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Higgs measurement with $H \rightarrow \gamma\gamma$ channel in CEPC

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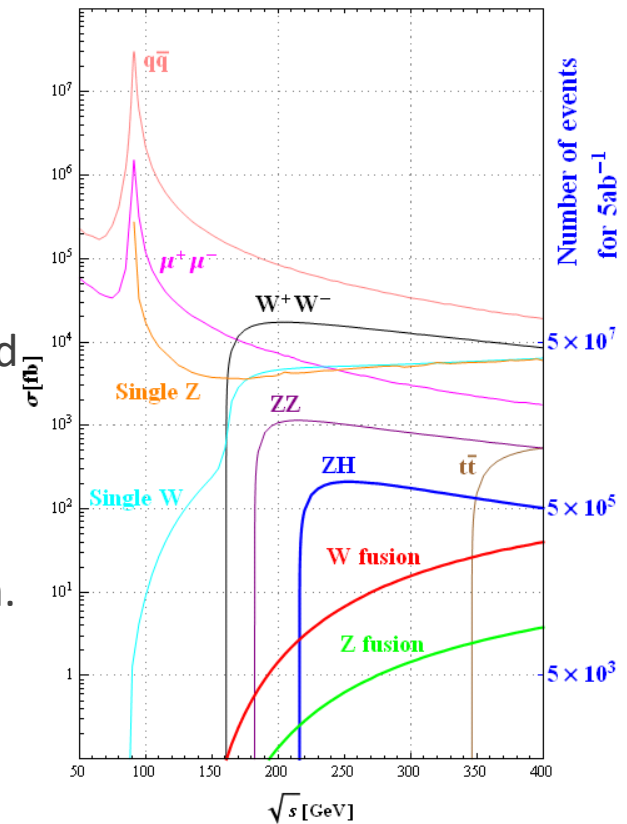
Extrapolation for 360GeV.

Conclusion .

Introduction

Higgs physics in CEPC

- Higgs production: $ee \rightarrow ZH$ process @ 240GeV e^+e^- collider.
- $H \rightarrow \gamma\gamma$ could be studied in 3 sub-channels, depending on Z decay(leptonic, hadronic and invisible).
- Important for Higgs precise measurement in CEPC
- Also a benchmark for EM calorimeter design.



Review of previous analysis

$H \rightarrow \gamma\gamma$ physics analysis in [CEPC CDR\(2018\)](#):

- Design point at CEPC_v4, $\sqrt{s} = 240\text{GeV}$, $\mathcal{L} = 5.6\text{ab}^{-1}$
- Whizard 1.95 + MoccaC generator, dedicated fast simulation + smearing function based on parametrized detector response.
- Considered $H \rightarrow \gamma\gamma$ signal and 2 fermion dominant background
- Result: $\delta(Br(H \rightarrow \gamma\gamma) \times \sigma(ZH))=6.84\%$ in 3 combined channels.

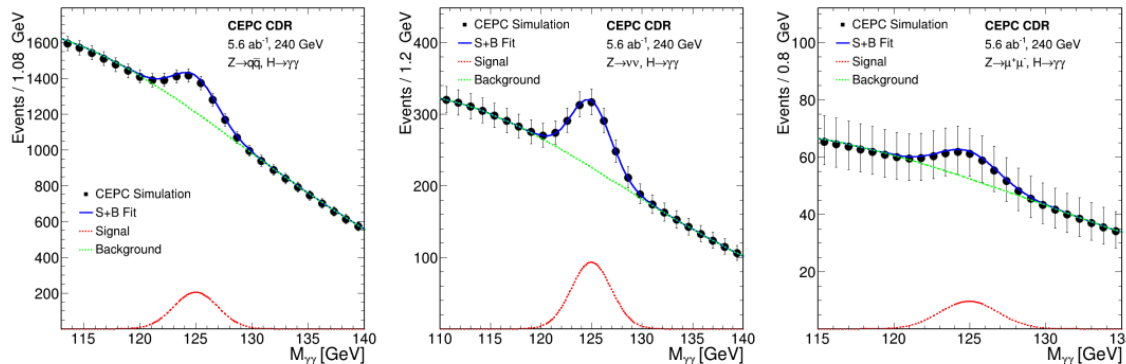


Figure1. di-photon invariant mass distributions in 3 sub-channel

| Channel | Precision |
|------------------------|-----------|
| $q\bar{q}\gamma\gamma$ | 9.84% |
| $l\bar{l}\gamma\gamma$ | 23.7% |
| $\nu\nu\gamma\gamma$ | 10.5% |
| Combined | 6.84% |

[Ref: Precision Higgs Physics at the CEPC](#)

MC samples and simulation

MC samples: Whizard 1.95 + MoccaC, 3 sub-channels

- Signal: $ee \rightarrow ZH \rightarrow qq\gamma\gamma/\mu\mu\gamma\gamma/\nu\nu\gamma\gamma$, 10k events for each channel.
- Background: 2 fermion process $ee \rightarrow ff$ +radiation photons

Simulation:

- Background:

Fast simulation: smear the objects with the resolution and efficiency with parametrized detector response to obtain a continuum spectrum.

- Signal:

Full CEPC detector V4 simulation. Photon reconstruction & Isolation, jet clustering, etc.

define: γ_1/f_1 as photon/jet with lower energy, and γ_2/f_2 as higher energy one.

MC samples and simulation

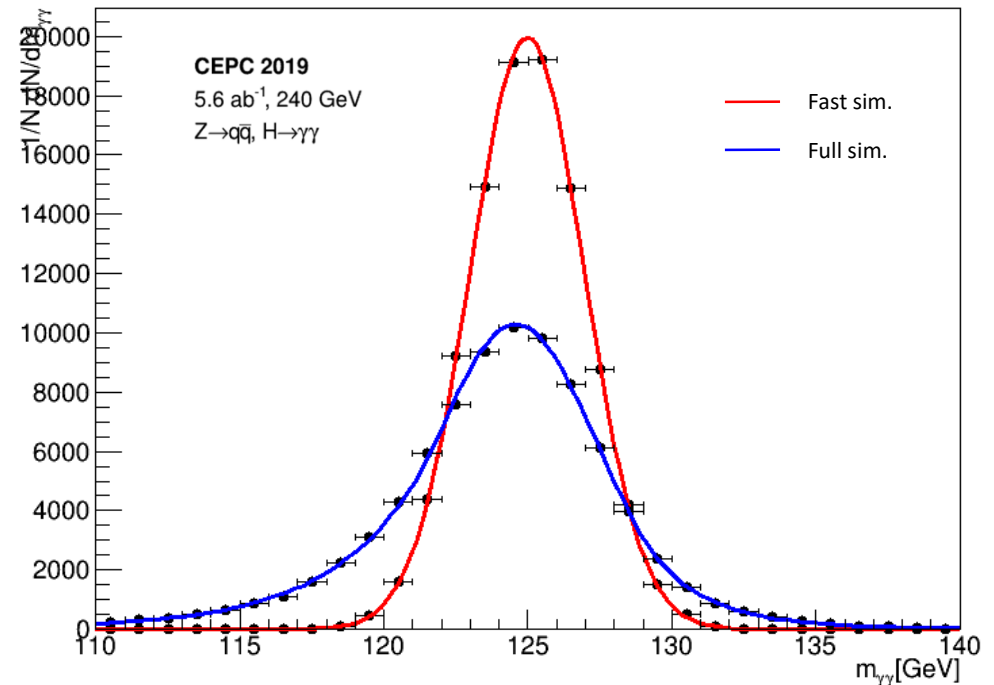
$qq\gamma\gamma$ channel sample:

| | $qq\gamma\gamma$ eff | Mass width |
|----------|----------------------|------------|
| Fast sim | 99.9% | 1.98GeV |
| Full sim | 85.6% | 2.81GeV |

$\mu\mu\gamma\gamma$ channel:

Lepton PID efficiency:87%

→ $\mu\mu\gamma\gamma$ final state eff=70%
(also ~100% in fast sim.)



$m_{\gamma\gamma}$ shape for fast and full simulation in $ZH \rightarrow qq\gamma\gamma$ channel.

Fit shape: Gaussian for fast sim, Double-side Crystal Ball(DSCB) for full sim.

MC samples and simulation

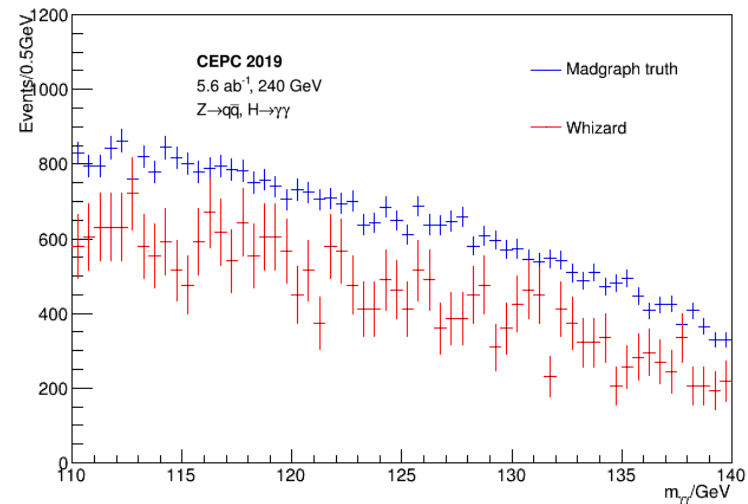
Background cross section validation in $q\bar{q}\gamma\gamma$ channel

- MadGraph_aMC , $e^+e^- \rightarrow q\bar{q}\gamma\gamma$ process, truth level MC.
- Whizard 1.95, $e^+e^- \rightarrow q\bar{q} + ISR$, reconstructed with smearing.

Apply the selection(next page), compare the weighted event number in signal region.

- Whizard: 26849.38 ($\epsilon_{reco} \sim 70\%$)
- Truth Madgraph: 38145.34

Whizard is reliable in $\sigma(ee \rightarrow qq)$ calculation.



Di-photon invariant mass in signal region, Madgraph and Whizard sample.

MVA based $\delta(\sigma \times Br)$ measurement

Pre-selection

$E_{\gamma 1} > 25\text{GeV}$
 $35\text{GeV} < E_{\gamma 2} < 96\text{GeV}$
 $\cos\theta_{\gamma\gamma} > -0.95,$
 $\cos\theta_{jj} > -0.95$
 $pT_{\gamma 1} > 20\text{GeV},$
 $pT_{\gamma 1} > 30\text{GeV}$
 $110\text{GeV} < m_{\gamma\gamma} < 140\text{GeV}$
 $E_{\gamma\gamma} > 120\text{GeV}$
 $\min|\cos\theta_{\gamma j}| < 0.9$

| | Signal | background |
|-------------------------------|--------|------------|
| Total eff | 61.51% | 0.02% |
| Scaled to 5.6fb^{-1} | 766.64 | 26849.38 |

$E_{\gamma} > 35\text{GeV}$
 $|\cos\theta_{\gamma}| < 0.9$
 $10\text{GeV} < pT_{\gamma 1} < 70\text{GeV}$
 $30\text{GeV} < pT_{\gamma 2} < 100\text{GeV}$
 $110\text{GeV} < m_{\gamma\gamma} < 140\text{GeV}$
 $84\text{GeV} < M_{\gamma\gamma}^{\text{recoil}} < 103\text{GeV}$
 $125\text{GeV} < E_{\gamma\gamma} < 143\text{GeV}$

| | Signal | background |
|-------------------------------|--------|------------|
| Total eff | 45.69% | 0.01% |
| Scaled to 5.6fb^{-1} | 39.32 | 2662.77 |

$E_{\gamma} > 30\text{GeV}$
 $|\cos\theta_{\gamma}| < 0.8$
 $pT_{\gamma} > 20\text{GeV}$
 $M_{\text{missing}} > 60\text{GeV}$
 $110\text{GeV} < m_{\gamma\gamma} < 140\text{GeV}$
 $120\text{GeV} < E_{\gamma\gamma} < 150\text{GeV}$

| | Signal | Background |
|-------------------------------|--------|------------|
| Total eff | 57.08% | 0.002% |
| Scaled to 5.6fb^{-1} | 335.88 | 3640.20 |

MVA based $\delta(\sigma \times Br)$ measurement

MVA analysis

- Base variables: 4-vector of 4 particles in final state.
- Considered variables for MVA: constructed with 4-vector P , p_T , E , $\cos\theta$, recoil mass, missing mass(for ν channel) for photons, fermions, systems.

ΔP , ΔE , $\Delta\Phi$, $\Delta\cos\theta$, ΔR for 2 objects or systems.

- Separation power: $\langle S^2 \rangle = \frac{1}{2} \int \frac{(\hat{y}_s(y) - \hat{y}_b(y))^2}{\hat{y}_s(y) + \hat{y}_b(y)} dy.$

y : discriminating variable

$\hat{y}_s(y)$ and $\hat{y}_b(y)$: the distributions of the variable for signal and background samples

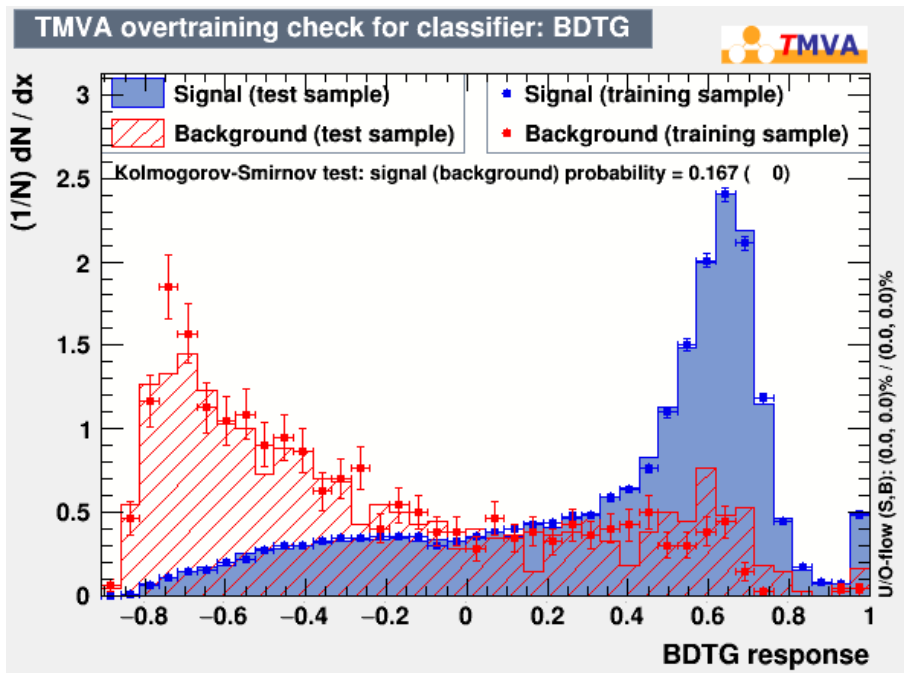
MVA based $\delta(\sigma \times Br)$ measurement --- $qq\gamma\gamma$ channel

Remain variables' separation power

| Variable | Definition | $\langle S^2 \rangle$ |
|----------------------------------|--|-----------------------|
| $pT_{\gamma 1} / pT_{\gamma 2}$ | pT of $\gamma 1$ or $\gamma 2$ | 0.39 / 0.30 |
| $\cos\theta_{\gamma 2}$ | Cosine polar angle of $\gamma 2$ | 0.39 |
| $ \Delta\Phi_{\gamma\gamma} $ | $ \Delta\Phi $ between 2 photons | 0.30 |
| $\min\Delta R_{\gamma,j}$ | Minimum ΔR between photon and jet | 0.09 |
| $\cos\theta_{j1}$ | Cosine polar angle of $j1$ | 0.08 |
| pT_{j2} | pT of $j2$ | 0.08 |
| E_{j1} | Energy of $j1$ | 0.03 |
| $\cos\theta_{\gamma 2-j2}$ | Cosine value of the angle between $\gamma 2$ and $j2$ | 0.03 |
| $\cos\theta_{\gamma 1-j1}$ | Cosine value of the angle between $\gamma 1$ and $j1$ | 0.02 |
| $ \Delta\Phi_{\gamma\gamma-jj} $ | $ \Delta\Phi $ between $\gamma\gamma$ and jj system | 0.01 |
| $\cos\theta_{\gamma\gamma-jj}$ | Cosine value of the angle between $\gamma\gamma$ and jj system | 0.01 |

MVA based $\delta(\sigma \times Br)$ measurement --- $qq\gamma\gamma$ channel

BDT training



BDT response distribution for signal and background

Training parameter:
“BDTG”, “NTrees=900:nEventsMin=50:
BoostType=Grad:Shrinkage=0.06:UseB
aggedGrad:GradBaggingFraction=0.6:n
Cuts=20:MaxDepth=3”

Perform the training in 3 sub-channels separately.

MVA based $\delta(\sigma \times Br)$ measurement --- $qq\gamma\gamma$ channel

Signal strength extraction $\mu = N_{H \rightarrow \gamma\gamma}^{obs} / N_{H \rightarrow \gamma\gamma}^{SM}$

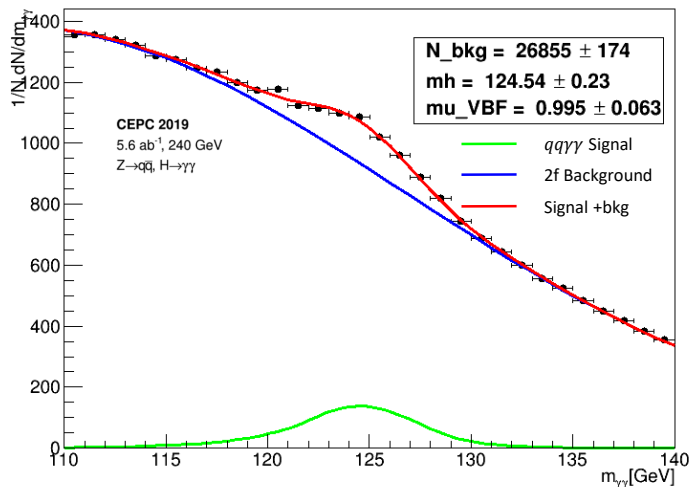
- Individual 2-D fit on $m_{\gamma\gamma}$ and BDT response.

Fit function for $m_{\gamma\gamma}$: DSCB for signal, 2nd polynomial exponential for Bkg.

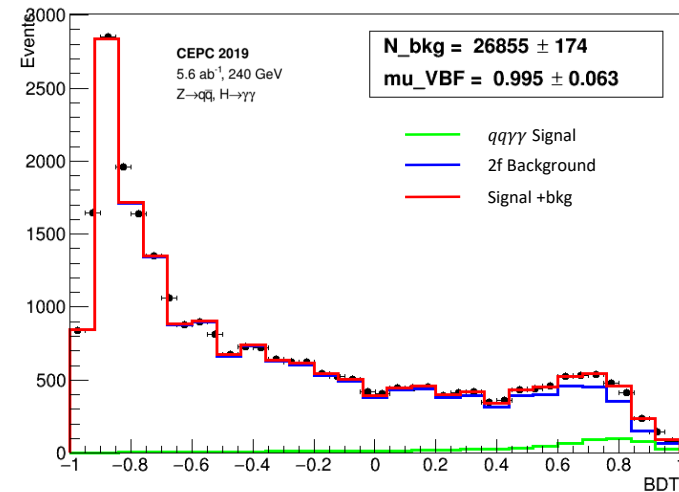
Model for BDT: binned PDF for signal and Bkg

$$PDF_{2D} = PDF_{m_{\gamma\gamma}} \times PDF_{BDT} (|Corr_{m_{\gamma\gamma}-BDT}| = 3\%(15\%) \text{ for signal(Bkg)})$$

Fit $m_{\gamma\gamma}$ in $qq\gamma\gamma$ channel



BDTout distribution in $qq\gamma\gamma$ channel



MVA based $\delta(\sigma \times Br)$ measurement

Results

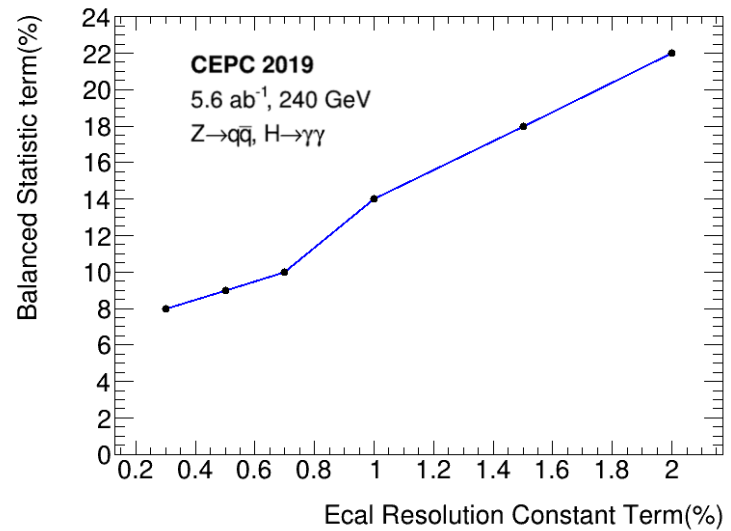
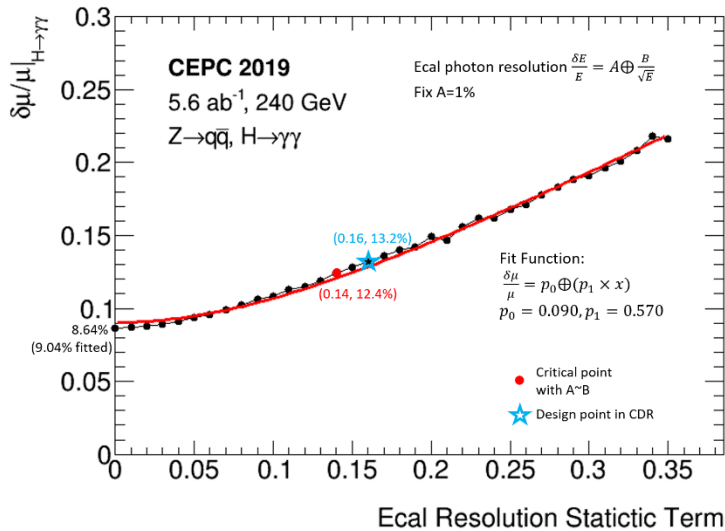
| Channel | Full sim + MVA (New) | Fast sim + noMVA (CDR) | Change |
|----------------------|-------------------------|---------------------------|---------------|
| $qq\gamma\gamma$ | 6.31% | 9.84% | 36% improved |
| $\mu\mu\gamma\gamma$ | 39% | 23.7% | 64% decreased |
| $\nu\nu\gamma\gamma$ | 18% | 10.5% | 71% decreased |
| combined | 5.70% | 6.84% | 16% improved |

FCC-ee case:

- 3% @240GeV, $10ab^{-1}$, based on CMS ECal resolution, [TLEP physics, 2013](#)
- 9% @240GeV, $5ab^{-1}$, [FCC-ee CDR, 2018](#)

ECal resolution influence

Smear photon energy to different resolution $\frac{\delta E}{E} = A \oplus \frac{B}{\sqrt{E}}$, and fit $m_{\gamma\gamma}$ distribution to extract $\delta\mu(H \rightarrow \gamma\gamma)$



$\frac{\delta\mu}{\mu} = p_0 \oplus (p_1 \times B)$, p_0 represent constant term contribution in $\delta\mu$, p_1 represent statistics term.

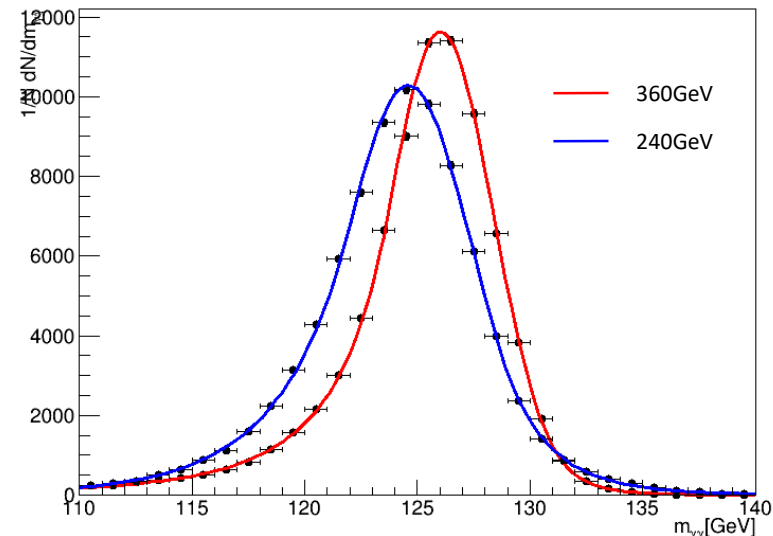
Critical point(A-B balance) definition: $\delta\mu(B_c) = \sqrt{2}\delta\mu(B = 0)$, ← $p_0 = p_1 B$

Extrapolation for 360GeV

$\mu\mu\gamma\gamma$ Whizard MC @ $\sqrt{s} = 360\text{GeV} + 240\text{GeV}$ simulation.

Difference:

- $m_{\gamma\gamma}$ width:
2.84GeV@240GeV
2.34GeV@360GeV
➡ Better photon resolution
- Efficiency:
80%@360GeV, 85%@240GeV
- Mass peak:
126.03GeV@360GeV.
➡ Re-calibration for detector



Conclusion

Full simulation + MVA analysis for $H \rightarrow \gamma\gamma$ channel

- Improvement from MVA + decrease from full simulation. combined precision 5.7% in 3 sub-channels.
- Photon correction like photon conversion was not included in full simulation, lepton PID efficiency need further study.

ECal resolution and precision

- 14% statistics term \sim 1% constant term.
- CEPC baseline detector still has improvement space.

CEPC @ $t\bar{t}$ (360GeV)

- Several topics need further discussion. (Reconstruction, calibration, etc.)
- $\sigma \times Br$ precision @360GeV is in plan.

Thank you

Back up

Full cutflow in 3 sub-channels

| | signal | bkg |
|--|----------|----------|
| $qq\gamma\gamma$ | 85.56% | 69.57% |
| $E_{\gamma_1} > 25\text{GeV}$ | 100.00% | 2.35% |
| $E_{\gamma_2} \in [35,96]\text{GeV}$ | 98.37% | 35.33% |
| $\cos\theta_{\gamma\gamma} > -0.95$ | 95.20% | 68.01% |
| $\cos\theta_{jj} > -0.95$ | 90.86% | 85.54% |
| $pT_{\gamma_1} > 20\text{GeV}$ | 93.42% | 56.94% |
| $pT_{\gamma_1} > 30\text{GeV}$ | 93.25% | 54.54% |
| $m_{\gamma\gamma} \in [110,140]\text{GeV}$ | 97.50% | 21.14% |
| $E_{\gamma\gamma} > 120\text{GeV}$ | 99.47% | 98.41% |
| $\min \cos\theta_{\gamma j} < 0.9$ | 71.67% | 48.05% |
| Total eff | 61.51% | 0.02% |
| Scaled to 5.6 fb^{-1} | 766.6433 | 26849.38 |

$qq\gamma\gamma$ channel

| | signal | bkg |
|---|----------|----------|
| $\mu\mu\gamma\gamma$ | 70.18% | 5.18% |
| $E_{\gamma} > 35\text{GeV}$ | 99.21% | 8.39% |
| $ \cos\theta_{\gamma} < 0.9$ | 83.79% | 38.14% |
| $pT_{\gamma_1} \in [10,70]\text{GeV}$ | 99.84% | 86.30% |
| $pT_{\gamma_2} \in [30,100]\text{GeV}$ | 99.96% | 95.59% |
| $m_{\gamma\gamma} \in [110,140]\text{GeV}$ | 98.08% | 37.62% |
| $M_{\gamma\gamma}^{\text{recoil}} \in [84,103]\text{GeV}$ | 80.12% | 21.29% |
| $E_{\gamma\gamma} \in [125,143]\text{GeV}$ | 99.88% | 95.86% |
| Total eff | 45.69% | 0.01% |
| Scaled to 5.6 fb^{-1} | 39.32263 | 2662.774 |

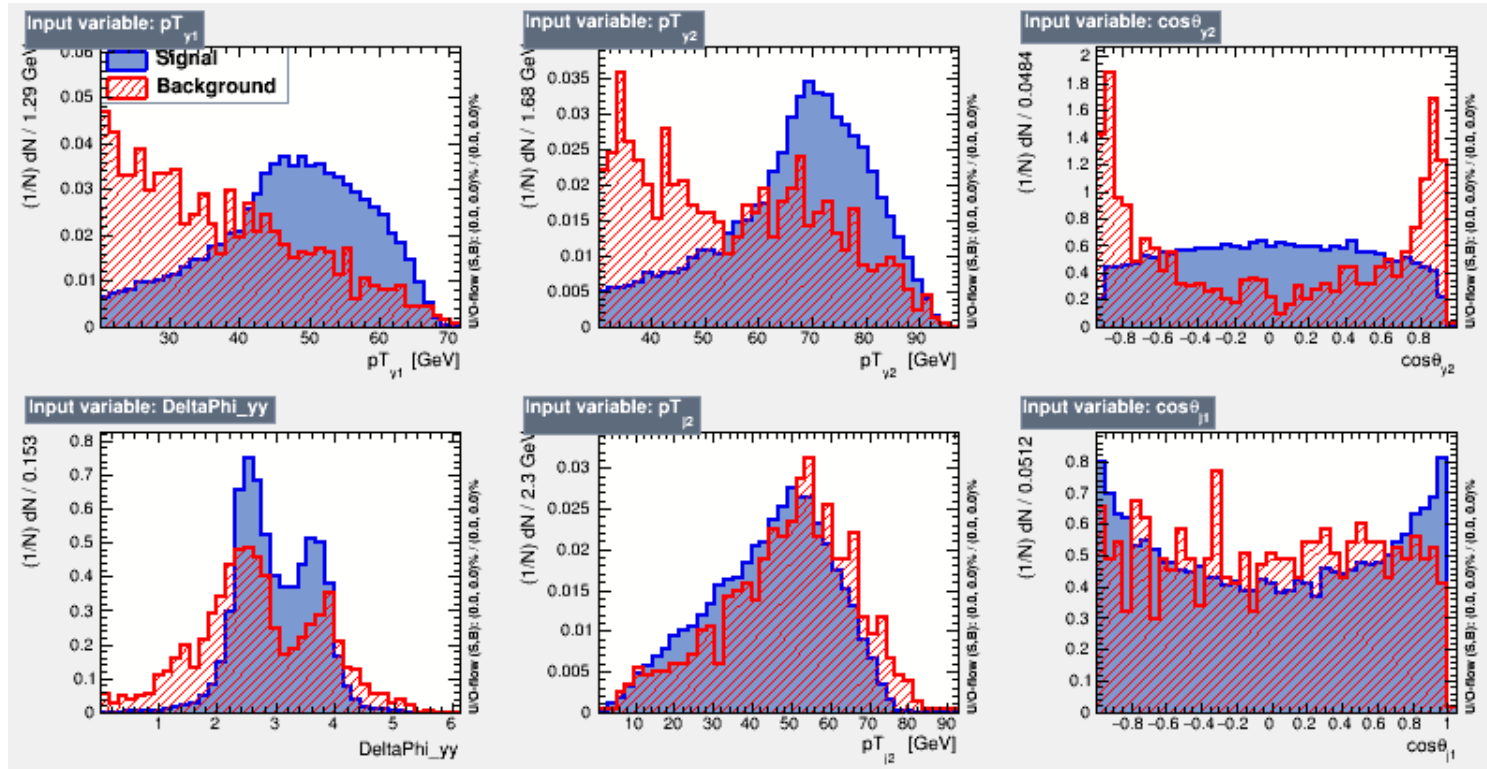
$\mu\mu\gamma\gamma$ channel

| | signal | bkg |
|--|----------|-----------|
| $\nu\nu\gamma\gamma$ | 85.51% | 0.337% |
| $E_{\gamma} > 30\text{GeV}$ | 99.81% | 20.131% |
| $ \cos\theta_{\gamma} < 0.8$ | 70.48% | 11.558% |
| $pT_{\gamma} > 20\text{GeV}$ | 99.97% | 99.260% |
| $M_{\text{missing}} > 60\text{GeV}$ | 98.17% | 99.711% |
| $m_{\gamma\gamma} \in [110,140]\text{GeV}$ | 97.51% | 22.864% |
| $E_{\gamma\gamma} \in [120,150]\text{GeV}$ | 99.16% | 99.577% |
| Total eff | 57.08% | 0.002% |
| Scaled to 5.6 fb^{-1} | 335.8863 | 3640.1967 |

$\nu\nu\gamma\gamma$ channel

MVA based $\delta(\sigma \times Br)$ measurement

--- $qq\gamma\gamma$ channel



MVA based $\delta(\sigma \times Br)$ measurement

--- $qq\gamma\gamma$ channel

