Status of Higgs physics at CEPC

Yaquan Fang (IHEP) on behalf of CEPC Higgs working group

the 2020 International workshop on the High Energy Circular Electron Positron Collider

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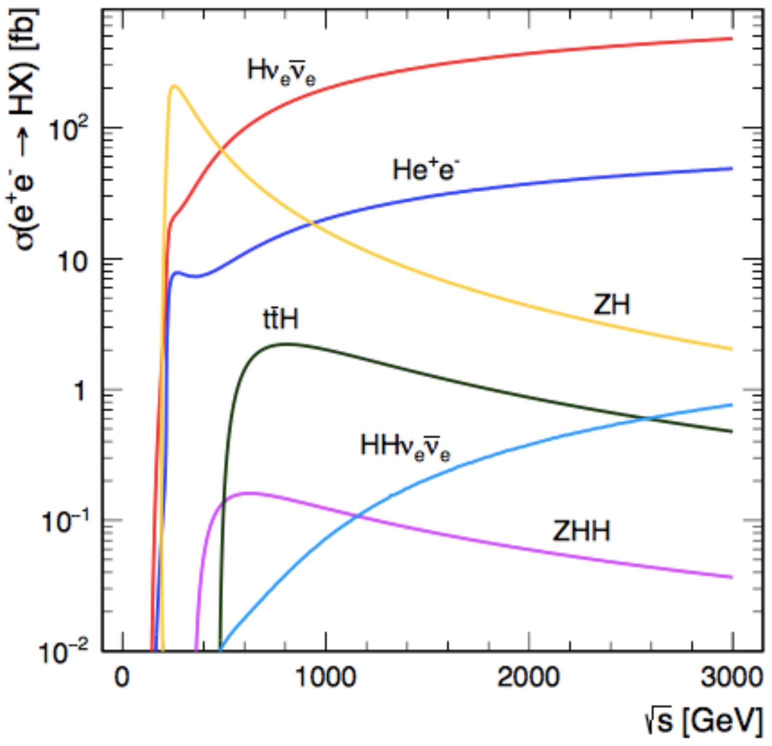
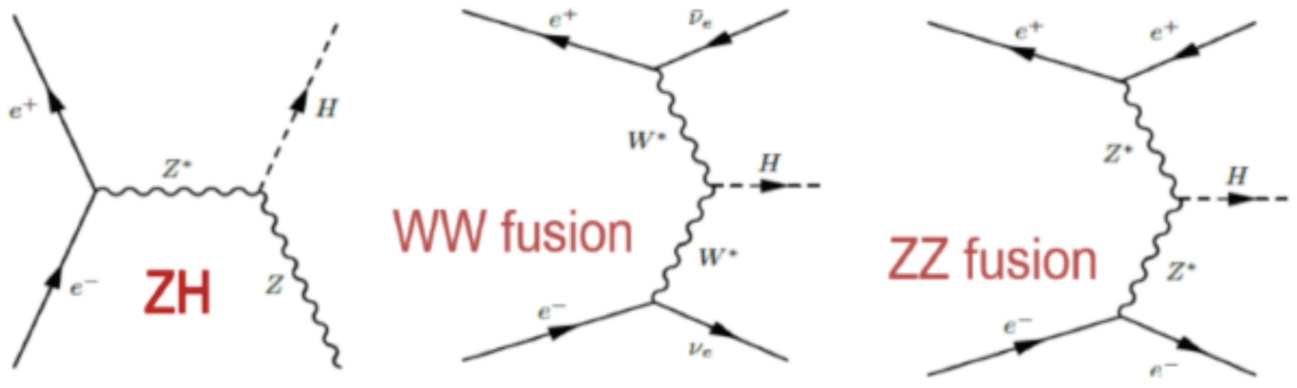
Shanghai Jiao Tong University, Shanghai, China

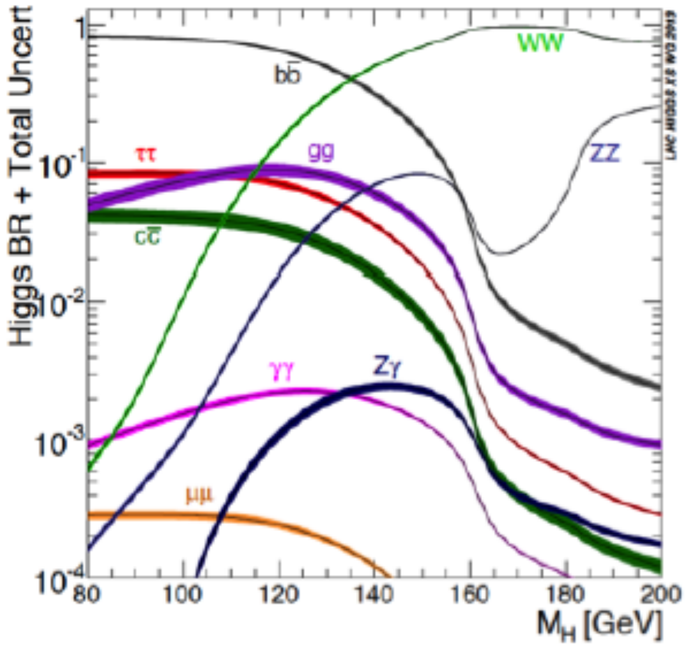
Higgs related physics at e^+e^- collider

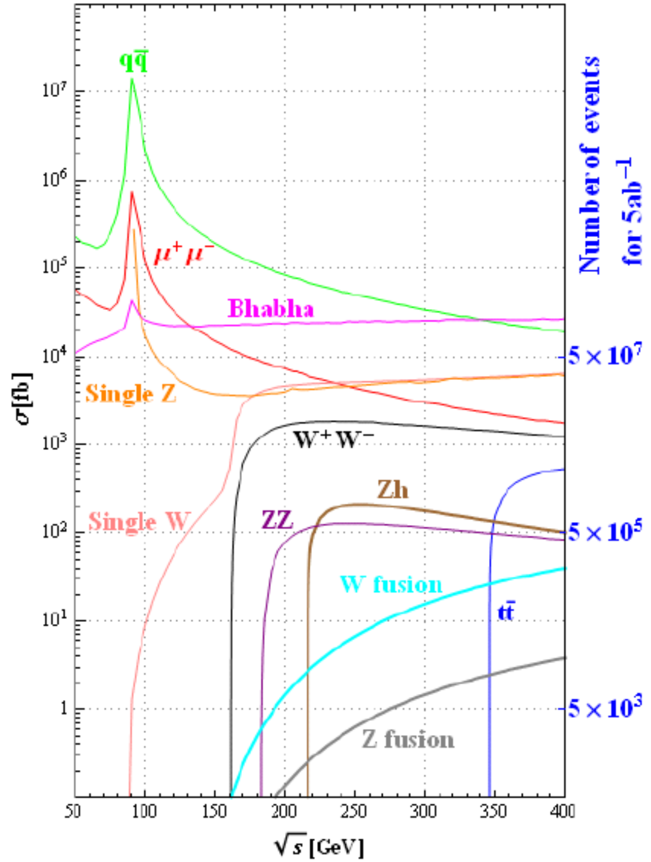




- ➢ With the increase of the energy, different Higgs related physics can be explored at e^+e^- collider.
- ➢ With the energy around 240 GeV, ZH as well as ww/zz fusion can be intensively studied.
  - the dominant production is from HZ, the WW/ZZ fusions contribute a few percent of the total cross-section.

SM Higgs decay branching ratio, Bkg process

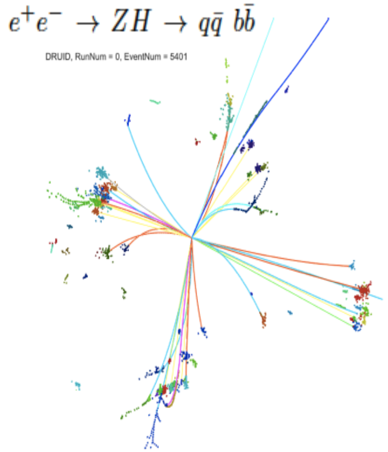


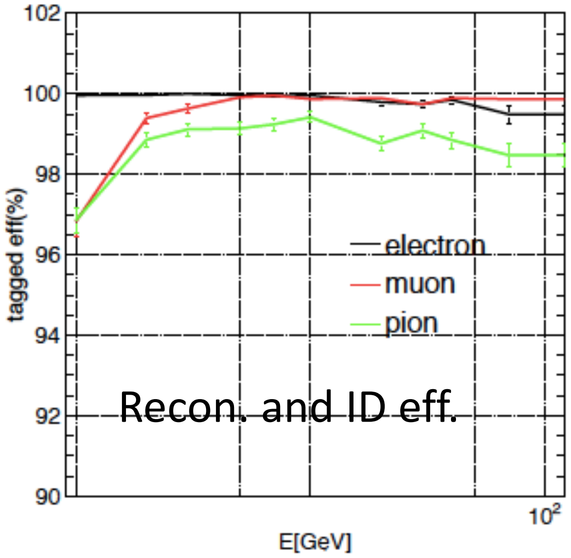


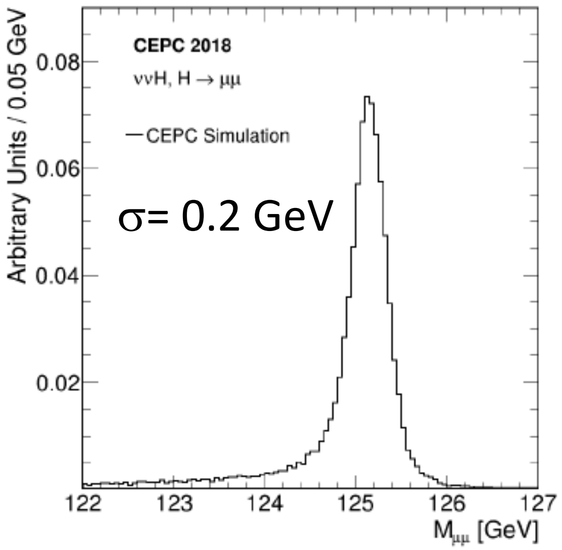
✓ e^+e^- collider provides a good opportunity to measure the jj, invisible decay of Higgs.

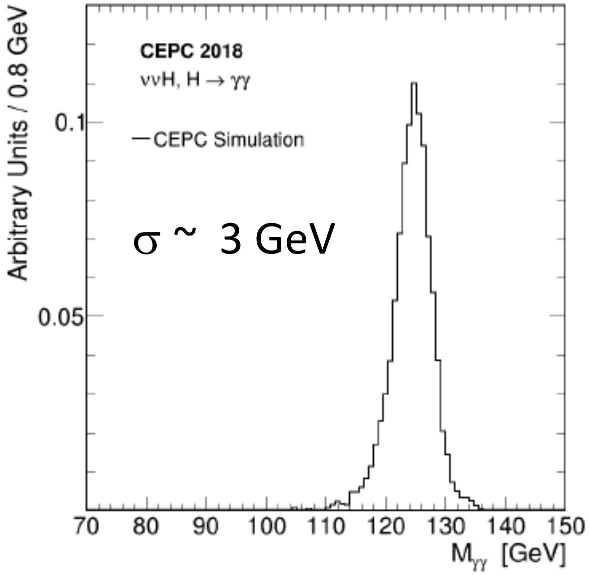
✓ For 5.6 ab^{-1} data with CEPC, 1M Higgs, 10M Z, 100M W are produced.

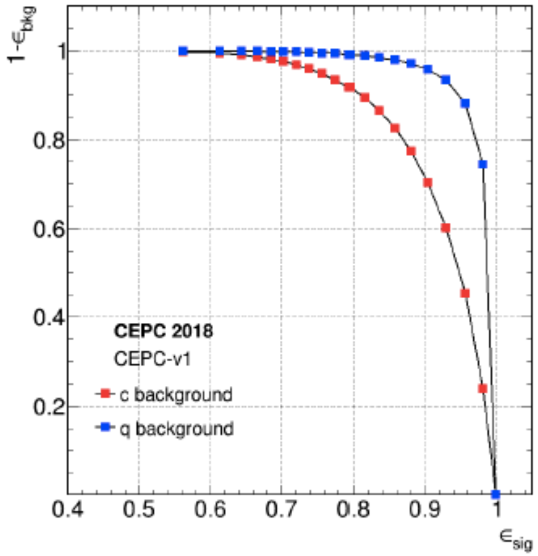
Performance



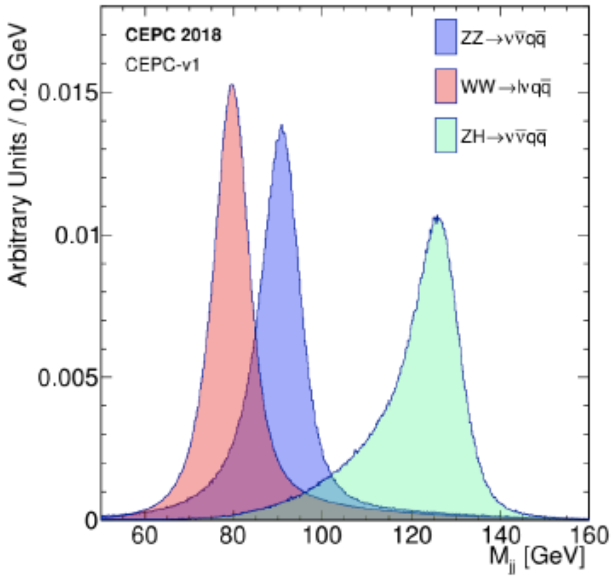






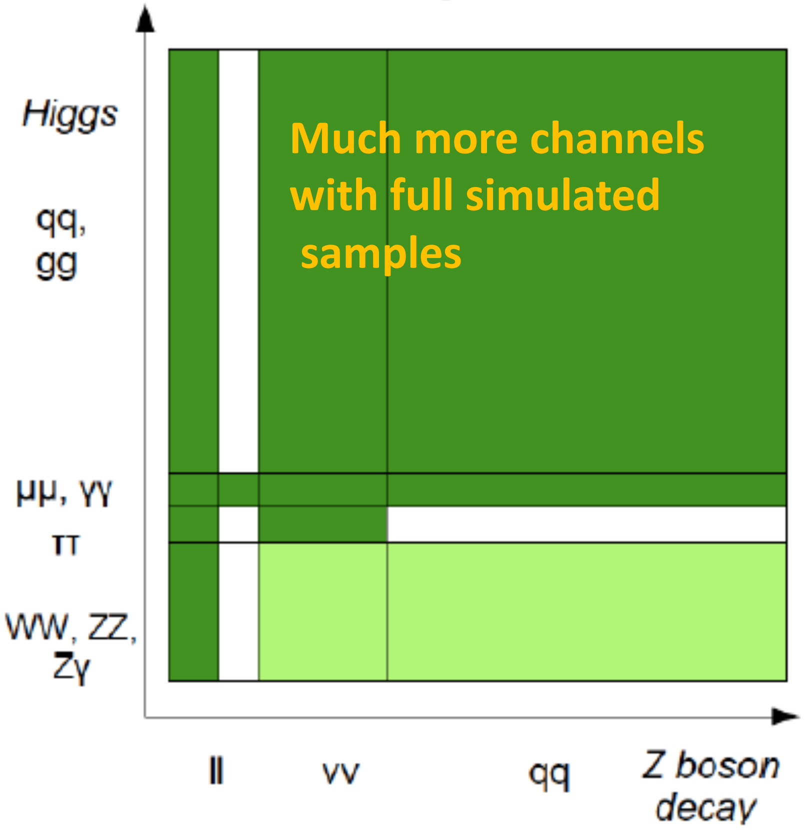


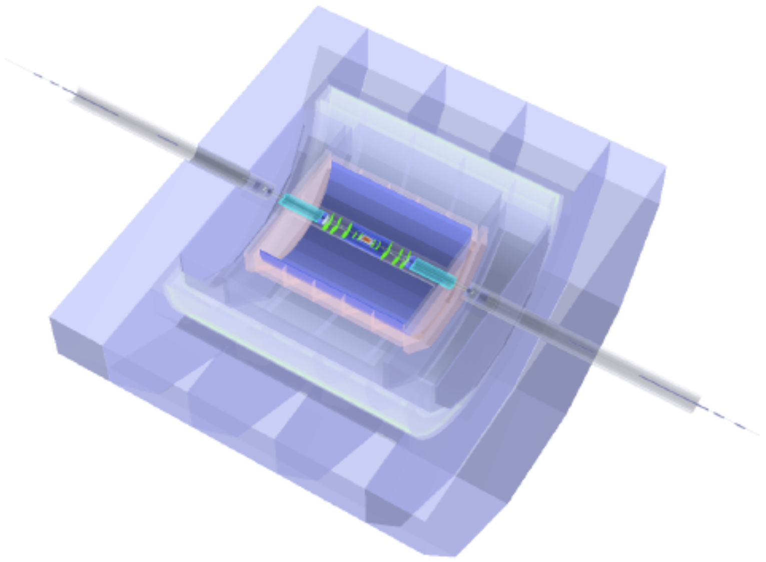
B-tagging eff. vs rejection of other jets



- Reliable Particle recon., ID and fake rejection
- Good mass resolution of Higgs masses.

Higgs analyses @CEPC CDR

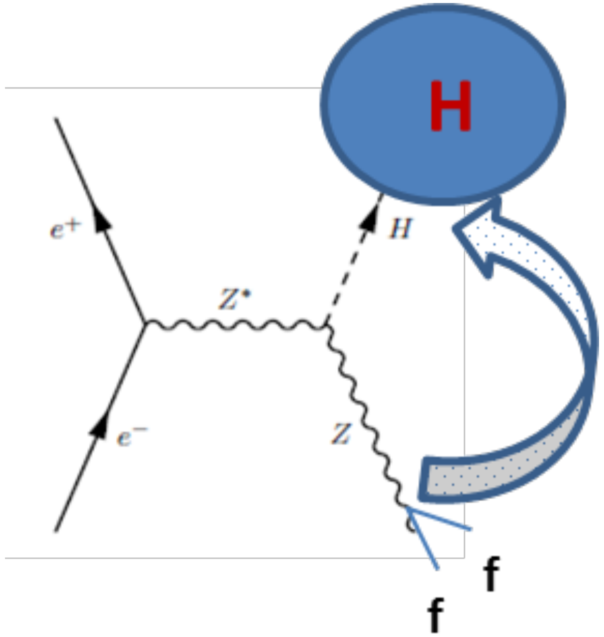




A lot of decay channels can be investigated.

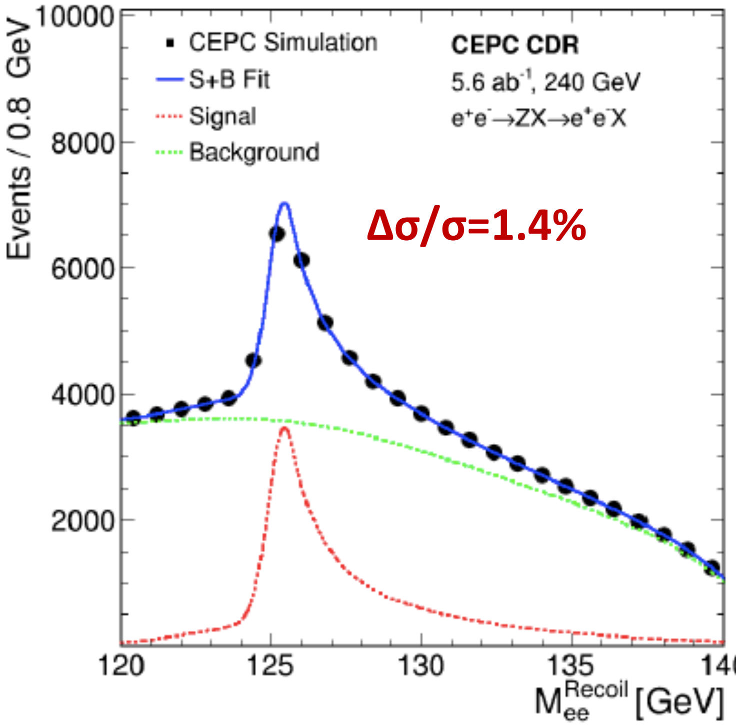
Direct measurement of Higgs cross-section

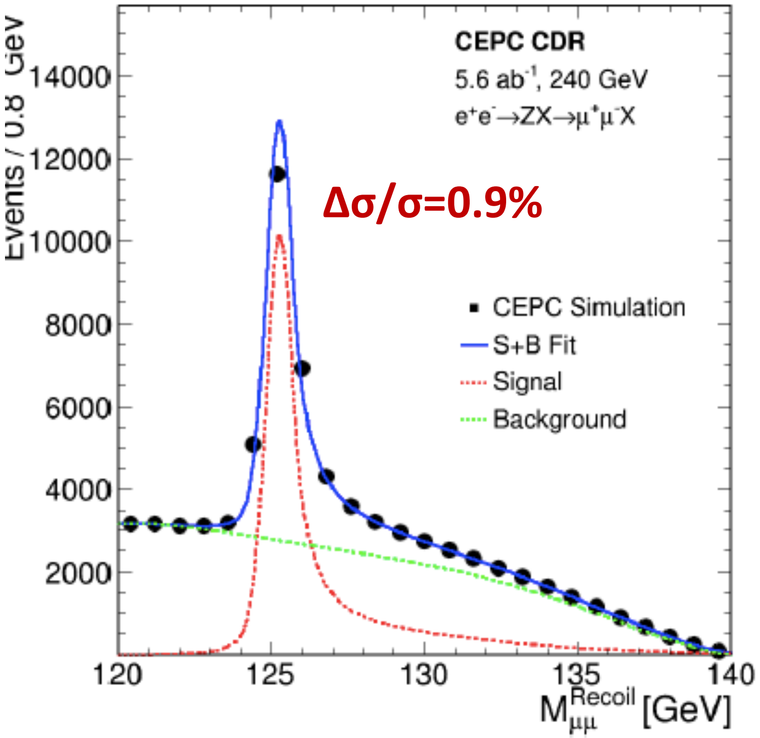
$$M^2_{\text{recoil}} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$

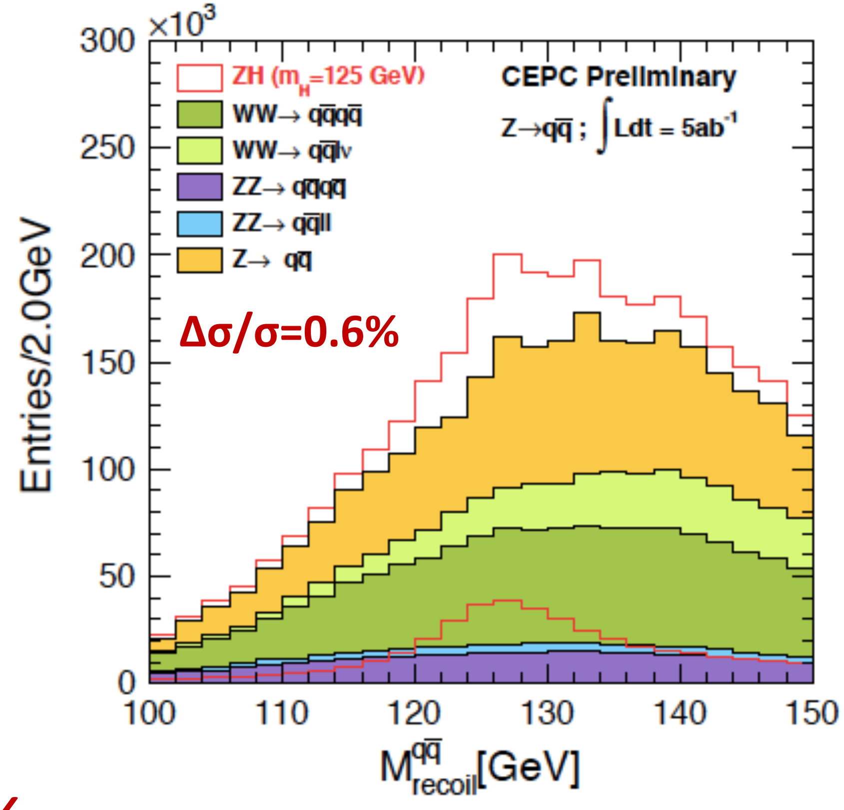


- ✓ **For this model independent analysis, we reconstruct the recoil mass of Z without touching the other particles in a event.**
- ✓ **The M_{recoil} should exhibit a resonance peak at m_H for signal; Bkg is expected to smooth.**
- ✓ **The best resolution can be achieved from $Z(\rightarrow e^+e^-,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

Direct measurement of Higgs cross-section and m_H







- ✓ **The combined precision with three channels is Δσ/σ=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→μμ (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%

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

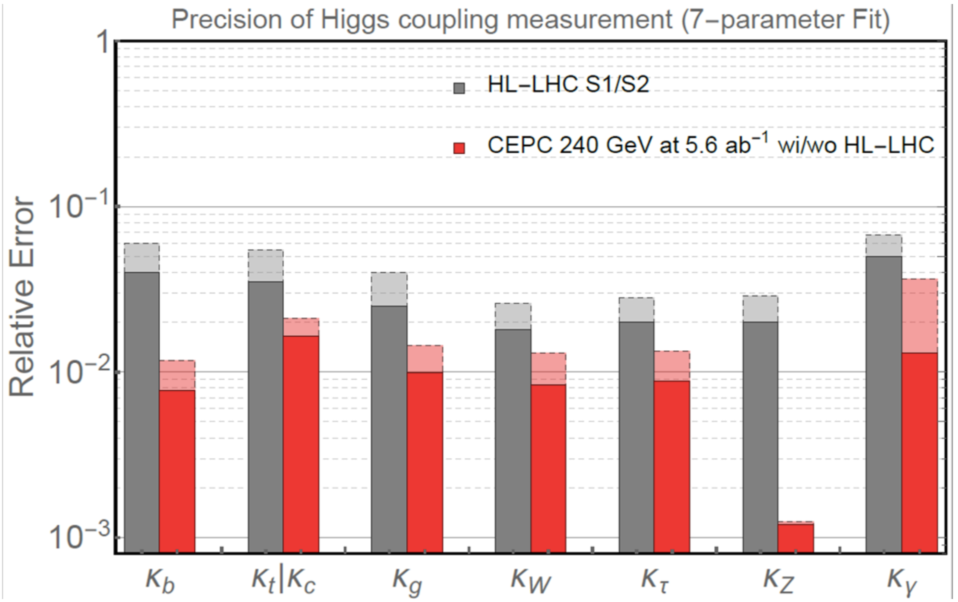
Precision : 3.5%

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

Precision : 2.8%

Precision for the Measurement of Higgs

Property	Estimated Precision CEPC-v1		Estimated Precision CEPC-v4	
m_H	5.9 MeV		5.9 MeV	
Γ_H	2.7%		2.8%	
$\sigma(ZH)$	0.5%		0.5%	
$\sigma(\nu\bar{\nu}H)$	3.0%		3.2%	
Decay mode	$\sigma \times$ BR	BR	$\sigma \times$ BR	BR
$H \to b\bar{b}$	0.26%	0.56%	0.27%	0.56%
$H \to c\bar{c}$	3.1%	3.1%	3.3%	3.3%
$H \to gg$	1.2%	1.3%	1.3%	1.4%
$H \to WW^*$	0.9%	1.1%	1.0%	1.1%
$H \to ZZ^*$	4.9%	5.0%	5.1%	5.1%
$H \to \gamma\gamma$	6.2%	6.2%	6.8%	6.9%
$H \to Z\gamma$	13%	13%	16%	16%
$H \to \tau^+\tau^-$	0.8%	0.9%	0.8%	1.0%
$H \to \mu^+\mu^-$	16%	16%	17%	17%
$\mathrm{BR}^{\mathrm{BSM}}_{\mathrm{inv}}$	–	$< 0.28\%$	–	$< 0.30\%$



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Precision Higgs Physics at the CEPC*

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- ✓ **With combination of σ▪Br of ννH(→bb) /Br(H→bb)/Br(H→ww) and the direct measurement, one can obtain the decay width of Higgs with the precision at ~3%.**
- ✓ **The measurement of Br is done by introducing the uncertainty of xsection of ZH from the direct measurement around sub-precent level.**
- ✓ **Most precisions are a few percent or lower (bb, invisible), allowing us to be sensitive to BSM deviation**
- ✓ **CEPC is complementary to LHC at the Higgs precision measurement.**
- ✓ **Higgs white paper are published at CPC (arxiv: 1810.09037) and results are included in CDR.**
  - ✓ **Other publications:** $\sigma(ZH)$:1601.05352; bb/cc/gg: 1905.12903; $\tau\tau$:1903.1232
    Invisible: 2001.05912 **(new)**

Precision for the measurement of Higgs

CEPC CDR: arxiv: 1811.10545

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
$H \to b\bar{b}$	0.27%	0.56%
$H \to c\bar{c}$	3.3%	3.3%
$H \to gg$	1.3%	1.4%
$H \to WW^*$	1.0%	1.1%
$H \to ZZ^*$	5.1%	5.1%
$H \to \gamma\gamma$	6.8%	6.9%
$H \to Z\gamma$	15%	15%
$H \to \tau^+\tau^-$	0.8%	1.0%
$H \to \mu^+\mu^-$	17%	17%
$H \to$ inv	–	$< 0.30\%$

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

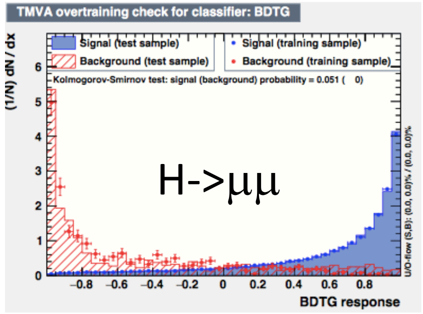
$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \to$ any	±0.5		±0.9	
$H \to b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H \to c\bar{c}$	±2.2		±6.5	±10
$H \to gg$	±1.9		±3.5	±4.5
$H \to W^+W^-$	±1.2		±2.6	±3.0
$H \to ZZ$	±4.4		±12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

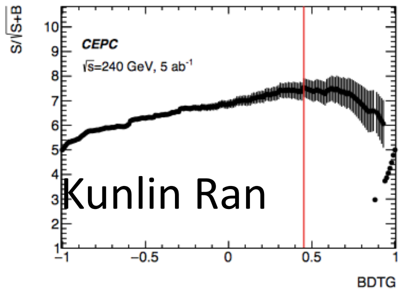
- Fcc-ee has similar results as CEPC but including a 365 GeV run improving the measurement of Higgs width.

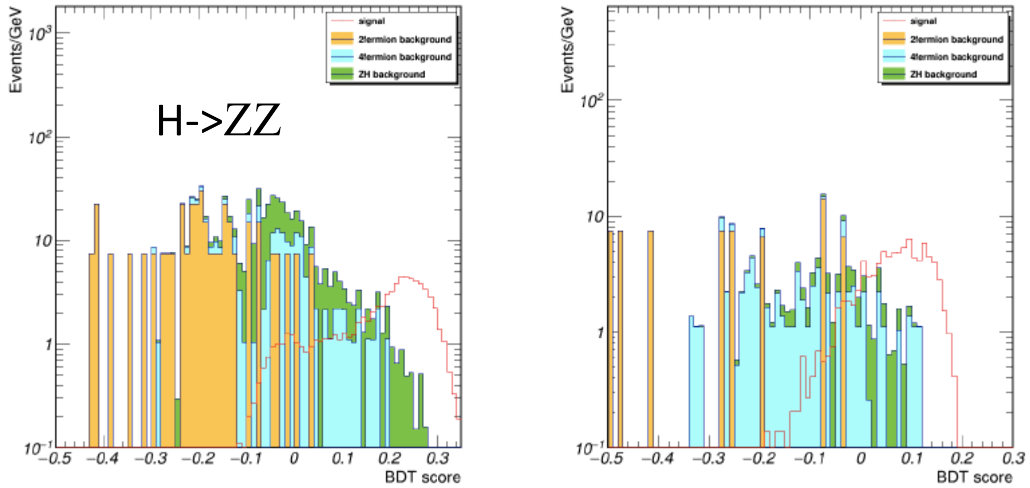
MVA methods used in different channels and other activities

Ryuta et al., will have a publication soon

- 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

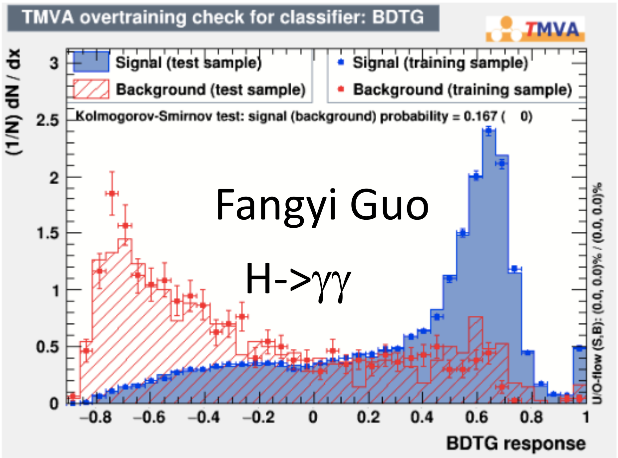
	Sig yield	Bkg yield	Sensitivity	Mass range (GeV)
BDTG > 0.45	86.20 +/- 0.51	198.20 +/- 19.82	7.46 +/- 0.27	[120.78 - 125.33]
BDTG < 0.45	29.77 +/- 0.30	1402.95 +/- 52.73	1.08 +/- 0.03	[114.08 - 125.28]
Total	115.97 +/- 0.59	1601.15 +/- 56.33	7.54 +/- 0.38	

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

H->ZZ

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

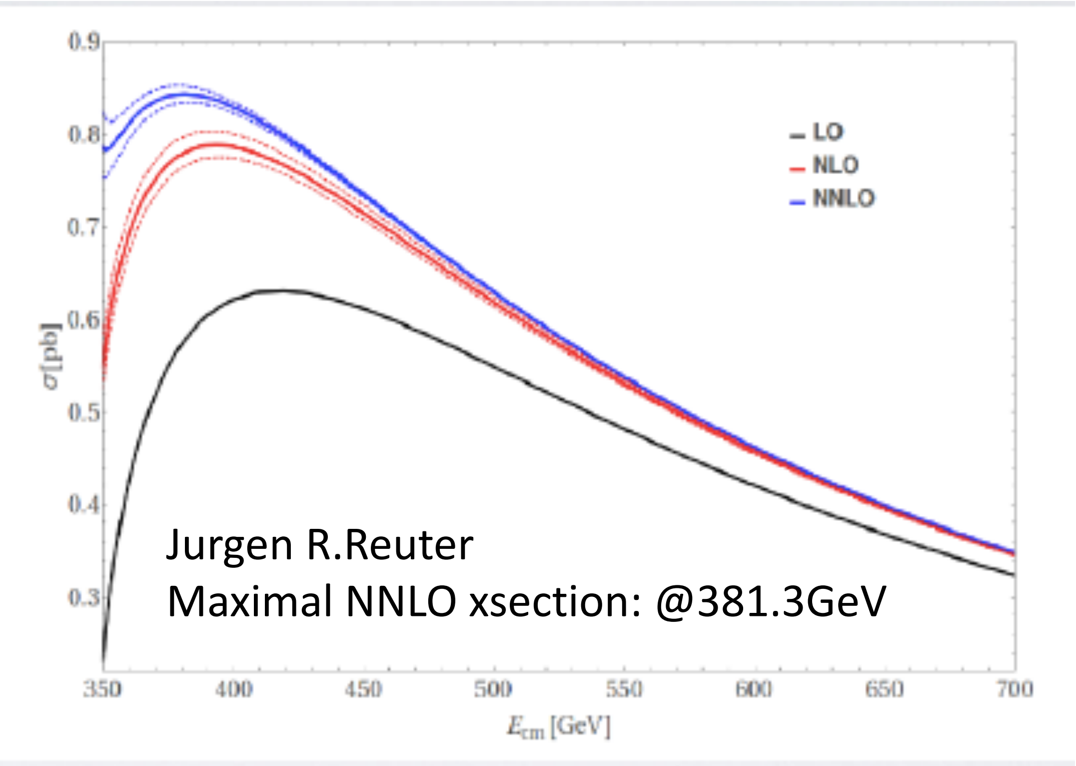
- The overall precision has been improved from 6.8% to 5.7% with MVA as well as full simulated samples used for H->γγ.

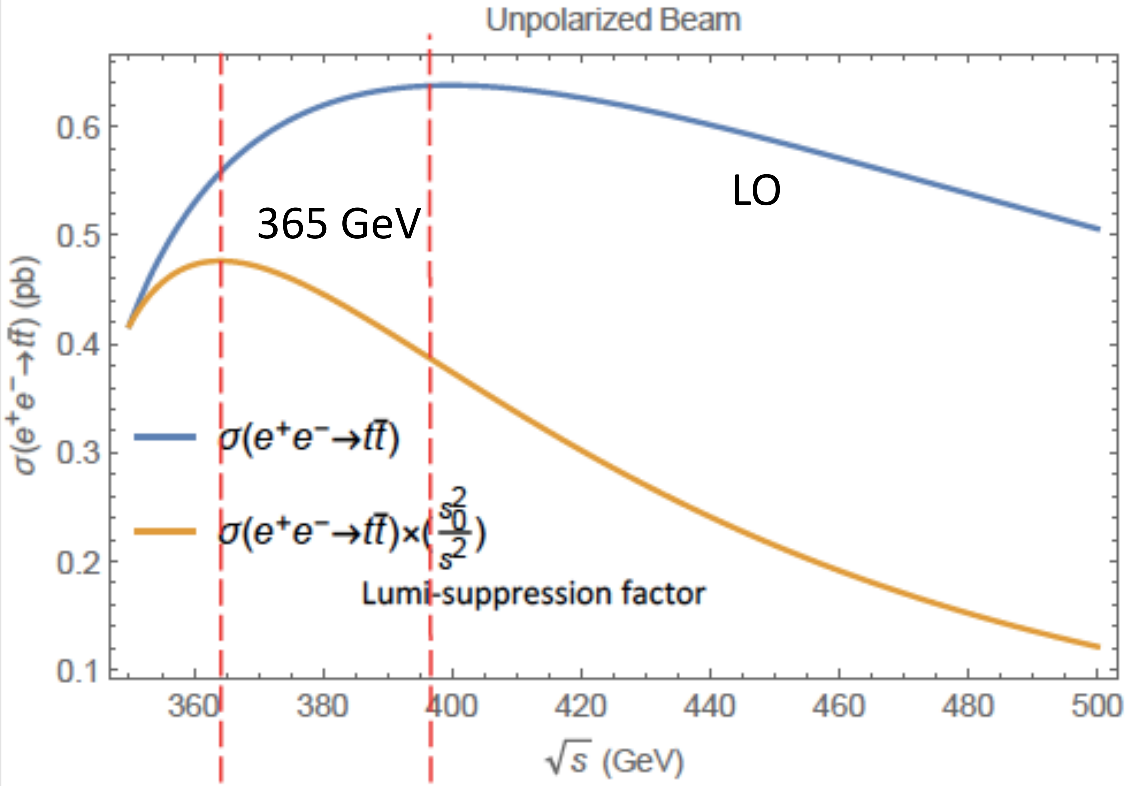


- Higgs CP study (see Fangyi's talk)

Higgs related physics at 360 GeV (generic study)

Zhen Liu, Liantao Wang et al.

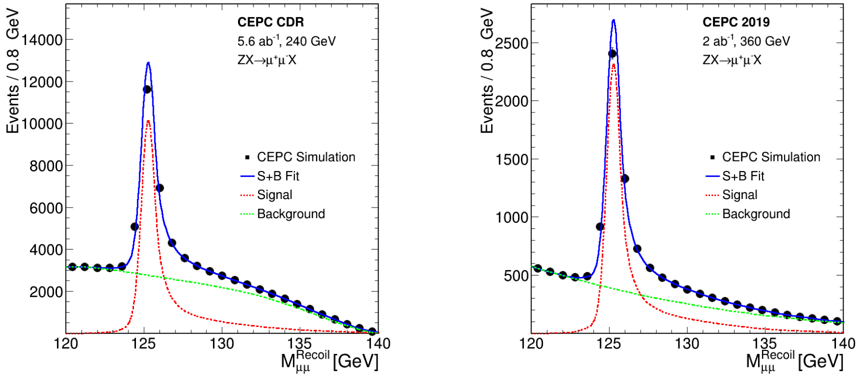




- With the NNLO calcuation, the highest xsection is at the energy of 381.3 GeV
- Considering the Lumi-suppression factor when going to higher energy, the effective highest xsection is around 365 GeV.
- The effective xsection from 360 GeV is not much different from that of 365 GeV.
- If we choose higher order correction, the peak could be even lower than 360 GeV.
- For 2 ab^{-1} data, it will take 4-5 years with optimized setup of the accelerator.

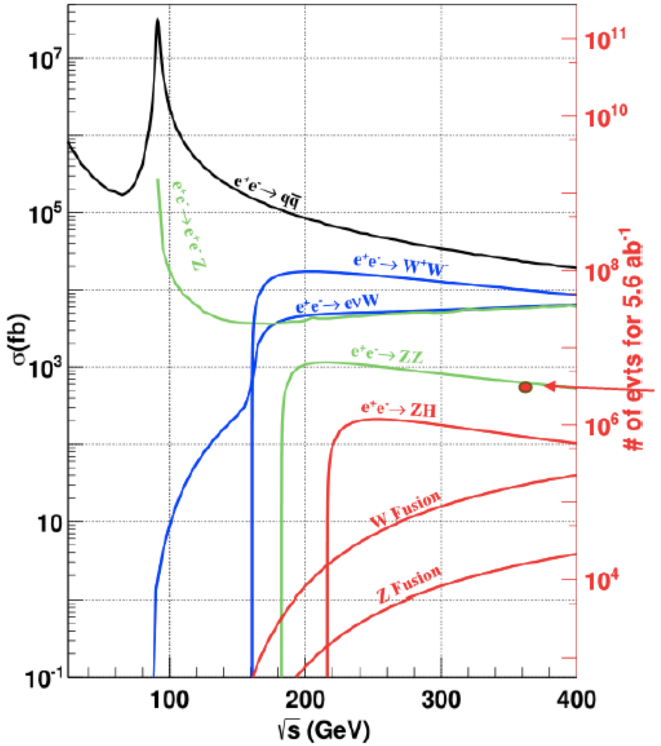
Extrapolations

- Mainly scale yields from 240GeV case.
- $\sigma(ZH)$: preliminarily, around 1%
    - Need patient work on qqH channel
- Resolution change: 2 benchmarks
    - dimuon: would worse; from ~0.3GeV to 1GeV; (23% -> 29%)
    - diphoton: would better; from ~2.5GeV to 2GeV; (9% -> 8%)



Ideal inclusive $Z \rightarrow \mu\mu$: $0.92\% \rightarrow 1.72\%$

Additional sensitivity on Higgs measurement



	240GeV, 5.6ab^{-1}	360GeV, 2ab^{-1}	
	ZH	ZH	ννH
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%**
$H \to \gamma\gamma$	**5.4%**	**8%**	**11%**
$H \to \mu\mu$	**12%**	**29%**	**40%**
$\mathrm{Br_{upper}}(H \to \mathrm{inv.})$	**0.2%**	\	\
$\sigma(ZH) * \mathrm{Br}(H \to Z\gamma)$	**16%**	**25%**	\
Width	**2.9%**		
Combined Width 240/360	**1.4%**		

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
$H \to$ any	± 0.5		± 0.9	
$H \to b\bar{b}$	± 0.3	± 3.1	± 0.5	± 0.9
$H \to c\bar{c}$	± 2.2		± 6.5	± 10
$H \to gg$	± 1.9		± 3.5	± 4.5
$H \to W^+W^-$	± 1.2		± 2.6	± 3.0
$H \to ZZ$	± 4.4		± 12	± 10
$H \to \tau\tau$	± 0.9		± 1.8	± 8
$H \to \gamma\gamma$	± 9.0		± 18	± 22
$H \to \mu^+\mu^-$	± 19		± 40	
$H \to$ invisible	< 0.3		< 0.6	

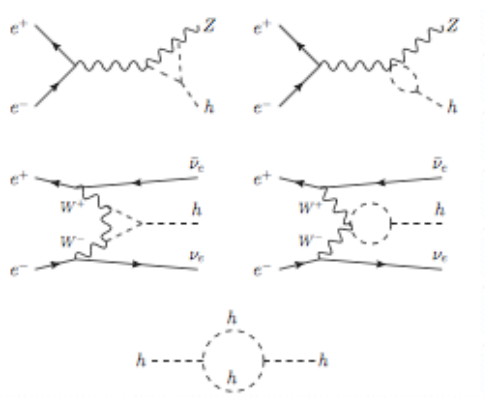
combined width: 1.3%

For Higgs physics results, there are no significant different for the colliding energy with 360 GeV or 365 GeV.

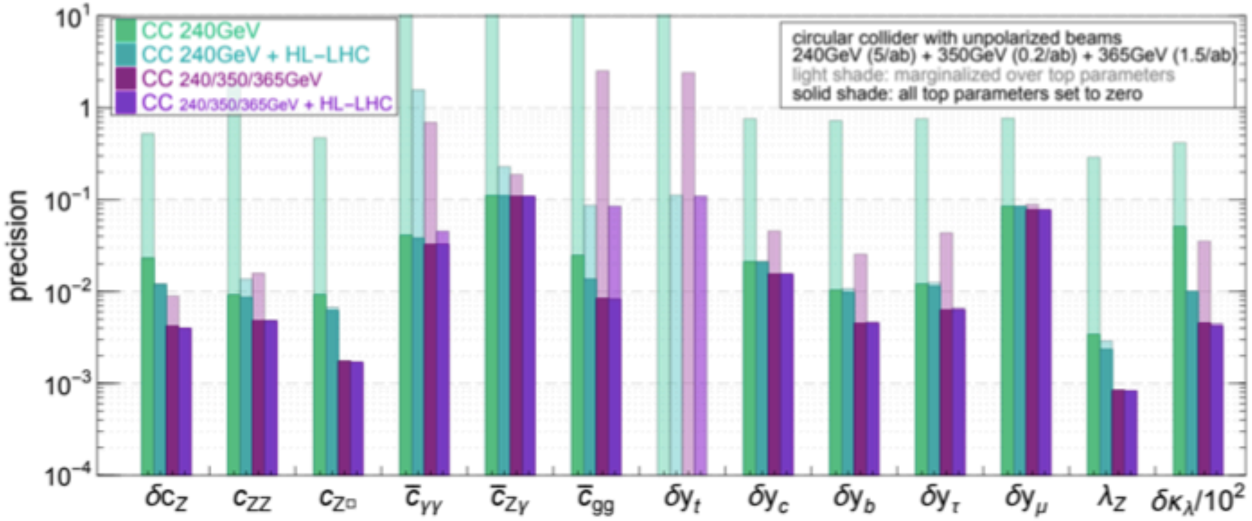
Jiayin Gu, Cen Zhang et al.,

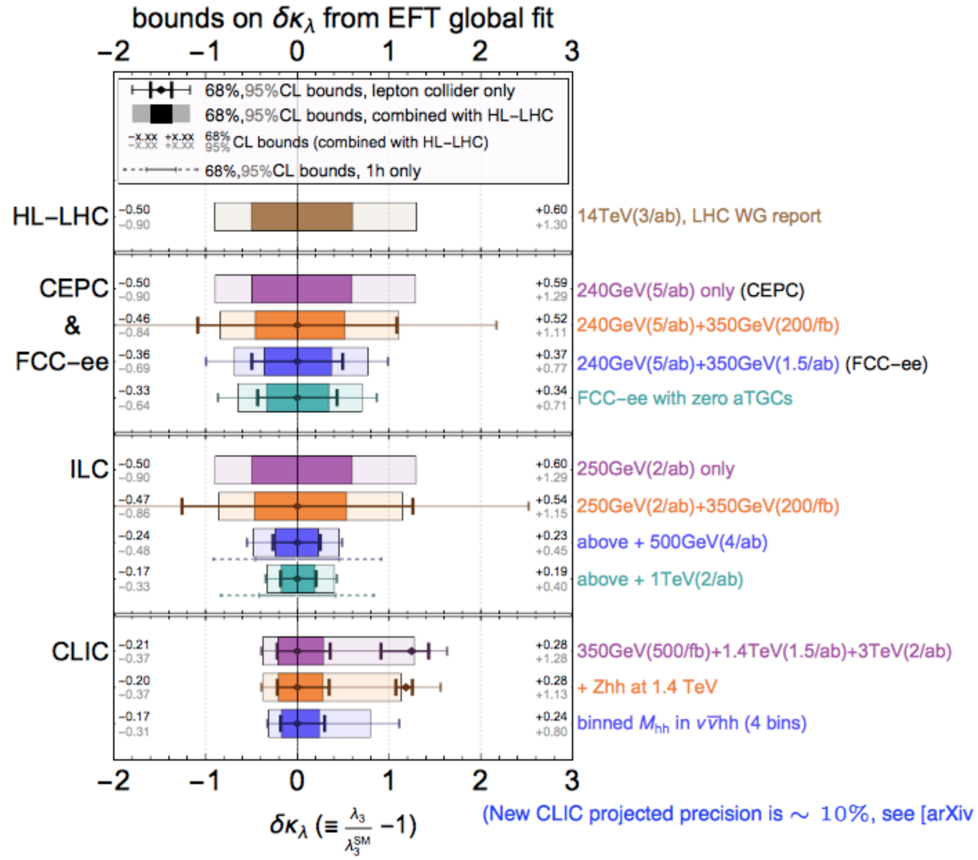
Impact on Higgs

Triple Higgs coupling:



light shades: 12 Higgs op. floated + 6 top op. floated
dark shades: 12 Higgs op. floated + 6 top op. → 0





Uncertainties on the top have a big effect on the Higgs

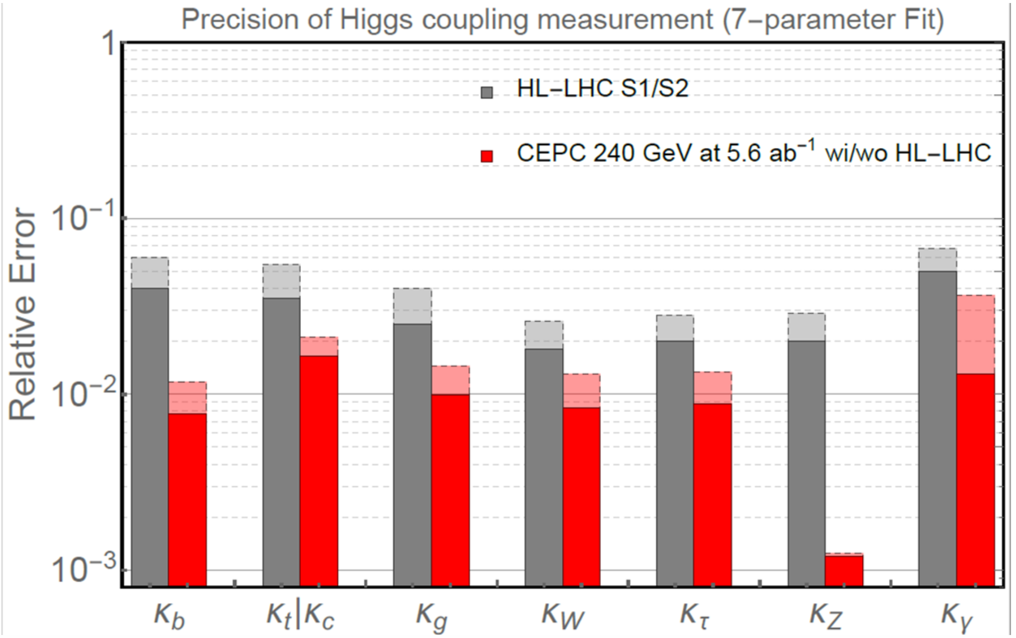
- Higgsstr. run: insufficient
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$: large y_t contaminations in various coefficients
- Higgsstr. run $\oplus$ top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma,gg,Z\gamma,ZZ}$
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$ $\oplus$ top@HL-LHC: top contam. in $\bar{c}_{gg}$ only

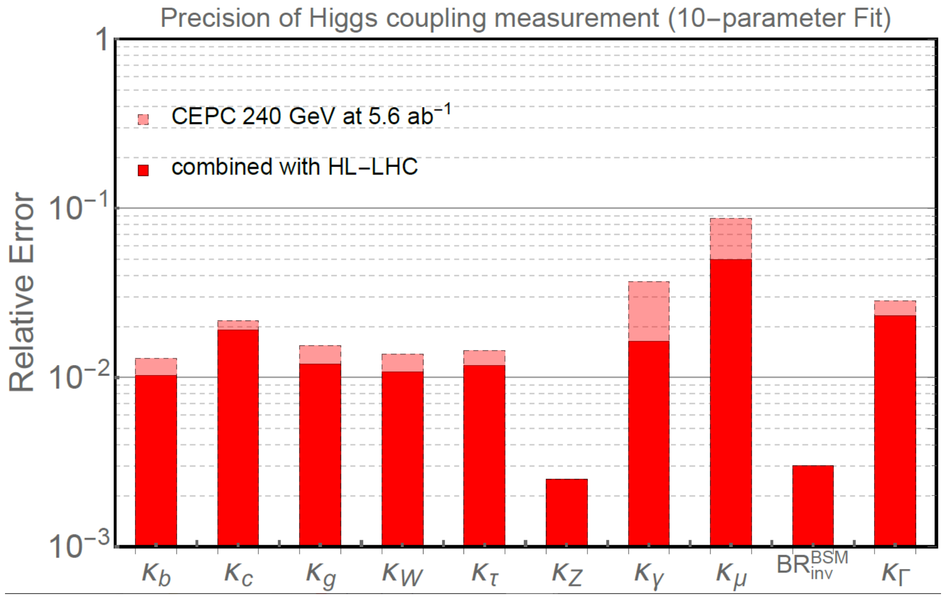
Conclusion

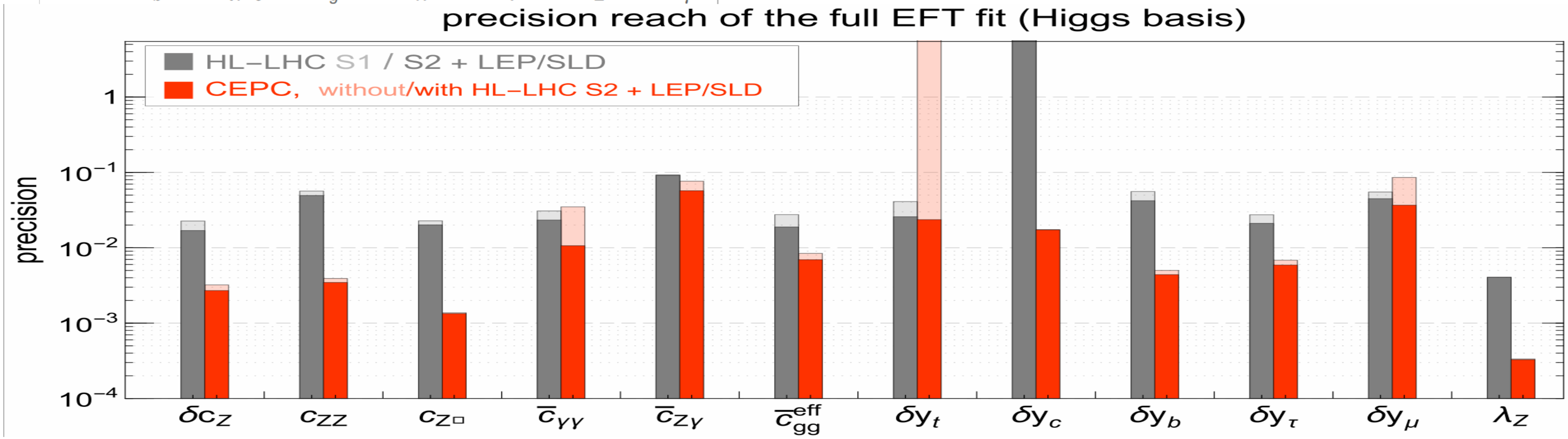
- After the Higgs white paper and CDR are done, analyses from individual channels have been documented. Several publications of them are available now.
- Improved analyses on each individual channels are on going.
- We also have a generic study on Higgs physics at 360 GeV (360 GeV/2 ab^{-1} as a benchmark)
  - Can bring some improvements in Higgs precision measurement in addition to top coupling measurements.
    - Significant improvement on Higgs width measurement.
  - Top coupling measurements itself has some impact on Higgs

backup slides

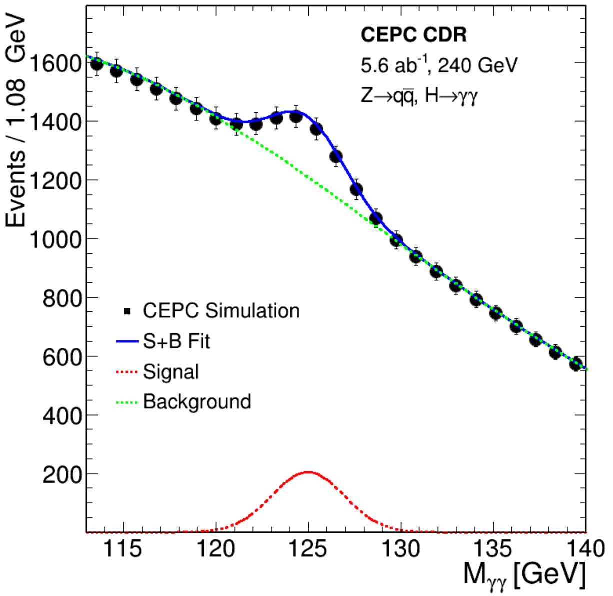
Combination/comparisons with HL-LHC

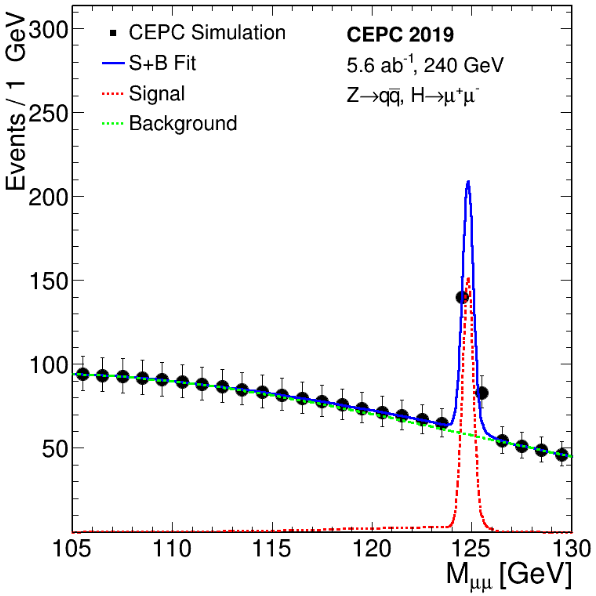


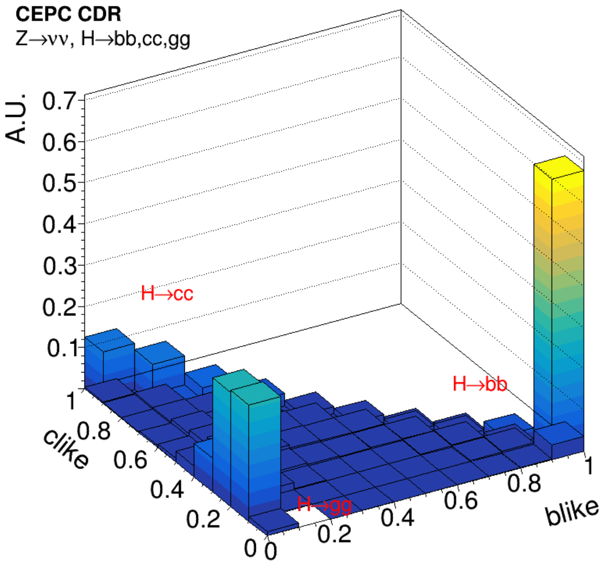


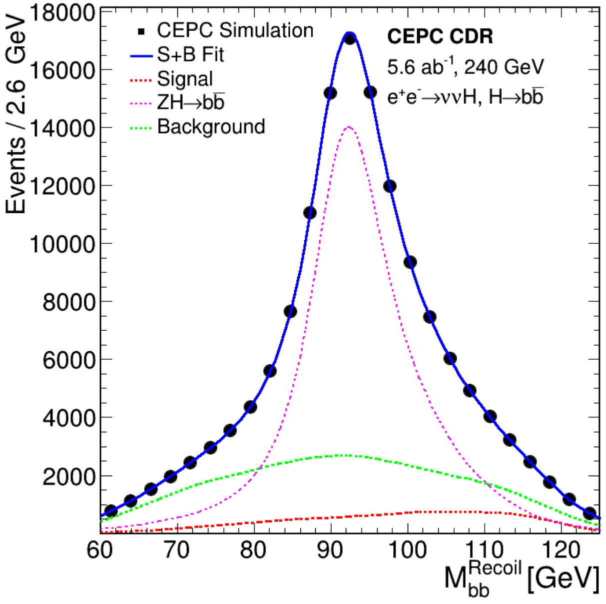


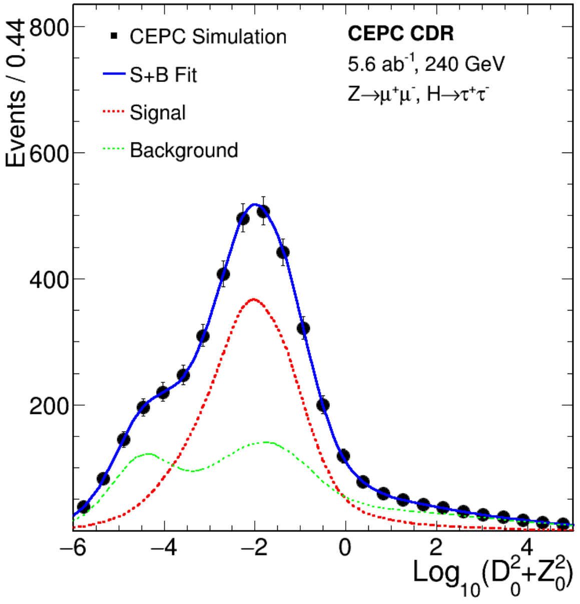
Typical individual channels











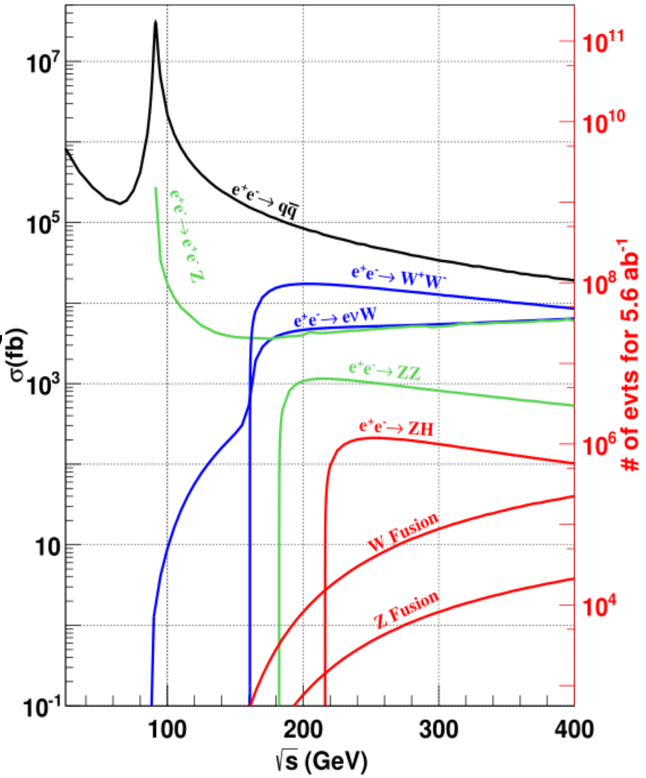
Signal/bkg Cross Sections

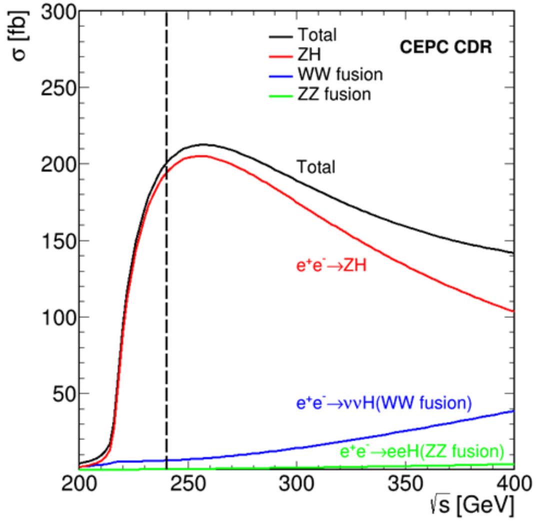
Kaili Zhang

- 240GeV:
  - ZH: 196.9; vvH: 6.2; interference: ~10% of vvH; about 318:10:1; (Z->vv
- 360GeV: (vvH ~ 117% Z->vv), (eeH ~ 67% Z->ee)

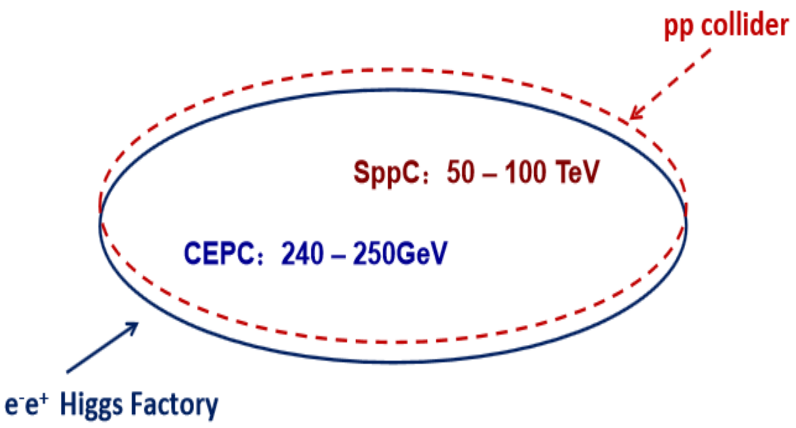
fb	240	350	360	365	360/240
ZH	196.9	133.3	126.6	123.0	-36%
WW fusion	6.2	26.7	29.61	31.1	+377%
ZZ fusion	0.5	2.55	2.80	2.91	+460%
Total	203.6		159.0		
Total Events	1.14M		0.32M		

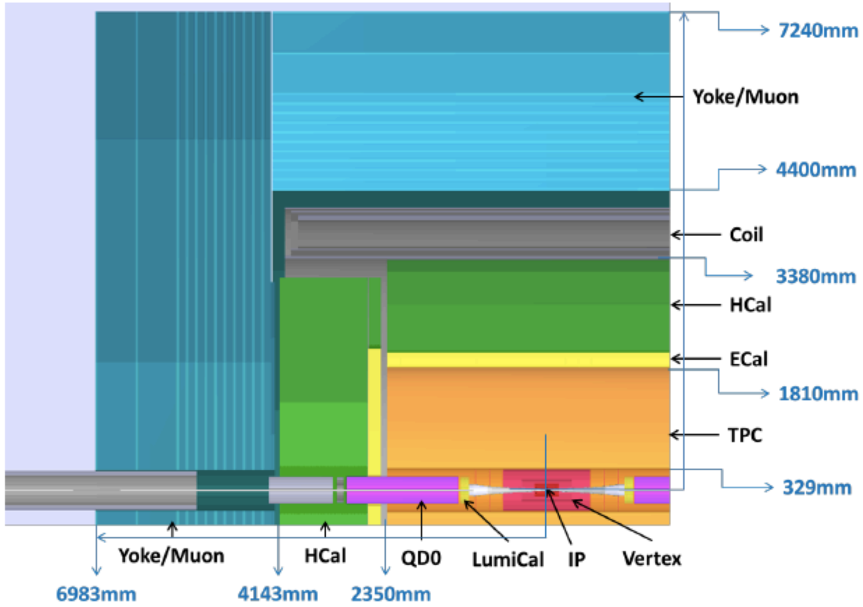
In total ~1.5M Higgs would be collected in CEPC 240+360.
More fusion events, also eeH can not be ignored in 360GeV.





CEPC





- ✓ **A CEPC (phase I)+ Super proton-proton Collider (SPPC) was proposed**
- ✓ **Ecm ~240-250 GeV, Lum 5.6 ab^{-1} for 10 years**

Table 2. Key characteristic/performance of a conceptual CEPC detector.

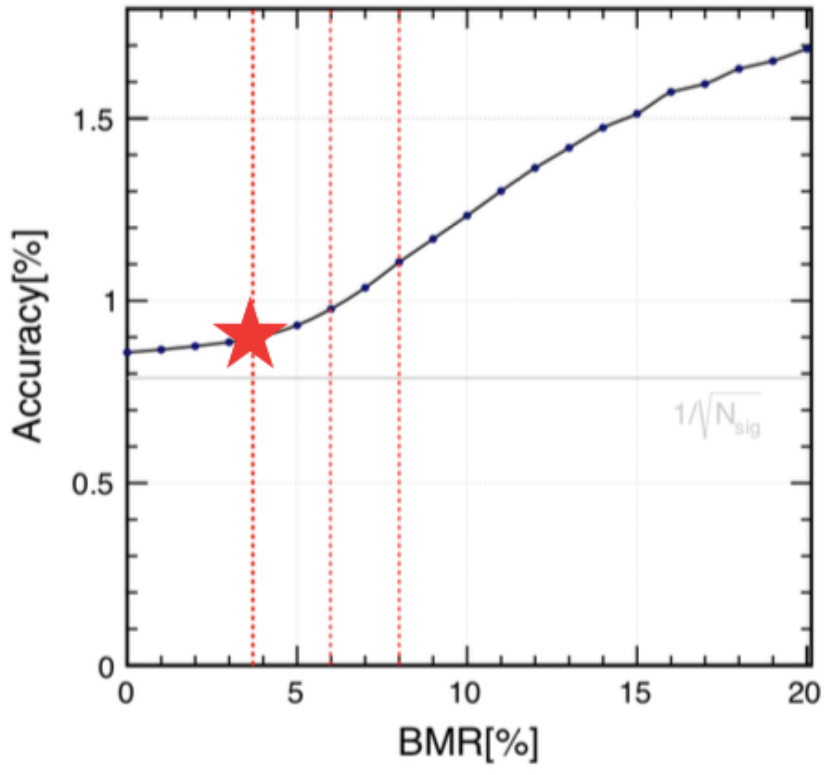
Geometry acceptance	TPC (97%), FTD (99.5%)
Tracking efficiency	$\sim$ 100% within geometry acceptance
Tracking performance	$\Delta(1/p_T) \sim 2 \times 10^{-5}$ (1/GeV)
ECAL intrinsic energy resolution	$16\%/\sqrt{E} \oplus 1\%$ (GeV)
HCAL intrinsic energy resolution	$60\%/\sqrt{E} \oplus 1\%$ (GeV)
Jet energy resolution	3-4%
Impact parameter resolution	5 μm

Status of H->ττ

- Develop signal strength analysis with and without jets
  - MVA for the former
  - TAURUS package
- Study BMR dependency
- Decay modes ID….

Dan Yu's talk

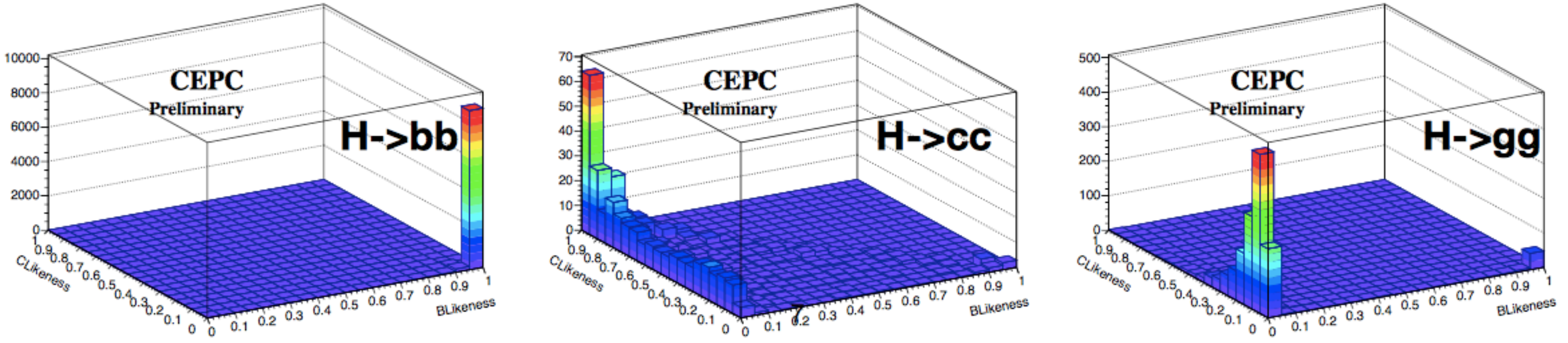
	$\delta(\sigma\times BR)/(\sigma\times BR)$
$\mu\mu H$	2.8%
eeH	5.1%
$\nu\nu H$	7.9%
qqH	0.9%
combined	0.8%



Status of H->bb,cc,gg

More at Yu Bai's talk

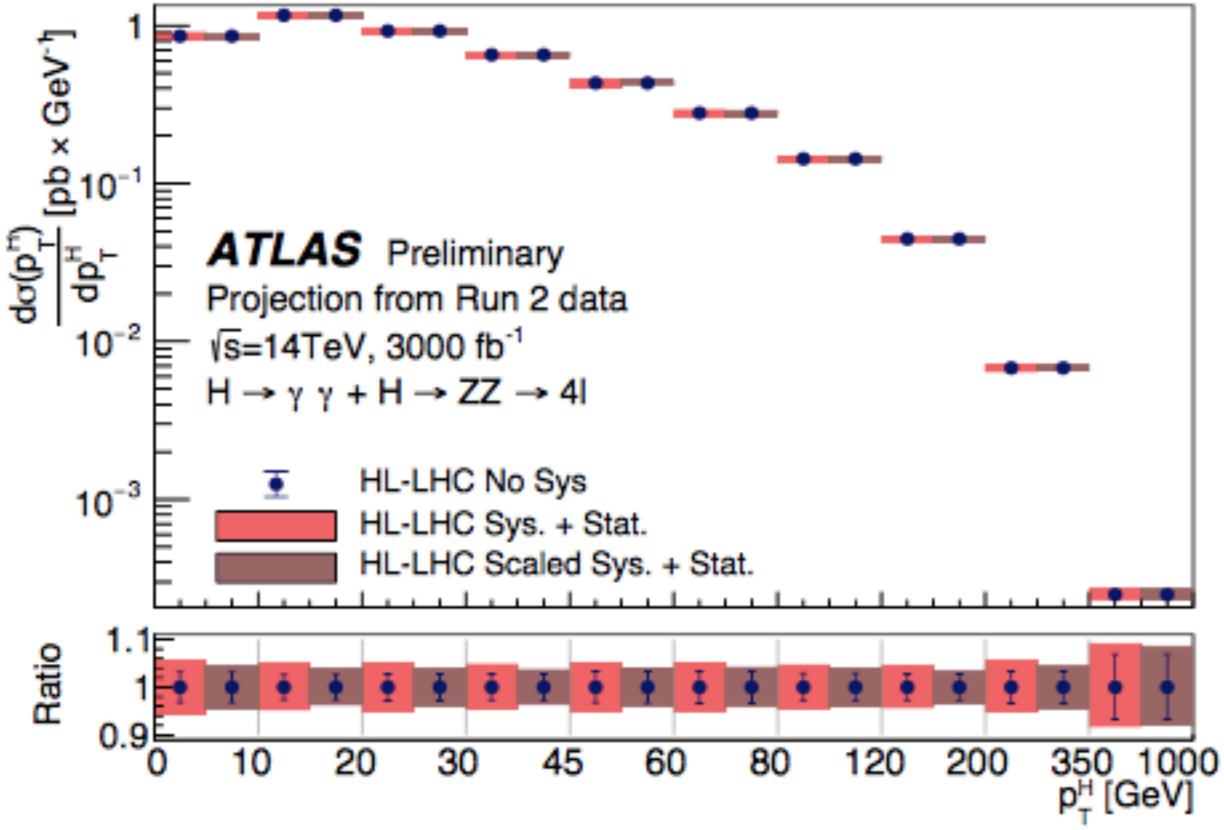
- Wrap the analysis into a note and submit to CPC.
- Flavor tagging used in the fit (3 dim)

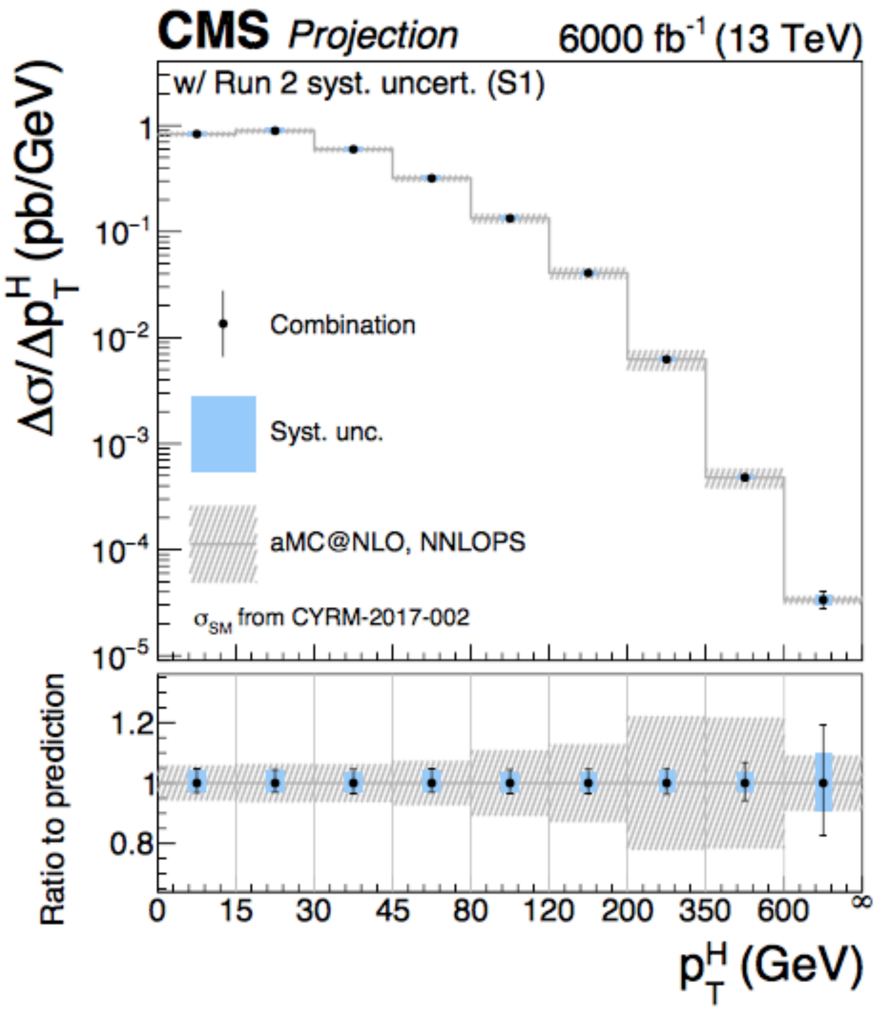


- Start to consider the systematics.

Decay mode	$\sigma(ZH) \times$ BR	BR
$H \to b\bar{b}$	0.28%	0.57%
$H \to c\bar{c}$	2.2%	2.3%
$H \to gg$	1.6%	1.7%

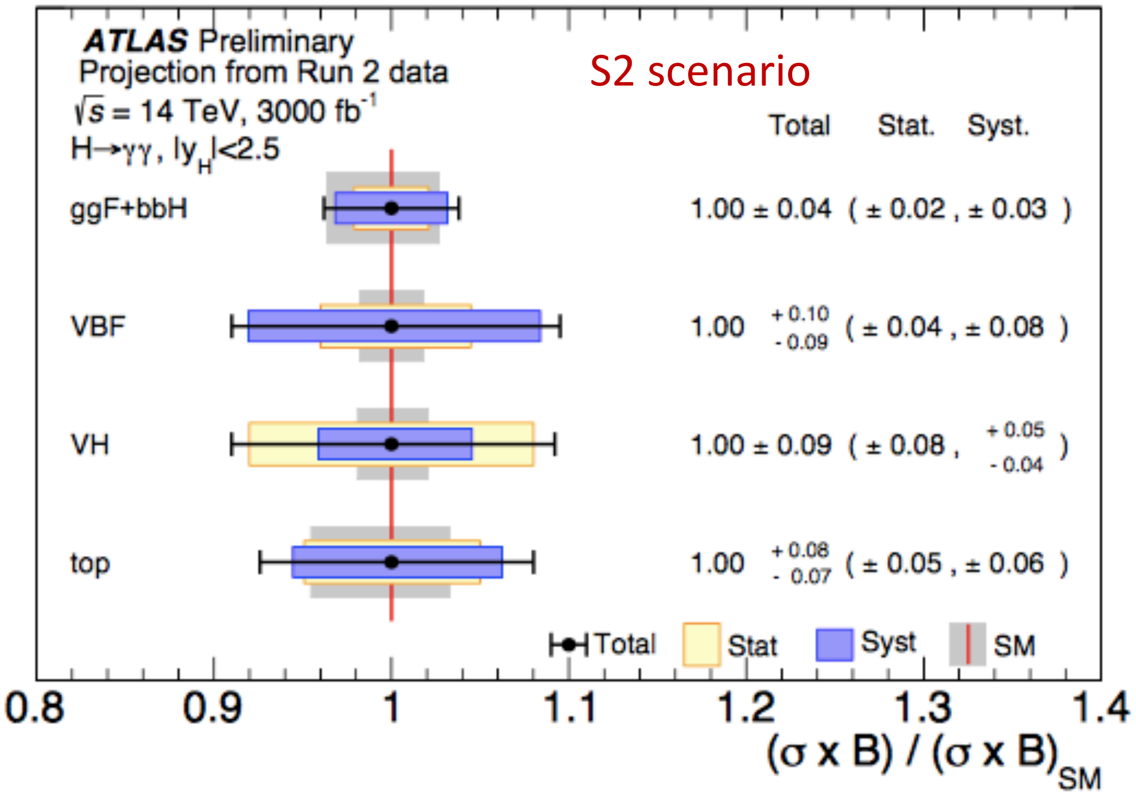
HL-LHC: Differential xsection measurement

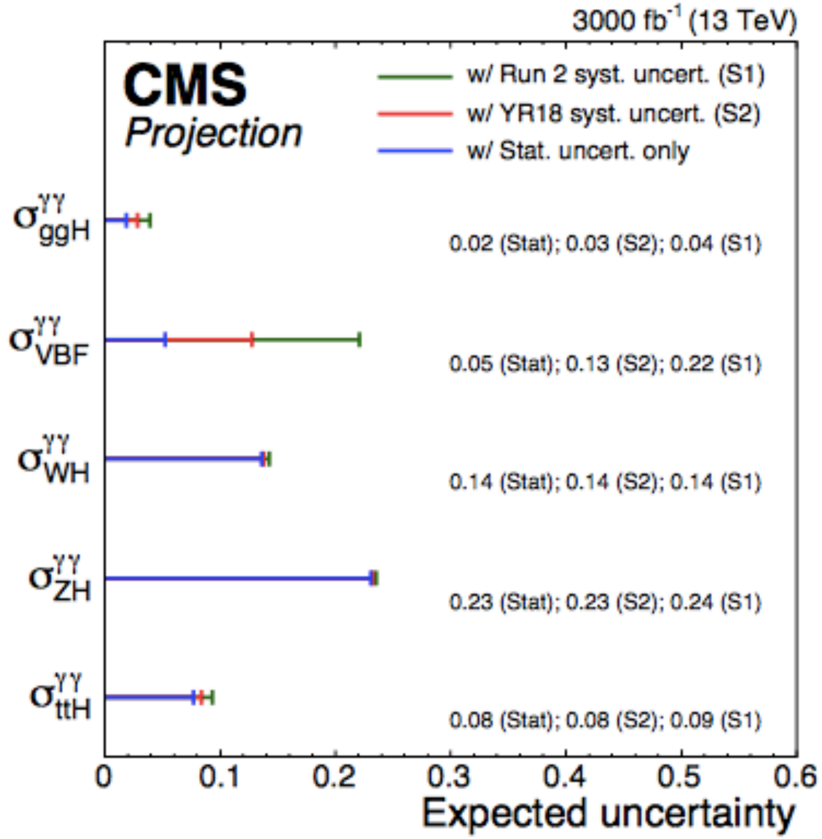




The precision can reach a few percent for different p_T bins.

HL-LHC H->γγ: one example



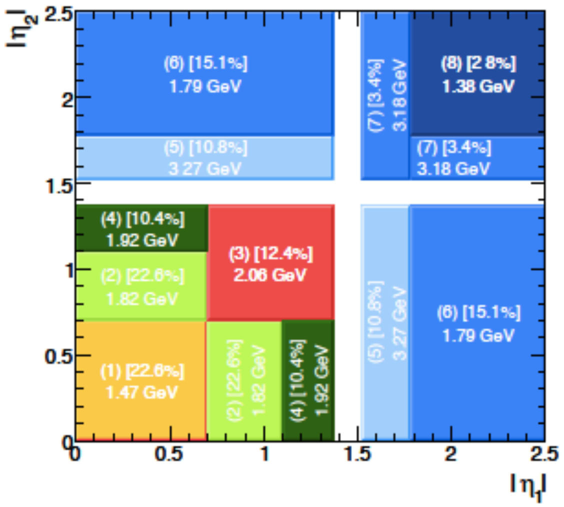


Scenario S1: Total uncertainty is half of the one used for the result of 80 fb^{-1}.
Scenario S2: Total uncertainty is 1/3 of the one for 80 fb^{-1}.

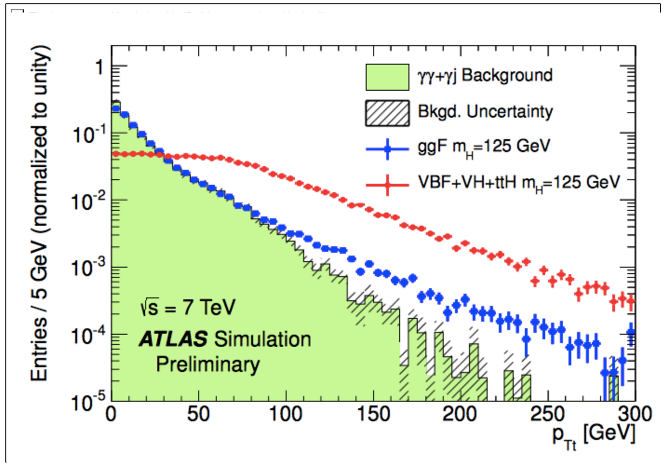
HL-LHC H->γγ: very advanced analyses (example)

- The inclusive analysis is very simple :
  - Photon ID, Isolation, Kinematic cuts on leading/subleading photon.
- Explore other possible improvements ?
  - Divide events into different categories.

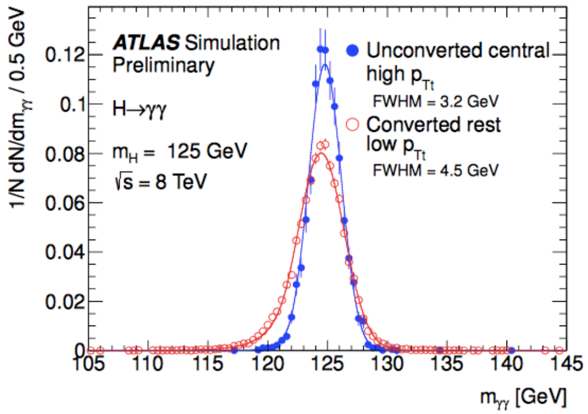
Divide different eta regions for two photons



P_T of Higgs (P_{Tt} is perpendicular to the thrust direction of two photon)



Conversion of the photons



Higgs white paper @ CDR

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Precision Higgs Physics at the CEPC*

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arXiv:1810.09037v2 [hep-ex] 4 Mar 2019

	Estimated Precision			
Property	CEPC-v1		CEPC-v4	
m_H	5.9 MeV		5.9 MeV	
Γ_H	2.7%		2.8%	
$\sigma(ZH)$	0.5%		0.5%	
$\sigma(\nu\bar{\nu}H)$	3.0%		3.2%	
Decay mode	$\sigma\times$BR	BR	$\sigma\times$BR	BR
$H\to b\bar{b}$	0.26%	0.56%	0.27%	0.56%
$H\to c\bar{c}$	3.1%	3.1%	3.3%	3.3%
$H\to gg$	1.2%	1.3%	1.3%	1.4%
$H\to WW^*$	0.9%	1.1%	1.0%	1.1%
$H\to ZZ^*$	4.9%	5.0%	5.1%	5.1%
$H\to\gamma\gamma$	6.2%	6.2%	6.8%	6.9%
$H\to Z\gamma$	13%	13%	16%	16%
$H\to\tau^+\tau^-$	0.8%	0.9%	0.8%	1.0%
$H\to\mu^+\mu^-$	16%	16%	17%	17%
$\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}}$	–	$<0.28\%$	–	$<0.30\%$

V2 is at arxiv.
CPC : Vol 43, No.4 (2019) 043002

Thanks to those colleagues for great efforts.
Welcome to new colleagues to join in.

CEPC Higgs to TDR

该二维码7天内(7月8日前)有效，重新进入将更新

Mailing list: cepc-physics@maillist.ihep.ac.cn

One example

ATLAS-CONF-2016-017

Category	Events	B_{90}	S_{90}	f_{90}	Z_{90}	S_{90}^{fit}
Central low-$p_{\text{T}t}$	31907	3500	180	0.05	3.04	120
Central high-$p_{\text{T}t}$	1319	140	20	0.13	1.66	15
Forward low-$p_{\text{T}t}$	85129	13000	310	0.02	2.73	200
Forward high-$p_{\text{T}t}$	3977	540	33	0.06	1.38	25

The improvement of significance w.r.t. inclusive one is from 4.0 to 4.6, corresponding 13% improvement on the precision.

Results and systematics for H->bb,cc,gg

Combination of the 4 channels:

Statistic precision of σ(ZH)*Br(H->bb/cc/gg) is 0.3% 3.3% and 1.3%

Consistent with the goal expected in pre-CDR with full simulation samples

Decay mode	$\sigma(ZH) \times$ BR	BR
$H \to b\bar{b}$	0.28%	0.57%
$H \to c\bar{c}$	2.2%	2.3%
$H \to gg$	1.6%	1.7%

llH with 3D fit and systematic uncertainties considered:

Table 2. Uncertainties of $H \to b\bar{b}$, $H \to c\bar{c}$ and $H \to gg$

	$\mu^+\mu^- H$			$e^+e^- H$		
	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$
Statistic Uncertainty	1.1%	10.5%	5.4%	1.6%	14.7%	10.5%
Fixed Background	-0.2% +0.1%	+4.1% -4.2%	7.6%	-0.2% +0.1%	+4.1% -4.2%	7.6%
Event Selection	+0.7% -0.2%	+0.4% -1.1%	+0.7% -1.7%	+0.7% -0.2%	+0.4% -1.1%	+0.7% -1.7%
Flavor Tagging	-0.4% +0.2%	+3.7% -5.0%	+0.2% -0.7%	-0.4% +0.2%	+3.7% -5.0%	+0.2% -0.7%
Non uniformity	< 0.1%			< 0.1%		
Combined Systematic Uncertainty	+0.7% -0.5%	+5.5% -6.6%	+7.6% -7.8%	+0.7% -0.5%	+5.5% -6.6%	+7.6% -7.8%

Analysis with more reliable approaches. Systematic uncertainties considered.

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.**

Precision : 2.8%