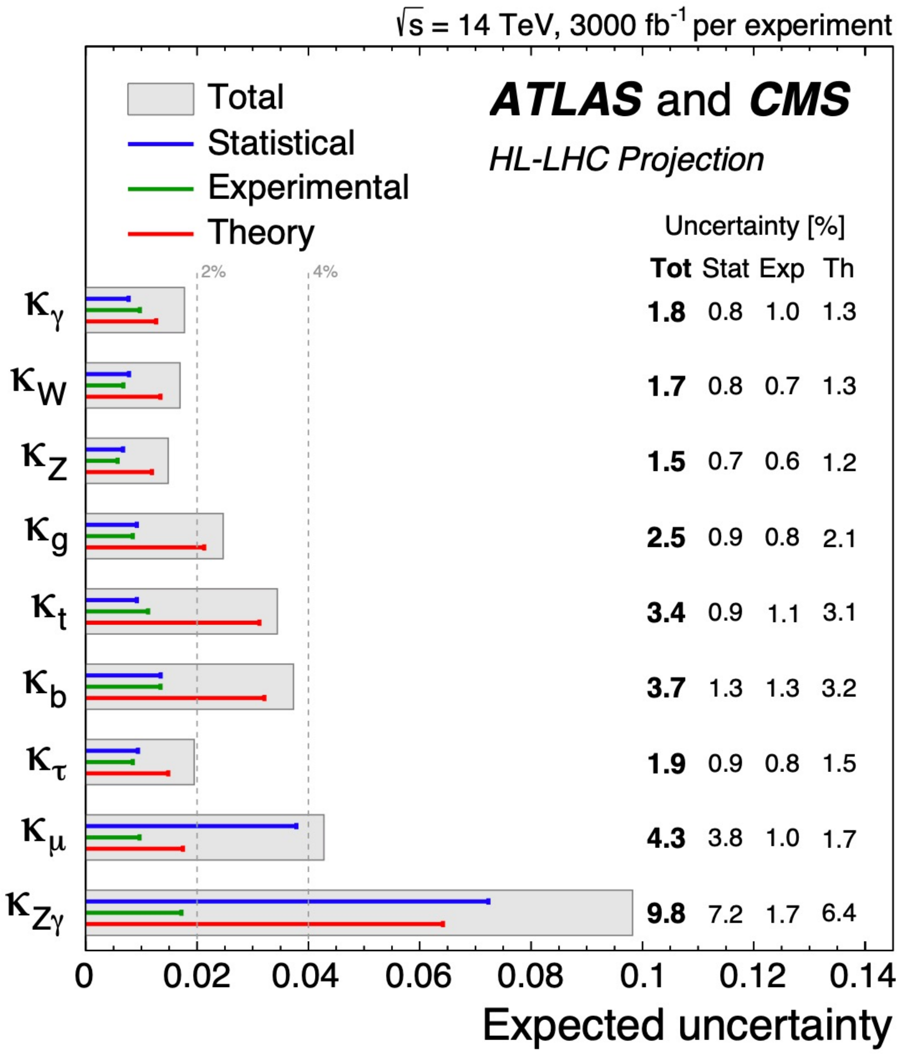
The Precision of Higgs Measurement at CEPC

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

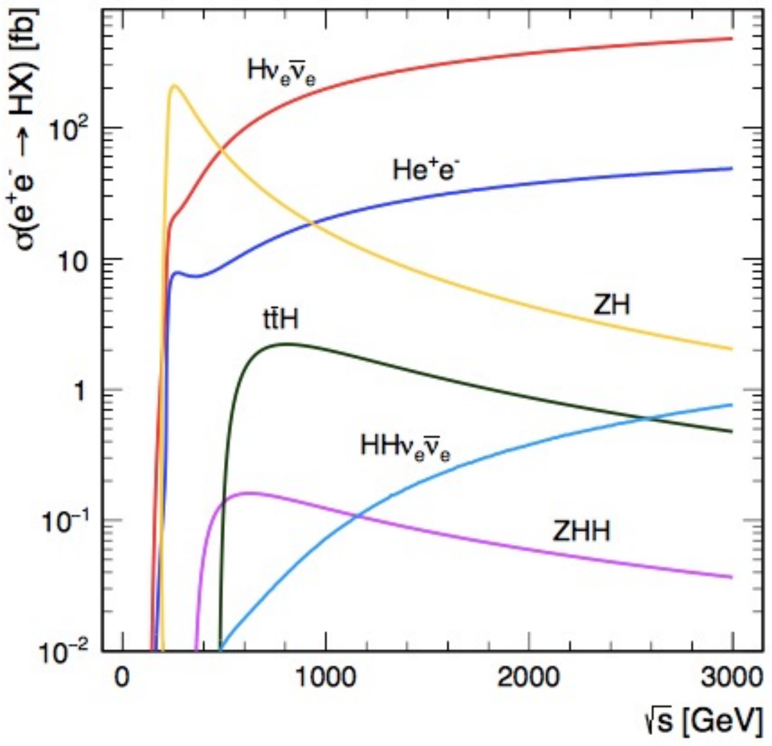
SUSY2021
August 23-28, 2021
Chengdu, China

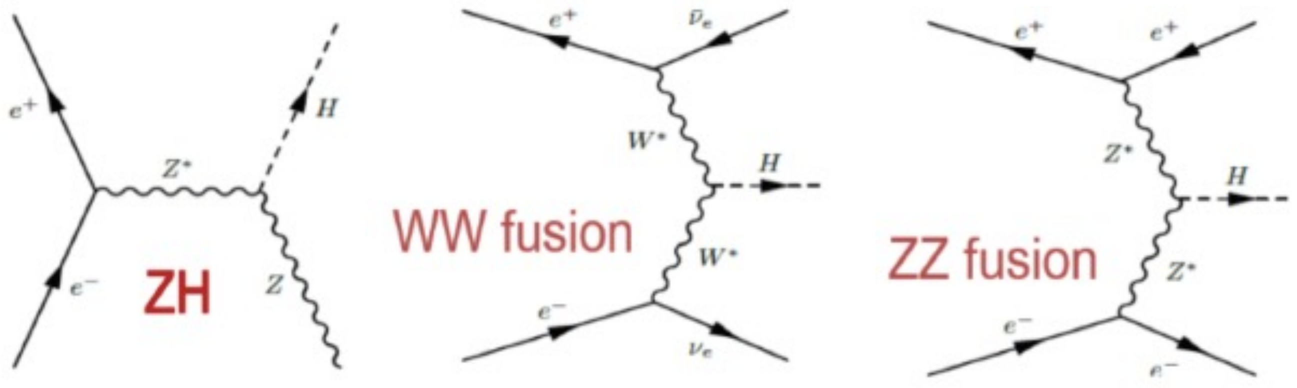
Why do we need e^+e^- collider



- LHC and HL-LHC is a discovery machine at TeV scale:
  - The precisions of measurements of Higgs coupling with HL-LHC are at the level of a few percent.
  - Theoretical uncertainties start to be the dominant one.
- If the new physics is at the sub-percent level, need e^+e^- machine to precisely measure Higgs properties as well as explore new physics.
  - Complementary to LHC.

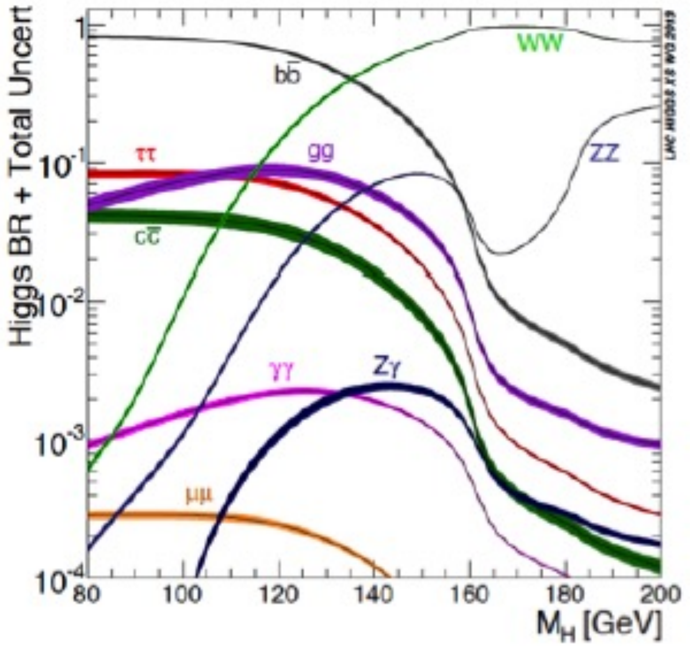
Higgs related physics at e^+e^- collider

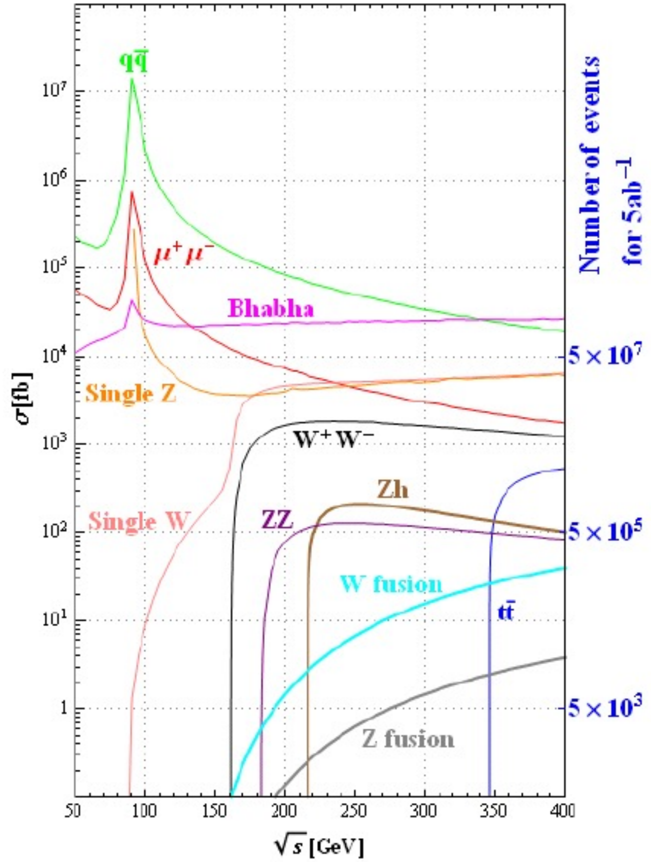




- With the increase of the energy, different Higgs related physics can be explored at e^+e^- collider.
- With the energy around 240 GeV, ZH as well as ww/zz fusion can be intensively studied.
  - the dominant production is from HZ, the WW/ZZ fusions contribute a few percent of the total cross-section.

SM Higgs decay branching ratio, Bkg process

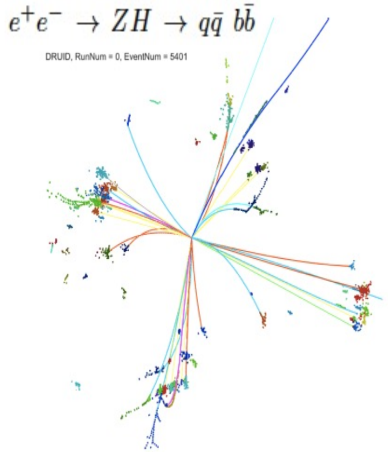


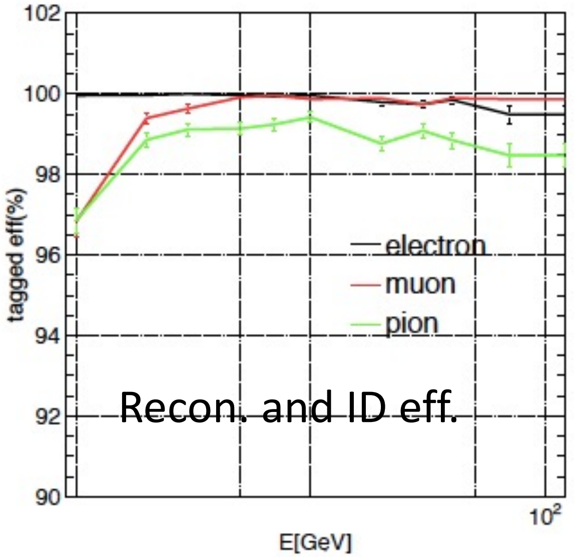


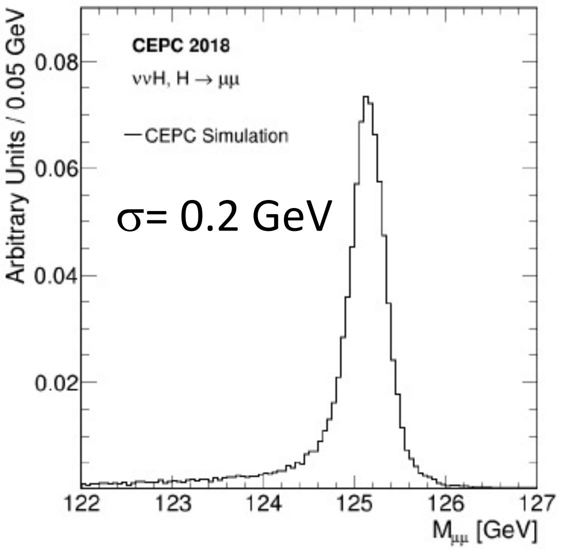
✓ **e^+e^- collider provides a good opportunity to measure the jj, invisible decay of Higgs.**

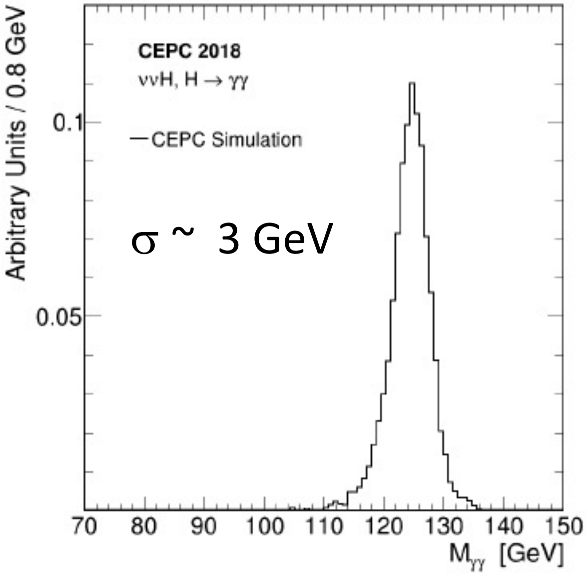
✓ **For 5.6 ab^{-1} data with CEPC, 1M Higgs, 10M Z, 100M W are produced.**

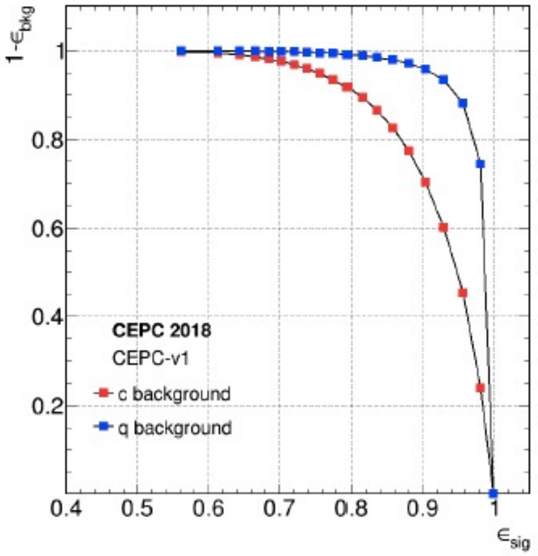
Performance



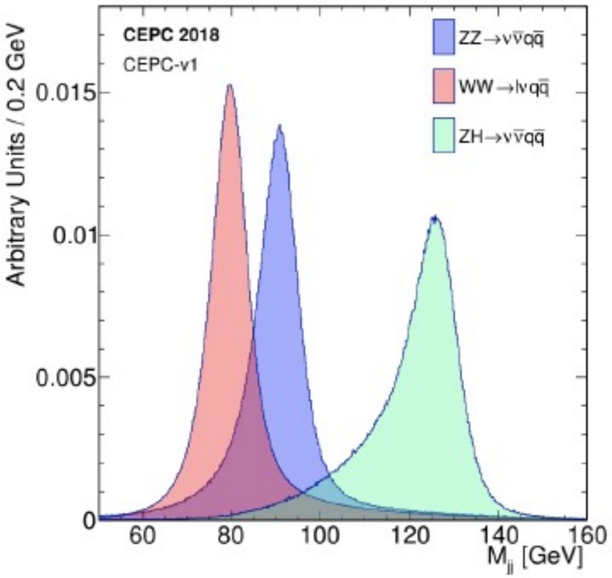






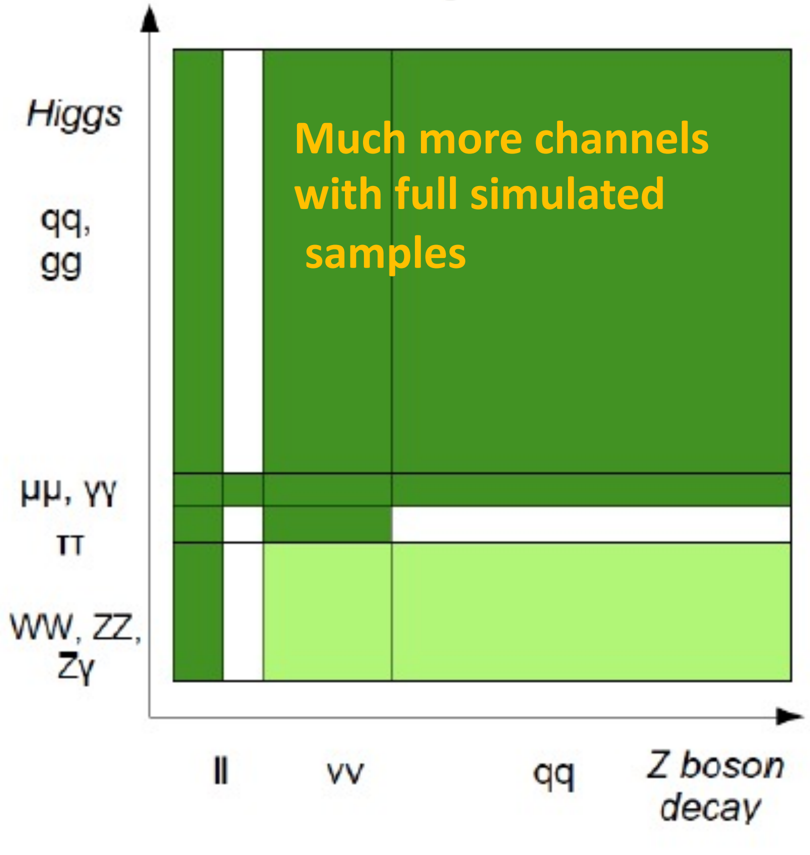


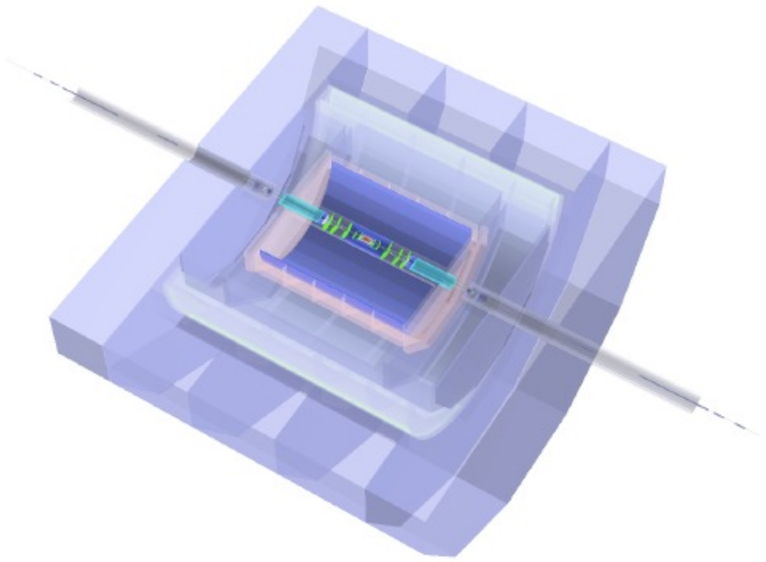
B-tagging eff. vs rejection of other jets



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

Higgs analyses @CEPC CDR

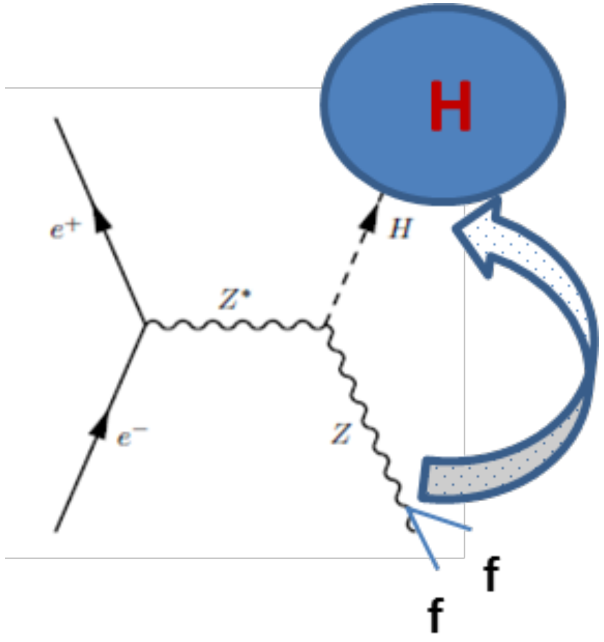




A lot of decay channels can be investigated.

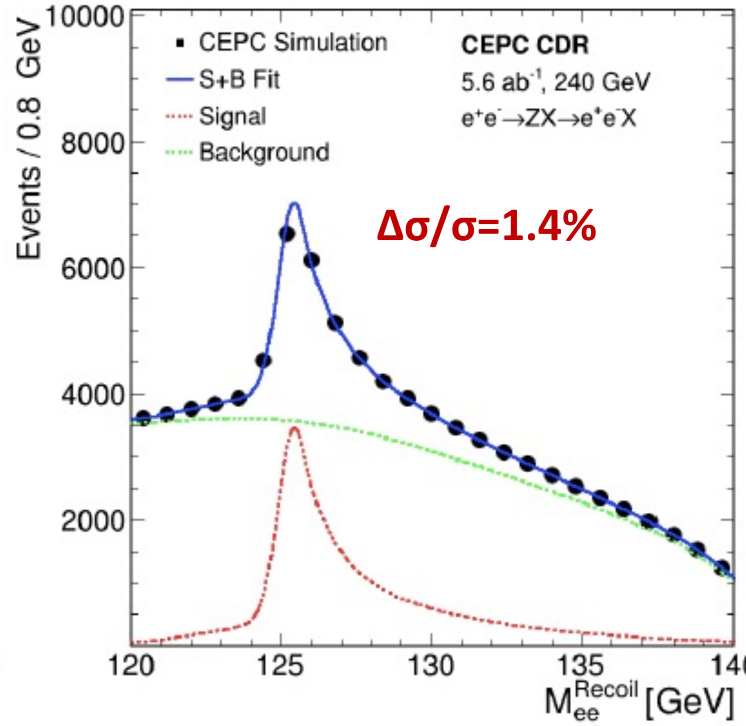
Direct measurement of Higgs cross-section

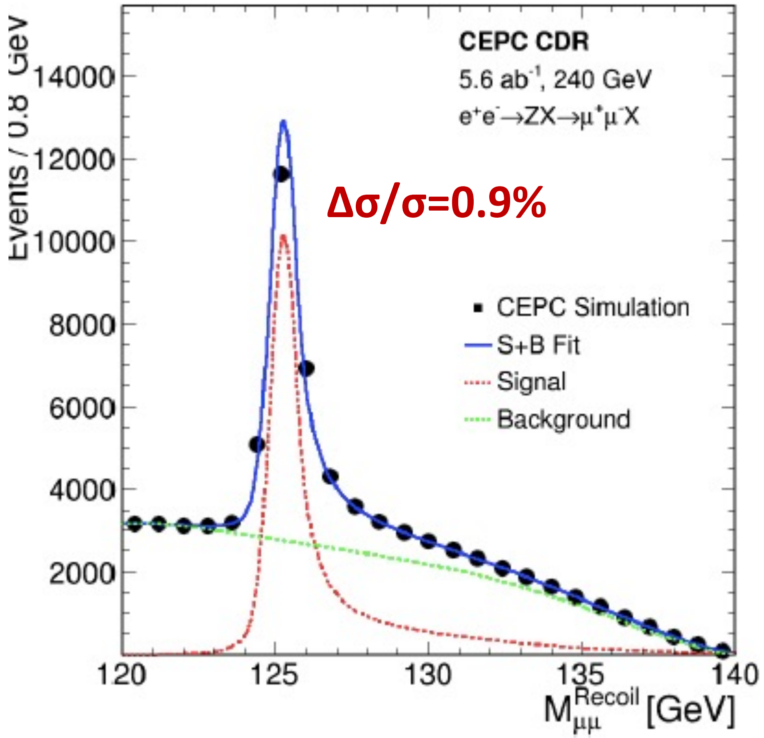
$$M^2_{\text{recoil}} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$

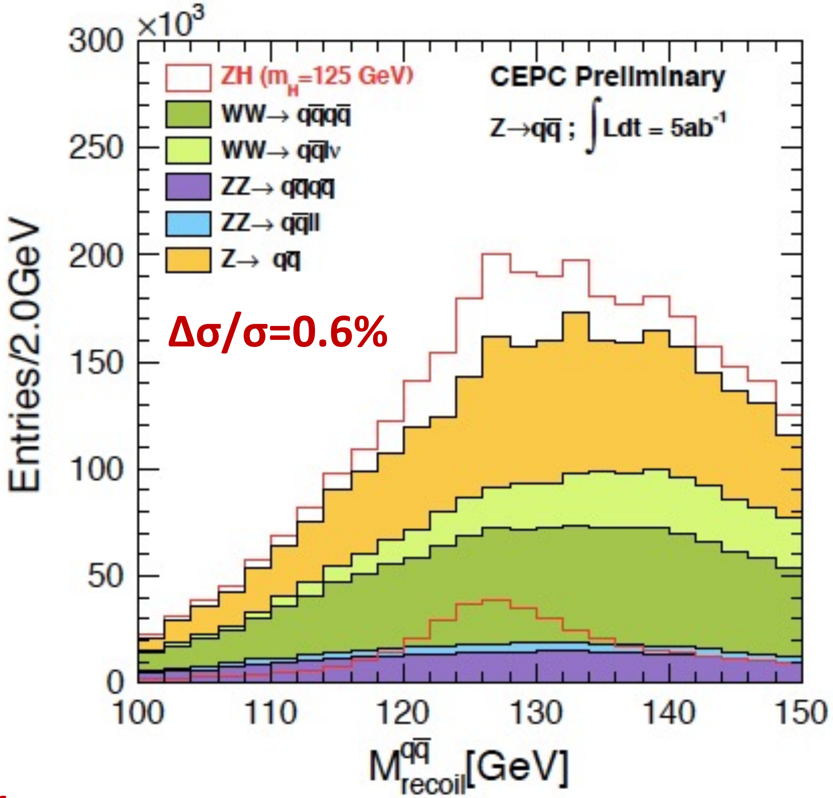


- ✓ **For this model independent analysis, we reconstruct the recoil mass of Z without touching the other particles in a event.**
- ✓ **The M_{recoil} should exhibit a resonance peak at m_H for signal; Bkg is expected to smooth.**
- ✓ **The best resolution can be achieved from $Z(\rightarrow e^+e^-,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

Direct measurement of Higgs cross-section and m_H







- ✓ **The combined precision with three channels is $\Delta\sigma/\sigma=0.5\%$**
- ✓ **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 σ(ZH) and Br. of (H->ZZ*)**

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

Precision : 5.1%

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

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

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

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

3.0%

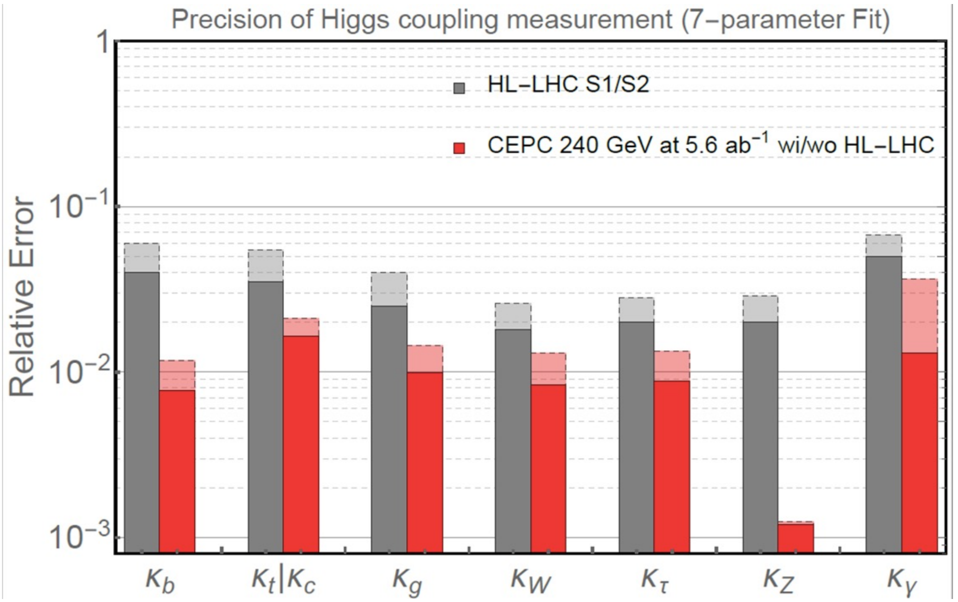
Precision : 3.5%

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

Combined Precision : 2.9%

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%



- ✓ 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

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

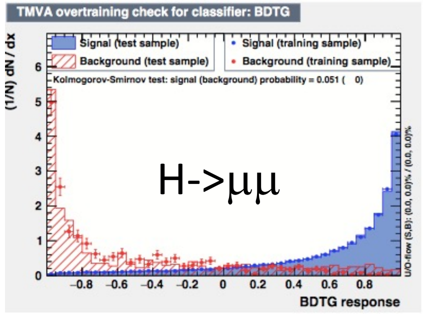
Fcc-ee 240 GeV/365 GeV:
CERN-ACC-2018-0057

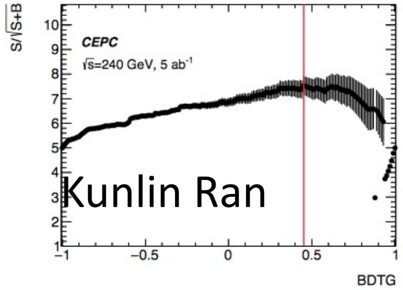
$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \to any$	±0.5		±0.9	
$H \to b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H \to c\bar{c}$	±2.2		±6.5	±10
$H \to gg$	±1.9		±3.5	±4.5
$H \to W^+W^-$	±1.2		±2.6	±3.0
$H \to ZZ$	±4.4		±12	±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

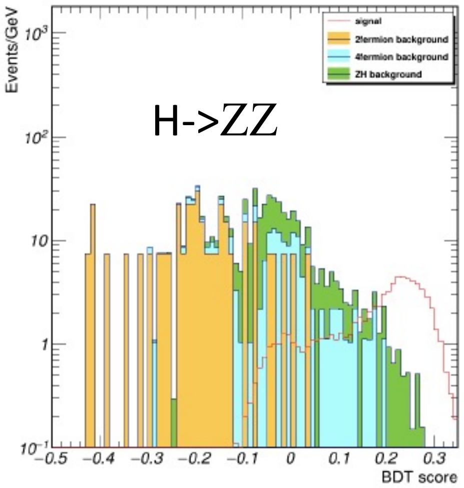
- After training with 6 variables: $cos\theta_{ee}$, $cos\theta_{\mu\mu}$, $\Delta_{\mu,\mu}$, M_{qq}, E_{ee}, $E_{qq\mu\mu}$, get the BDTG response

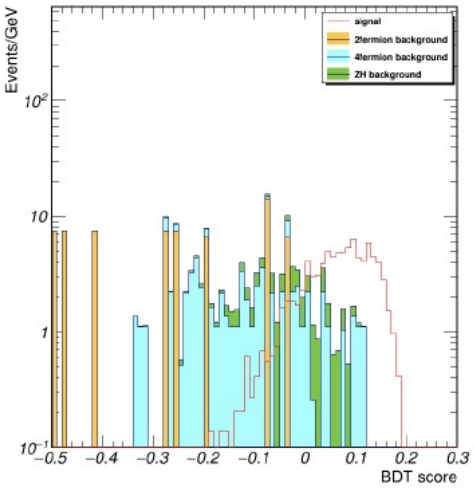




- There is a overtraining in the background due to poor statistics: ~1600
- Scan the total sensitivity ($S/\sqrt{S+B}$) vs BDTG to find the optimal BDTG point
- The sensitivity is estimated in the 90% signal coverage region

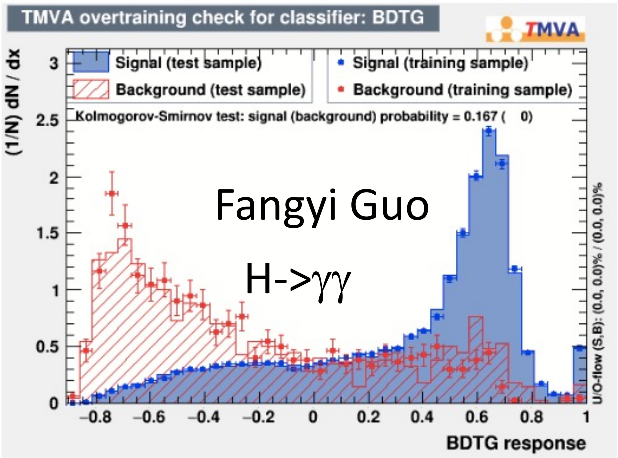
	Sig yield	Bkg yield	Sensitivity	Mass range (GeV)
BDTG > 0.45	86.20 +/- 0.51	198.20 +/- 19.82	7.46 +/- 0.27	[120.78 - 125.33]
BDTG < 0.45	29.77 +/- 0.30	1402.95 +/- 52.73	1.08 +/- 0.03	[114.08 - 125.28]
Total	115.97 +/- 0.59	1601.15 +/- 56.33	7.54 +/- 0.38	





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

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



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

Global analysis for CEPC Higgs

Efficiency modulate N → n

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

Similar for their covariances

$$\mathbf{\Sigma}^n \equiv \left(c^n_{ij}\right) = \mathbf{E}\mathbf{\Sigma}^N\mathbf{E}^T \ ,$$

We know the covariance of N

~ multinomial

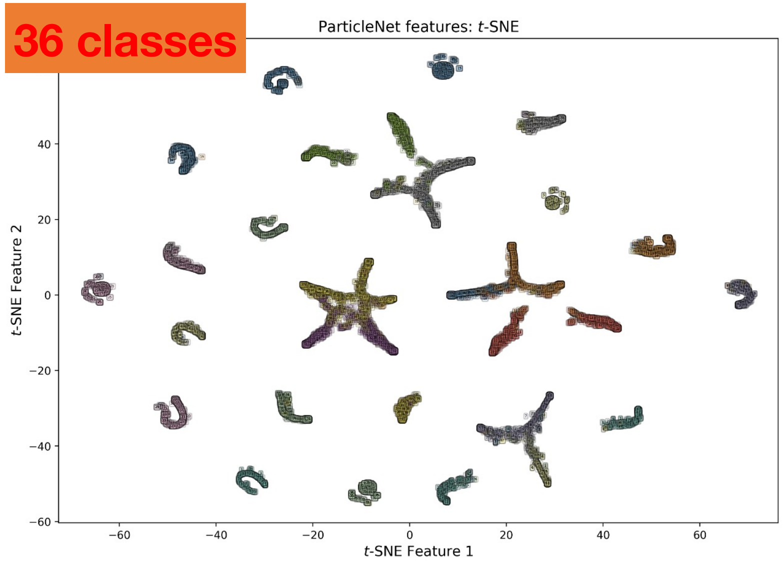
so Σ^n is easy

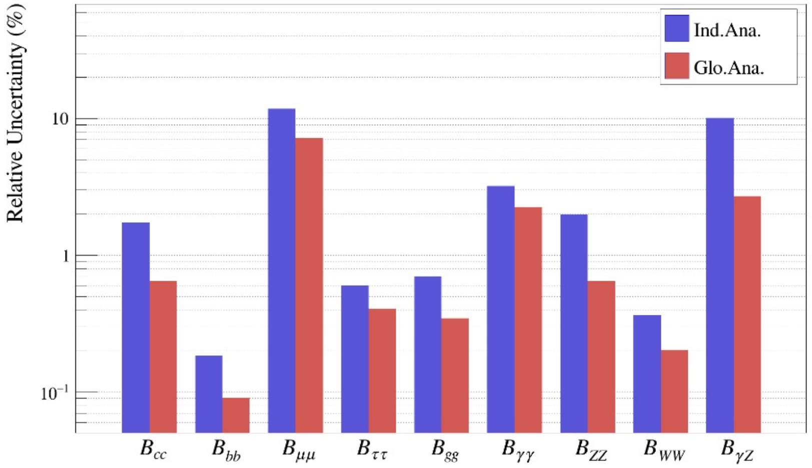
$$\mathbf{\Sigma}^N = N^e_t \begin{pmatrix} B_1(1-B_1) & -B_1B_2 & \dots & -B_1B_m \\ -B_2B_1 & B_2(1-B_2) & \dots & -B_2B_m \\ \vdots & \vdots & \ddots & \vdots \\ -B_mB_1 & -B_mB_2 & \dots & B_m(1-B_m) \end{pmatrix} ,$$

Solve all Ni by minimizing

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

Global analysis : Enhance Higgs coupling precision





ArXiv:2105.14997

calculate the efficiency matrix

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

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

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

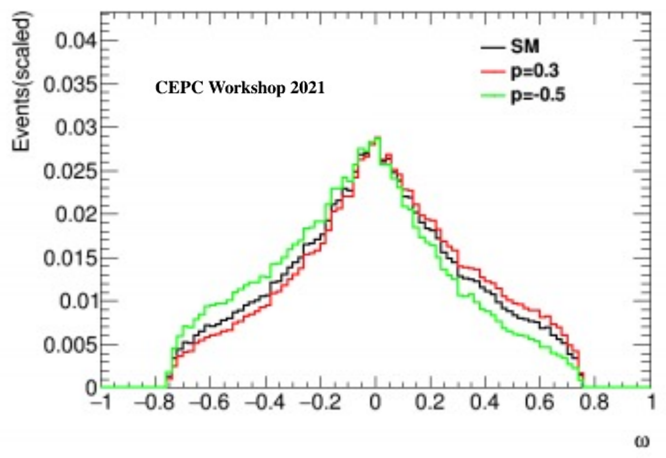
Full simulation study is ongoing …

Higgs CP study at CEPC

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

Differential cross section could be represent as:

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



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

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

Used ML-fit in ω distribution to extract p.

Result:

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

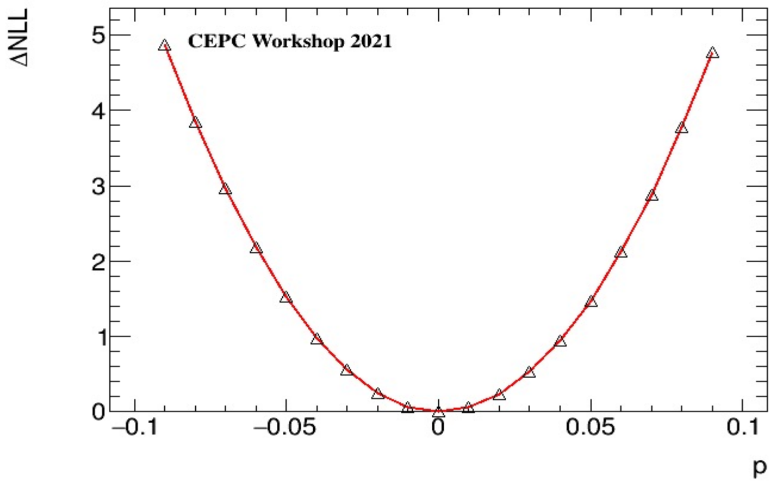
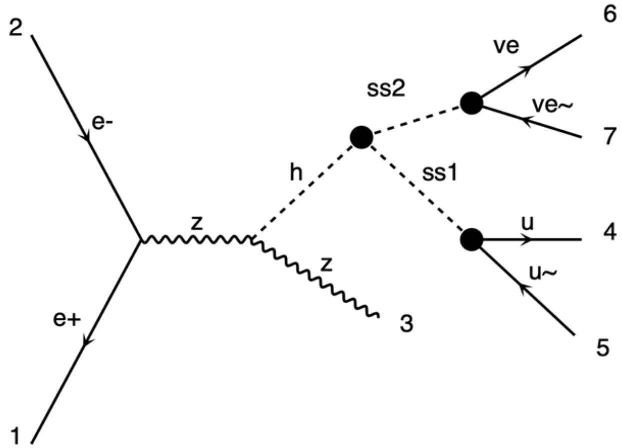
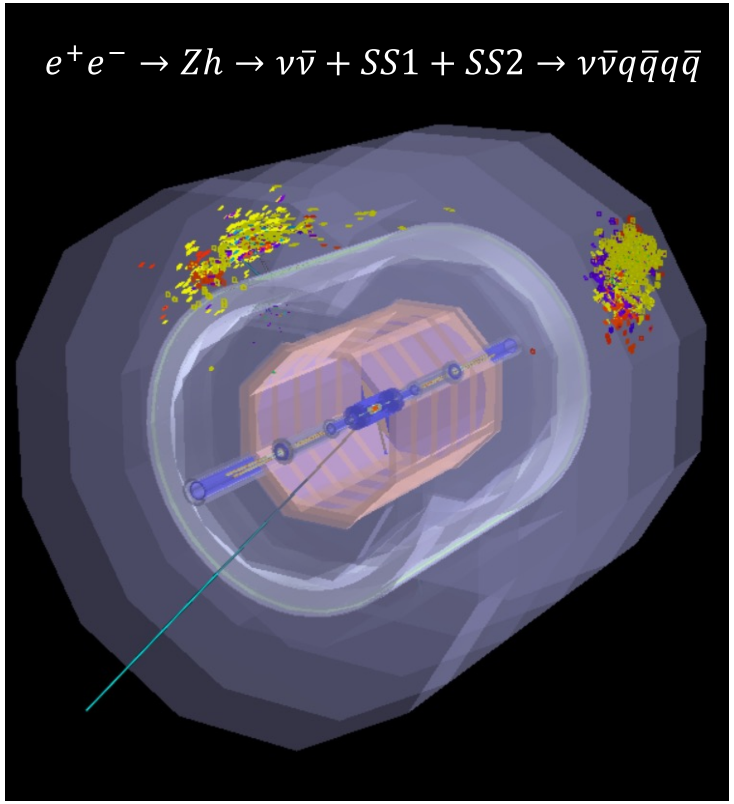
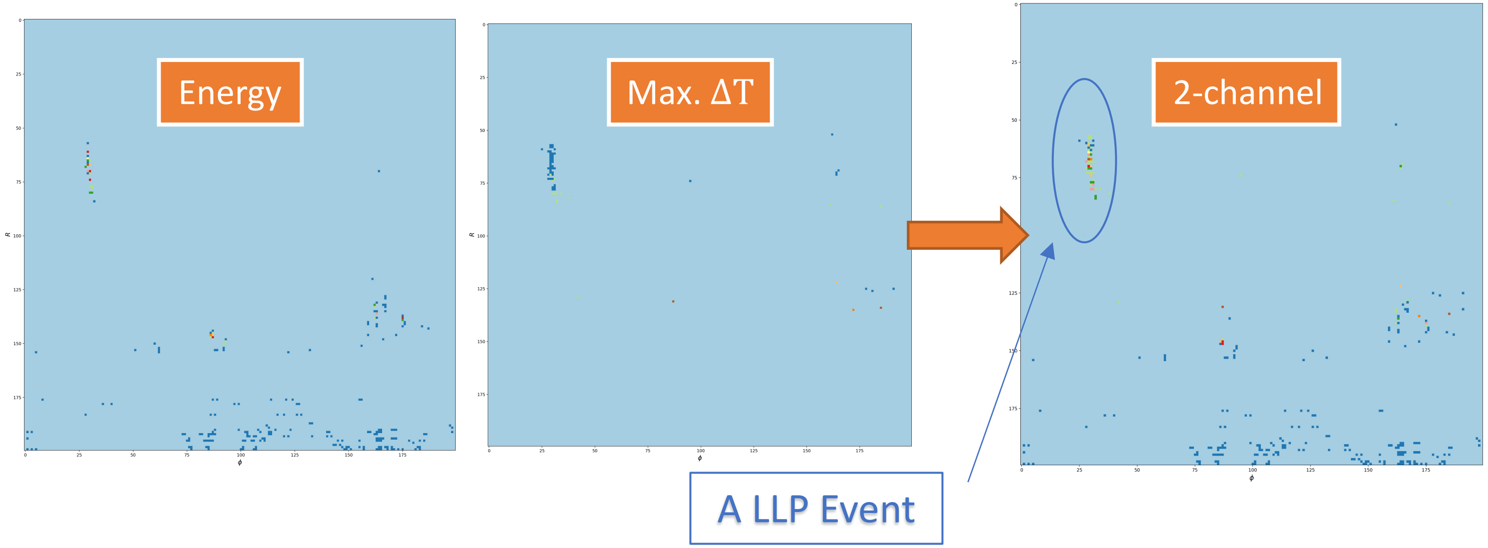


Image Recognition Techniques to Identify Long-Lived Particles(h->LLPs)

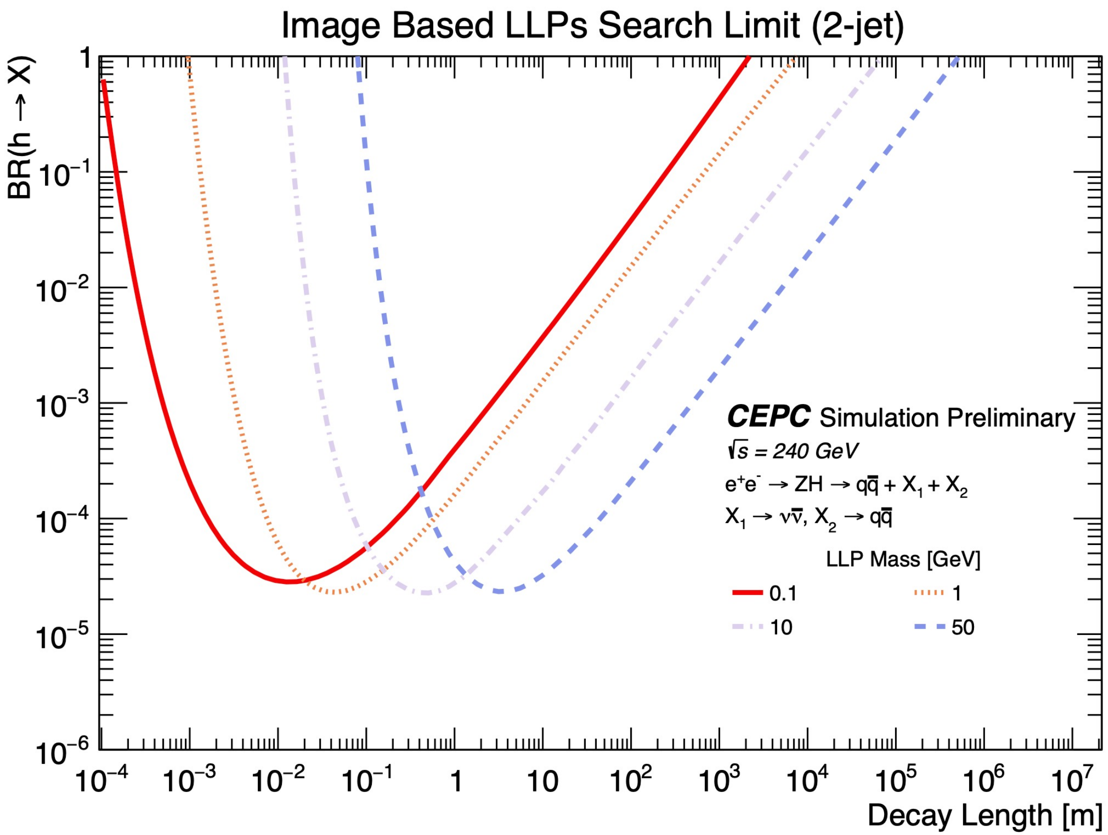




- Mapping the raw detector information to a 2D image
- Input information: image with resolution of $(\mathrm{R}, \phi) = 200\times200$ and 1 to 2 channel(s)
  - R starts from 0 to 8 m, ϕ starts from $-\pi$ to π
  - Energy is the sum of Calorimeter hits.
  - Time is the maximum ΔT $(E > 0.1\ GeV)$ within (R, ϕ) pixel
- Model: ResNet18 (Classification), ResNet50 (Vertex Finding)
- **Binary Cross Entropy Loss:** $loss(x_i, y_i) = -\omega_i[y_i \log(x_i) + (1 - y_i)\log(1 - x_i)]$



Expected Search Sensitivity



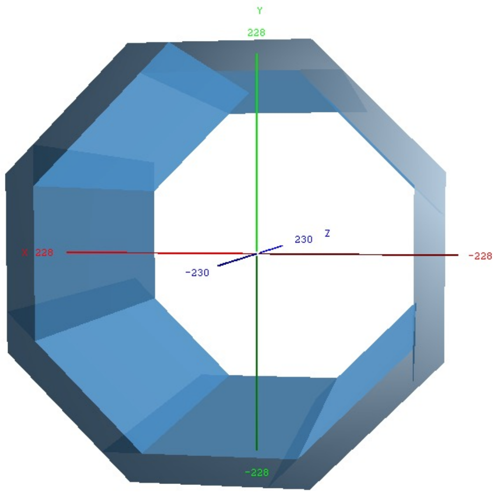
Signal Efficiency of ML-based and Cut-based analysis for $Z \rightarrow \bar{\nu}\nu$

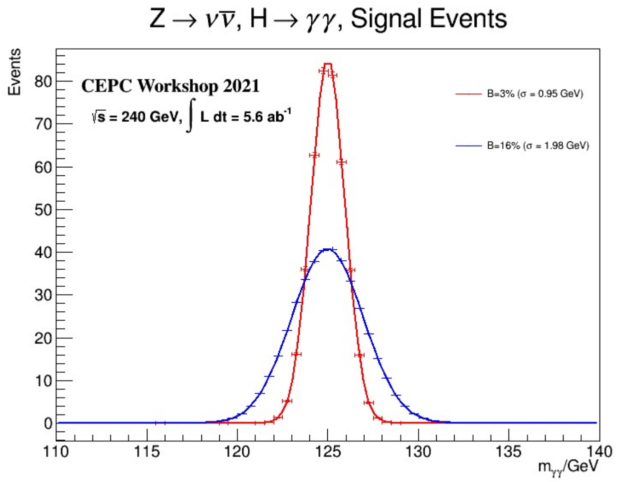
Selections	Signal: $Z \to \nu\bar{\nu}$	$ee \to q\bar{q}$	$ee \to ZH$
-		2.5×10^8	
-	1.0×10^6	0.99×10^7	
$\not{E} > 190\text{GeV},\ N_{PFOs} > 8$	88,077	290	3,361
ML score > 0.95	87,050	0	0
Efficiency (ML-based)	98.83%		
$E_{2j} \geq 30\text{GeV}$	67,244	0	0
Efficiency (cut-based)	75.19%		

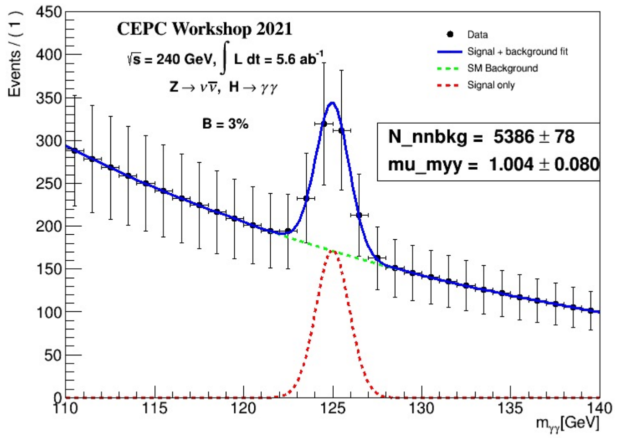
- Best branching ratio exclusion limit at decay length around a few meters: $BR(h \rightarrow XX) > \sim 10^{-5}$ for most LLP masses
- Good sensitivity for low LLP mass (as low as 1 GeV)

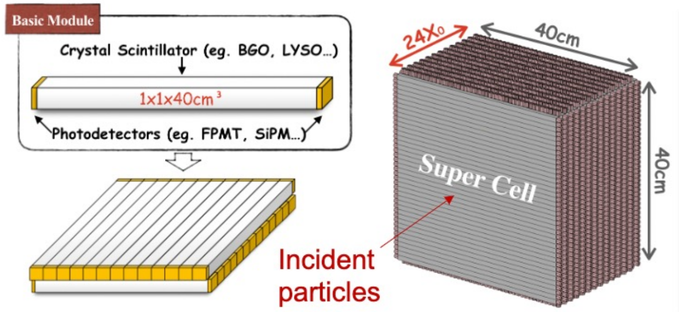
$H \to \gamma\gamma$ precision @ CEPC conceptual detector

- 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.
- $\sigma(ZH) \times Br(H \to \gamma\gamma)$ precision @ CEPC:
  - Only consider the σ_E influence in $m_{\gamma\gamma}$ shape in $\nu\nu H \to \gamma\gamma$ and $\mu\mu H \to \gamma\gamma$ channels, with cut-based analysis.
  - Combined statistical only precision: $\delta Br(H \to \gamma\gamma) = 8.0\%$ (11% @ SiW ECAL scheme, 27% improvement.)





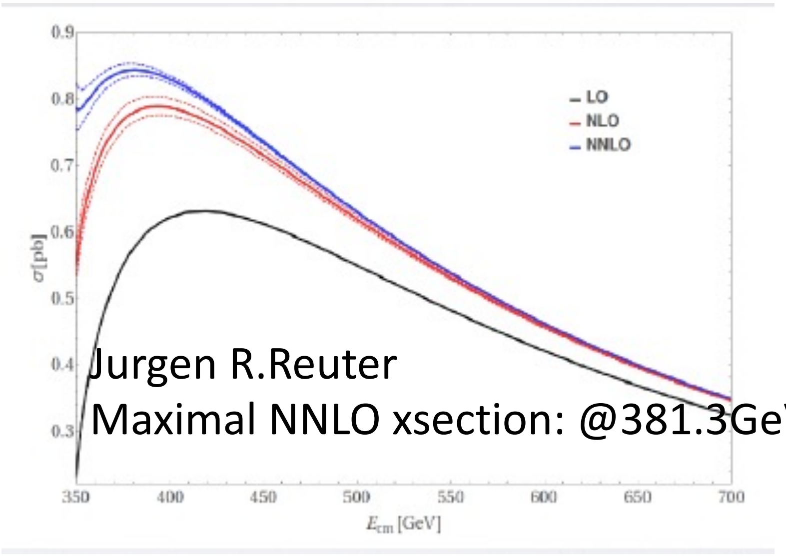


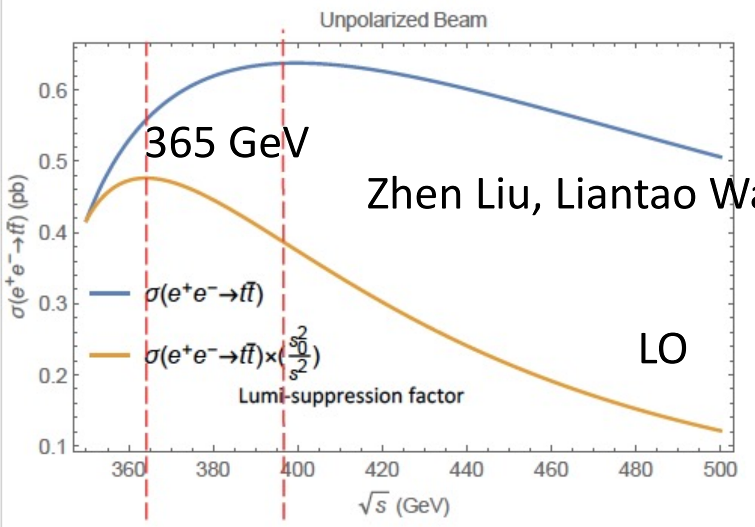


New Concept

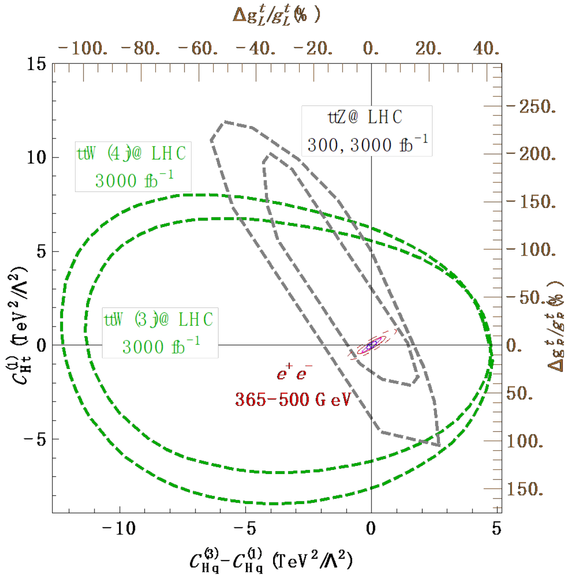
EM Resolution	$\delta(\sigma \times Br)$
$3\%/\sqrt{E} \oplus 1\%$	8.0%
$16\%/\sqrt{E} \oplus 1\%$	11%

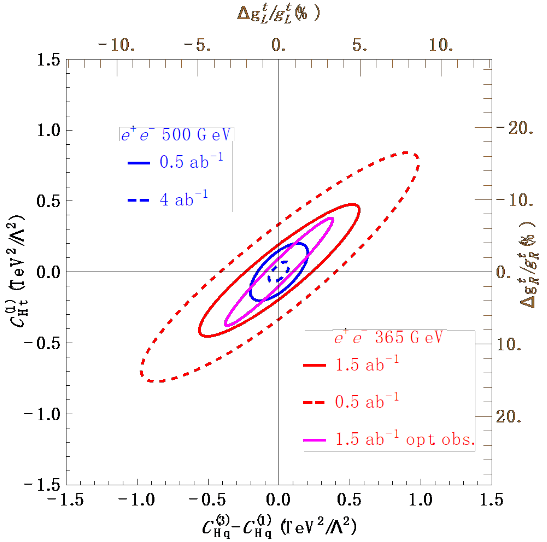
Higgs related physics at 360 GeV (generic study)





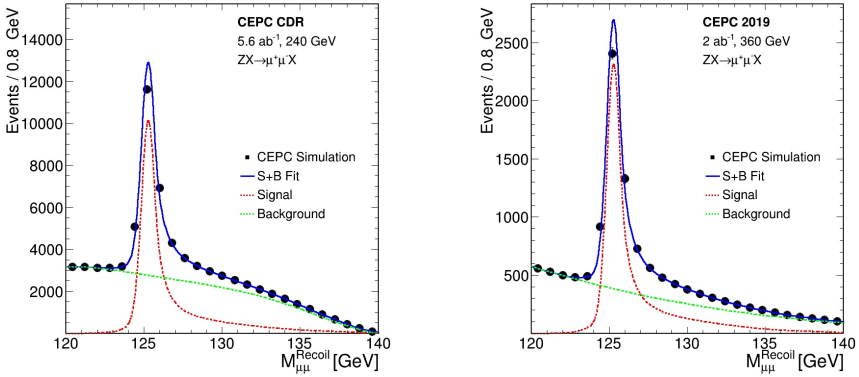
- With the NNLO calcuation, the highest xsection is at the energy of 381.3 GeV
- Considering the Lumi-suppression factor when going to higher energy, the effective highest xsection is around 365 GeV.
- The effective xsection from 360 GeV is not much different from that of 365 GeV.
- If we choose higher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





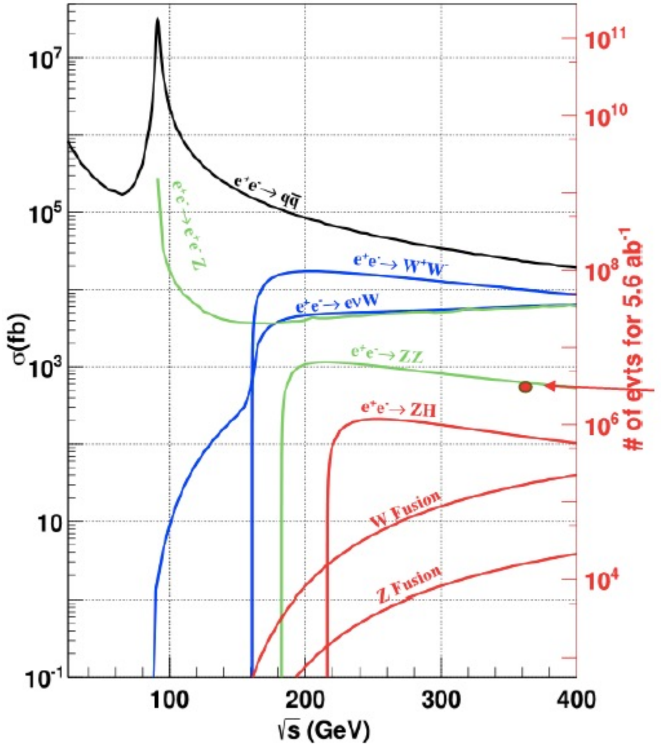
Extrapolations

- 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 ~2.8GeV to 2.3GeV; (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%**
$H \to \gamma\gamma$	**5.7%**	**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%

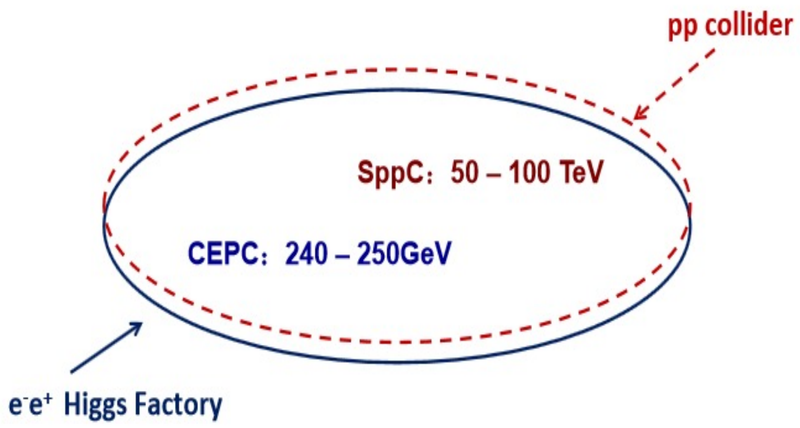
- 360 GeV run can significantly improve the Higgs width measurement.
- For Higgs physics results, there are no significant difference for the colliding energy with 360 GeV or 365 GeV.

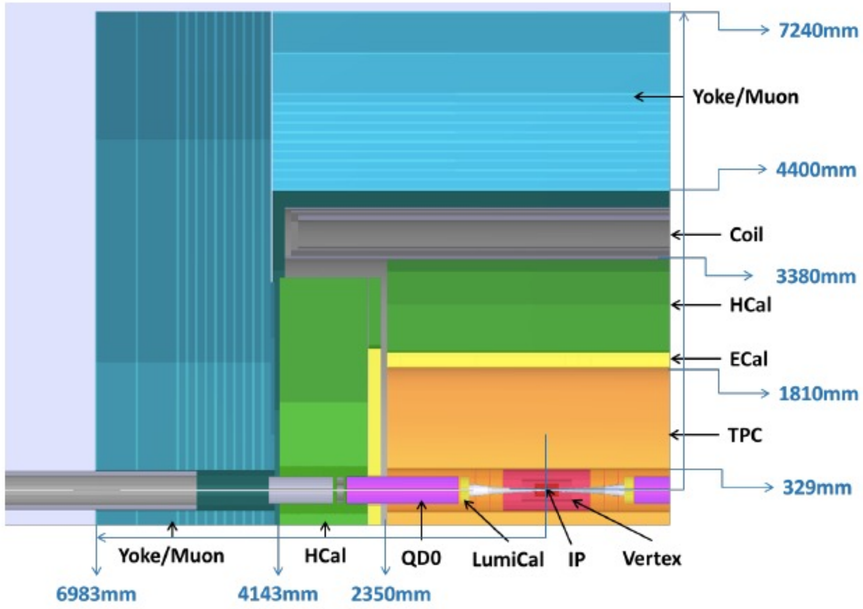
Conclusion

- 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 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.

backup slides

CEPC





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

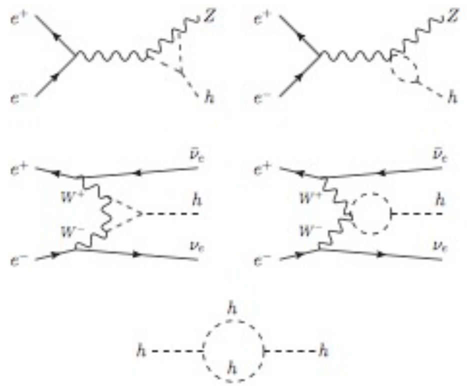
Table 2. Key characteristic/performance of a conceptual CEPC detector.

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

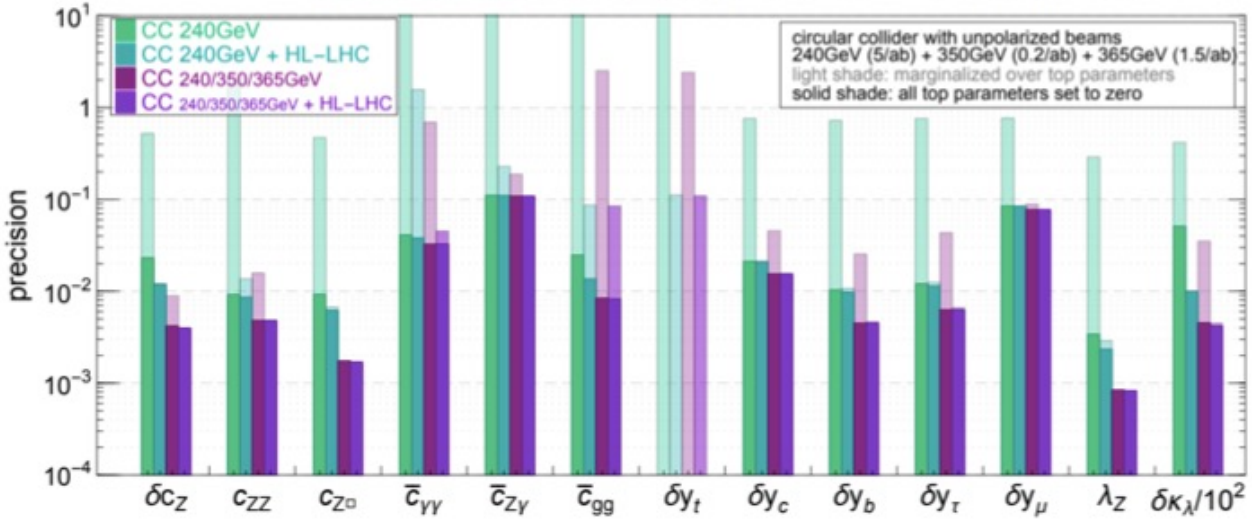
Jiayin Gu, Cen Zhang et al.,

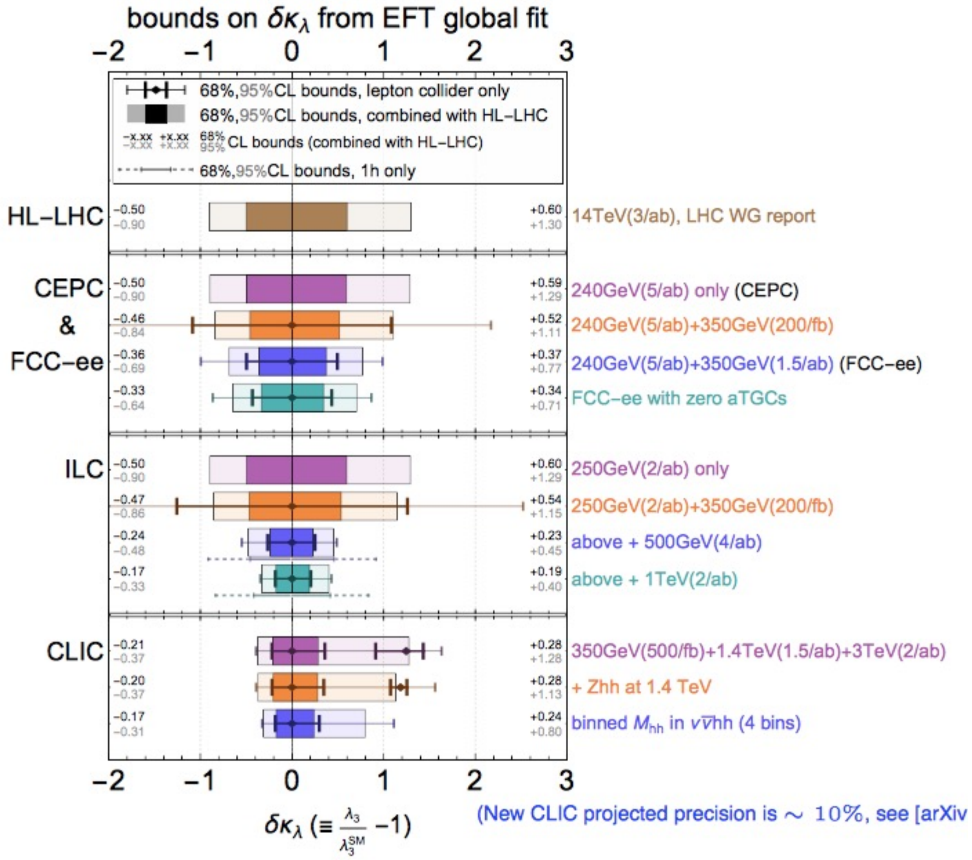
Impact on Higgs

Triple Higgs coupling:



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

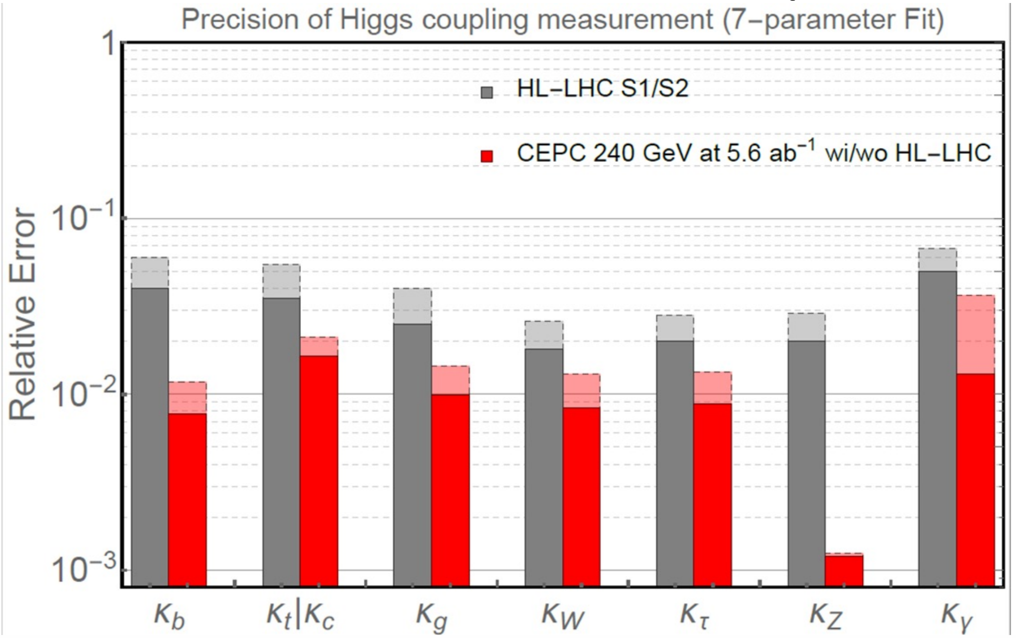


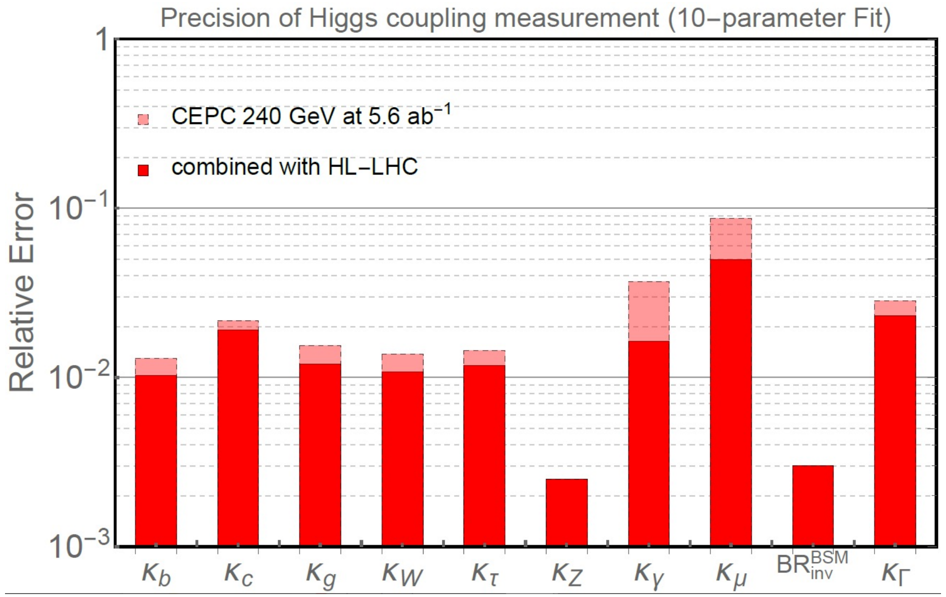


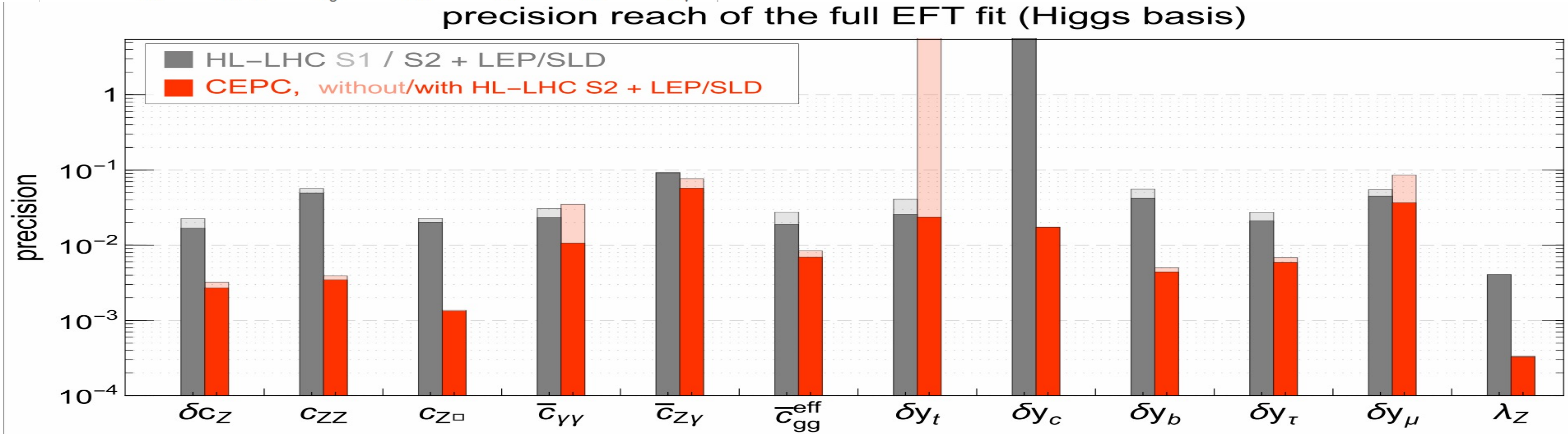
Uncertainties on the top have a big effect on the Higgs

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

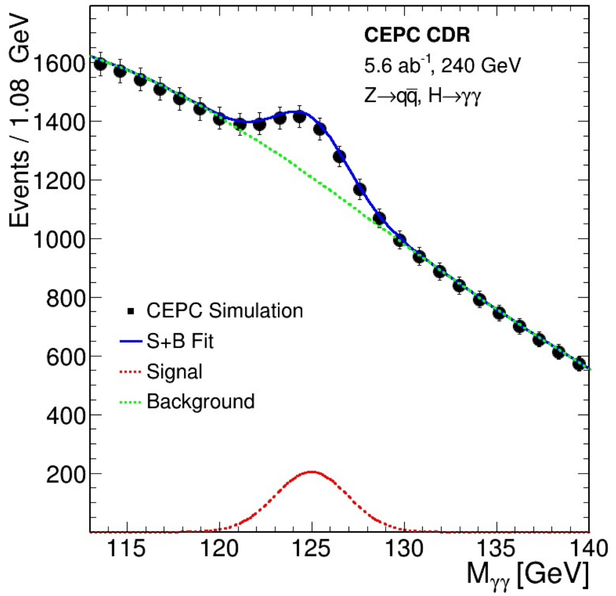
Combination/comparisons with HL-LHC

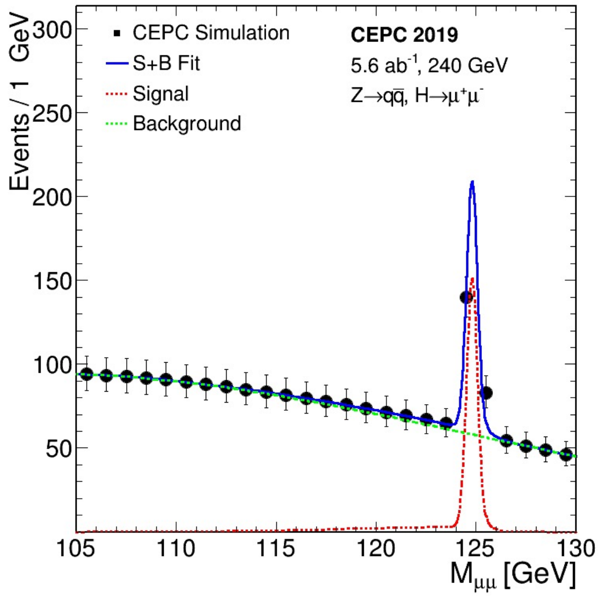


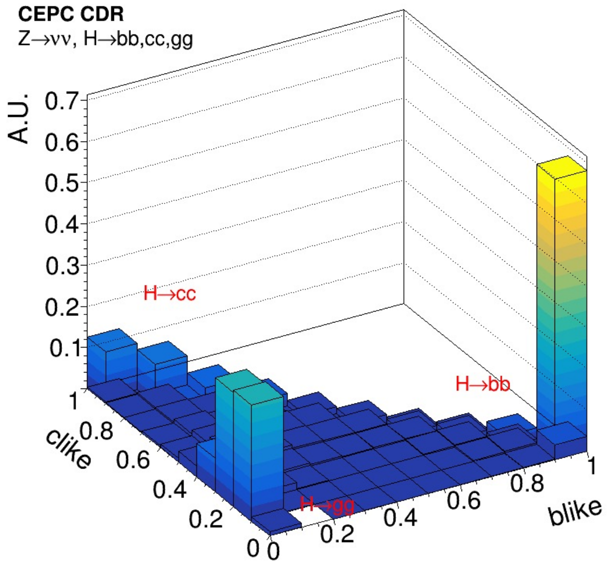


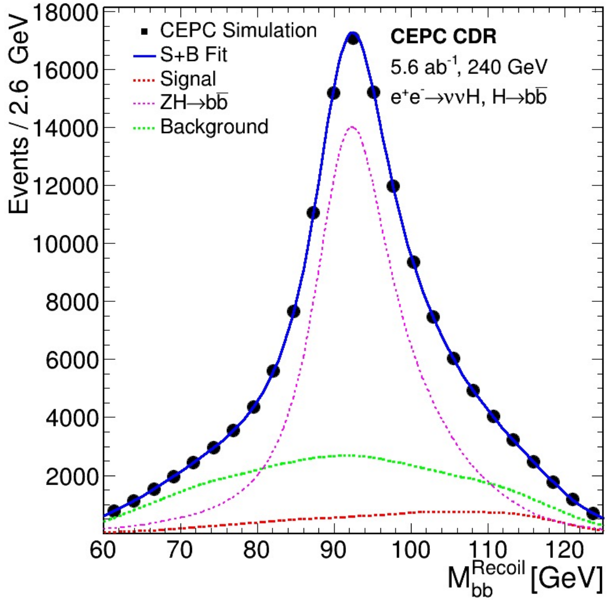


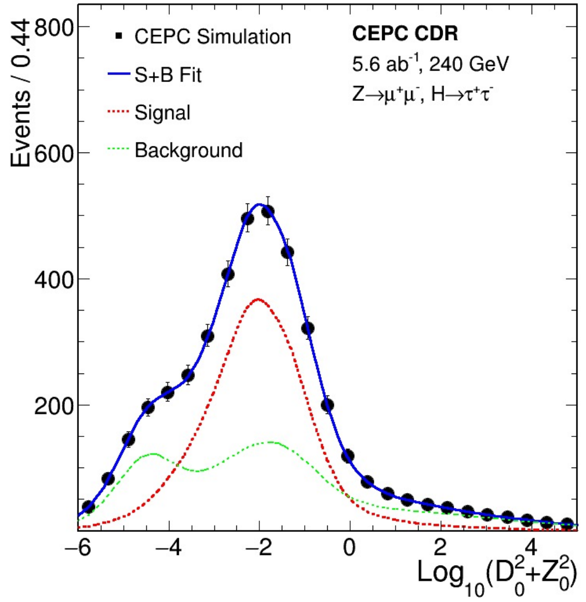
Typical individual channels











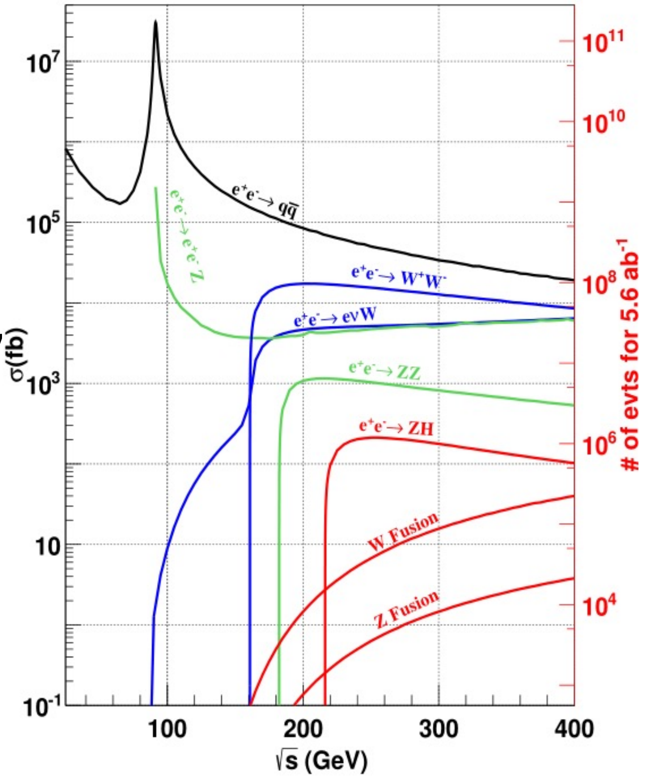
Signal/bkg Cross Sections

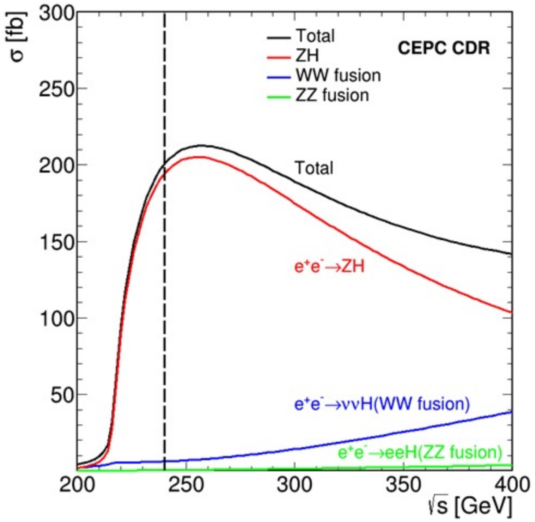
Kaili Zhang

- 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.



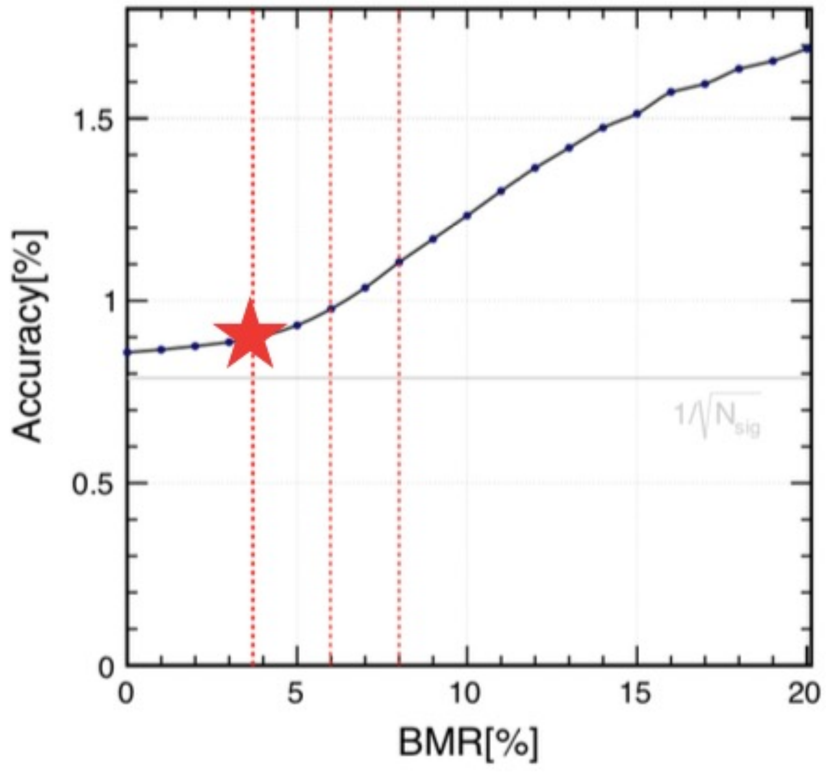


Status of H->ττ

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

Dan Yu's talk

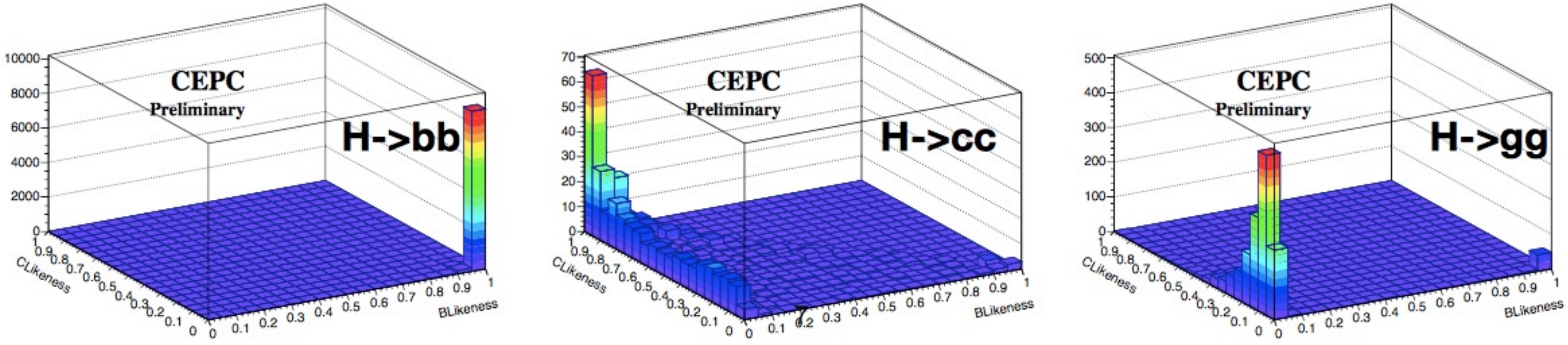
	$\delta(\sigma\times BR)/(\sigma\times BR)$
$\mu\mu H$	2.8%
eeH	5.1%
$\nu\nu H$	7.9%
qqH	0.9%
combined	0.8%



Status of H->bb,cc,gg

More at Yu Bai's talk

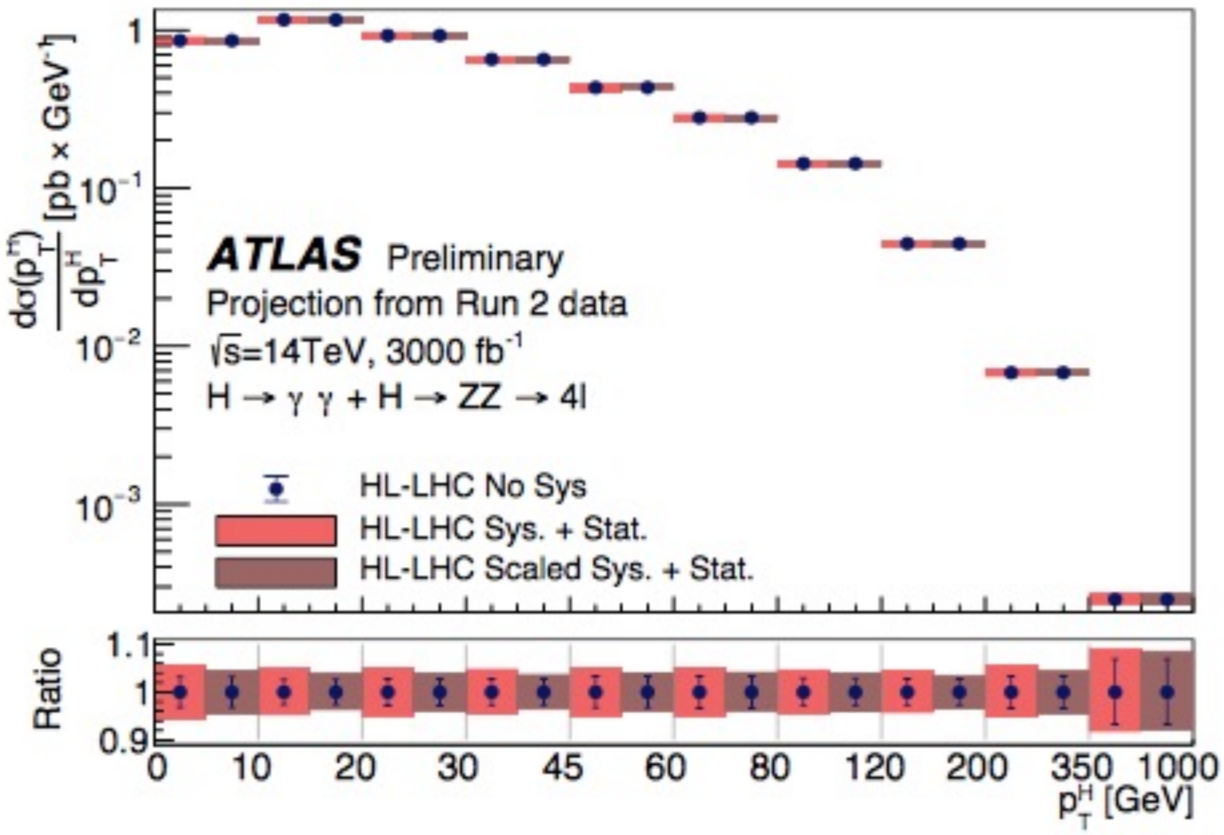
- Wrap the analysis into a note and submit to CPC.
- Flavor tagging used in the fit (3 dim)

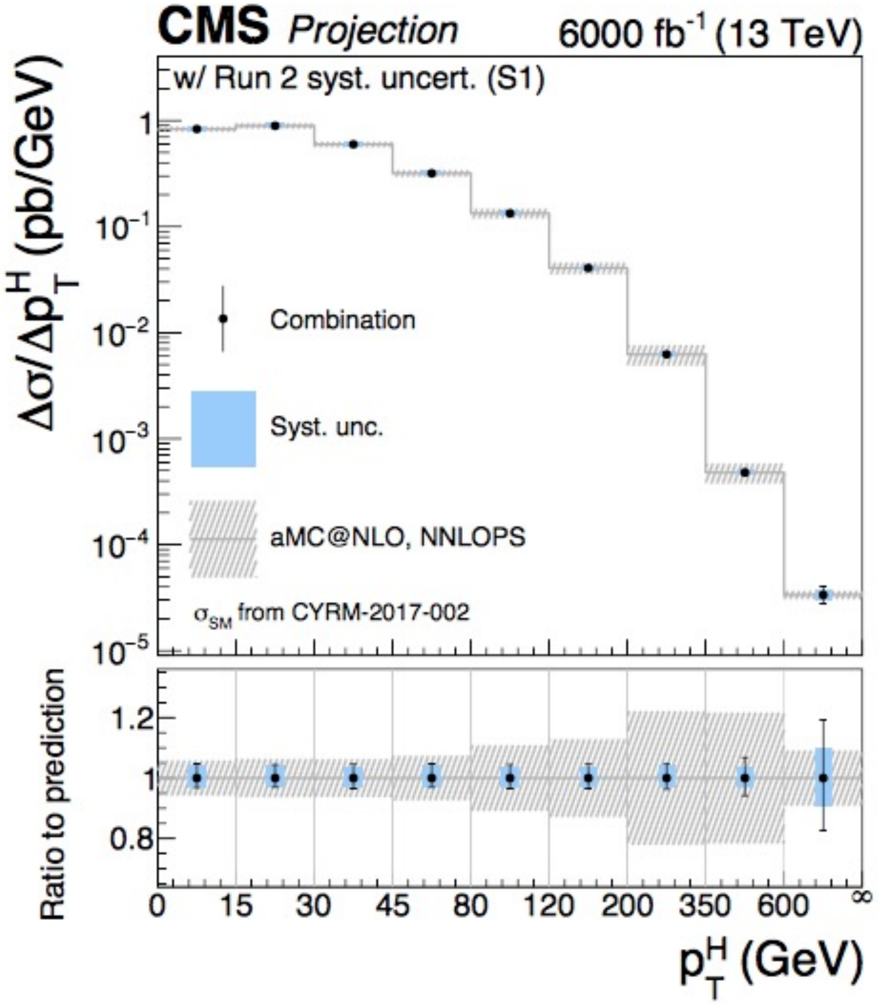


- Start to consider the systematics.

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.

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.

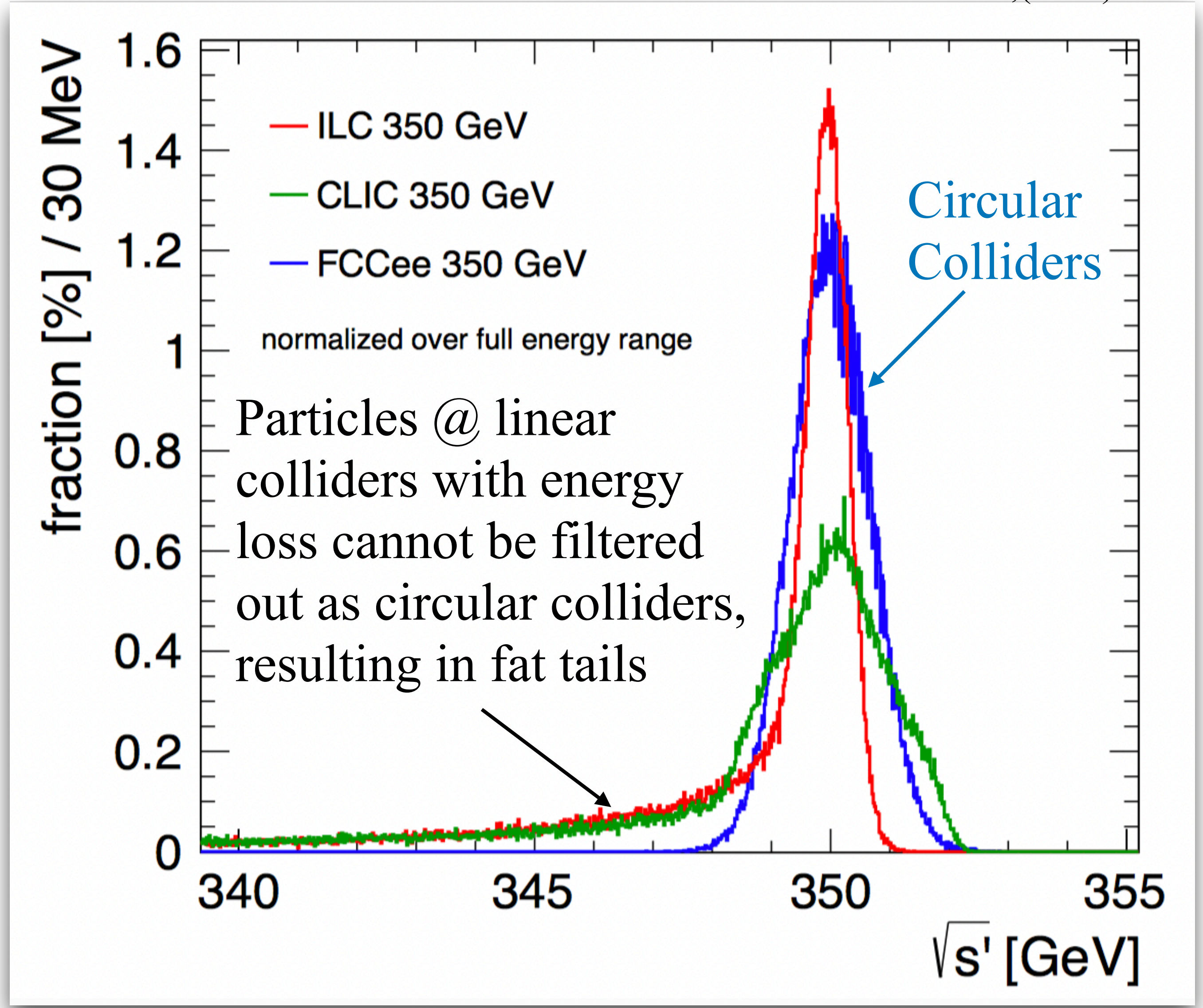
Advantages from circular colliders

X

- 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 tt threshold

EPJC 73,(2013)2530



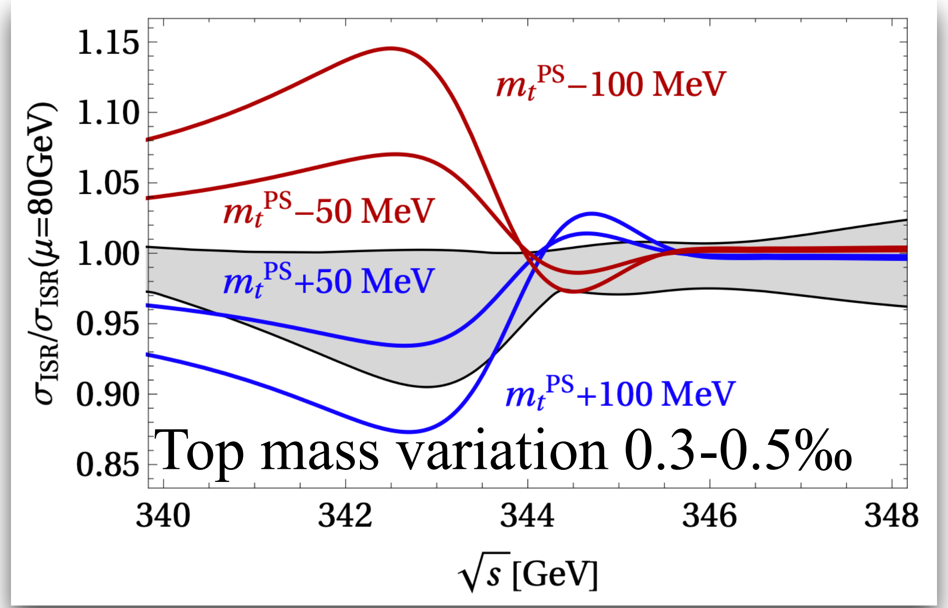
Our setup

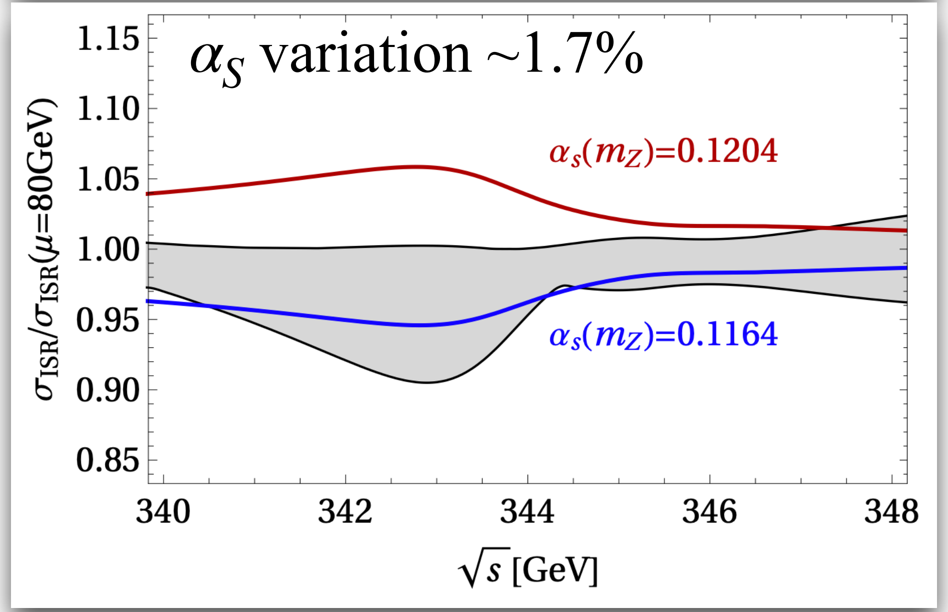
Comput. Phys. Commun. 209 (2016) 96-115
JHEP 1802 (2018) 125

- Use the package "QQbar_threshold" to calculate cross-section near threshold in ee-colliders at N^3LO 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

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

- 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

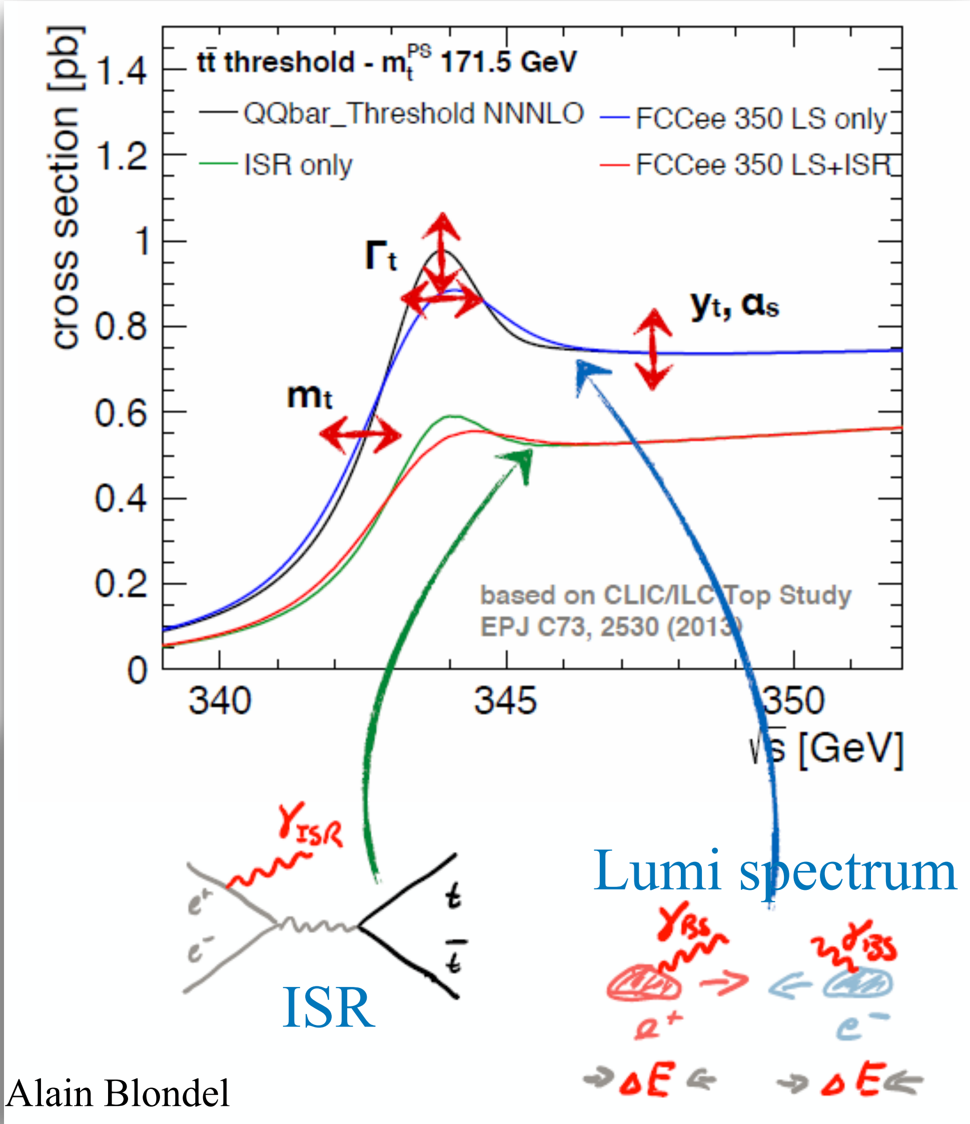


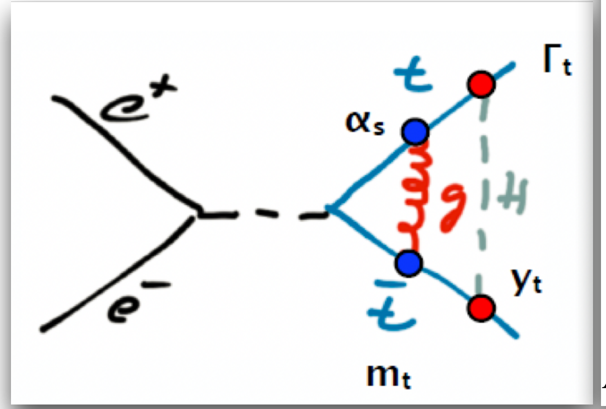


tt threshold scan

- 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
  - α_S

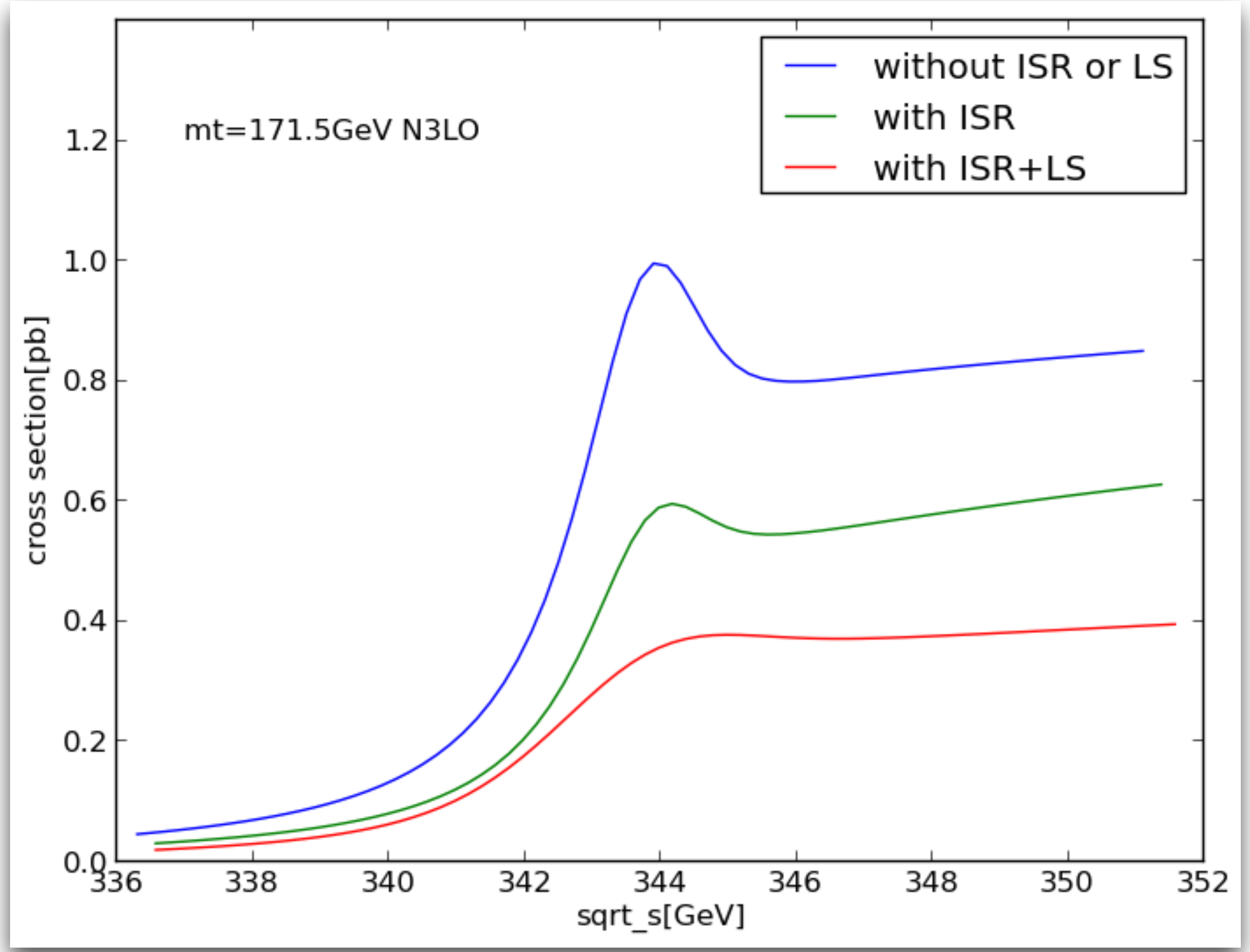
EPJC 73,(2013)2530





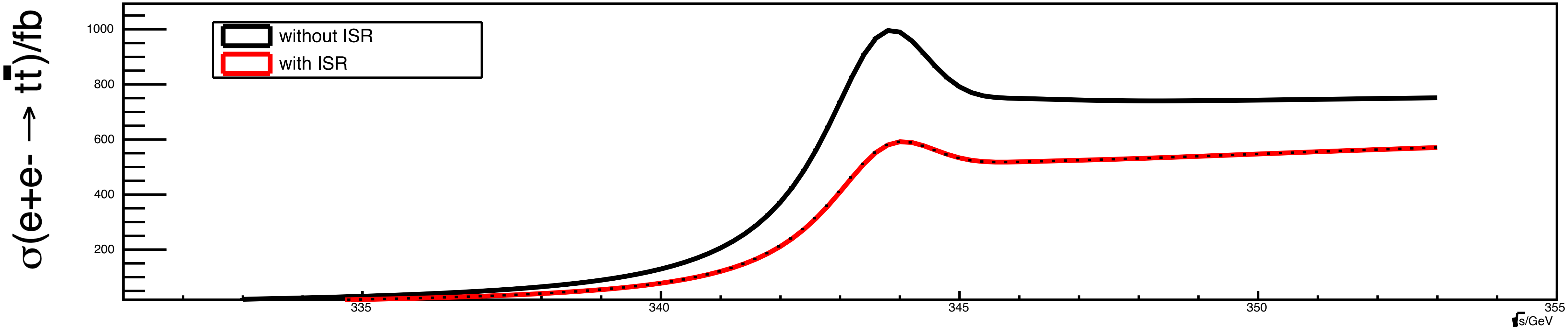
ISR and LS effects

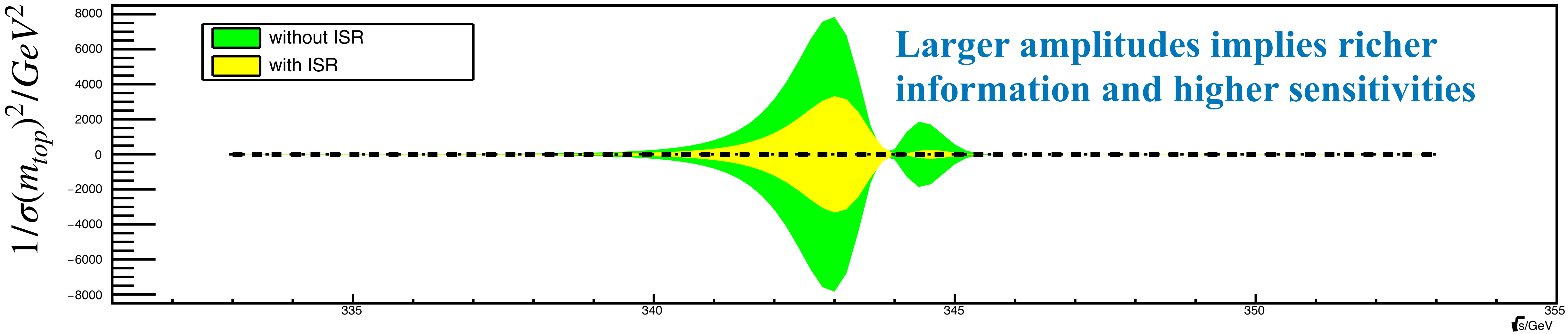
X



- The cross section as a function of centre-of-mass energy
  - A clear peak of production can be seen at around the tt 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





$\sqrt{s}$ scan points

X

- 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

$$L = \prod_i P(\vec{D}_i \,|\, \vec{E}_i(\sigma(m_{top}, \Gamma_{top}, \alpha_S, \sqrt{s}), \mathscr{L}_i, \vec{\theta}))$$

i corresponds to the i-th $\sqrt{s}$ scan point

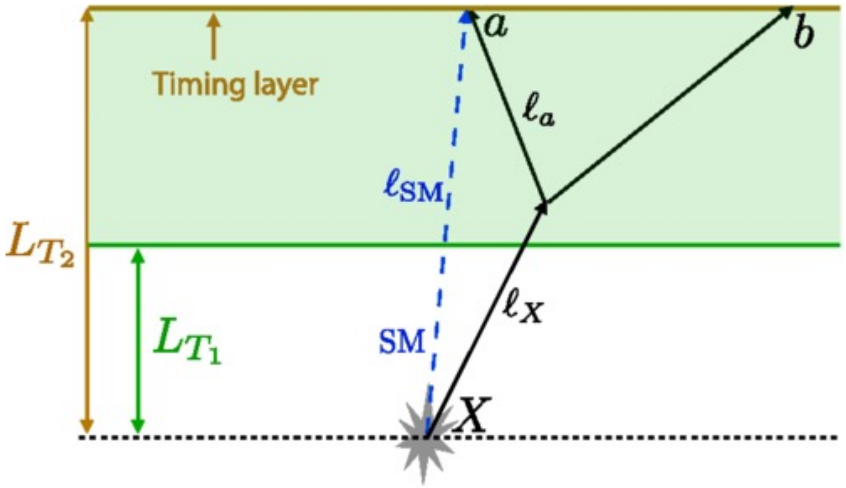
Sixth workshop of the LHC LLP Community

What is a long-lived particle?

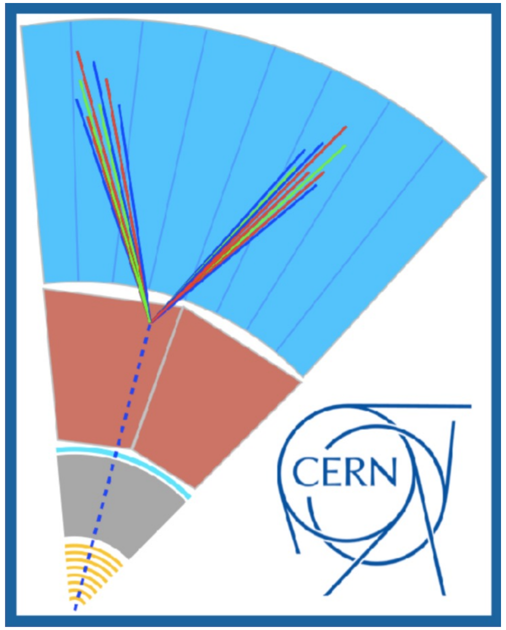
*Object (neutral or charged) decaying a **macroscopic** and **reconstructible** distance from IP*

Signal signature of a long-lived particle:

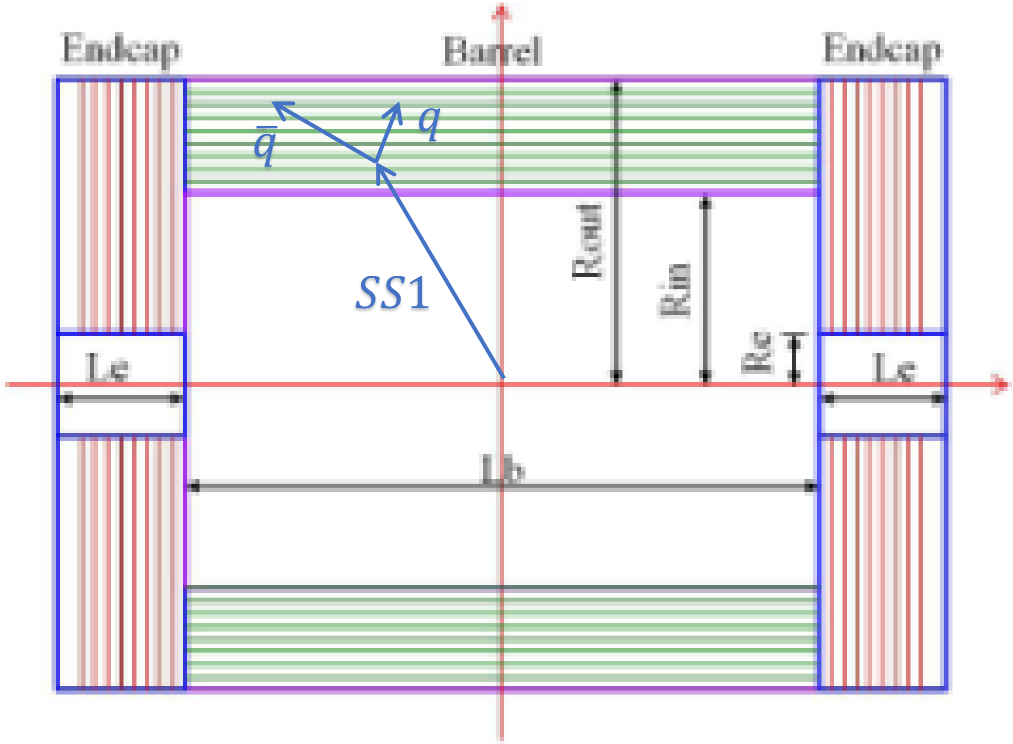
Neutral LLP decays are a spectacular signature, and the burst of energy appearing out of nowhere sets it apart from the collision point.



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



Basic Setup



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

Expected Limits for LLPs

	Signal	Total Background	Expected Limits
$e^+e^- \to Zh \to (Z: \bar{q}q)\bar{q}q\bar{v}v$	373308	0.02 (CR)	2.4×10^{-5}
$e^+e^- \to Zh \to (Z: \bar{v}v)\bar{q}q\bar{v}v$	87,050	0.02 (CR)	9.8×10^{-5}
Combined limit: $\mathbf{1.9\times10^{-5}}$			

- 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: $n_s = \mathcal{L}\times\sigma(e^+e^- \to Zh)\times\sigma(Z \to qq, \bar{v}v)\times\epsilon_{sig}\times\epsilon_{CR}$

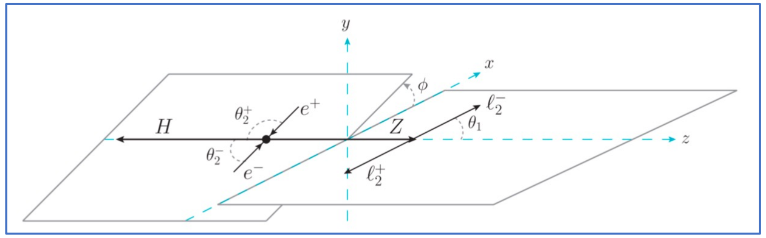
Theory model

JHEP 03(2016) 050 JHEP 11(2014) 028

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

$$\frac{d\sigma}{dcos\theta_1 dcos\theta_2 d\phi} = \frac{\mathcal{N}_\sigma(q^2)}{m_H^2}\mathcal{J}(q^2,\theta_1,\theta_2,\phi),$$

$$\mathcal{N}_\sigma(q^2) = \frac{1}{2^{10}(2\pi)^3}\cdot\frac{1}{\sqrt{r}\gamma_Z}\cdot\frac{\sqrt{\lambda(1,s,r)}}{s^2}$$



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

Variables for studying distribution: θ_1, θ_2, ϕ

Qiyu Sha shaqiyu@ihep.ac.cn

Efficiecy 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