Higgs/top Physics at CEPC

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(IHEP)

HKUST IAS Program on High Energy Physics

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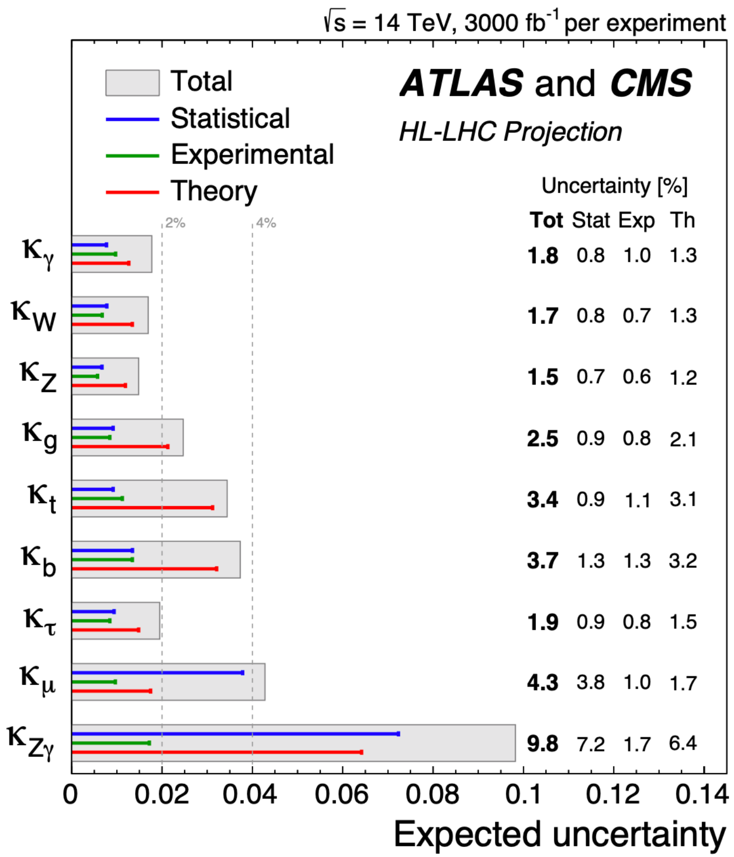
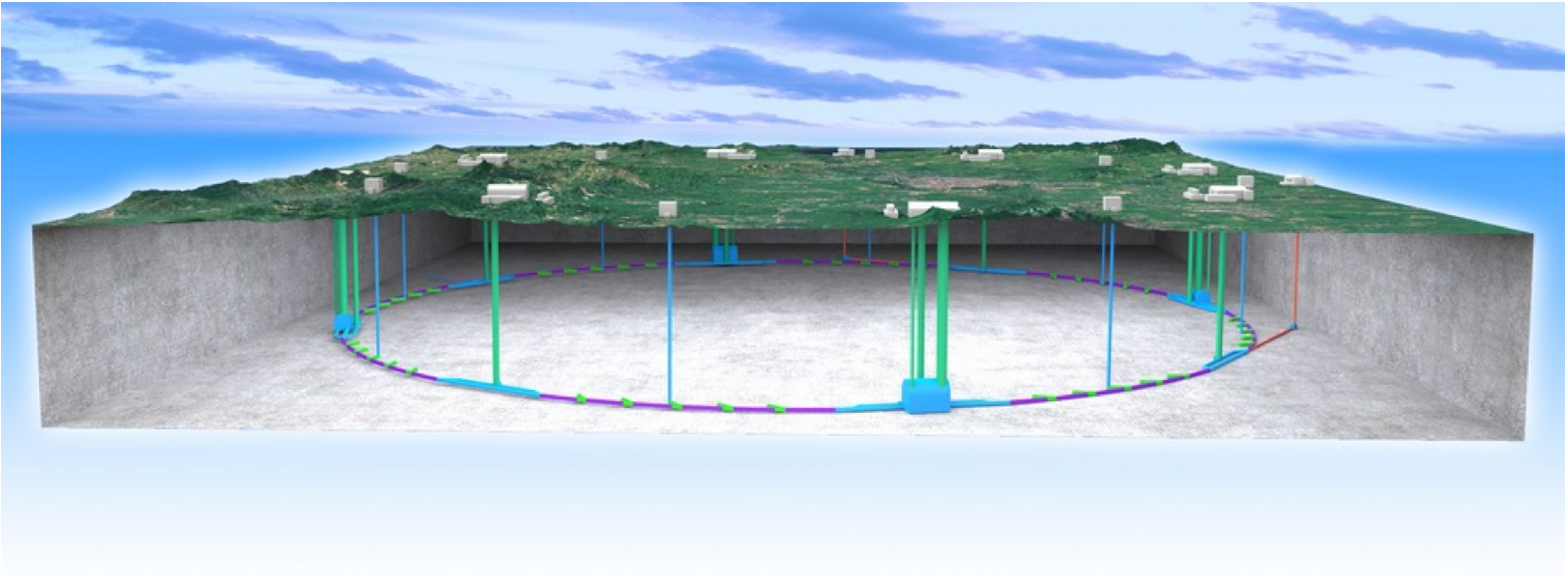
Why do we need e^+e^- collider?



- 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

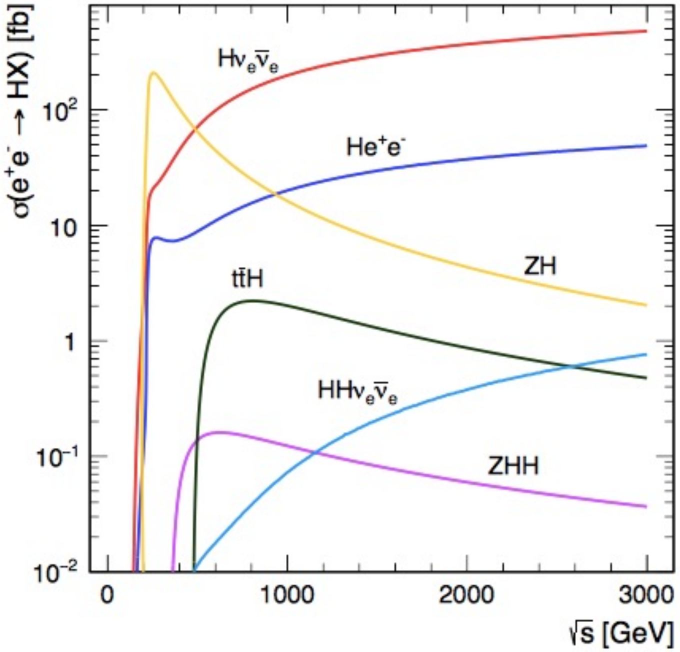
- Thanks to the low mass Higgs, CEPC+SPPC was proposed:
  - Circular e+e- collider(CEPC) has a higher luminosity
  - The tunnel can be re-used for Super proton-proton Collider(SppC), and AA, ep colliders in the far future:

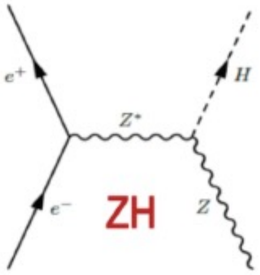


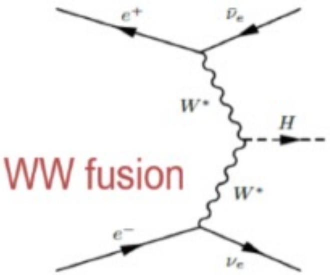
First in the world to have such a proposal, reported at HF2012 at Fermilab

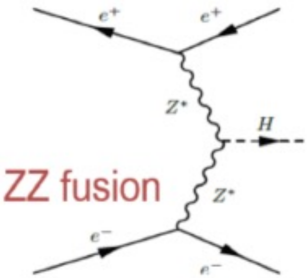
Baseline: 100 km, 30 MW; Upgradable to 50 MW

Higgs productions at e^+e^- collider



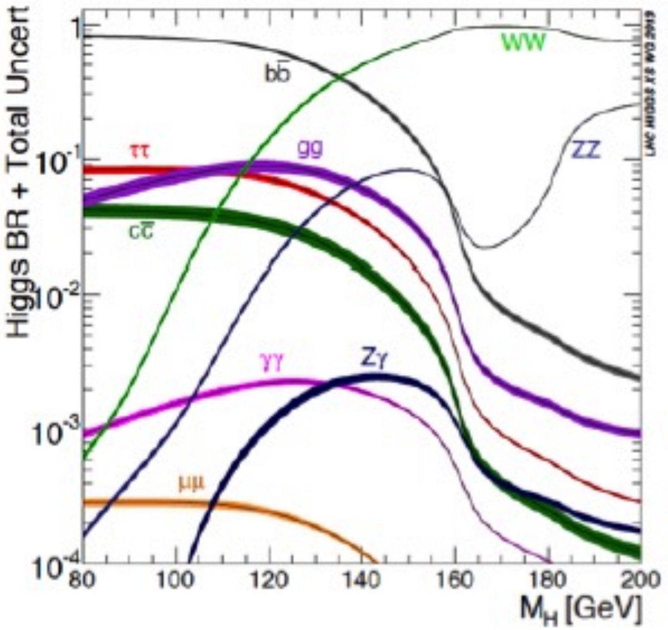


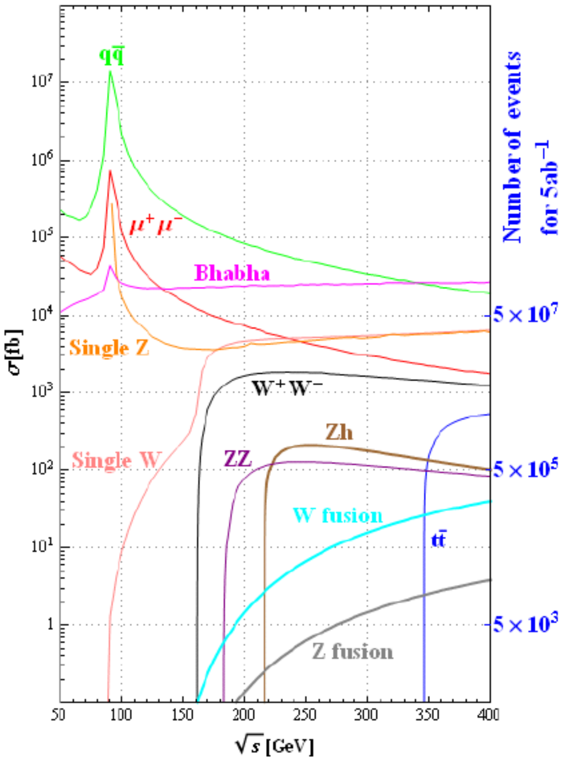




- With the increase of the energy, different Higgs related physics can be explored at e^+e^- collider.
- With the energy around 240 GeV, ZH as well as ww/zz fusion can be intensively studied.
  - the dominant production is from HZ, the WW/ZZ fusions contribute a few percent of the total cross-section.

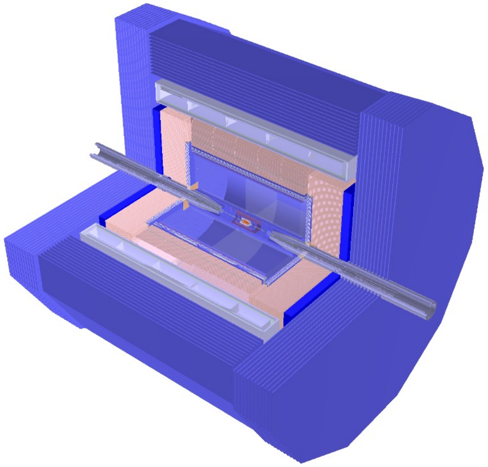
SM Higgs decay branching ratio, Bkg process

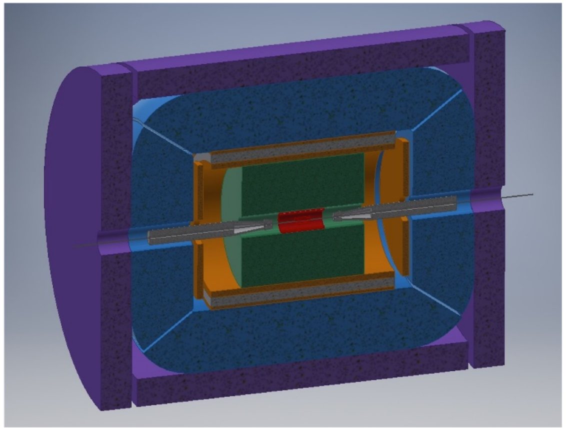


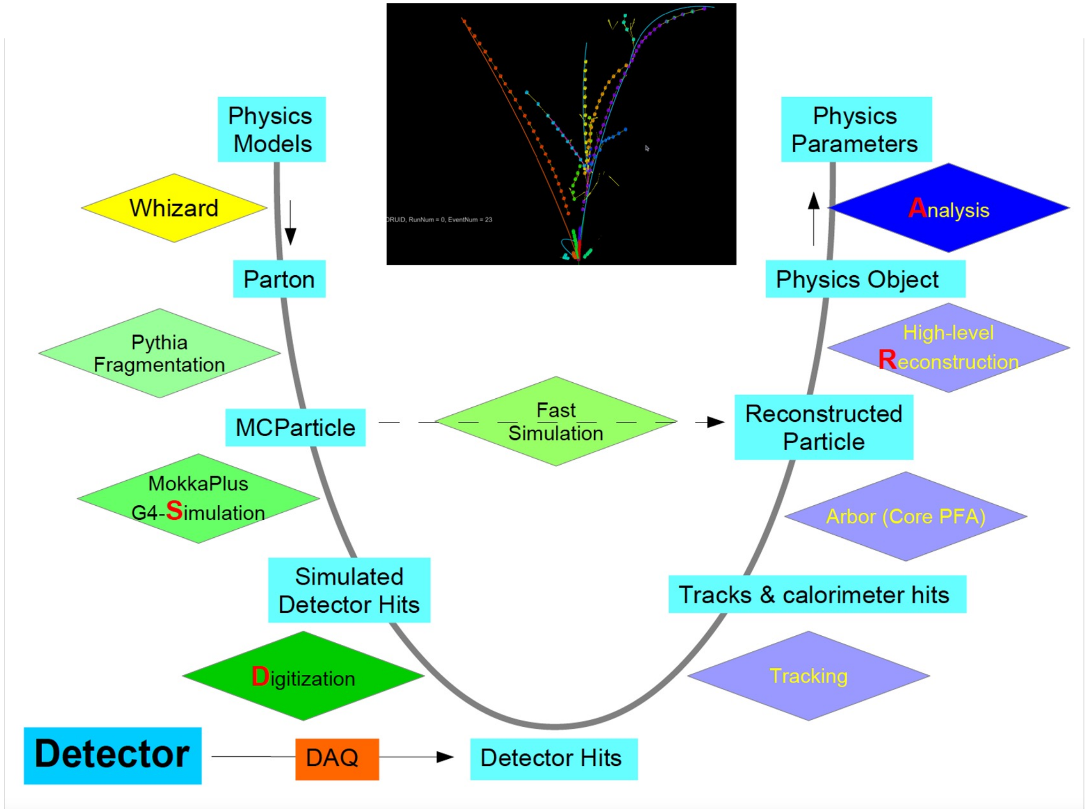


- ✓ **e^+e^- collider provides a good opportunity to measure the jj, invisible decay of Higgs.**
- ✓ **For 5.6 ab^{-1} data with CEPC, 1M Higgs, 10M Z, 100M W are produced.**

Detector & Software







Physics Models

Whizard

Parton

Pythia Fragmentation

MCParticle

MokkaPlus G4-Simulation

Simulated Detector Hits

Digitization

Detector

DAQ

Detector Hits

Tracking

Tracks & calorimeter hits

Arbor (Core PFA)

Reconstructed Particle

Fast Simulation

High-level Reconstruction

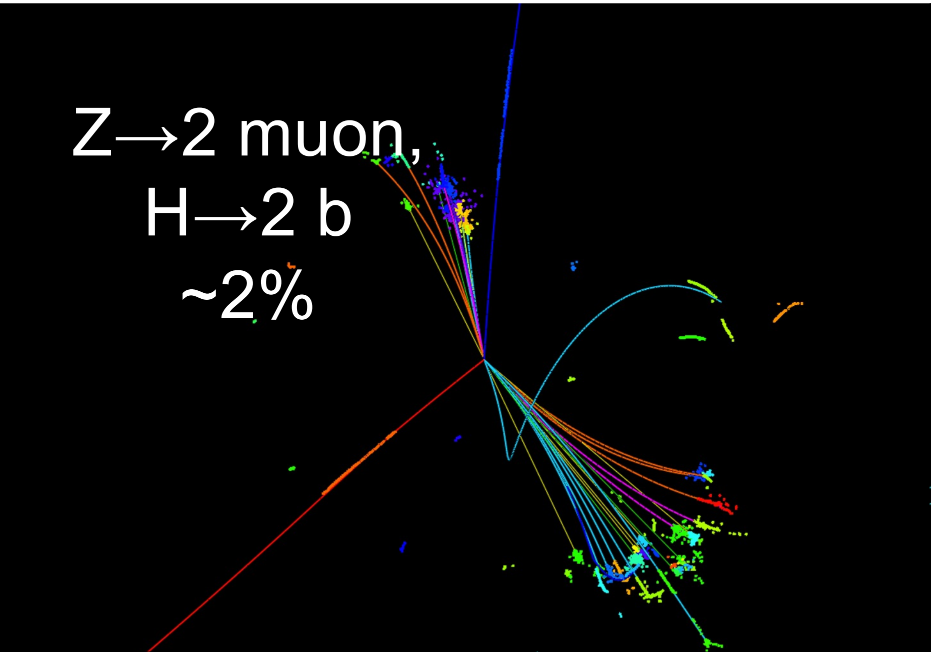
Physics Object

Analysis

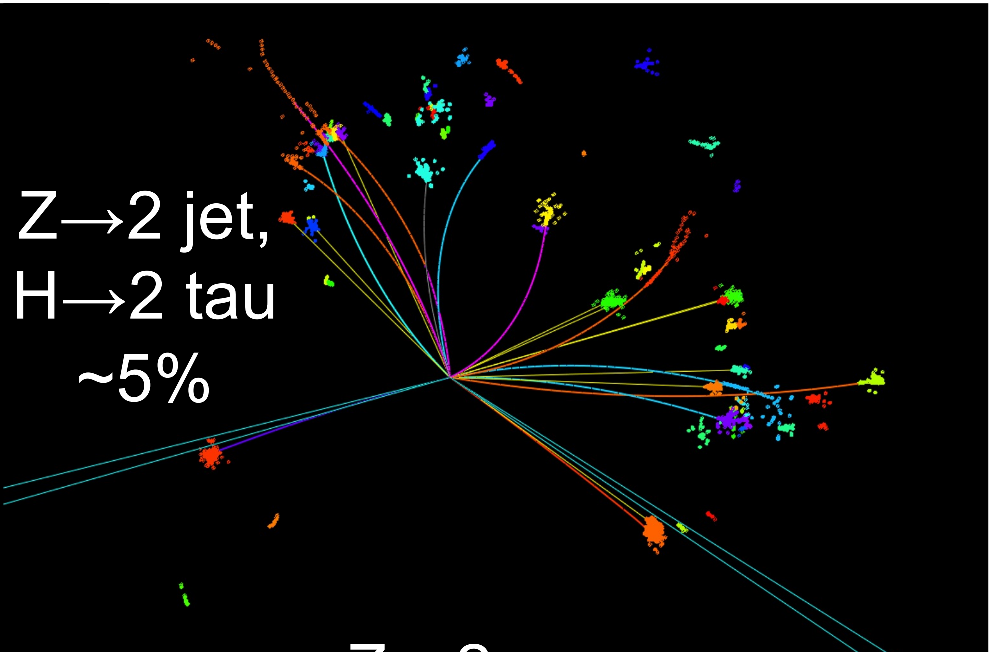
Physics Parameters

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

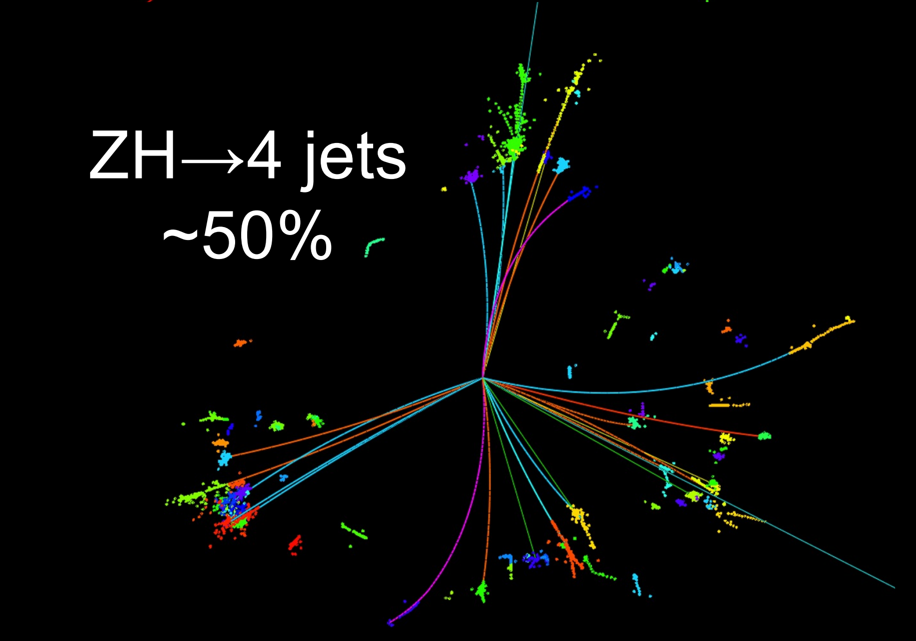
Events Display for Higgs



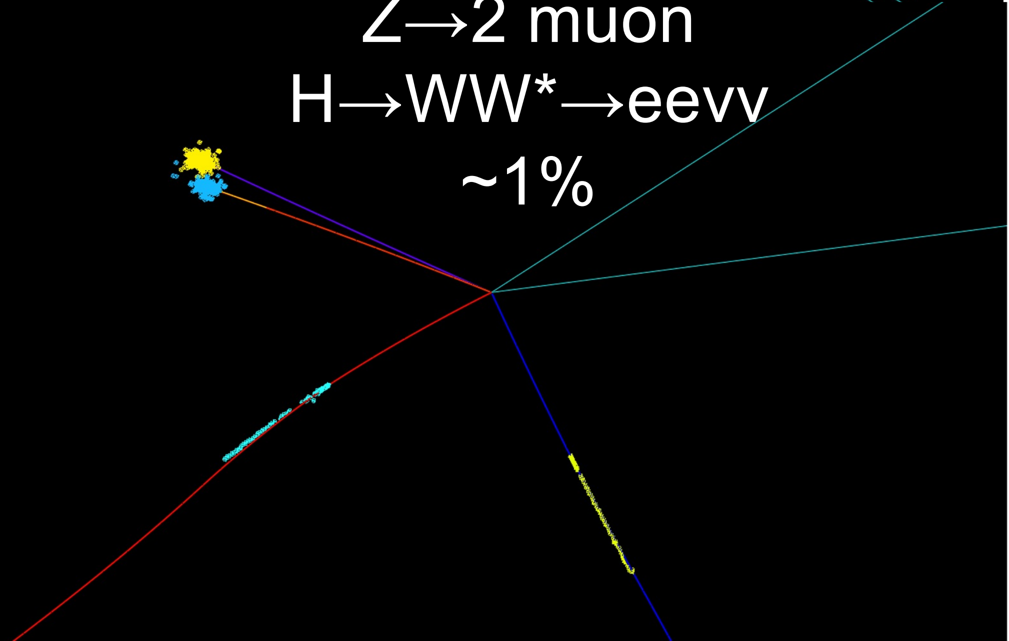
Z→2 muon,
H→2 b
~2%



Z→2 jet,
H→2 tau
~5%

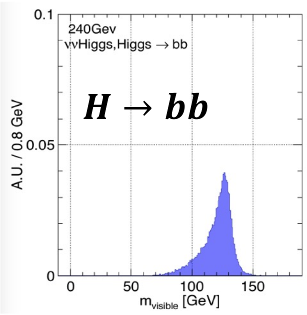


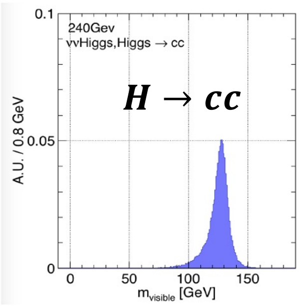
ZH→4 jets
~50%

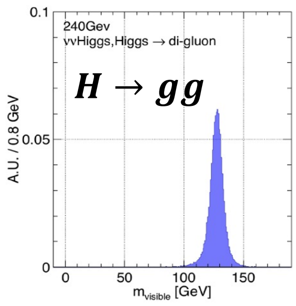


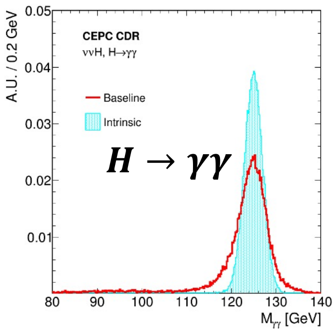
Z→2 muon
H→WW*→eeνν
~1%

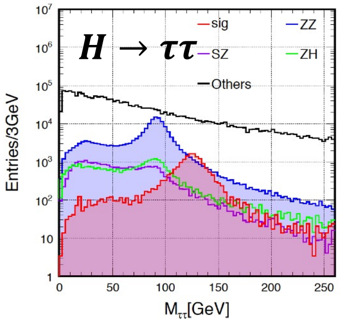
Reminder: Recon. Higgs Signatures& Detector Performance@CDR

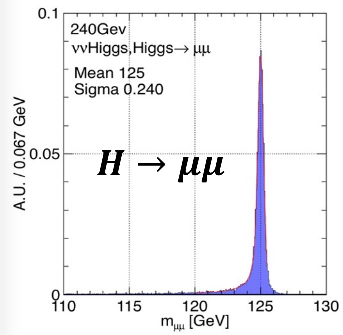


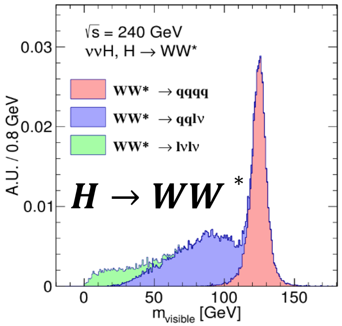


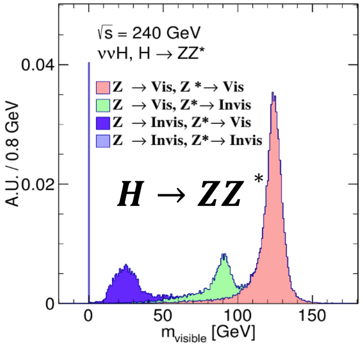






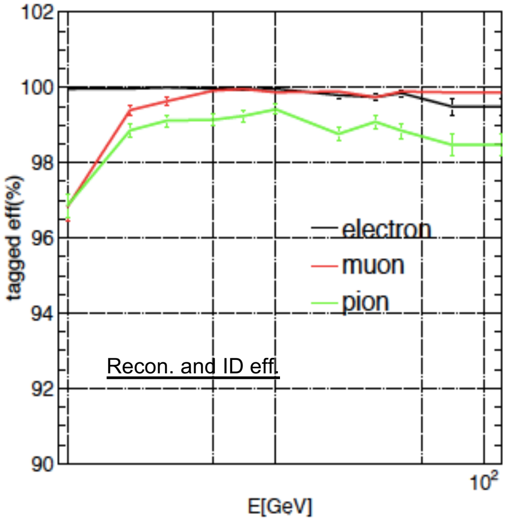


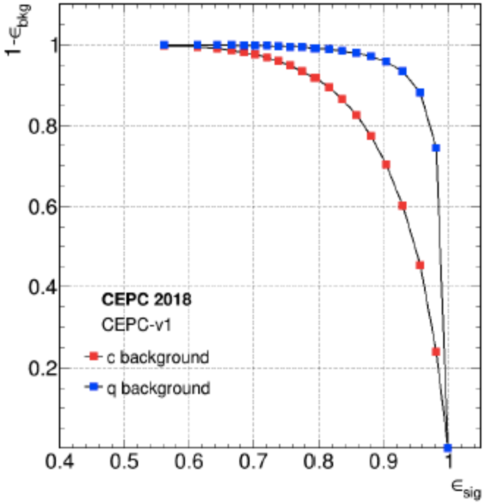




- ✓ Clear Higgs Signature in all SM decay modes
- ✓ Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level
- ✓ *Di-tau mass distribution at qqH events using collinear approximation*

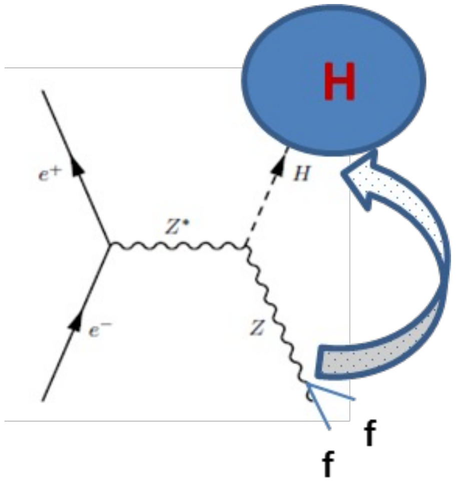
- ✓ Acceptance: $|\cos(\theta)| < 0.99$
- ✓ Tracks: Pt threshold, ~ 100 MeV
  - ✓ $\delta p/p \sim o(0.1\%)$
- ✓ Photons:
  - ✓ Energy threshold, ~ 100 MeV
  - ✓ δE/E: 3 – 15%/sqrt(E)
- ✓ BMR: 3.7%
- ✓ b-tagging: eff*purity @ Z→qq: 70%
- ✓ c-tagging: eff*purity @ Z→qq: 40%





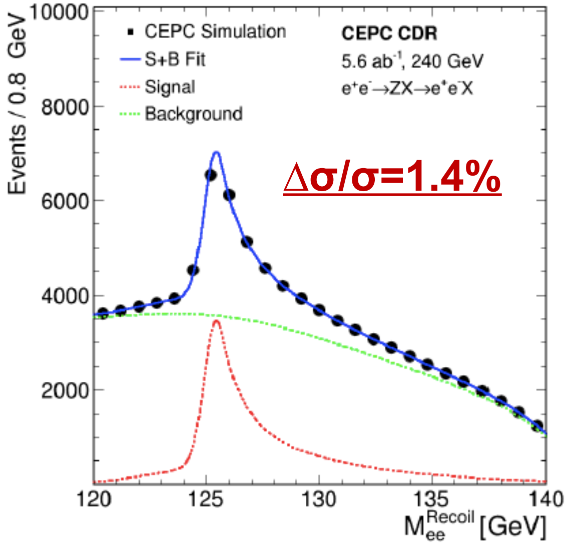
Direct measurement of Higgs cross-section

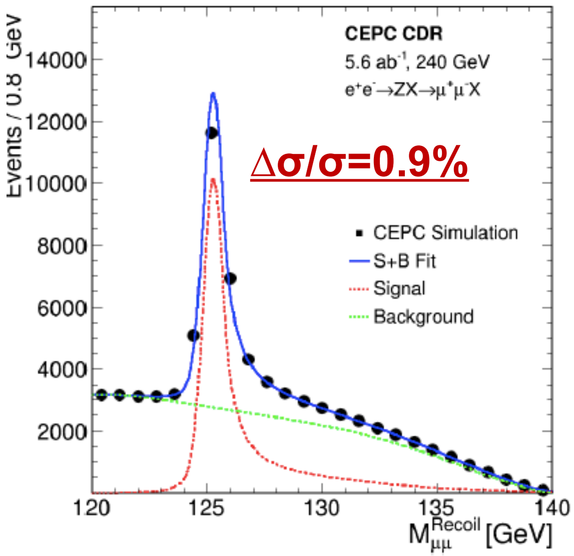
$$M_{\mathrm{recoil}}^2 = (\sqrt{s} - E_{ff})^2 - p_{ff}^2 = s - 2E_{ff}\sqrt{s} + m_{ff}^2$$

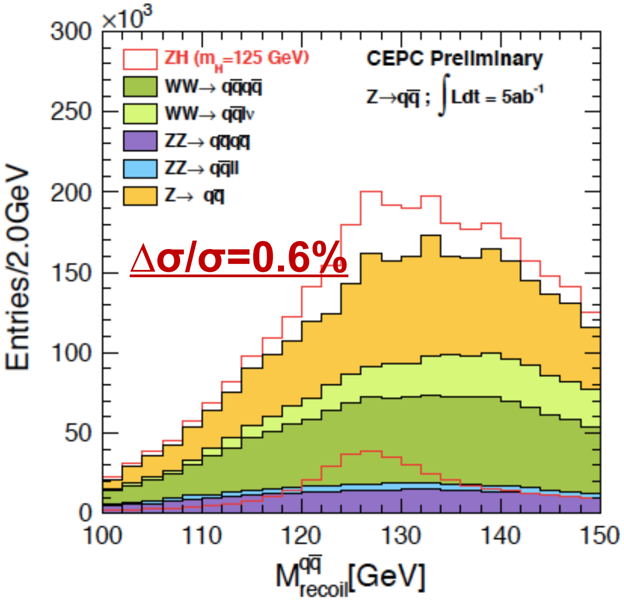


- ✓ **For this model independent analysis, we reconstruct the recoil mass of Z without touching the other particles in a event.**
- ✓ **The M_{recoil} should exhibit a resonance peak at m_H for signal; Bkg is expected to smooth.**
- ✓ **The best resolution can be achieved from Z(→e^+e^-, $\mu^+\mu^-$).**

Direct measurement of Higgs cross-section and m_H







- ✓ The combined precision with three channels is $\Delta\sigma/\sigma=0.5\%$
- ✓ Similar sub-percent level for ILC/FCC-ee
- ✓ The mass of Higgs can be measured with a precision 5.9 MeV combining Z→ee (14 MeV) and $Z\to\mu\mu$ (6.5 MeV)

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:**

$$\Gamma_H \propto \frac{\Gamma(H\to bb)}{BR(H\to bb)}$$

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

3.0%

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

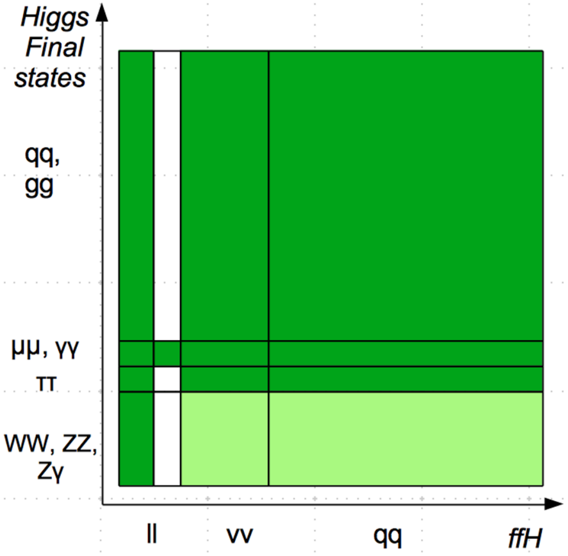
Precision : 3.5%

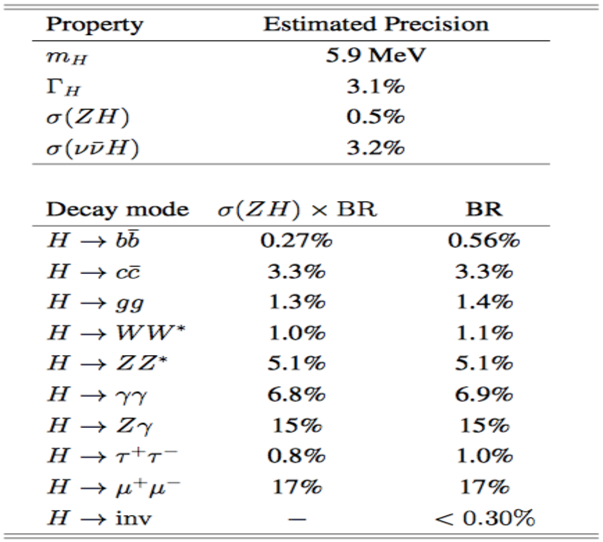
- **These two orthogonal methods can be combined to reach the best precision.**

Combined Precision : 2.9%

In practice，a combined fit is implemented to extract it.

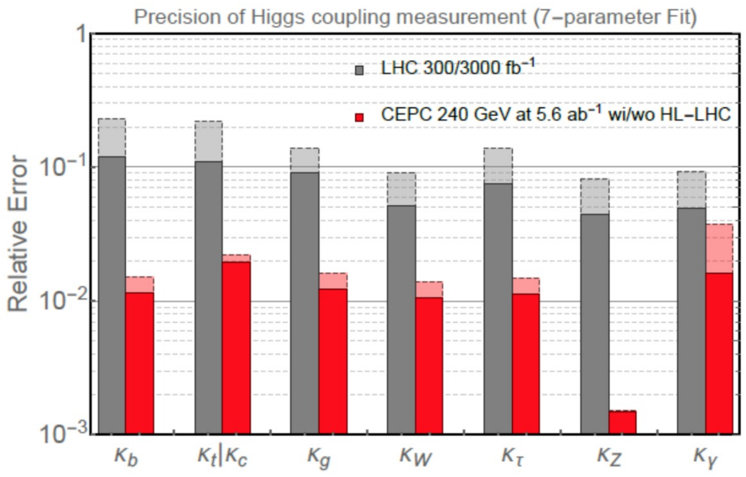
Reminder: Physics Potential@ CDR



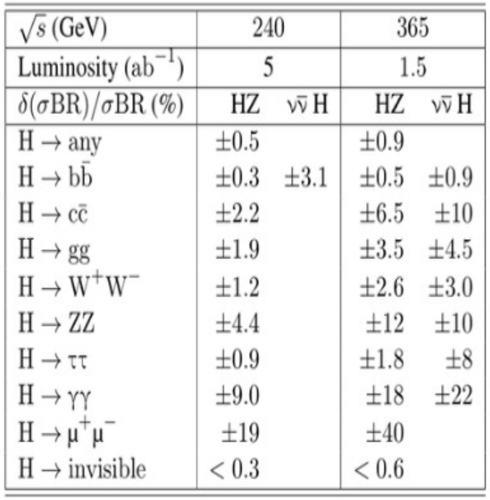


Property	Estimated Precision
m_H	5.9 MeV
Γ_H	3.1%
$\sigma(ZH)$	0.5%
$\sigma(\nu\bar{\nu}H)$	3.2%

Decay mode	$\sigma(ZH)\times$ BR	BR
$H\rightarrow b\bar{b}$	0.27%	0.56%
$H\rightarrow c\bar{c}$	3.3%	3.3%
$H\rightarrow gg$	1.3%	1.4%
$H\rightarrow WW^*$	1.0%	1.1%
$H\rightarrow ZZ^*$	5.1%	5.1%
$H\rightarrow\gamma\gamma$	6.8%	6.9%
$H\rightarrow Z\gamma$	15%	15%
$H\rightarrow\tau^+\tau^-$	0.8%	1.0%
$H\rightarrow\mu^+\mu^-$	17%	17%
$H\rightarrow$ inv	–	$<0.30\%$



Fcc-ee 240 GeV/365 GeV:
CERN-ACC-2018-0057



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

- Fcc-ee has similar results as CEPC but including a 365 GeV run improving the measurement of Higgs width.

Higgs Studies postCDR

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

Higgs Global Analysis: CPC 46 (11) (2022) 113001 (Gang's talk)

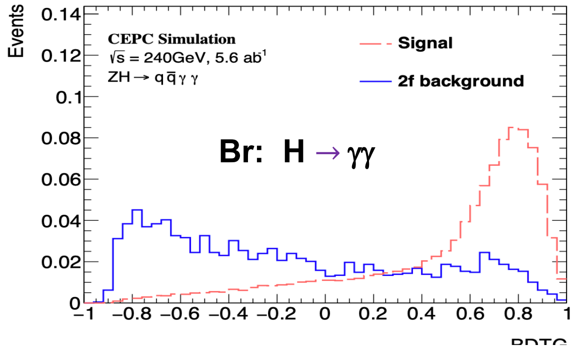
Higgs CP: ArXiv: 2203.11707, EPJC (2022)82:981 (Bo's talk)

H→ $\gamma\gamma$: ArXiv:2205.13269, Accepted by CPC

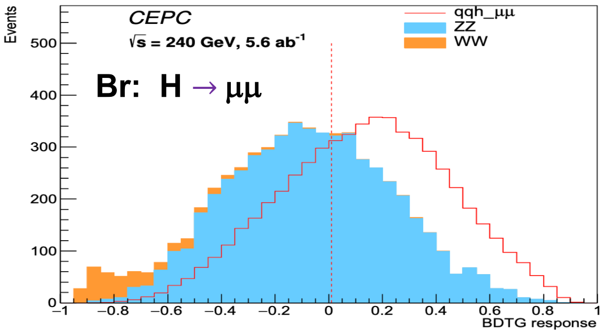
Update on H→ bb, cc, gg: ArXiv:2203.01469, JHEP 11 (2022) 100

H→ $\mu\mu$: CPC 46 (9) (2022) 093001.

Machine Learning widely used:



Br: H → γγ



Br: H → μμ

Higgs property studies (CP):

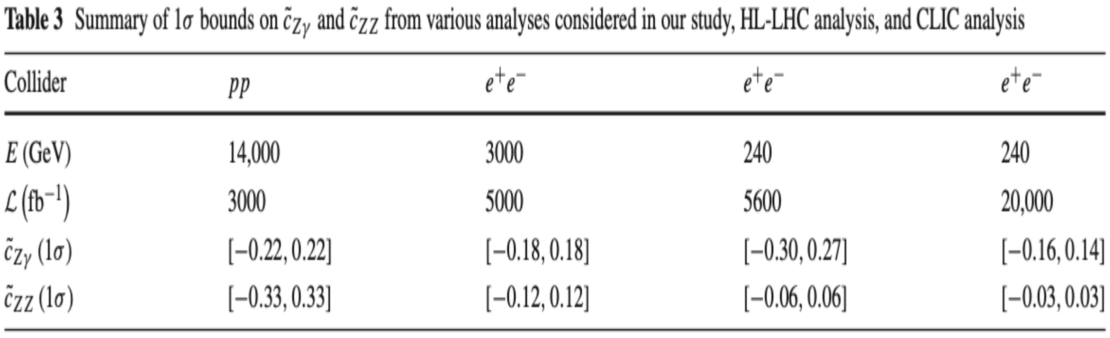
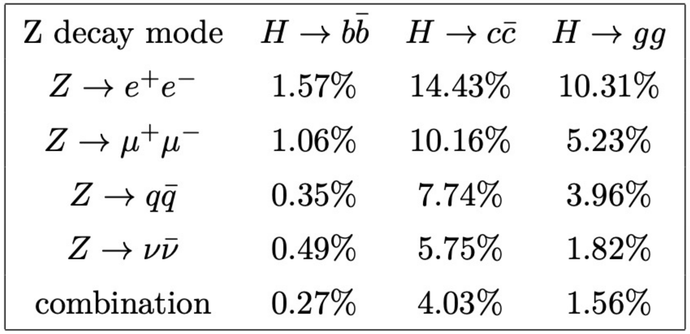


Table 3 Summary of 1σ bounds on $\tilde{c}_{Z\gamma}$ and $\tilde{c}_{ZZ}$ from various analyses considered in our study, HL-LHC analysis, and CLIC analysis

Collider	pp	e^+e^-	e^+e^-	e^+e^-
E (GeV)	14,000	3000	240	240
$\mathcal{L}$ (fb^{-1})	3000	5000	5600	20,000
$\tilde{c}_{Z\gamma}$ (1σ)	[−0.22, 0.22]	[−0.18, 0.18]	[−0.30, 0.27]	[−0.16, 0.14]
$\tilde{c}_{ZZ}$ (1σ)	[−0.33, 0.33]	[−0.12, 0.12]	[−0.06, 0.06]	[−0.03, 0.03]

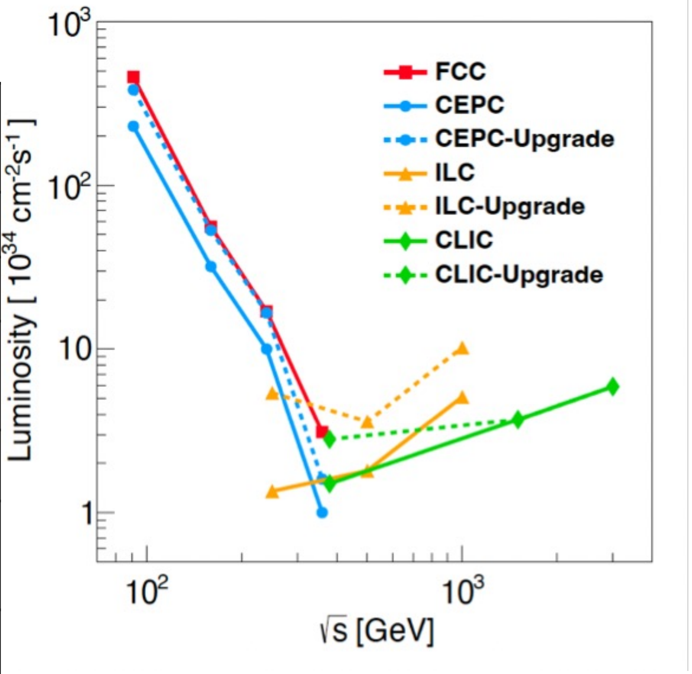
Revisit &expand the analyses:

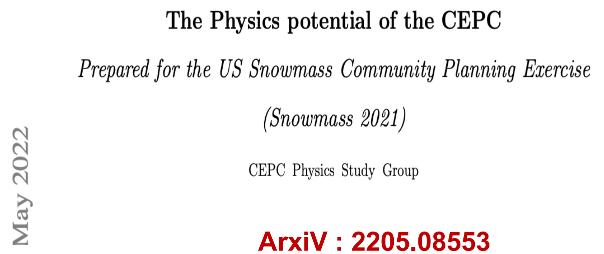


Z decay mode	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$
$Z \to e^+e^-$	1.57%	14.43%	10.31%
$Z \to \mu^+\mu^-$	1.06%	10.16%	5.23%
$Z \to q\bar{q}$	0.35%	7.74%	3.96%
$Z \to \nu\bar{\nu}$	0.49%	5.75%	1.82%
combination	0.27%	4.03%	1.56%

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

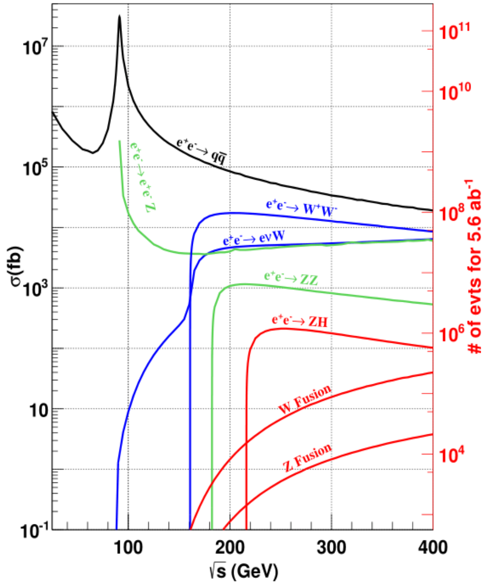
- ✓The luminosity of Higgs run can be upgradable from 5.6 ab^{-1} to 20 ab^{-1}.
- ✓In addition to W/Z run improvement, CEPC is also upgradable to have top run with 1 ab^{-1}.

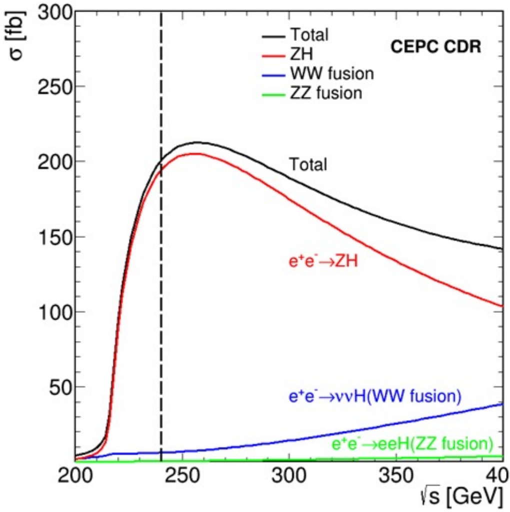
Cross Sections of Signal/Bkg Change from 240 GeV to 360 GeV

Kaili Zhang

- **240GeV:**
  - ZH: 196.9; vvH: 6.2; (Z → vv) H: vvH = 6.4:1
- **360GeV:** vvH / Z(→ vv)H ~ 117% ; eeH/Z(→ ee)H ~ 67%

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	4.1M		0.16M		



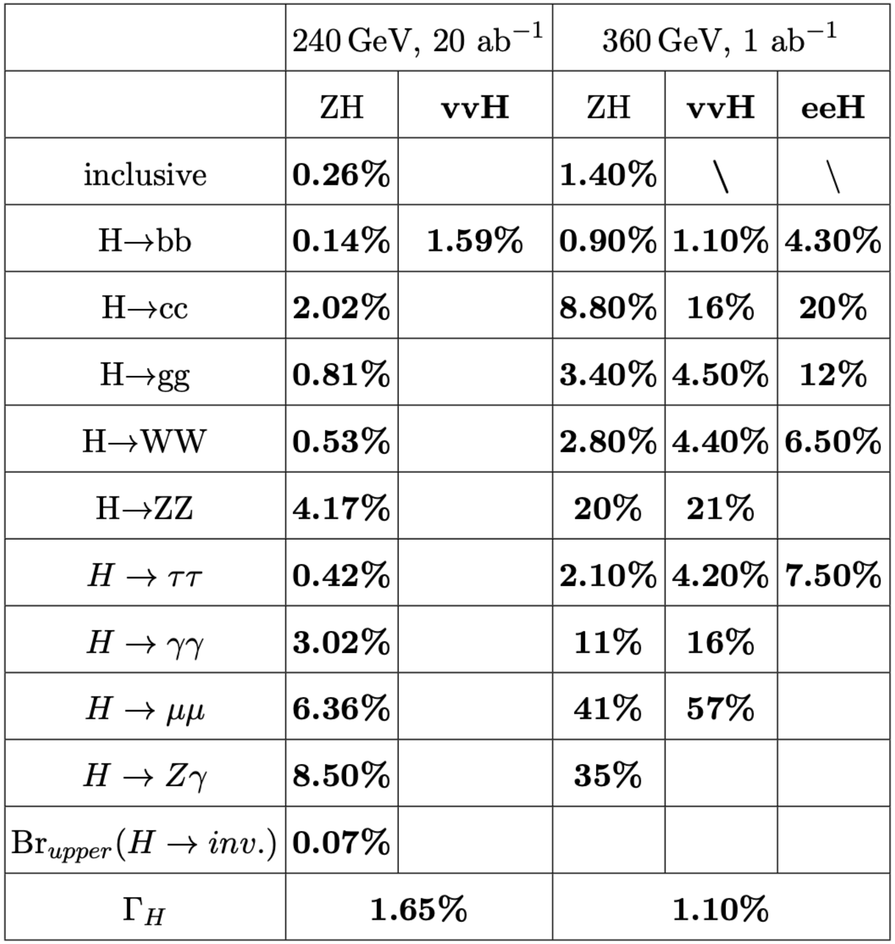


- ✓ In total ~4.3M Higgs events will be collected in CEPC for 240 （20 ab^{-1}) +360 GeV (1 ab^{-1}) runs.
- ✓ Substantial fusion events are expected and even eeH is not negligible with 360GeV run.

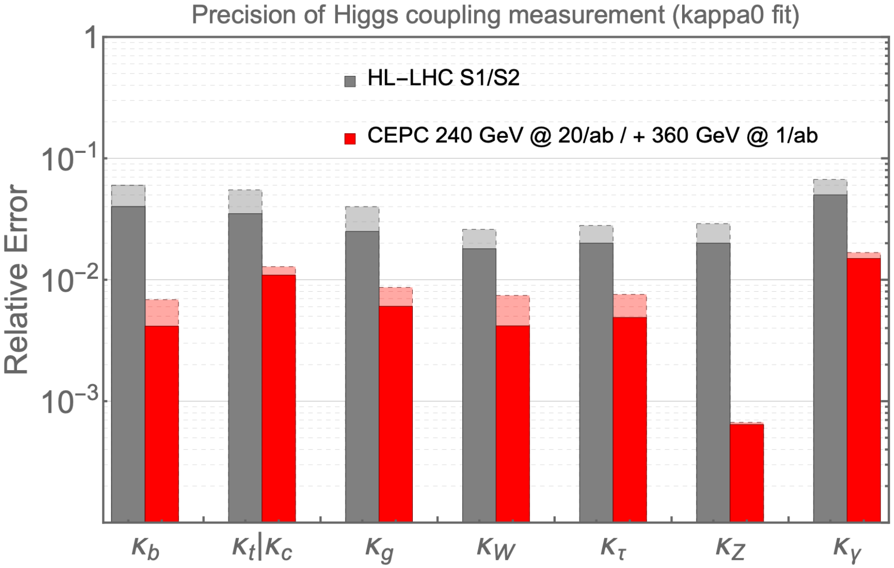
Impact of the updated running plans on Higgs

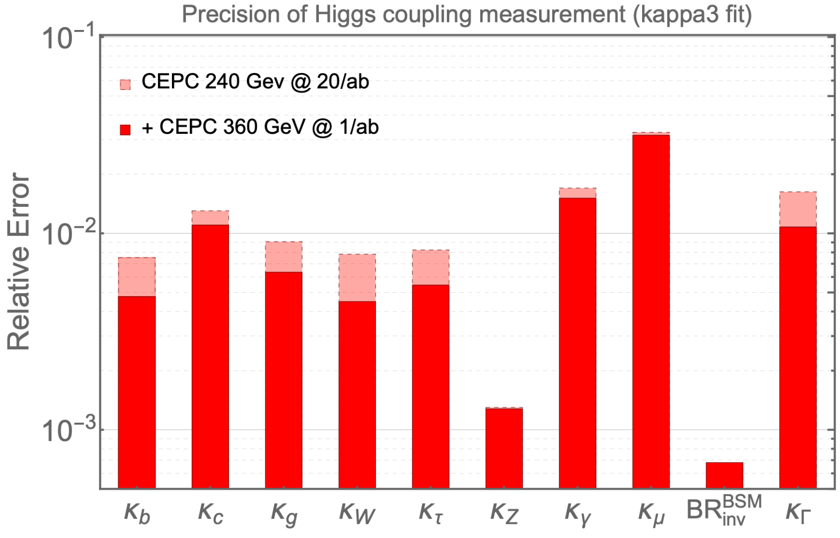
Kaili Zhang
Zhen Liu

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



	$240\,\mathrm{GeV},\ 20\ \mathrm{ab}^{-1}$		$360\,\mathrm{GeV},\ 1\ \mathrm{ab}^{-1}$		
	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%**		



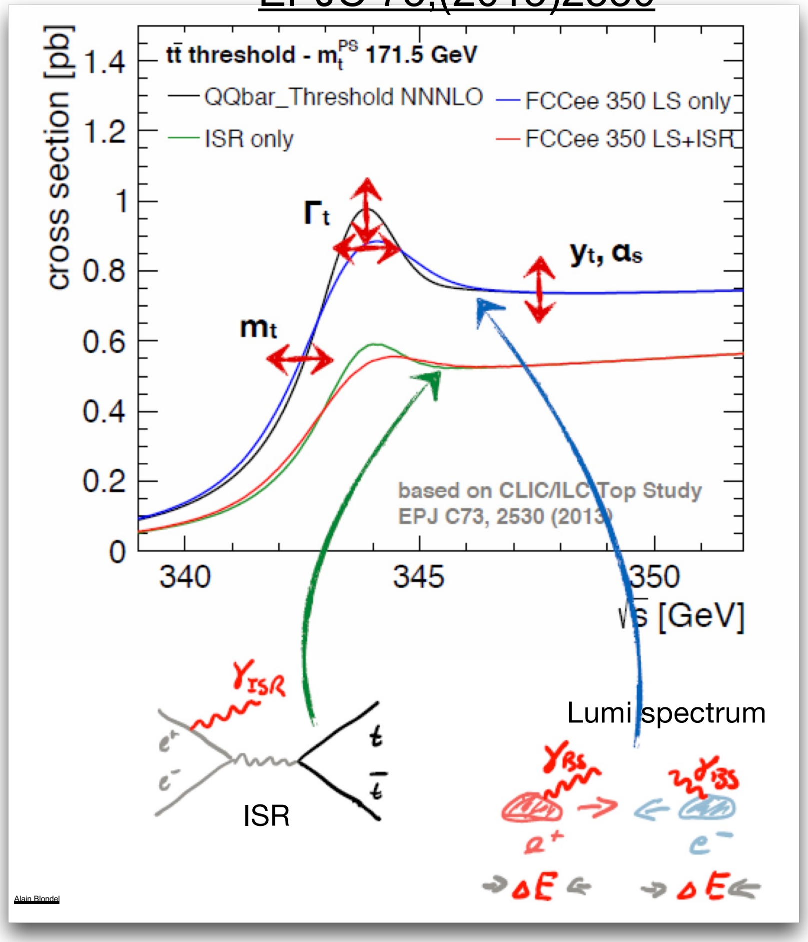


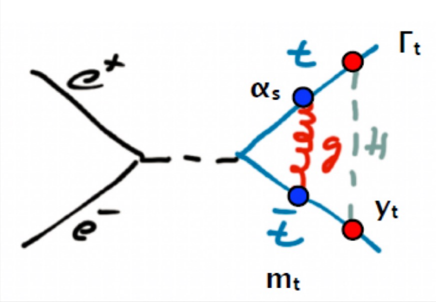
The precision of the Higgs width is 1.3% for Fcc-ee.

Top measurement @ CEPC

- Study possible solutions for CEPC of top quark measurements with tt threshold scans
- ee-colliders provide not only the top reconstruction method but also the tt threshold scan
- The scan is made against sqrt{s} and cross-section is the direct observable
- This brings measurements of top mass and a bunch of other parameters
  - Top width
  - Top Yukawa coupling
  - alpha_S

EPJC 73,(2013)2530



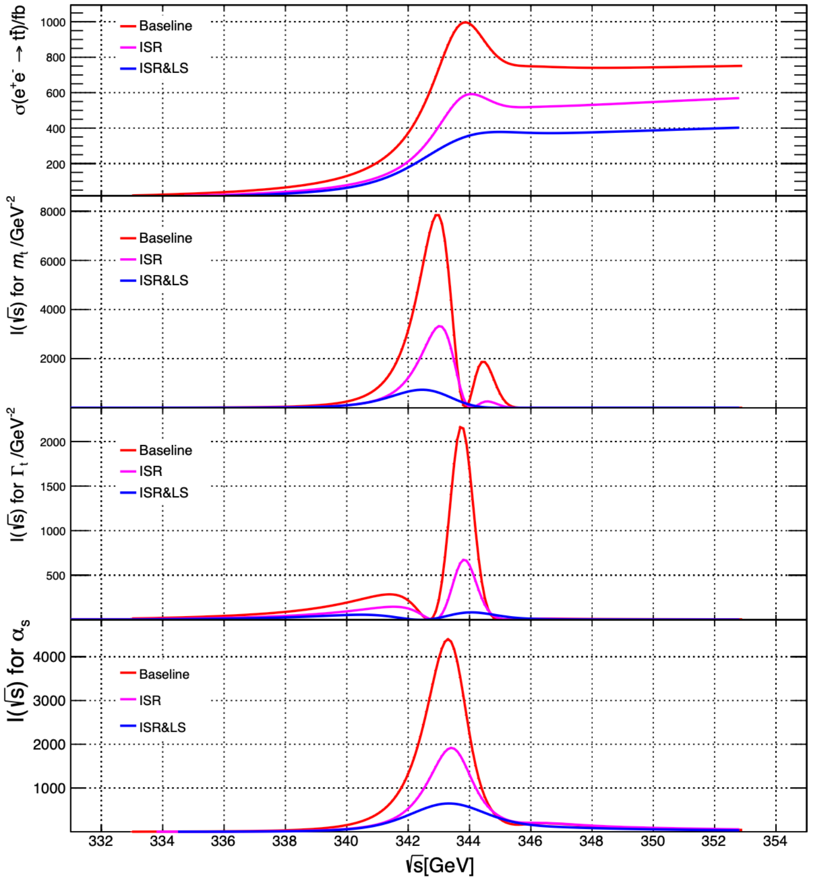


Top measurement at CEPC (cont.)

- Construct Fisher information out of the cross-section curve

$$I(\sqrt{s}) = \int \left(\frac{\partial log(G(\sigma|\sigma_0(\sqrt{s},\theta), \sqrt{\sigma_0(\sqrt{s},\theta)}))}{\partial\theta}\right)^2 \times G(\sigma|\sigma_0(\sqrt{s},\theta), \sqrt{\sigma_0(\sqrt{s},\theta)})d\sigma$$

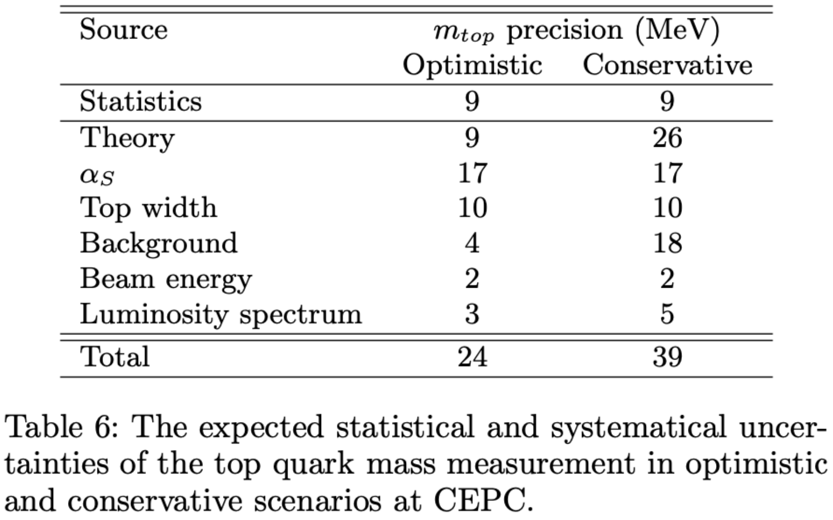
  - The larger the Y value is, the more sensitive the energy point will be to the top mass, width and alpha_S, respectively
- This is used as a guide of locating the energy point that is most sensitive to the measurement



Top measurement at CEPC (cont.)

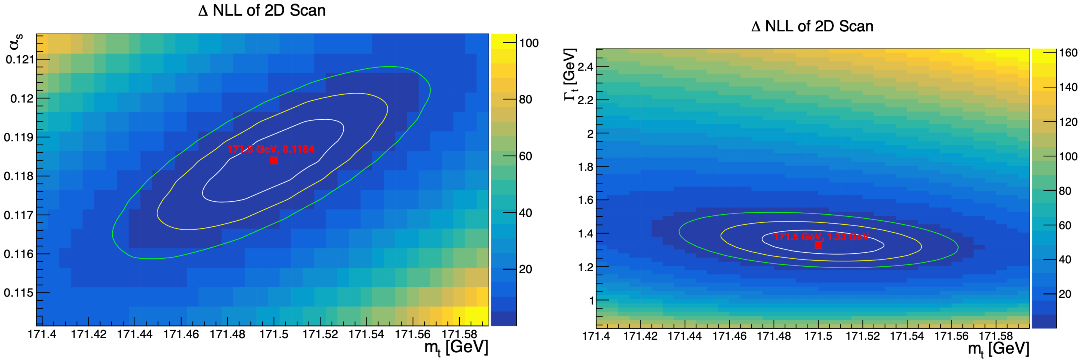
Zhan Li, Xiaohu Sun et al.

- Studied in details the uncertainties of top mass measurements in the 1D scan using one energy point
  - Theory, alpha_S, width and background can be leading factors
  - The luminosity spectrum does not impact much mostly due to its good resolution in circular colliders
  - A quick energy scan with low luminosity to find the optimal energy point
- Performed 2D scans as well
  - Using two energy points
  - Measuring two parameters simultaneously is possible
- Available at arXiv:2207.12177
  - submitted to EPJC



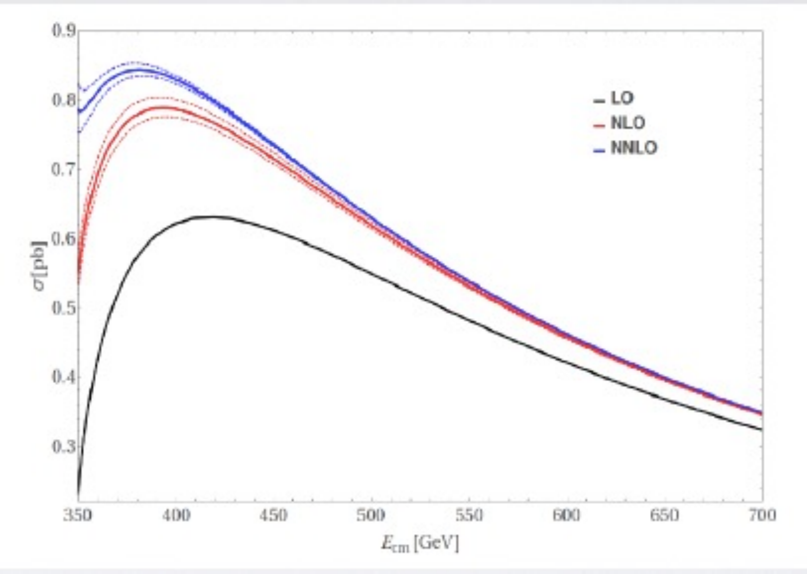
Source	m_{top} precision (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	9	26
α_S	17	17
Top width	10	10
Background	4	18
Beam energy	2	2
Luminosity spectrum	3	5
Total	24	39

Table 6: The expected statistical and systematical uncertainties of the top quark mass measurement in optimistic and conservative scenarios at CEPC.

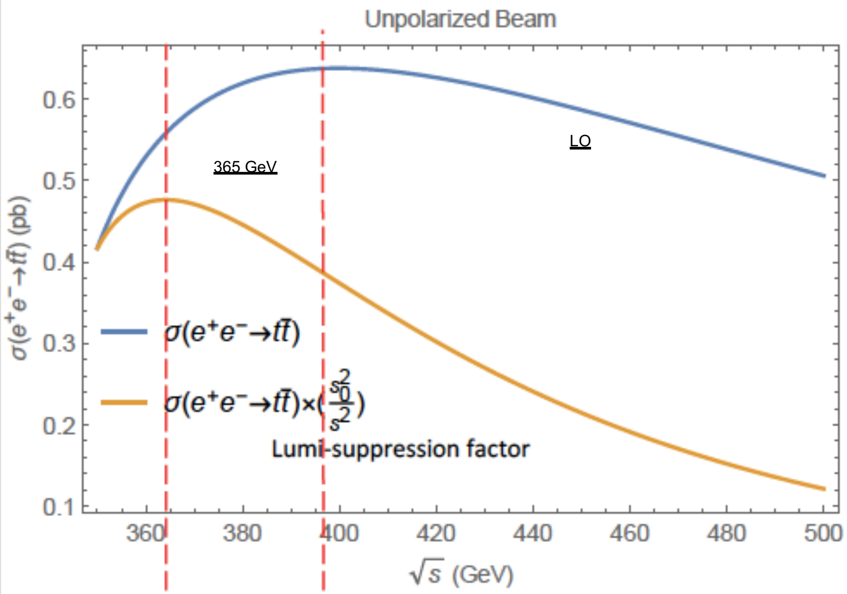


Top coupling measurements: why choosing 360 GeV?

Jurgen R.Reuter
Maximal NNLO xsection:
@381.3GeV



Zhen Liu, Liantao Wang et al.

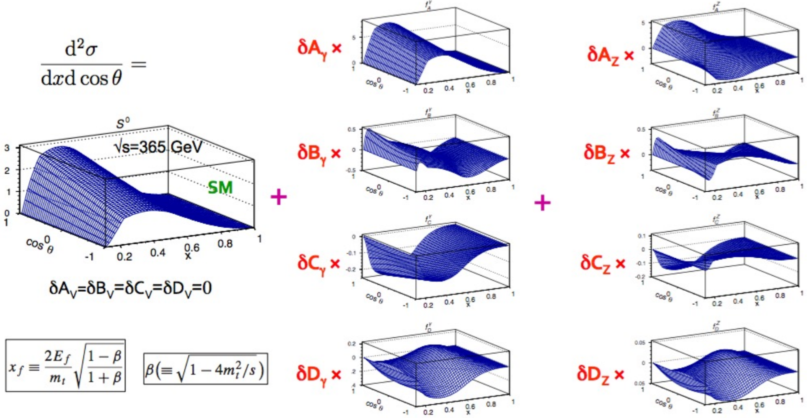


- ❖ With the NNLO calcuation, the highest xsection is at the energy of 381.3 GeV
- ❖ Considering the Lumi-suppression factor when going to higher energy,
- ❖ the effective highest xsection is around 365 GeV (Fcc-ee).
- ❖ The effective xsection from 360 GeV is not much different from that of 365 GeV.
- ❖ If we choose higher order correction, the peak could be even lower than 360 GeV.

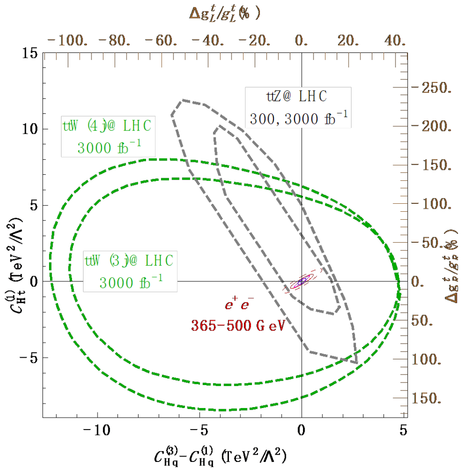
Top quark and Higgs EFT $O_{Hq}^{(1)}, O_{Hq}^{(3)}, O_{Ht}$

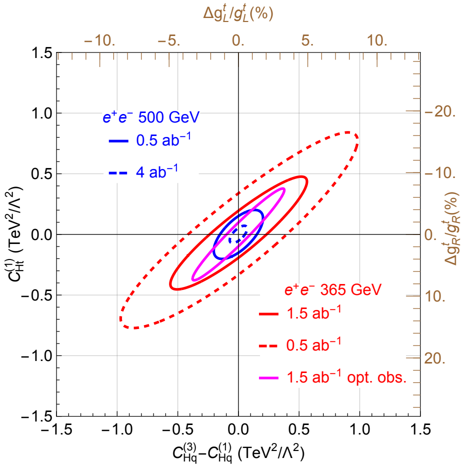
At or above $t\bar{t}$ threshold at lepton colliders, one immediately again great sensitivities to the top gauge couplings.

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.

Conclusion

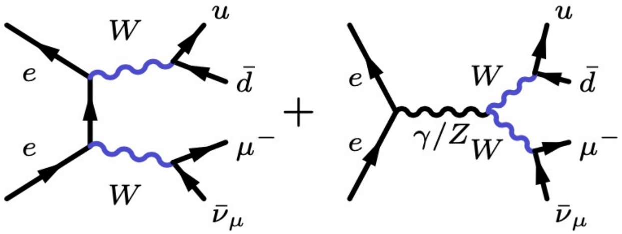
- After the Higgs white paper and CDR are done, analyses from individual channels have been documented. Several publications of them are available now.
- With the upgradable running plans, the expected results have been updated.
  - Can bring some improvements in Higgs precision measurement in addition to top coupling measurements.
    - Significant enhancement on Higgs width measurement.
  - The impacts of 360GeV/1 ab^{-1} on Higgs are studied.
  - Top mass measurements have been studied.

backup Slides

W mass measurement at CEPC

Gang LI

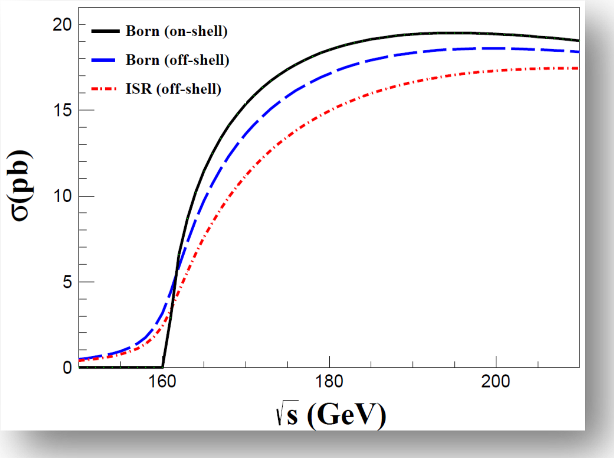
- ✓ scan the threshold to measurement the W mass, similar as top mass measurement.
- ✓ The scenario of 1-3 energy points are tested :
  - ✓ With most systematics taken into account except the theoretical ones, 1 MeV and 3 MeV uncertainties for W mass and width could be achieved, respectively.
  - ✓ Challenges 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

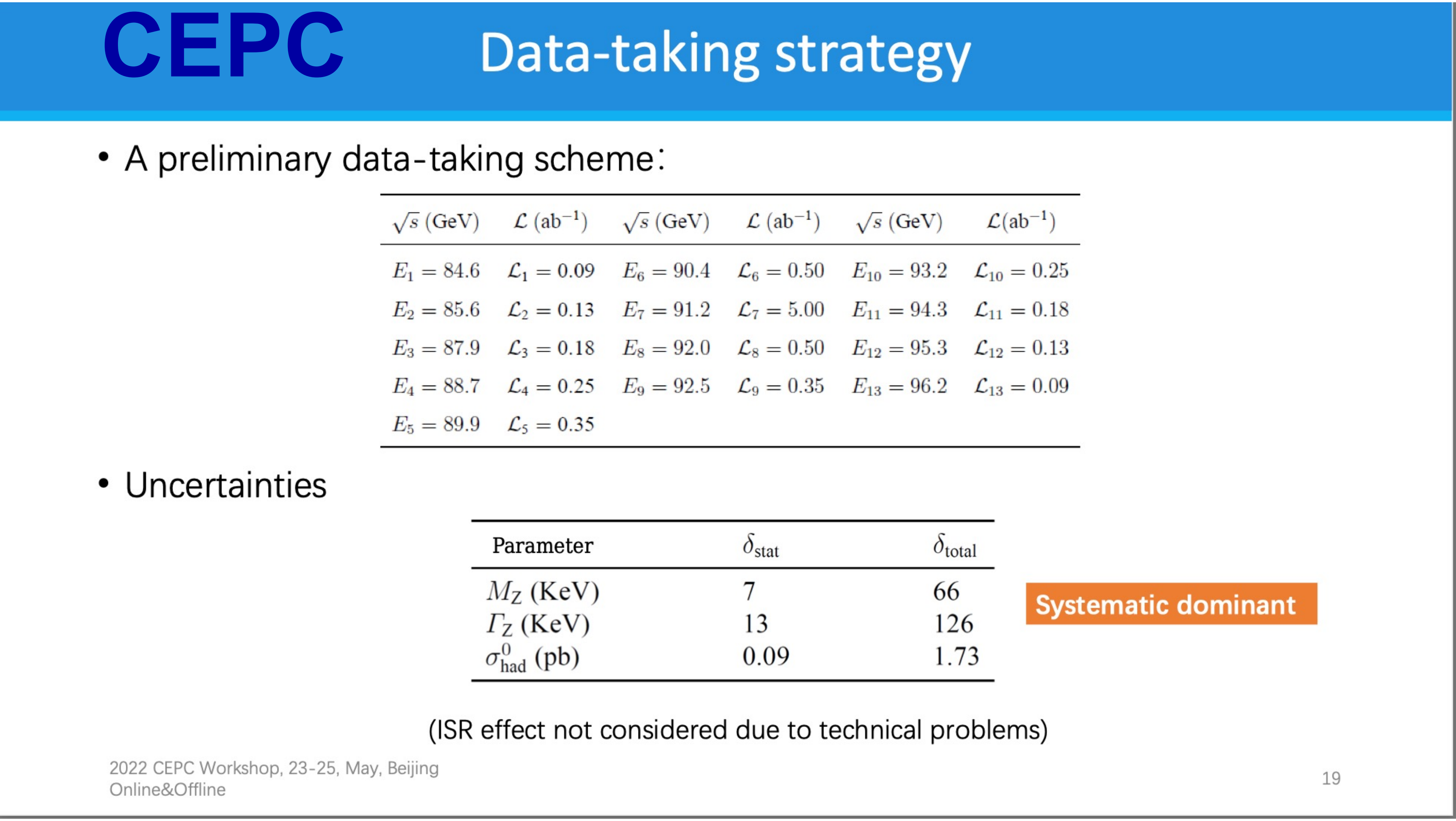
$\Delta L(\Delta\epsilon)<10^{-4}, \Delta\sigma_B<10^{-3}$
$\sigma_E=1\times10^{-3}$, ΔE=0.7MeV
$\Delta\sigma_E$=0.1



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:

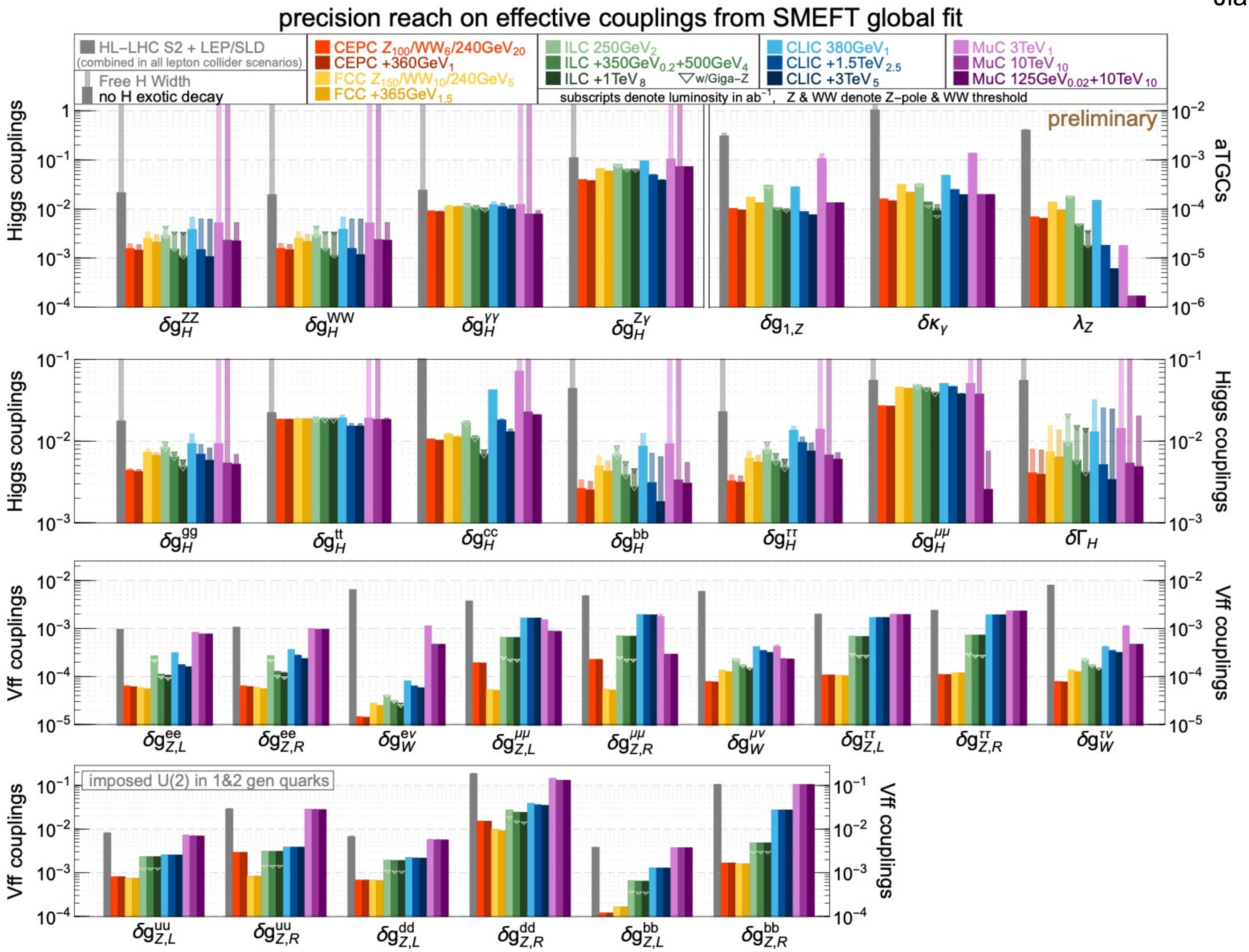
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (ab^{-1})	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (ab^{-1})	$\sqrt{s}$ (GeV)	$\mathcal{L}$(ab^{-1})
$E_1 = 84.6$	$\mathcal{L}_1 = 0.09$	$E_6 = 90.4$	$\mathcal{L}_6 = 0.50$	$E_{10} = 93.2$	$\mathcal{L}_{10} = 0.25$
$E_2 = 85.6$	$\mathcal{L}_2 = 0.13$	$E_7 = 91.2$	$\mathcal{L}_7 =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

- 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)

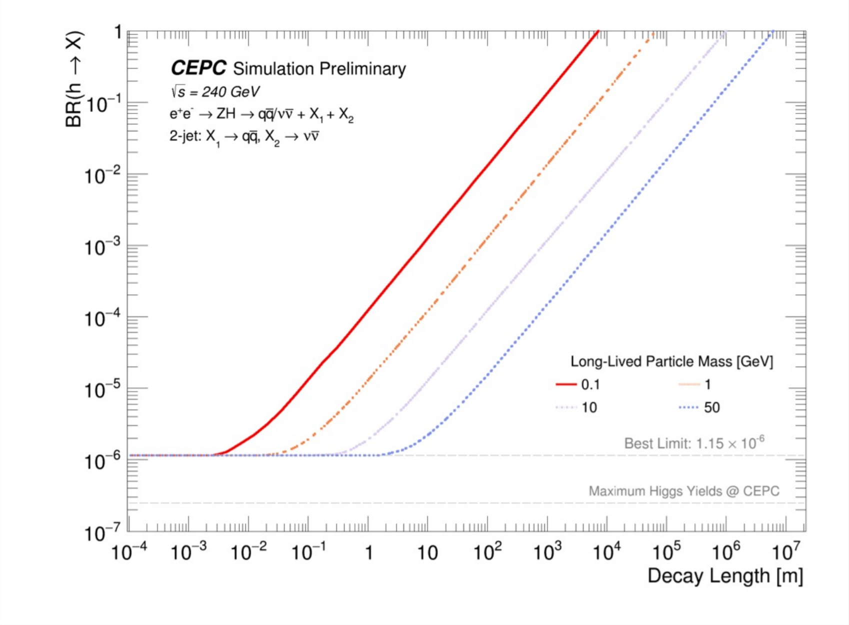


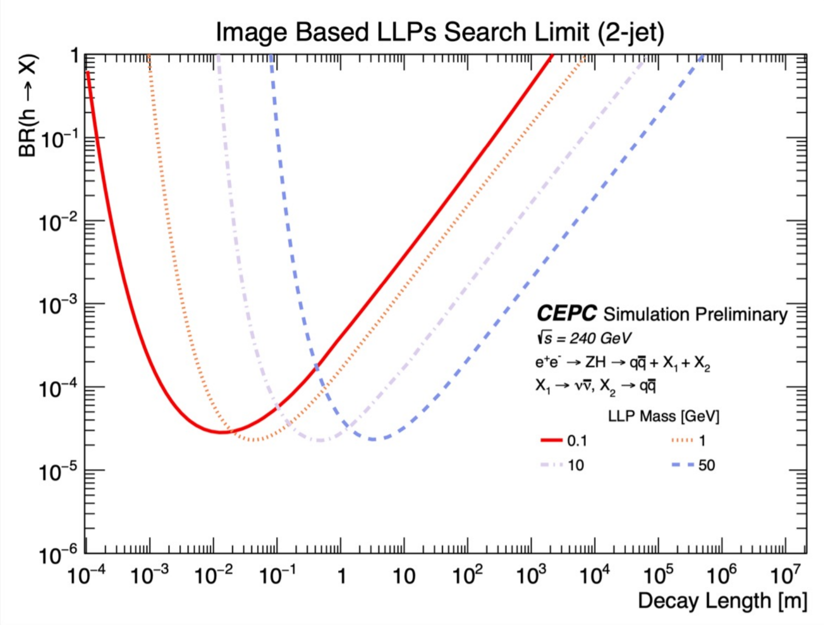
precision reach on effective couplings from SMEFT global fit

H→ $long\ lived\ particles$

Yulei Zhang

Sensitivity (compared with previous 2-jet analysis)

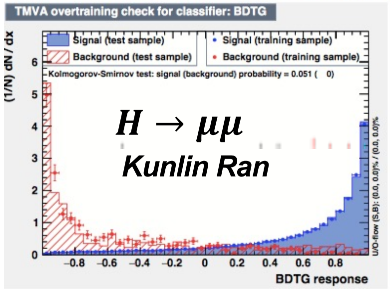


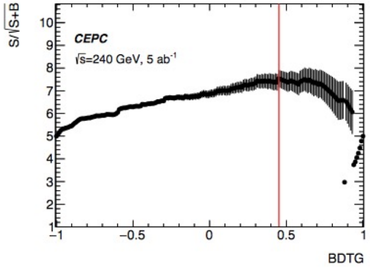


- Previous best limit: $\sim 1 \times 10^{-5}$ ($5.6\ \mathrm{ab}^{-1}$), Current best limit: $\sim 1 \times 10^{-6}$ ($20\ \mathrm{ab}^{-1}$)
- Main improvement on geometry acceptance: $r_{\mathbf{decay}}$ from [1,6] to (0,6]

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

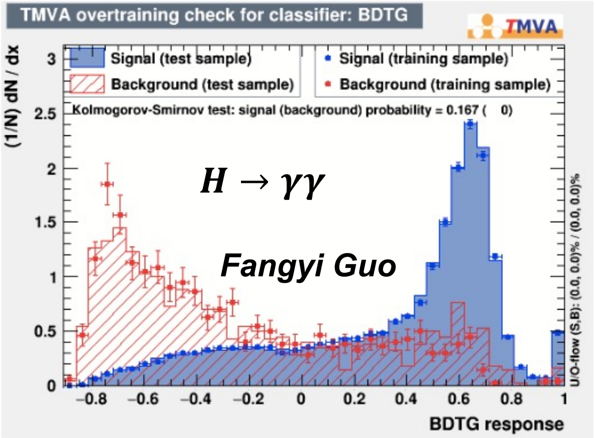




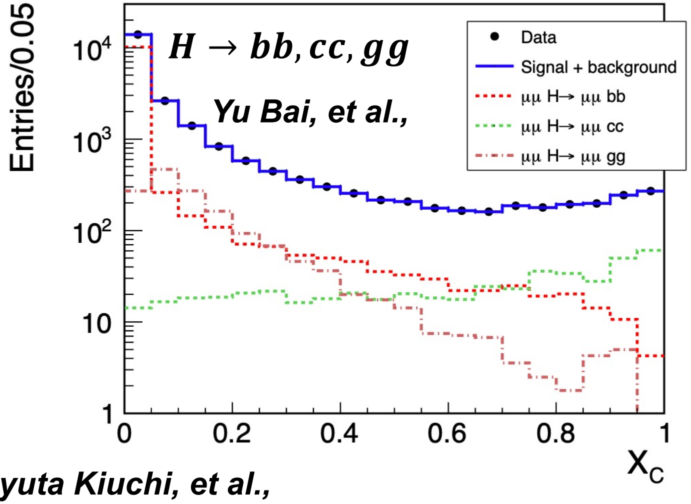
- There is a overtraining in the background due to poor statistics: ~1600
- Scan the total sensitivity ($S/\sqrt{S+B}$) vs BDTG to find the optimal BDTG point
- The sensitivity is estimated in the 90% signal coverage region

	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	

- ➢ For H->μμ, the improvement is ~35% w.r.t cut based one for the signal significance (improvement on precision 17%-12%).
- ➢ The overall precision has been improved from 6.8% to 5.7% with MVA as well as full simulated samples used for H->γγ.



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



Ryuta Kiuchi, et al.,

$H \to ZZ$ ArXiv: 2103.09633

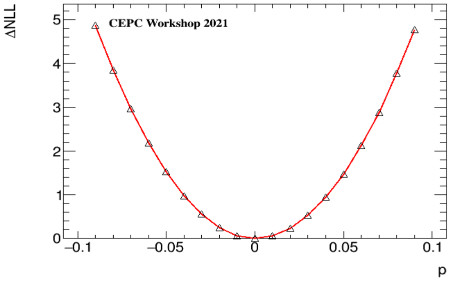
Category	$\frac{\Delta(\sigma \cdot BR)}{(\sigma \cdot BR)}$ [%] cut-based	BDT
$\mu\mu H\nu\nu qq^{\mathrm{cut/mva}}$	15.5	13.6
$\mu\mu Hqq\nu\nu^{\mathrm{cut/mva}}$	48.0	42.1
$\nu\nu H\mu\mu qq^{\mathrm{cut/mva}}$	11.9	12.5
$\nu\nu Hqq\mu\mu^{\mathrm{cut/mva}}$	23.5	20.5
$qqH\nu\nu\mu\mu^{\mathrm{cut/mva}}$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

Other activities in Higgs group

Higgs CP Study

Study channel: ***Qiyu Sha***

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

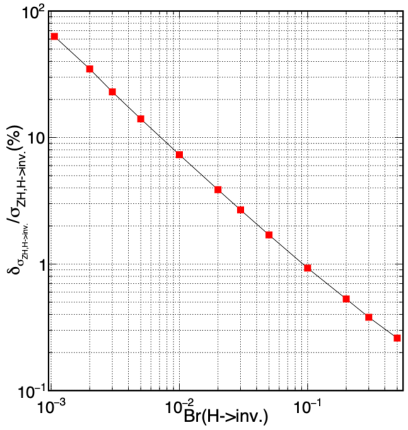


68% CL: $[-2.9\times10^{-2}, 2.9\times10^{-2}]$
95% CL: $[-5.7\times10^{-2}, 5.7\times10^{-2}]$

Higgs invisible decays

ArXiv:2103.09633

Ryuta Kiuchi, et al.



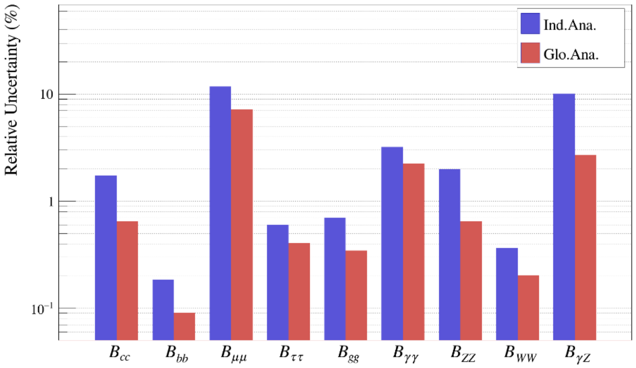
Global analysis

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

Gang Li

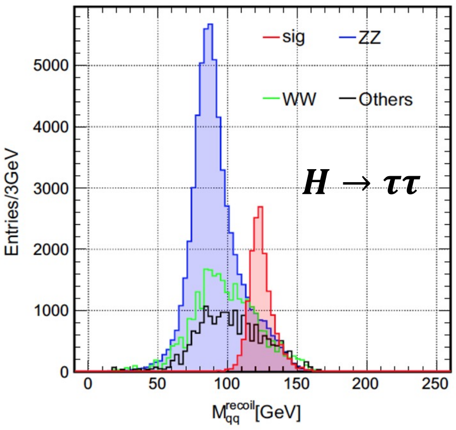
ArXiv:2105.14997

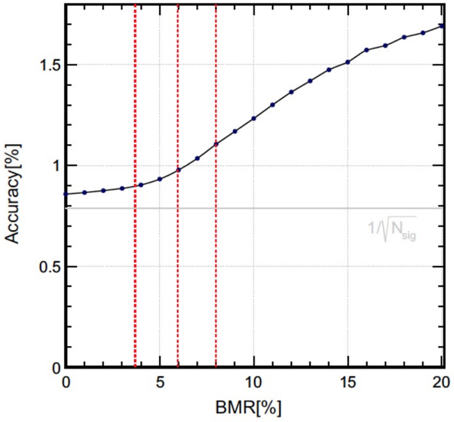
- ✓ Calculate the efficiency matrix
- ✓ Particle level information as the input.
- ✓ Proof-of-Principle study shows precision improved by a factor of ~2.
- ✓ Full simulation study is ongoing.



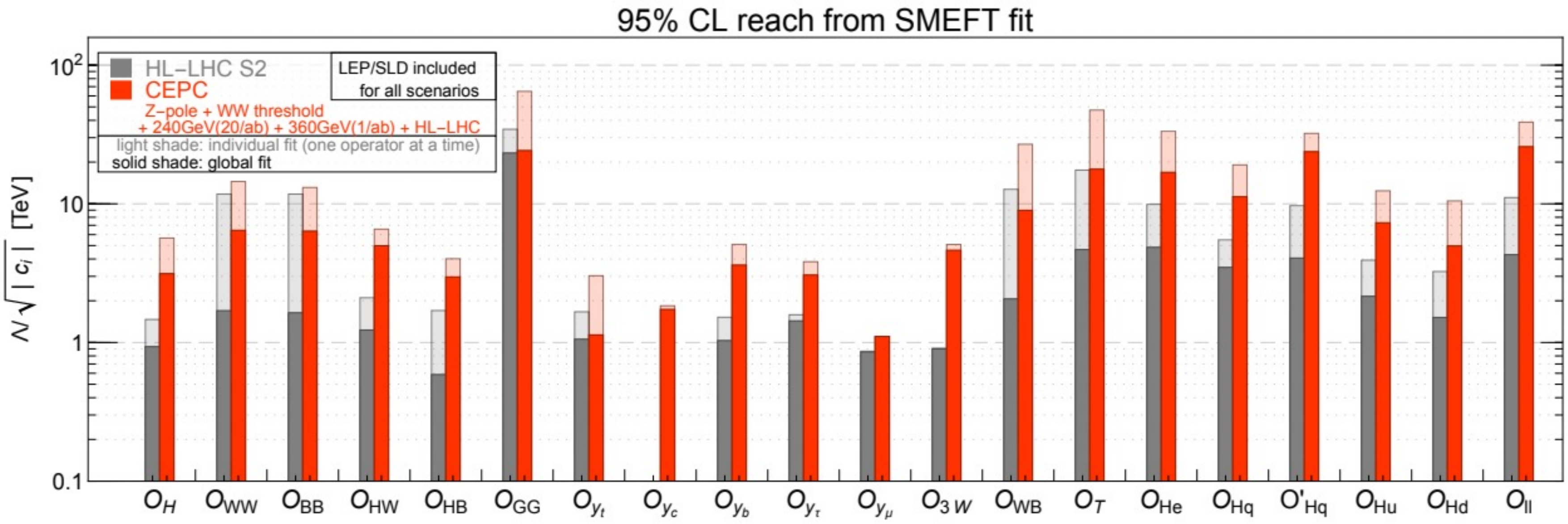
Higgs decays to $\tau\tau$

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





Energy Scale for the new physics



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

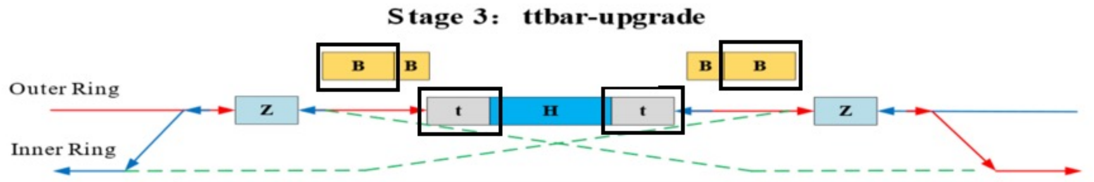
https://indico.ihep.ac.cn/event/13888/

- 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*

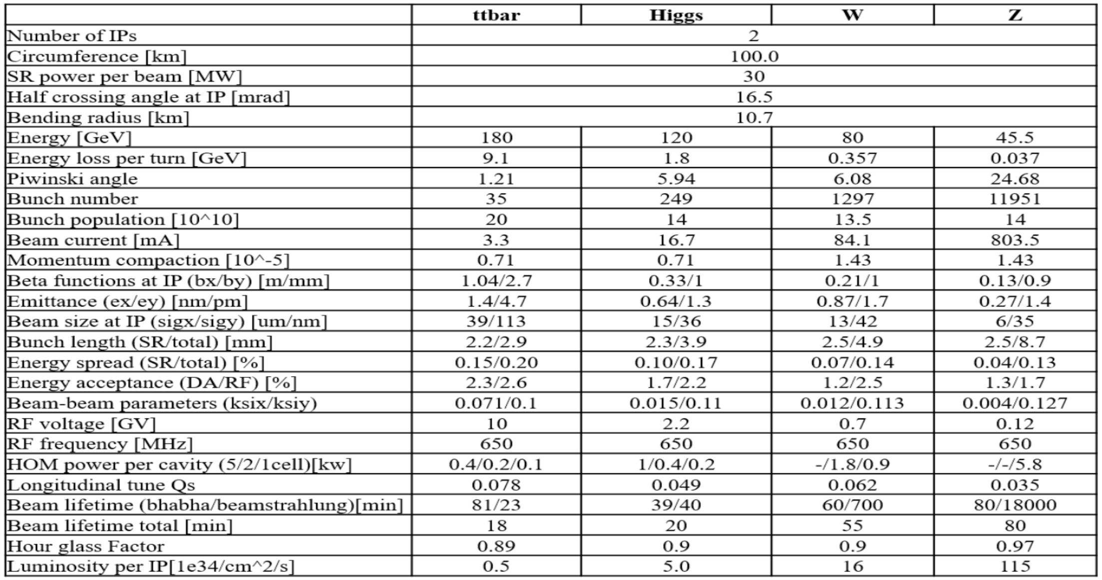
Accelerator at ttbar

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, currer design achieved a luminosity of 0.5E34/cm^2/s/IP
  - corresponding to $1\,ab^{-1}$ 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 anc increasing the synchrotron radiation power limit.

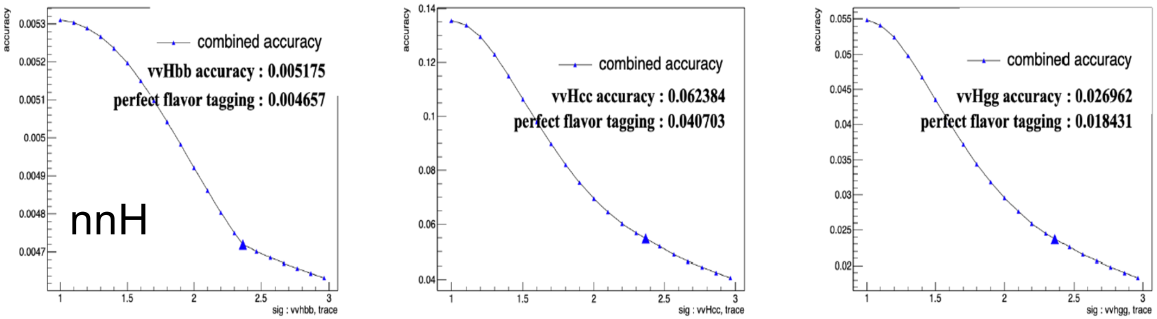


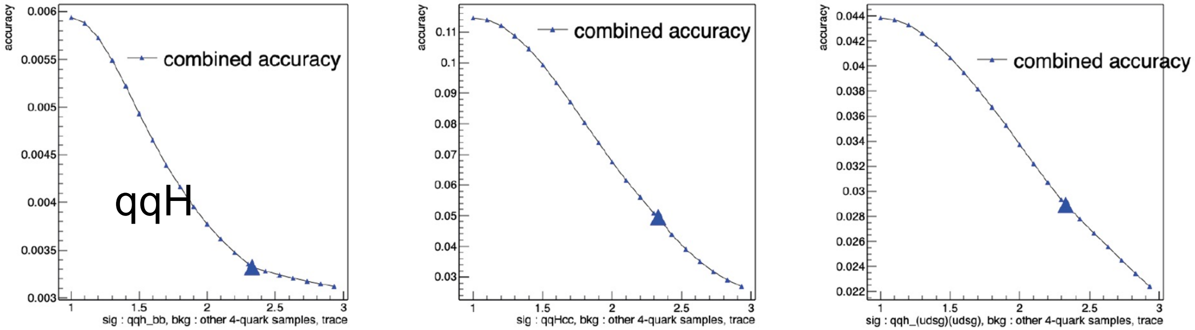
Extra RF cavities for ttbar in collider ring and booster ring

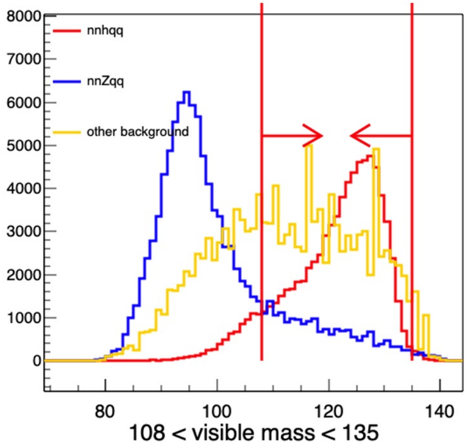


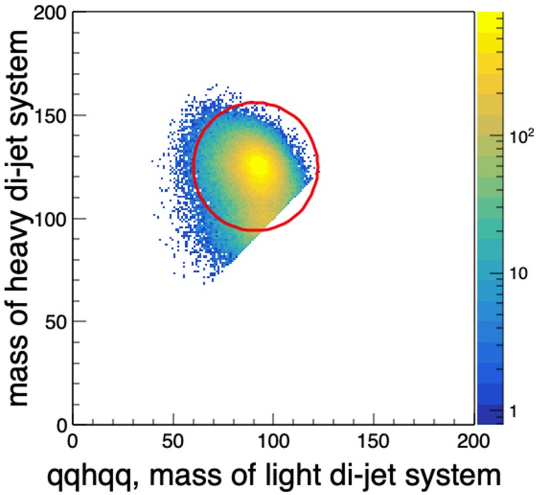
	ttbar	Higgs	W	Z
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	30			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
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

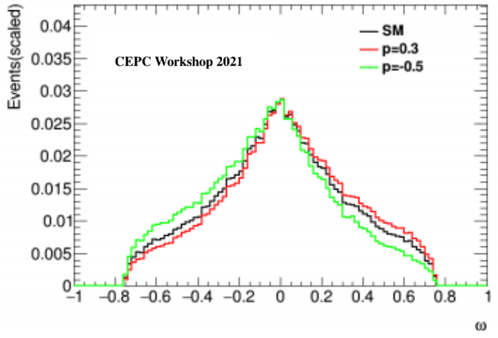
How to develop Jet Charge?

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

Differential cross section could be represent as:

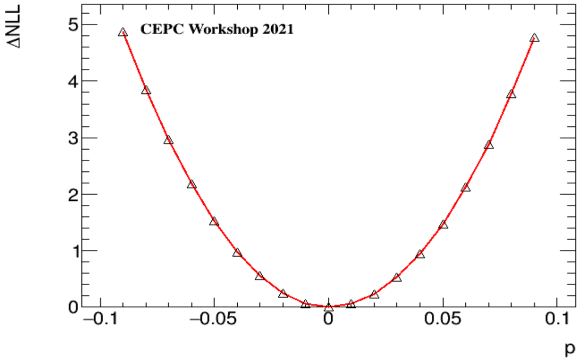
$$\frac{d\sigma}{dcos\theta_1 dcos\theta_2 d\phi} = N \times (J_{CP-even}(\theta_1, \theta_2, \phi) + p \times J_{CP-odd}(\theta_1, \theta_2, \phi)).$$

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

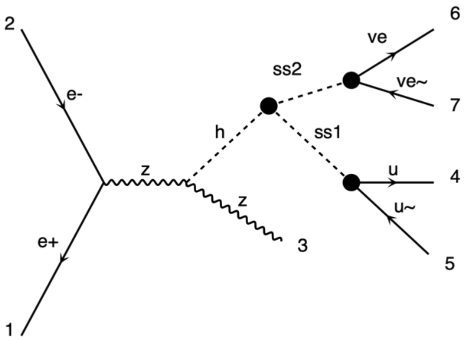
Used ML-fit in ω distribution to extract p.

Result:



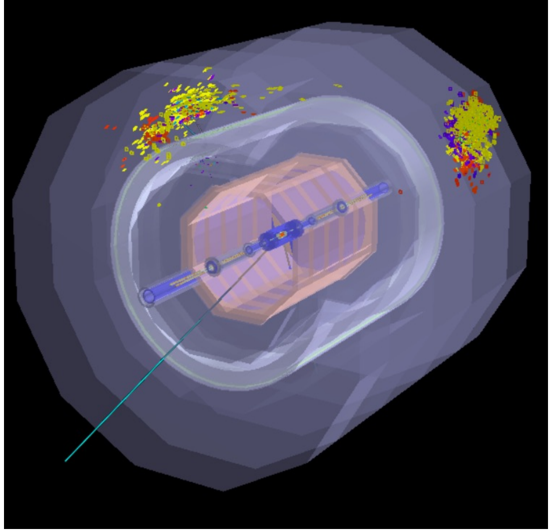
For p:
68% CL: $[-2.9\times10^{-2}, 2.9\times10^{-2}]$
95% CL: $[-5.7\times10^{-2}, 5.7\times10^{-2}]$

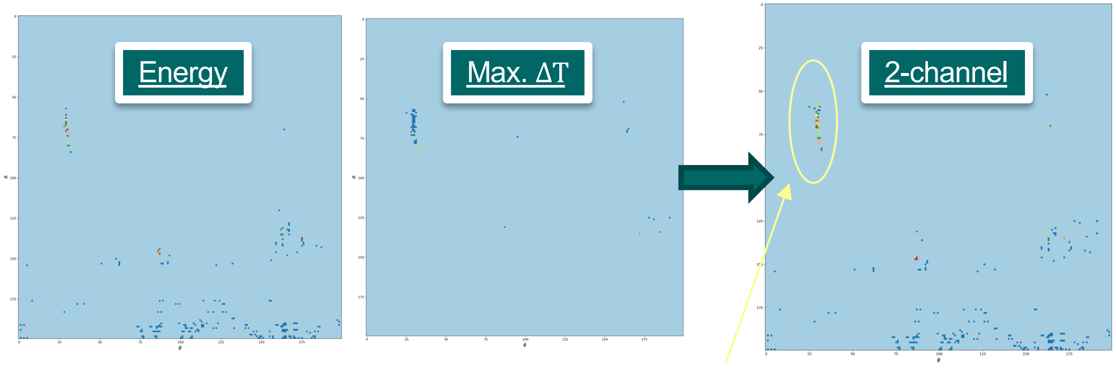
Image Recognition Techniques to Identify Long-Lived Particles(h->LLPs)



- 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 ΔT $(E > 0.1\ GeV)$ within (R, ϕ) pixel
- Model: ResNet18 (Classification), ResNet50 (Vertex Finding)
- **Binary Cross Entropy Loss:** $loss(x_i, y_i) = -\omega_i[y_i \log(x_i) + (1 - y_i)\log(1 - x_i)]$

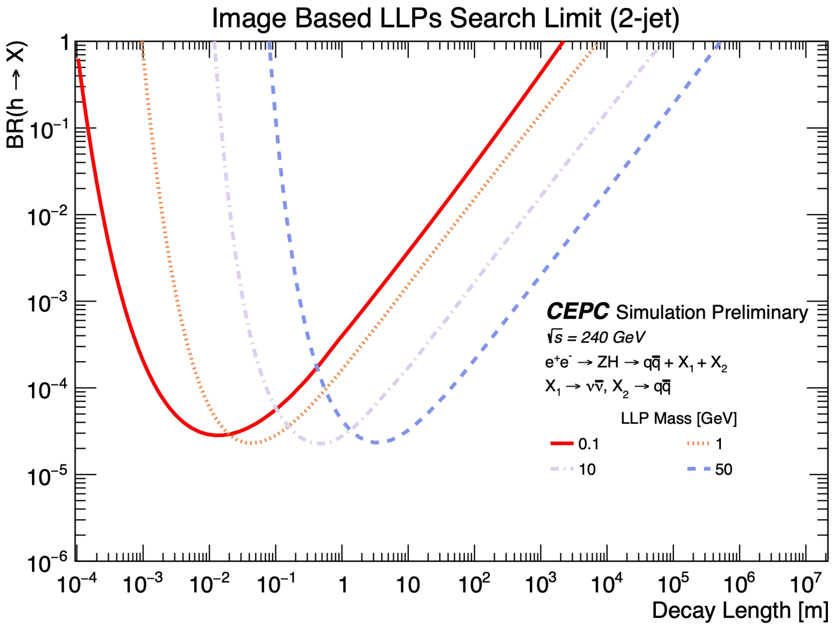
$e^+e^- \to Zh \to \nu\bar{\nu} + SS1 + SS2 \to \nu\bar{\nu}q\bar{q}q\bar{q}$





A LLP Event

Expected Search Sensitivity



<u>Signal Efficiency of ML-based and Cut-based analysis for</u>

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

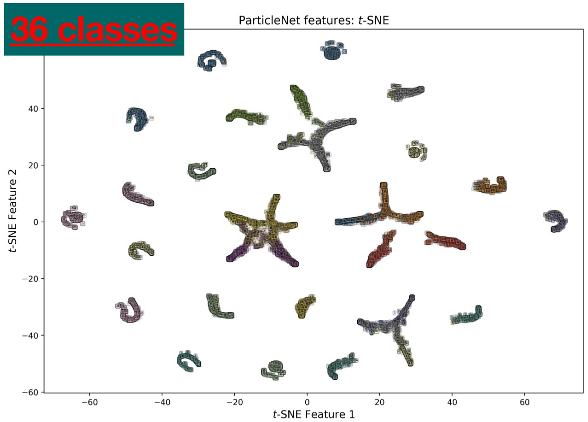
so Σ^n is easy

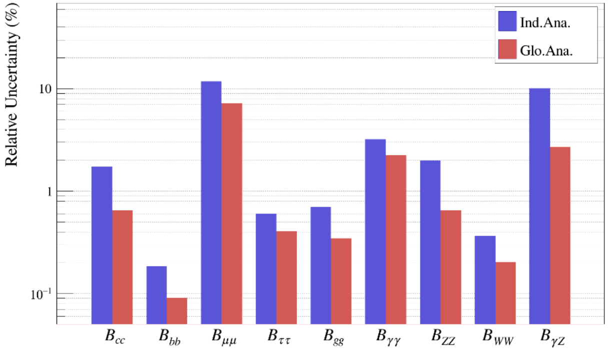
$$\mathbf{\Sigma}^N = N_t^e \begin{pmatrix} B_1(1-B_1) & -B_1B_2 & \dots & -B_1B_m \\ -B_2B_1 & B_2(1-B_2) & \dots & -B_2B_m \\ \vdots & \vdots & \ddots & \vdots \\ -B_mB_1 & -B_mB_2 & \dots & B_m(1-B_m) \end{pmatrix} ,$$

Solve all Ni by minimizing

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

Global analysis : Enhance Higgs coupling precision





ArXiv:2105.14997

calculate the efficiency matrix

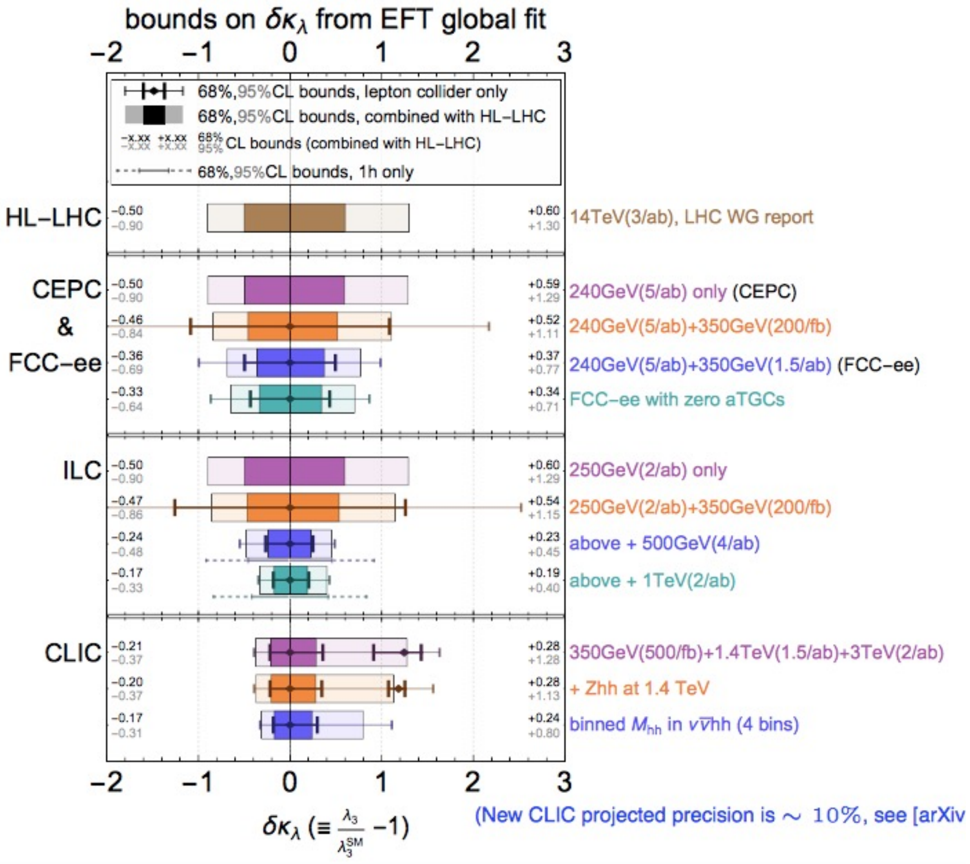
Decay Mode	Ind.Ana.	Glo.Ana.	IP	CEPC CDR
$H \to c\bar{c}$	1.8%	0.65%	2.7	3.3%
$H \to b\bar{b}$	0.19%	0.09%	2.1	0.56%
$H \to \mu^+\mu^-$	12%	7.2%	1.7	17%
$H \to \tau^+\tau^-$	0.61%	0.41%	1.4	1.0%
$H \to gg$	0.7%	0.35%	2.0	1.4%
$H \to \gamma\gamma$	3.3%	2.3%	1.4	6.9%
$H \to ZZ$	2.0%	0.65%	3.0	5.1%
$H \to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

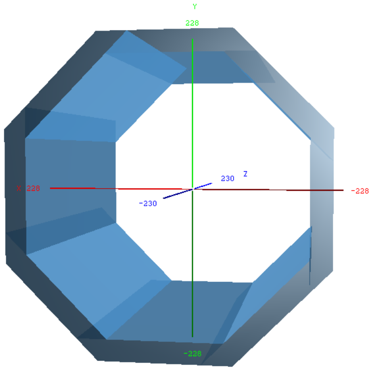
Impact on Higgs self-coupling

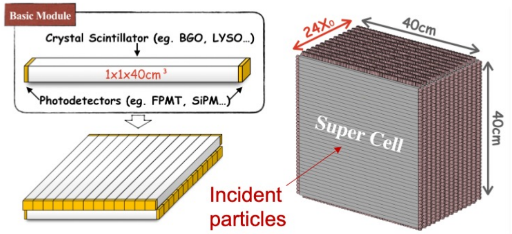


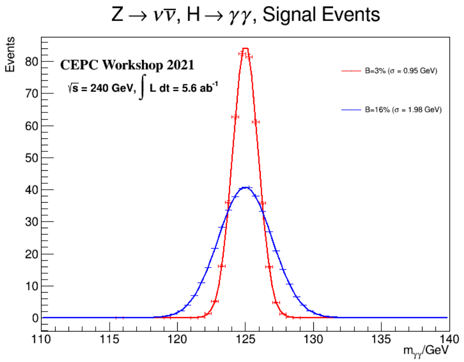
(New CLIC projected precision is $\sim 10\%$, see [arXiv

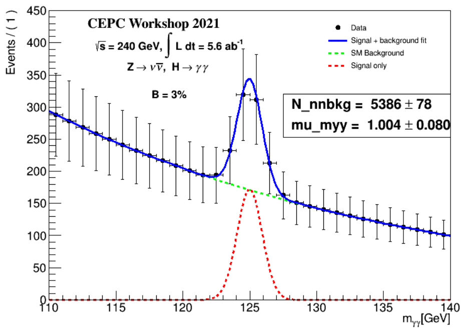
$H \rightarrow \gamma\gamma$ precision @ CEPC conceptual detector

- 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%