Status of Higgs physics at CEPC

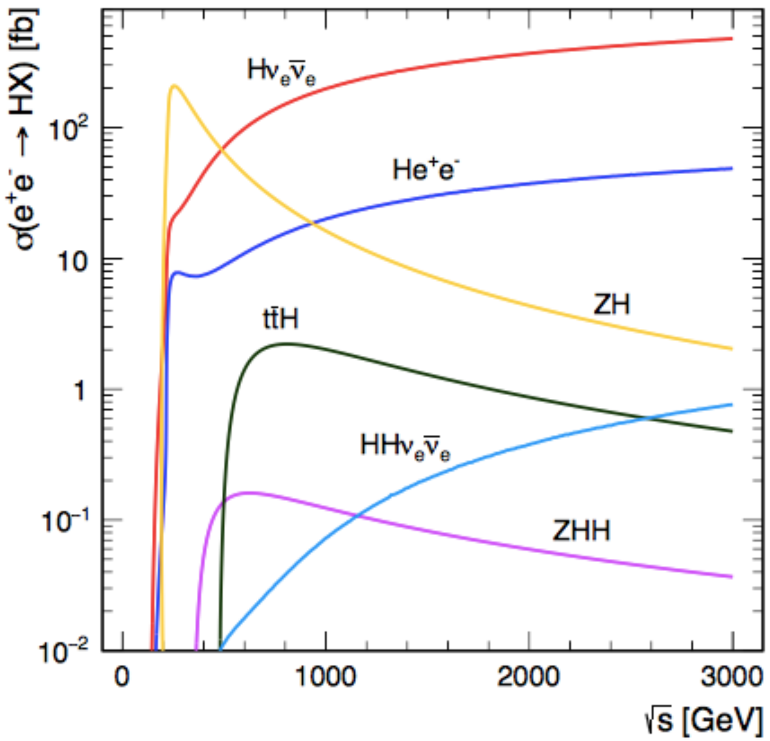
Yaquan Fang (IHEP) on behalf of CEPC Higgs working group

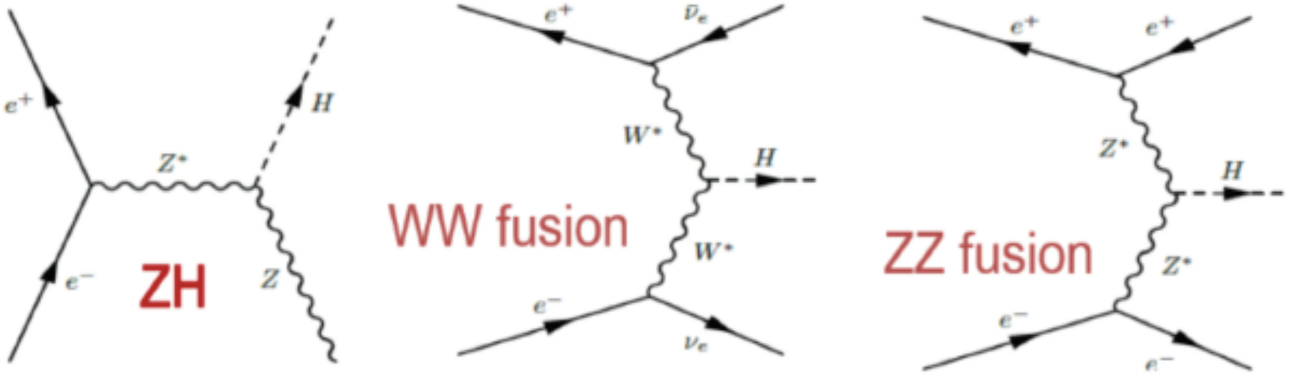
The 6th China LHC Physics Workshop

November 6-9, 2020

Tsinghua University

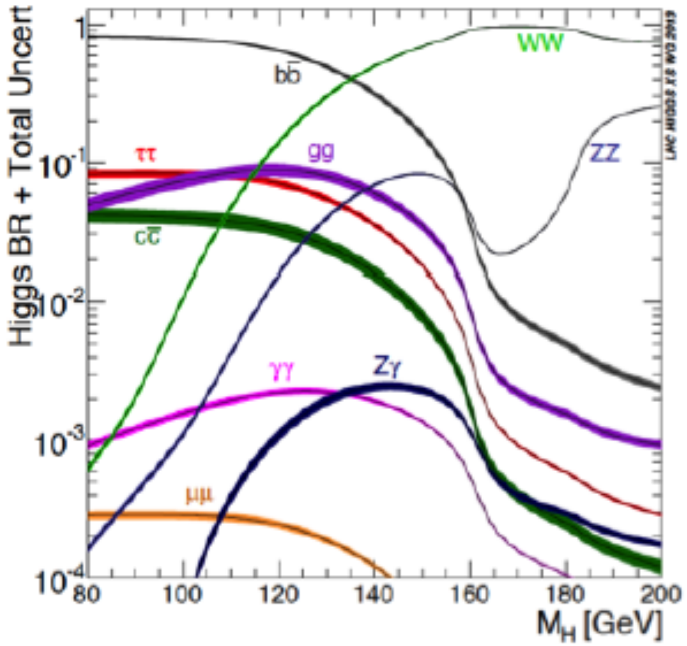
Higgs related physics at e^+e^- collider

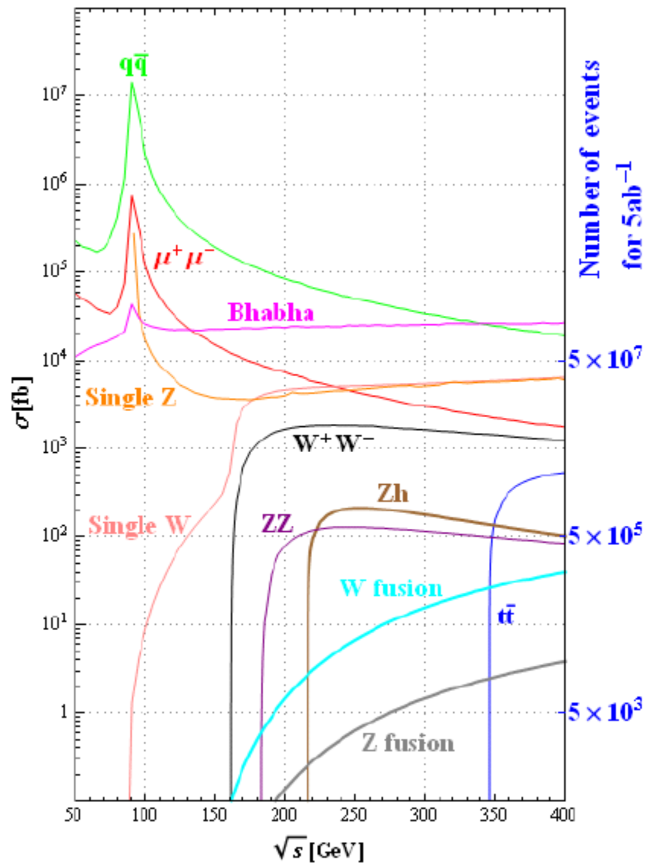




- ➢ With the increase of the energy, different Higgs related physics can be explored at e^+e^- collider.
- ➢ With the energy around 240 GeV, ZH as well as ww/zz fusion can be intensively studied.
  - the dominant production is from HZ, the WW/ZZ fusions contribute a few percent of the total cross-section.

SM Higgs decay branching ratio, Bkg process

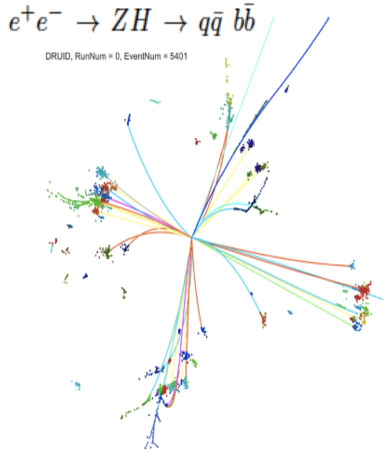


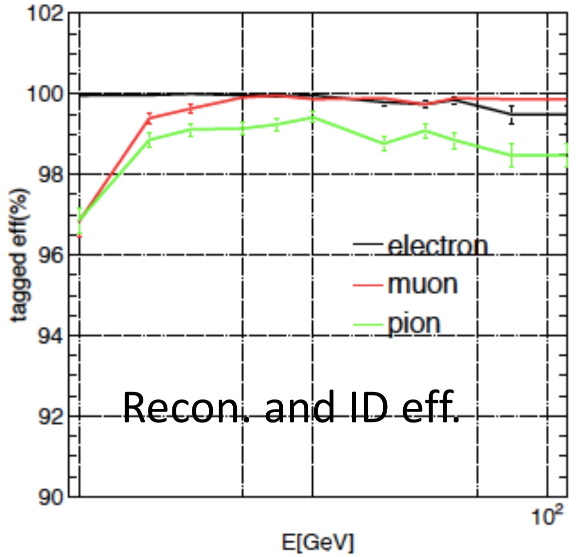


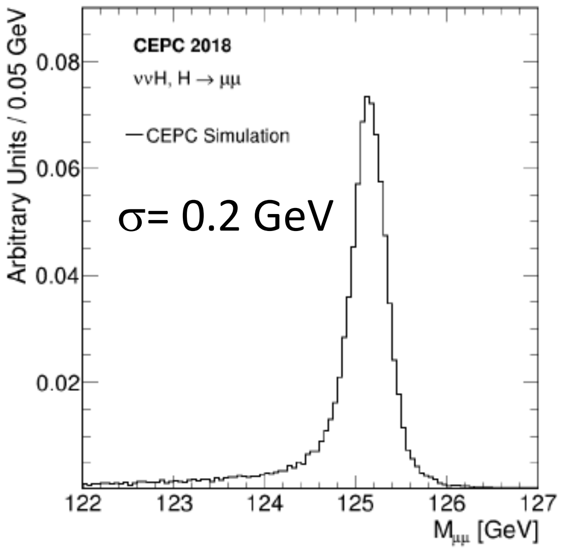
✓ e^+e^- collider provides a good opportunity to measure the jj, invisible decay of Higgs.

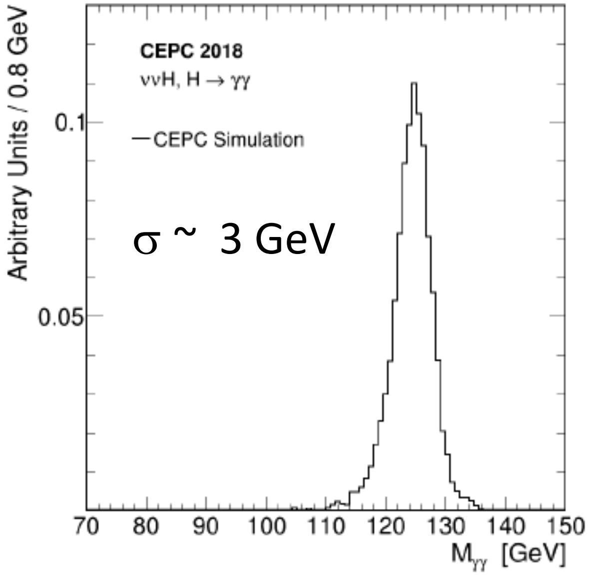
✓ For 5.6 ab^{-1} data with CEPC, 1M Higgs, 10M Z, 100M W are produced.

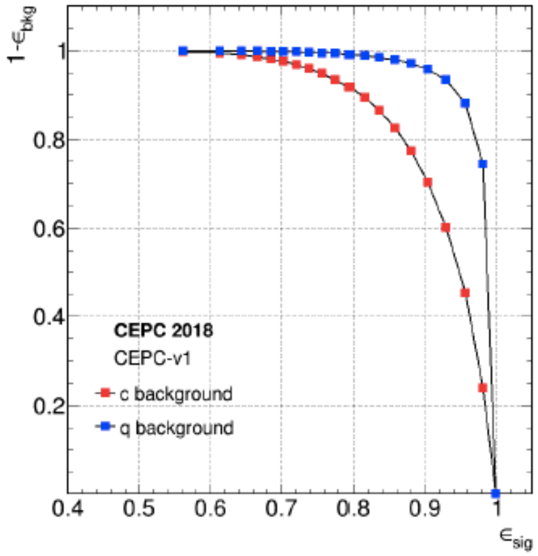
Performance



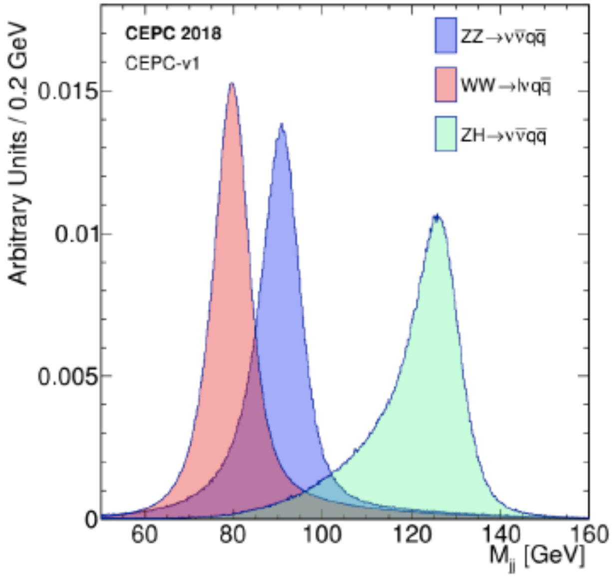






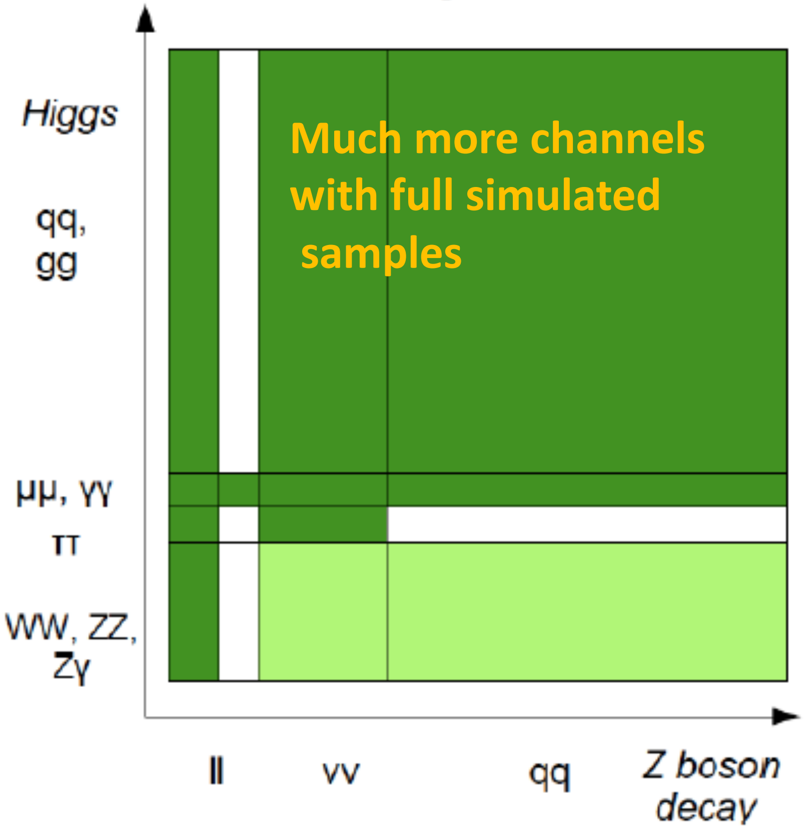


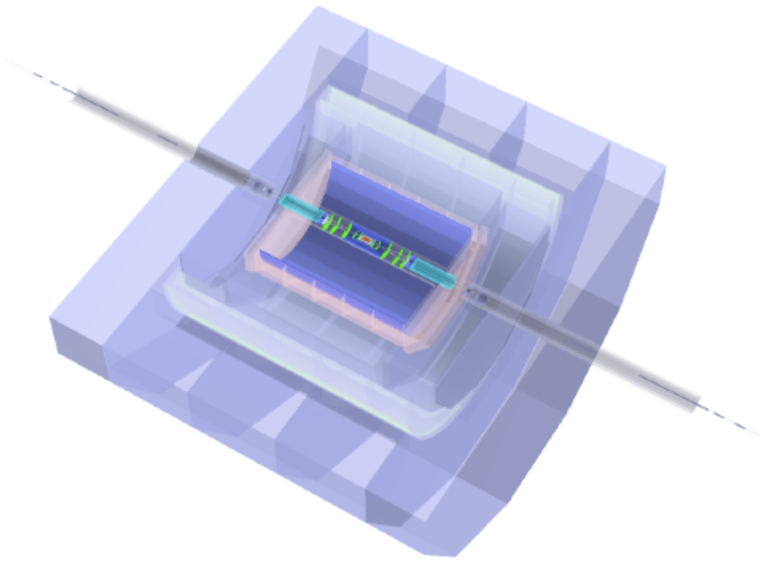
B-tagging eff. vs rejection of other jets



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

Higgs analyses @CEPC CDR

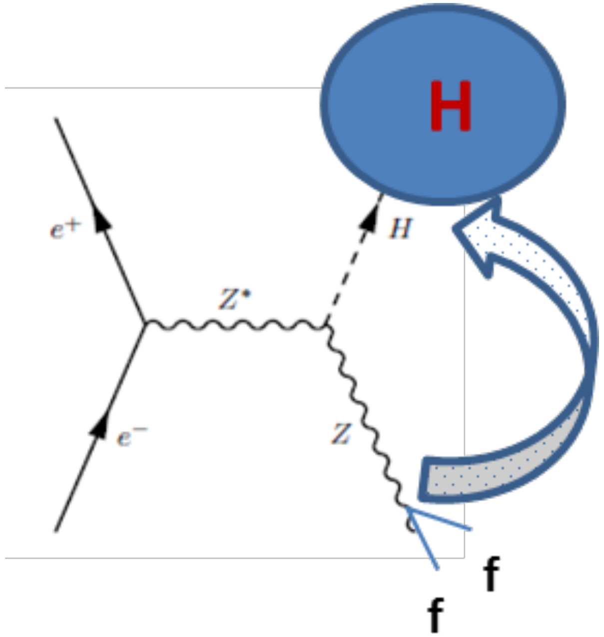




A lot of decay channels can be investigated.

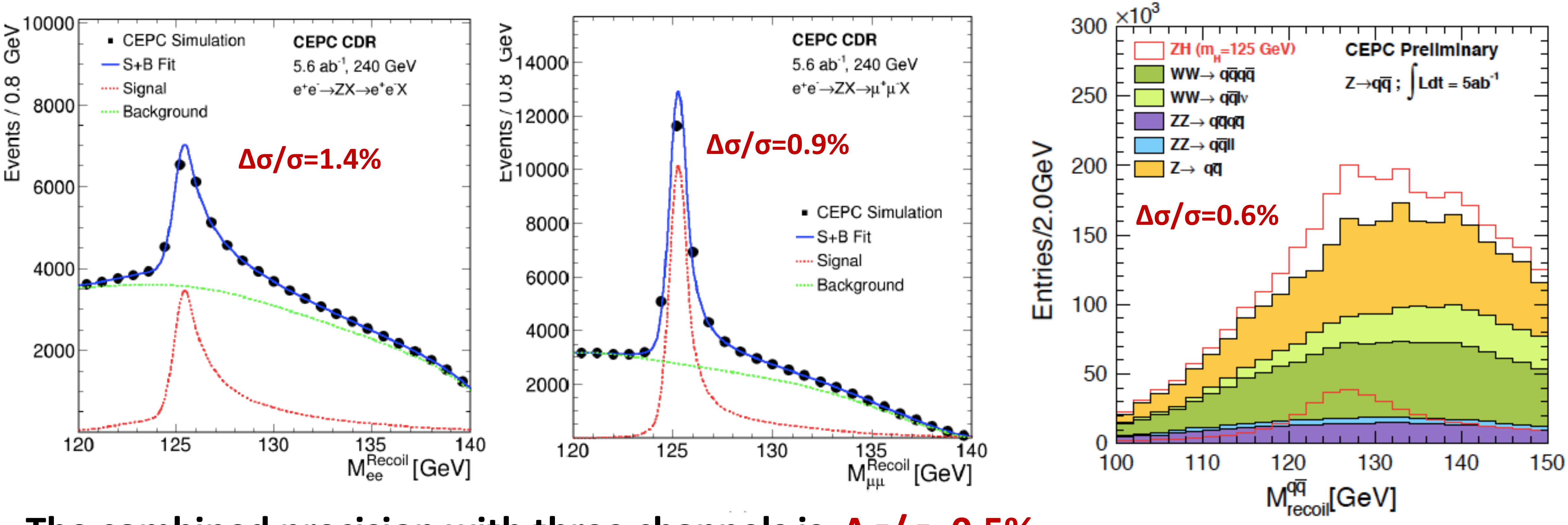
Direct measurement of Higgs cross-section

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



- ✓ **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:**

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

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

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

3.0%

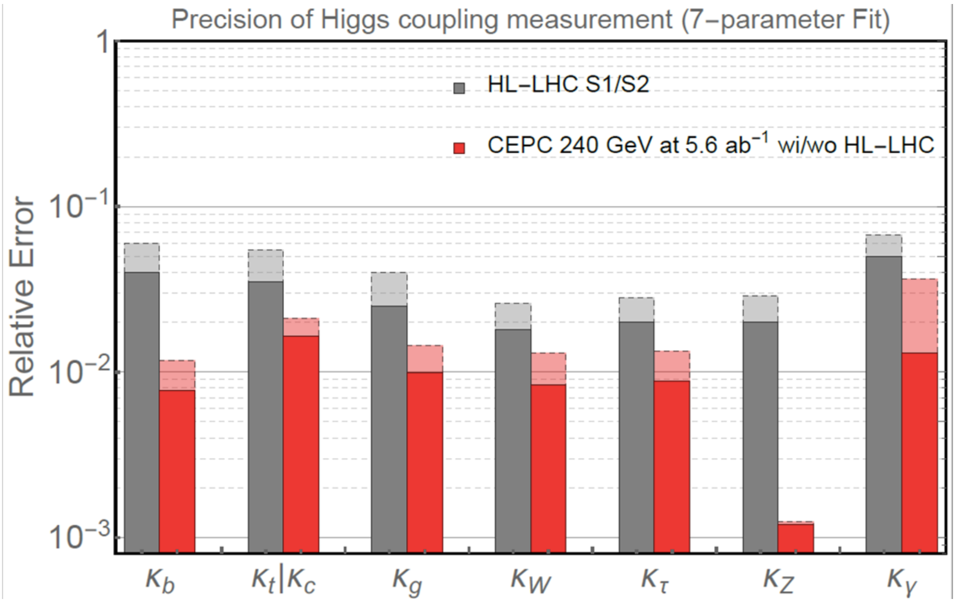
Precision : 3.5%

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

Precision : 2.8%

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%
BR^{BSM}_{inv}	–	$<0.28\%$	–	$<0.30\%$



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

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	$\sigma(ZH) \times \text{BR}$	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%
$H \to \text{inv}$	–	$< 0.30\%$

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

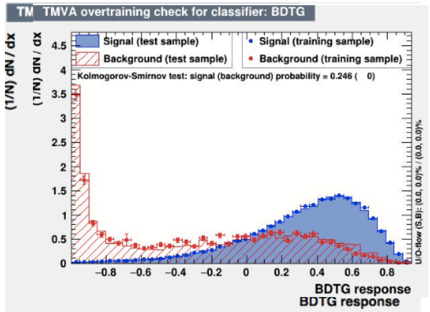
$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma\text{BR})/\sigma\text{BR}$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \to$ any	±0.5		±0.9	
$H \to b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H \to c\bar{c}$	±2.2		±6.5	±10
$H \to gg$	±1.9		±3.5	±4.5
$H \to W^+W^-$	±1.2		±2.6	±3.0
$H \to ZZ$	±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	

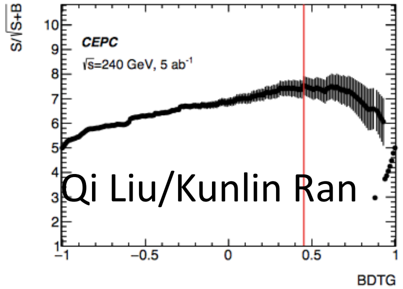
- Fcc-ee has similar results as CEPC but including a 365 GeV run improving the measurement of Higgs width.

MVA methods used in different channels and other activities

- 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

Ryuta et al., will have a publication soon

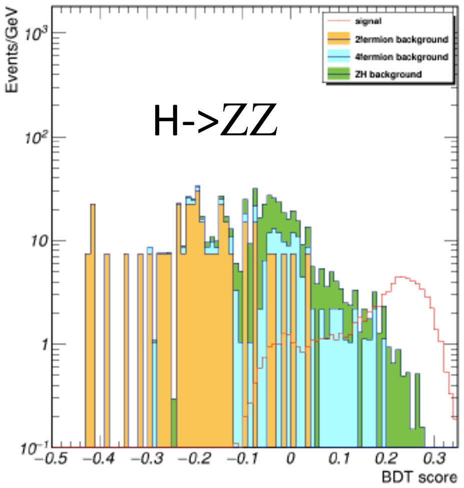


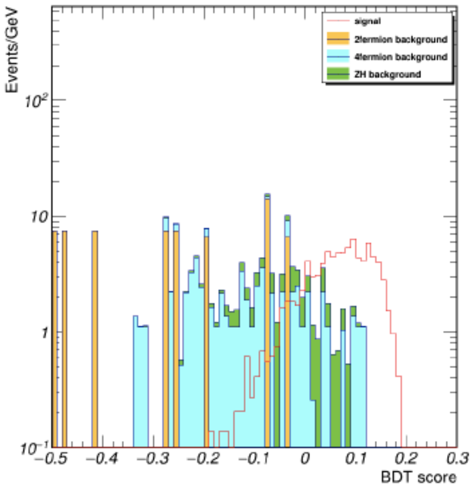


~20% improvement for newest update w.r.t inclusive one.

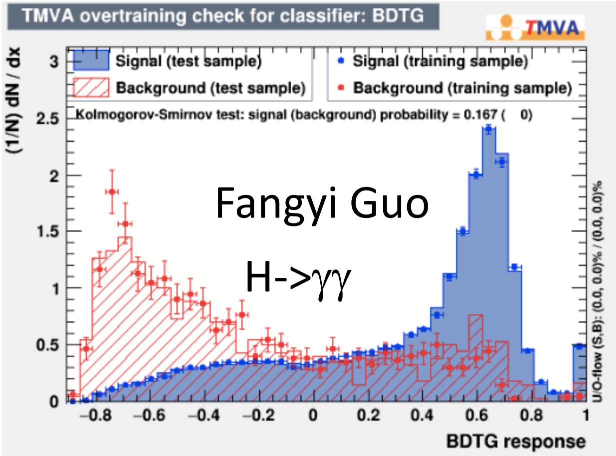
- There is a overtraining in the background due to poor statistics: ~1600
- Scan the total sensitivity ($S/\sqrt{S+B}$) vs BDTG to find the optimal BDTG point
- The sensitivity is estimated in the 90% signal coverage region

	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.



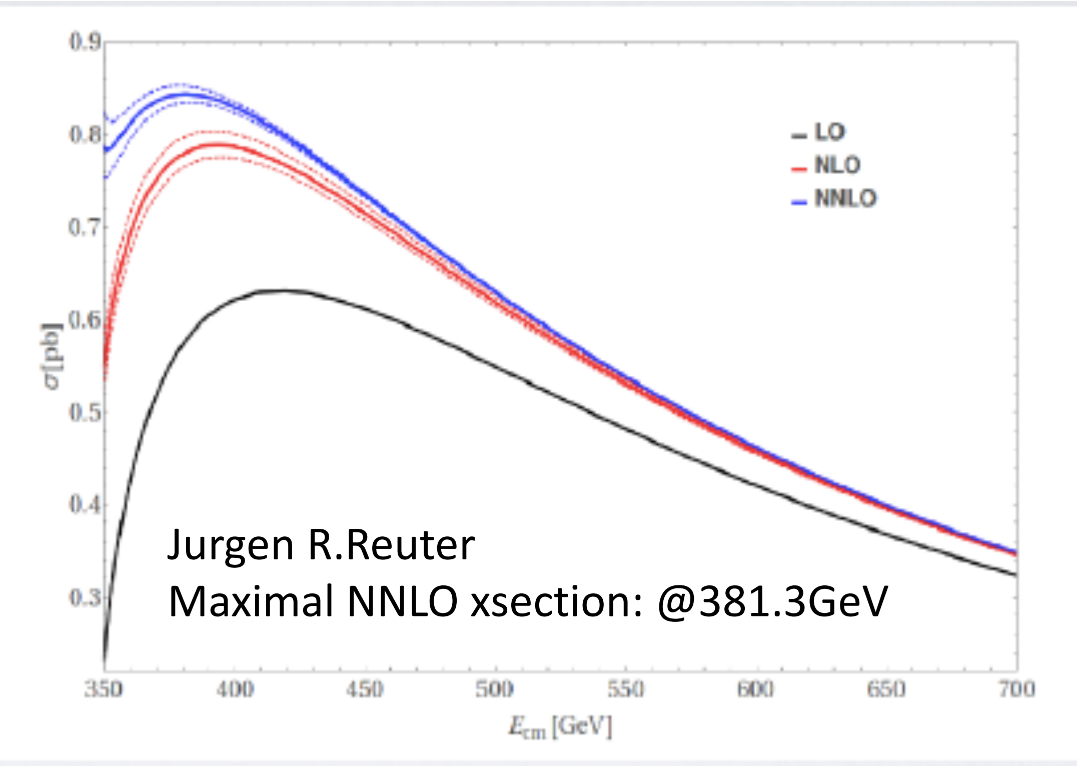
H->ZZ

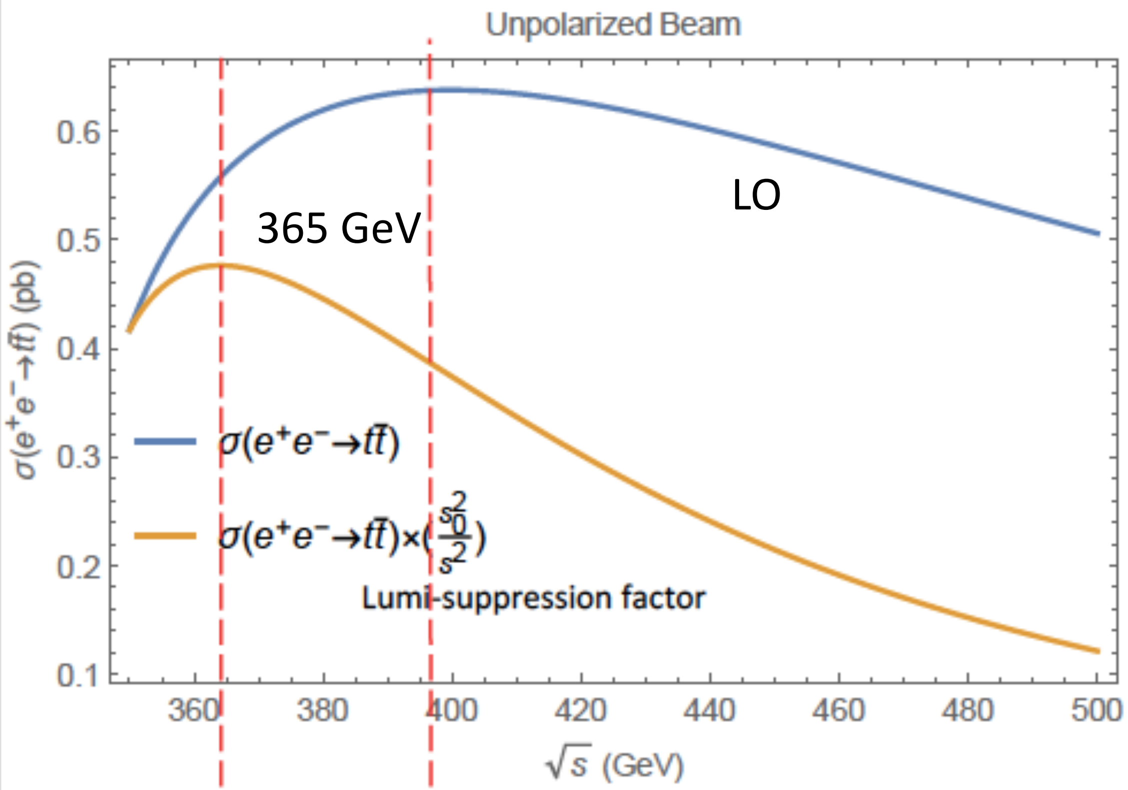
Category	$\frac{\Delta(\sigma \cdot BR)}{(\sigma \cdot BR)}$ [%] cut-based	BDT
$\mu\mu H\nu\nu qq^{cut/mva}$	15.5	13.6
$\mu\mu Hqq\nu\nu^{cut/mva}$	48.0	42.1
$\nu\nu H\mu\mu qq^{cut/mva}$	11.9	12.5
$\nu\nu Hqq\mu\mu^{cut/mva}$	23.5	20.5
$qqH\nu\nu\mu\mu^{cut/mva}$	45.3	37.0
$qqH\mu\mu\nu\nu^{cut/mva}$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

- Higgs CP study (Fangyi Guo)

Higgs related physics at 360 GeV (generic study)

Zhen Liu, Liantao Wang et al.

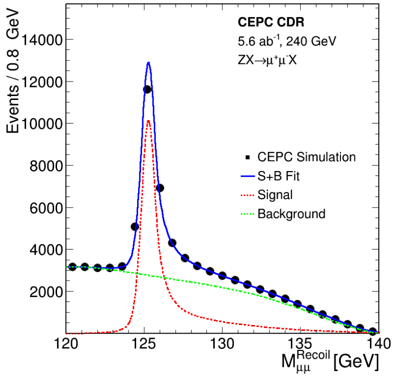


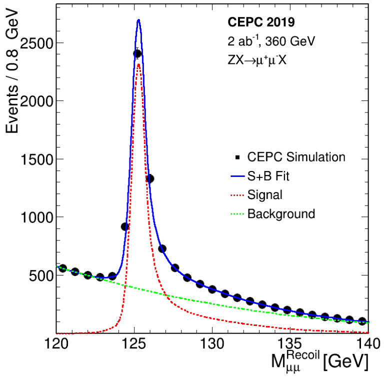


- With the NNLO calcuation, the highest xsection is at the energy of 381.3 GeV
- Considering the Lumi-suppression factor when going to higher energy, the effective highest xsection is around 365 GeV.
- The effective xsection from 360 GeV is not much different from that of 365 GeV.
- If we choose higher 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

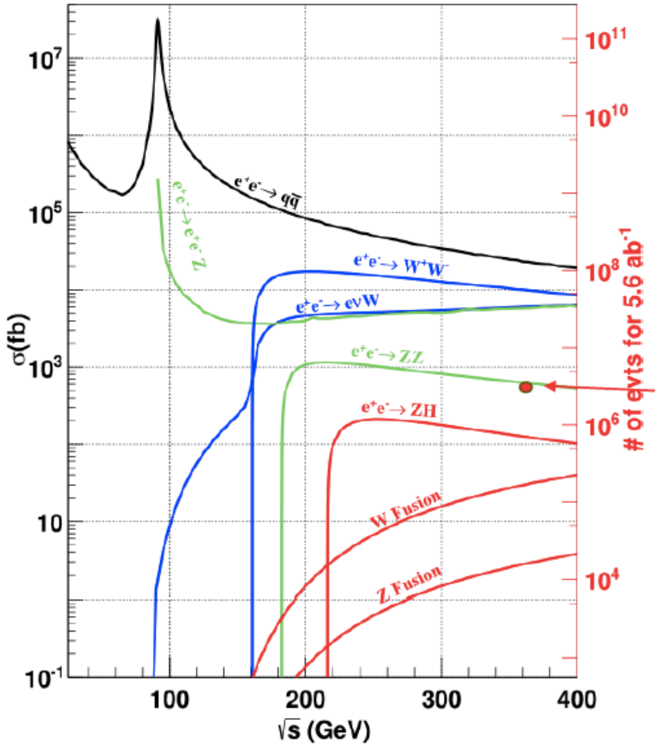
- Mainly scale yields from 240GeV case.
- $\sigma(ZH)$: preliminarily, around 1%
  - Need patient work on qqH channel
- Resolution change: 2 benchmarks
  - dimuon: would worse; from ~0.3GeV to 1GeV; (23% -> 29%)
  - diphoton: would better; from ~2.5GeV to 2GeV; (9% -> 8%)





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

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	

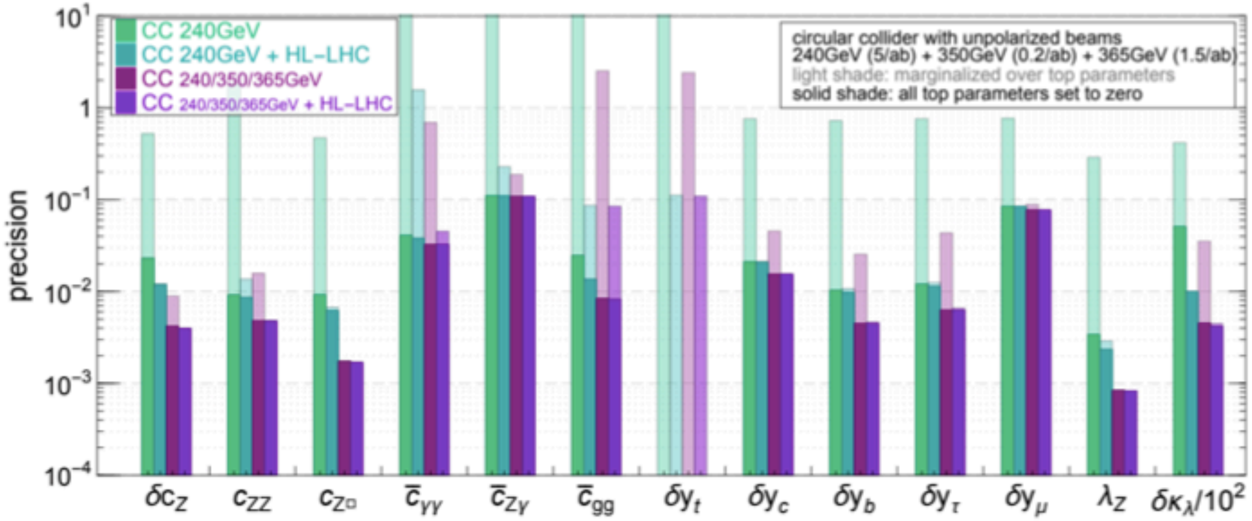
combined width: 1.3%

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

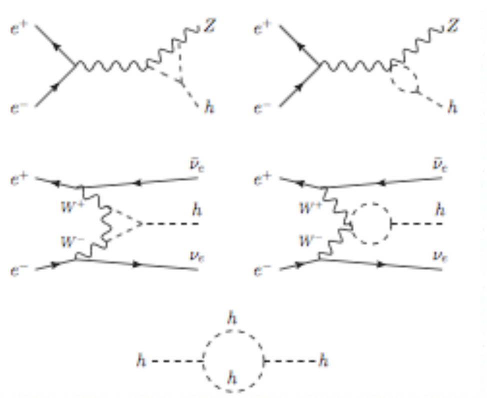
light shades: 12 Higgs op. floated + 6 top op. floated
dark shades: 12 Higgs op. floated + 6 top op. → 0

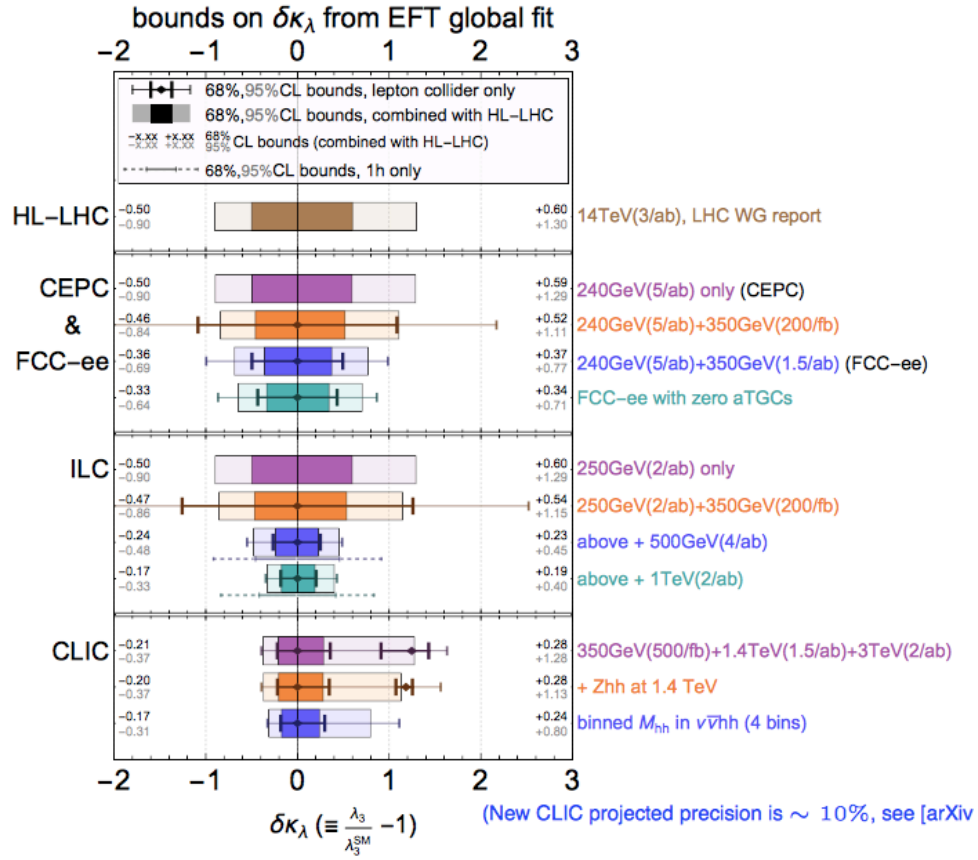


Uncertainties on the top have a big effect on the Higgs

- 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

Triple Higgs coupling:



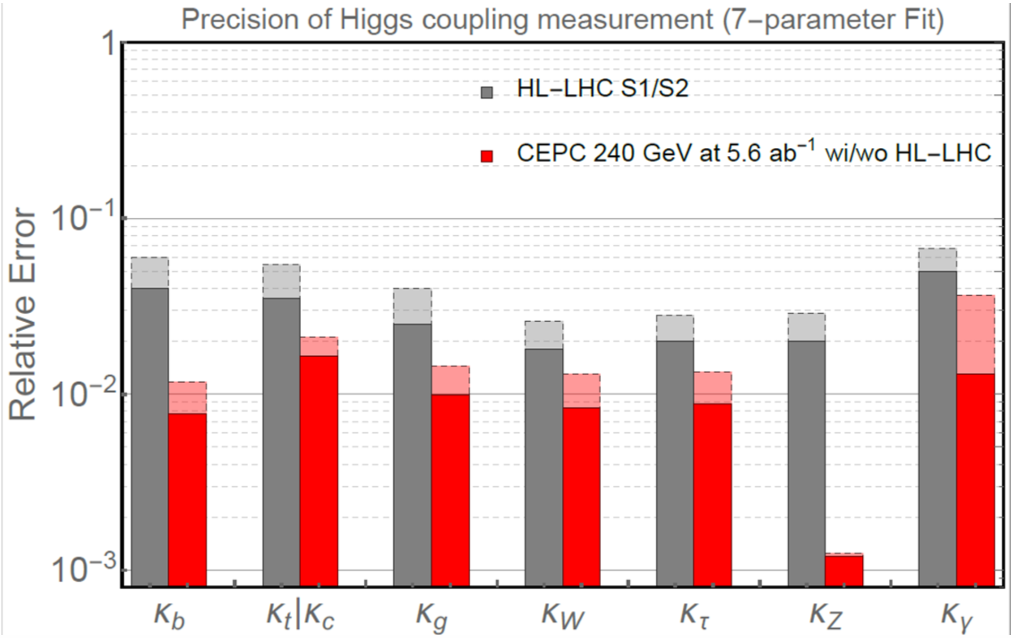


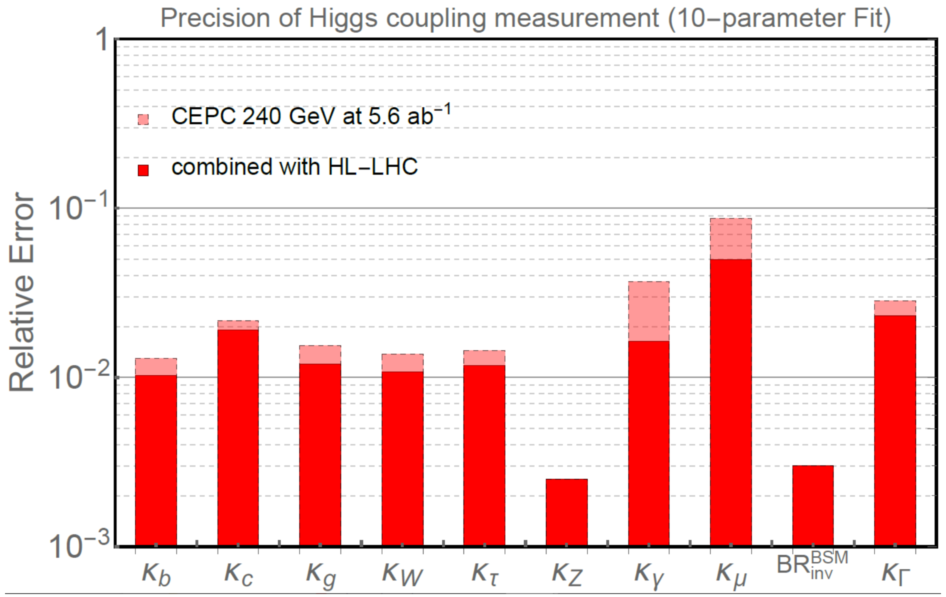
Conclusion

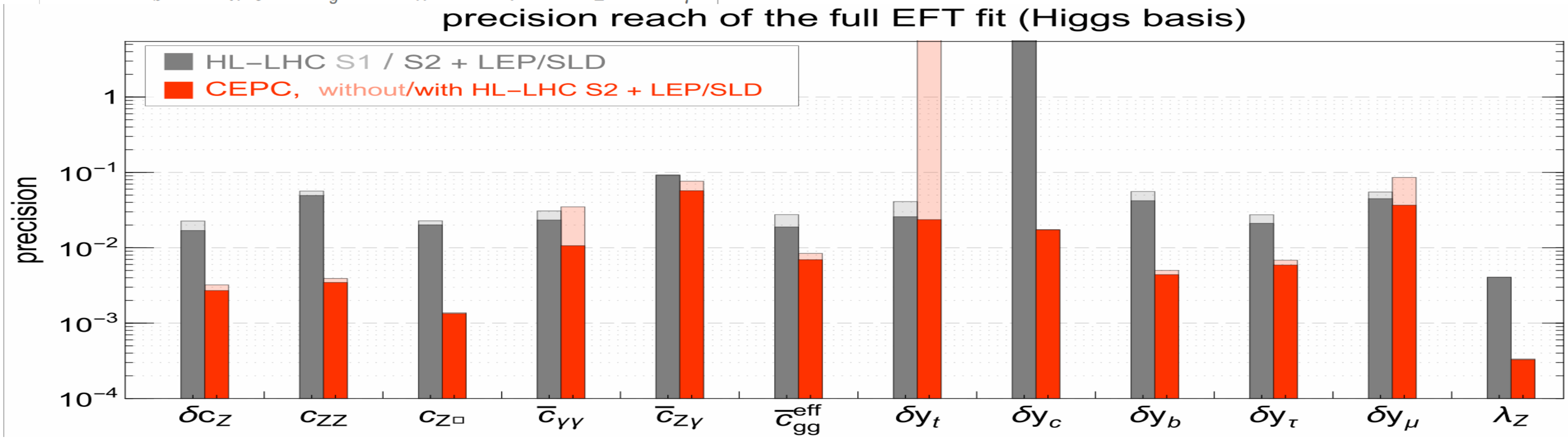
- After the Higgs white paper and CDR are done, analyses from individual channels have been documented. Several publications of them are available now.
- Improved analyses on each individual channels are on going.
- We also have a generic study on Higgs physics at 360 GeV (360 GeV/2 ab^{-1} as a benchmark)
  - 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

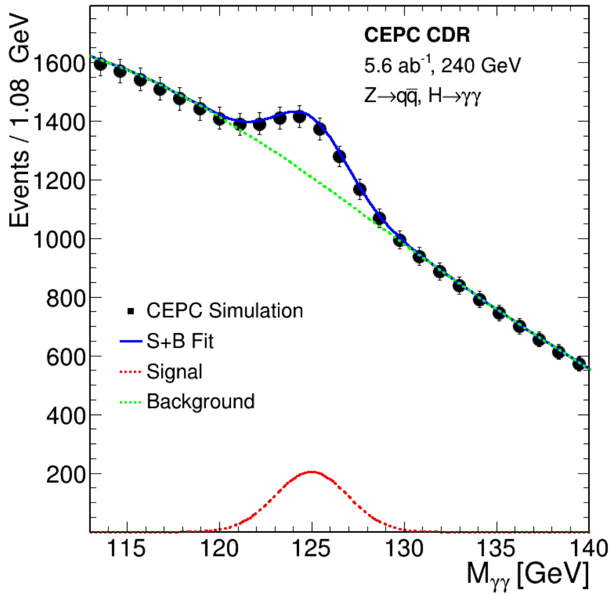
Combination/comparisons with HL-LHC

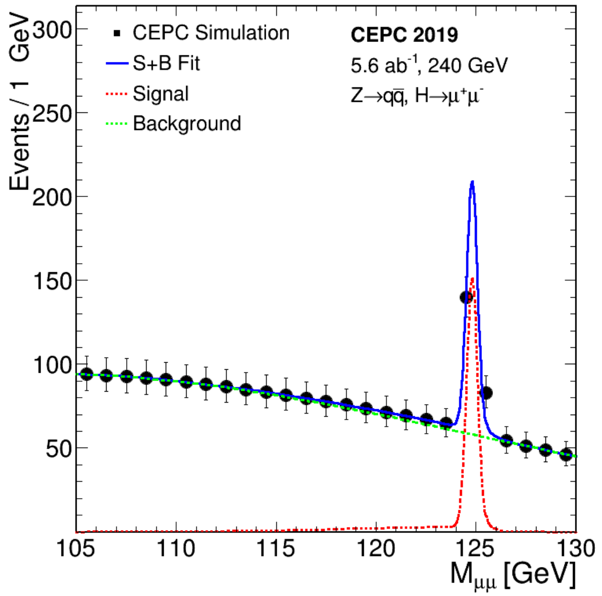


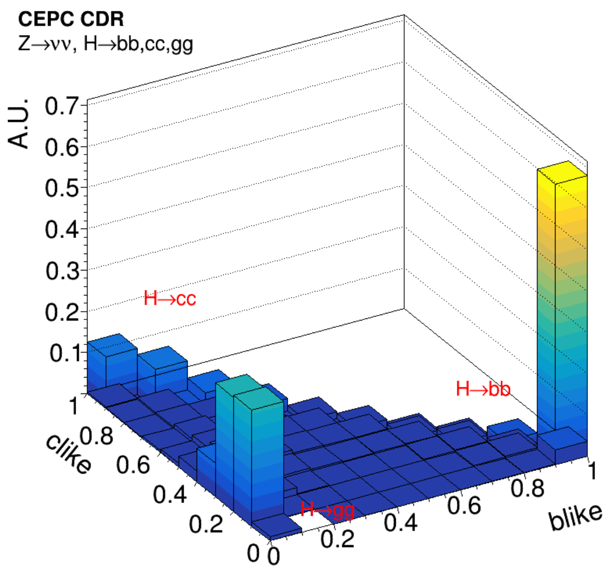


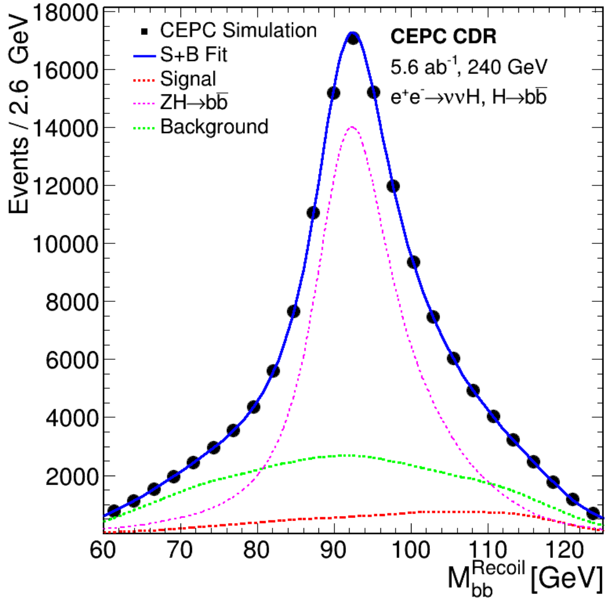


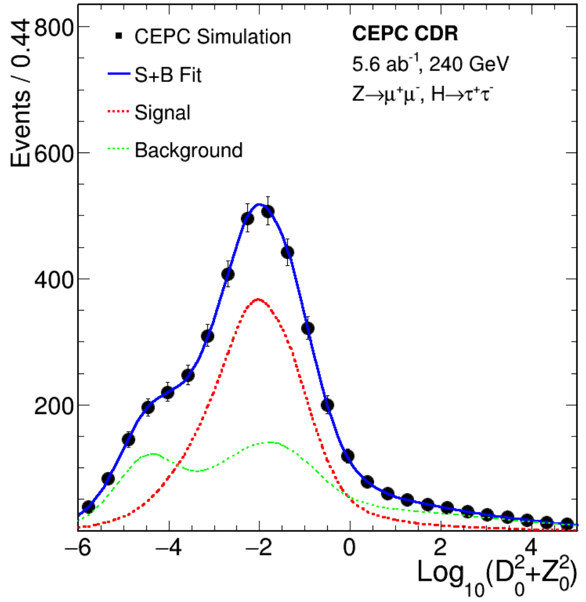
Typical individual channels











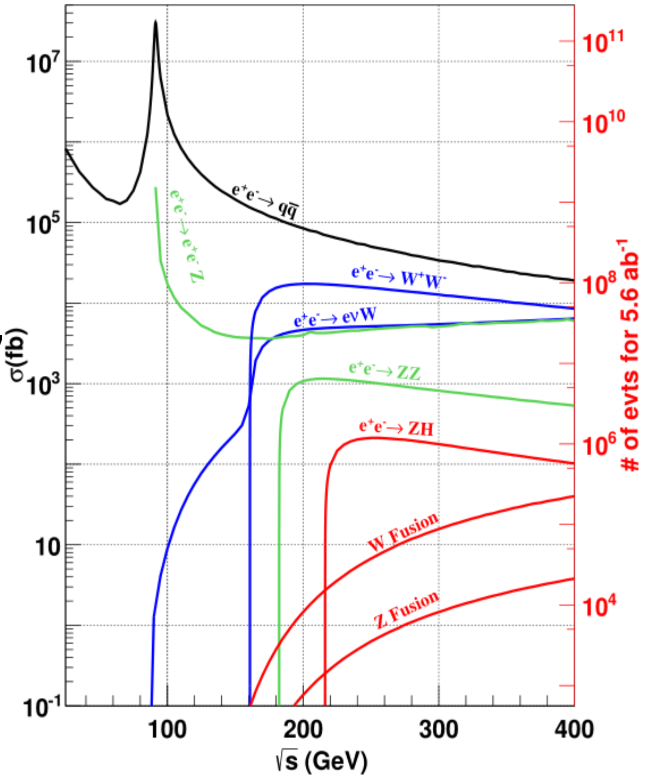
Signal/bkg Cross Sections

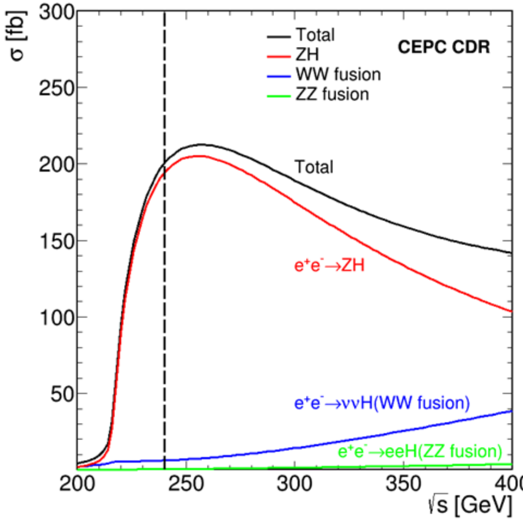
Kaili Zhang

- 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)

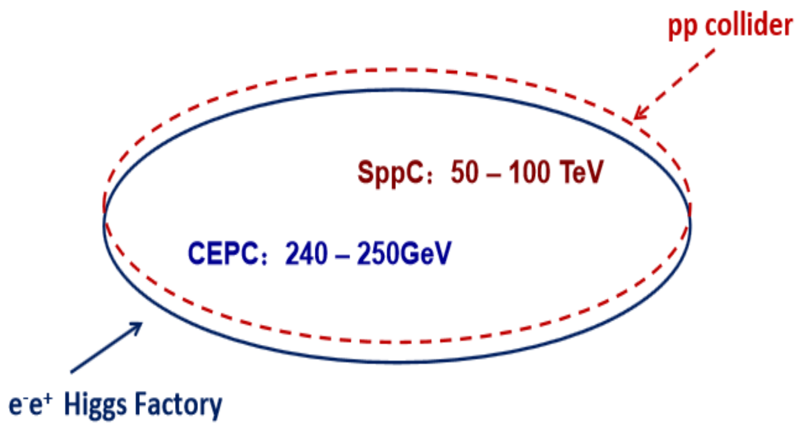
fb	240	350	360	365	360/240
ZH	196.9	133.3	126.6	123.0	-36%
WW fusion	6.2	26.7	29.61	31.1	+377%
ZZ fusion	0.5	2.55	2.80	2.91	+460%
Total	203.6		159.0		
Total Events	1.14M		0.32M		

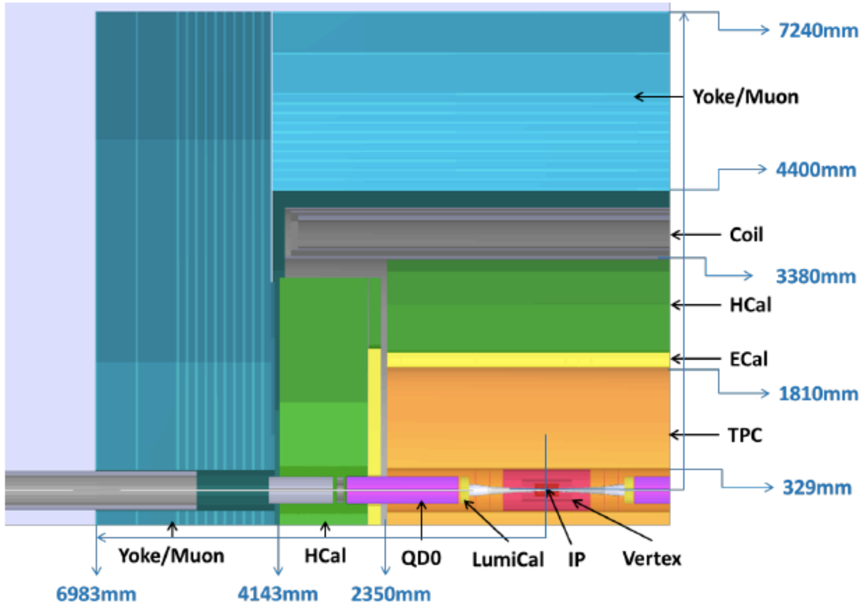
In total ~1.5M Higgs would be collected in CEPC 240+360.
More fusion events, also eeH can not be ignored in 360GeV.





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.

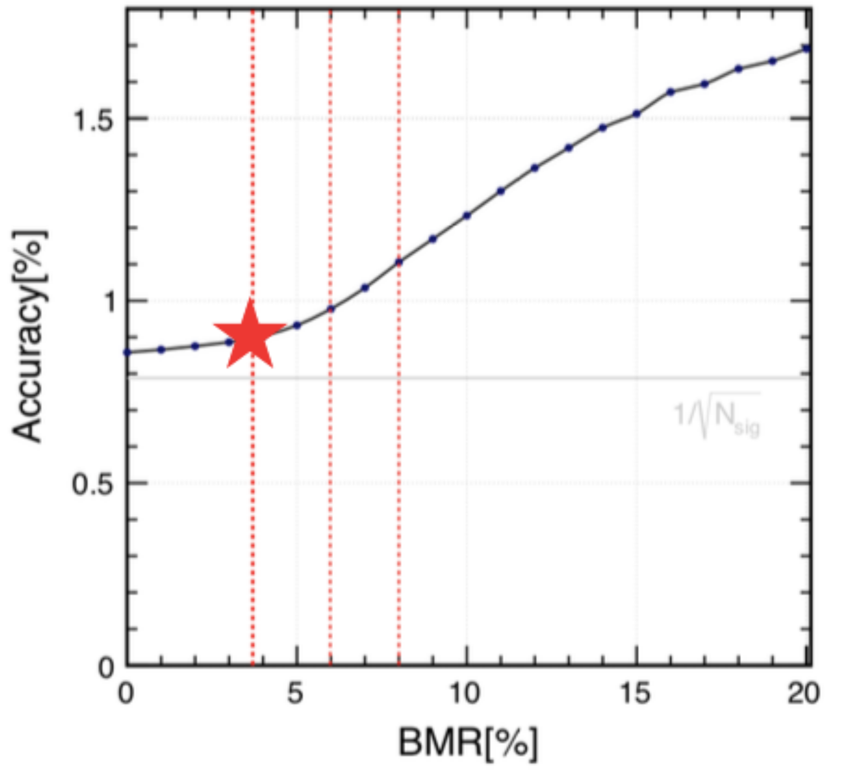
Geometry acceptance	TPC (97%), FTD (99.5%)
Tracking efficiency	$\sim$ 100% within geometry acceptance
Tracking performance	$\Delta(1/p_T) \sim 2 \times 10^{-5}$ (1/GeV)
ECAL intrinsic energy resolution	$16\%/\sqrt{E} \oplus 1\%$ (GeV)
HCAL intrinsic energy resolution	$60\%/\sqrt{E} \oplus 1\%$ (GeV)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

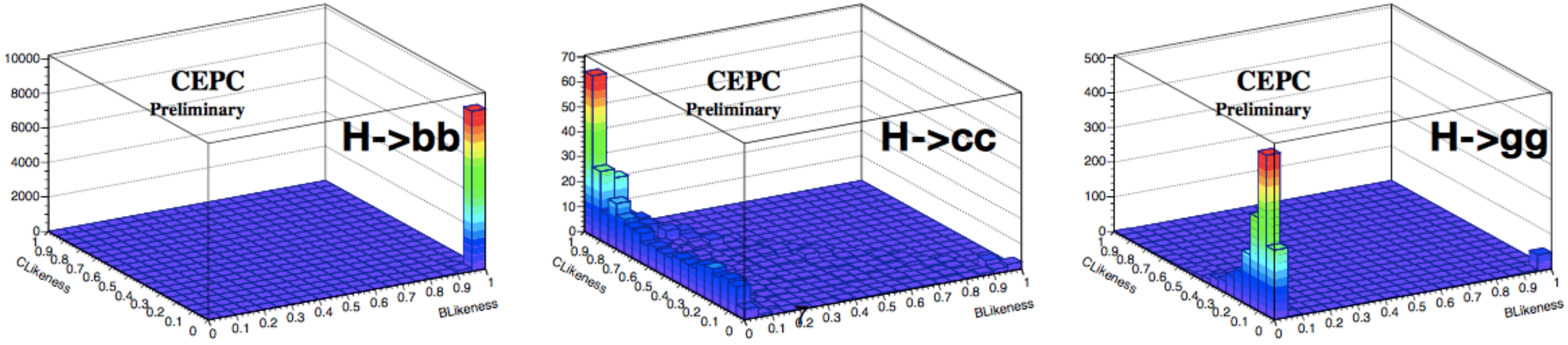
	$\delta(\sigma\times BR)/(\sigma\times BR)$
$\mu\mu H$	2.8%
eeH	5.1%
$\nu\nu H$	7.9%
qqH	0.9%
combined	0.8%



Status of H->bb,cc,gg

More at Yu Bai's talk

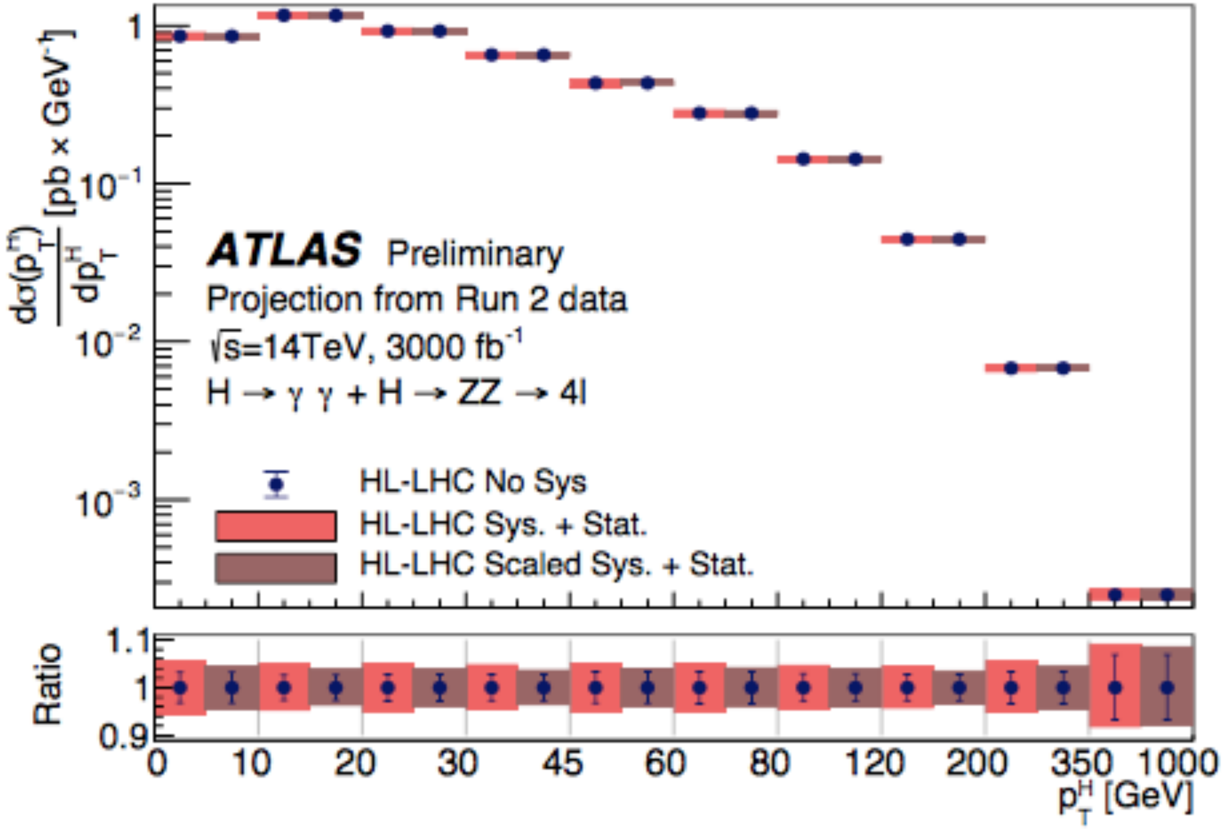
- Wrap the analysis into a note and submit to CPC.
- Flavor tagging used in the fit (3 dim)

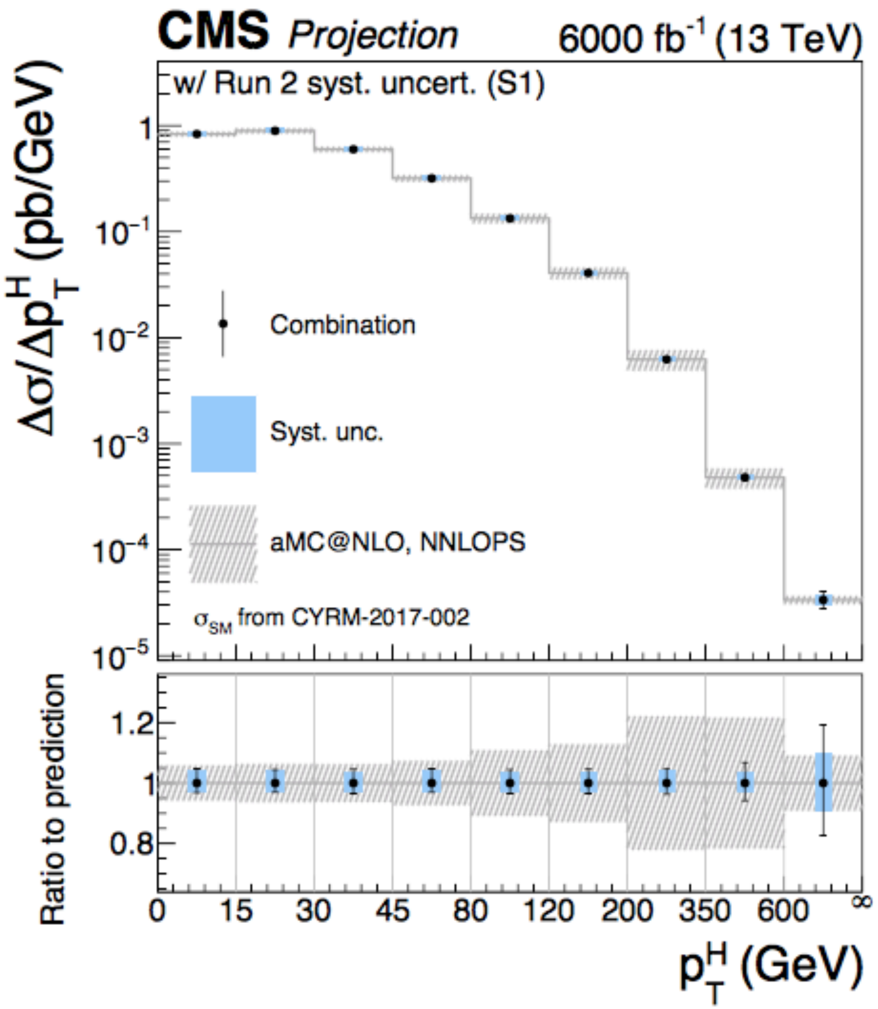


- Start to consider the systematics.

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%

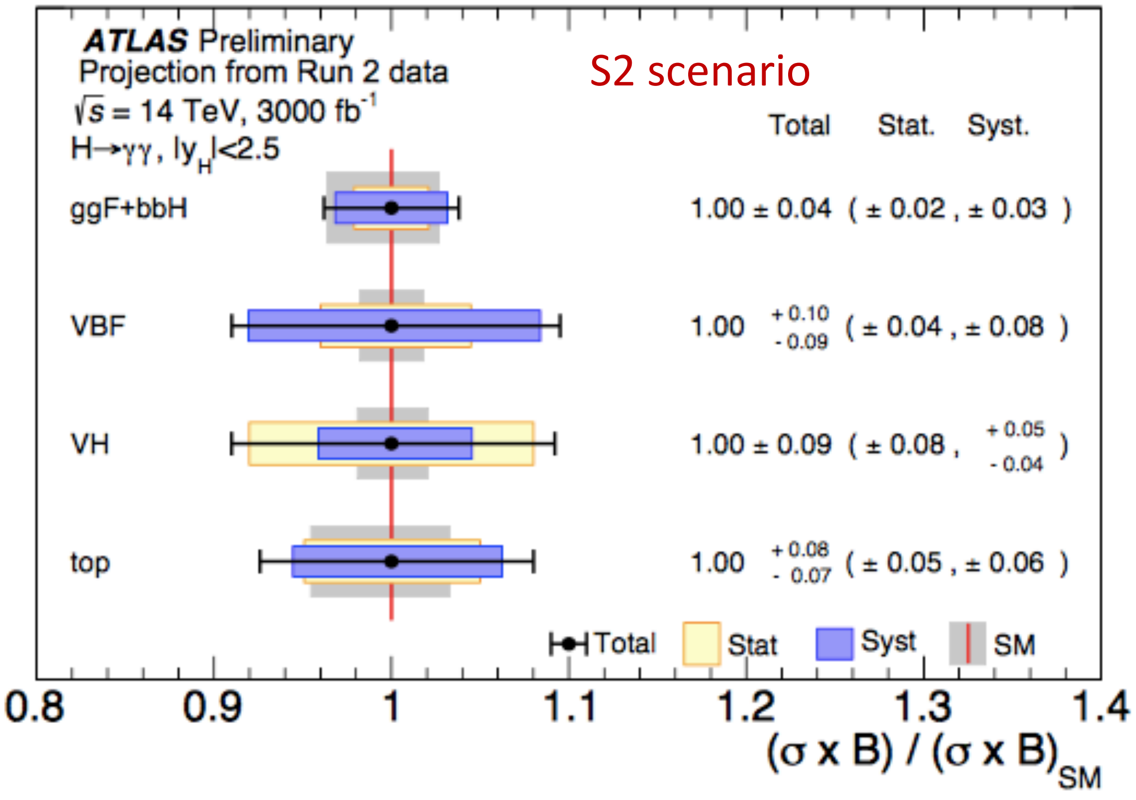
HL-LHC: Differential xsection measurement

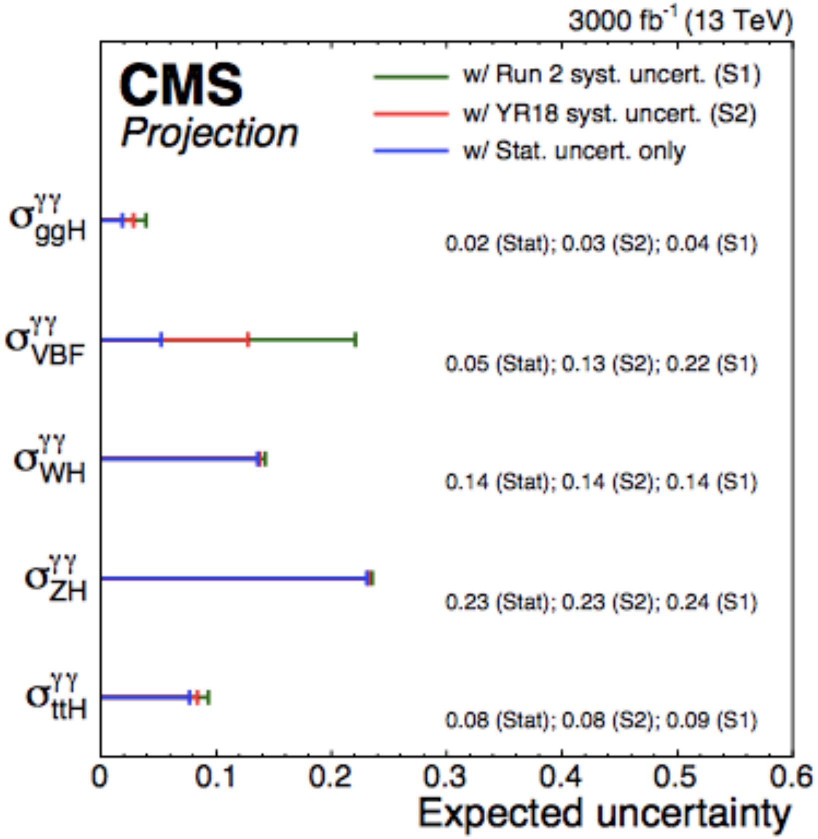




The precision can reach a few percent for different p_T bins.

HL-LHC H->γγ: one example



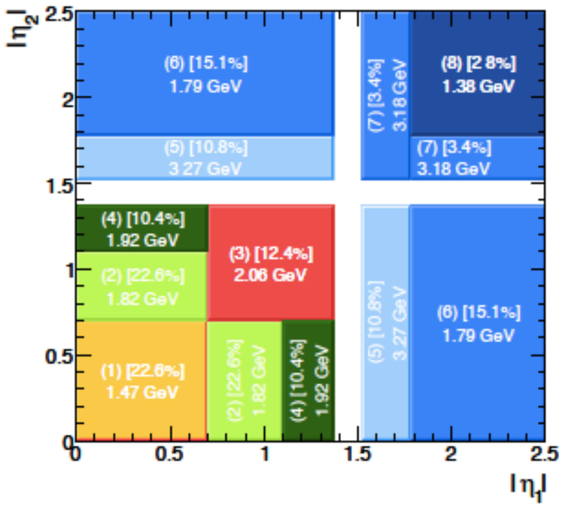


Scenario S1: Total uncertainty is half of the one used for the result of 80 fb^{-1}.
Scenario S2: Total uncertainty is 1/3 of the one for 80 fb^{-1}.

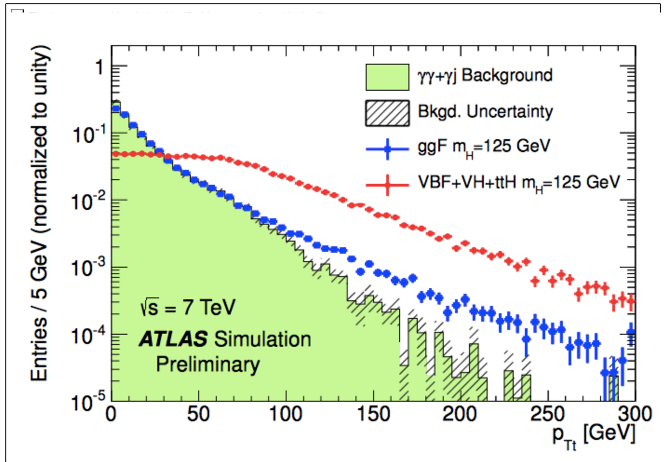
HL-LHC H->γγ: very advanced analyses (example)

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

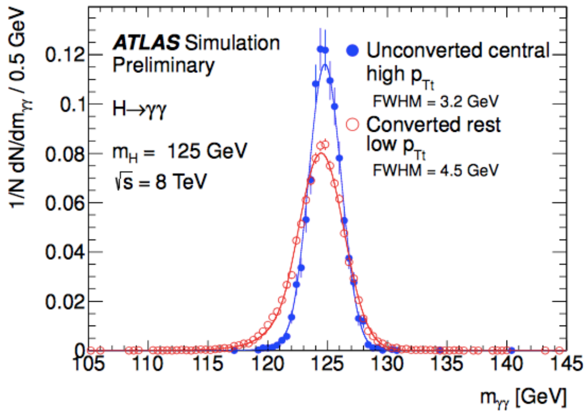
Divide different eta regions for two photons



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



Conversion of the photons



Higgs white paper @ CDR

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

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

Precision Higgs Physics at the CEPC*

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	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%
$\mathrm{BR}^{\mathrm{BSM}}_{\mathrm{inv}}$	–	$<0.28\%$	–	$<0.30\%$

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:**

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

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

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

3.0%

Precision : 3.5%

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

Precision : 2.8%