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Measurement of the Higgs decaying into two photons with the CEPC reference detector

The 2025 International Workshop on the High Energy Circular Electron Positron Collider, Guangzhou

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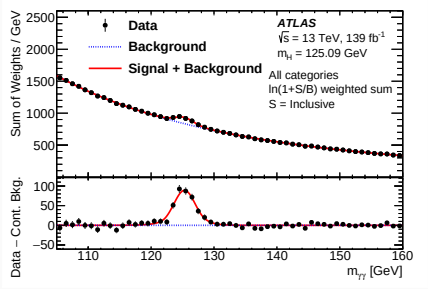
Introduction

Motivation:

- $H \to \gamma\gamma$ is a key probe, crucial to Higgs boson discovery + loop-mediated process sensitive to BSM physics.
- Important for precision measurements of Higgs boson properties
- Small *Br* yet very clean final state).



[1]

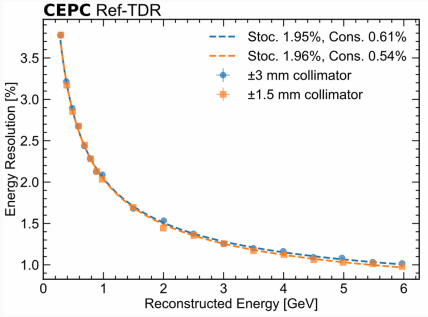
CEPC:

- Future e^+e^- collider: high-precision Higgs factory (4.3M H @ 21.6 ab^{-1} over 10 years).
- Expected luminosity, low background compared to hadron colliders.
- $H \to \gamma\gamma$ main benchmark for Physics at CEPC (ECAL Resolution)
- New ECAL technology (Crystal bar): significantly superior Electromagnetic energy resolution in the Ref-TDR

CEPC Detector & Experimental Setup

Electromagnetic calorimeter (ECAL) performance:

- PFA-oriented calorimetry: high-granularity homogeneous **crystal ECAL**
- **Crystal-bar ECAL energy resolution:** ($< 2\%/\sqrt{E} \oplus 1\%$ - around a factor of **10 times better** than previous technology in CDR Si-W ECAL: $16\%/\sqrt{E} \oplus 1\%$)

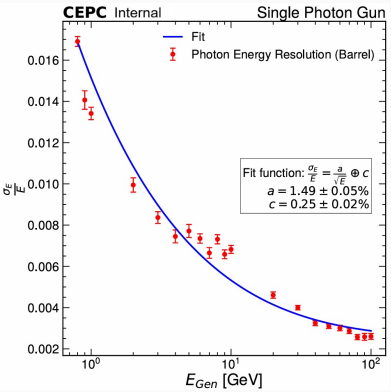


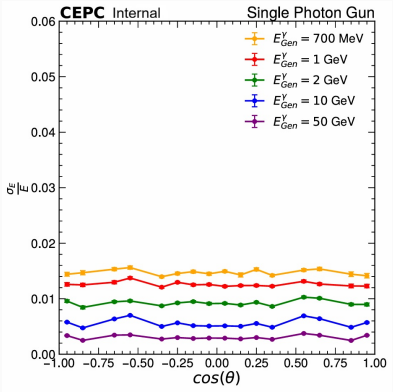
[2]

Trigger & event selection at CEPC: (almost **triggerless**)

- Pile-up free(@240 GeV and 360 GeV)
- Low background
- High hermeticity : a complete event without fake particles
- $|\cos\theta|$ up to 0.99

Photon performance at CEPC: Energy resolution

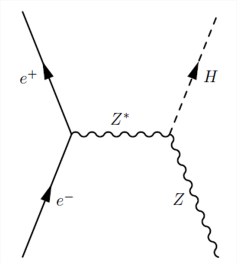




- Few discrepancies due to the gaps (dead material) alongside θ & Φ
- Good reconstruction relative to what was achieved with previous technology

$H \to \gamma\gamma$: Analysis strategy

- Main focus on **ZH** (ZH associate production/Higgsstrahlung) at $\sqrt{s} = 240$ *GeV*.
- For diphoton decay, **three main sub-channels** based on Z decays: $q\bar{q}\gamma\gamma$, $\mu^+\mu^-\gamma\gamma$, $\nu\bar{\nu}\gamma\gamma$ ($Z \to e^+e^-/\tau^+\tau^-$ not considered)



- **Diphoton invariant mass ($m_{\gamma\gamma}$):** key observable. (only considering unconverted photons)
- **Backgrounds:** mainly $e^+e^- \to f^+f^-$ with **ISR/FSR photons** ($e^+e^- \to q\bar{q}(\gamma\gamma)/\mu^+\mu^-(\gamma\gamma)/\nu\bar{\nu}(\gamma\gamma)$: each corresponding to one of the sub-channels).
- Other backgrounds are expected to be negligible such Higgs resonant contributions, $4f$ processes and reducible backgrounds from fake photons.

$H \to \gamma\gamma$ sub-channels

3 sub-channels with differents final state physics objects identification and selection within the signal samples

- $e^+e^- \to ZH \to q\bar{q}H(H \to \gamma\gamma)$
  - 2 photons
  - 2 jets
- $e^+e^- \to ZH \to \mu^+\mu^- H(H \to \gamma\gamma)$
  - 2 muons
  - 2 photons
  - Nothing else
- $e^+e^- \to ZH \to \nu\bar{\nu}H(H \to \gamma\gamma)$
  - 2 photons
  - Missing energy

Diphoton $q\bar{q}$ sub-channel: Selection cuts & Efficiencies

Signal events

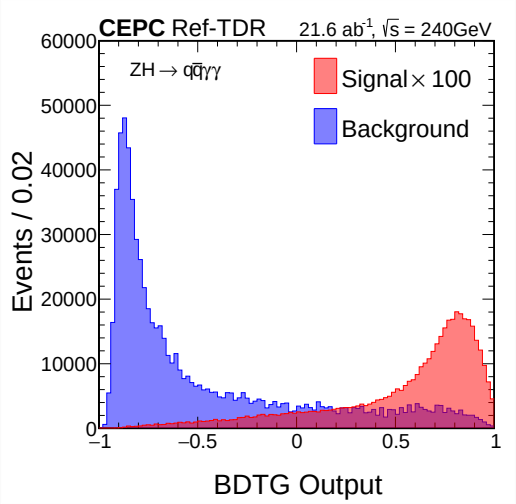
Selection Step	Events (Efficiency)
Total events generated	99800
Exclusive 2 jets and 2 photons	99800 (100%)
$E_{\gamma 1} > 20$ GeV	90691 (90.87%)
30 GeV $< E_{\gamma 2} <$ 100 GeV	82251 (90.69%)
$\cos\theta_{\gamma\gamma} > -0.95$	80521 (97.90%)
$\cos\theta_{jj} > -0.95$	78808 (97.87%)
$p_{T,\gamma 1} > 20$ GeV	72117 (91.51%)
$p_{T,\gamma 2} > 30$ GeV	68236 (94.62%)
$110 < m_{\gamma\gamma} <$ 140 GeV	64496 (94.52%)
$E_{\gamma\gamma} > 110 GeV$	64496 (100%)
$\min\lvert\cos_{\gamma j}\rvert > 0.9$	64496 (100%)
Final selected events	64496 (64.63%)
Expected yield at 21.6 ab^{-1}	4335.11 events

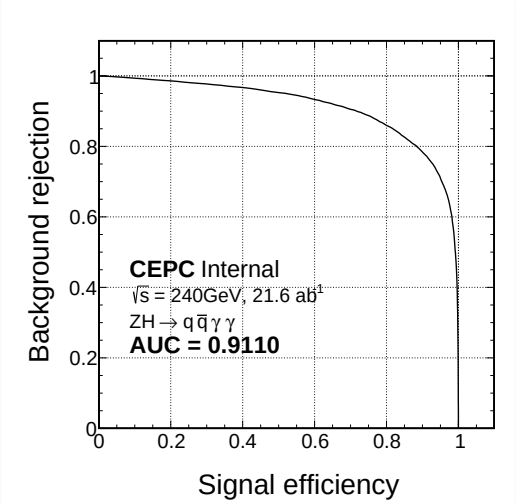
Background events

Selection Step	Events (Efficiency)
Total events generated	24739403 (100%)
Gen Filter ($m_{\gamma\gamma} \geq 90$)	3375000 (13.64%)
Delphes fast sim ($m_{\gamma\gamma} \geq 90$)	440203 (13.04%)
$E_{\gamma 1} > 20$ GeV	433340 (98.44%)
30 GeV $< E_{\gamma 2} <$ 100 GeV	109508 (25.27%)
$\cos\theta_{\gamma\gamma} > -0.95$	98097 (89.58%)
$\cos\theta_{jj} > -0.95$	87978 (89.68%)
$p_{T,\gamma 1} > 20$ GeV	45863 (52.13%)
$p_{T,\gamma 2} > 30$ GeV	34073 (74.29%)
$110 < m_{\gamma\gamma} <$ 140 GeV	15069 (44.23%)
$E_{\gamma\gamma} >$ 110 GeV	15069 (100%)
$\min\lvert\cos_{\gamma j}\rvert > 0.9$	15034 (99.77%)
Final selected events	15034 (0.0607%)
Expected yield at 21.6 ab^{-1}	710218 events

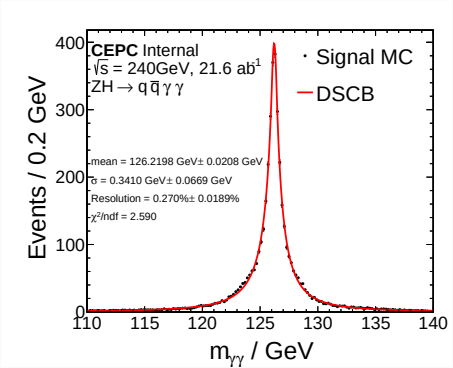
Diphoton $q\bar{q}$ sub-channel: BDTG training

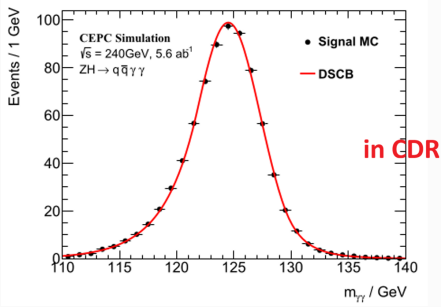
Input variables: $p_T^{\gamma 1}$, $cos\theta_{\gamma 2}$, $\Delta\Phi_{\gamma\gamma}$, p_T^{j2}, $cos\theta_{j1}$, E_{j1}, $cos\theta_{\gamma 1 j1}$, $\min\Delta R_{\gamma j}$, $\Delta\Phi_{\gamma\gamma jj}$, $cos\theta_{\gamma\gamma jj}$





Diphoton $q\bar{q}$ sub-channel: $m_{\gamma\gamma}$ signal distribution (comparison with CDR)

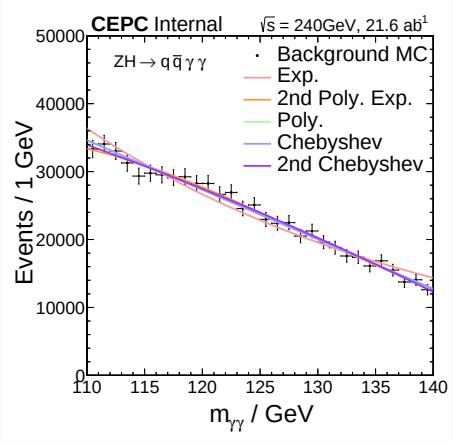


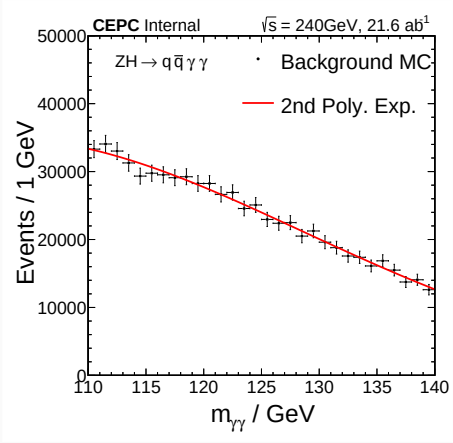


Resolution $\sigma_m = 2.81\ GeV$ [3]

- in Ref-TDR, narrow distribution thanks to new ECAL tech (Crystal Bar)
- Tails with weird aspect (right one more important) due to reconstruction issues in CyberPFA - calibration also needed
- in CDR, different detector baseline, specifically ECAL (Silicion-Tungsten previously vs.): stochastic term around 16% $\Rightarrow$ wider distribution

Diphoton $q\bar{q}$ sub-channel: $m_{\gamma\gamma}$ background distribution

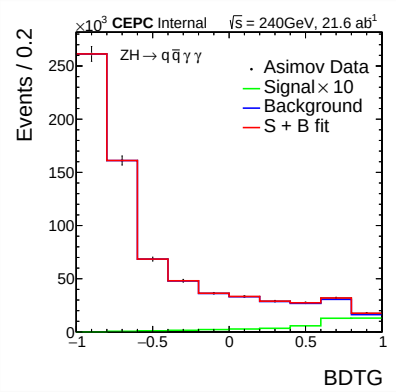


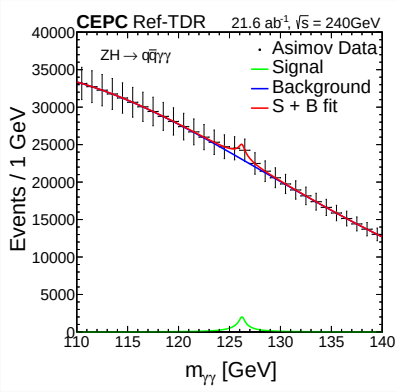


Considering a 2nd order polynomial exponential fit function (best fit: lowest χ^2) for our background after trying different fit functions

Diphoton $q\bar{q}$ sub-channel: Signal over background plot

- 2D extended binned likelihood fit on $m_{\gamma\gamma}$ and BDTG with Asimov data





Signal strength: $\mu \approx 1.00002 \pm \mathbf{0.0384}$

- Currently only statistical uncertainty considered

Expected precision on $\sigma \times Br$

Table 1: Expected statistical precision on $\sigma(ZH) \times \mathrm{Br}(\to \gamma\gamma)$ from Asimov data fitting in the three channels and their combination with 21.6 ab^{-1} data.

	$\Delta(\sigma \times \mathrm{Br})/(\sigma \times \mathrm{Br})_{SM}$
$q\bar{q}\gamma\gamma$	0.038
$\mu^+\mu^-\gamma\gamma$	0.153
$\nu\bar{\nu}\gamma\gamma$	0.048
Combined	**0.031**

- Improvement in TDR (vs. CDR), around 20% improvement for whole channel
- Systematic impact in CDR has 15% degradation on the precision.

CDR results:

	5.6 ab^{-1}		20 ab^{-1}	
	$\frac{\Delta_{\mathrm{tot}}}{(\sigma\times\mathrm{Br})_{\mathrm{SM}}}$	$\frac{\Delta_{\mathrm{stat}}}{(\sigma\times\mathrm{Br})_{\mathrm{SM}}}$	$\frac{\Delta_{\mathrm{tot}}}{(\sigma\times\mathrm{Br})_{\mathrm{SM}}}$	$\frac{\Delta_{\mathrm{stat}}}{(\sigma\times\mathrm{Br})_{\mathrm{SM}}}$
$q\bar{q}\gamma\gamma$	0.101	0.098	0.056	0.052
$\mu^+\mu^-\gamma\gamma$	0.373	0.371	0.202	0.200
$\nu\bar{\nu}\gamma\gamma$	0.130	0.127	0.071	0.067
Combined	0.079	0.077	0.046	0.040

[3]

latest ATLAS results:

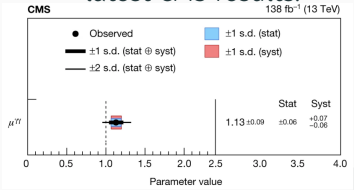
The overall Higgs boson signal strength relative to its SM prediction is measured to be

$$\mu = 1.04^{+0.10}_{-0.09} = 1.04 \pm 0.06\ (\mathrm{stat.})^{+0.06}_{-0.05}\ (\mathrm{theory\ syst.})\ ^{+0.05}_{-0.04}\ (\mathrm{exp.\ syst.}).$$

in good agreement with the SM.

[1]

latest CMS results:



[4]

Summary

- $H \to \gamma\gamma$ is a main channel to study in CEPC for precision measurements of H boson properties ($\sigma \times Br$)
- Excellent photon reconstruction at CEPC thanks to new tech crystal-bar ECAL ($\sigma_E/E =< 2\%/\sqrt{E} \oplus 1\%$)
- A precision of 3.1% (stat.) for the $\sigma \times Br$ measurement to be reached in the $H \to \gamma\gamma$ channel of the CEPC with 21.6 ab^{-1} data.

Perspectives and ongoing work:

- Systematic uncertainties estimation
- Update on BDTG training with more input variable such as number of PFOs, etc.

References i

[1] Georges Aad et al. **"Measurement of the properties of Higgs boson production at $\sqrt{s} = 13$ TeV in the $H \to \gamma\gamma$ channel using 139 fb^{-1} of pp collision data with the ATLAS experiment".** In: *JHEP* 07 (2023), p. 088. DOI: 10.1007/JHEP07(2023)088. arXiv: 2207.00348 [hep-ex].

[2] The CEPC Study Group. ***CEPC Technical Design Report – Reference Detector.*** 2025. arXiv: 2510.05260 [hep-ex]. URL: https://arxiv.org/abs/2510.05260.

[3] Fangyi Guo et al. **"Expected measurement precision of the branching ratio of the Higgs boson decaying to the di-photon at the CEPC*".** In: *Chinese Physics C* 47.4 (Apr. 2023), p. 043002. ISSN: 2058-6132. DOI: 10.1088/1674-1137/acaa22. URL: http://dx.doi.org/10.1088/1674-1137/acaa22.

References ii

[4] Armen Tumasyan et al. **“A portrait of the Higgs boson by the CMS experiment ten years after the discovery.”.** In: *Nature* 607.7917 (2022). [Erratum: Nature 623, (2023)], pp. 60–68. DOI: *10.1038/s41586-022-04892-x*. arXiv: *2207.00043 [hep-ex]*.

[5] M.H.M. Soleiman, S.S. Abdel-Aziz, and M.S.E. Sobhi. **“Higgs production enhancement in P-P collisions using Monte Carlo techniques at $\sqrt{s} = 13$ TeV”.** In: *EPJ Web of Conferences* 145 (June 2017), p. 14003. DOI: *10.1051/epjconf/201714514003*.

[6] Sofia Maria Consonni. ***Higgs search at ATLAS.*** Tech. rep. Comments: 12 pages, 26 figures, LISHEP2013 Proceedings. Geneva: CERN, 2013. arXiv: *1305.3315*. URL: *https://cds.cern.ch/record/1546765*.

Thank you!

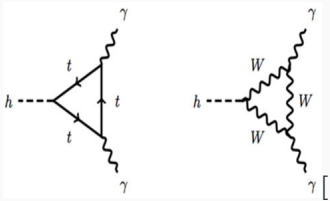
Back-up

Back-up

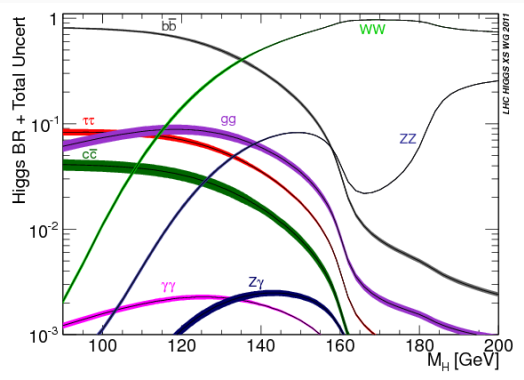
- **Theoretical background:**

Branching ratio & SM predictions (≈0.23% in SM).

Sensitivity to new physics (charged particles entering loops).



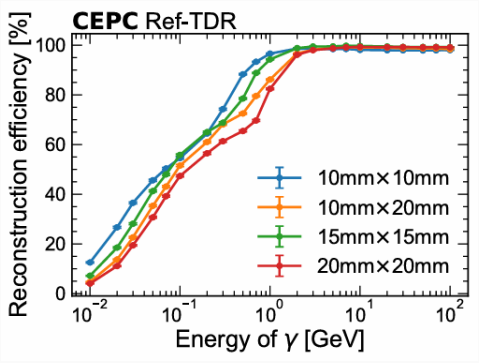
[5]



[6]

Back-up

- **Photon performance:** Reconstruction efficiency

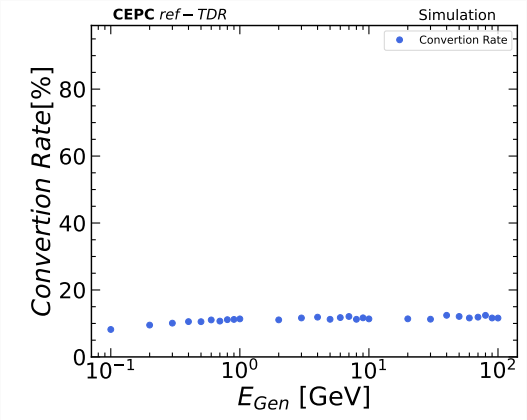


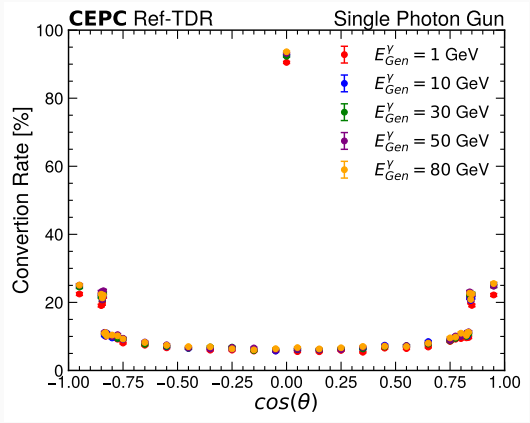
[2]

Photons over 3 GeV are reconstructed at 100% efficiency rate

Back-up

- **Photon performance:** Convertion Rate

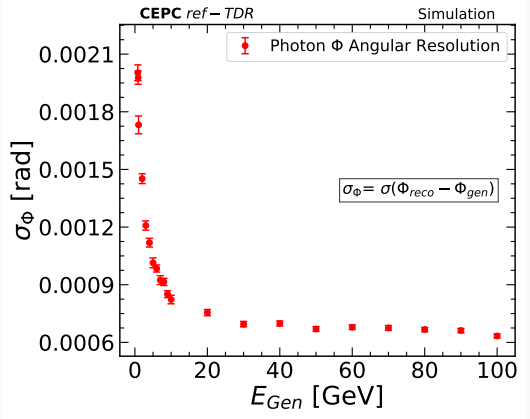


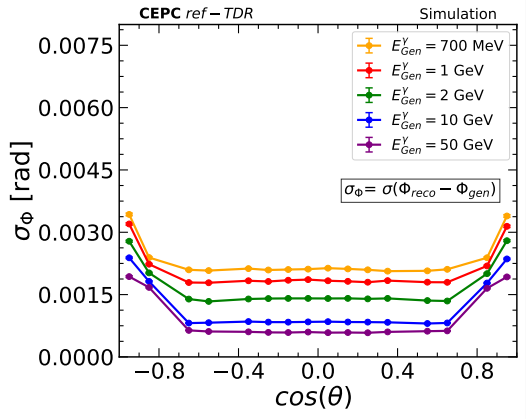


Over the whole range, the Convertion Rate is at around 10% (6-8% in barrel/up to 25% in endcap)

Back-up

- **Photon performance:** Angular resolution over Φ

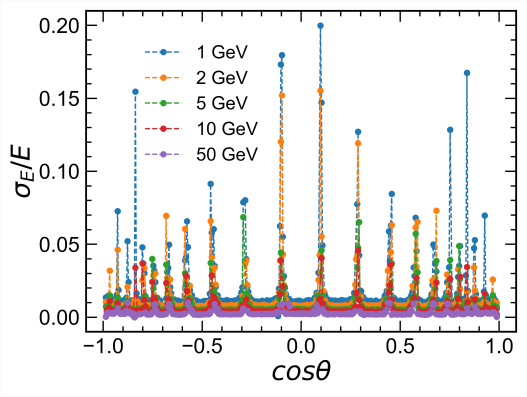


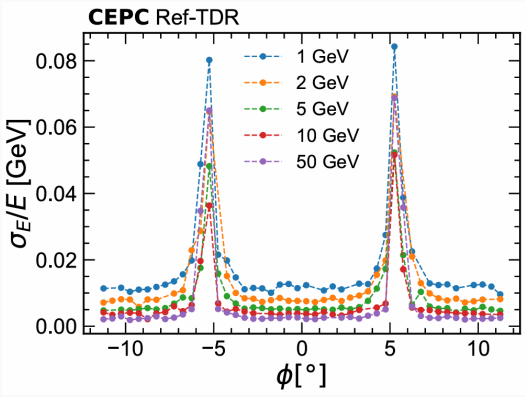


Photon Φ angular resolution better than expected: expecting around 0.045° or 0.000785 rad (approximation from ECAL shower position reso. around 1/10*15mm = 1.5mm)

Back-up

Photon performance: Angular resolution over cos(θ) & Φ





[2]

Gaps impact studied and to be corrected for further

Back-up

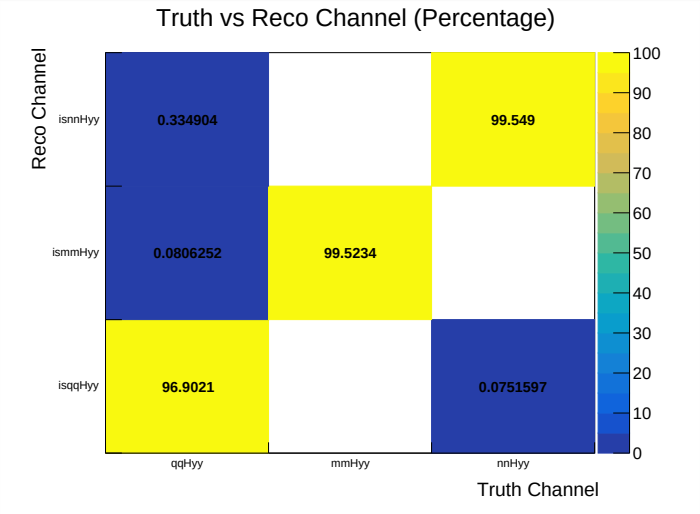


Figure 1: Contamination between channels after selection cuts

Back-up

- $\mu^+\mu^-$ sub-channel

Signal events

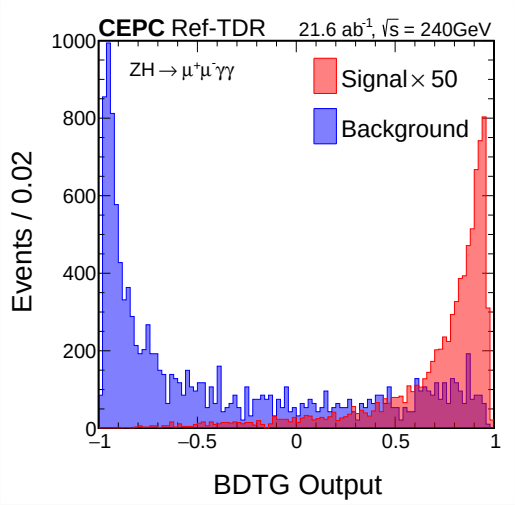
Selection Step	Events (Efficiency)
Total events generated	10000
Exclusive 2 photons & 2 muons	7201 (72.01%)
$E_\gamma > 35$ GeV	6777 (94.11%)
$\lvert\cos(\theta_\gamma)\rvert < 0.9$	5771 (85.16%)
$10\ GeV < p_T^{\gamma 1} < 70\ GeV$	5769 (99.97%)
$30\ GeV < p_T^{\gamma 2} < 100\ GeV$	5758 (99.81%)
$110\ GeV < m_{\gamma\gamma} < 140\ GeV$	5672 (98.51%)
85 GeV $< m_{\gamma\gamma}^{recoil} <$ 105 GeV	5044 (88.92%)
125 GeV $< E_{\gamma\gamma} <$ 145 GeV	5036 (99.84%)
Final selected events	5036 (50.36%)
Expected yield at 21.6 ab^{-1}	167.168 events

Background events

Selection Step	Events (Efficiency)
Total events generated	10778370 (100%)
Gen Filter ($M_{\gamma\gamma} \geq 90$)	882451 (8.19%)
Delphes fast sim ($M_{\gamma\gamma} \geq 90$)	64029 (7.26%)
$E_\gamma > 35$ GeV	39609 (61.86%)
$\lvert\cos\theta_\gamma\rvert < 0.9$	14208 (35.87%)
$10GeV < p_T^{\gamma 1} < 70GeV$	13192 (92.85%)
$30GeV < p_T^{\gamma 2} < 100GeV$	11502 (87.19%)
$110GeV < m_{\gamma\gamma} > 140GeV$	5574 (48.46%)
85 GeV $< m_{\gamma\gamma}^{recoil} <$ 105 GeV	1198 (21.49%)
125 GeV $< E_{\gamma\gamma} <$ 145 GeV	1176 (98.16%)
Final selected events	1176 (0.01 %)
Expected yield at 21.6 ab^{-1}	12567.70 events

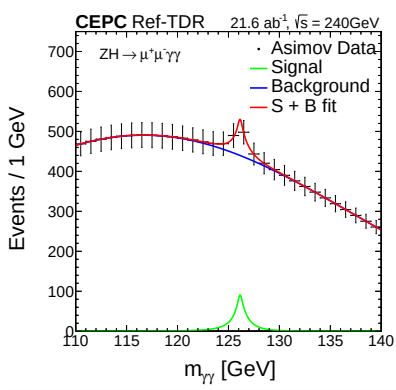
Back-up

BDTG trained inputs: $E^{\gamma 2}$, $cos\theta_{\gamma 2}$, $\Delta\Phi_{\gamma\gamma}$, $cos\theta_{\mu 1}$, $E_{\mu\mu}$, $cos\theta_{\gamma 1\mu 1}$, $\min\Delta R_{\gamma\mu}$, $cos\theta_{\gamma\gamma\mu\mu}$



Back-up

- $\mu^+\mu^-$ **sub-channel:** Signal over background plot (2D model fit)



Signal strength ≈ 0.9997 ± **0.1533** (stat.)

Back-up

- $\nu\bar{\nu}$ sub-channel

Signal events

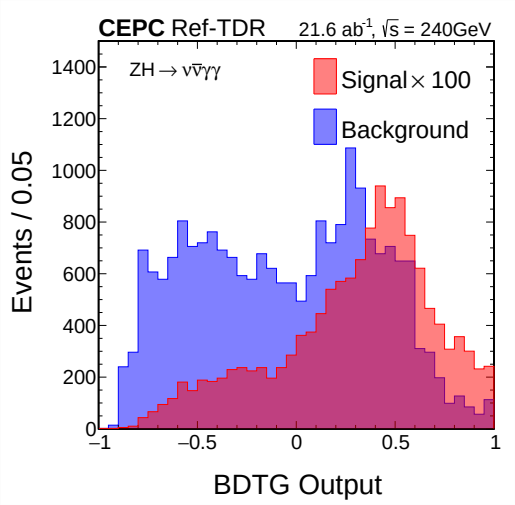
Selection Step	Events (Efficiency)
Total events generated	9019
Inclusive 2 photons	8930 (99.01%)
$E_\gamma > 30$ GeV	8013 (89.73%)
$\lvert\cos(\theta_\gamma)\rvert < 0.8$	5740 (71.63%)
$p_{T,\gamma} > 20$ GeV	5730 (100%)
$M_{\text{missing}} > 60$ GeV	5489 (95.63%)
110 GeV $< m_{\gamma\gamma} <$ 140 GeV	5351 (97.49%)
120 GeV $< E_{\gamma\gamma} <$ 150 GeV	5322 (99.46%)
Final selected events	5322 (59.01%)
Expected yield at 21.6 ab^{-1}	1355.24 events

Background events

Selection Step	Events (Efficiency)
Total events generated	82804236 (100%)
Gen Filter ($M_{\gamma\gamma} \geq 90$)	1491000 (1.80%)
Delphes fast sim ($M_{\gamma\gamma} \geq 90$)	50138 (3.36%)
$E_\gamma > 30$ GeV	41930 (83.63%)
$\lvert\cos\theta_\gamma\rvert < 0.8$	3114 (7.43%)
$p_{T,\gamma} > 20$ GeV	3099 (99.52%)
$M_{\text{missing}} > 60$ GeV	3086 (99.58%)
110 GeV $< m_{\gamma\gamma} <$ 140 GeV	1505 (48.77%)
120 GeV $< E_{\gamma\gamma} <$ 150 GeV	1499 (99.60%)
Final selected events	1499 (0.0018 %)
Expected yield at 21.6 ab^{-1}	21227.94 events

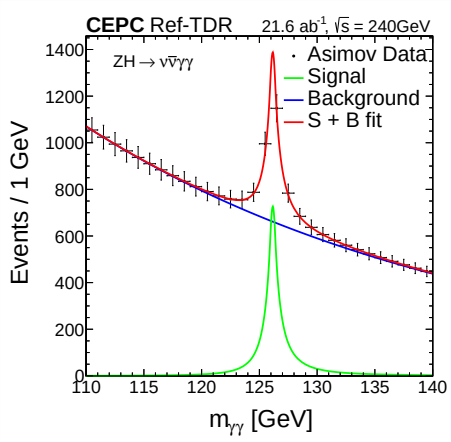
Back-up

- $\nu\bar{\nu}$ **sub-channel:** BDTG input variables (5 variables)



Back-up

- $\nu\bar{\nu}$ **sub-channel:** Signal over background (2D model fit)



Signal strength ≈ 0.9996 ± **0.0481** (stat.)

Back-up

Table 9. Decoupled contributions from considered systematic uncertainties of the $(\sigma \times \mathrm{Br})/(\sigma \times \mathrm{Br})_{\mathrm{SM}}$ measurement in the three channels. The 0.5% theoretical uncertainty was only considered in the $q\bar{q}\gamma\gamma$ channel.

	$q\bar{q}\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$	$\nu\bar{\nu}\gamma\gamma$
Theo 0.5%	0.005	-	-
Lumi 0.1%	0.001	0.001	0.001
photon eff 1%	0.019	0.020	0.020
PES 0.05%	0.001	<0.001	0.001
PER 0.05%	<0.001	<0.001	<0.001
mH 5.9 MeV	<0.001	<0.001	<0.001
BDT	0.006	0.006	0.007
Bkg. modeling	0.029	0.062	0.006

[3]

15 % degradation on precision estimated from systematic uncertainties