



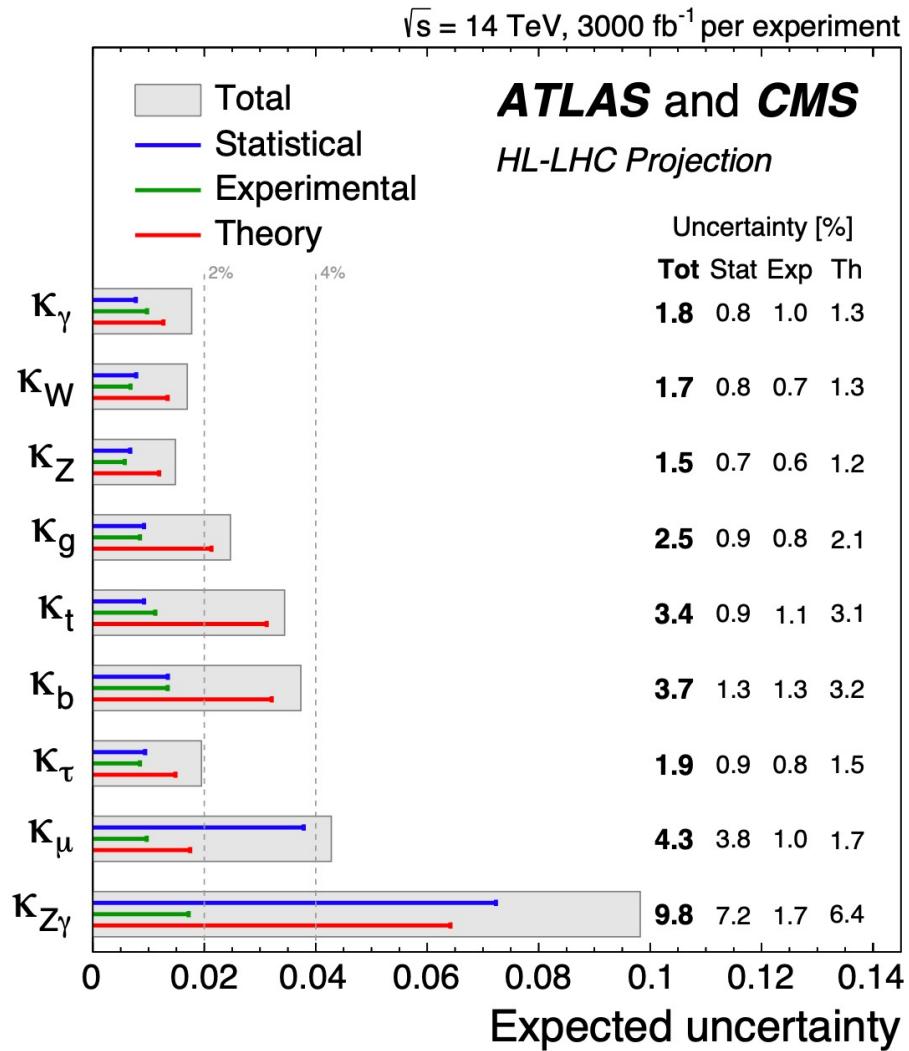
# Status of Higgs Physics and top physics at CEPC

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

August 16-19, 2021

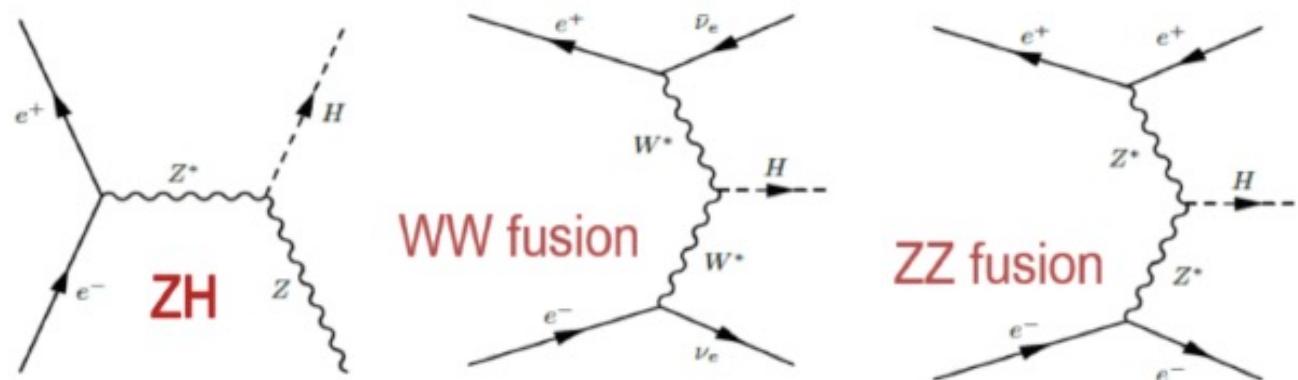
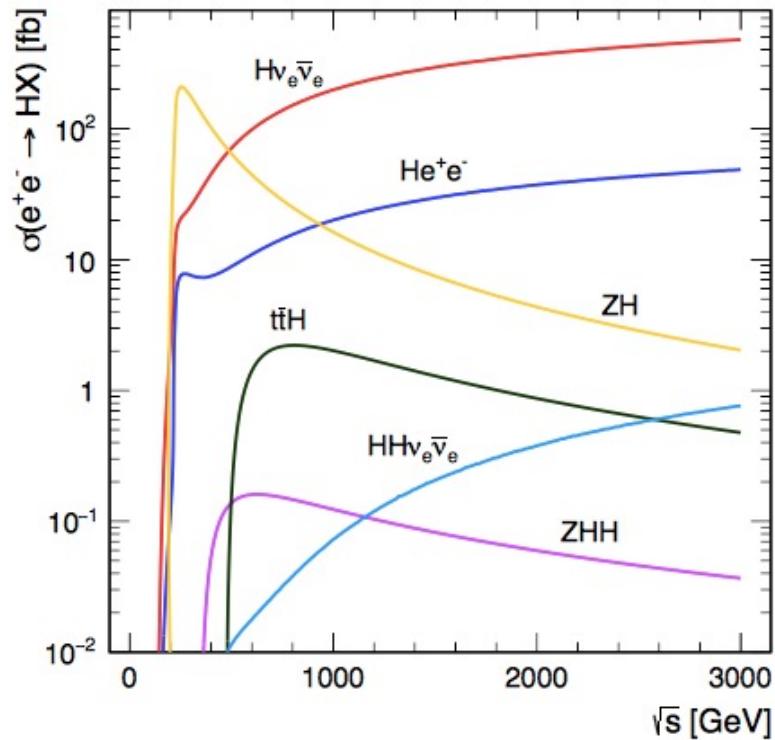
Qingdao, China

# Why do we need $e^+e^-$ collider



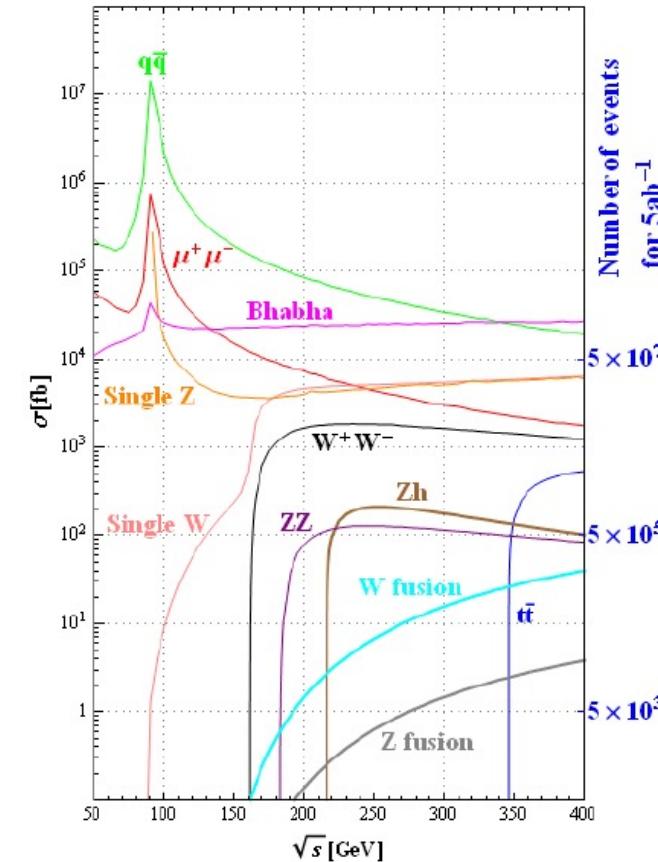
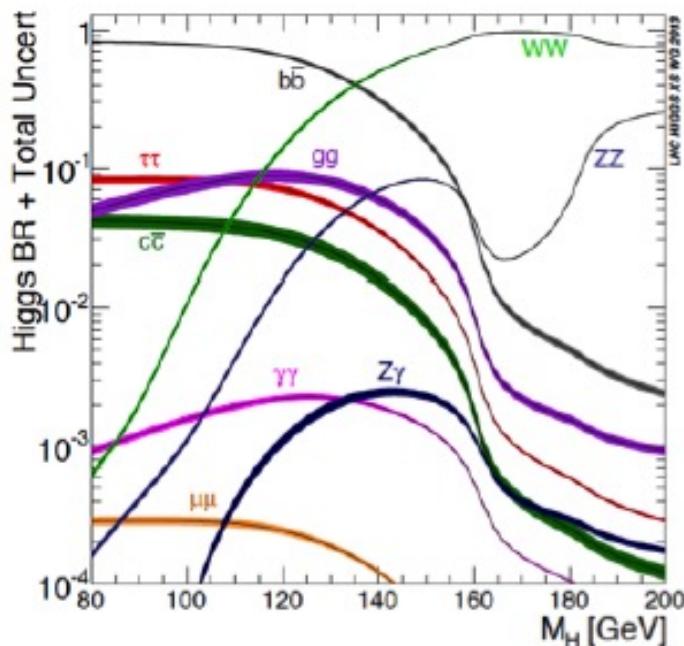
- For HL-LHC (3000 fb-1), the precisions of measurements of Higgs coupling parameters are not better than a few percent.
  - Theoretical uncertainties start to be the dominant one.
- If the new physics is at the sub-percent level, HL-LHC is not sensitive.
- Need  $e^+e^-$  machine to precisely measure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

# Higgs related physics at $e^+e^-$ collider



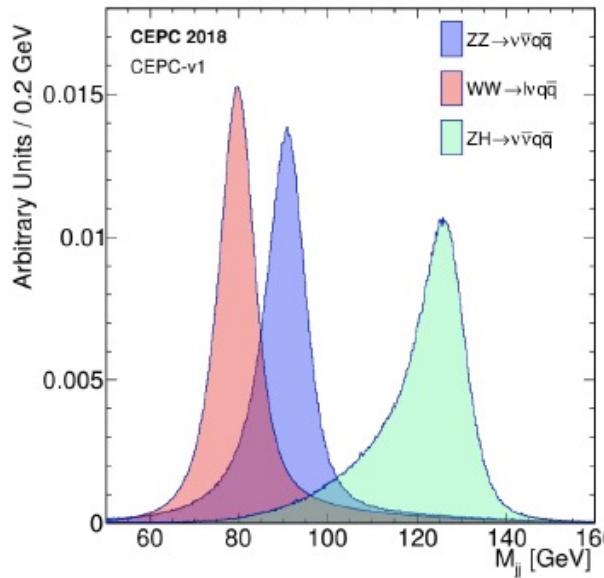
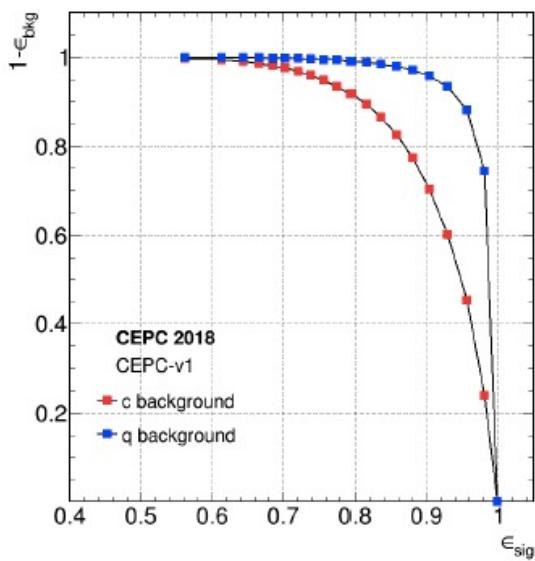
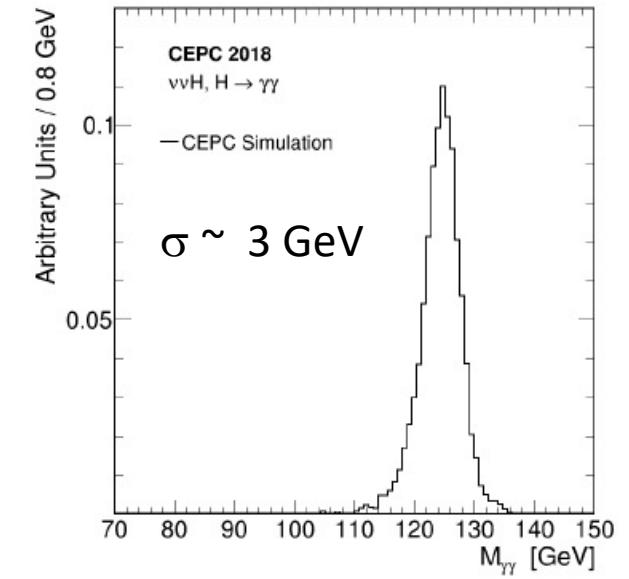
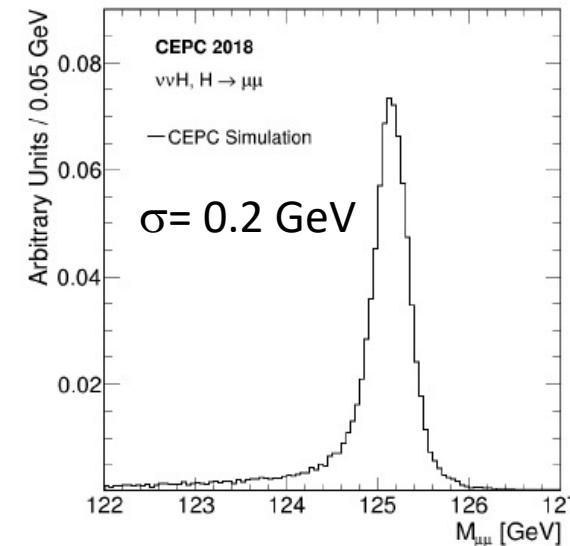
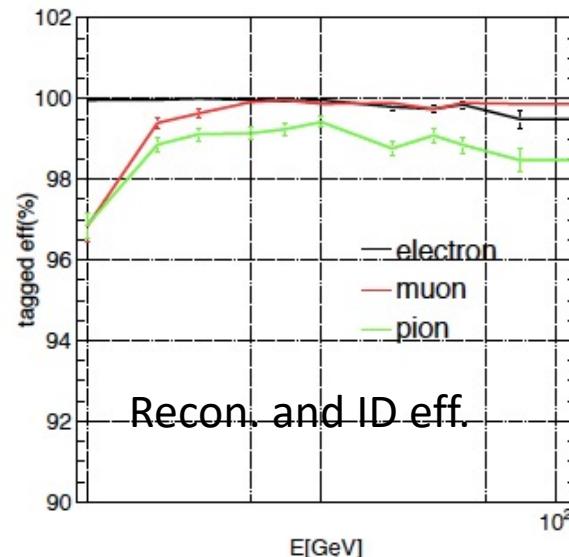
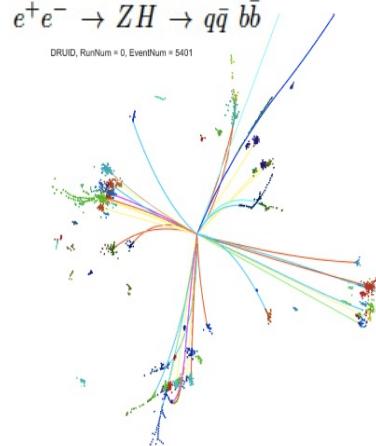
- With the increase of the energy, different Higgs related physics can be explored at  $e^+e^-$  collider.
- With the energy around 240 GeV, ZH as well as WW/ZZ fusion can be intensively studied.
  - the dominant production is from HZ, the WW/ZZ fusions contribute a few percent of the total cross-section.

# SM Higgs decay branching ratio, Bkg process



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

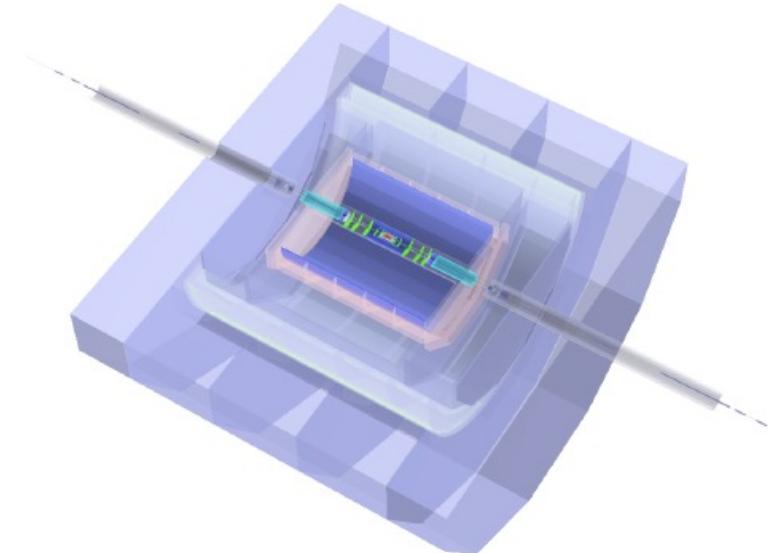
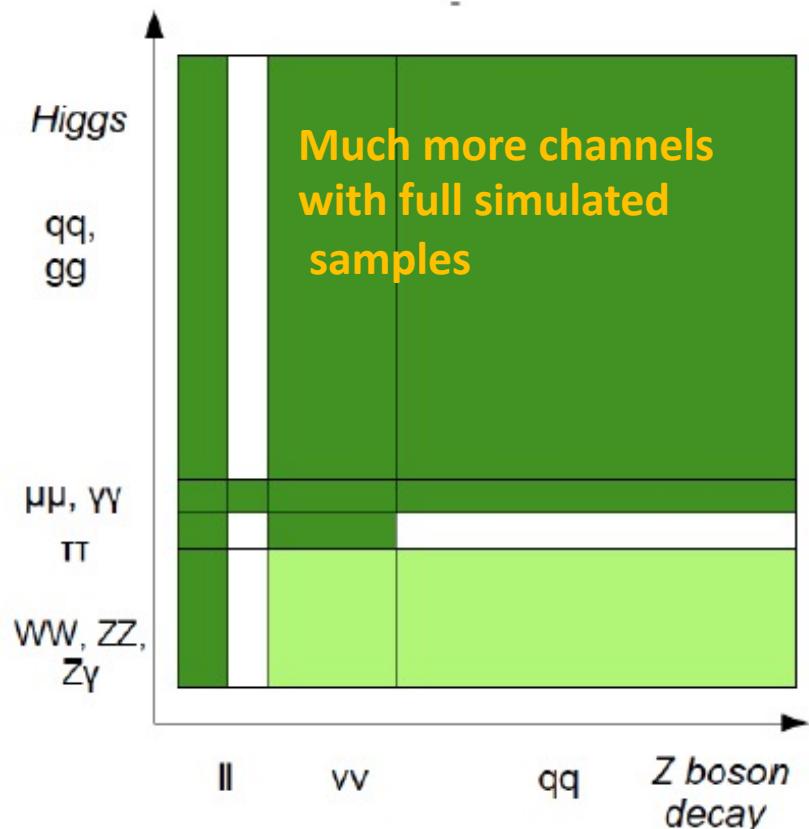
# Performance



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

B-tagging eff. vs rejection of other jets

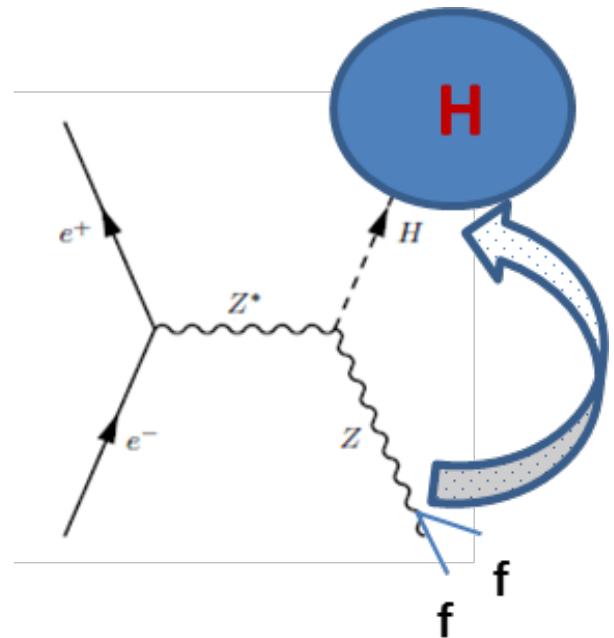
# Higgs analyses @CEPC CDR



A lot of decay channels can be investigated.

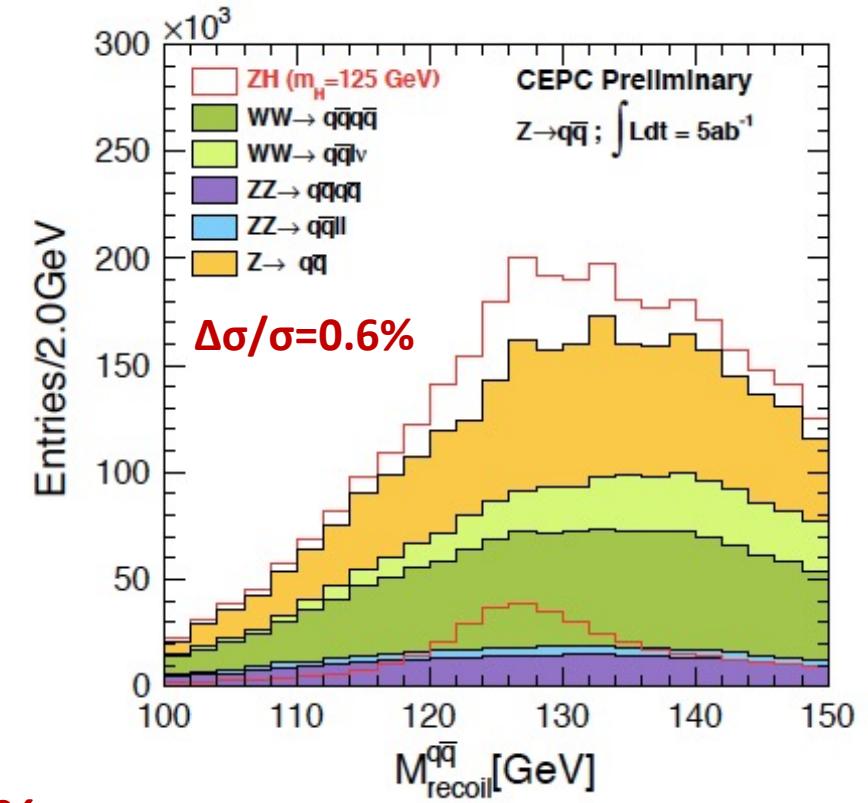
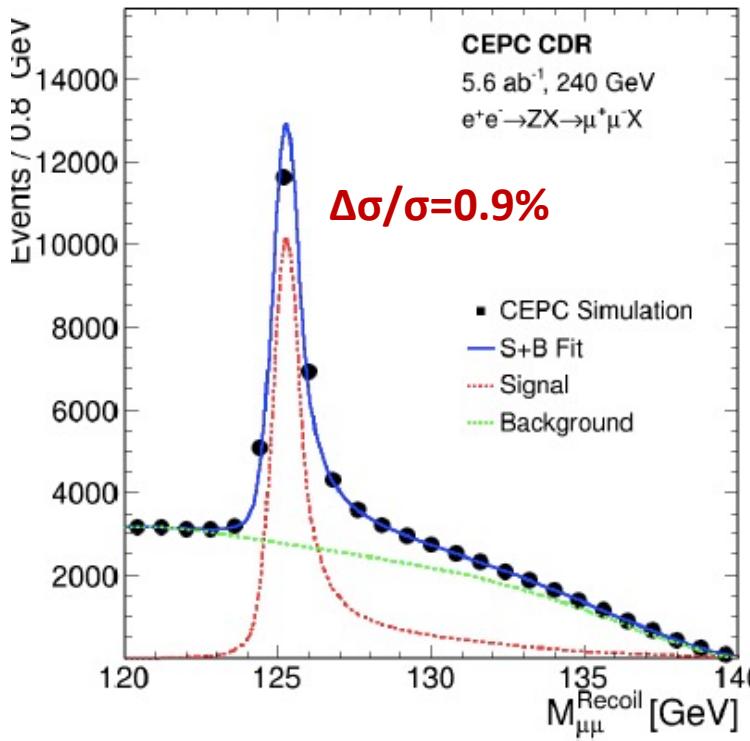
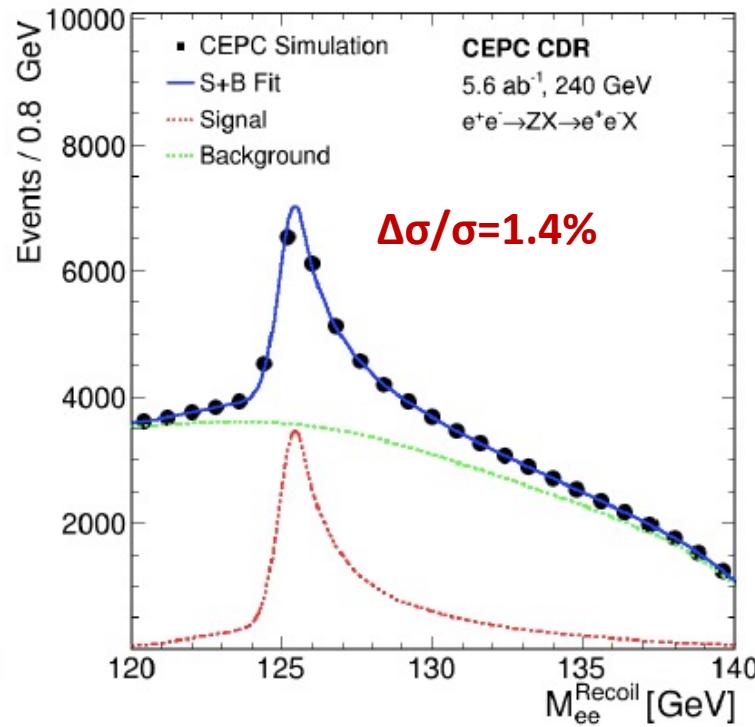
# Direct measurement of Higgs cross-section

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



- ✓ For this model independent analysis, we reconstruct the recoil mass of  $Z$  without touching the other particles in a event.
- ✓ The  $M_{\text{recoil}}$  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  $\Delta\sigma/\sigma=0.5\%$
- ✓ Similar sub-percent level for ILC/FCC-ee
- ✓ The mass of Higgs can be measured with a precision 5.9 MeV combining  $Z \rightarrow ee$  (14 MeV) and  $Z \rightarrow \mu\mu$  (6.5 MeV)

# Measurement of Higgs width

- **Method 1:** Higgs width can be determined directly from the measurement of  $\sigma(ZH)$  and Br. of  $(H \rightarrow ZZ^*)$

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

Precision : 5.1%

- But the uncertainty of  $\text{Br}(H \rightarrow ZZ^*)$  is relatively high due to low statistics.
- **Method 2:** It can also be measured through:

$$\Gamma_H \propto \frac{\Gamma(H \rightarrow bb)}{\text{BR}(H \rightarrow bb)} \quad \sigma(\nu\bar{\nu}H \rightarrow \nu\bar{\nu}bb) \propto \Gamma(H \rightarrow WW^*) \cdot \text{BR}(H \rightarrow bb) = \Gamma(H \rightarrow bb) \cdot \text{BR}(H \rightarrow WW^*)$$

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

3.0%

Precision : 3.5%

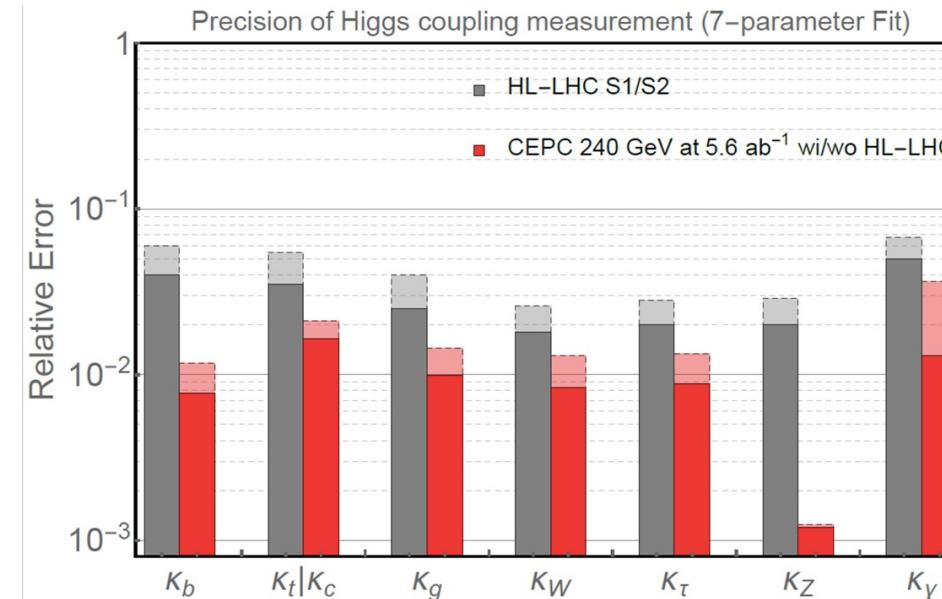
- These two orthogonal methods can be combined to reach the best precision.

Precision : 2.8%

# Precision for the Measurement of Higgs

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

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



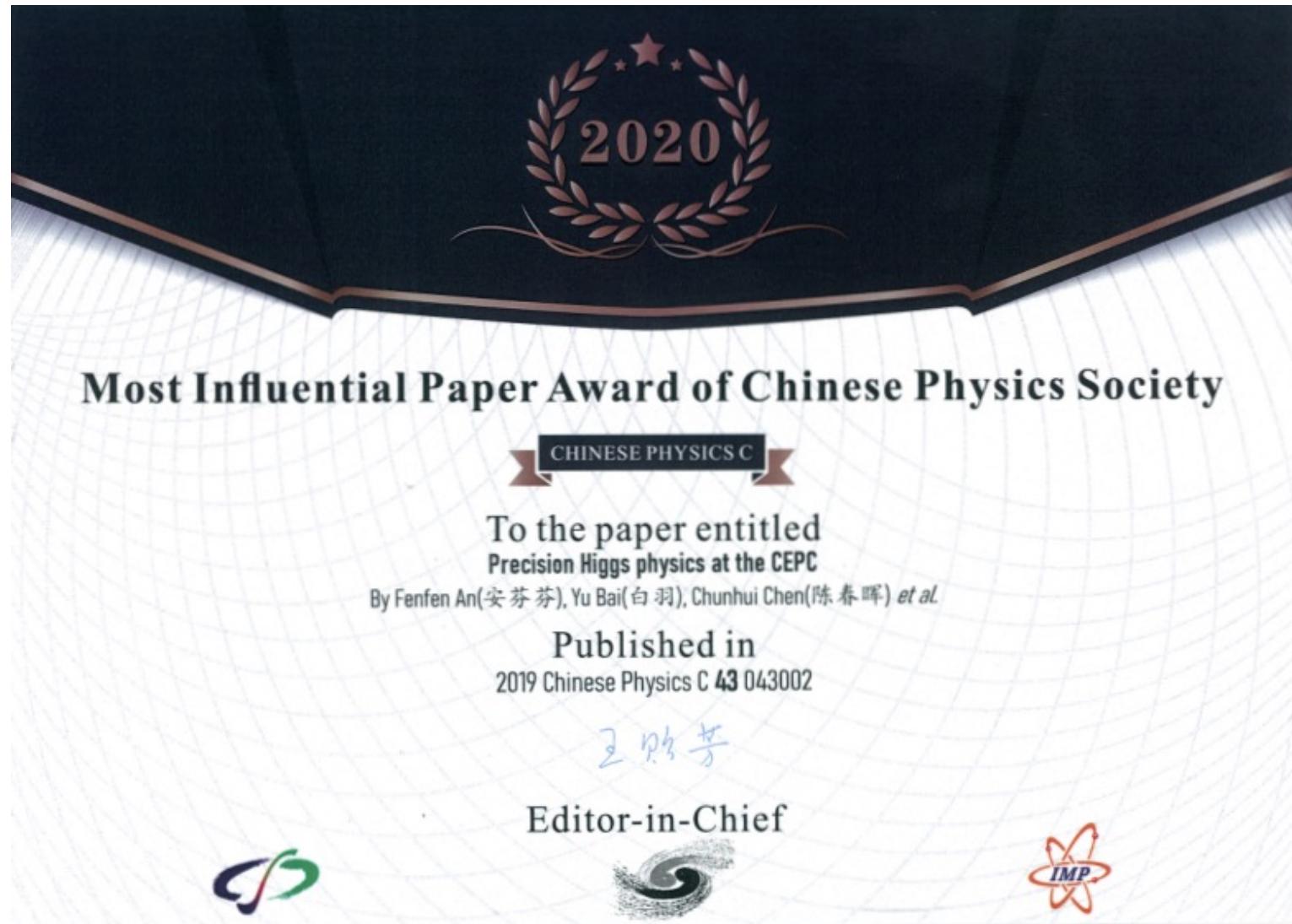
arXiv:1810.09037v2 [hep-ex] 4 Mar 2019

## Precision Higgs Physics at the CEPC\*

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- ✓ With combination of  $\sigma \times \text{Br}$  of  $v\nu H \rightarrow bb$  /  $\text{Br}(H \rightarrow bb)$  /  $\text{Br}(H \rightarrow ww)$  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](https://arxiv.org/abs/1810.09037)) and results are included in CDR.
- ✓ Other publications:  $\sigma(ZH)$ : [1601.05352](https://arxiv.org/abs/1601.05352);  $bb/cc/gg$ : [1905.12903](https://arxiv.org/abs/1905.12903);  $\tau\tau$ : [1903.1232](https://arxiv.org/abs/1903.1232)  
Invisible: [2001.05912](https://arxiv.org/abs/2001.05912)

# CEPC Higgs white paper : Most Influential Paper Award of CPS in 2020



# Precision for the measurement of Higgs

CEPC CDR: arxiv: 1811.10545

Property	Estimated Precision	
$m_H$	5.9 MeV	
$\Gamma_H$	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%
$H \rightarrow \text{inv}$	—	< 0.30%

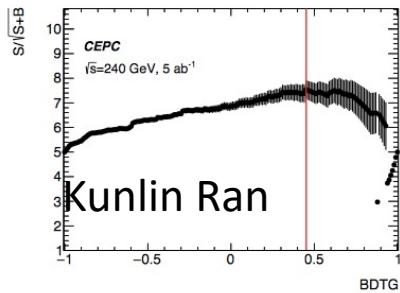
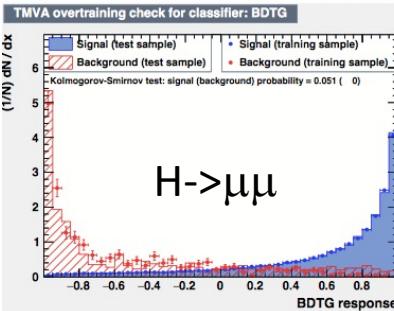
Fcc-ee 240 GeV/365 GeV:  
[CERN-ACC-2018-0057](https://cds.cern.ch/record/2305457)

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

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

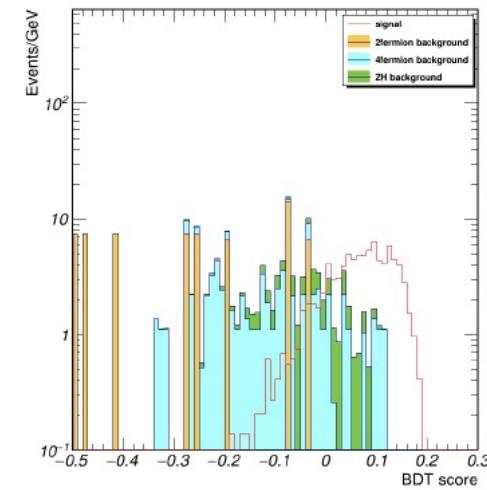
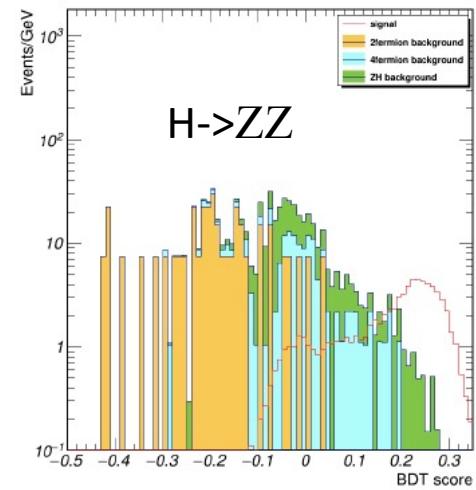
# MVA methods used in different channels and other activities

- 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



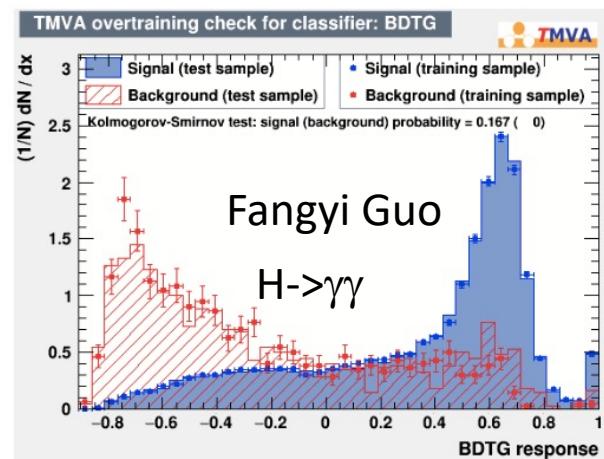
- There is an overtraining in the background due to poor statistics:  $\sim 1600$
- Scan the total sensitivity ( $S/\sqrt{S+B}$ ) vs BDTG to find the optimal BDTG point
- The sensitivity is estimated in the 90% signal coverage region

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



➤ For  $H \rightarrow \mu\mu$ , the improvement is  $\sim 35\%$  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  $H \rightarrow \gamma\gamma$ .



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

# Higgs CP study at CEPC

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

Differential cross section could be represent as:

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

An **Optimal Variable  $\omega$**  which combines the information from  $\{\theta_1, \theta_2, \phi\}$  defined as:

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

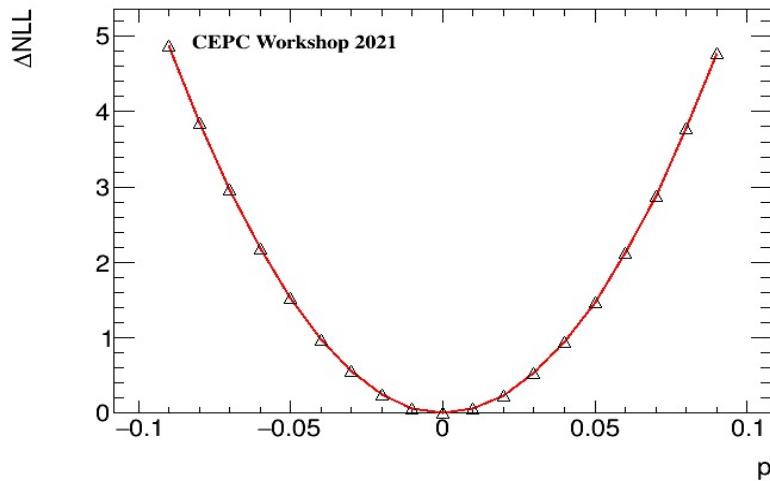
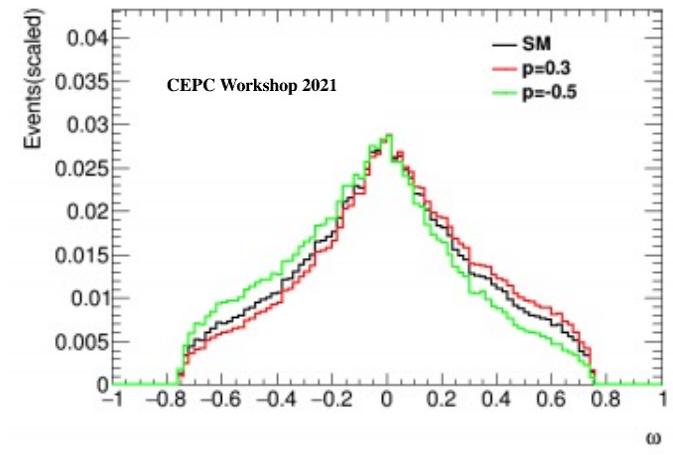
Used ML-fit in  $\omega$  distribution to extract  $p$ .

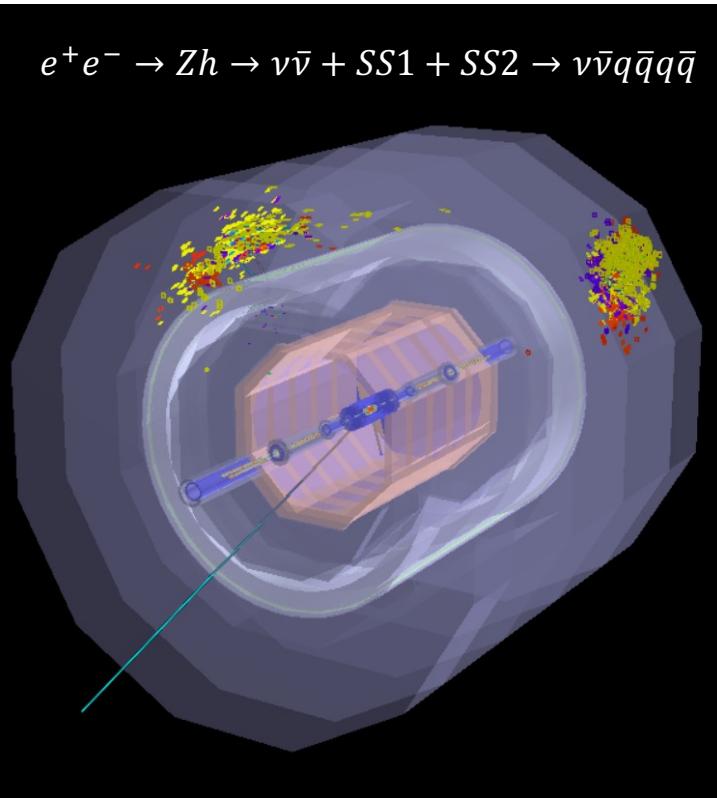
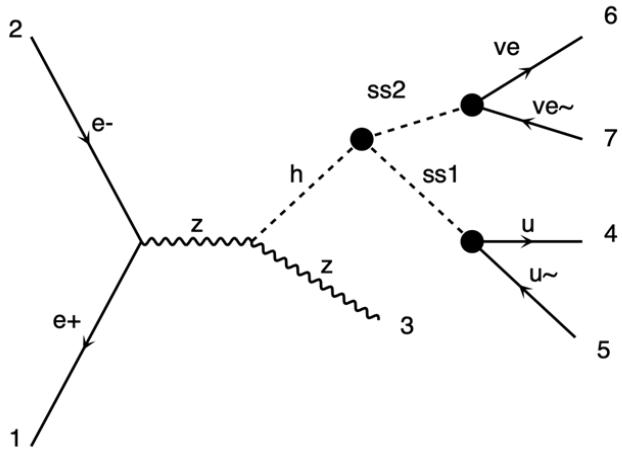
Result:

For  $p$ :

68% CL:  $[-2.9 \times 10^{-2}, 2.9 \times 10^{-2}]$

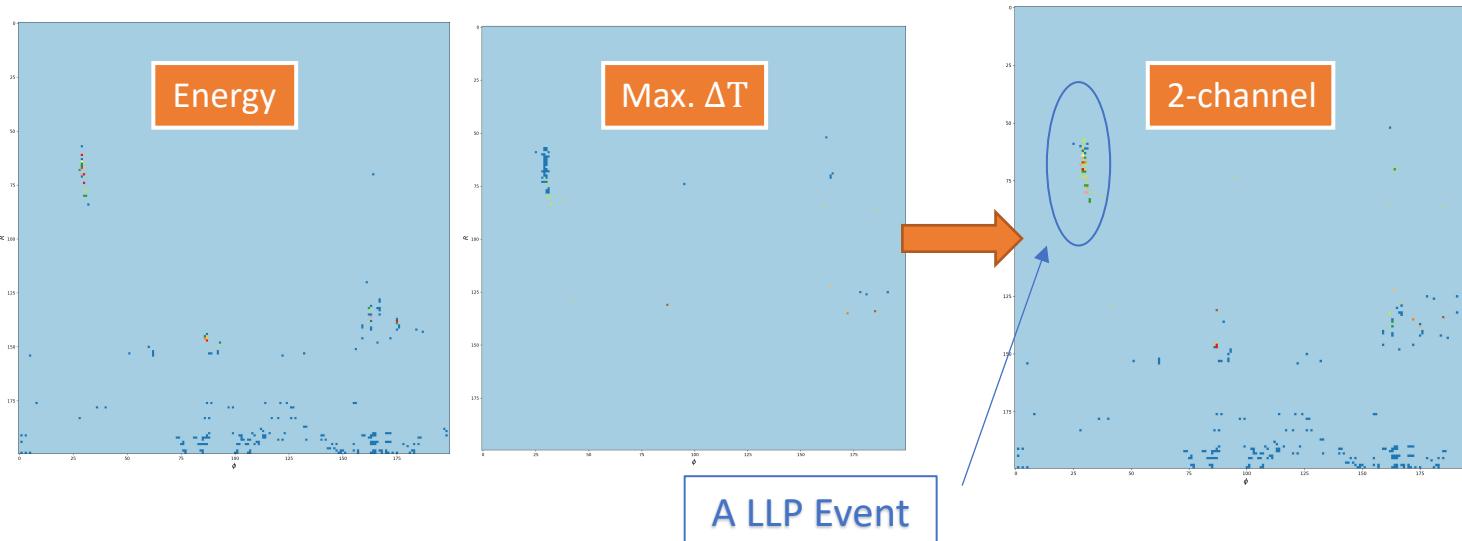
95% CL:  $[-5.7 \times 10^{-2}, 5.7 \times 10^{-2}]$



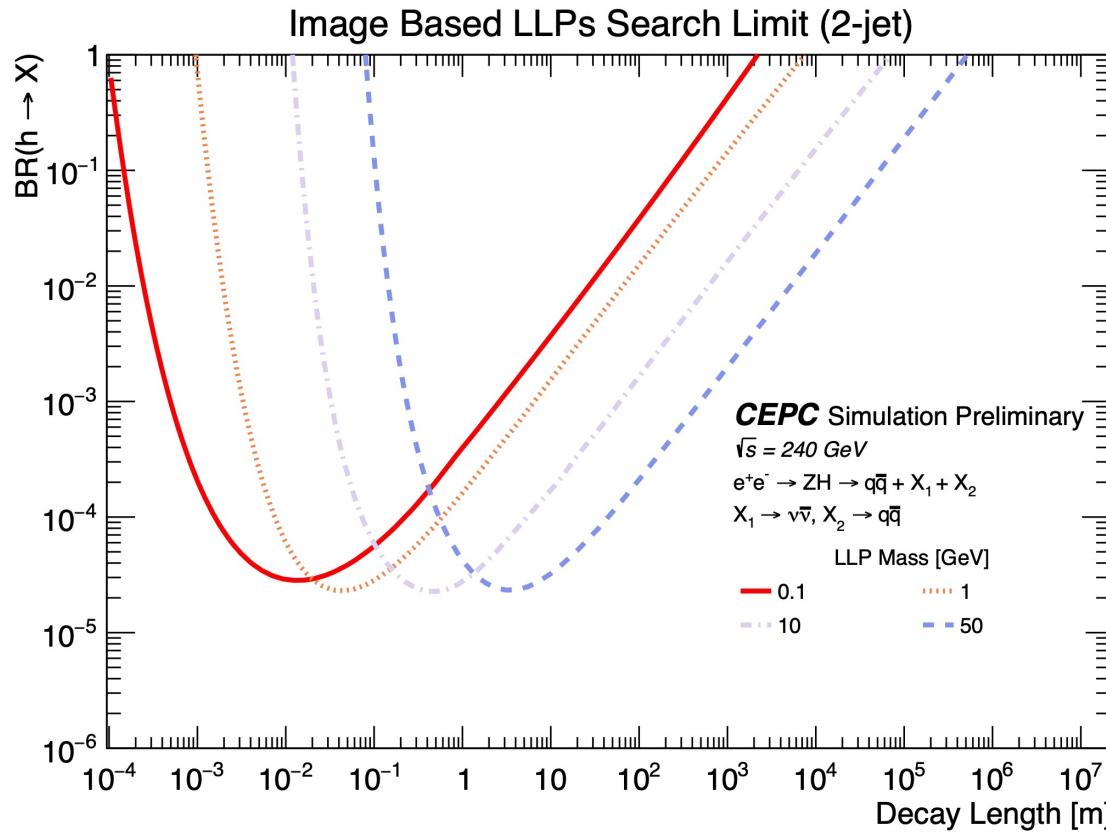


# Image Recognition Techniques to Identify Long-Lived Particles( $h \rightarrow \text{LLPs}$ )

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



# Expected Search Sensitivity



Signal Efficiency of ML-based and Cut-based analysis for  $Z \rightarrow \nu\bar{\nu}$

Selections	Signal: $Z \rightarrow \nu\bar{\nu}$	$ee \rightarrow q\bar{q}$	$ee \rightarrow ZH$
-	$2.5 \times 10^8$		
-	$1.0 \times 10^6$	$0.99 \times 10^7$	
$\cancel{E} > 190 \text{ GeV}, N_{PFOs} > 8$	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:  $BR(h \rightarrow XX) > \sim 10^{-5}$  for most LLP masses
- Good sensitivity for low LLP mass (as low as 1 GeV)

# Global analysis for CEPC Higgs

**Efficiency modulate  $\mathbf{N} \rightarrow \mathbf{n}$**

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

Similar for their covariances

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

**We know the covariance of  $\mathbf{N}$**

~ multinomial

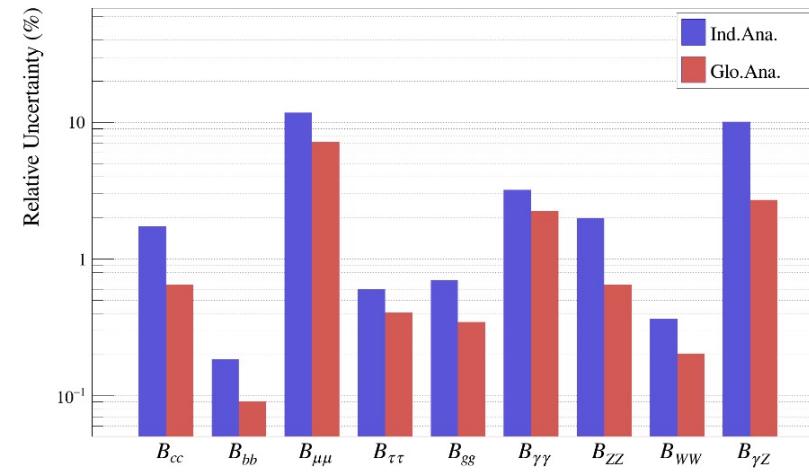
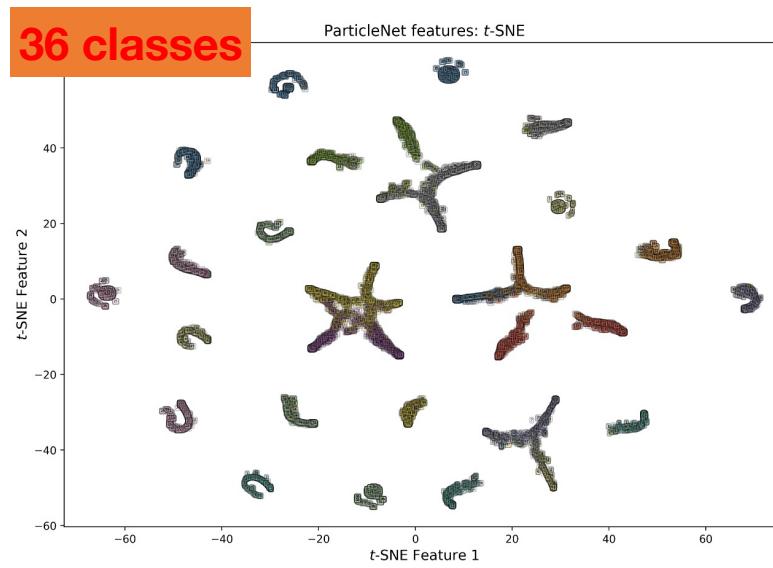
so  $\Sigma^n$  is easy

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

**Solve all  $N_i$  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

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

Proof-of-principle study shows precision improved by a factor of  $\sim 2$

Full simulation study is ongoing ...

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

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

- BGO crystal ECAL in CEPC conceptual detector:

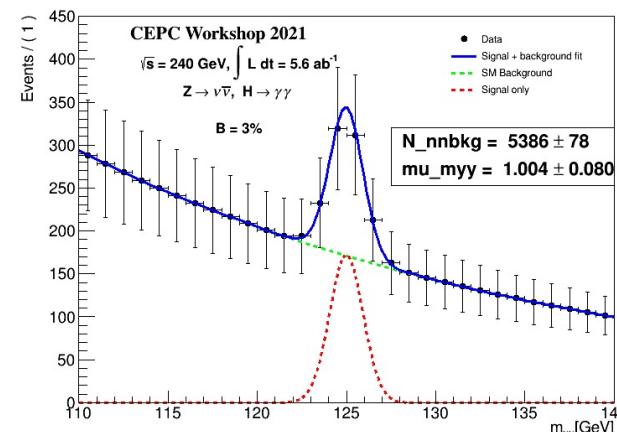
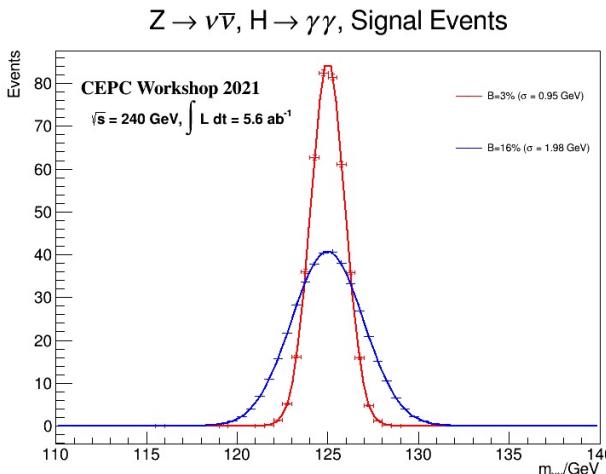
- full BGO crystal, 24  $X_0$ , expected energy resolution  $\frac{\sigma_E}{E} \sim \frac{3\%}{\sqrt{E}} \oplus \sim 1\%$ .

- Simulate the detector response by smearing truth MC.

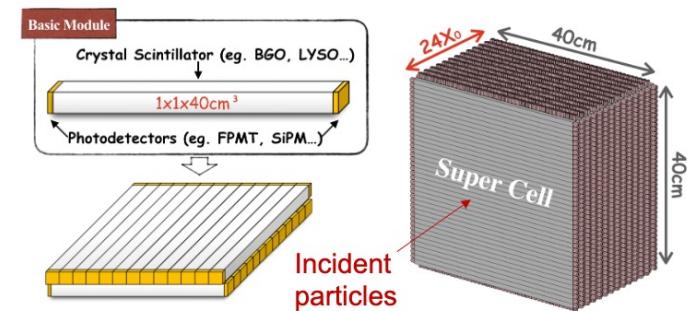
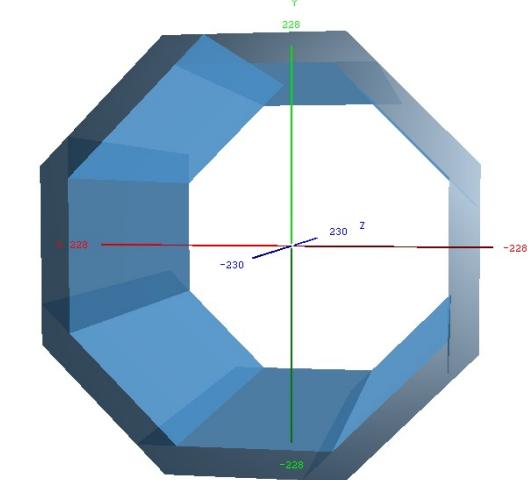
- $\sigma(ZH) \times Br(H \rightarrow \gamma\gamma)$  precision @ CEPC:

- Only consider the  $\sigma_E$  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

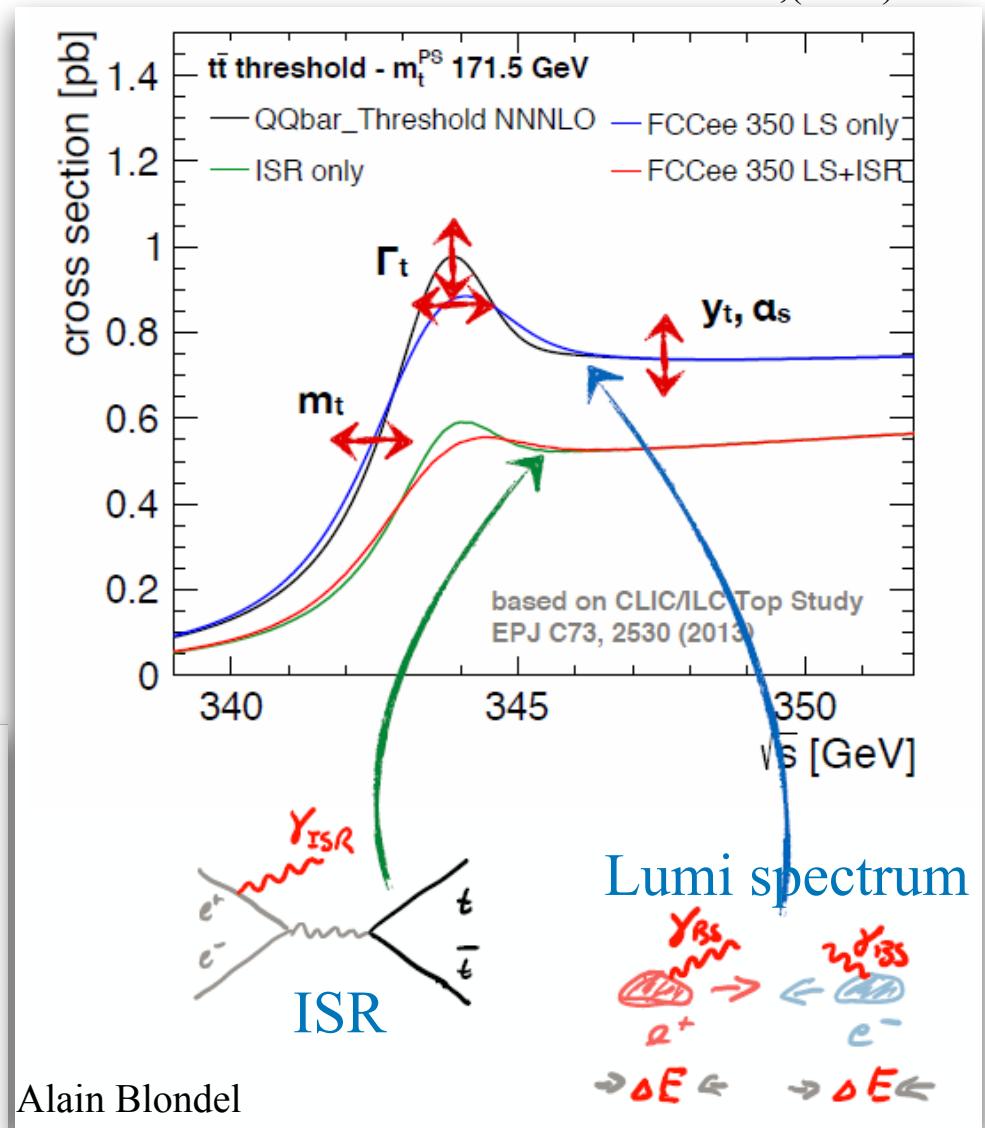
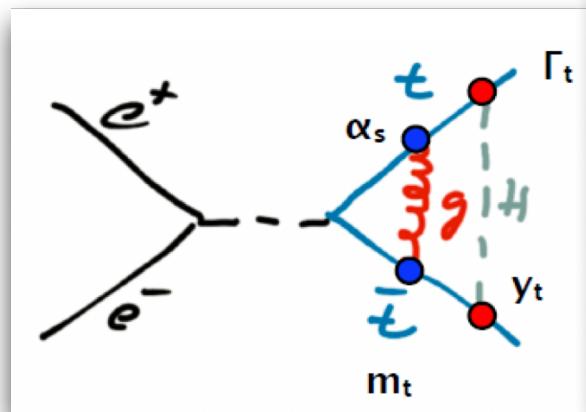


EM Resolution	$\delta(\sigma \times Br)$
$3\%/\sqrt{E} \oplus 1\%$	8.0%
$16\%/\sqrt{E} \oplus 1\%$	11%

# tt threshold scan

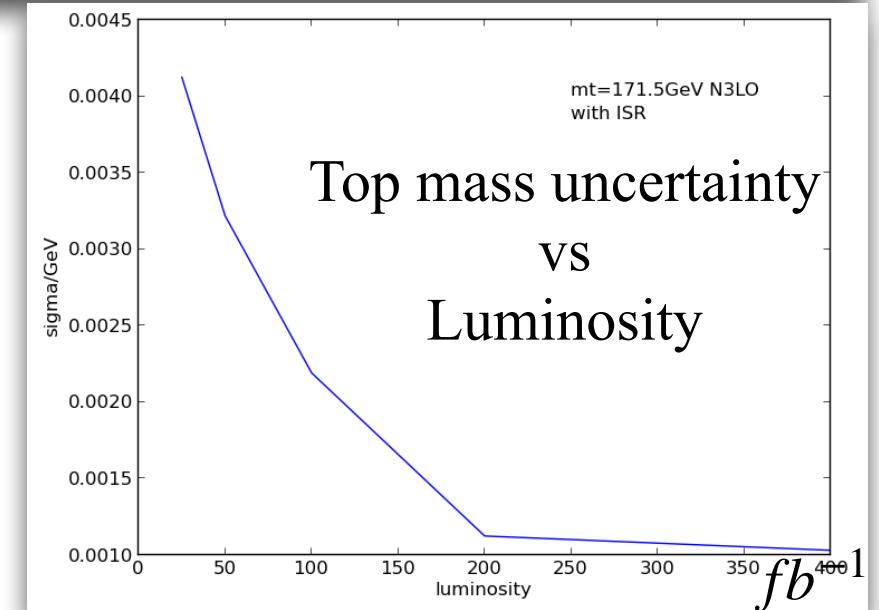
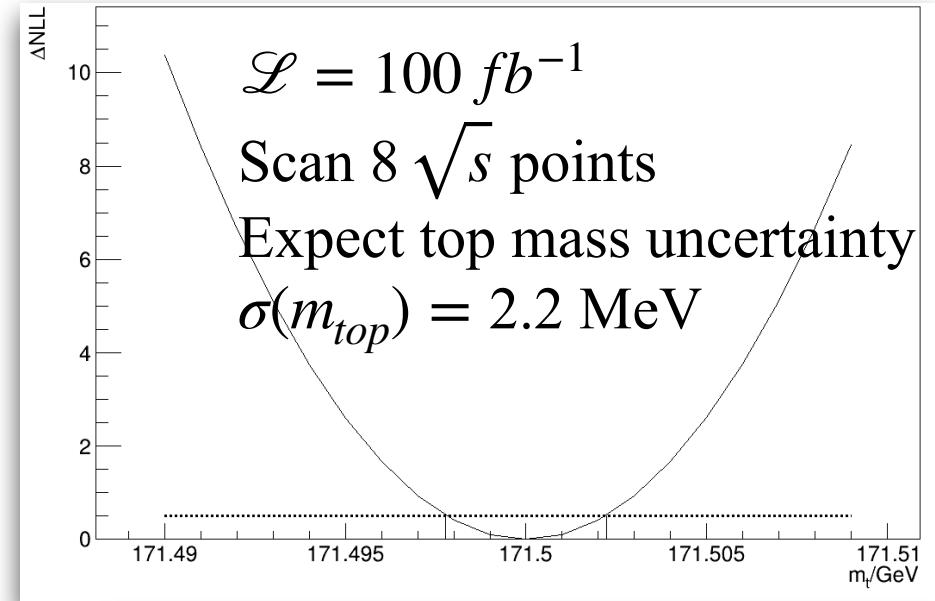
EPJC 73,(2013)2530

- Our plan is to study possible solutions for CEPC for 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
  - $\alpha_s$

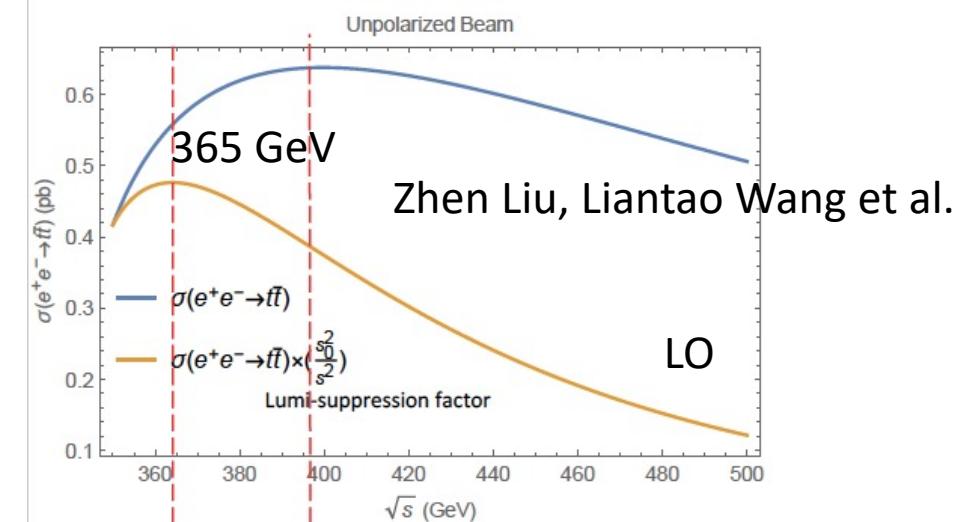
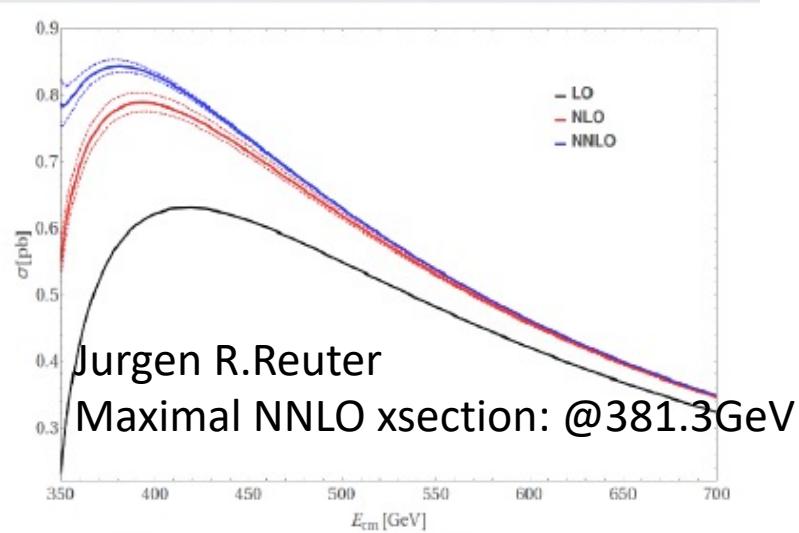


# Status and plans

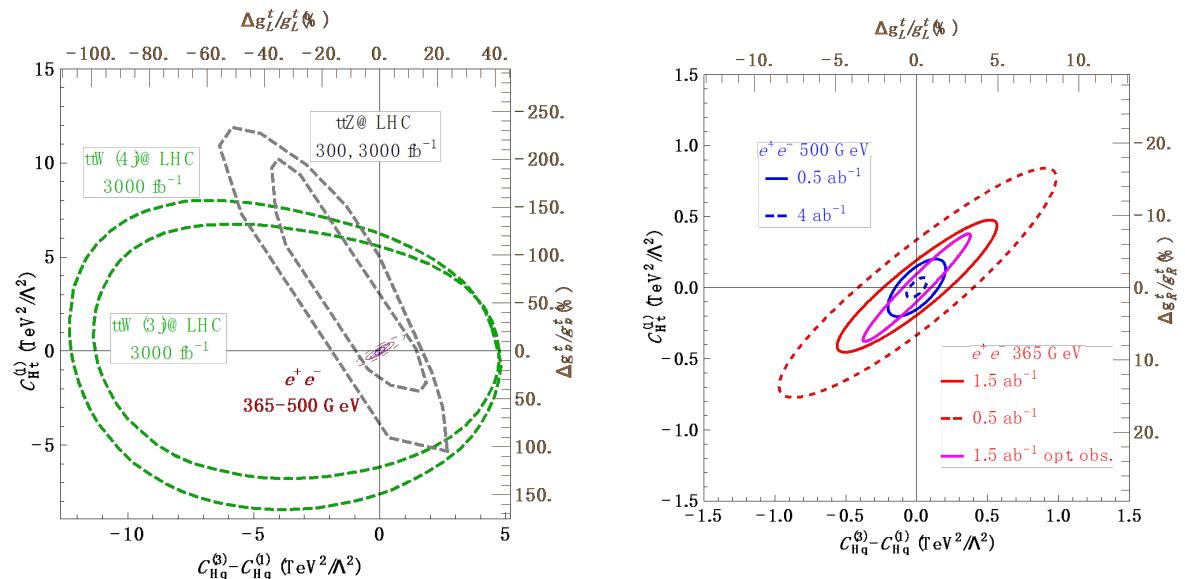
- Recent progresses of the CEPC top mass team
  - Extract information in the cross-section curve at the  $t\bar{t}$  threshold
  - Construct 1D likelihood to make scan to estimate measurement uncertainties
  - Preliminary tests with a few proposals of luminosities and energies  $\sqrt{s}$
- Todo
  - Top width,  $\alpha_S$  extraction
  - Add signal acceptance and efficiency
  - Add background contributions



# Higgs related physics at 360 GeV (generic study)

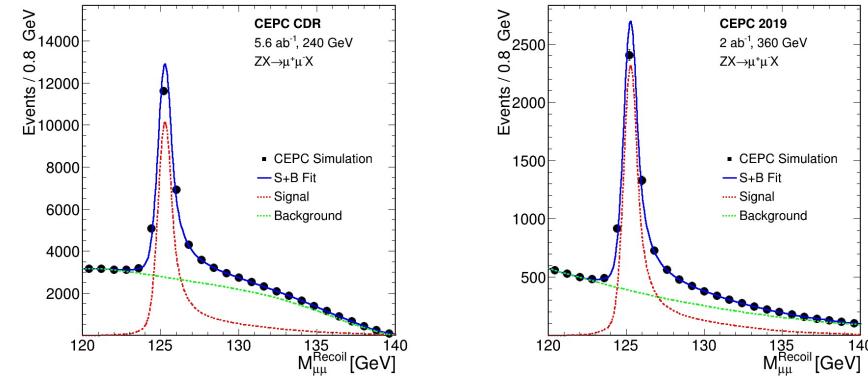


- ❖ With the NNLO calculation, the highest xsection is at the energy of 381.3 GeV
- ❖ Considering the Lumi-suppression factor when going to higher energy, the effective highest xsection is around 365 GeV.
- ❖ The effective xsection from 360 GeV is not much different from that of 365 GeV.
- ❖ If we choose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



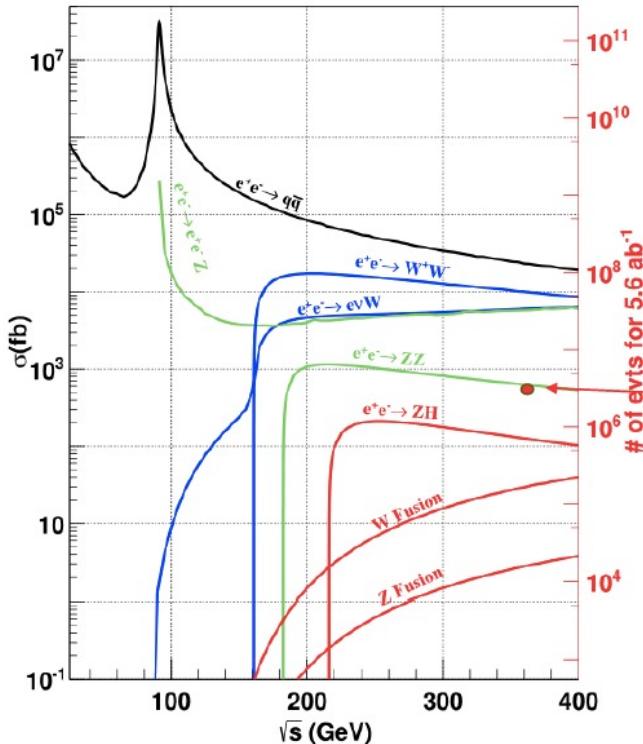
# Extrapolations

- 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  $\sim 0.3\text{GeV}$  to  $1\text{GeV}$ ;  $(23\% \rightarrow 29\%)$
  - diphoton: would better; from  $\sim 2.5\text{GeV}$  to  $2\text{GeV}$ ;  $(9\% \rightarrow 8\%)$



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

# Additional sensitivity on Higgs measurement



	240GeV, 5.6ab <sup>-1</sup>	360GeV, 2ab <sup>-1</sup>	
	ZH	ZH	$\nu\bar{\nu}H$
any	<b>0.50%</b>	<b>1%</b>	\
$H \rightarrow bb$	<b>0.27%</b>	<b>0.63%</b>	<b>0.76%</b>
$H \rightarrow cc$	<b>3.3%</b>	<b>6.2%</b>	<b>11%</b>
$H \rightarrow gg$	<b>1.3%</b>	<b>2.4%</b>	<b>3.2%</b>
$H \rightarrow WW$	<b>1.0%</b>	<b>2.0%</b>	<b>3.1%</b>
$t\bar{t}$ : here $H \rightarrow ZZ$	<b>5.1%</b>	<b>12%</b>	<b>13%</b>
$H \rightarrow \tau\tau$	<b>0.8%</b>	<b>1.5%</b>	<b>3%</b>
$H \rightarrow \gamma\gamma$	<b>5.4%</b>	<b>8%</b>	<b>11%</b>
$H \rightarrow \mu\mu$	<b>12%</b>	<b>29%</b>	<b>40%</b>
$\text{Br}_{\text{upper}}(H \rightarrow \text{inv.})$	<b>0.2%</b>	\	\
$\sigma(ZH) * \text{Br}(H \rightarrow Z\gamma)$	<b>16%</b>	<b>25%</b>	\
Width	<b>2.9%</b>		
Combined Width 240/360	<b>1.4%</b>		

Fcc-ee 240 GeV/365 GeV:  
[CERN-ACC-2018-0057](#)

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

combined width: 1.3%

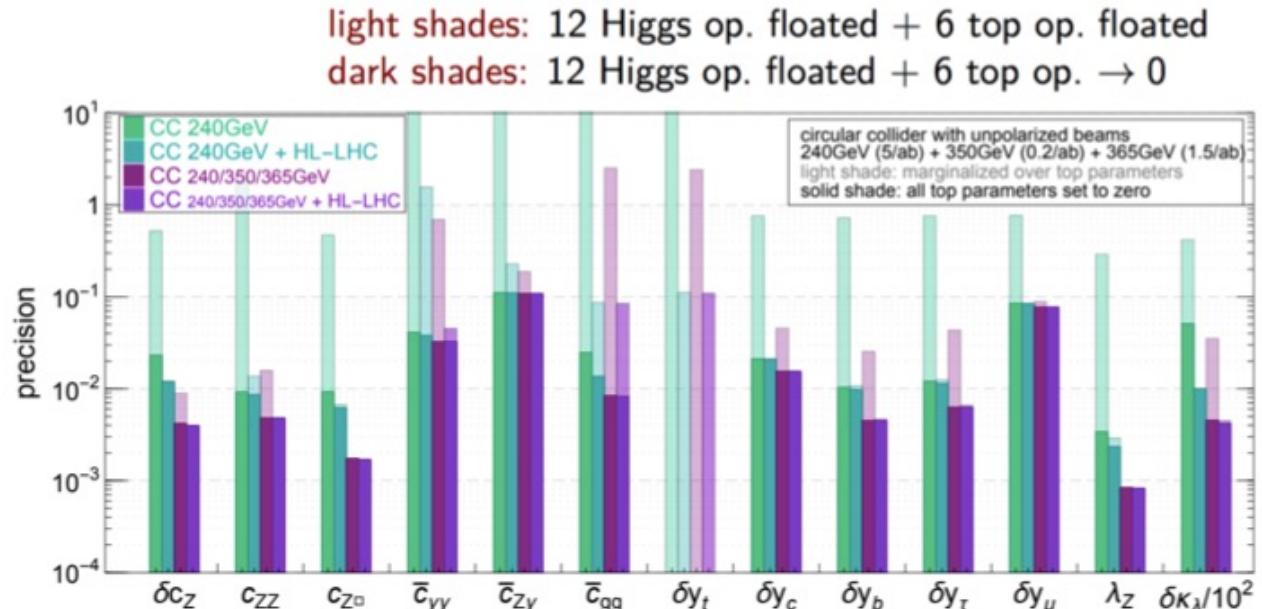
For Higgs physics results, there are no significant differences for the colliding energy with 360 GeV or 365 GeV.

# 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 CEPC Higgs are on going
- We also have a generic study on Higgs physics at 360 GeV ( $360 \text{ GeV}/2 \text{ ab}^{-1}$  as a benchmark)
  - Can bring some improvements in Higgs precision measurement in addition to top coupling measurements.
    - Significant improvement on Higgs width measurement.

backup slides

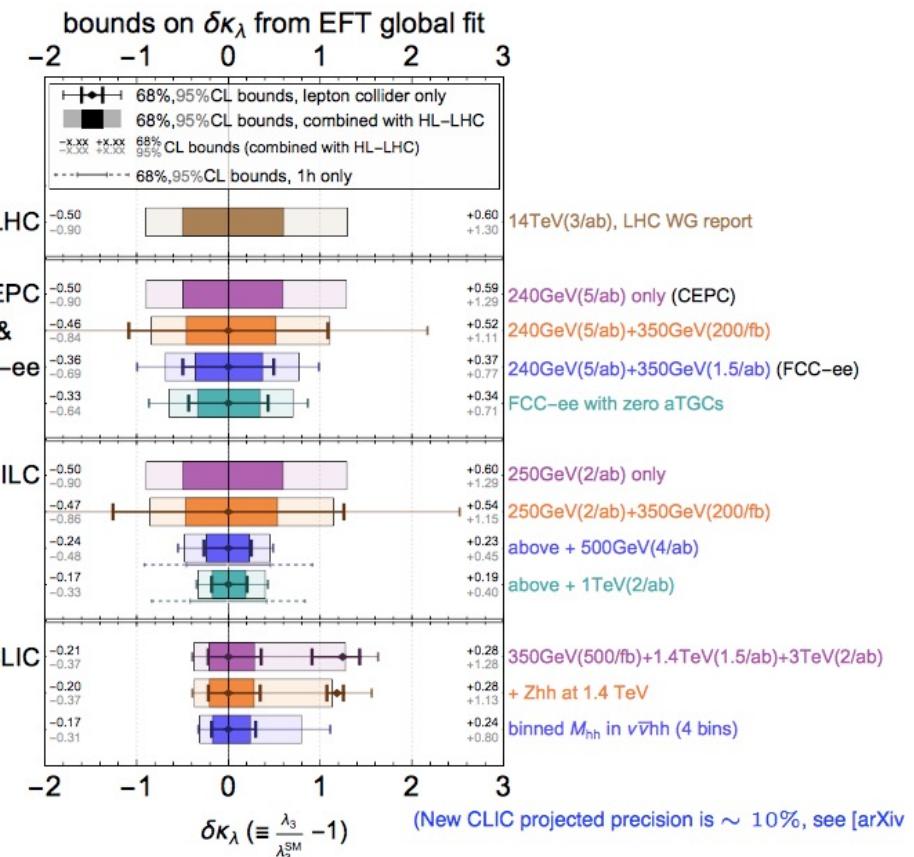
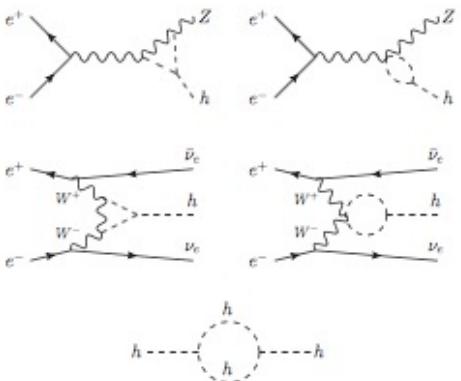
# Impact on Higgs



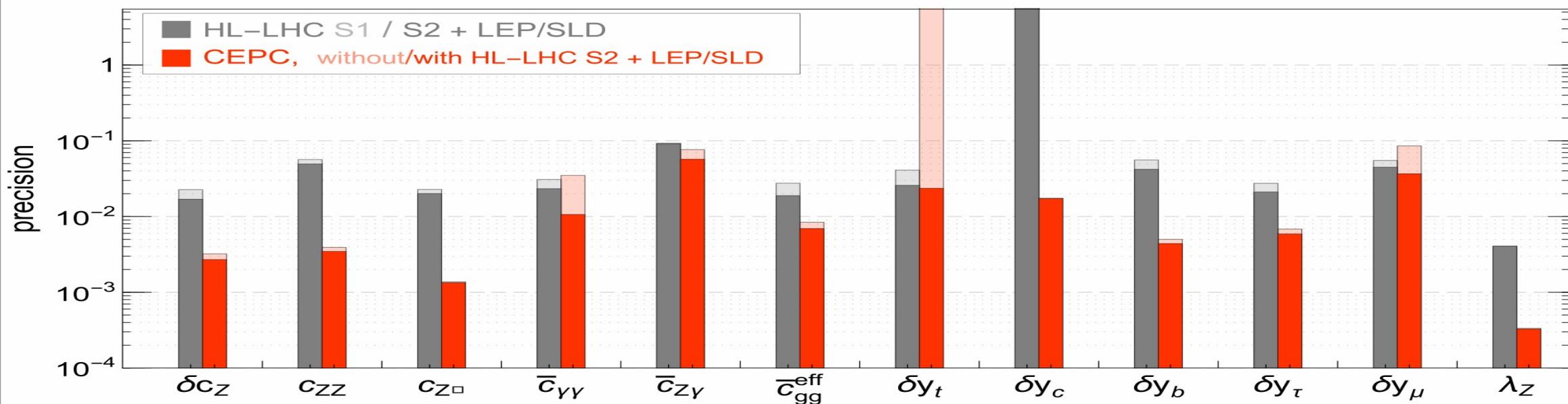
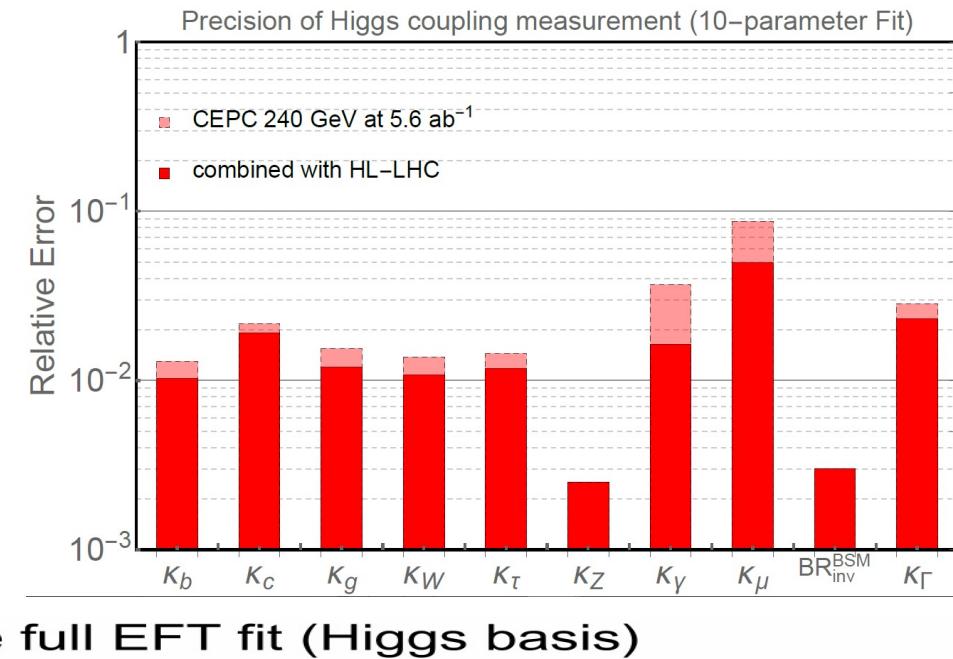
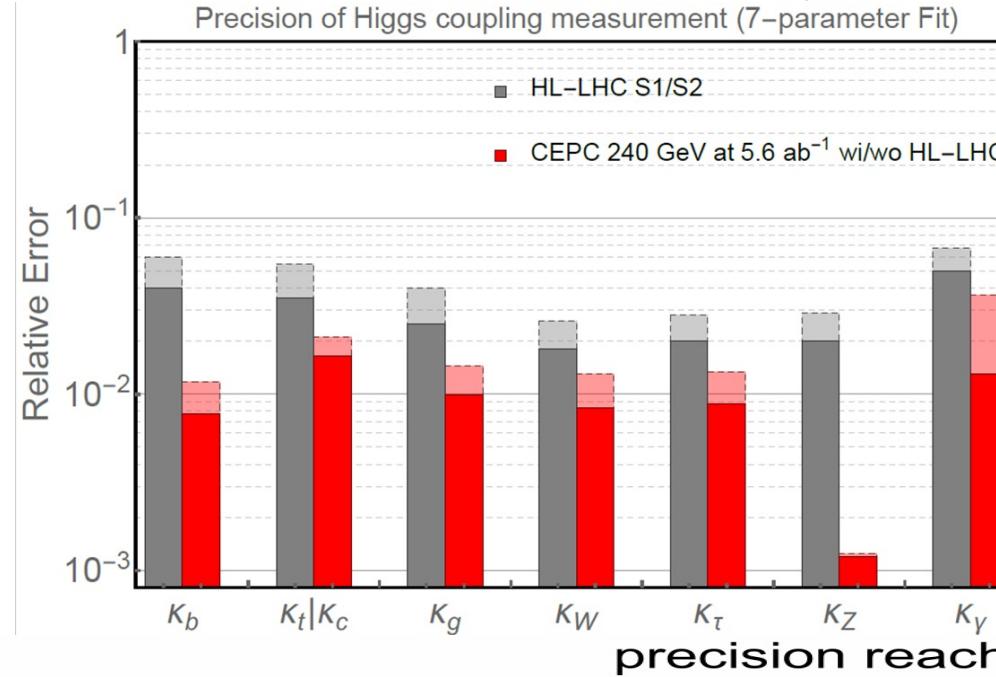
Uncertainties on the top have a big effect on the Higgs

- Higgsstr. run: insufficient
- Higgsstr. run  $\oplus e^+e^- \rightarrow t\bar{t}$ : 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  $\oplus e^+e^- \rightarrow t\bar{t} \oplus$  top@HL-LHC: top contam. in  $\bar{c}_{gg}$  only

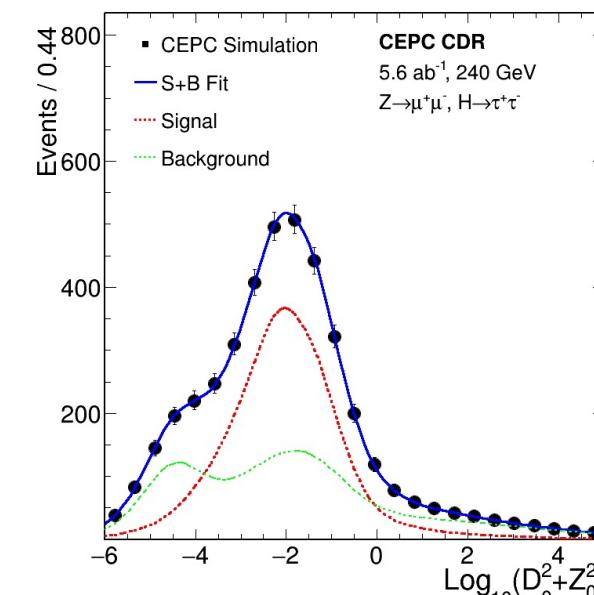
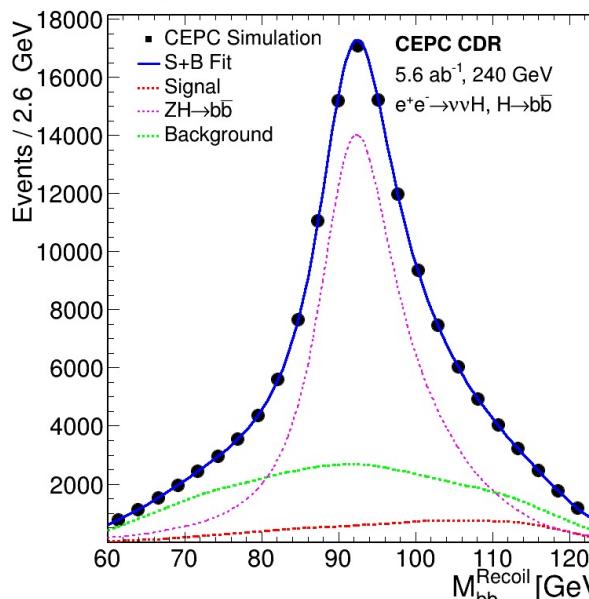
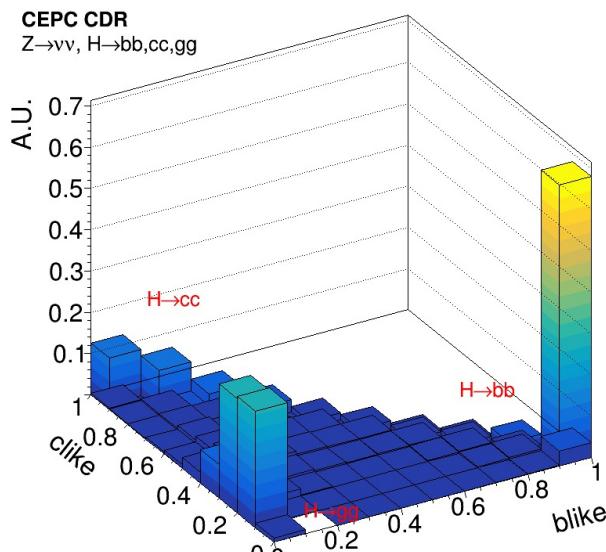
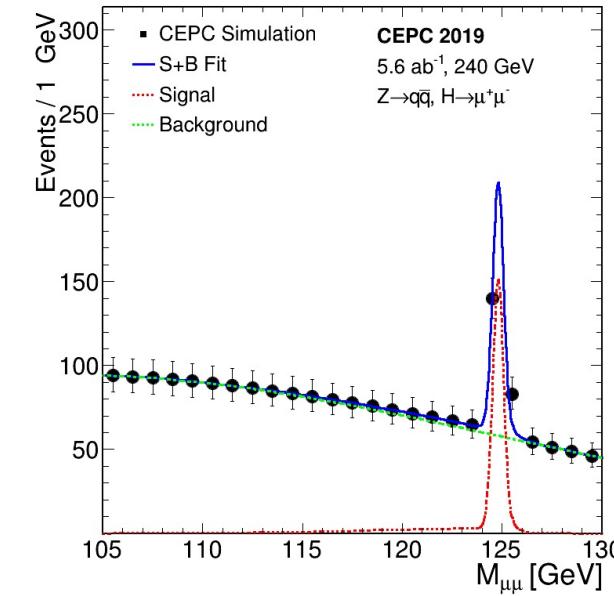
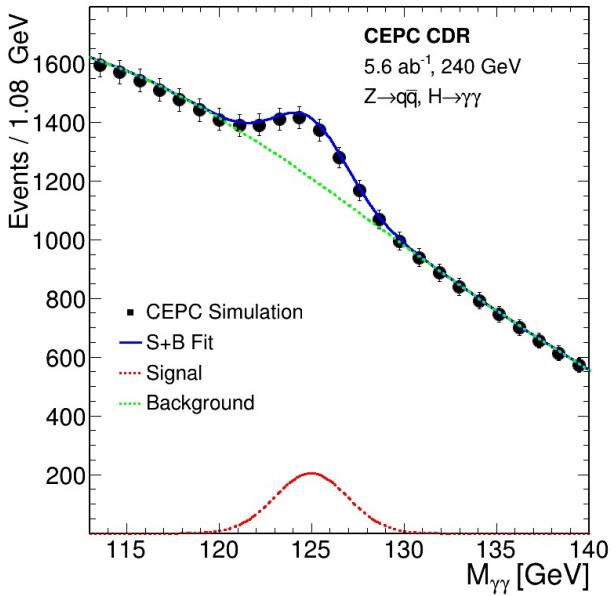
## Triple Higgs coupling:



# Combination/comparisons with HL-LHC



# Typical individual channels



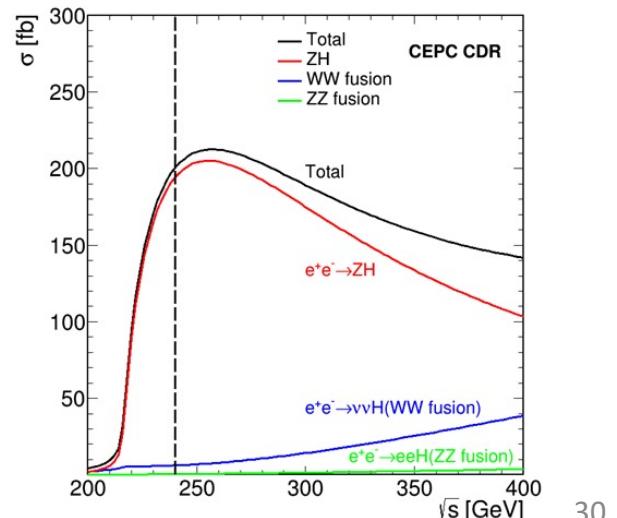
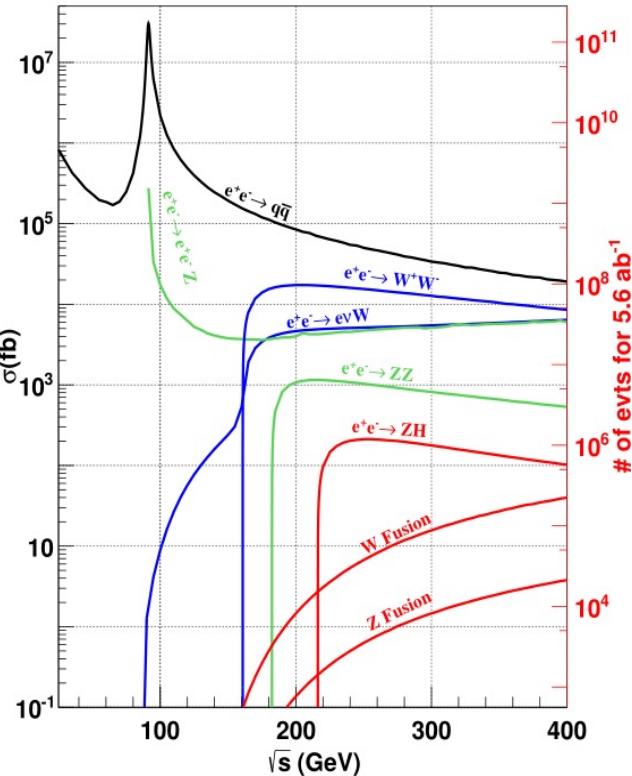
# Signal/bkg Cross Sections

Kaili Zhang

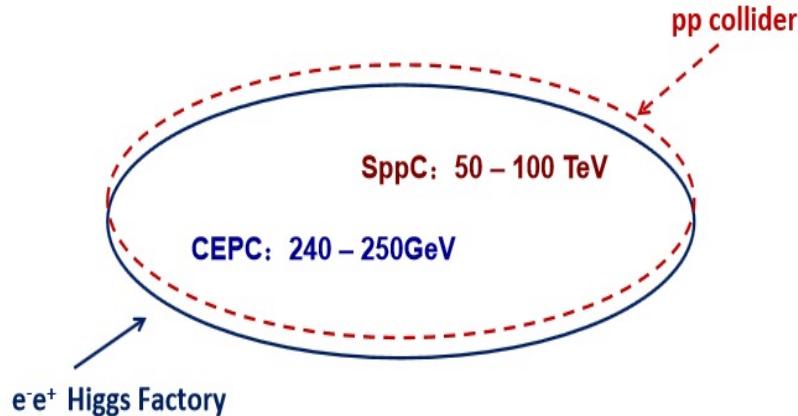
- 240GeV:
  - ZH: 196.9; vvH: 6.2; interference: ~10% of vvH; about 318:10:1; ( $Z \rightarrow vv$ )
- 360GeV: ( $vvh \sim 117\% Z \rightarrow vv$ ), ( $eeh \sim 67\% Z \rightarrow ee$ )

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<sup>-1</sup> for 10 years

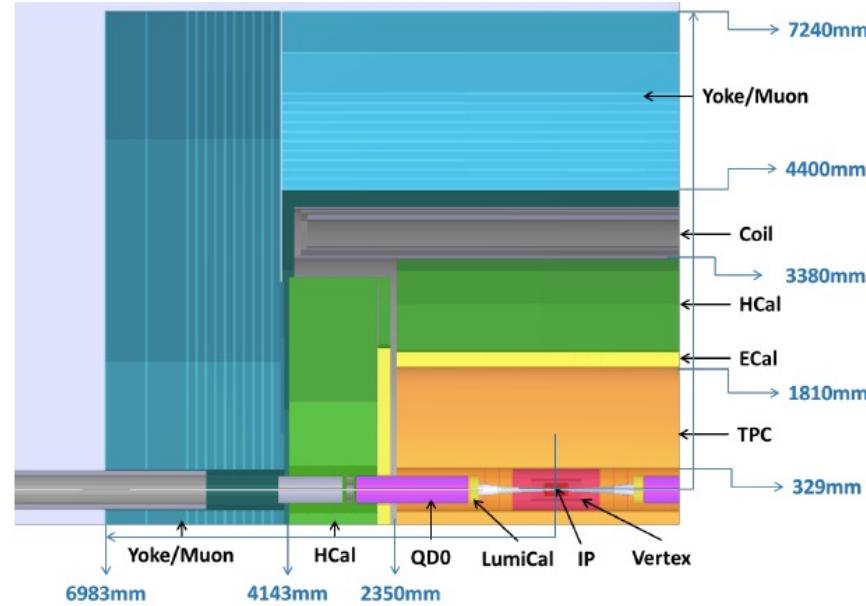


Table 2. Key characteristic/performance of a conceptual CEPC detector.

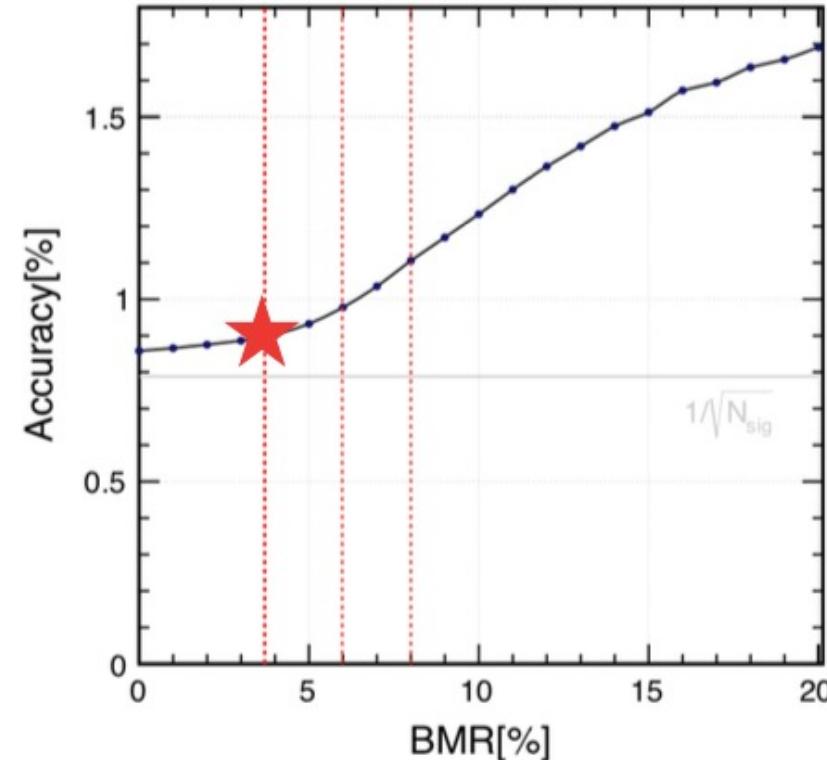
Geometry acceptance	TPC (97%), FTD (99.5%)
Tracking efficiency	~ 100% within geometry acceptance
Tracking performance	$\Delta(1/p_T) \sim 2 \times 10^{-5}$ (1/GeV)
ECAL intrinsic energy resolution	$16\%/\sqrt{E} \oplus 1\%$ (GeV)
HCAL intrinsic energy resolution	$60\%/\sqrt{E} \oplus 1\%$ (GeV)
Jet energy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

# Status of H- $\rightarrow\tau\tau$

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

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

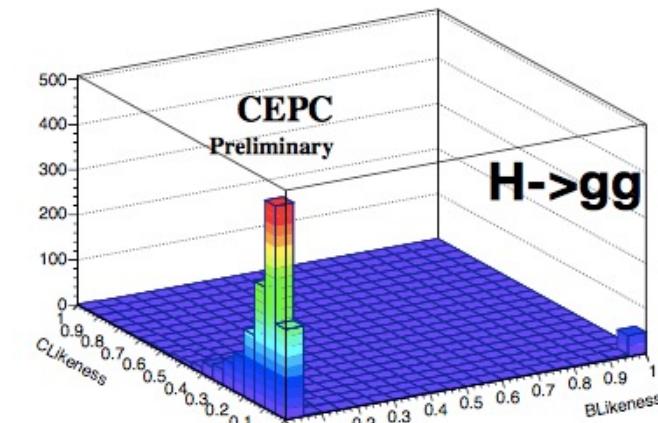
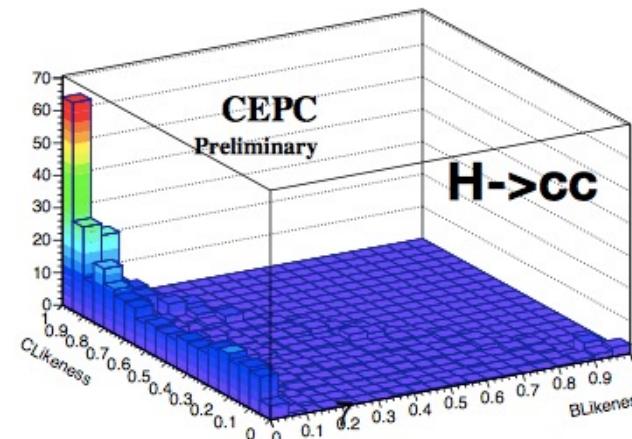
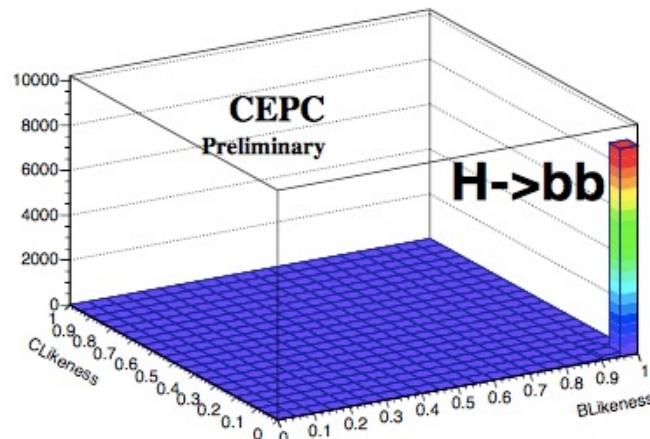
Dan Yu's [talk](#)



# Status of $H \rightarrow bb, cc, gg$

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

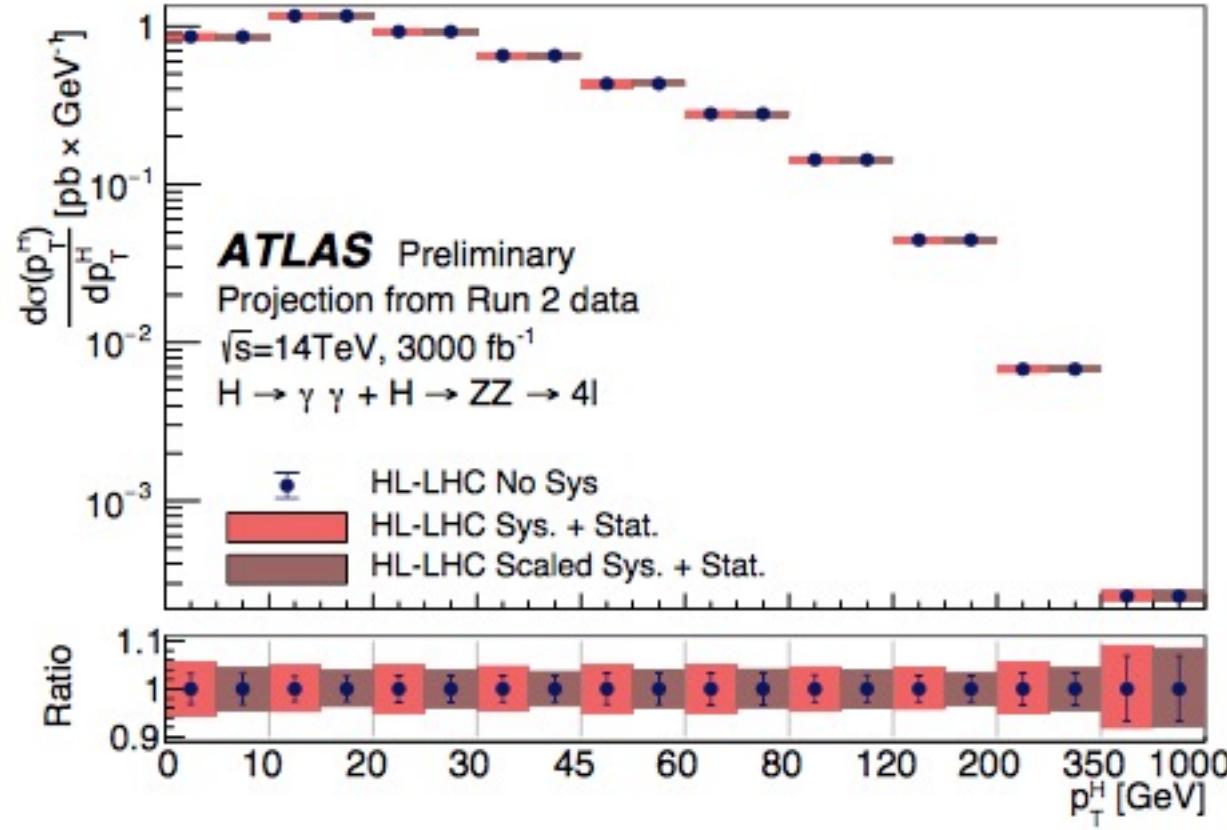
More at Yu Bai's talk



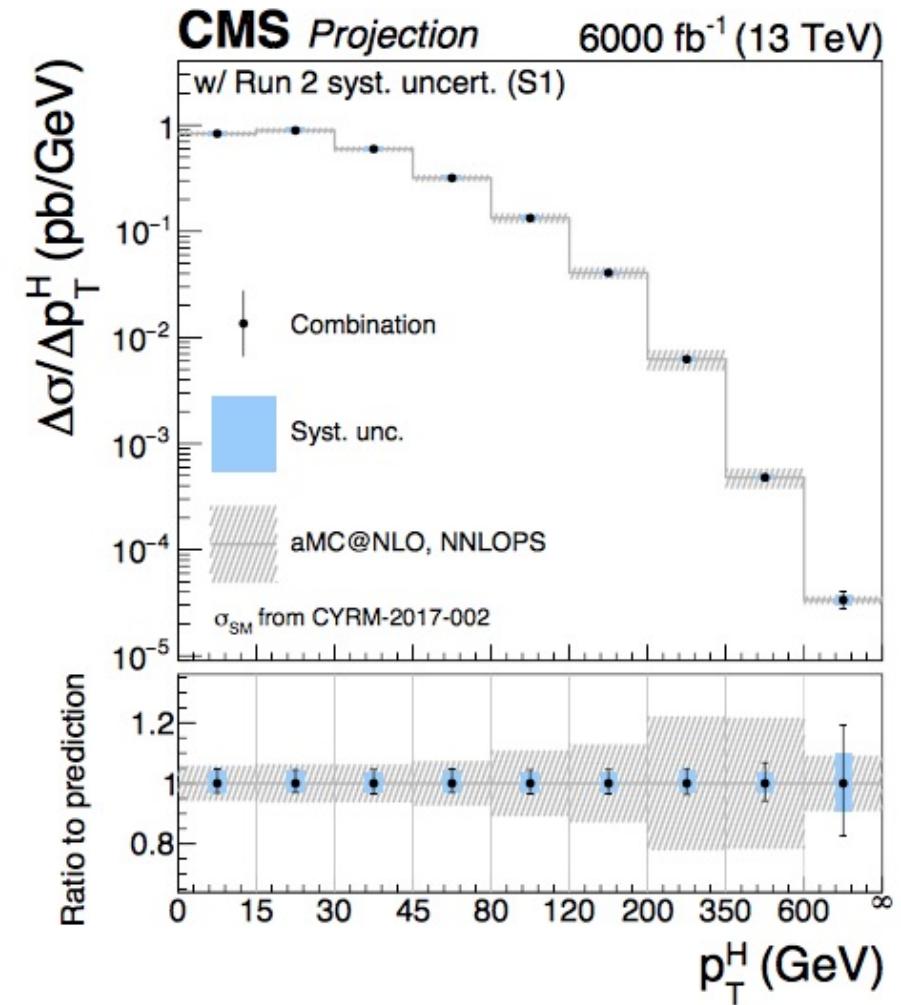
- Start to consider the systematics.

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

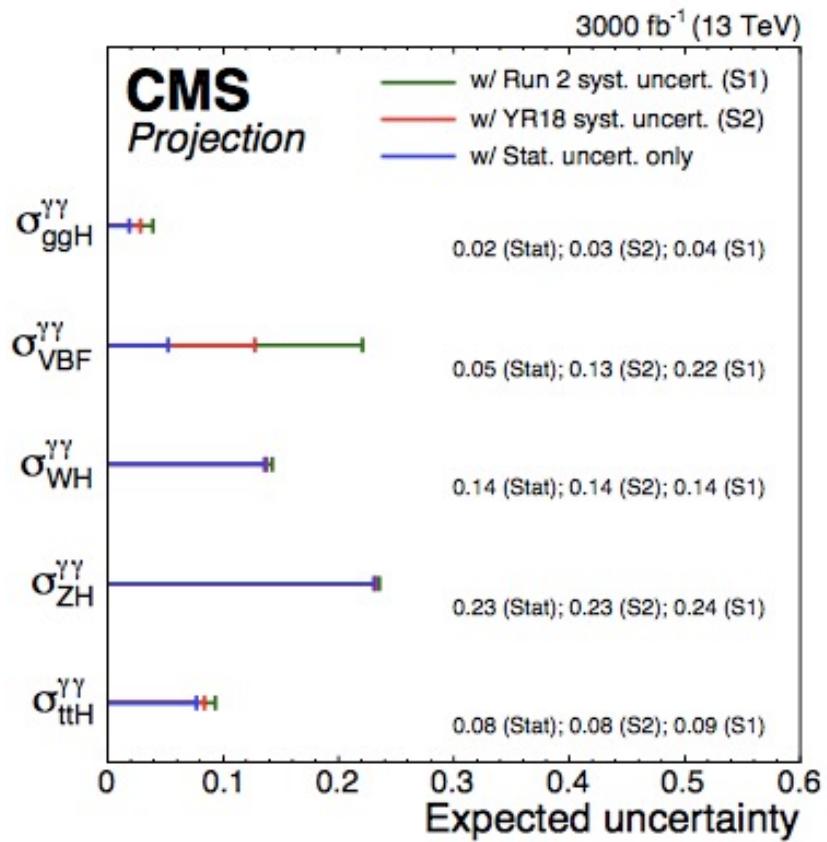
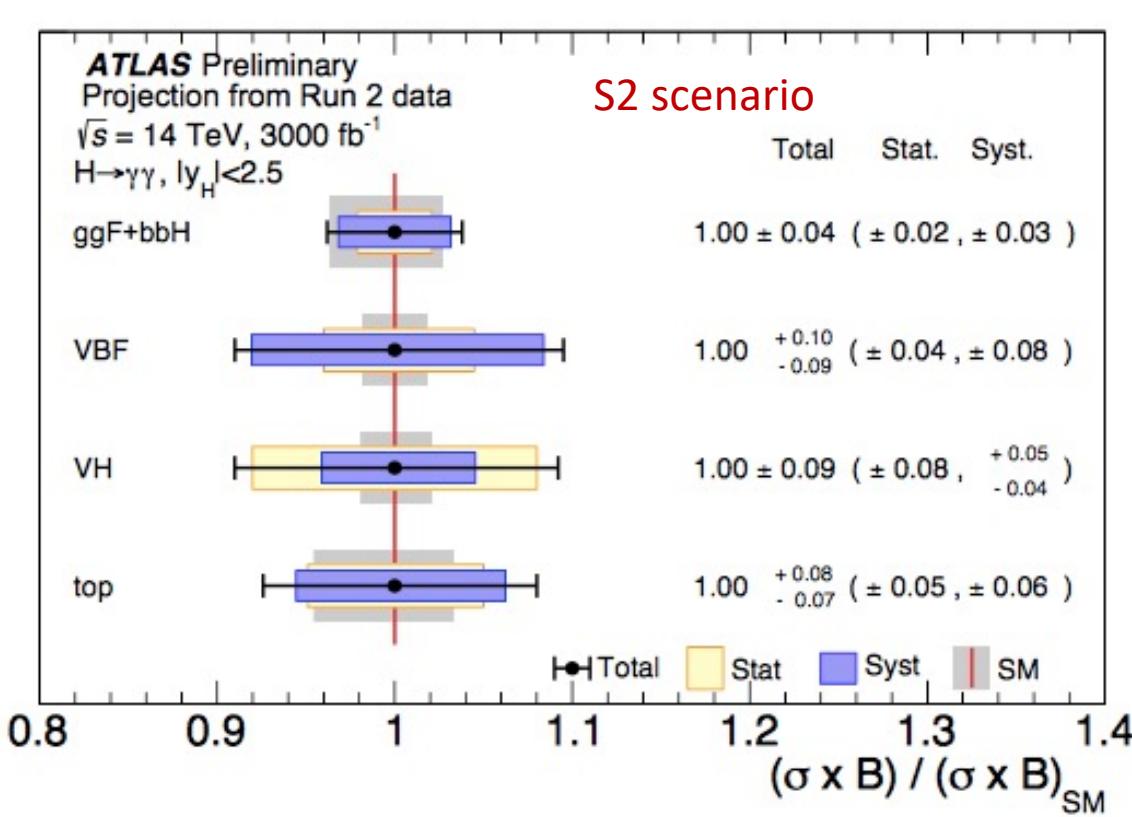
# HL-LHC: Differential xsection measurement



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



# HL-LHC H $\rightarrow\gamma\gamma$ : one example



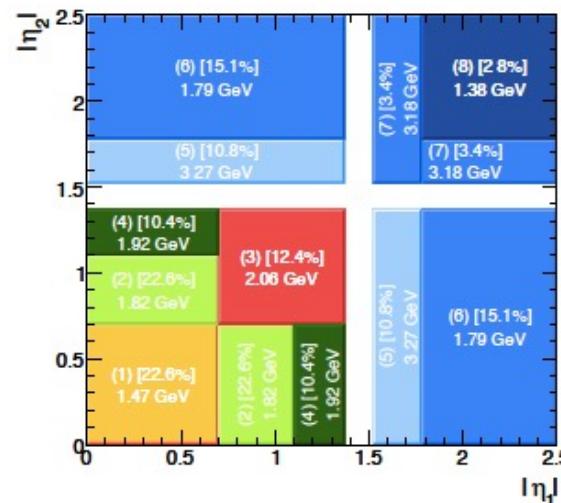
Scenario S1: Total uncertainty is half of the one used for the result of  $80 \text{ fb}^{-1}$ .

Scenario S2: Total uncertainty is  $1/3$  of the one for  $80 \text{ fb}^{-1}$ .

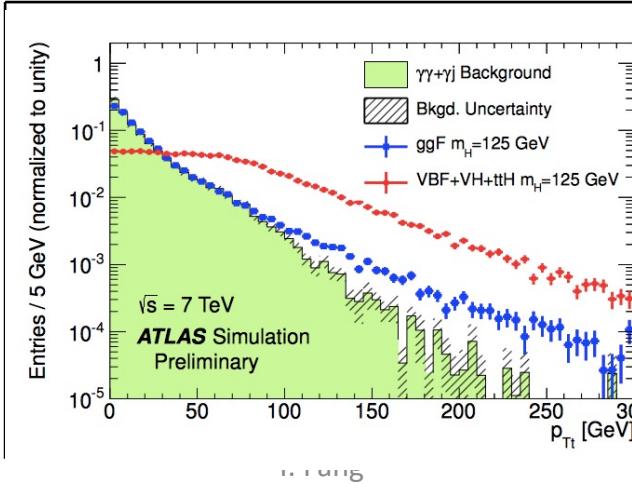
# HL-LHC H-> $\gamma\gamma$ : very advanced analyses (example)

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

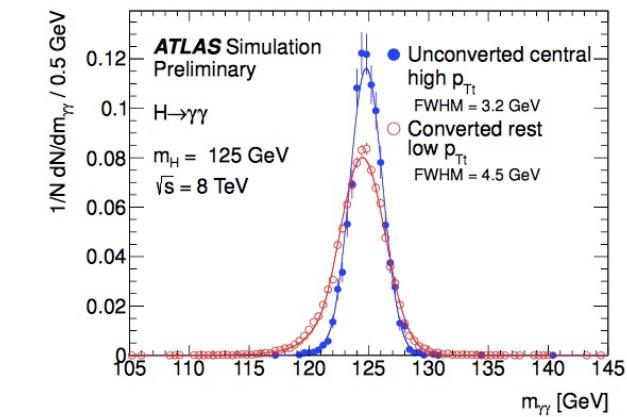
Divide different eta regions  
for two photons



$P_T$  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

## Precision Higgs Physics at the CEPC\*

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 Zhenwei Cui<sup>3</sup> Yaquan Fang<sup>4,6,34</sup> Chengdong Fu<sup>4</sup> Jun Gao<sup>10</sup> Yanyan Gao<sup>22</sup> Yuanning Gao<sup>3</sup>  
 Shao-Feng Ge<sup>15,29</sup> Jiayin Gu<sup>13</sup> Fangyi Guo<sup>1,4</sup> Jun Guo<sup>10</sup> Tao Han<sup>5,31</sup> Shuang Han<sup>4</sup>  
 Hong-Jian He<sup>11,10</sup> Xianke He<sup>10</sup> Xiao-Gang He<sup>11,10,20</sup> Jifeng Hu<sup>10</sup> Shih-Chieh Hsu<sup>32</sup> Shan Jin<sup>8</sup>  
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 Congqiao Li<sup>3</sup> Gang Li<sup>4,34</sup> Haifeng Li<sup>12</sup> Liang Li<sup>10</sup> Shu Li<sup>11,10</sup> Tong Li<sup>12</sup>  
 Qiang Li<sup>3</sup> Hao Liang<sup>4,6</sup> Zhijun Liang<sup>4,34</sup> Libo Liao<sup>4</sup> Bo Liu<sup>4,23</sup> Jianbei Liu<sup>1</sup>  
 Tao Liu<sup>14</sup> Zhen Liu<sup>26,30</sup> Xinchou Lou<sup>4,6,33,34</sup> Lianliang Ma<sup>12</sup> Bruce Mellado<sup>17,18</sup> Xin Mo<sup>4</sup>  
 Mila Pandurovic<sup>16</sup> Jianming Qian<sup>24</sup> Zhuoni Qian<sup>19</sup> Nikolaos Rompotis<sup>22</sup> Manqi  
 Lian-You Shan<sup>4</sup> Jingyuan Shi<sup>9</sup> Xin Shi<sup>14</sup> Shufang Su<sup>25</sup> Dayong Wang<sup>2</sup>  
 Lian-Tao Wang<sup>27</sup> Yifang Wang<sup>4,6</sup> Yuqian Wei<sup>4</sup> Yue Xu<sup>5</sup> Haijun Yang<sup>10</sup>

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V2 is at arxiv.

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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@mailist.ihep.ac.cn](mailto:cepc-physics@mailist.ihep.ac.cn)

# One example

ATLAS-CONF-2016-017

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Category	Events	$B_{90}$	$S_{90}$	$f_{90}$	$Z_{90}$	$S_{90}^{\text{fit}}$
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  $\sigma(ZH) \times \text{Br}(H \rightarrow \text{bb/cc/gg})$  is 0.3% 3.3% and 1.3%**

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

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

**I/H with 3D fit and systematic uncertainties considered:**

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

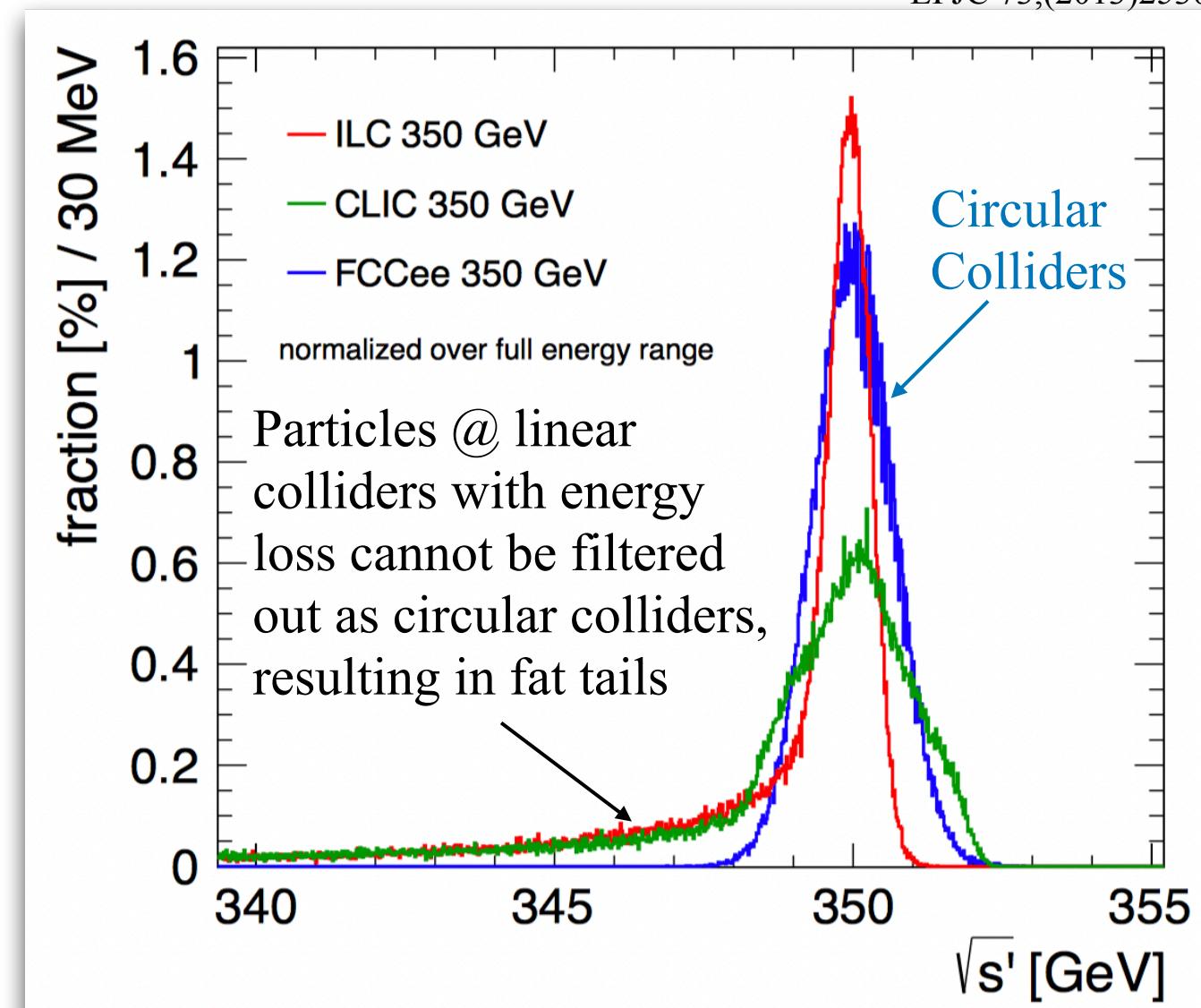
	$\mu^+ \mu^- H$			$e^+ e^- H$		
	$H \rightarrow b\bar{b}$	$H \rightarrow c\bar{c}$	$H \rightarrow gg$	$H \rightarrow b\bar{b}$	$H \rightarrow c\bar{c}$	$H \rightarrow gg$
Statistic Uncertainty	1.1%	10.5%	5.4%	1.6%	14.7%	10.5%
Fixed Background	-0.2% +0.1%	+4.1% -4.2%	7.6%	-0.2% +0.1%	+4.1% -4.2%	7.6%
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.**

# Advantages from circular colliders

EPJC 73,(2013)2530

- The luminosity spectrum at linear colliders is obviously worse than circular colliders given the particles with energy loss not being removed by the bending magnets
- This can substantially change the cross-section curve at around the  $t\bar{t}$  threshold

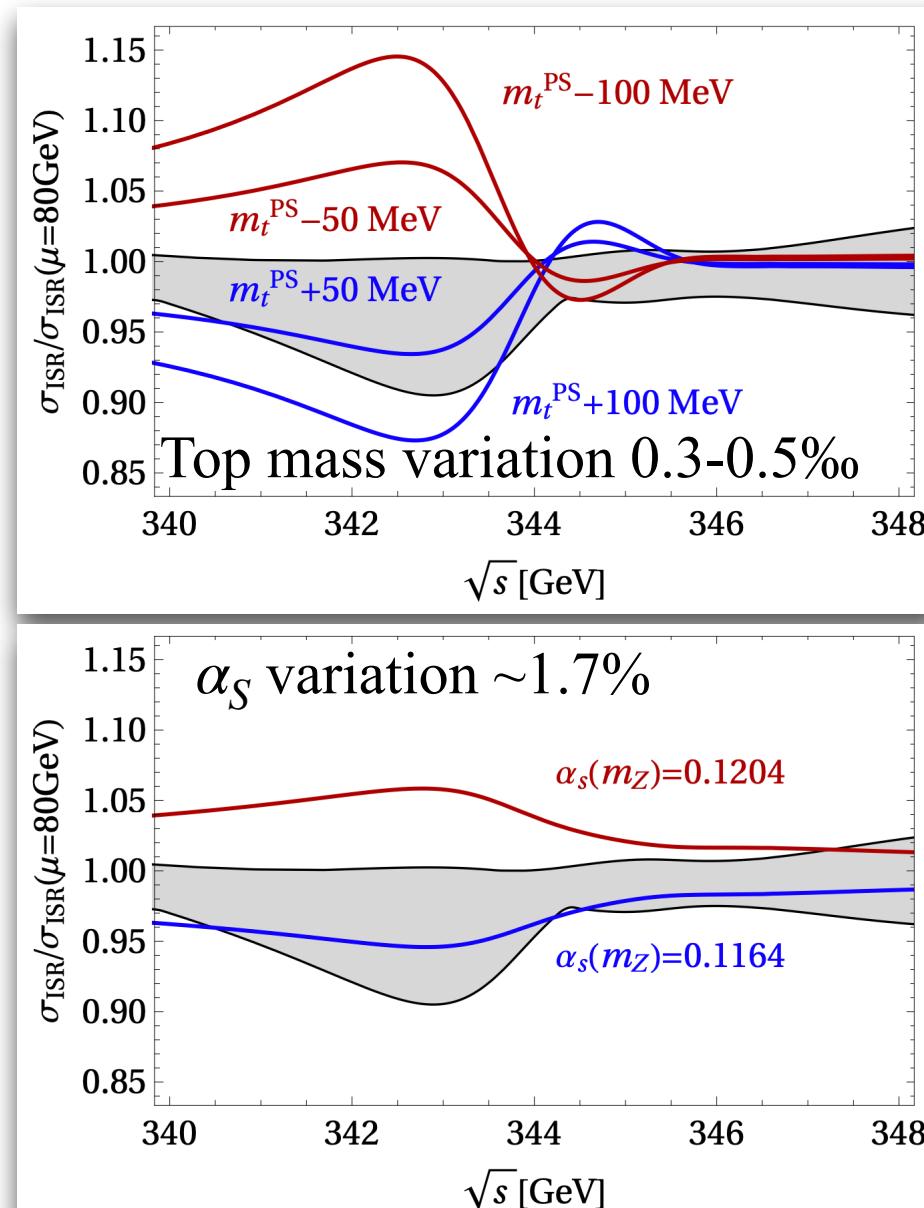


# Our setup

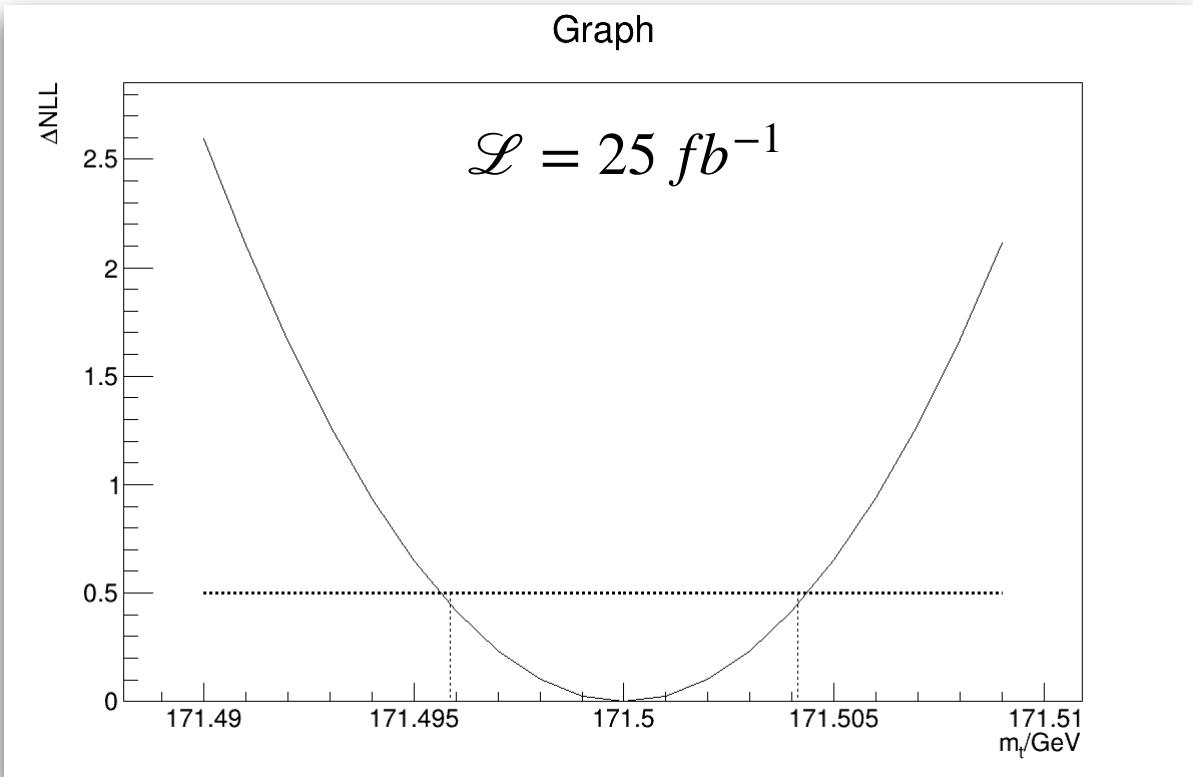
- Use the package “QQbar\_threshold” to calculate cross-section near threshold in ee-colliders at N<sup>3</sup>LO in resummed non-relativistic perturbation theory
  - Coulomb interactions between the quark and the antiquark leading to a strong enhancement of the cross section is included
- To avoid IR renormalon ambiguities, the PS shift (PSS) mass scheme is applied by default in the package

$$m_t^{\text{PS}} = 171.5 \text{ GeV}, \quad \alpha_s(m_Z) = 0.1184$$

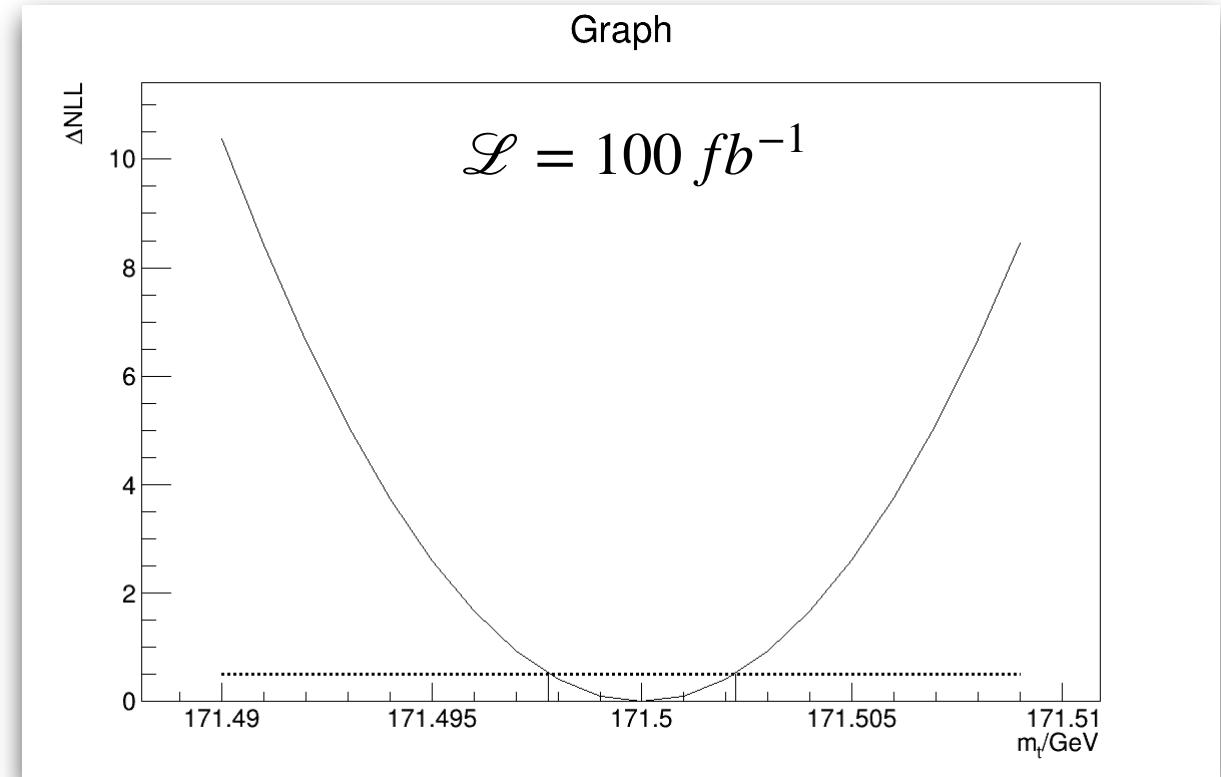
- ISR effects are also included in the package
- We incorporate luminosity spectrum by a simple Gaussian function with 1 GeV as the energy resolution at the moment



# 8- $\sqrt{s}$ scheme

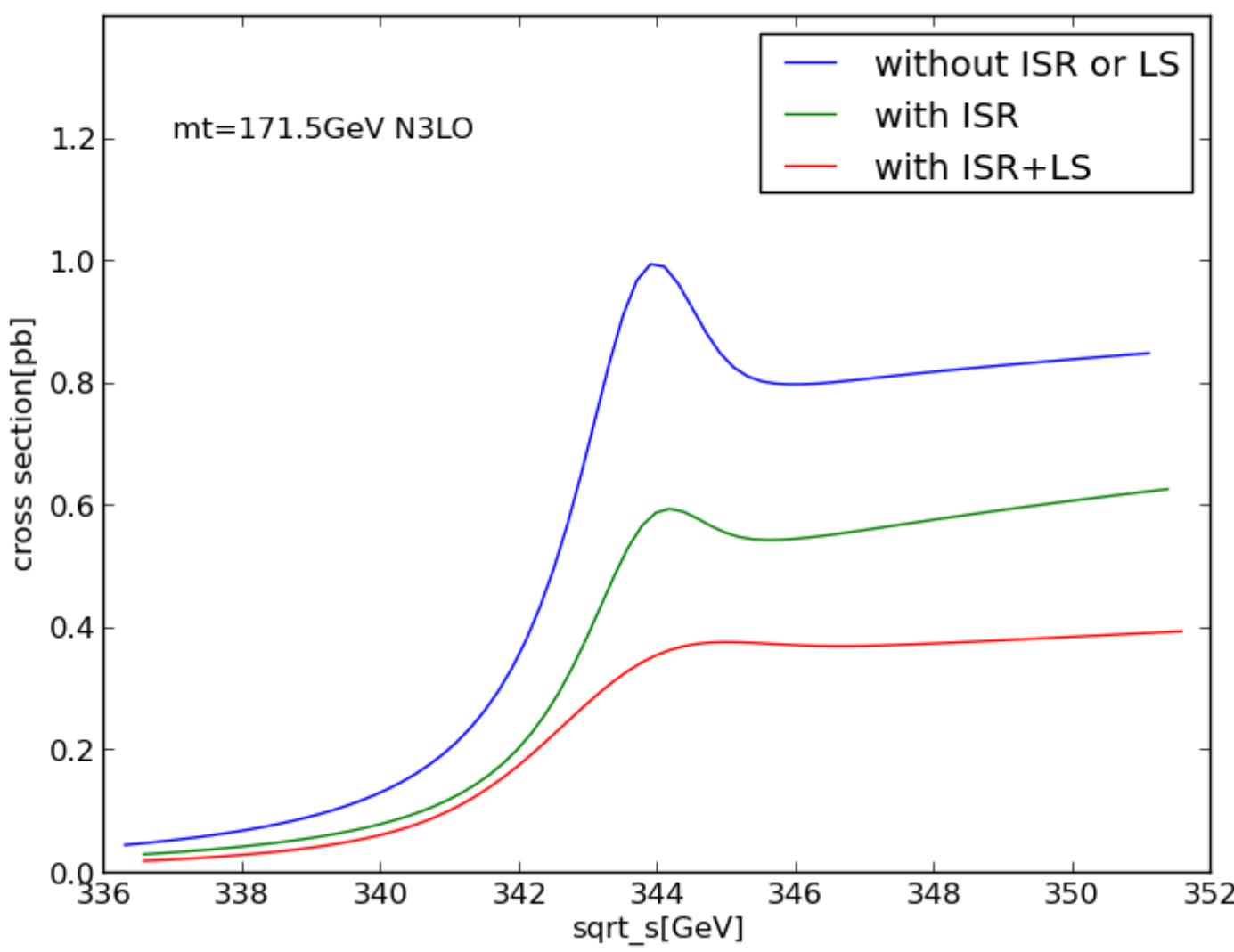


$$\sigma(m_{top}) = 4.1 \text{ MeV}$$



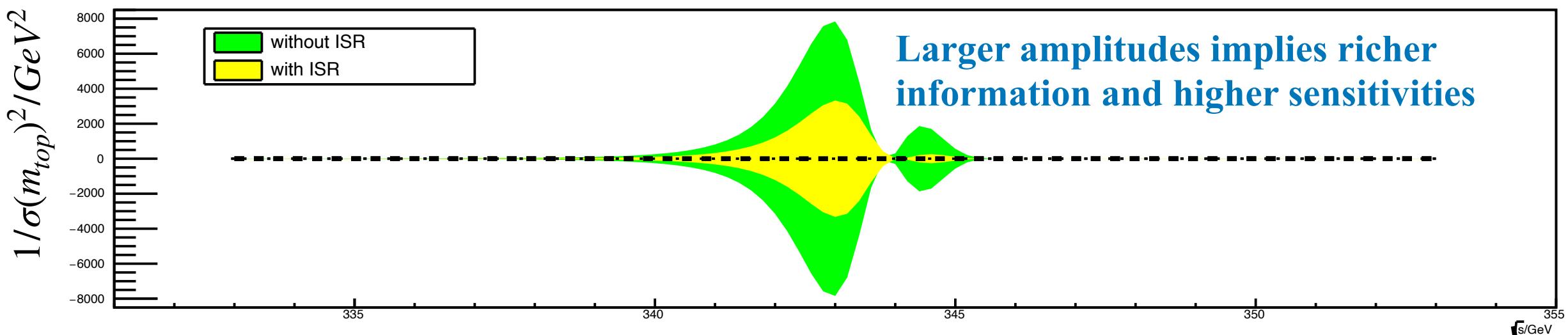
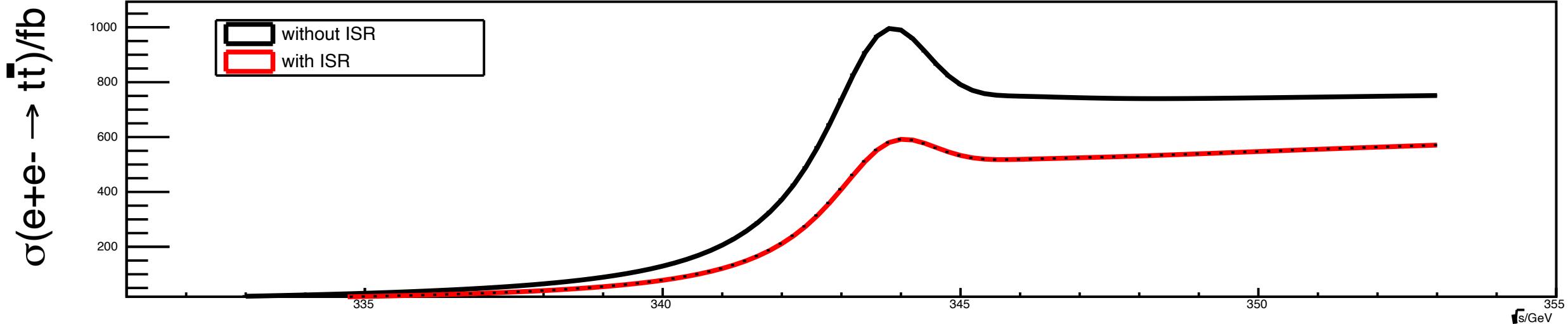
$$\sigma(m_{top}) = 2.2 \text{ MeV}$$

# ISR and LS effects

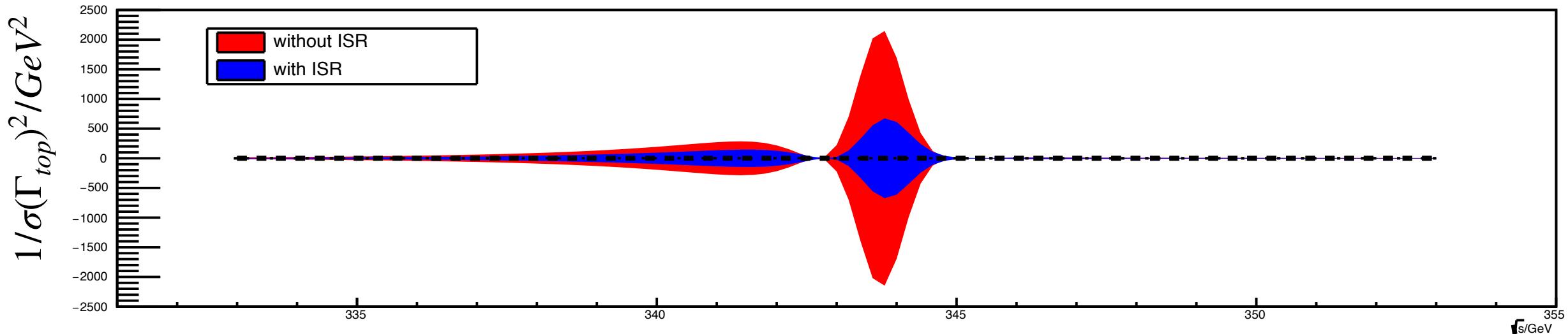
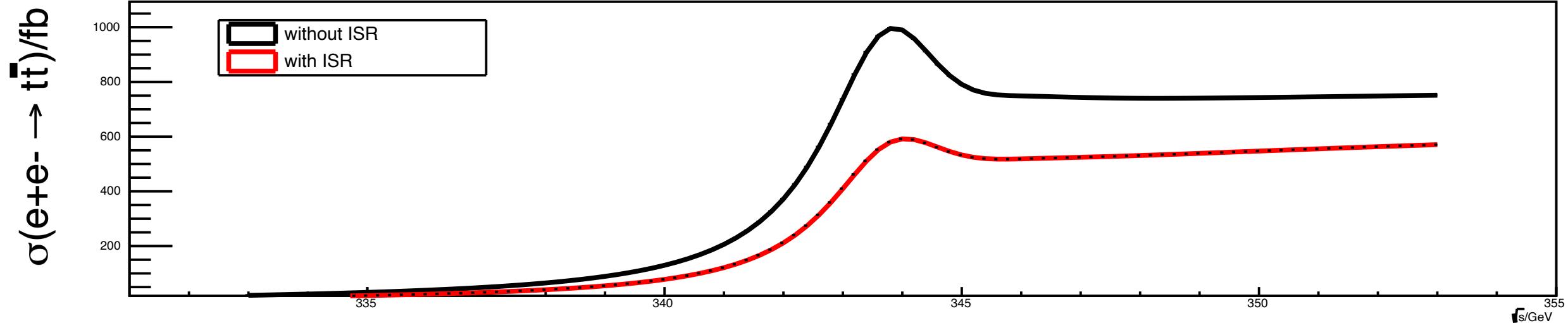


- The cross section as a function of centre-of-mass energy
  - A clear peak of production can be seen at around the  $t\bar{t}$  threshold
  - Adding ISR and LS (1 GeV width), the position of peak is hardly affected, but the sharpness is weakened and the total rate is suppressed in this region

# Fisher information



# Fisher information



# $\sqrt{s}$ scan points

- Test with a series of centre-of-mass energy grids
  - 4- $\sqrt{s}$  scheme = {341.5,342.5,343,344.5} GeV
  - 6- $\sqrt{s}$  scheme = {341,342,342.5,343,343.5,344.5} GeV
  - 8- $\sqrt{s}$  scheme = {340,341,342,342.5,343,343.5,344.5,345} GeV
- Top mass is assumed as 171.5 GeV; the acceptance and efficiency is assumed to be 100% at the moment; ISR is considered; but LS is yet to be included
- Luminosity per scan point is assumed to range from 25/fb to 100/fb
- A likelihood is constructed to combine the statistical power of all scan points

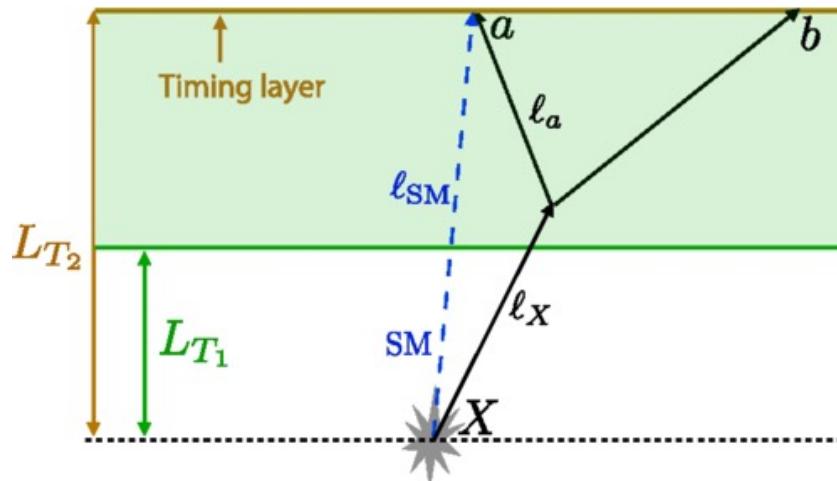
$$L = \prod_i P(\vec{D}_i | \vec{E}_i(\sigma(m_{top}, \Gamma_{top}, \alpha_S, \sqrt{s}), \mathcal{L}_i, \vec{\theta})) \quad i \text{ corresponds to the } i\text{-th } \sqrt{s} \text{ scan point}$$

# What is a long-lived particle?

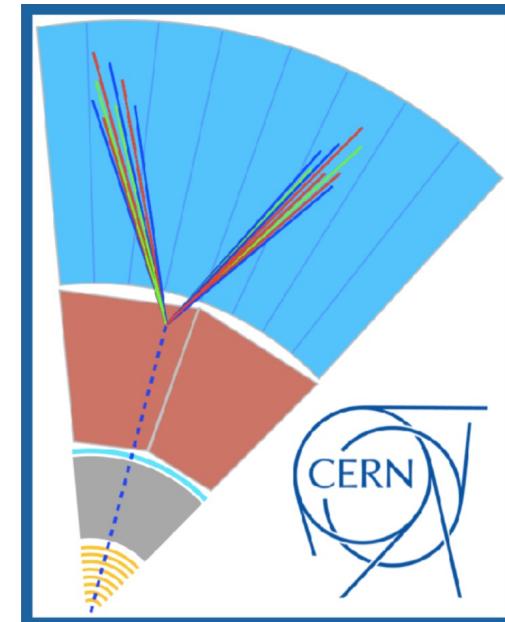
*Object (neutral or charged) decaying a **macroscopic** and **reconstructible** distance from IP*

Signal signature of a long-lived particle:

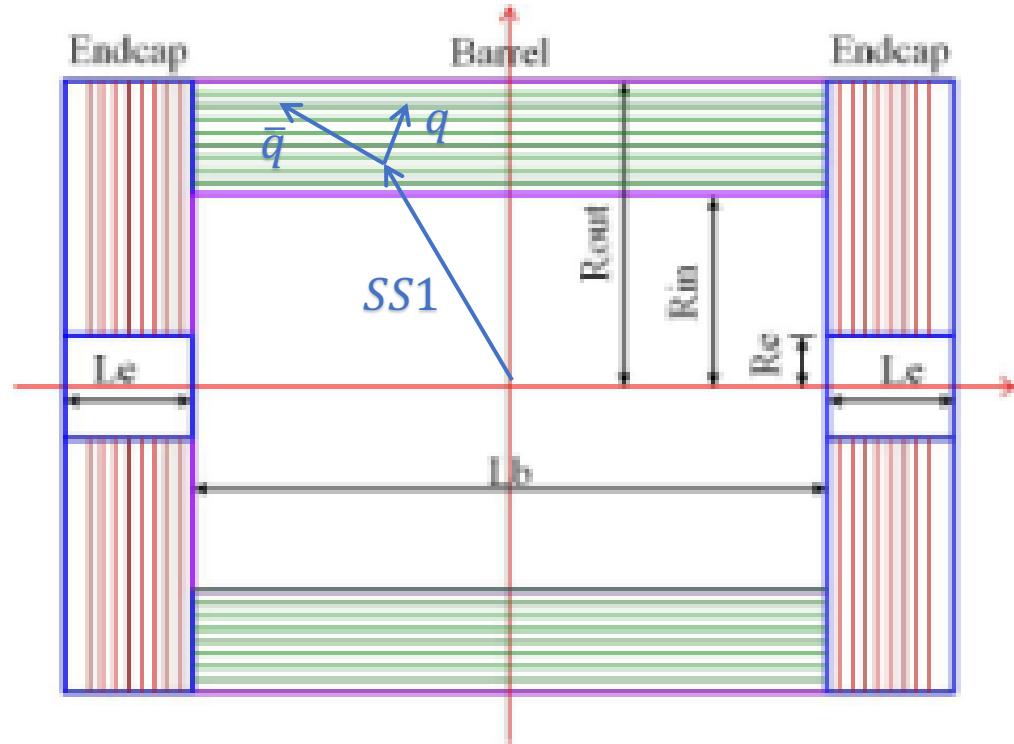
Neutral LLP decays are a spectacular signature, and the **burst of energy** appearing out of nowhere sets it apart from the collision point.



Phys. Rev. Lett. **122**, 131801 – 2019.04.03



# Basic Setup



- Muon Detector
  - $R_{in} \approx 4m$
  - $R_{out} \approx 6m$
- $\Delta t = t_{\text{Hit}} - r_{\text{Hit}}/c$
- Dominant Background
  - $e^+e^- \rightarrow ZH$
  - $e^+e^- \rightarrow qq$
- **Full simulation** with CEPC official software

# Expected Limits for LLPs

	Signal	Total Background	Expected Limits
$e^+e^- \rightarrow Zh \rightarrow (Z:\bar{q}q)\bar{q}q\bar{\nu}\nu$	373308	0.02 (CR)	$2.4 \times 10^{-5}$
$e^+e^- \rightarrow Zh \rightarrow (Z:\bar{\nu}\nu)\bar{q}q\bar{\nu}\nu$	87,050	0.02 (CR)	$9.8 \times 10^{-5}$
<b>Combined limit: <math>1.9 \times 10^{-5}</math></b>			

- Limits are the minimal branching ratio of Higgs decaying to LLPs (the smaller the better).
- Cosmic Ray(CR) veto efficiency is calculated by the filter that the time difference of two clusters on the outermost cell must be less than 2.4 meters. ( signal inefficiency~ 2.1%)
- Signal Yield:  $n_s = \mathcal{L} \times \sigma(e^+e^- \rightarrow Zh) \times \sigma(Z \rightarrow q\bar{q}, \bar{\nu}\nu) \times \epsilon_{sig} \times \epsilon_{CR}$

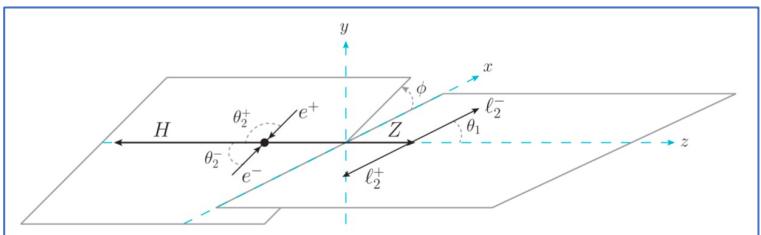
# Theory model

[JHEP 03\(2016\) 050](#)

[JHEP 11\(2014\) 028](#)

- Differential cross section for  $ee \rightarrow ZH \rightarrow llH$  :

$$\frac{d\sigma}{dcos\theta_1 dcos\theta_2 d\phi} = \frac{\mathcal{N}_\sigma(q^2)}{m_H^2} \mathcal{J}(q^2, \theta_1, \theta_2, \phi),$$
$$\mathcal{N}_\sigma(q^2) = \frac{1}{2^{10}(2\pi)^3} \cdot \frac{1}{\sqrt{r}\gamma_Z} \cdot \frac{\sqrt{\lambda(1,s,r)}}{s^2}$$



$$\begin{aligned} \mathcal{J}(q^2, \theta_1, \theta_2, \phi) = & J_1(1 + \cos^2 \theta_1 \cos^2 \theta_2 + \cos^2 \theta_1 + \cos^2 \theta_2) \\ & + J_2 \sin^2 \theta_1 \sin^2 \theta_2 + J_3 \cos \theta_1 \cos \theta_2 \\ & + (J_4 \sin \theta_1 \sin \theta_2 + J_5 \sin 2\theta_1 \sin 2\theta_2) \sin \phi \\ & + (J_6 \sin \theta_1 \sin \theta_2 + J_7 \sin 2\theta_1 \sin 2\theta_2) \cos \phi \\ & + J_8 \sin^2 \theta_1 \sin^2 \theta_2 \sin 2\phi + J_9 \sin^2 \theta_1 \sin^2 \theta_2 \cos 2\phi. \end{aligned}$$

Variables for studying distribution:  $\theta_1, \theta_2, \phi$

## Efficiency matrix determined by DL multi-classification

$$\begin{pmatrix} n_1 \\ n_2 \\ \vdots \\ n_9 \end{pmatrix} = \begin{pmatrix} \epsilon_{11} & \epsilon_{12} & \cdots & \epsilon_{19} \\ \epsilon_{21} & \epsilon_{22} & \cdots & \epsilon_{29} \\ \vdots & \vdots & \ddots & \vdots \\ \epsilon_{91} & \epsilon_{92} & \cdots & \epsilon_{99} \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \\ \vdots \\ N_9 \end{pmatrix}$$

“on-shop” measurement: 9 quantities  
more efficient, better precision