity to measure the jj, invisible decay of Higgs.
- ✓ For 5.6 ab^{-1} data with CEPC, 1M Higgs, 10M Z, 100M W are produced.

Detector & Software







Physics Models

Whizard

Parton

Pythia Fragmentation

MCParticle

MokkaPlus G4-Simulation

Simulated Detector Hits

Digitization

Detector

DAQ

Detector Hits

Fast Simulation

Physics Parameters

Analysis

Physics Object

High-level Reconstruction

Reconstructed Particle

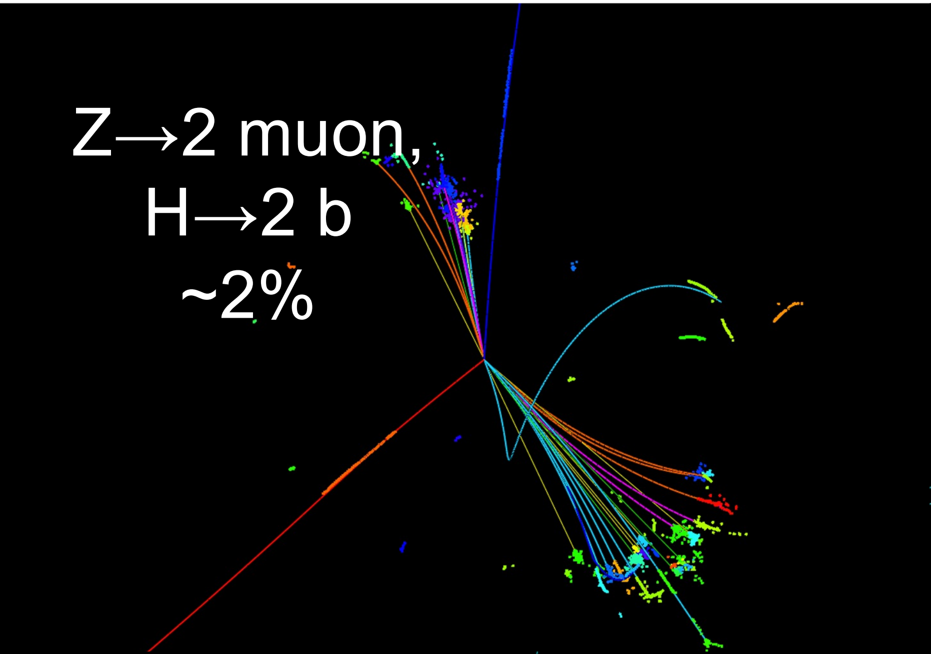
Arbor (Core PFA)

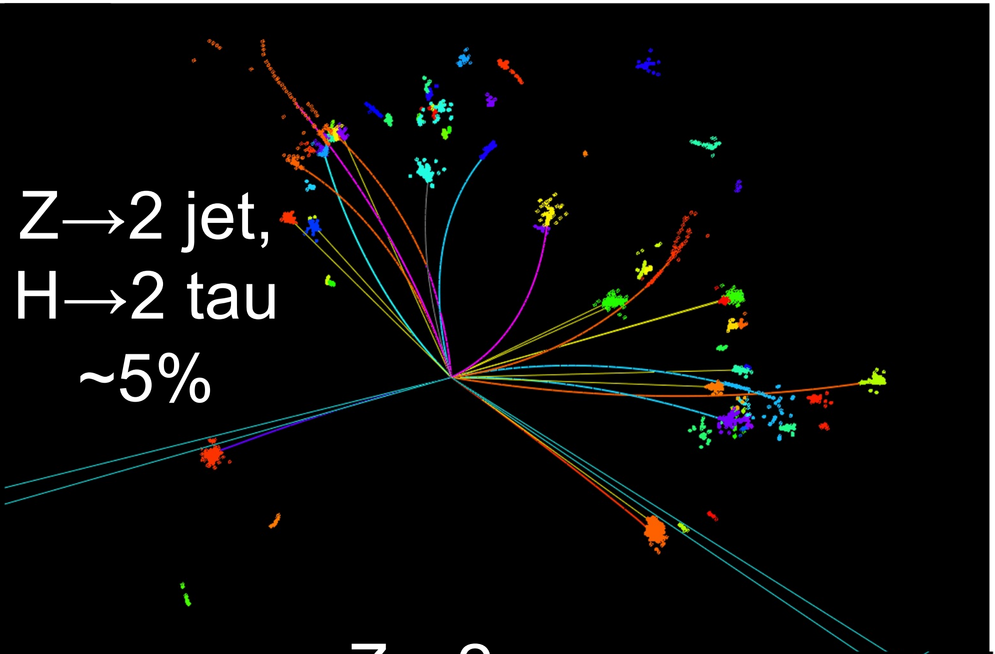
Tracks & calorimeter hits

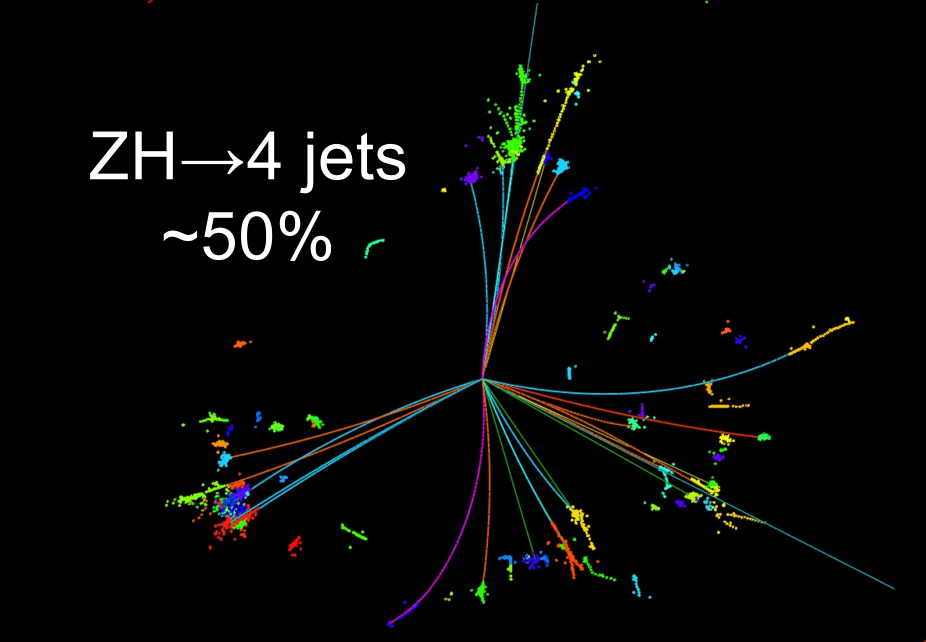
Tracking

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

Events Display for Higgs

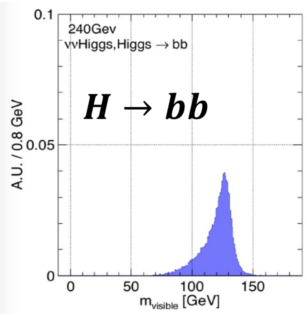

Z→2 muon,
H→2 b
~2%

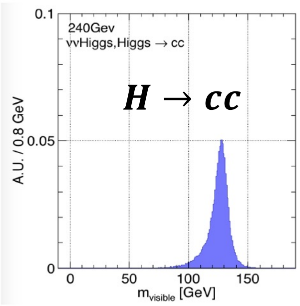

Z→2 jet,
H→2 tau
~5%

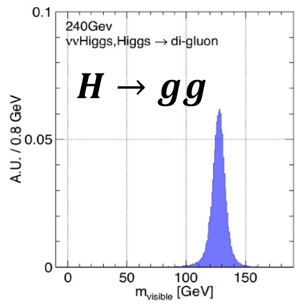

ZH→4 jets
~50%

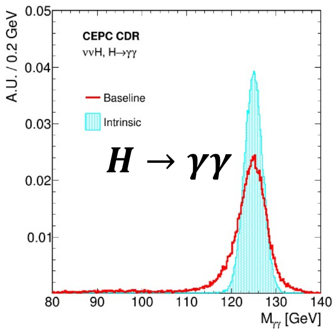

Z→2 muon
H→WW*→eeνν
~1%

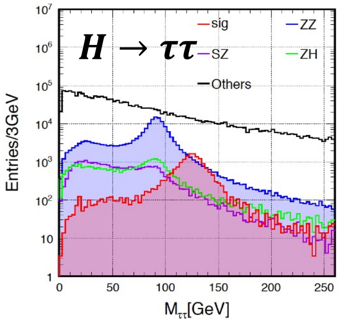
Reminder: Recon. Higgs Signatures& Detector Performance@CDR

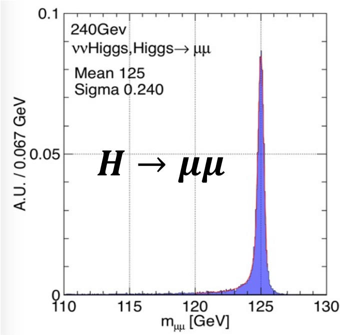


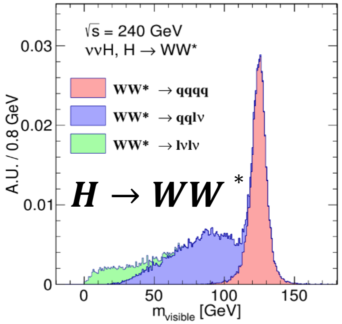


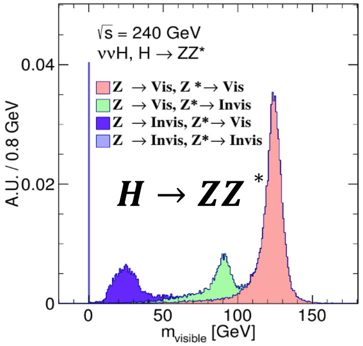






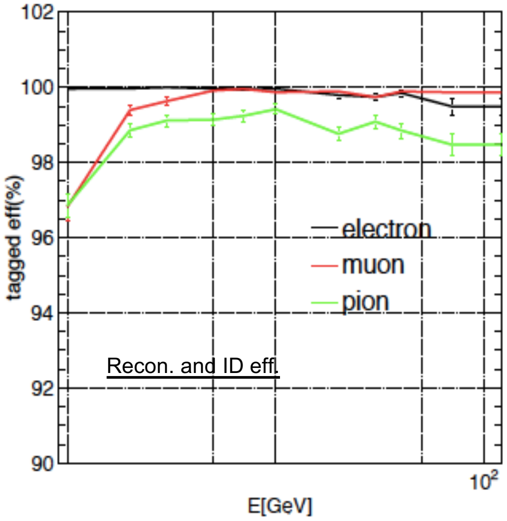


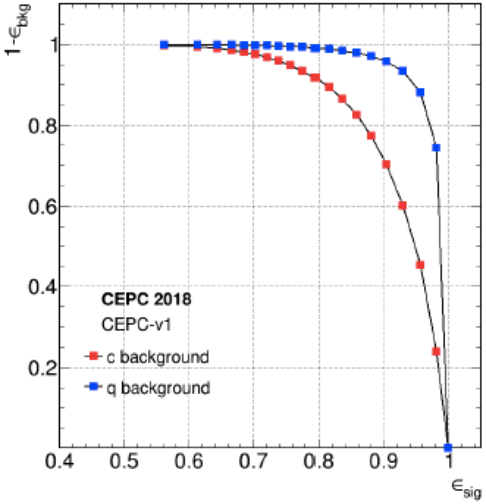




- ✓ Clear Higgs Signature in all SM decay modes
- ✓ Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level
- ✓ *Di-tau mass distribution at qqH events using collinear approximation*

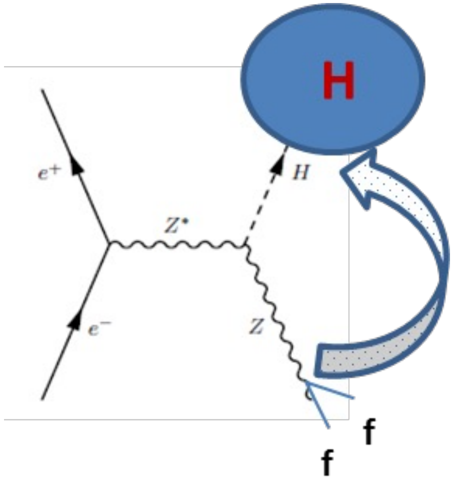
- ✓ Acceptance: $|\cos(\theta)| < 0.99$
- ✓ Tracks: Pt threshold, ~ 100 MeV
  - ✓ $\delta p/p \sim o(0.1\%)$
- ✓ Photons:
  - ✓ Energy threshold, ~ 100 MeV
  - ✓ $\delta E/E$: 3 – 15%/sqrt(E)
- ✓ BMR: 3.7%
- ✓ b-tagging: eff*purity @ Z→qq: 70%
- ✓ c-tagging: eff*purity @ Z→qq: 40%





Direct measurement of Higgs cross-section

$$M^2_{\text{recoil}} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$



✓For this model independent analysis, we reconstruct the recoil mass of Z without touching the other particles in a event.

✓The M_{recoil} should exhibit a resonance peak at m_H for signal; Bkg is expected to smooth.

✓The best resolution can be achieved from Z(→e^+e^-, $\mu^+\mu^-$).

Measurement of Higgs width

- **Method 1**: **Higgs width can be determined directly from the measurement of σ(ZH) and Br. of (H->ZZ*)**

$$\Gamma_H \propto \frac{\Gamma(H \to ZZ^{*})}{\mathrm{BR}(H \to ZZ^{*})} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^{*})}$$

Precision : 5.1%

  - **But the uncertainty of Br(H->ZZ*) is relatively high due to low statistics.**

- **Method 2**: **It can also be measured through:**

$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{BR(H \to bb)} \qquad \sigma(\nu\bar{\nu}H \to \nu\bar{\nu}b\bar{b}) \propto \Gamma(H \to WW^{*}) \cdot \mathrm{BR}(H \to bb) = \Gamma(H \to bb) \cdot \mathrm{BR}(H \to WW^{*})$$

$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{\mathrm{BR}(H \to bb)} \propto \frac{\sigma(\nu\bar{\nu}H \to \nu\bar{\nu}b\bar{b})}{\mathrm{BR}(H \to b\bar{b}) \cdot \mathrm{BR}(H \to WW^{*})}$$

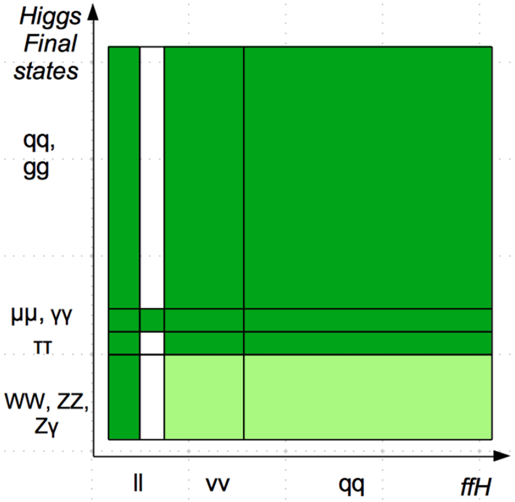
3.0%

Precision : 3.5%

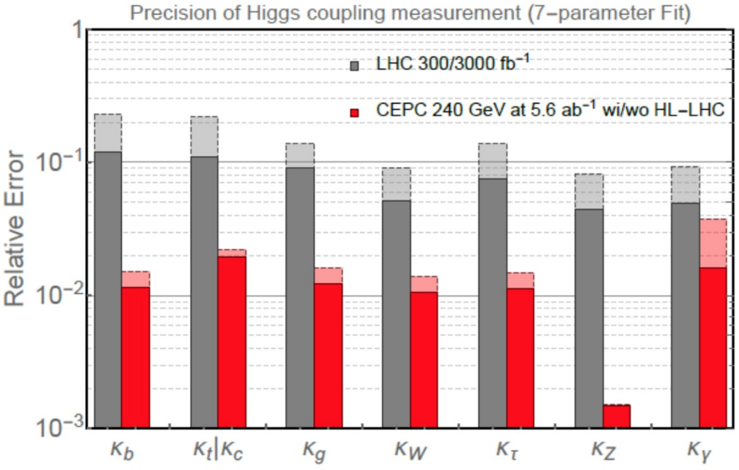
- **These two orthogonal methods can be combined to reach the best precision.**

Combined Precision : 2.9%

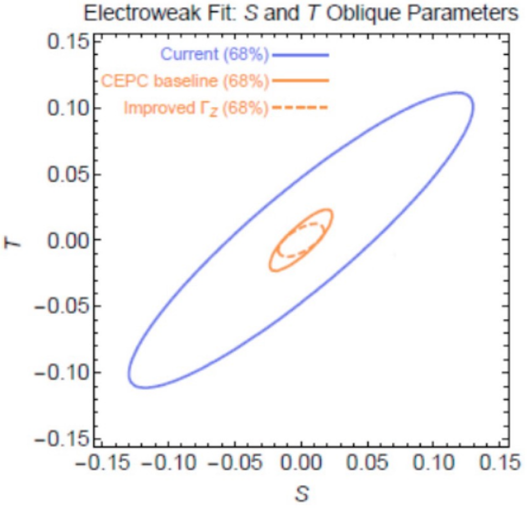
Reminder: Physics Potential@ CDR

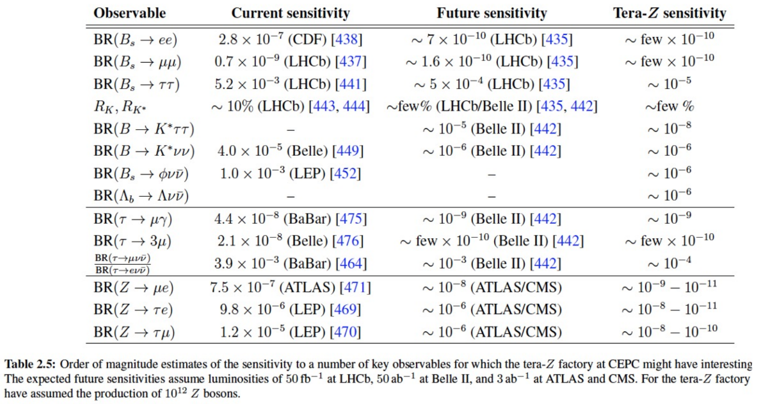


Higgs



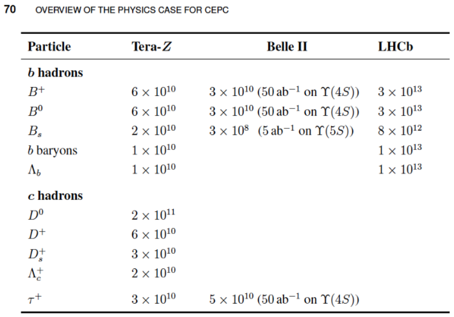
EW





Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
BR($B_s \to ee$)	2.8×10^{-7} (CDF) [438]	$\sim 7 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
BR($B_s \to \mu\mu$)	0.7×10^{-9} (LHCb) [437]	$\sim 1.6 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
BR($B_s \to \tau\tau$)	5.2×10^{-3} (LHCb) [441]	$\sim 5 \times 10^{-4}$ (LHCb) [435]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim$ 10% (LHCb) [443, 444]	$\sim$few% (LHCb/Belle II) [435, 442]	$\sim$few %
BR($B \to K^*\tau\tau$)	–	$\sim 10^{-5}$ (Belle II) [442]	$\sim 10^{-8}$
BR($B \to K^*\nu\nu$)	4.0×10^{-5} (Belle) [449]	$\sim 10^{-6}$ (Belle II) [442]	$\sim 10^{-6}$
BR($B_s \to \phi\nu\bar{\nu}$)	1.0×10^{-3} (LEP) [452]	–	$\sim 10^{-6}$
BR($\Lambda_b \to \Lambda\nu\bar{\nu}$)	–	–	$\sim 10^{-6}$
BR($\tau \to \mu\gamma$)	4.4×10^{-8} (BaBar) [475]	$\sim 10^{-9}$ (Belle II) [442]	$\sim 10^{-9}$
BR($\tau \to 3\mu$)	2.1×10^{-8} (Belle) [476]	$\sim$ few $\times 10^{-10}$ (Belle II) [442]	$\sim$ few $\times 10^{-10}$
$\frac{\text{BR}(\tau \to \mu\nu\bar{\nu})}{\text{BR}(\tau \to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [464]	$\sim 10^{-3}$ (Belle II) [442]	$\sim 10^{-4}$
BR($Z \to \mu e$)	7.5×10^{-7} (ATLAS) [471]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
BR($Z \to \tau e$)	9.8×10^{-6} (LEP) [469]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
BR($Z \to \tau\mu$)	1.2×10^{-5} (LEP) [470]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

Table 2.5: Order of magnitude estimates of the sensitivity to a number of key observables for which the tera-Z factory at CEPC might have interesting
The expected future sensitivities assume luminosities of 50 fb^{-1} at LHCb, 50 ab^{-1} at Belle II, and 3 ab^{-1} at ATLAS and CMS. For the tera-Z factory
have assumed the production of 10^{12} Z bosons.



70 OVERVIEW OF THE PHYSICS CASE FOR CEPC

Particle	Tera-Z	Belle II	LHCb
***b* hadrons**			
B^+	6×10^{10}	3×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}		1×10^{13}
Λ_b	1×10^{10}		1×10^{13}
***c* hadrons**			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
τ^+	3×10^{10}	5×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	

Publications post CDR

H→ bb, cc, gg: CPC Vol. 44, No.1 (2020)013001

H → ZZ : $EPJC$ 81, 879 (2021)

H→ $invisible$: CPC Vol. 44, No.1 (2020)123001

H→ $\tau\tau$: Euro. Phys. J. C(2020) 80:7

H→ $\mu\mu$: *Accepted by CPC*

Higgs Global Analysis: ArXiv:2105.14997

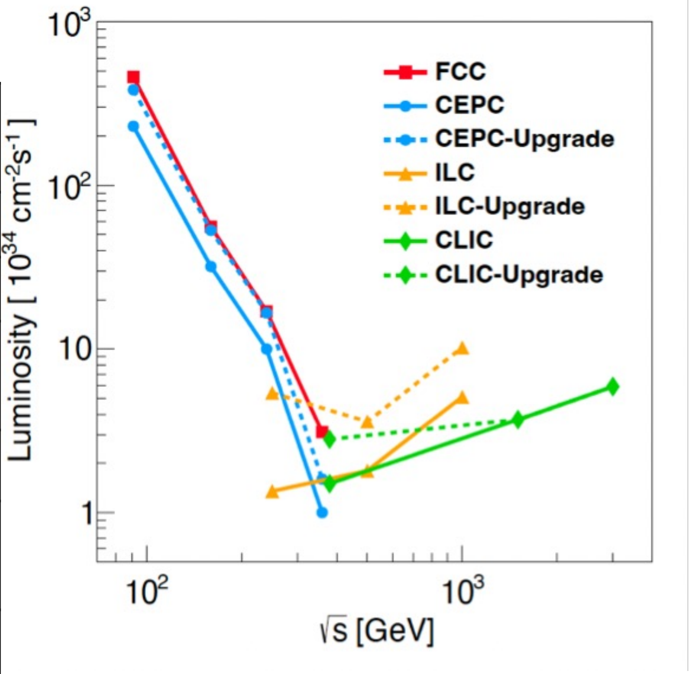
Higgs CP: ArXiv: 2203.11707

H→ $\gamma\gamma$: ArXiv:2205.13269

Update on H→ bb, cc, gg: ArXiv:2203.01469

Latest Setups of Runs at CEPC

Operation mode		ZH	Z	W^+W^-	ttbar (new)
$\sqrt{s}$ [GeV]		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7/10	2	1	~5
CDR	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	3	32	10	
	$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	
	Event yields [2 IPs]	1×10^{6}	7×10^{11}	2×10^{7}	
Latest	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	8.3	191.7	26.6	0.83
	$\int L\,dt$ [ab^{-1}, 2 IPs]	20	100	6.0	1.0
	Event yields [2 IPs]	4×10^{6}	3×10^{12}	1×10^{8}	5×10^{5}



The Physics potential of the CEPC

Prepared for the US Snowmass Community Planning Exercise

(Snowmass 2021)

CEPC Physics Study Group

May 2022

ArxiV : 2205.08553

✓The luminosity of Higgs run can be upgradable from 5.6 ab^{-1} to 20 ab^{-1}.

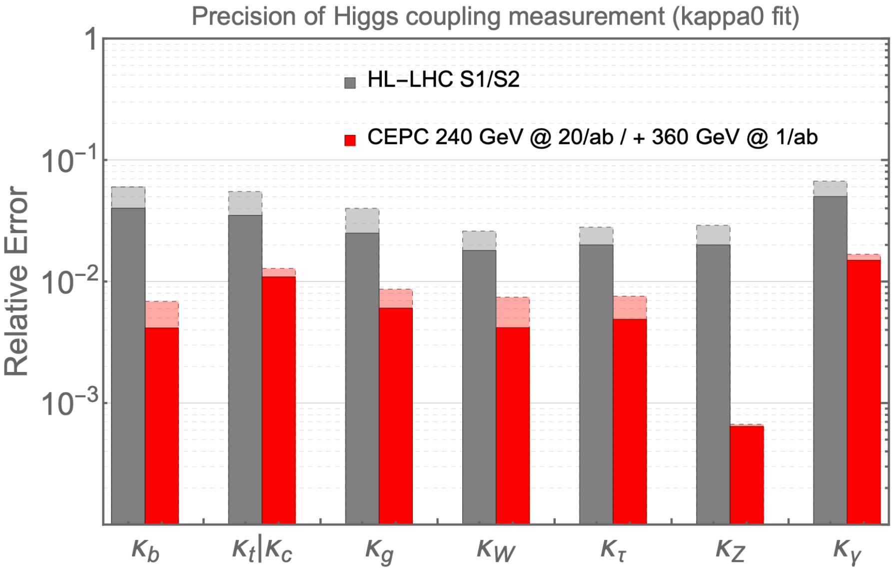
✓In addition to W/Z run improvement, CEPC is also upgradable to have top run with 1 ab^{-1}.

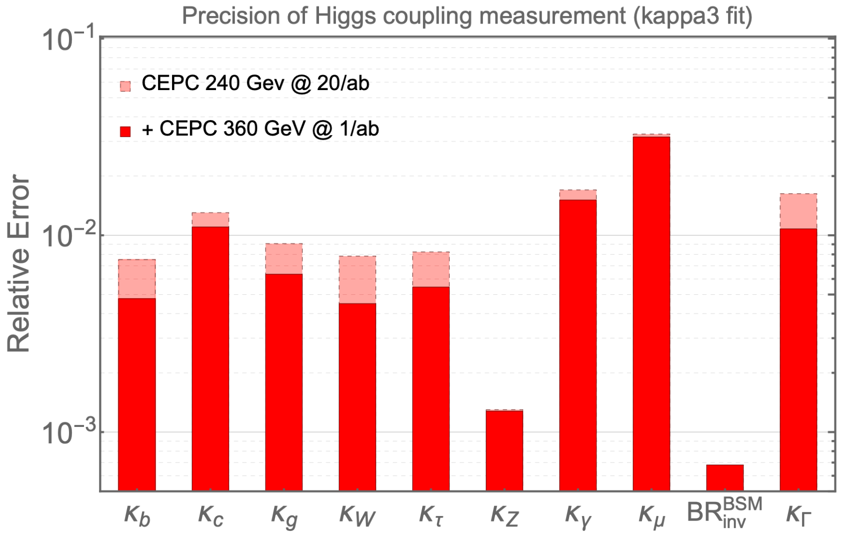
Impact of the updated running plans on Higgs

Kaili Zhang
ZhenLiu

- 1 ab^{-1}@360 GeV
- Improvement on Higgs width with 360 GeV run :
  - 1.65% →1.1%. vs. CDR 2.9%

	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	vvH	ZH	vvH	eeH
inclusive	0.26%		1.40%	\	\
H→bb	0.14%	1.59%	0.90%	1.10%	4.30%
H→cc	2.02%		8.80%	16%	20%
H→gg	0.81%		3.40%	4.50%	12%
H→WW	0.53%		2.80%	4.40%	6.50%
H→ZZ	4.17%		20%	21%	
$H \to \tau\tau$	0.42%		2.10%	4.20%	7.50%
$H \to \gamma\gamma$	3.02%		11%	16%	
$H \to \mu\mu$	6.36%		41%	57%	
$H \to Z\gamma$	8.50%		35%		
$\mathrm{Br}_{upper}(H \to inv.)$	0.07%				
Γ_H	1.65%		1.10%		



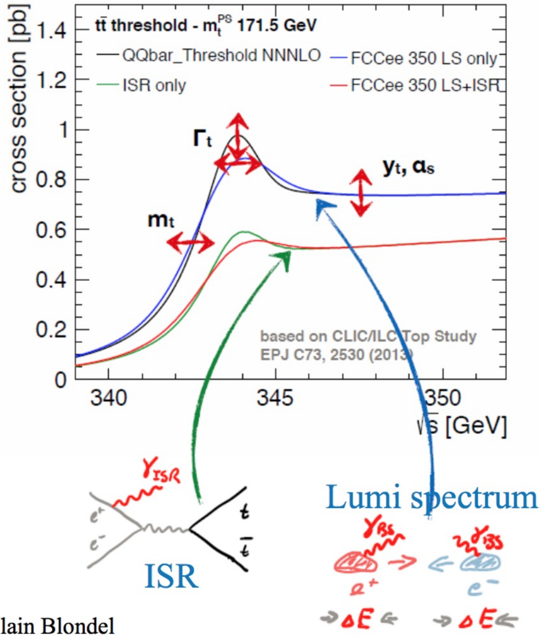


Top property measurement

Zhan Li

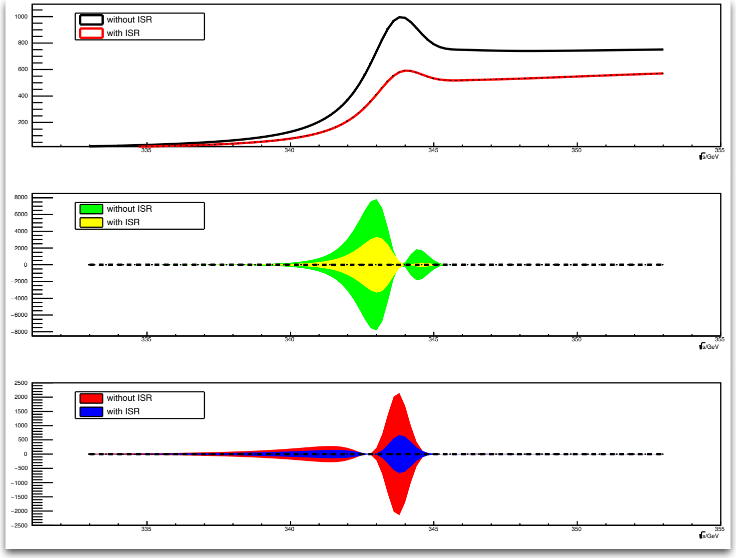
- 360 GeV runs open a door to measure top properties in high precision that hadron colliders cannot reach
- Currently we study the top mass and width measurements using the tt threshold method at ~360 GeV
  - One order of magnitude better precision than the hadron collider is expected
  - A single run at the energy where the tt xsection varies most largely in a given top mass range is found to provide the best performance
  - A quick energy scan with low luminosity to find the optimal energy point before data taking with the full luminosity is proposed
  - Simultaneous measurements of the top mass, width and α_s are also done.

Source	m_{top} precision (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	9	26
Background	4	18
Beam energy	2	2
Luminosity spectrum	3	5
Total	14	34



Alain Blondel

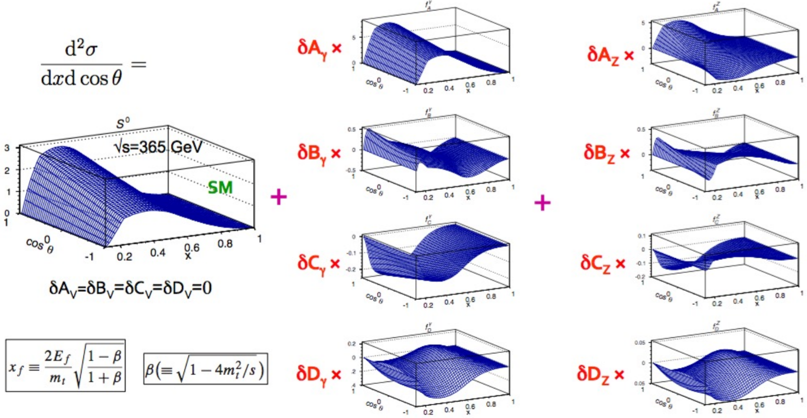
The peak indicates the optimal sqrt{s} for the top mass



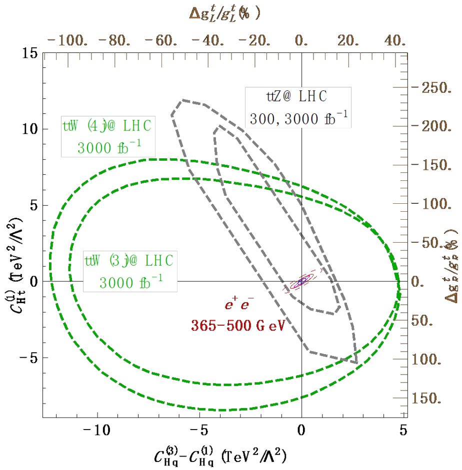
Top quark and Higgs EFT $O_{Hq}^{(1)}, O_{Hq}^{(3)}, O_{Ht}$

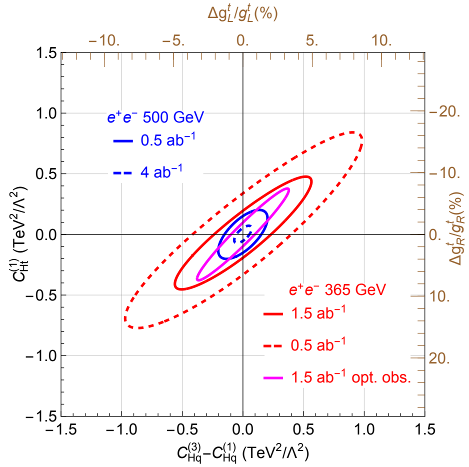
At or above $t\bar{t}$ threshold at lepton colliders, one immediately again great sensitivities to the top gauge couplings.

Patrick Janot



Zhen Liu



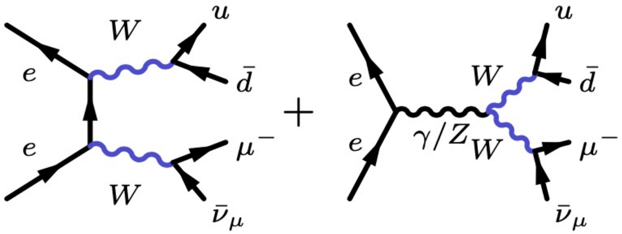


- ✓ Note that the opt. obs. Analysis is a rescaling of the study from Janot, we are working on CEPC simulation and analysis
- ✓ Expect to be consistent with FCC-ee.

W mass measurement at CEPC

Gang LI

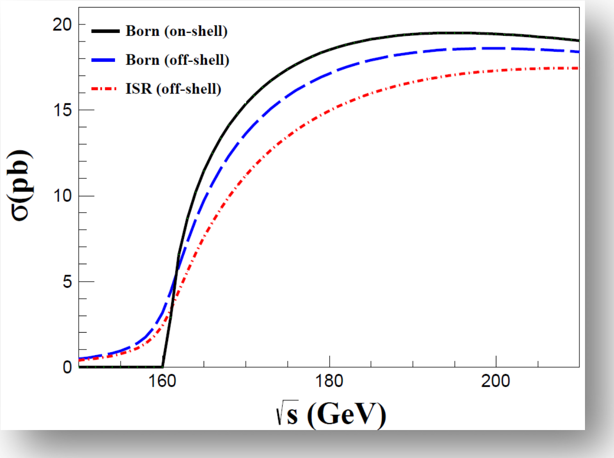
- ✓ scan the threshold to measurement the W mass, similar as top mass measurement.
- ✓ The scenario of 1-3 energy points are tested :
  - ✓ With most systematics taken into account except the theoretical ones, 1 MeV and 3 MeV uncertainties for W mass and width could be achieved, respectively.
  - ✓ Challenges for theorists : σ_{WW} of ~O(0.01)%



E_1	157.5 GeV
E_2	162.5 GeV
E_3	161.5 GeV
F_1	0.3
F_2	0.9

Δm_W~0.98 MeV
$\Delta\Gamma_W$ ~3.37 MeV

$\Delta L(\Delta\epsilon)<10^{-4}, \Delta\sigma_B<10^{-3}$
$\sigma_E=1\times10^{-3}$, ΔE=0.7MeV
$\Delta\sigma_E$=0.1



Data-taking scheme	mass or width	δ_{stat} (MeV)	δ_{sys} (MeV)				Total (MeV)
			ΔE	$\Delta\sigma_E$	δ_B	δ_c	
One point	Δm_W	0.65	0.37	–	0.17	0.34	0.84
Two points	Δm_W	0.80	0.38	–	0.21	0.33	0.97
	$\Delta\Gamma_W$	2.92	0.54	0.56	1.38	0.20	3.32
Three points	Δm_W	0.81	0.30	–	0.23	0.29	0.98
	$\Delta\Gamma_W$	2.93	0.52	0.55	1.38	0.20	3.37

Z mass measurement at CEPC

Sudong Wang

Data-taking strategy

- A preliminary data-taking scheme：

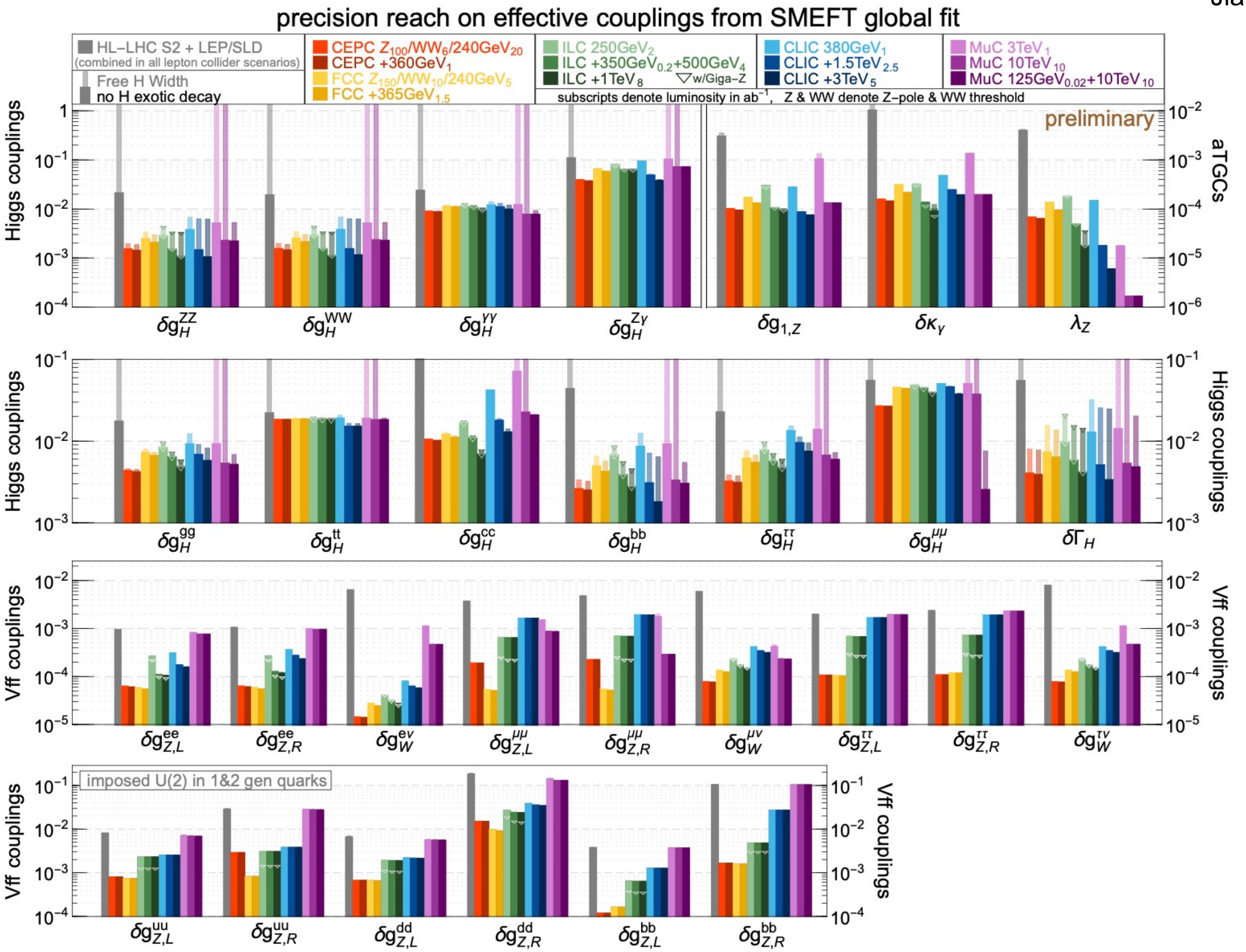
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (ab^{-1})	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (ab^{-1})	$\sqrt{s}$ (GeV)	$\mathcal{L}$(ab^{-1})
$E_1 = 84.6$	$\mathcal{L}_1 = 0.09$	$E_6 = 90.4$	$\mathcal{L}_6 = 0.50$	$E_{10} = 93.2$	$\mathcal{L}_{10} = 0.25$
$E_2 = 85.6$	$\mathcal{L}_2 = 0.13$	$E_7 = 91.2$	$\mathcal{L}_7 = 5.00$	$E_{11} = 94.3$	$\mathcal{L}_{11} = 0.18$
$E_3 = 87.9$	$\mathcal{L}_3 = 0.18$	$E_8 = 92.0$	$\mathcal{L}_8 = 0.50$	$E_{12} = 95.3$	$\mathcal{L}_{12} = 0.13$
$E_4 = 88.7$	$\mathcal{L}_4 = 0.25$	$E_9 = 92.5$	$\mathcal{L}_9 = 0.35$	$E_{13} = 96.2$	$\mathcal{L}_{13} = 0.09$
$E_5 = 89.9$	$\mathcal{L}_5 = 0.35$				

- Uncertainties

Parameter	δ_{stat}	δ_{total}
M_Z (KeV)	7	66
Γ_Z (KeV)	13	126
σ^0_{had} (pb)	0.09	1.73

Systematic dominant

(ISR effect not considered due to technical problems)


precision reach on effective couplings from SMEFT global fit
HL–LHC S2 + LEP/SLD
(combined in all lepton collider scenarios)
Free H Width
no H exotic decay
CEPC Z_{100}/WW_{6}/240GeV_{20}
CEPC +360GeV_{1}
FCC Z_{150}/WW_{10}/240GeV_{5}
FCC +365Ge$V_{1.5}$
ILC 250GeV_{2}
ILC +350Ge$V_{0.2}$+500GeV_{4}
ILC +1TeV_{8}
▽w/Giga–Z
CLIC 380GeV_{1}
CLIC +1.5Te$V_{2.5}$
CLIC +3TeV_{5}
MuC 3TeV_{1}
MuC 10TeV_{10}
MuC 125Ge$V_{0.02}$+10TeV_{10}
subscripts denote luminosity in ab^{-1}, Z & WW denote Z–pole & WW threshold
preliminary
Higgs couplings
aTGCs
Vff couplings
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
δg_H^{ZZ}
δg_H^{WW}
$\delta g_H^{\gamma\gamma}$
$\delta g_H^{Z\gamma}$
$\delta g_{1,Z}$
$\delta\kappa_\gamma$
λ_Z
δg_H^{gg}
δg_H^{tt}
δg_H^{cc}
δg_H^{bb}
$\delta g_H^{\tau\tau}$
$\delta g_H^{\mu\mu}$
$\delta\Gamma_H$
$\delta g_{Z,L}^{ee}$
$\delta g_{Z,R}^{ee}$
$\delta g_W^{e\nu}$
$\delta g_{Z,L}^{\mu\mu}$
$\delta g_{Z,R}^{\mu\mu}$
$\delta g_W^{\mu\nu}$
$\delta g_{Z,L}^{\tau\tau}$
$\delta g_{Z,R}^{\tau\tau}$
$\delta g_W^{\tau\nu}$
imposed U(2) in 1&2 gen quarks
$\delta g_{Z,L}^{uu}$
$\delta g_{Z,R}^{uu}$
$\delta g_{Z,L}^{dd}$
$\delta g_{Z,R}^{dd}$
$\delta g_{Z,L}^{bb}$
$\delta g_{Z,R}^{bb}$

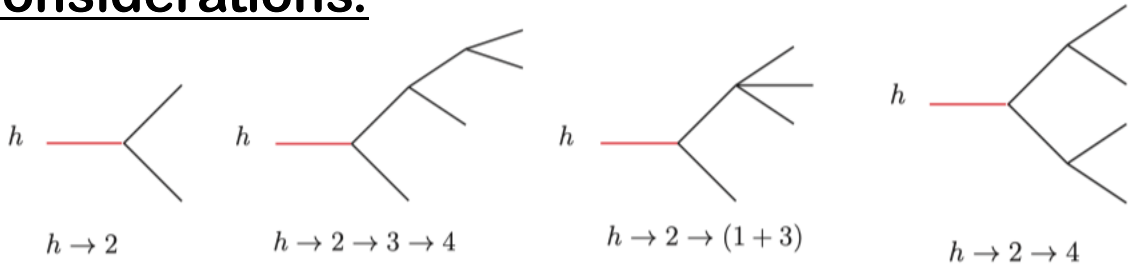
BSM Status

Xuai Zhuang

- BSM Higgs (1709.06103; 1808.02037; 1912.01431; 2008.05492； 2011.04540)
- SUSY Searches
  - Direct SUSY Searches (CPC46(2022)013106; 2101.12131; 2203.10580;2202.11011)
  - Indirect search of SUSY (2010.09782)
  - Global fit of SUSY (2203.04828)
- Dark Matter and Dark Sector searches
  - Lepton portal DM (JHEP 06 (2021) 149)
  - Asymmetric DM (PRD 104(2021)055008)
  - Dark Sector from exotic Z decay (1712.07237)
  - DM (Millicharged DM, Vector portal DM, DM with EFT interactions): 1903.1211
  - Mono-gamma (2205.05560)
- Long-lived particles (1904.10661, 1911.06576, 2201.08960)
- More exotics:
  - Heavy neutrinos (2102.12826);
  - Axion-like particles (2103.05218, 2204.04702, Jia Liu's talk)
  - Electroweak phase transition (1911.10210,1911.10206,2011.04540)
  - ……

BSM Higgs

- **A large class of BSM physics, such as singlet extensions, two Higgs-doublet-models (2HDM), SUSY models, Higgs portals, gauge extensions of the SM, motivates these exotic decay considerations.**

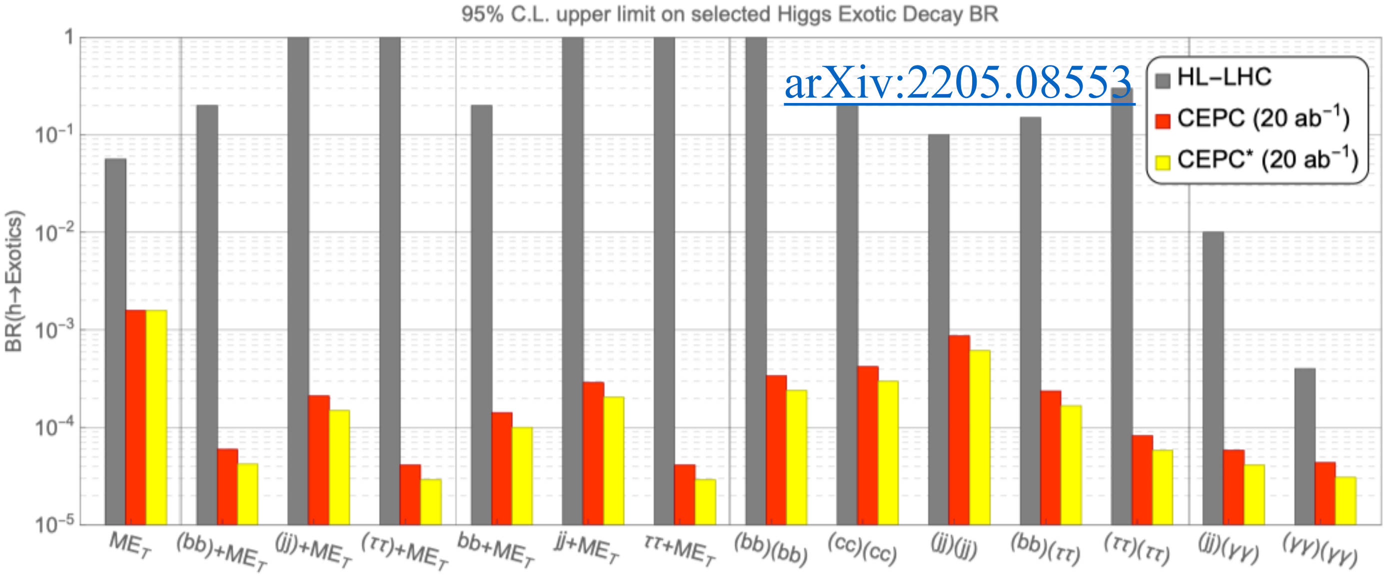


Representative topologies of the Higgs exotic decays

- Reference:
  - 2HDM searches: 1709.06103; 1808.02037; 1912.01431; 2008.05492; 2011.04540
  - Exotic higgs decay: 1612.09284 , 2110.13225 , 2203.08206, 2002.05554 , 2003.01662 , 2006.03527 …
  - **Summarized at 2205.08553.**

Exotic Higgs Decay

- **Exotic decays of the 125 GeV Higgs boson at future e +e − lepton colliders, Z. Liu, L.-T. Wang, and H. Zhang,** 1612.09284
- **Exotic Higgs Decays to Four Taus at Future Electron-Positron Colliders, J. Shelton and D. Xu,** 2110.13225
- **CEPC is very sensitive for signals with jets, heavy quarks and taus, which is challenge at LHC**



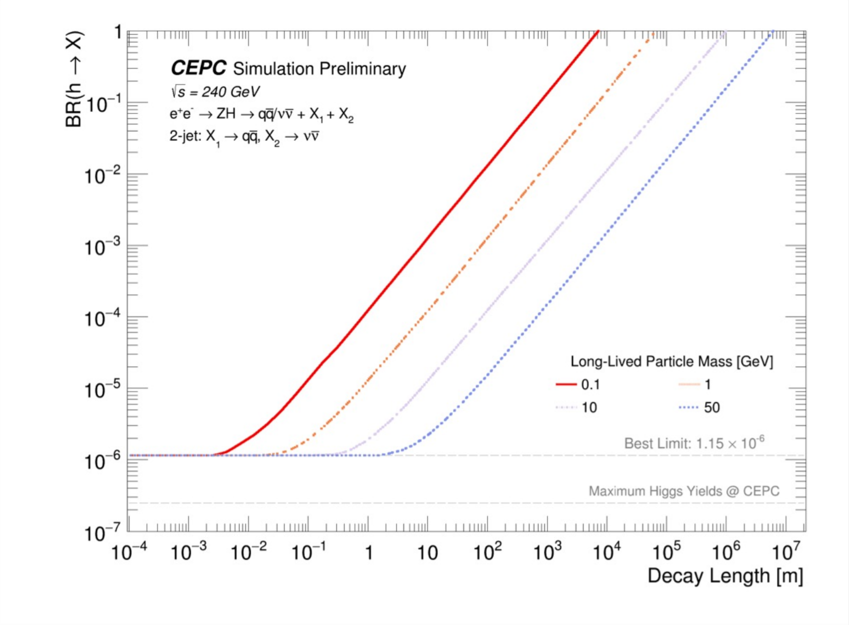
arXiv:2205.08553

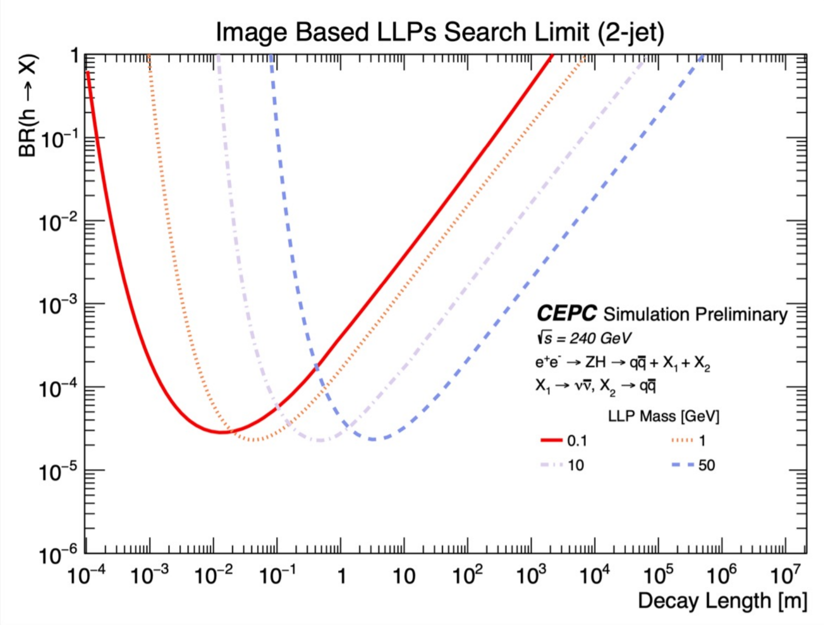
The 95% C.L. upper limit on selected Higgs exotic decay BR

H→ *long lived particles*

Yulei Zhang

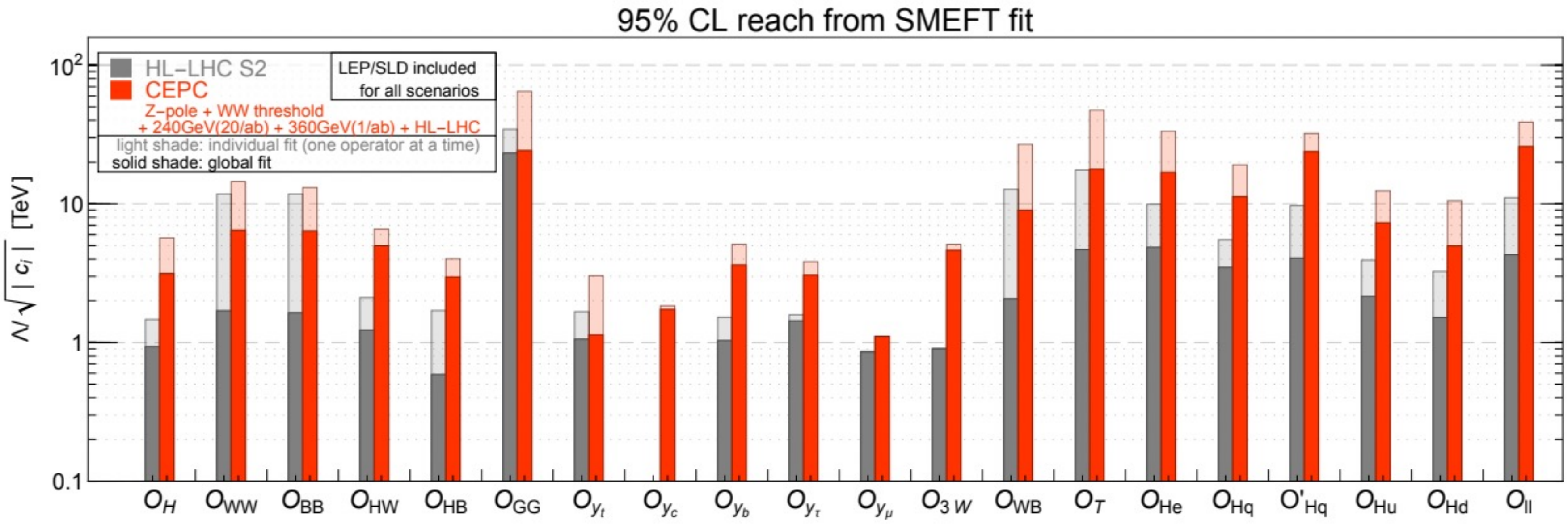
Sensitivity (compared with previous 2-jet analysis)





- Previous best limit: $\sim 1\times 10^{-5}$ ($5.6\ \mathrm{ab}^{-1}$), Current best limit: $\sim 1\times 10^{-6}$ ($20\ \mathrm{ab}^{-1}$)
- Main improvement on geometry acceptance: $\boldsymbol{r}_{\mathbf{decay}}$ from [1,6] to (0,6]

Energy Scale for the new physics



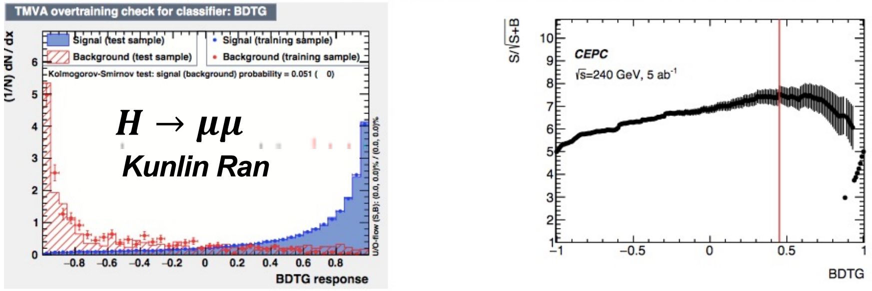
Conclusion

- After the Higgs white paper and CDR are done, analyses from individual channels have been documented. Several publications of them are available now.
- With the upgradable running plans, the results have been updated.
  - Can bring some improvements in Higgs precision measurement in addition to top coupling measurements.
    - Significant enhancement on Higgs width measurement.
  - The impacts of 360GeV/1 ab^{-1} on Higgs are studied.
  - Top/W/Z mass measurements.
  - BSM
  - Flavor physics not covered here but can be found at :
    - https://arxiv.org/abs/2205.08553
- Aim at Physics white papers (BSM, Physics with top run, Flavor, EW…) and actively participate the Snowmass studies.

backup Slides

MVA methods widely used Higgs analyses

- After training with 6 variables: $cos\theta_{ee}$, $cos\theta_{\mu\mu}$, $\Delta_{\mu,\mu}$, M_{qq}, E_{ee}, $E_{qq\mu\mu}$, get the BDTG response



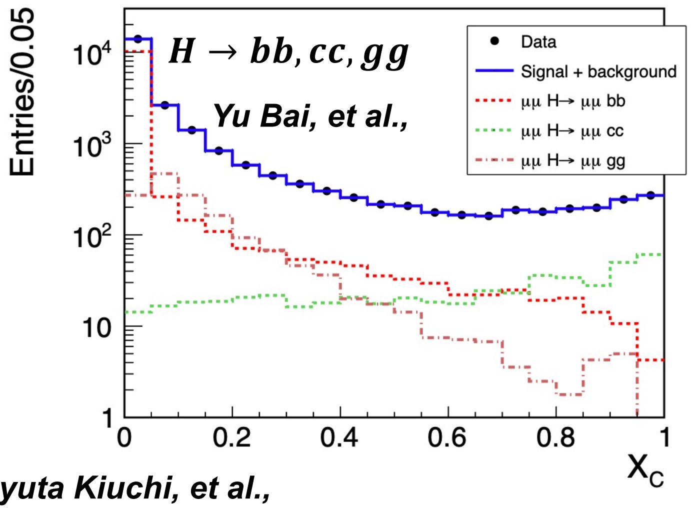
$H \rightarrow \mu\mu$

Kunlin Ran

- There is a overtraining in the background due to poor statistics: ~1600
- Scan the total sensitivity ($S/\sqrt{S+B}$) vs BDTG to find the optimal BDTG point
- The sensitivity is estimated in the 90% signal coverage region

	Sig yield	Bkg yield	Sensitivity	Mass range (GeV)
BDTG > 0.45	86.20 +/- 0.51	198.20 +/- 19.82	7.46 +/- 0.27	[120.78 - 125.33]
BDTG < 0.45	29.77 +/- 0.30	1402.95 +/- 52.73	1.08 +/- 0.03	[114.08 - 125.28]
Total	115.97 +/- 0.59	1601.15 +/- 56.33	7.54 +/- 0.38	

CPC Vol. 44, No.1 (2020)013001



$H \rightarrow bb, cc, gg$

Yu Bai, et al.,

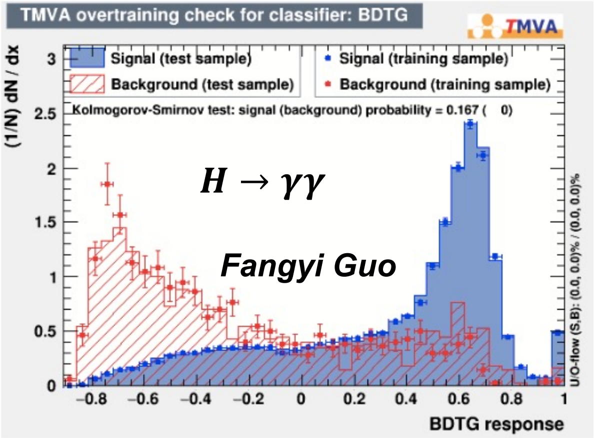
Ryuta Kiuchi, et al.,

- ➢ For H->μμ, the improvement is ~35% w.r.t cut based one for the signal significance (improvement on precision 17%-12%).

$H \rightarrow ZZ$ ArXiv: 2103.09633

Category	$\frac{\Delta(\sigma \cdot BR)}{(\sigma \cdot BR)}$ [%] cut-based	BDT
$\mu\mu H\nu\nu qq^{cut/mva}$	15.5	13.6
$\mu\mu Hqq\nu\nu^{cut/mva}$	48.0	42.1
$\nu\nu H\mu\mu qq^{cut/mva}$	11.9	12.5
$\nu\nu Hqq\mu\mu^{cut/mva}$	23.5	20.5
$qqH\nu\nu\mu\mu^{cut/mva}$	45.3	37.0
$qqH\mu\mu\nu\nu^{cut/mva}$	52.4	44.4
Combined	8.34	7.89

- ➢ The overall precision has been improved from 6.8% to 5.7% with MVA as well as full simulated samples used for H->γγ.



$H \rightarrow \gamma\gamma$

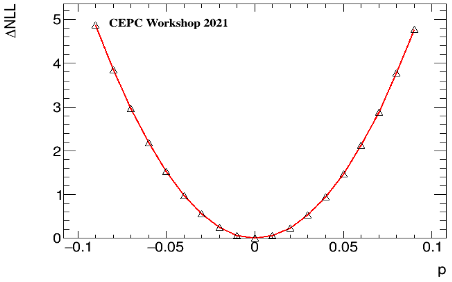
Fangyi Guo

Other activities in Higgs group

Higgs CP Study

Study channel: *Qiyu Sha*

$ee \to ZH \to \mu\mu H(\to b\bar{b}/c\bar{c}/gg)$



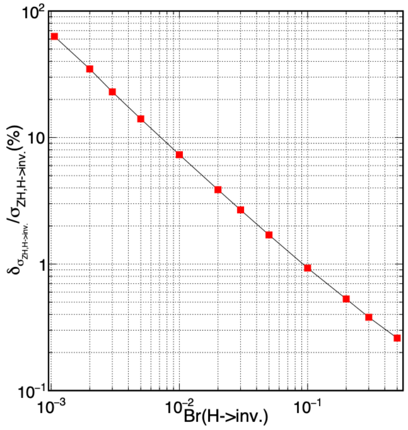
68% CL: $[-2.9\times10^{-2}, 2.9\times10^{-2}]$

95% CL: $[-5.7\times10^{-2}, 5.7\times10^{-2}]$

Higgs invisible decays

ArXiv:2103.09633

Ryuta Kiuchi, et al.



Global analysis

$$\Sigma^N = N_t^e \begin{pmatrix} B_1(1-B_1) & -B_1B_2 & \dots & -B_1B_m \\ -B_2B_1 & B_2(1-B_2) & \dots & -B_2B_m \\ \vdots & \vdots & \ddots & \vdots \\ -B_mB_1 & -B_mB_2 & \dots & B_m(1-B_m) \end{pmatrix},$$

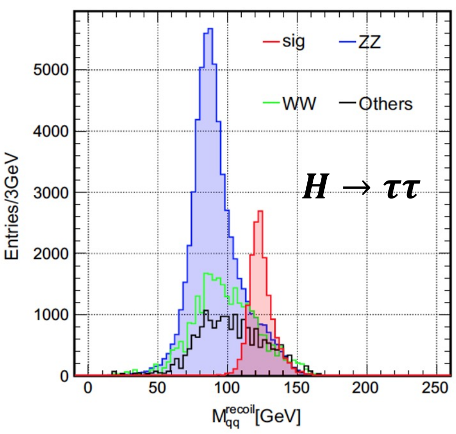
Gang Li

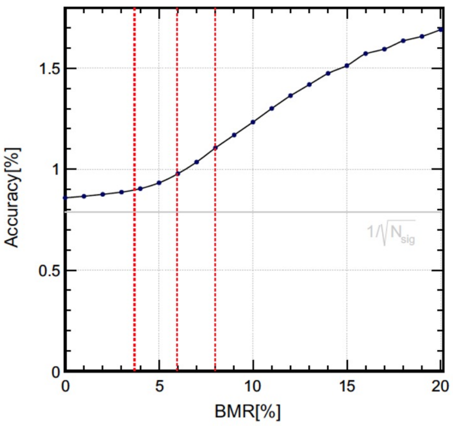
ArXiv:2105.14997

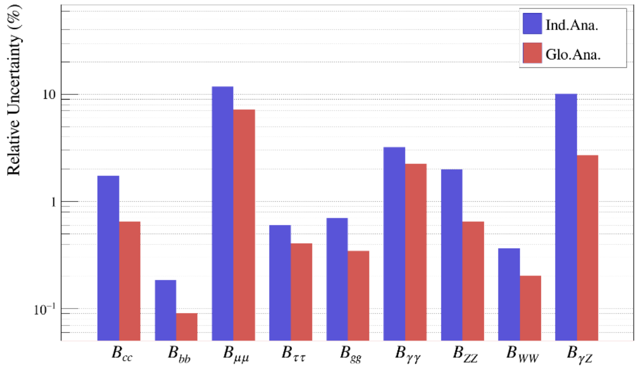
- ✓ Calculate the efficiency matrix
- ✓ Particle level information as the input.
- ✓ Proof-of-Principle study shows precision improved by a factor of ~2.
- ✓ Full simulation study is ongoing.

Higgs decays to $\tau\tau$

Euro. Phys. J. C(2020) 80:7 **Dan Yu**







Workshops for white papers

White paper activities:

- 2019.3 Higgs White Paper delivered
- 2019.7 WS @ PKU: EW, Flavor, QCD working group formed
- 2020.1 WS @ HKIAS: Review progress & iterate. EW Draft Ready
- 2021.4 WS @ Yangzhou: BSM working group formed

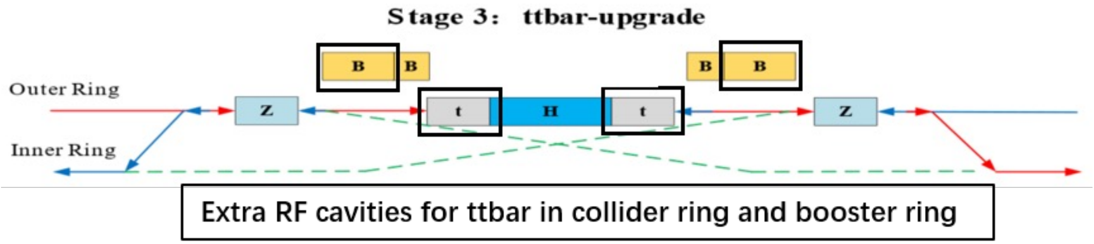
https://indico.ihep.ac.cn/event/13888/

- CEPC Physics/Detector WS, **April 2021 @ Yangzhou**
  - ~ 45 Physics reports
  - ~ 10 Performance/Optimization study
  - Significant Fresh
- *Higgs: Impact of 360 GeV Runs*
- *Top physics at 360 GeV*
- *EW: Draft ready*
- *QCD: intensive discussions...*
- *Flavor + BSM:*
  - *Many Performance & Benchmark analyses*

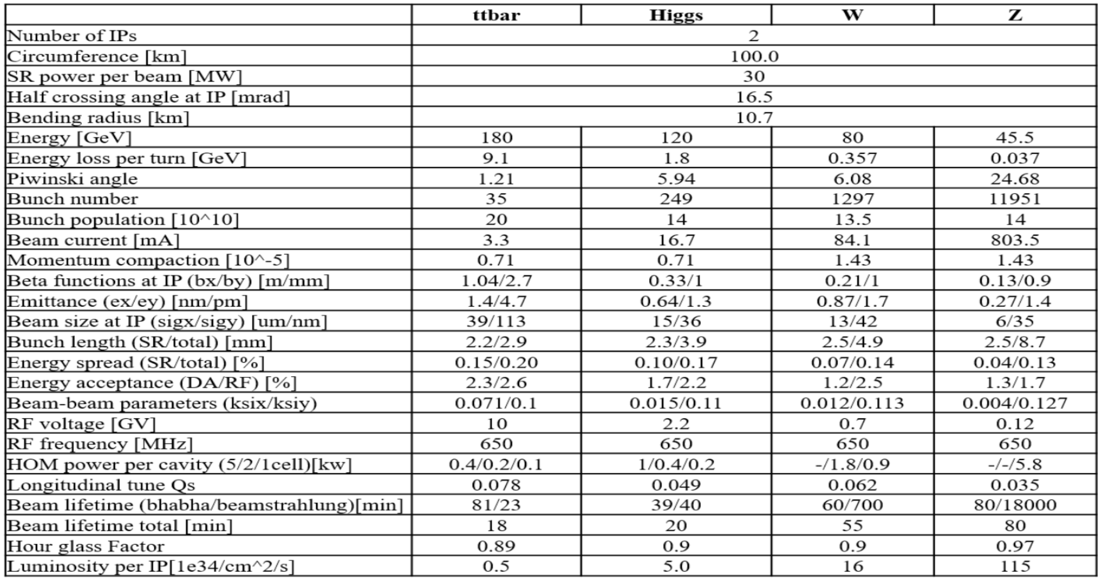
Accelerator at ttbar

Yiwei Wang

- Extra Hardware:
  - ttbar cavities (international sharing): Collider + 7 GV 650 MHz 5-cell cavity, Booster + 6 GV 1.3 GHz 9-cell cavity
  - some septum magnets for beam separation in the RF regions
  - several quadrupole magnets for final focusing
- Accelerator physics design:
  - With SR power limit of 30MW, curren design achieved a luminosity of 0.5E34/cm^2/s/IP
  - corresponding to 1ab^{-1} for 7.7 years with 1.3 Snowmass units running/year
- To achieve 2 ab^{-1} for 7.7 years
  - reducing the βy*, coupling factor and increasing the synchrotron radiation power limit.

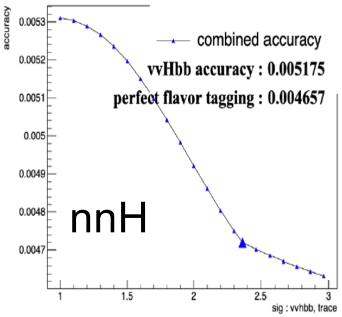


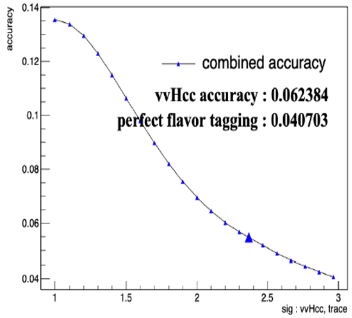
Extra RF cavities for ttbar in collider ring and booster ring

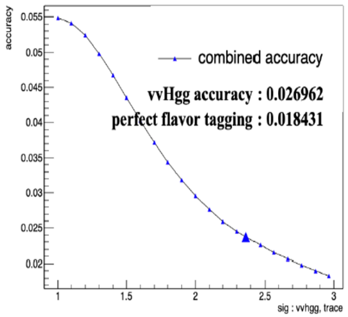


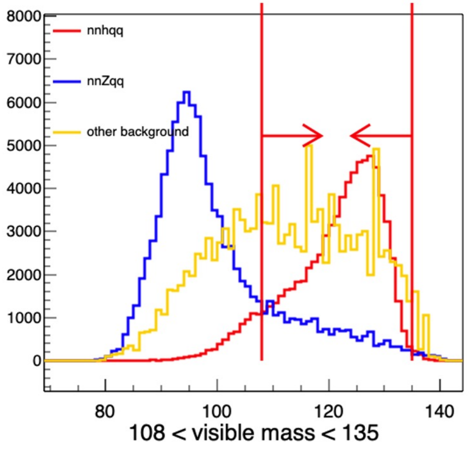
	ttbar	Higgs	W	Z
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	30			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	0.27/1.4
Beam size at IP (sigx/sigy) [um/nm]	39/113	15/36	13/42	6/35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/3.9	2.5/4.9	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	0.10/0.17	0.07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	2.3/2.6	1.7/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	0.071/0.1	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/0.9	-/-/5.8
Longitudinal tune Qs	0.078	0.049	0.062	0.035
Beam lifetime (bhabha/beamstrahlung)[min]	81/23	39/40	60/700	80/18000
Beam lifetime total [min]	18	20	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

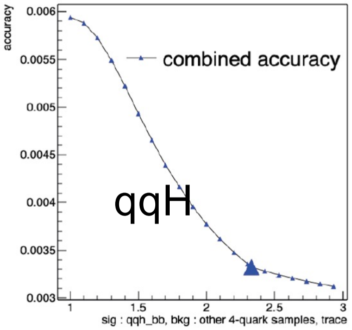
H→bb, cc, gg: BMR, Color Singlet id (CSI) & Flavor tagging (Preliminary)

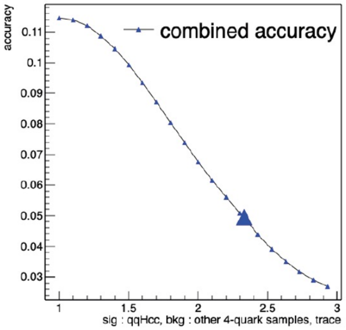


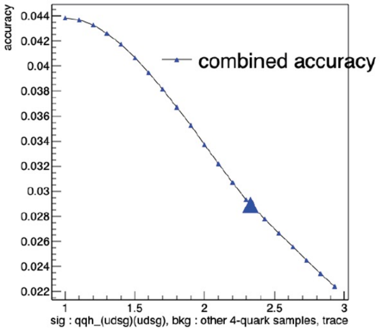


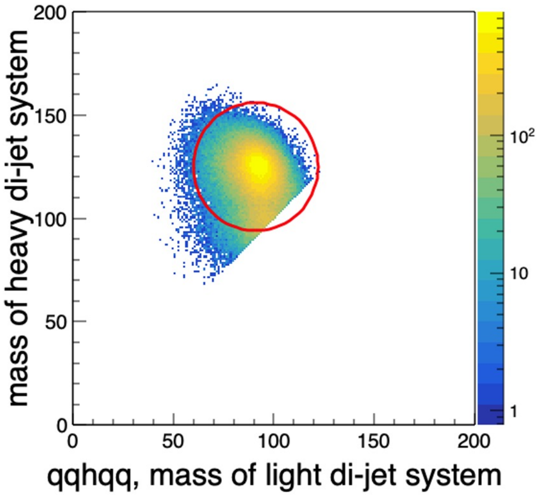












- BMR is good enough... Huge penitential compared to Baseline FT + Naive CSI (ee-kt jet clustering & matching)
- Ideal CSI improves the accuracies by up to 2 times...
- Ideal Flavor tagging improves the accuracy of of Hcc by 2 times @ qqH, & 50% @ nnH

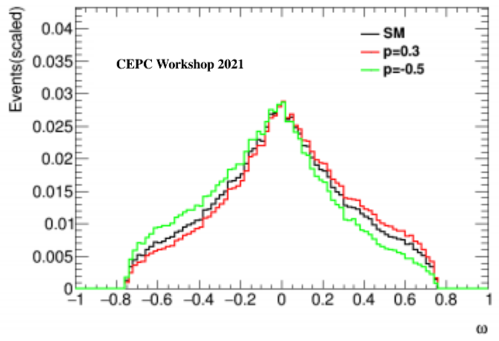
How to develop Jet Charge?

Jet Charge Algorithm:

- *Use Jet Clustering to divide final leading particles into two jets*
- *Find the relationship between observables(charge, energy) of final leading particles and jet charge:*
  - *For* $Z \to b\bar{b}$ *samples:*
    - $e^-, \mu^-, K^-, \pi^-, p^+$ *are closer to* b *jet*
    - $e^+, \mu^+, K^+, \pi^+, p^-$ *are closer to* $\bar{b}$ *jet*
  - *For* $Z \to c\bar{c}$ *samples:*
    - $e^+, \mu^+, K^-, \pi^+, p^+$ *are closer to* c *jet*
    - $e^-, \mu^-, K^+, \pi^-, p^+$ *are closer to* $\bar{c}$ *jet*

- *Combine the information of final leading particles of two jets*
- *Use those observables(charge, energy) of final leading particles to measure jet charge*
- *Use Misjudgment rate ω and effective tagging power to describe Jet Charge*

Higgs CP study at CEPC



Study channel: $ee \rightarrow ZH \rightarrow \mu\mu H(\rightarrow b\bar{b}/c\bar{c}/gg)$

Differential cross section could be represent as:

$$\frac{d\sigma}{dcos\theta_1 dcos\theta_2 d\phi} = N \times (J_{CP-even}(\theta_1, \theta_2, \phi) + p \times J_{CP-odd}(\theta_1, \theta_2, \phi)).$$

An Optimal Variable ω which combines the information from $\{\theta_1,\ \theta_2,$

$\omega = \frac{J_{CP-odd}(\theta_1,\theta_2,\phi)}{J_{CP-even}(\theta_1,\theta_2,\phi)}$ to measure p

Used ML-fit in ω distribution to extract p.

Result:

For p:
68% CL: $[-2.9\times10^{-2}, 2.9\times10^{-2}]$
95% CL: $[-5.7\times10^{-2}, 5.7\times10^{-2}]$

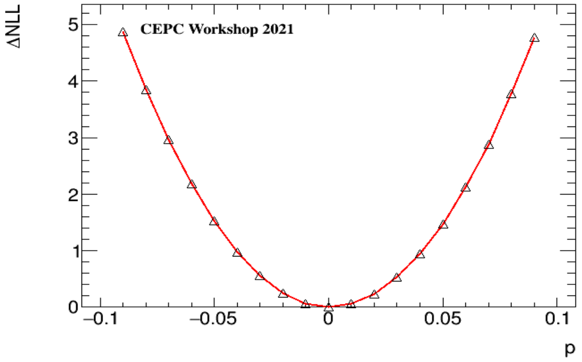
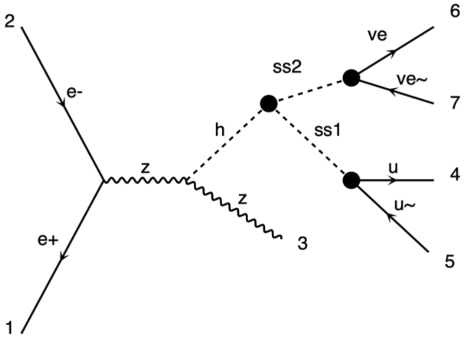
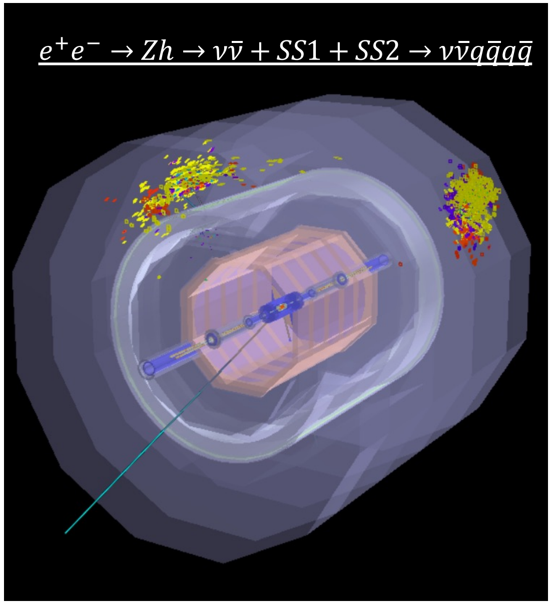


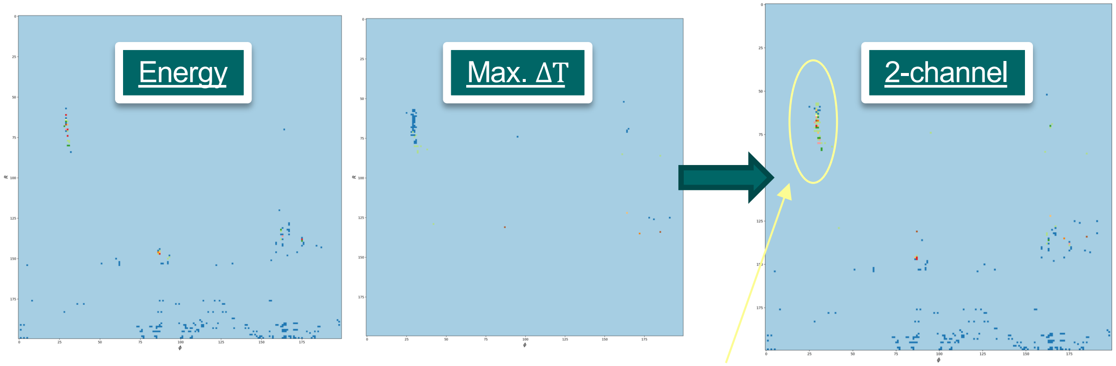
Image Recognition Techniques to Identify Long-Lived Particles(h->LLPs)



- Mapping the raw detector information to a 2D image
- Input information: image with resolution of $(\mathrm{R}, \phi) = 200 \times 200$ and 1 to 2 channel(s)
  - R starts from 0 to 8 m, ϕ starts from $-\pi$ to π
  - Energy is the sum of Calorimeter hits.
  - Time is the maximum $\Delta T\ (E > 0.1\ GeV)$ within (R, ϕ) pixel
- Model: ResNet18 (Classification), ResNet50 (Vertex Finding)
- **Binary Cross Entropy Loss:** $loss(x_i, y_i) = -\omega_i[y_i \log(x_i) + (1 - y_i)\log(1 - x_i)]$

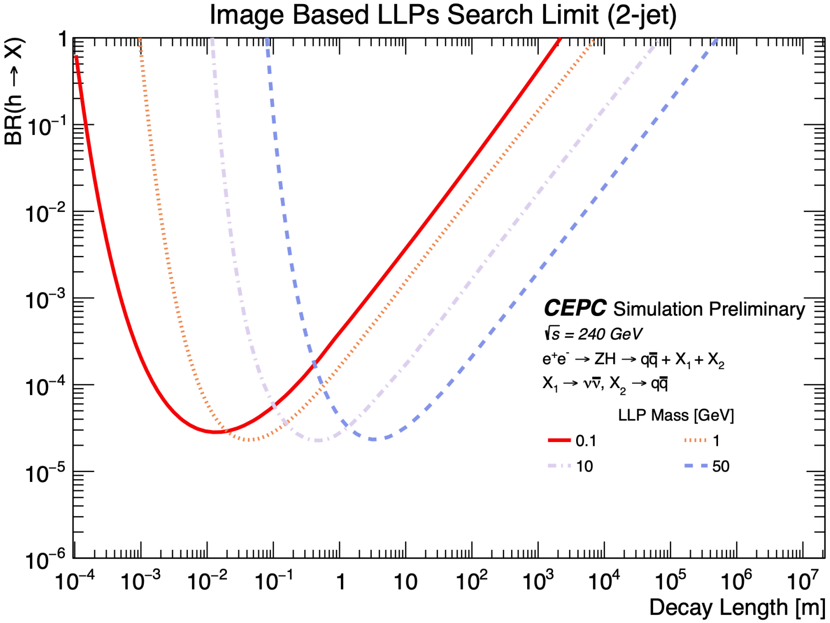


$e^+e^- \to Zh \to \nu\bar{\nu} + SS1 + SS2 \to \nu\bar{\nu}q\bar{q}q\bar{q}$

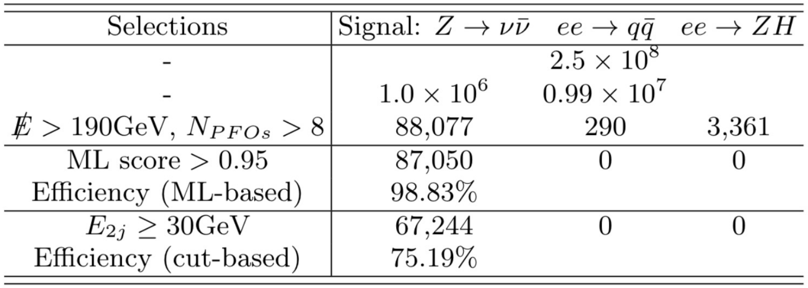


A LLP Event

Expected Search Sensitivity



Signal Efficiency of ML-based and Cut-based analysis for



Selections	Signal: $Z \to \nu\bar{\nu}$	$ee \to q\bar{q}$	$ee \to ZH$
-		2.5×10^{8}	
-	1.0×10^{6}	0.99×10^{7}	
$\not{E} > 190\text{GeV}$, $N_{PFOs} > 8$	88,077	290	3,361
ML score > 0.95	87,050	0	0
Efficiency (ML-based)	98.83%		
$E_{2j} \geq 30\text{GeV}$	67,244	0	0
Efficiency (cut-based)	75.19%		

- Best branching ratio exclusion limit at decay length around a few meters: $BR(h \to XX) > \sim 10^{-5}$ for most LLP masses
- Good sensitivity for low LLP mass (as low as 1 GeV)

Global analysis for CEPC Higgs

Efficiency modulate N → n

$$\mathbf{n} = \mathbf{E}\mathbf{N} \ .$$

Similar for their covariances

$$\mathbf{\Sigma}^n \equiv (c_{ij}^n) = \mathbf{E}\mathbf{\Sigma}^N\mathbf{E}^T \ ,$$

We know the covariance of N

~ multinomial

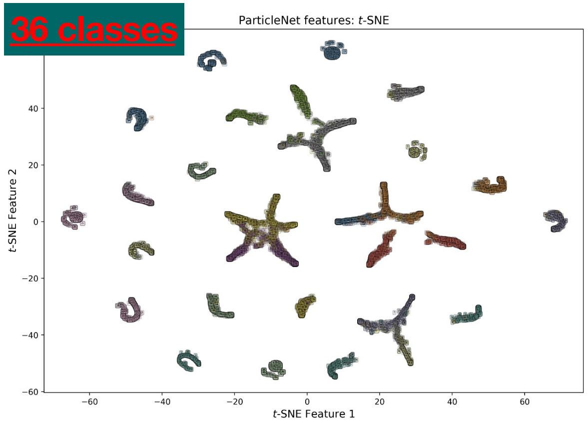
so Σ^n is easy

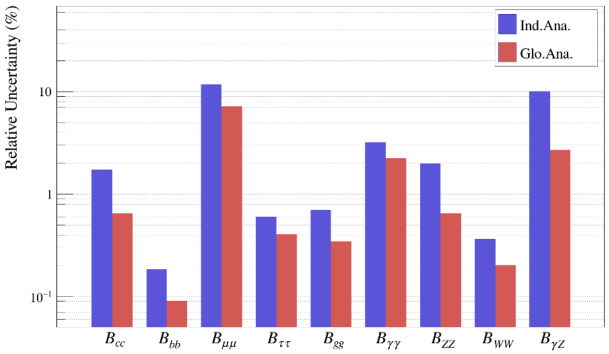
$$\mathbf{\Sigma}^N = N_t^e \begin{pmatrix} B_1(1-B_1) & -B_1B_2 & \dots & -B_1B_m \\ -B_2B_1 & B_2(1-B_2) & \dots & -B_2B_m \\ \vdots & \vdots & \ddots & \vdots \\ -B_mB_1 & -B_mB_2 & \dots & B_m(1-B_m) \end{pmatrix} ,$$

Solve all Ni by minimizing

$$\chi^2_{ee} = \sum_i \frac{(\sum_k \epsilon_{ik}N_k - n_i)^2}{c_{ii}} + \frac{(\sum_k N_k - N_t^e)^2}{\sigma^2_{N_t}},$$

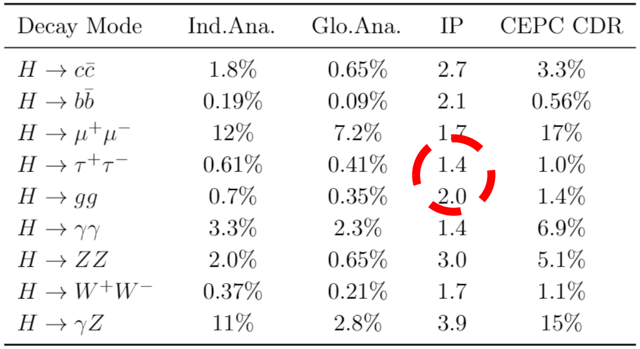
Global analysis : Enhance Higgs coupling precision


36 classes



ArXiv:2105.14997

calculate the efficiency matrix



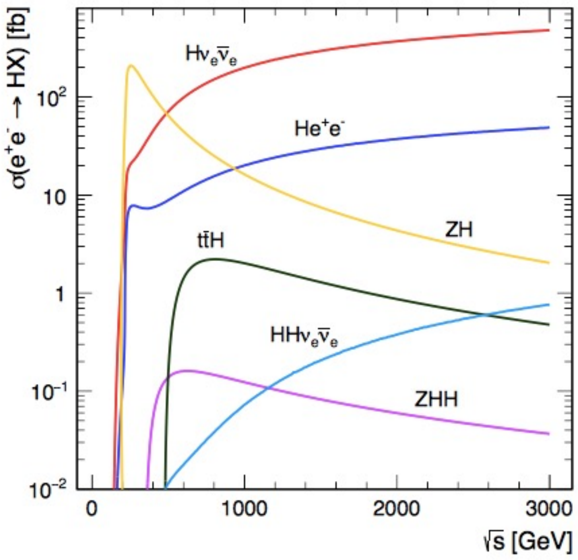
Decay Mode	Ind.Ana.	Glo.Ana.	IP	CEPC CDR
$H \to c\bar{c}$	1.8%	0.65%	2.7	3.3%
$H \to b\bar{b}$	0.19%	0.09%	2.1	0.56%
$H \to \mu^+\mu^-$	12%	7.2%	1.7	17%
$H \to \tau^+\tau^-$	0.61%	0.41%	1.4	1.0%
$H \to gg$	0.7%	0.35%	2.0	1.4%
$H \to \gamma\gamma$	3.3%	2.3%	1.4	6.9%
$H \to ZZ$	2.0%	0.65%	3.0	5.1%
$H \to W^+W^-$	0.37%	0.21%	1.7	1.1%
$H \to \gamma Z$	11%	2.8%	3.9	15%

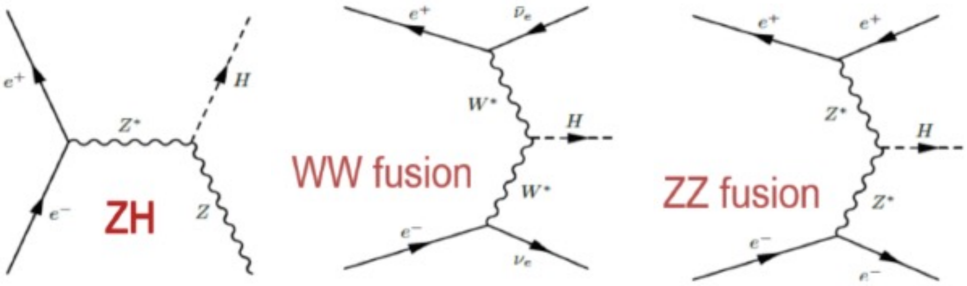
Particle level information as input, no dependence on jet-clustering, …

Proof-of-principle study shows precision improved by a factor of ~2

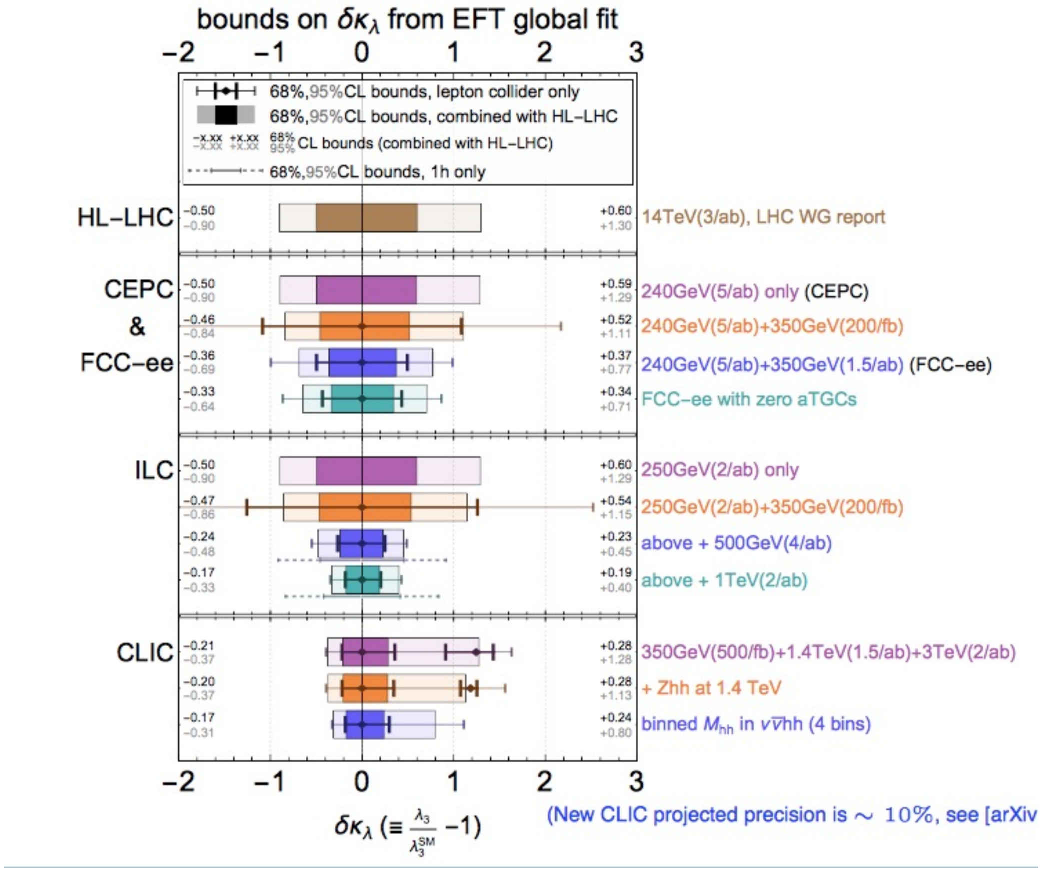
Full simulation study is ongoing …

Higgs related physics at e^+e^- collider



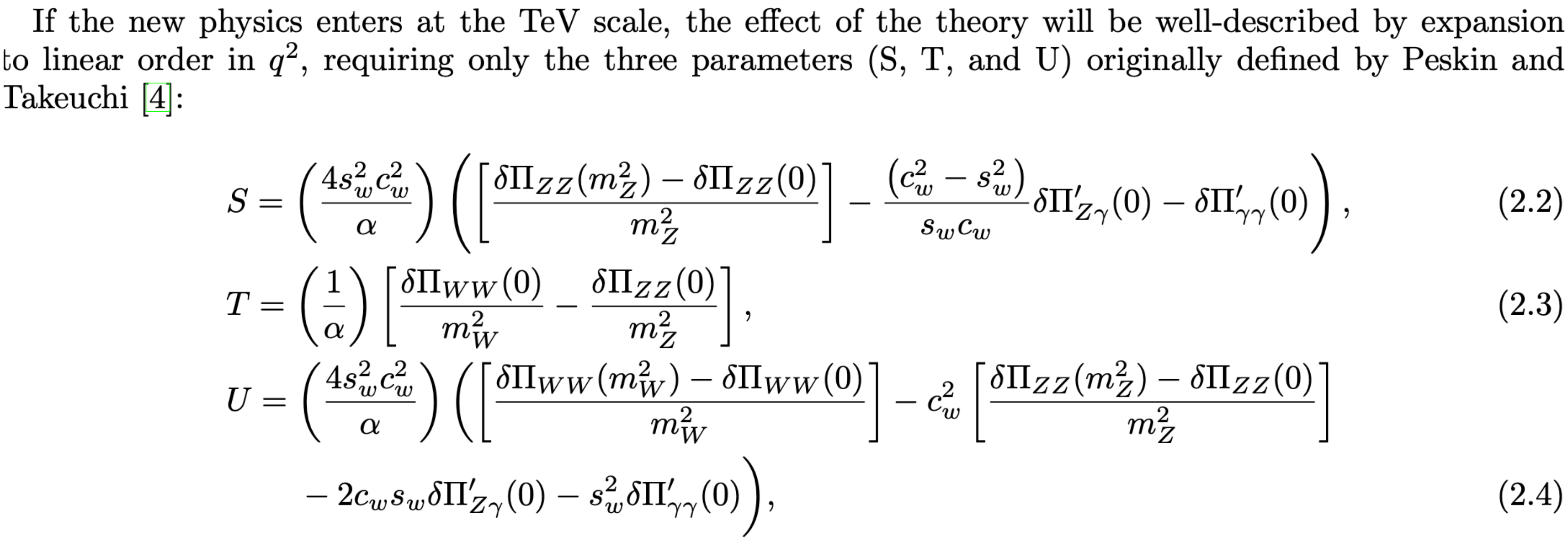


Impact on Higgs self-coupling



(New CLIC projected precision is $\sim$ 10%, see [arXiv

S and T in EW



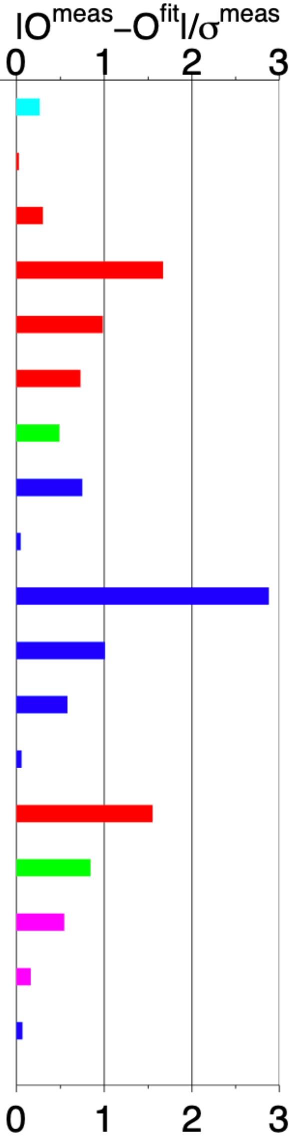
If the new physics enters at the TeV scale, the effect of the theory will be well-described by expansion to linear order in q^2, requiring only the three parameters (S, T, and U) originally defined by Peskin and Takeuchi [4]:

$$S = \left(\frac{4s_w^2c_w^2}{\alpha}\right)\left(\left[\frac{\delta\Pi_{ZZ}(m_Z^2) - \delta\Pi_{ZZ}(0)}{m_Z^2}\right] - \frac{(c_w^2 - s_w^2)}{s_wc_w}\delta\Pi'_{Z\gamma}(0) - \delta\Pi'_{\gamma\gamma}(0)\right), \tag{2.2}$$

$$T = \left(\frac{1}{\alpha}\right)\left[\frac{\delta\Pi_{WW}(0)}{m_W^2} - \frac{\delta\Pi_{ZZ}(0)}{m_Z^2}\right], \tag{2.3}$$

$$\begin{aligned} U = \left(\frac{4s_w^2c_w^2}{\alpha}\right)\Bigg(\left[\frac{\delta\Pi_{WW}(m_W^2) - \delta\Pi_{WW}(0)}{m_W^2}\right] - c_w^2\left[\frac{\delta\Pi_{ZZ}(m_Z^2) - \delta\Pi_{ZZ}(0)}{m_Z^2}\right] \\ - 2c_ws_w\delta\Pi'_{Z\gamma}(0) - s_w^2\delta\Pi'_{\gamma\gamma}(0)\Bigg), \end{aligned} \tag{2.4}$$

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2012

Lepton Flavor Universality (Violation)

Lepton flavor universality (LFU) demands that charged leptons have (almost) identical interactions, only differ by their Yukawa couplings and hence their masses.

However, in both flavor changing neutral current (FCNC) and flavor changing **charged current** (FCCC) processes

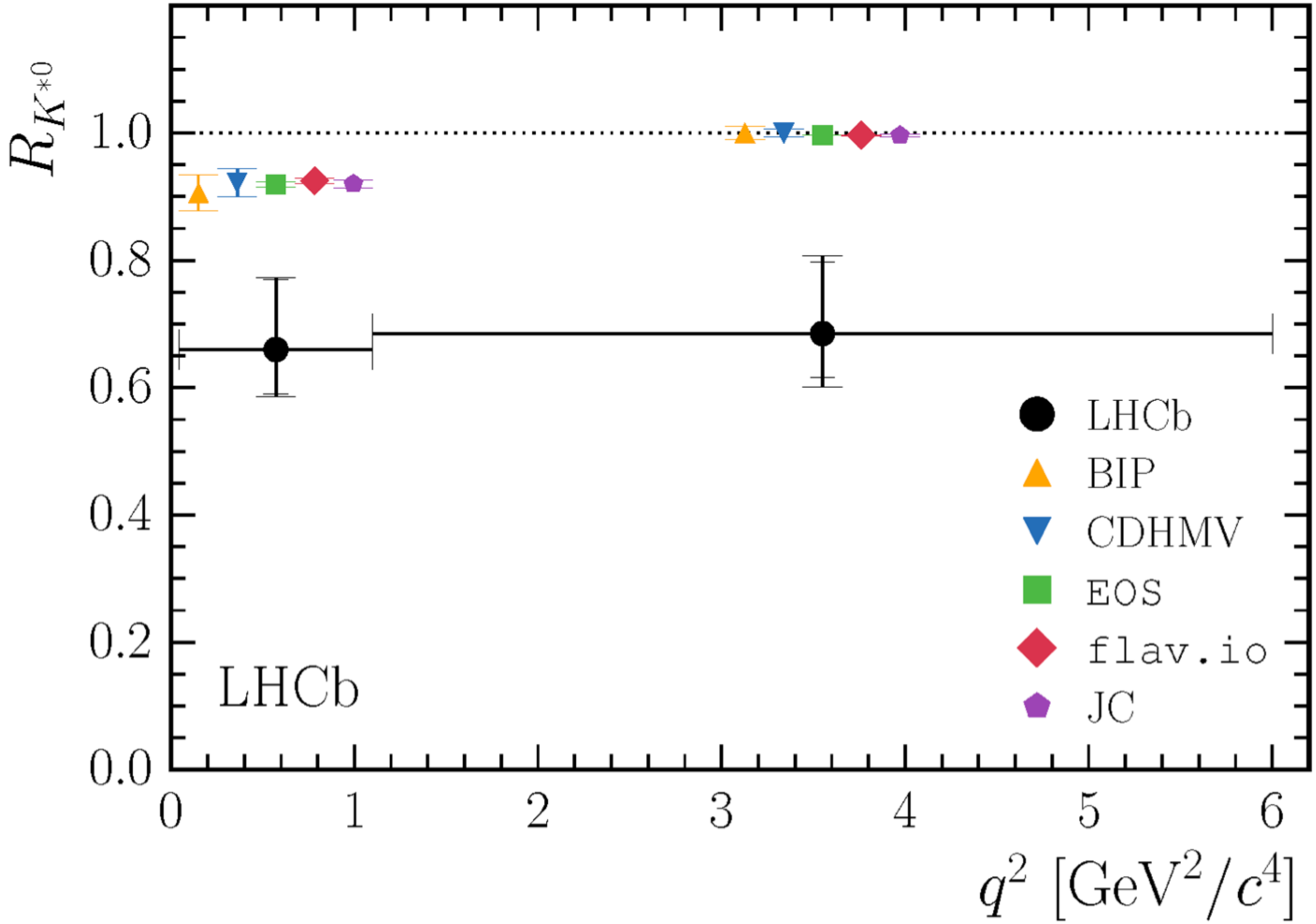
$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} \,, \tag{1}$$

$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \,, \tag{2}$$

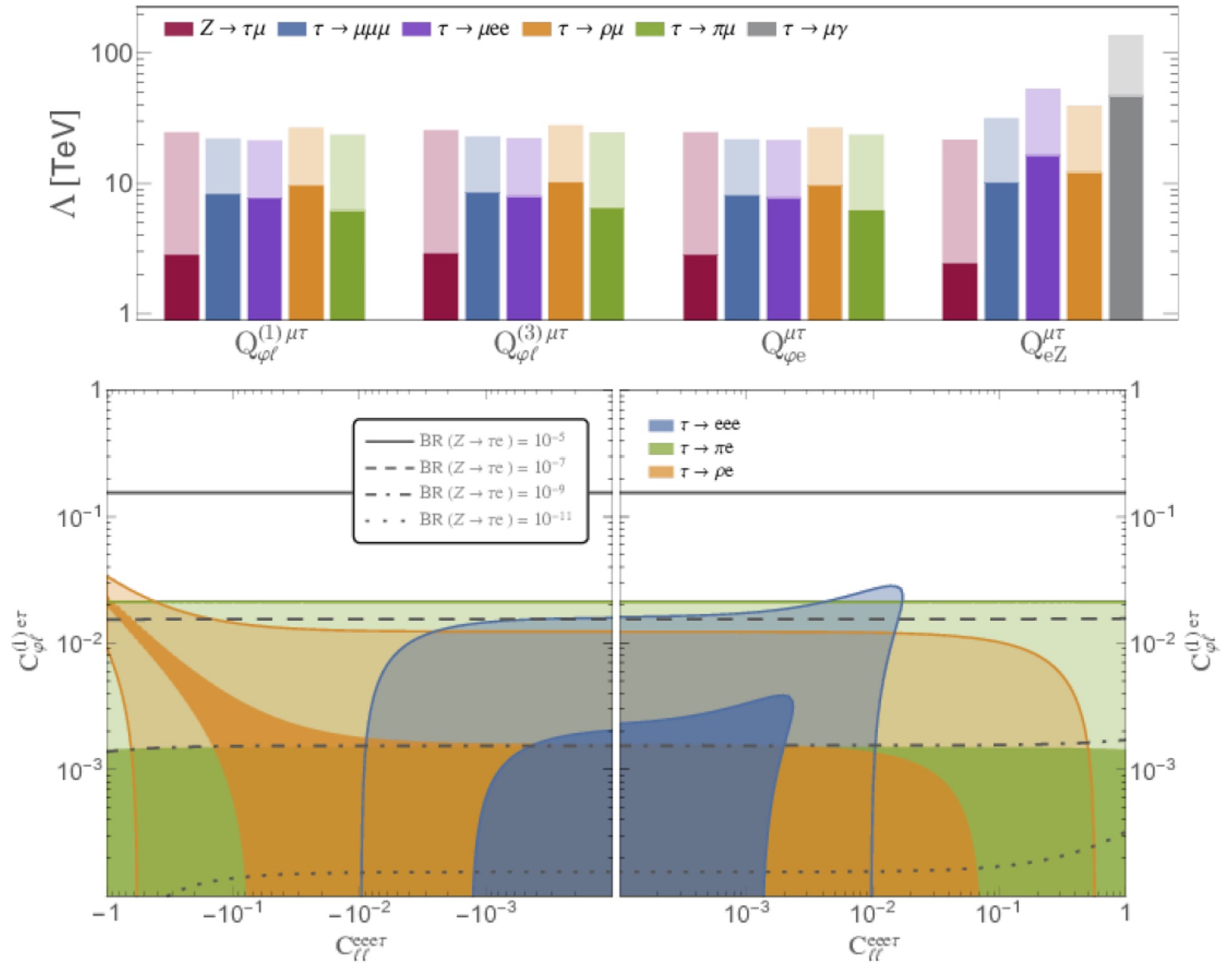
$$R_{J/\psi} \equiv \frac{\mathrm{BR}(B_c \to J/\psi\tau\nu)}{\mathrm{BR}(B_c \to J/\psi\ell\nu)} \,, \tag{3}$$

LFU is challenged.

LHCb LFUV results



Lepton Flavor Violation (II)

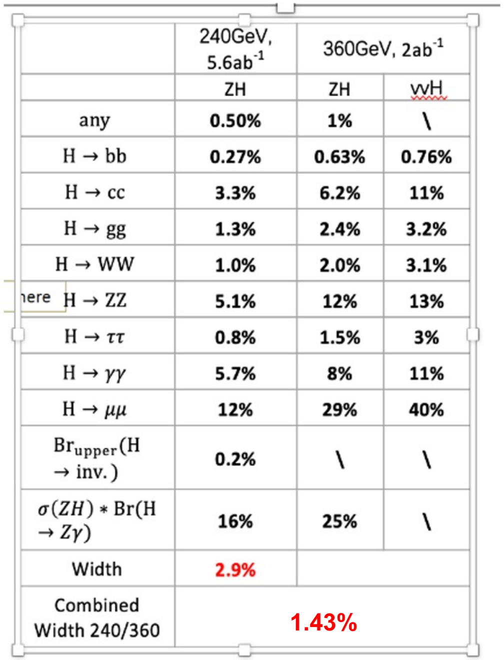


[Calibbi et al., 2021]

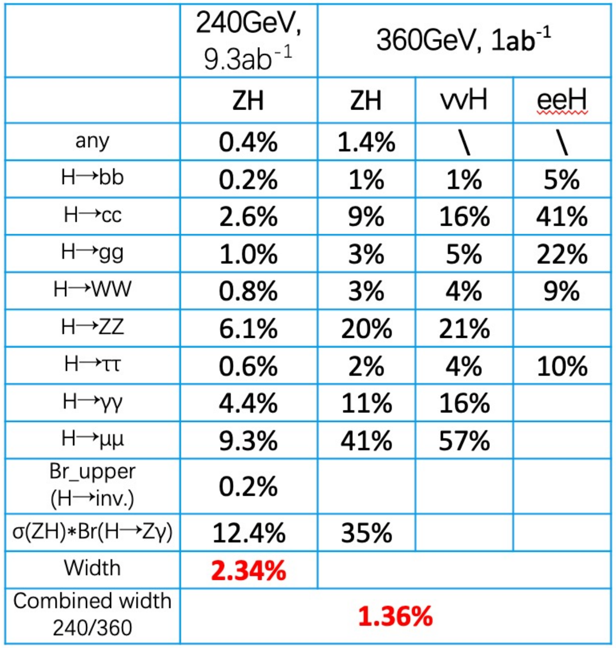
Impact of the updated running plans on Higgs physics

With the Lum@ 240 GeV：5.6 ab^{-1} → 9.3 ab^{-1} & the Lum@360 GeV Run： 2 ab^{-1} → 1 ab^{-1}:

the precision for Higgs width : 1.43% → 1.36% (very stable ☺)



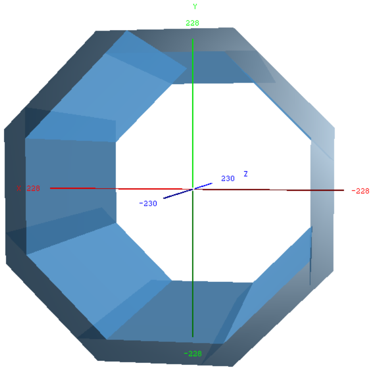
	240GeV, 5.6ab^{-1}	360GeV, 2ab^{-1}	
	ZH	ZH	vvH
any	**0.50%**	**1%**	\
$H \to bb$	**0.27%**	**0.63%**	**0.76%**
$H \to cc$	**3.3%**	**6.2%**	**11%**
$H \to gg$	**1.3%**	**2.4%**	**3.2%**
$H \to WW$	**1.0%**	**2.0%**	**3.1%**
$H \to ZZ$	**5.1%**	**12%**	**13%**
$H \to \tau\tau$	**0.8%**	**1.5%**	**3%**
$H \to \gamma\gamma$	**5.7%**	**8%**	**11%**
$H \to \mu\mu$	**12%**	**29%**	**40%**
$\mathrm{Br}_{\mathrm{upper}}(\mathrm{H} \to \mathrm{inv.})$	**0.2%**	\	\
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to Z\gamma)$	**16%**	**25%**	\
Width	**2.9%**		
Combined Width 240/360	**1.43%**		

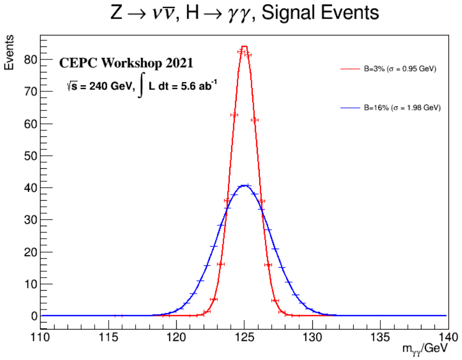


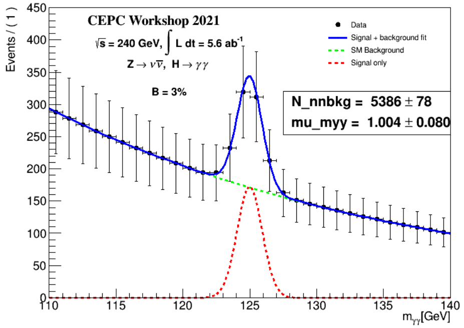
	240GeV, 9.3ab^{-1}	360GeV, 1ab^{-1}		
	ZH	ZH	vvH	eeH
any	0.4%	1.4%	\	\
H→bb	0.2%	1%	1%	5%
H→cc	2.6%	9%	16%	41%
H→gg	1.0%	3%	5%	22%
H→WW	0.8%	3%	4%	9%
H→ZZ	6.1%	20%	21%	
H→ττ	0.6%	2%	4%	10%
H→γγ	4.4%	11%	16%	
H→μμ	9.3%	41%	57%	
Br_upper (H→inv.)	0.2%			
σ(ZH)∗Br(H→Zγ)	12.4%	35%		
Width	**2.34%**			
Combined width 240/360	**1.36%**			

$H \rightarrow \gamma\gamma$ precision @ CEPC conceptual detector

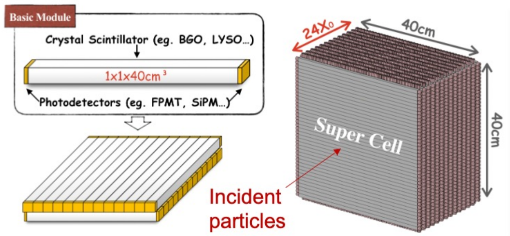
- BGO crystal ECAL in CEPC conceptual detector:
  - full BGO crystal, 24 X_0, expected energy resolution $\frac{\sigma_E}{E} \sim \frac{3\%}{\sqrt{E}} \oplus \sim 1\%$.
  - Simulate the detector response by smearing truth MC.
- $\sigma(ZH) \times Br(H \rightarrow \gamma\gamma)$ precision @ CEPC:
  - Only consider the σ_E influence in $m_{\gamma\gamma}$ shape in $\nu\nu H \rightarrow \gamma\gamma$ and $\mu\mu H \rightarrow \gamma\gamma$ channels, with cut-based analysis.
  - Combined statistical only precision: $\delta Br(H \rightarrow \gamma\gamma) = 8.0\%$ (11% @ SiW ECAL scheme, 27% improvement.)







New Concept



EM Resolution	$\delta(\sigma \times Br)$
$3\%/\sqrt{E} \oplus 1\%$	8.0%
$16\%/\sqrt{E} \oplus 1\%$	11%