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$H \rightarrow \gamma\gamma$ channel branching ratio measurement in CEPC

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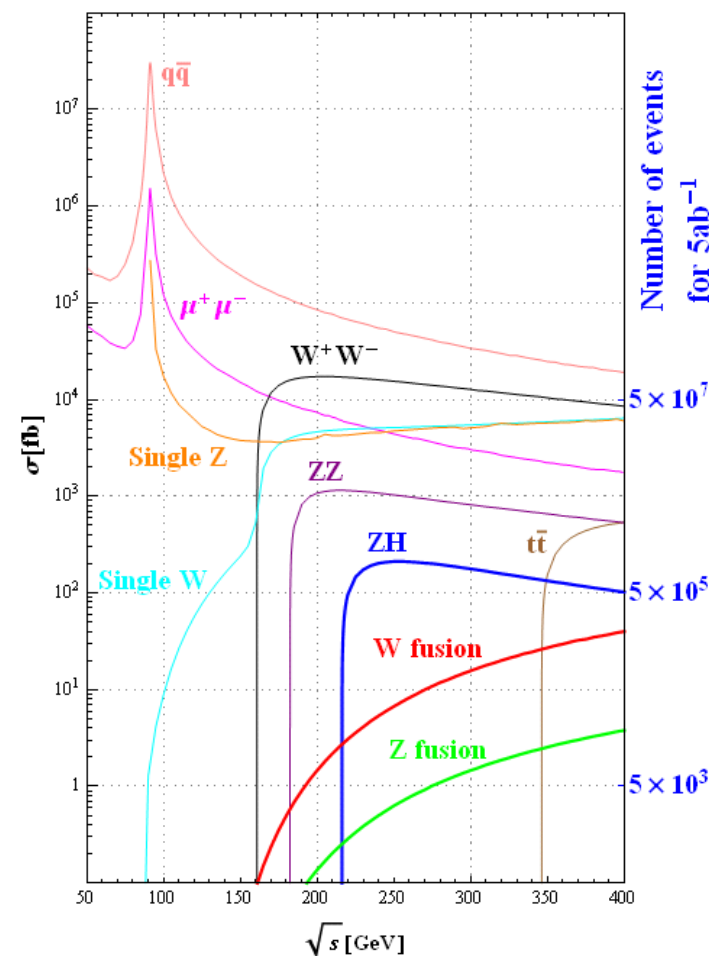
27th June, 2018, IHEP

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Motivation

- Standard Model Higgs physics is one of the major topic in the CEPC
- CEPC project
Electron-Positron collider, operate as Higgs Factory
Hope to have more precise measurement in Higgs-relative parameters.
- In center of mass energy $\sqrt{s} \sim 250 \text{ GeV}$ in lepton collider, the Higgsstrahlung(ZH) process is the main production mode
- Design point:
preCDR(CEPC_v1): $\sqrt{s} = 250 \text{ GeV}$, magnetic field $B=3.5\text{T}$, etc.
Present(CEPC_v4): $\sqrt{s} = 240 \text{ GeV}$, magnetic field $B=3.0\text{T}$, etc.



Motivation

- $\text{Br}(H \rightarrow \gamma\gamma) \approx 0.227\%$, low branching ratio but clean final state topology.

The measurement should achieve a relative high precision.

- Present results from LHC ATLAS group:

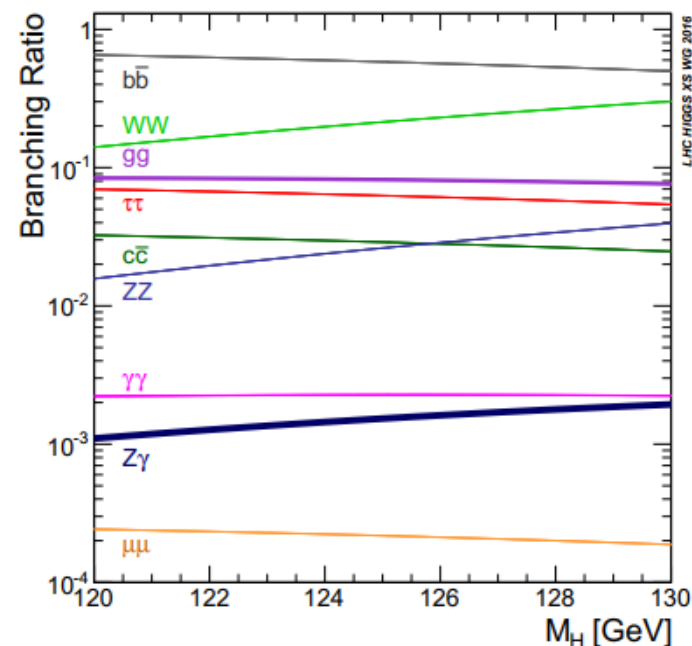
$$\mu_{global} = 0.99^{+0.14}_{-0.13} (\mathcal{L} = 36.1 fb^{-1})$$

[Arxiv:1802.04146](https://arxiv.org/abs/1802.04146)

- Difficulty:

Complex background components

Low $\text{Br}(H \rightarrow \gamma\gamma)$ VS. Large background process XS



Monte Carlo Samples

(Generated with Whizard1.95, include ISR)

- Signal

$$ee \rightarrow ZH \rightarrow ll\gamma\gamma$$

$$ee \rightarrow ZH \rightarrow qq\gamma\gamma$$

$$ee \rightarrow ZH \rightarrow \nu\nu\gamma\gamma$$

100k events
per channel

$$ee \rightarrow ZH, H \rightarrow \gamma\gamma, Z \rightarrow \text{inclusive} \quad 400\text{k totally}$$

Monte Carlo Samples

- Background Components

Similar final states with ISR photon

Signal	Background	Dominant one(chosen one)	Generated event number
$ZH \rightarrow ll + \gamma\gamma$	$ee \rightarrow Z \rightarrow ee/\mu\mu/\tau\tau + \text{ISR photon}$ $ee \rightarrow WW \rightarrow l\nu l\nu + \text{ISR photon}$ $ee \rightarrow ZZ \rightarrow ll\nu\nu + \text{ISR photon}$	$ee \rightarrow Z \rightarrow ee/\mu\mu/\tau\tau + \text{ISR photon}$	$\sim 26\text{M}(\mu\mu) + 10\text{M}(\tau\tau)$
$ZH \rightarrow qq + \gamma\gamma$	$ee \rightarrow Z \rightarrow qq + \text{ISR photon}$ $ee \rightarrow WW \rightarrow qq\gamma\gamma$ $ee \rightarrow ZZ \rightarrow qq\nu\nu + \text{photon}$	$ee \rightarrow Z \rightarrow qq + \text{ISR photon}$	20M
$ZH \rightarrow \nu\nu + \gamma\gamma$	$ee \rightarrow Z \rightarrow \nu\nu + \text{photon}$ Other $ee \rightarrow \text{invisible process} + \text{photon}$	$ee \rightarrow Z \rightarrow \nu\nu + \text{photon}$	200M

Simulation

- Full simulation

Use Geant4-based tools to simulate the detector response

$ee \rightarrow ZH, H \rightarrow \gamma\gamma, Z \rightarrow \text{inclusive}$ signal sample

- Fast simulation

Smear the objects with the resolutions and efficiencies from full simulation

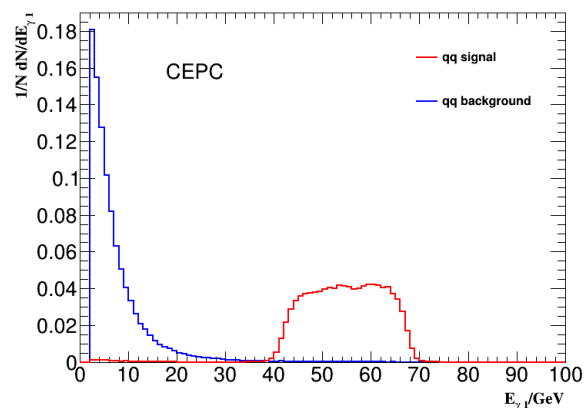
$ee \rightarrow ZH \rightarrow ll/qq/\nu\nu + \gamma\gamma$ signal samples

All background samples

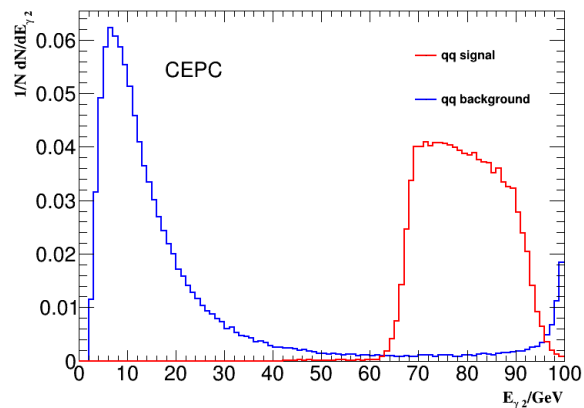
Event selection — $qq\gamma\gamma$ channel

- Signal: $ee \rightarrow ZH \rightarrow qq\gamma\gamma$
 - Background: $ee \rightarrow qq\gamma\gamma$
- Whizard1.95+Fast simulation,
B=3.0T, $\sqrt{s} = 240\text{GeV}$
- Photon: 2 on-shell photon whose invariant mass is closest to $m_H = 125\text{GeV}$
 - Jets: Force the other particles into 2 jets
 - Define:
 - γ_1/j_1 : *photon/jet with lower energy*
 - γ_2/j_2 : *photon/jet with higher energy*

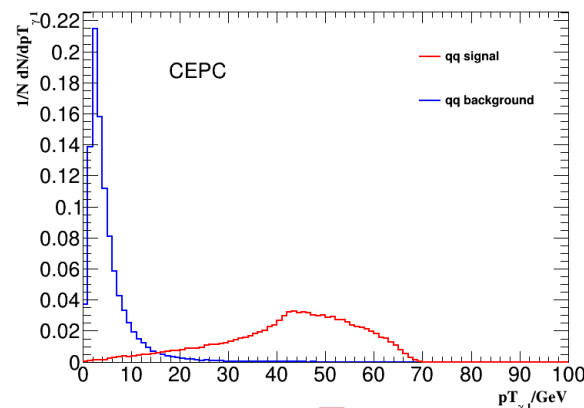
Event selection — $qq\gamma\gamma$ channel distribution



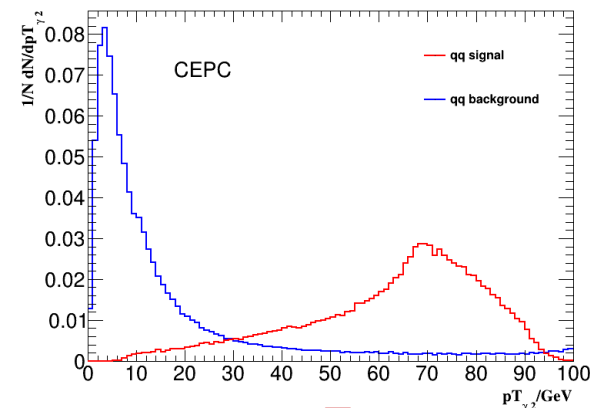
γ_1 Energy



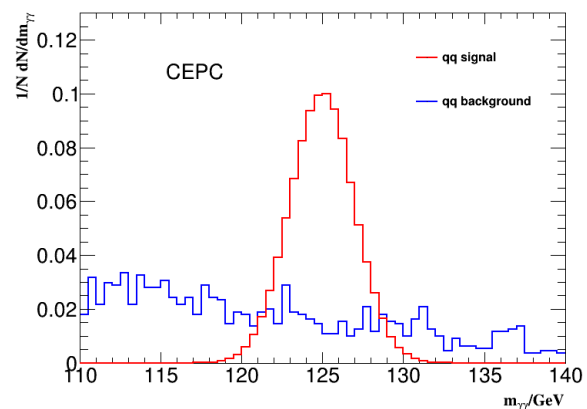
γ_2 Energy



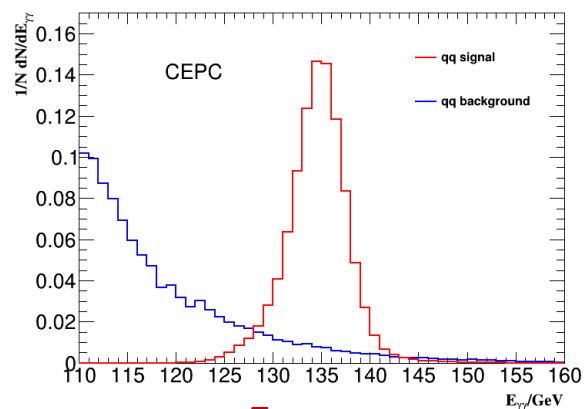
γ_1 pT



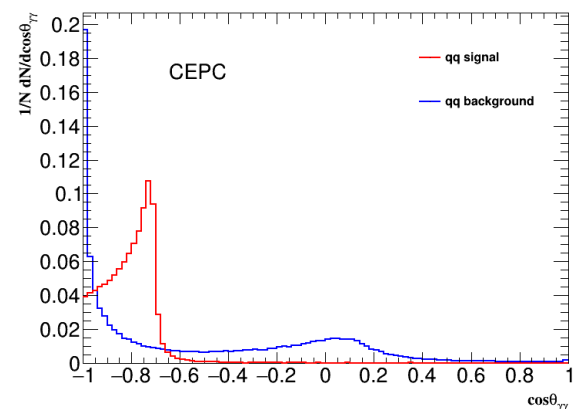
γ_2 pT



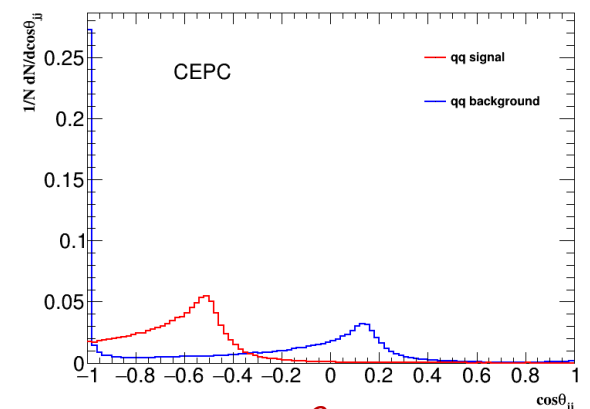
$\gamma\gamma$ invariant mass



$\gamma\gamma$ Energy



$\cos\theta_{\gamma\gamma}$



$\cos\theta_{jj}$

Event selection — $qq\gamma\gamma$ channel selection criteria

$$E_{\gamma 1} > 35\text{GeV}$$

$$35\text{GeV} < E_{\gamma 2} < 96\text{GeV}$$

$$\cos\theta_{\gamma\gamma} > -0.95, \cos\theta_{jj} > -0.95 \quad \leftarrow \text{Cosine polar angle between two photons/ two jets}$$

$$pT_{\gamma 1} > 20\text{GeV}, pT_{\gamma 2} > 30\text{GeV}$$

$$110\text{GeV} < m_{\gamma\gamma} < 140\text{GeV}$$

$$125\text{GeV} < E_{\gamma\gamma} < 145\text{GeV}$$

$$\min|\cos\theta_{\gamma j}| < 0.9 \quad \leftarrow \text{Minimum cosine polar angle between the photon and jet}$$

Event selection — $qq\gamma\gamma$ channel cut flow

	qq signal		qq background	
generated	100000		20000000	
$qq\gamma\gamma$	99893	99.893%	13914611	69.573%
$E_{\gamma 1} > 35\text{GeV}$	99025	99.131%	120726	0.868%
$35\text{GeV} < E_{\gamma 2} < 96\text{GeV}$	97922	98.886%	55583	46.041%
$\cos\theta_{jj} > -0.95$	93631	95.618%	44012	79.182%
$\cos\theta_{\gamma\gamma} > -0.95$	84930	90.707%	36794	83.600%
$pT_{\gamma 1} > 20\text{GeV}$	79339	93.417%	22481	61.100%
$pT_{\gamma 2} > 30\text{GeV}$	73929	93.181%	11733	52.191%
$110\text{GeV} < m_{\gamma\gamma} < 140\text{GeV}$	73927	99.997%	4316	36.785%
$125\text{GeV} < E_{\gamma\gamma} < 145\text{GeV}$	73571	99.518%	3912	90.639%
$\min \cos\theta_{\gamma j} < 0.9$	53088	72.159%	1972	50.409%
		53.088%		0.010%
scaled to 5 ab-1	824.38		26674.65	

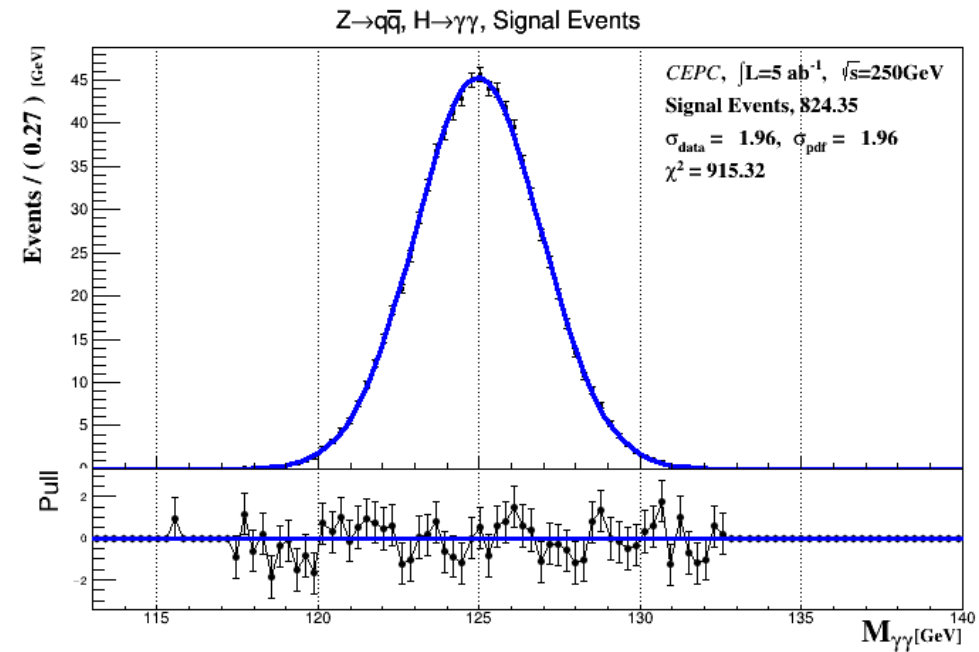
Fit model—— $qq\gamma\gamma$ channel

Fit variable: di-photon invariant mass

- Signal model

Double-side Crystal Ball PDF

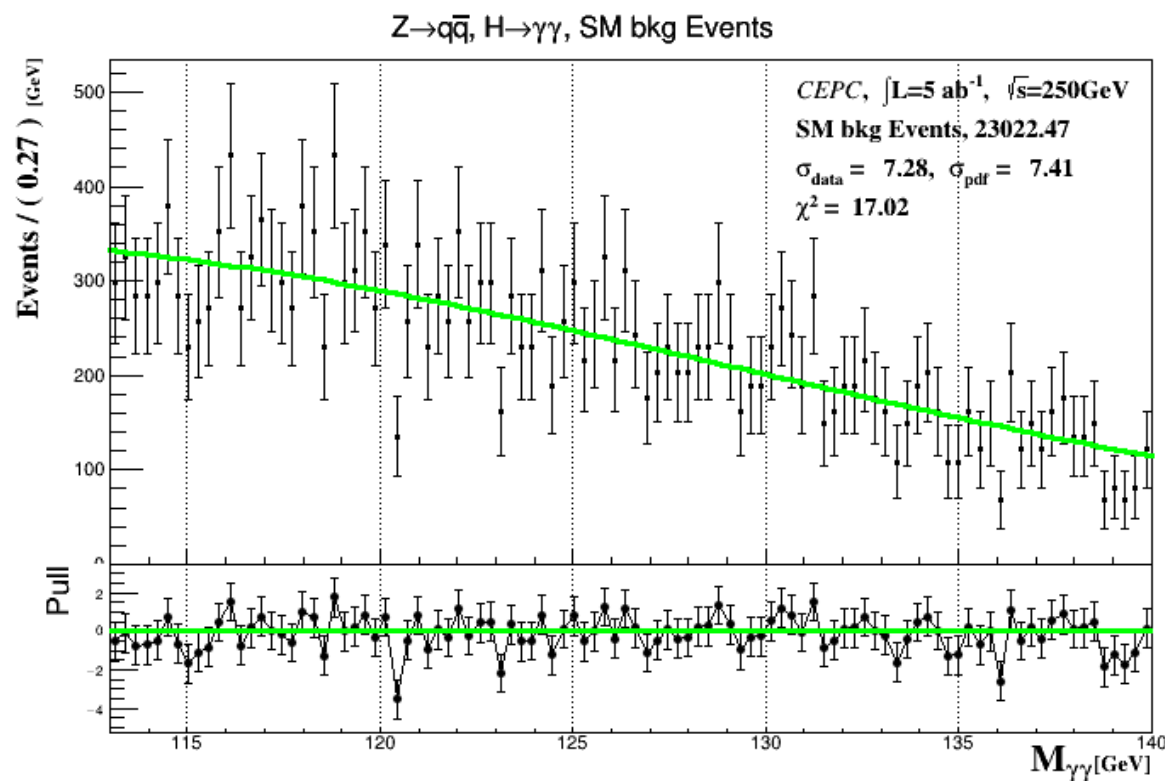
$$CB(m_{\gamma\gamma}) = N \times \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{low} \leq t \leq \alpha_{high} \\ \frac{e^{-\frac{1}{2}\alpha_{low}^2}}{\left[\frac{1}{R_{low}}(R_{low}-\alpha_{low}-t)\right]^{n_{low}}} & \text{if } t < -\alpha_{low} \\ \frac{e^{-\frac{1}{2}\alpha_{high}^2}}{\left[\frac{1}{R_{high}}(R_{high}-\alpha_{high}-t)\right]^{n_{high}}} & \text{if } t > \alpha_{high} \end{cases}$$
$$t = (m_{\gamma\gamma} - \mu_{CB})/\sigma_{CB}$$



Fit model—— $qq\gamma\gamma$ channel

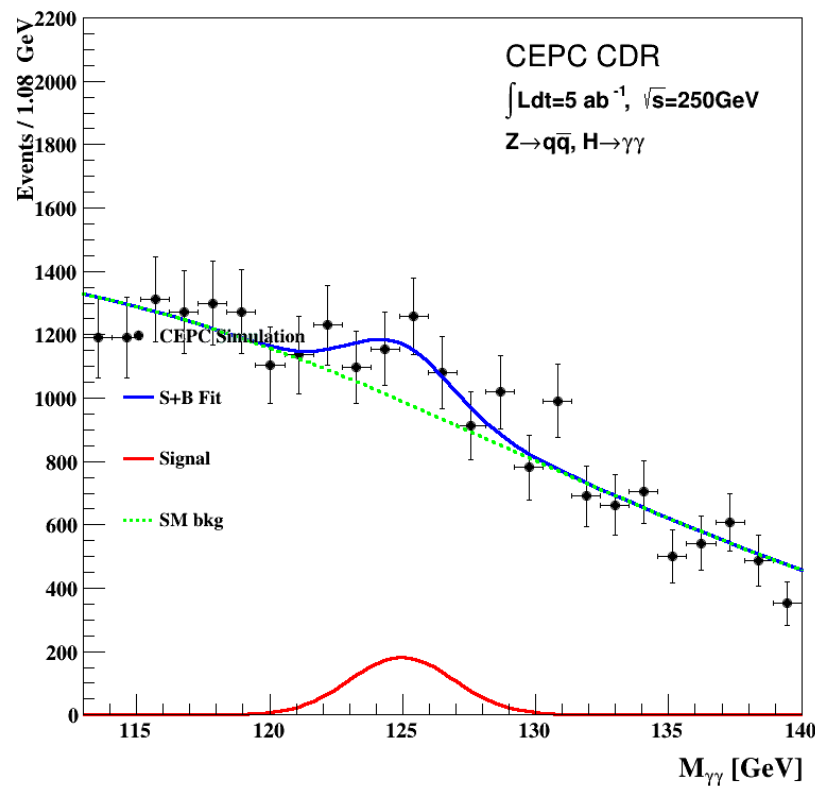
- Background Model
2nd polynomial exponential PDF

$$\text{PDF}(m_{\gamma\gamma}) = \exp\left[a \times \frac{(m_{\gamma\gamma} - 100)}{100} + b \times \left(\frac{m_{\gamma\gamma} - 100}{100}\right)^2\right]$$



Results— $qq\gamma\gamma$ channel

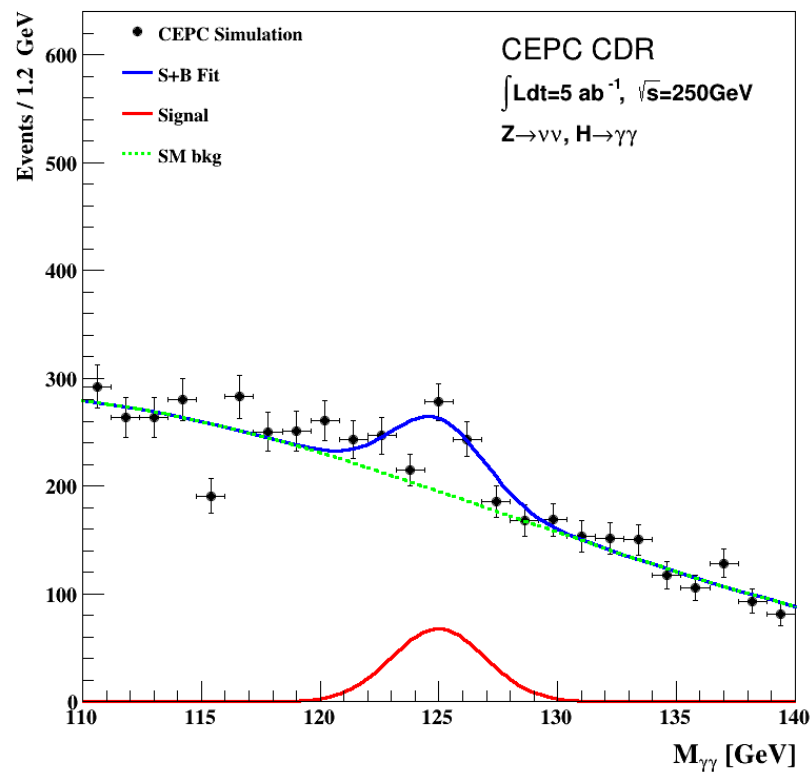
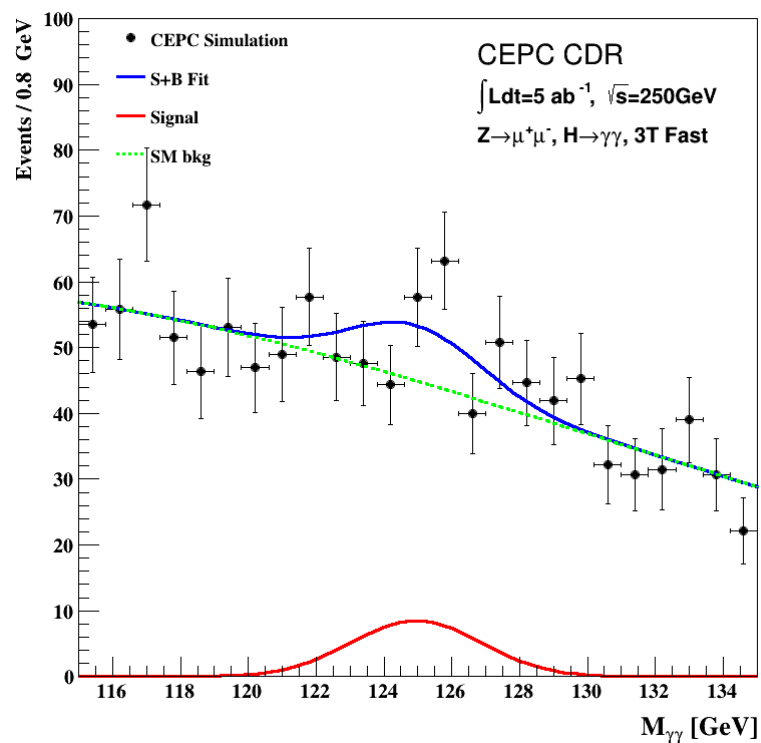
$$PDF_{sum} = \mu \times N_{sig}^{SM} \times PDF_{sig} + N_{bkg} \times PDF_{bkg}$$



$$\mu = 0.996^{+0.104}_{-0.103}$$

Results——all channels

Repeat the former process in the other 2 sub-channels



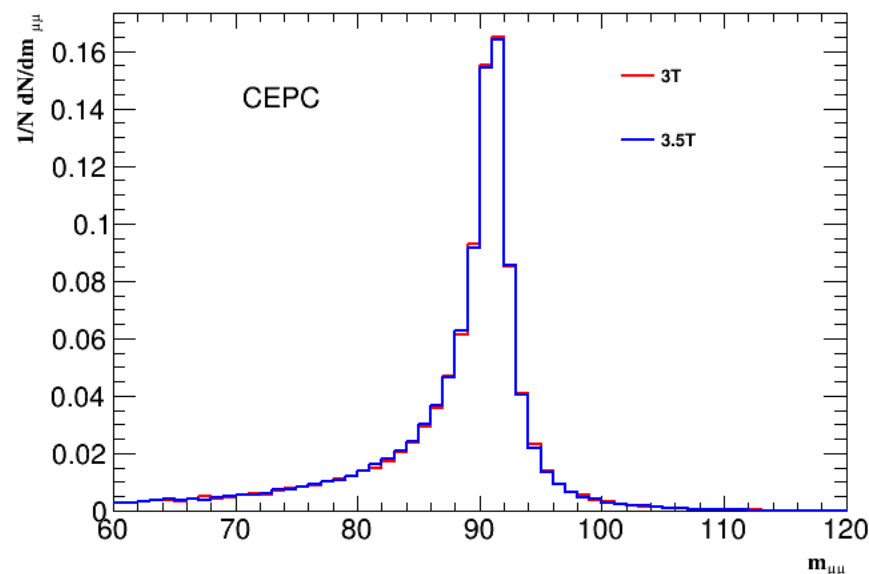
Channel	$\mu \pm \delta(\mu)(stats)$
$ll\gamma\gamma$	$0.997^{+0.419}_{-0.404}$
$qq\gamma\gamma$	$0.996^{+0.104}_{-0.103}$
$\nu\nu\gamma\gamma$	$0.997^{+0.138}_{-0.135}$
combined	$0.996^{+0.081}_{-0.081}$

Comparison due to different magnetic fields

— $\mu\mu\gamma\gamma$ channel

Magnetic field design: 3.5T(preCDR) $\rightarrow$ 3.0T(present)

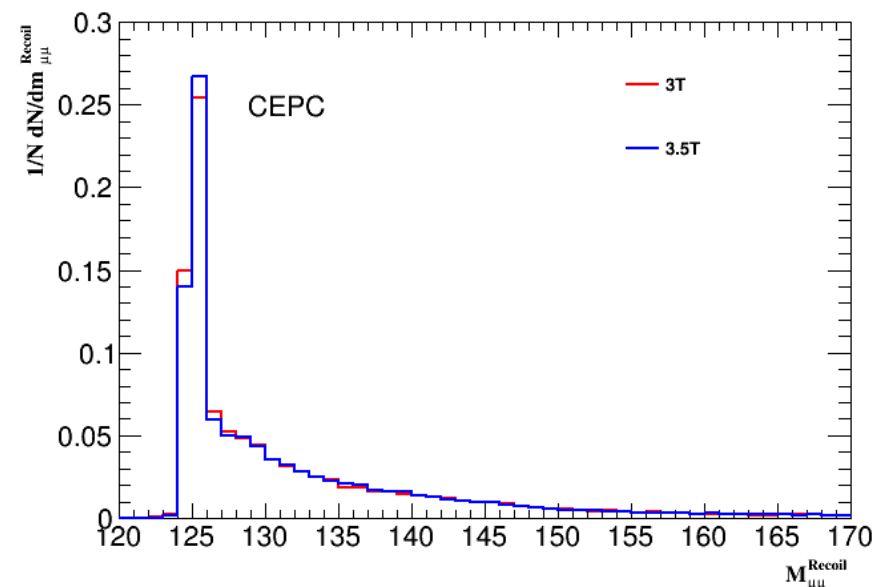
Effect: charged particle reconstruction and resolution



width(double-side CB)

3.5T: $1.01 \pm 0.73 \text{ GeV}$

3.0T: $1.05 \pm 0.69 \text{ GeV}$



width(double-side CB)

3.5T: $0.21 \pm 0.07 \text{ GeV}$

3.0T: $0.33 \pm 0.08 \text{ GeV}$

Comparison due to different magnetic fields

Measurement precision in 3.5T
fast simulation by Feng Wang

Channel	$\delta(Br \times \sigma)/(Br \times \sigma)$
$ZH \rightarrow \mu\mu\gamma\gamma$	30.04%
$ZH \rightarrow \tau\tau\gamma\gamma$	32.14%
$ZH \rightarrow qq\gamma\gamma$	13.56%
$ZH \rightarrow \nu\nu\gamma\gamma$	14.26%
Total	9.0%

Measurement precision in 3.0T
fast simulation present

Channel	$\delta(Br \times \sigma)/(Br \times \sigma)$
$ZH \rightarrow \mu\mu\gamma\gamma$	41.11%
$ZH \rightarrow \tau\tau\gamma\gamma$	
$ZH \rightarrow qq\gamma\gamma$	10.35%
$ZH \rightarrow \nu\nu\gamma\gamma$	13.65%
Total	8.09%

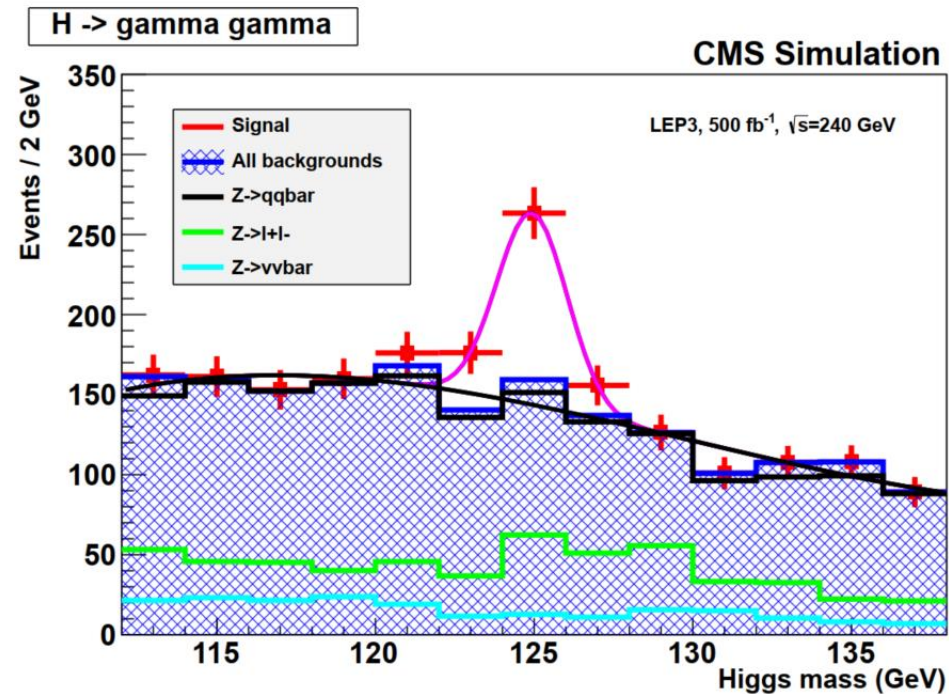
! Not completely repeat

Comparison with other experiments——FCC-ee

- Luminosity: 500 fb^{-1} , about 250 $H \rightarrow \gamma\gamma$ events
- Signal: $e^+e^- \rightarrow ZH \rightarrow f\bar{f}\gamma\gamma$
- Main background: $e^+e^- \rightarrow Z\gamma\gamma$, without the beamstrahlung (FSR) background.
- Simulation: CMS full simulation, Ecal resolution $\frac{\sigma_E}{E} = \frac{3.5\%}{\sqrt{E}} \oplus 0.3\%$
- Selection:
 - $E_\gamma > 40\text{GeV}$
 - Higgs candidate: diphoton recoil mass closest to the Z mass
 - the sum of two photon isolations less than 0.4 85% signal left
 - $\Delta\eta_{\gamma\gamma} < 1.8, \theta_{higgs} > 25^\circ$ 60% signal left
- Fit model: Gaussian signal and 3rd-order polynomial background
- Precision: 14%

Arxiv:1208.1662

Comparison with other experiments——FCC-ee



$\sqrt{s}$	240 GeV
Instant luminosity	5×10^{34}
Interaction point	4
Operation time	5 years
Total integrate luminosity	10 ab^{-1}
Precision	3.0%

Arxiv: 1308.6176

Further work

- Simulation method:

fast simulation



Include photon conversion,
track reconstruction, etc.

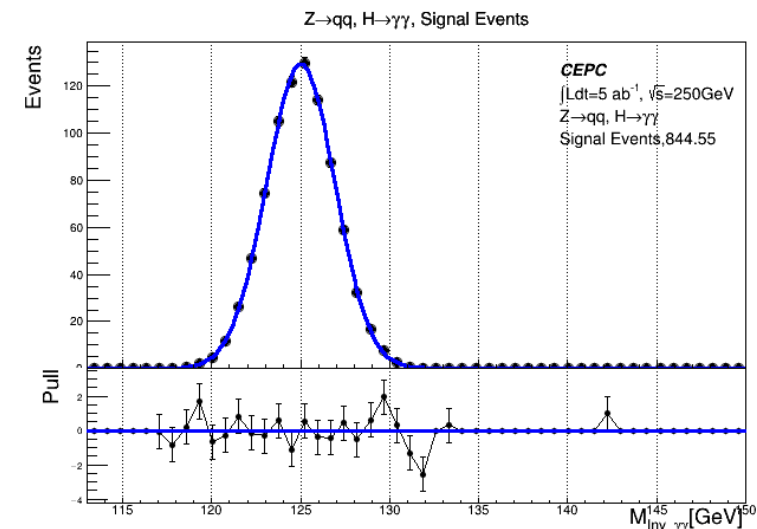
full simulation

Photon conversion:

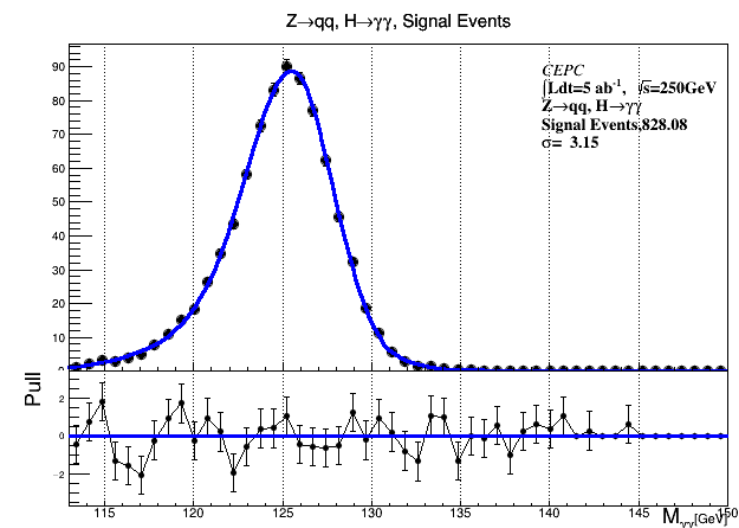
High- energy photon converted to di-electron, which is not considered in fast simulation

- Lose 7.5% events
- Broaden the $m_{\gamma\gamma}$ peak

Precision: 10.6%(fast sim.) vs. 12.8%(full sim.)



Fast sim. Width=1.93GeV

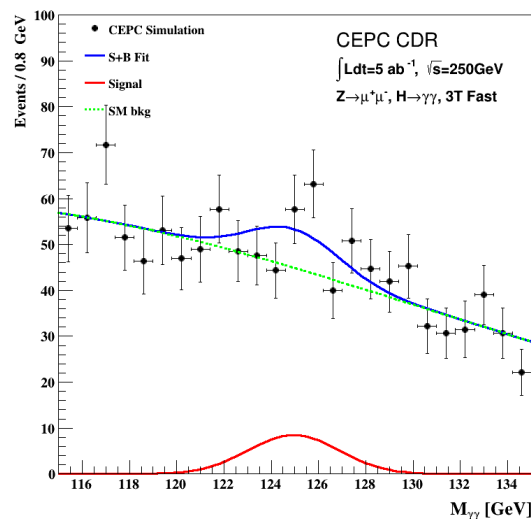


Full sim. Width=3.15GeV

Further work

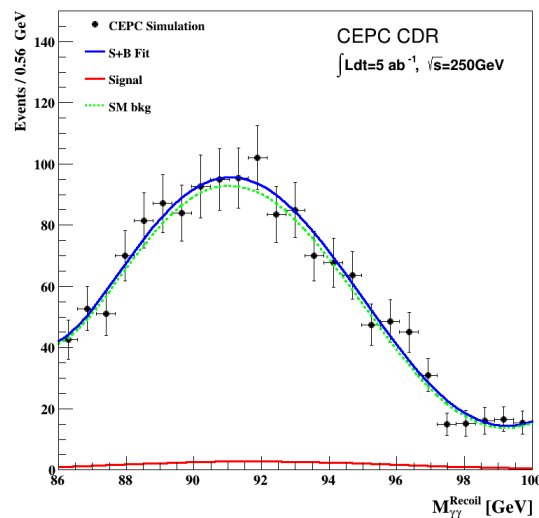
- Measurement variable (fast sim. $\mu\mu\gamma\gamma$ channel for example)

$$m_{\gamma\gamma}, m_{\gamma\gamma}^{recoil}, m_{\mu\mu}, m_{\mu\mu}^{recoil}$$



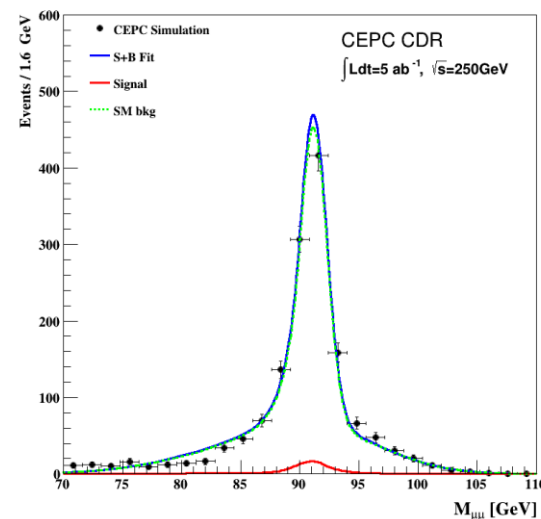
$$m_{\gamma\gamma}$$

Precision: 47.2%



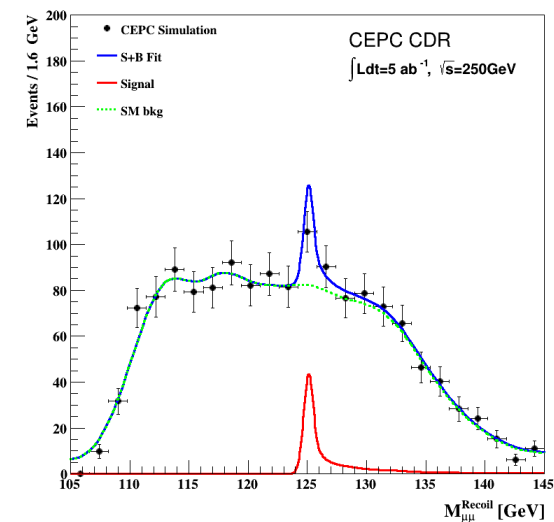
$$m_{\gamma\gamma}^{recoil}$$

Precision: 93.8%



$$m_{\mu\mu}$$

Precision: 81.6%



$$m_{\mu\mu}^{recoil}$$

Precision: 36.7%

Conclusion

- The present $\delta(Br \times \sigma)/(Br \times \sigma)$ for $H \rightarrow \gamma\gamma$ reaches to 8.09% with the results combined with 3 sub-channels, and can be approved by optimizing the selection methods.
- The change of magnetic field has limited influences in the measurement precision.
- Compared with the FCC-ee, the precision is a bit worse, mainly due to the Ecal resolution and the total luminosity.
- Next step: apply the full simulation into all sub-channels for a more credible simulation.

Thank you

Back up

$l\bar{l}\gamma\gamma$ channel cut flow

Select $\mu\mu\gamma\gamma$ final state from $l\bar{l}$ samples

	$\mu\mu$ signal		$\tau\tau$ signal		$\mu\mu$ background		$\tau\tau$ background	
generated	100000		100000		26930165		10000000	
$\mu\mu\gamma\gamma$	138039	138.039%	3274	3.274%	1393678	5.175%	6204	0.062%
$E_\gamma > 35\text{GeV}$	100602	72.879%	2980	91.020%	149107	10.699%	1045	16.844%
$ \cos\theta_\gamma < 0.9$	83759	83.258%	2470	82.886%	58507	39.238%	369	35.311%
$10\text{GeV} < pT_{\gamma 1} < 70\text{GeV}$	83740	99.977%	2470	100.000%	55978	95.677%	358	97.019%
$30\text{GeV} < pT_{\gamma 2} < 100\text{GeV}$	83509	99.724%	2466	99.838%	48173	86.057%	327	91.341%
$110\text{GeV} < m_{\gamma\gamma} < 140\text{GeV}$	81610	97.726%	2449	99.311%	16799	34.872%	126	38.532%
$84\text{GeV} < M_{\gamma\gamma}^{\text{recoil}} < 103\text{GeV}$	71416	87.509%	2180	89.016%	3174	18.894%	37	29.365%
$125\text{GeV} < E_{\gamma\gamma} < 143\text{GeV}$	71409	99.990%	2180	100.000%	3048	96.030%	35	94.595%
$\min \cos\theta_{\gamma l} < 0.9$	71248	99.775%	2172	99.633%	2704	88.714%	35	100.000%
		71.248%		2.172%		0.010%		0.0004%
scaled to 5 ab-1	55.43		1.66		2677.23		83.18	

$\nu\nu\gamma\gamma$ channel cut flow

	$\nu\nu$ signal		$\nu\nu$ background	
generated	100000		10000000	
$\nu\nu\gamma\gamma$	109362	109.362%	339131	3.391%
$E_\gamma > 30\text{GeV}$	107475	98.275%	241700	71.270%
$ \cos\theta_\gamma < 0.8$	71613	66.632%	31037	12.841%
$pT_\gamma > 20\text{GeV}$	69172	96.591%	10351	33.351%
$120\text{GeV} < E_{\gamma\gamma} < 150\text{GeV}$	68731	99.362%	3783	36.547%
$110\text{GeV} < m_{\gamma\gamma} < 140\text{GeV}$	68727	99.994%	1752	46.312%
		68.727%		0.018%
scaled to 5 ab-1	360.82		4436.2	

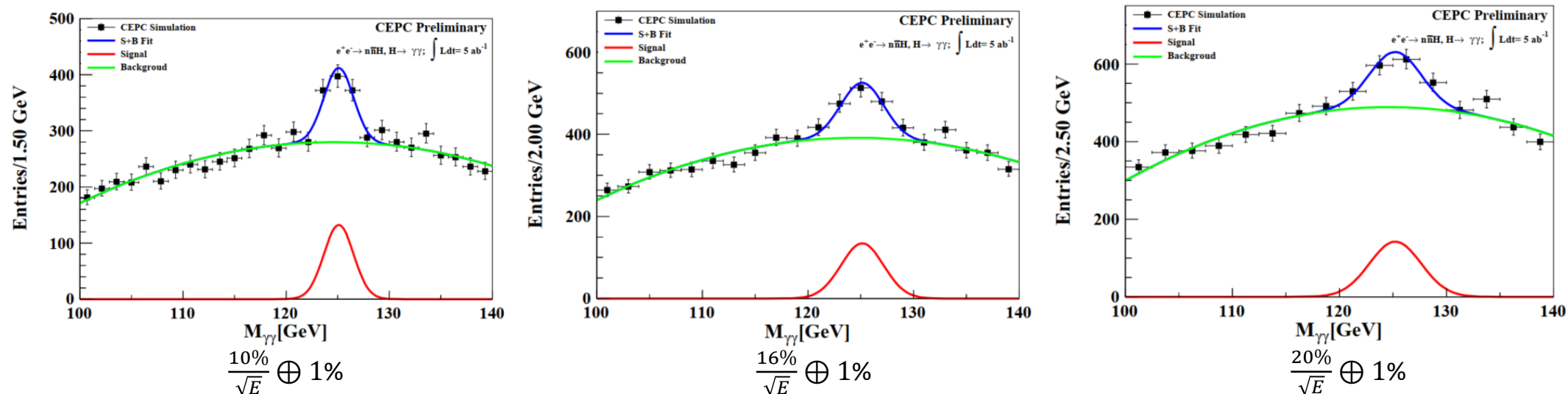
Results from Feng Wang — $\nu\nu\gamma\gamma$ channel

- Cut1: $E_\gamma > 35\text{GeV}$
- Cut2: $|\cos\theta_\gamma| < 0.84$
- Cut3: $M_{\gamma\gamma}^{\text{recoil}} < 110\text{GeV}$
- Cut4: $pT_{\gamma 1} > 37\text{GeV}$ & $pT_{\gamma 2} > 48\text{GeV}$

Channel	Generate	cut1	cut2	cut3	cut4
nnH_aa	Efficiency	100%	82.94%	61.22%	57.45%
nnH_aa	557	557	462	341	320
nnaa	1276400	401626	105008	16182	13231

Results from Feng Wang — $\nu\nu\gamma\gamma$ channel

Comparison due to the Ecal resolution



$\frac{\delta E}{E}$	$\frac{10\%}{\sqrt{E}} \oplus 1\%$	$\frac{16\%}{\sqrt{E}} \oplus 1\%$	$\frac{20\%}{\sqrt{E}} \oplus 1\%$
Signal yields (S)	334 ± 40	339 ± 46	342 ± 51
Background yields (B)	7059 ± 91	7053 ± 94	7047 ± 96
Significance	8.65σ	7.11σ	6.37σ
$\delta(Br \times \sigma)/(Br \times \sigma)$	11.98%	13.56%	14.91%

Results from Feng Wang — $qq\gamma\gamma$ channel

- Cut1: $E_\gamma > 35\text{GeV}$
- Cut2: $|\cos\theta_\gamma| < 0.9$
- Cut3: $20\text{GeV} < pT_{\gamma 1} < 97\text{GeV}$ & $26\text{GeV} < pT_{\gamma 2} < 100\text{GeV}$
- Cut4: $85\text{GeV} < M_{\gamma\gamma}^{\text{recoil}} < 100\text{GeV}$
- Cut5: $pT_{\gamma\gamma} > 118\text{GeV}$
- Cut6: $130\text{GeV} < E_{\gamma\gamma} < 150\text{GeV}$

Channel	Generate	cut1	cut2	cut3	cut4	cut5	cut6
qqH_aa	Efficiency	100%	89.41%	75.81%	54.38%	34.78%	34.78%
qqH_aa	1633	1633	1460	1238	888	568	568
qqaa	11011914	2027271	803856	228018	93878	24390	19184
ww	42455430	46318	20339	6616	17	0	0
zz	5805561	15716	2913	990	51	17	11
wworzz	19700221	18953	8723	3630	14	14	14

Results from Feng Wang — $ll\gamma\gamma$ channel

- Cut1: $E_\gamma > 35\text{GeV}$
- Cut2: $|\cos\theta_\gamma| < 0.9$
- Cut3: $20\text{GeV} < pT_{\gamma 1} < 93\text{GeV}$ & $30\text{GeV} < pT_{\gamma 2} < 100\text{GeV}$ ($\mu\mu$ channel)
 $30\text{GeV} < pT_{\gamma 1} < 93\text{GeV}$ & $36\text{GeV} < pT_{\gamma 2} < 100\text{GeV}$ ($\tau\tau$ channel)
- Cut4: $86\text{GeV} < M_{\gamma\gamma}^{\text{recoil}} < 100\text{GeV}$
- Cut5: $136\text{GeV} < E_{\gamma\gamma} < 148\text{GeV}$ ($\mu\mu$ channel)
 $130\text{GeV} < E_{\gamma\gamma} < 148\text{GeV}$ ($\mu\mu$ channel)
- Cut6: $\min|\cos\theta_{\gamma j}| < 0.9$

Channel	Generate	cut1	cut2	cut3	cut4	cut5	cut6
$\mu^+\mu^- H_{aa}$	Efficiency	100%	91.56%	72.28%	55.42%	54.21%	42.17%
$\mu^+\mu^- H_{aa}$	83	83	76	60	46	45	35
$\mu^+\mu^- aa$	1135659	214725	66703	23786	6427	1887	1026
$\tau^+\tau^- H_{aa}$	Efficiency	98.67%	89.33%	61.33%	48.00 %	46.67%	41.89%
$\tau^+\tau^- H_{aa}$	75	74	67	46	36	35	31
$\tau^+\tau^- aa$	429975	146922	49424	14533	3562	1778	1410

Results from Yitian—— $qq\gamma\gamma$ channel fast sim. VS. full sim.

Fast

	After:	UnCut	Cut1	Cut2	Cut3	Cut4
Signal 914	Run:	39997	39183	29304	25274	22378
	Weighted:	1632	1599	1196	1031	914
	Efficiency:	100%	97.96%	73.27%	63.19%	55.95%
Bkg 32744	Run:	11300000	99092	91418	51406	33601
	Weighted:	11011914	96565	89087	50095	32744
	Efficiency:	100%	0.88%	0.81%	0.45%	0.30%

Full

	After:	UnCut	Cut1	Cut2	Cut3	Cut4
Sig 828	Event:	37154	36540	27597	23821	20296
	Weighted:	1516	1491	1126	972	828
	Efficiency:	100%	98.35%	74.28%	64.11%	54.63%
Bkg 29137	Event:	11300000	92362	85041	51049	29900
	Weighted:	11011914	90007	82872	49747	29137
	Efficiency:	100%	0.82%	0.75%	0.45%	0.26%

Sig:	Fast: 914 * 92.5% = 845,	Full: 828
Bkg:	Fast: 32744 * 92.5% = 30288 (could be different)	Full: 29137

Cut1: $E_\gamma > 35\text{GeV}$, $|\cos\theta_\gamma| < 0.99$

Cut2: $(\cos\theta_{\gamma 1} + 1)(\cos\theta_{\gamma 2} - 1) < -0.07$
 $(\cos\theta_{\gamma 1} - 1)(\cos\theta_{\gamma 2} + 1) < -0.07$
 $|\cos\theta_{\gamma 1} + \cos\theta_{\gamma 2}| < 0.9$

Cut3: $\cos(p_{\gamma 1}, p_{recoil}) > -0.95$
 $\cos(p_{\gamma 2}, p_{recoil}) < 0.70$

Cut4: $E_{\gamma\gamma} < 0.48M_{\gamma\gamma} + 41\text{GeV}$
 $E_{\gamma\gamma} > 0.74M_{\gamma\gamma} + 41\text{GeV}$

Comparison with other experiments——ILC

$\sqrt{s}$	250 GeV
Instant luminosity	0.75×10^{34}
Total integrate luminosity	250 fb^{-1}
Precision	34%