Progress report on $e^+e^- \to \gamma\gamma$ study as luminosity process at CEPC

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Outline

1. Motivation
2. MC samples and selections
3. Distributions over main parameters
4. Possible systematical uncertainty sources
5. Summary

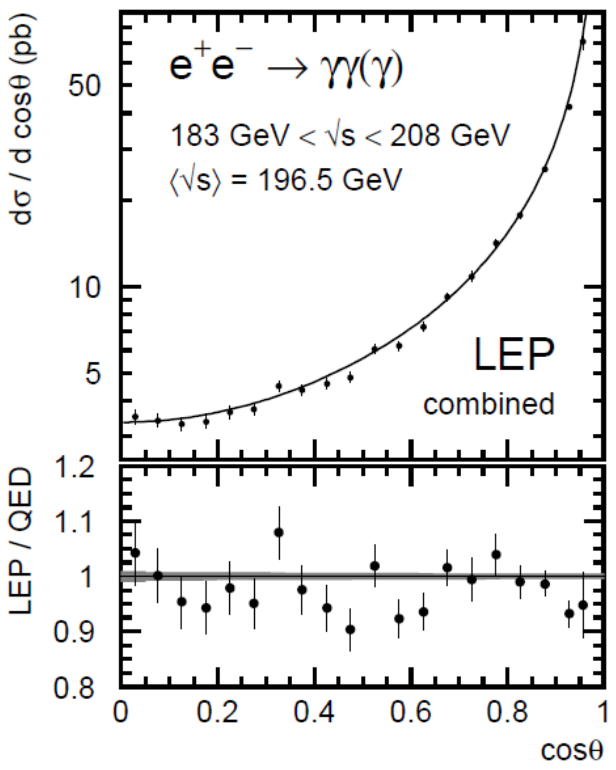
Motivation

According to the article [1] $ee \to ee$ theoretical uncertainty is limited by hadronic vacuum polarization at the level 10^{-4}, while for $ee \to \gamma\gamma$ process hadronic loops contribution is less then 10^{-5}.

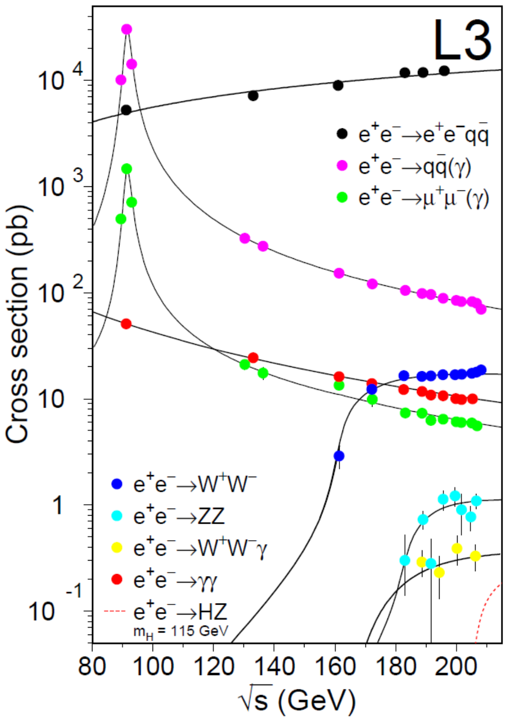
Current MC generators uncertainty for $ee \to \gamma\gamma$ is 10^{-3} at M_Z tested with BABAYagaNLO [2], if some NNLO corrections from [1] are applied the accuracy ~ 10^{-4} could be reached. To get accuracy 10^{-4}-10^{-5} a full calculation of NNLO QED corrections and, eventually, of two-loop weak contributions will be ultimately needed.

[1] Carlo M. Carloni Calame et all, Physics Letters B, Volume 798, 2019, 134976 (corrections for the $\theta>20°$ are present in this paper)
[2] G. Balossini et all, Phys.Lett.B663:209-213,2008

$e^+e^- \to \gamma\gamma$ at LEP



The process of two-photon annihilation of e^+e^- at energies above the Z boson mass was studied at the LEP collider [3]. Each of the 4 detectors observed approximately 5000 events [4-7]. The most accurate result was obtained at the OPAL detector [7], where the systematic uncertainty reaches 0.56%. The dominant part of the systematic uncertainty (0.46%) was related to the photon conversion probability, (0.23% Lum 0.17% cuts and bkg). At $2E = M_Z$ only ~2000 $e^+e^- \to \gamma\gamma$ events were observed [8] (IL = 65 pb^{-1}).



CEPC Lum = 1.15 $pb^{-1}s^{-1}$ (with 30 MW at Z)

14 days to get 10^8 events at $10<\theta<170°$ (10^{-4} stat unc.)

<1 day to get 10^6 events at $10<\theta<170°$ (10^{-3} stat unc.)

The way to the 10^{-3} accuracy is known, 10^{-4} accuracy is more challenging.

[3] The LEP Electroweak Working Group, et al., Physics Reports, Volume 532, Issue 4, 2013, Pages 119-244, arXiv:1302.3415 [hep-ex]
[4] ALEPH Collaboration, A. Heister et al., Eur.Phys.J. C28 (2003) 1–13
[5] DELPHI Collaboration, J. Abdallah et al., Eur.Phys.J. C37 (2004) 405–419
[6] L3 Collaboration, P. Achard et al., Phys.Lett. B531 (2002) 28–38
[7] OPAL Collaboration, G. Abbiendi et al., Eur.Phys.J. C26 (2003) 331–344
[8] L3 Collaboration, M. Acciaiti, et al., Physics Letters B 353 (1995) 136-144

Cross section for the $e^+e^- \to \gamma\gamma$ process

Cross section is calculated with BABAYagaNLO [2]. Expected systematical uncertainty is 10^{-3}. To get the uncertainty 10^{-4}, corrections from [2] should be used (calculated for $20<\theta<160°$).

$\sigma(5<\theta<175°) = 100.181$ +/- 0.019 pb
$\sigma(8<\theta<172°) = 80.299$ +/- 0.035 pb
$\sigma(10<\theta<170°) = 71.602$ +/- 0.034 pb

$\sigma(ee \to ee\ 5<\theta<175°) = 17375.6$ +/- 2.4 pb

$\sigma(20<\theta<160°) = 40.870(4)$ pb (calculated at [1] w h.o.)
Only this calculation have 10^{-4} accuracy

$\sigma(ee \to ee\ 20<\theta<160°) = 2625.9$ pb

$\sigma(5<\theta<175°\ \&\&\ |\Delta\theta|<10°) = 81.740$ +/- 0.003 pb
$\sigma(8<\theta<172°\ \&\&\ |\Delta\theta|<10°) = 65.978$ +/- 0.006 pb
$\sigma(10<\theta<170°\ \&\&\ |\Delta\theta|<10°) = 58.720$ +/- 0.005 pb

CEPC Lum = 1.15 $pb^{-1}s^{-1}$ (at 30 MW)
14 days to get 10^8 events at $10<\theta<170°$ (10^{-4} stat unc.)
<1 day to get 10^6 events at $10<\theta<170°$ (10^{-3} stat unc.)

[1] Carlo M. Carloni Calame et all, Physics Letters B, Volume 798, 2019, 134976 (corrections for the $\theta>20°$ are present in this paper)
[2] G. Balossini et all, Phys.Lett.B663:209-213,2008

MC samples

We using CEPCSW tdr25.3.3, all MC is for E = 91.2 GeV

The MC samples were processed through the

full CEPC detector simulation based on Geant4.

ee $\rightarrow \gamma\gamma$ 1M events produced with BABAYagaNLO (θ>10°)

+ 500k events (θ>5°)

ee $\rightarrow$ ee 200k events were prepared with Whizard+Phythia at LO

ee $\rightarrow \mu\mu$ 1M events were prepared with Whizard+Phythia at LO

ee $\rightarrow \tau\tau$ 200k events were prepared with Whizard+Phythia at LO

ee $\rightarrow$ bb 100k events were prepared with Whizard+Phythia at LO

ee $\rightarrow$ cc 100k events were prepared with Whizard+Phythia at LO

Selections

Selections:

$1 < nn < 10$ – number of neutral particles

$E_{\gamma 2} > 5$ GeV – energy of the second energetic neutral particle

nc=0 – number of charged particles

$40 < Etot < 100$ GeV – sum of all particle energies

$M_{2\gamma} > 40$ GeV – invariant mass of the 2 most energetic neutral particles

$20° < \theta_{1,2} < 160°$ – polar angle of the 2 most energetic neutral particles

Not used Ecal, $\Delta\varphi$, $\Delta\theta$ (could be used if some background will be present)

ee $\rightarrow \gamma\gamma$ 497531 selected from 1M (if no $\theta_{1,2}$ cut 753790, correspond to 75% efficiency)

ee $\rightarrow$ ee 0 selected from 200k events

ee $\rightarrow \mu\mu$ 0 selected from 1M events

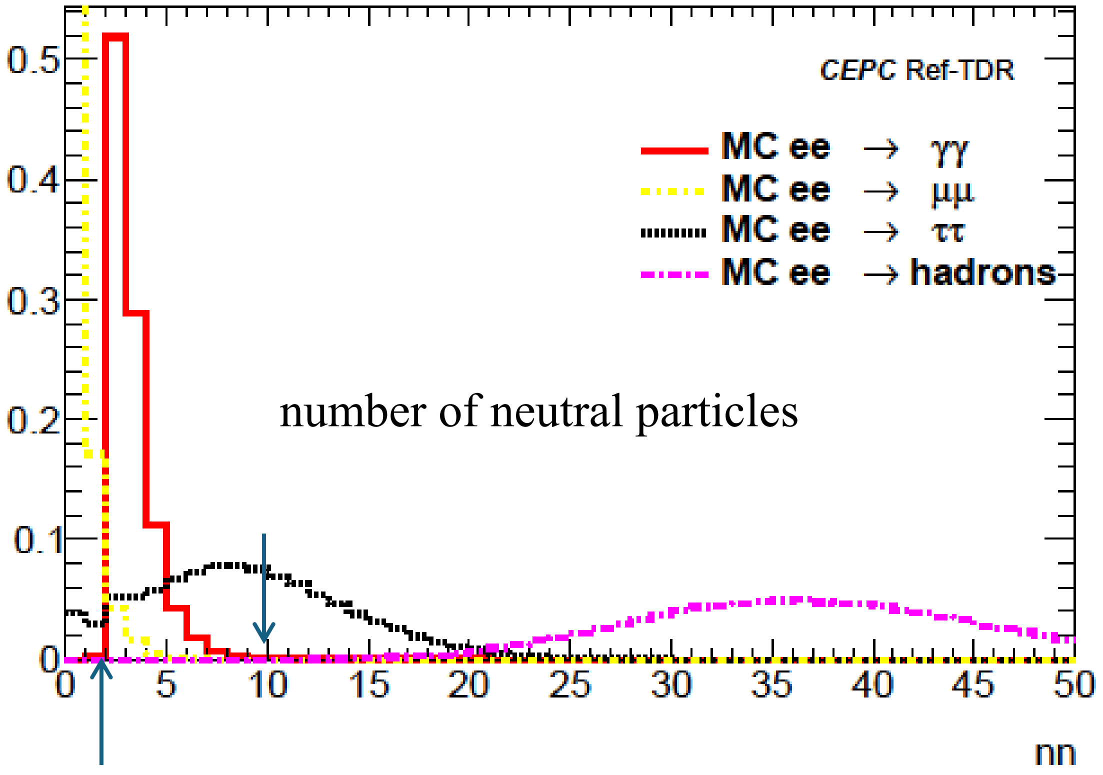
ee $\rightarrow \tau\tau$ 0 selected from 200k events

ee $\rightarrow$ bb 0 selected from 100k events

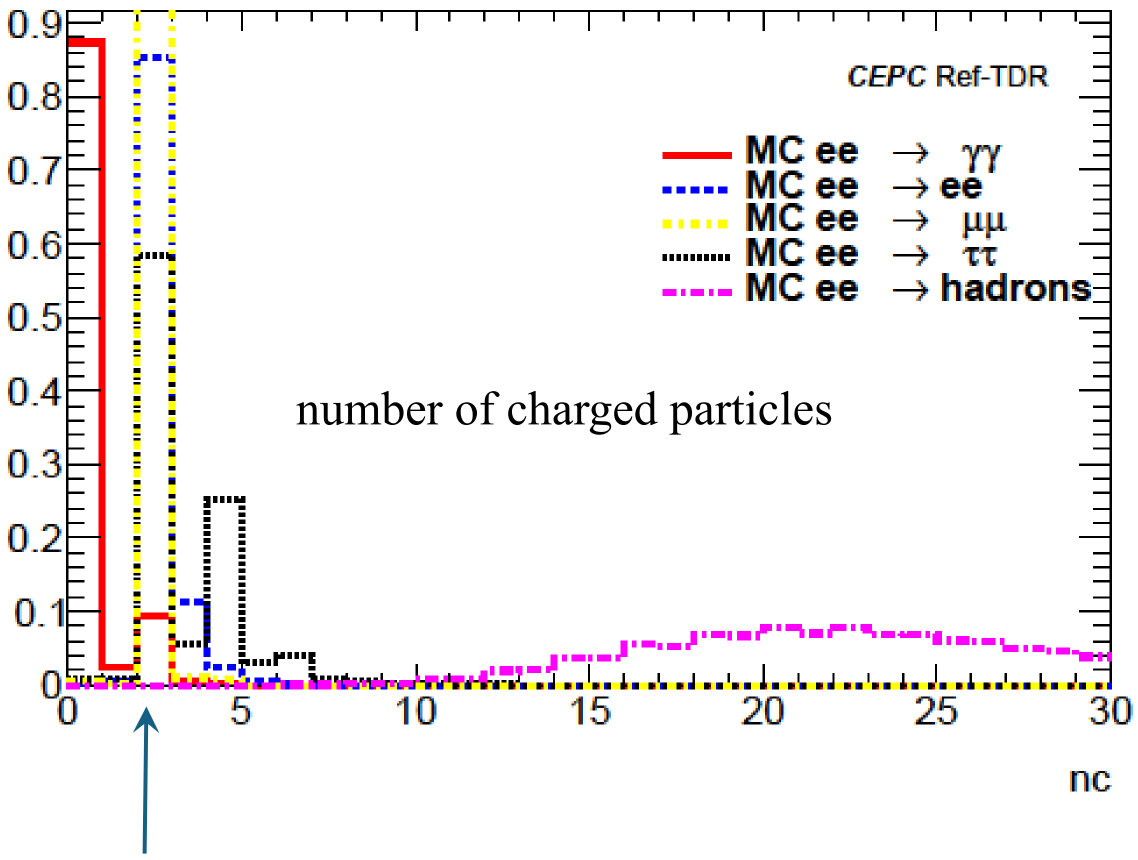
ee $\rightarrow$ cc 0 selected from 100k events

Distributions of the selection variables are at the next slides.

Selections: number of particles



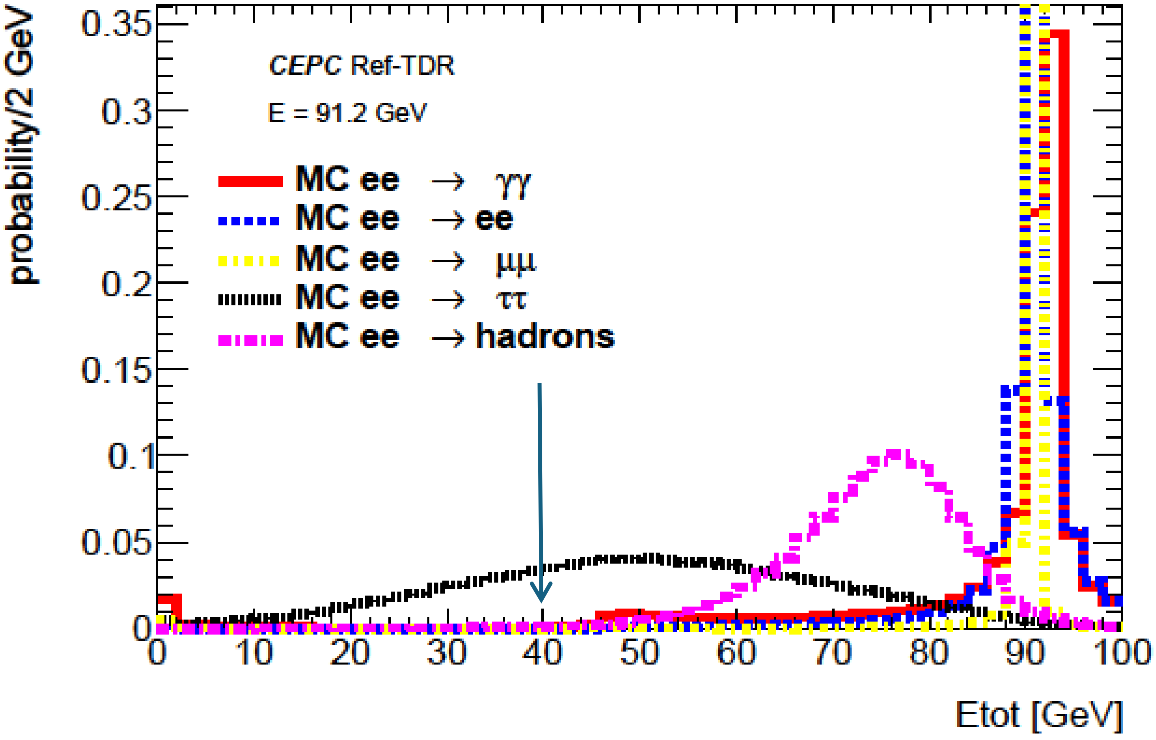
Strong suppression of the hadronic background

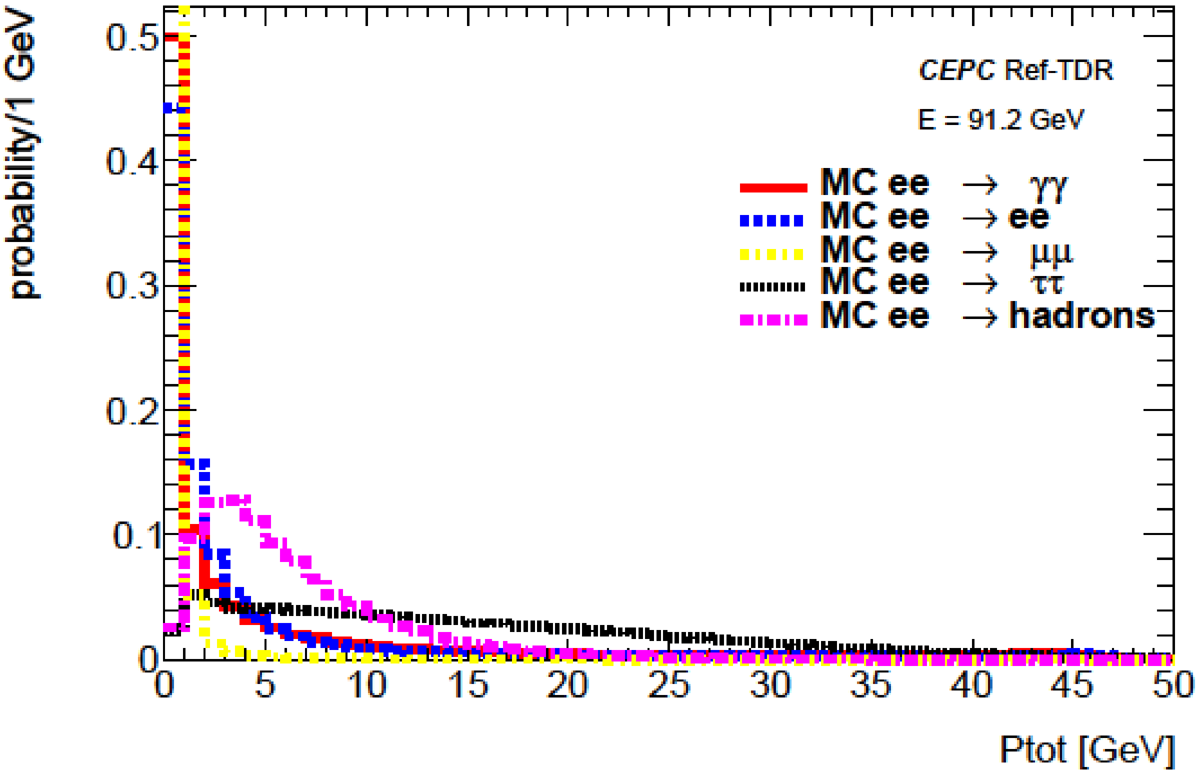


ee → γγ with conversion

Photon conversion should be studied in detail with data to control systematics of the nc==0 selection

Selections: total energy and momentum



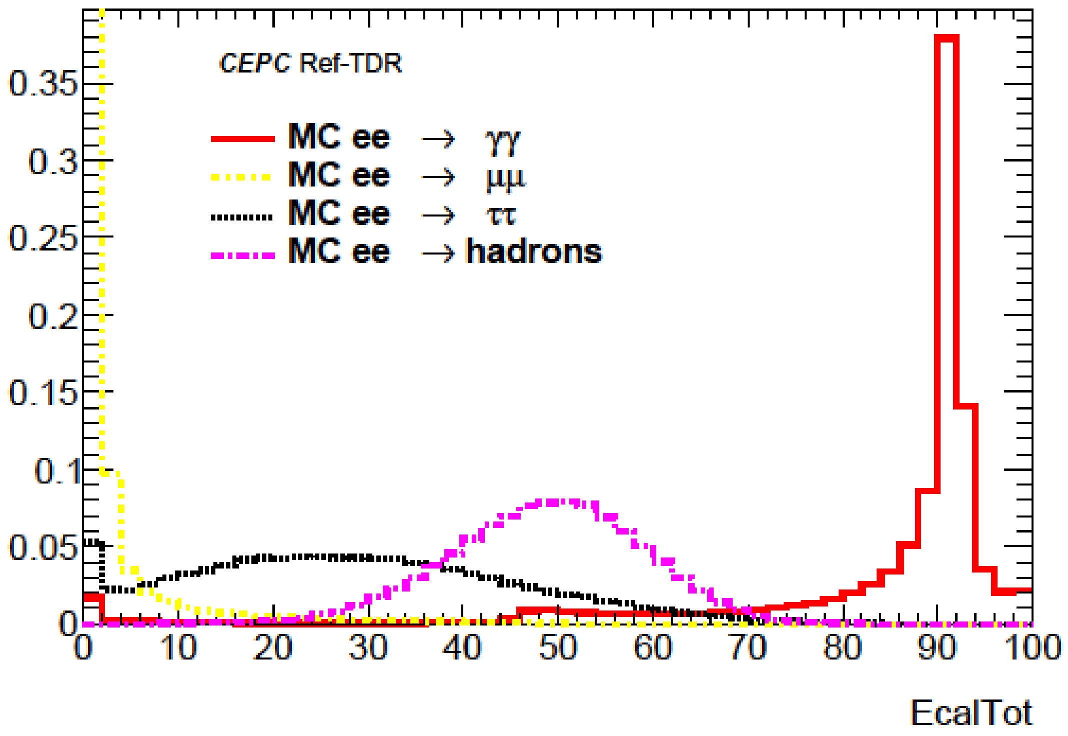


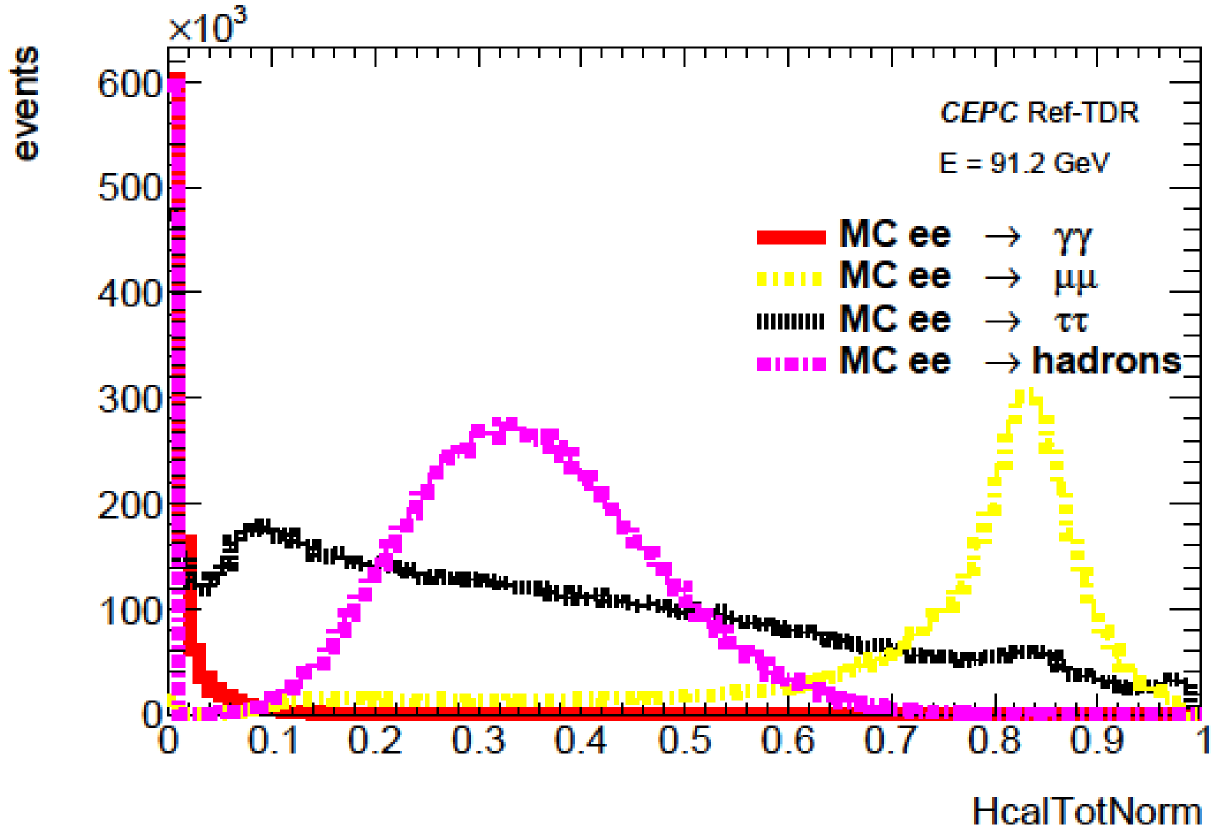
Etot = Sum PFO_E

Ptot = $|\text{Sum } \vec{p}|$

Processes with neutrino contamination in the final state could be rejected by energy and momentum conservation

Selections: Ecal and Hcal energy deposition



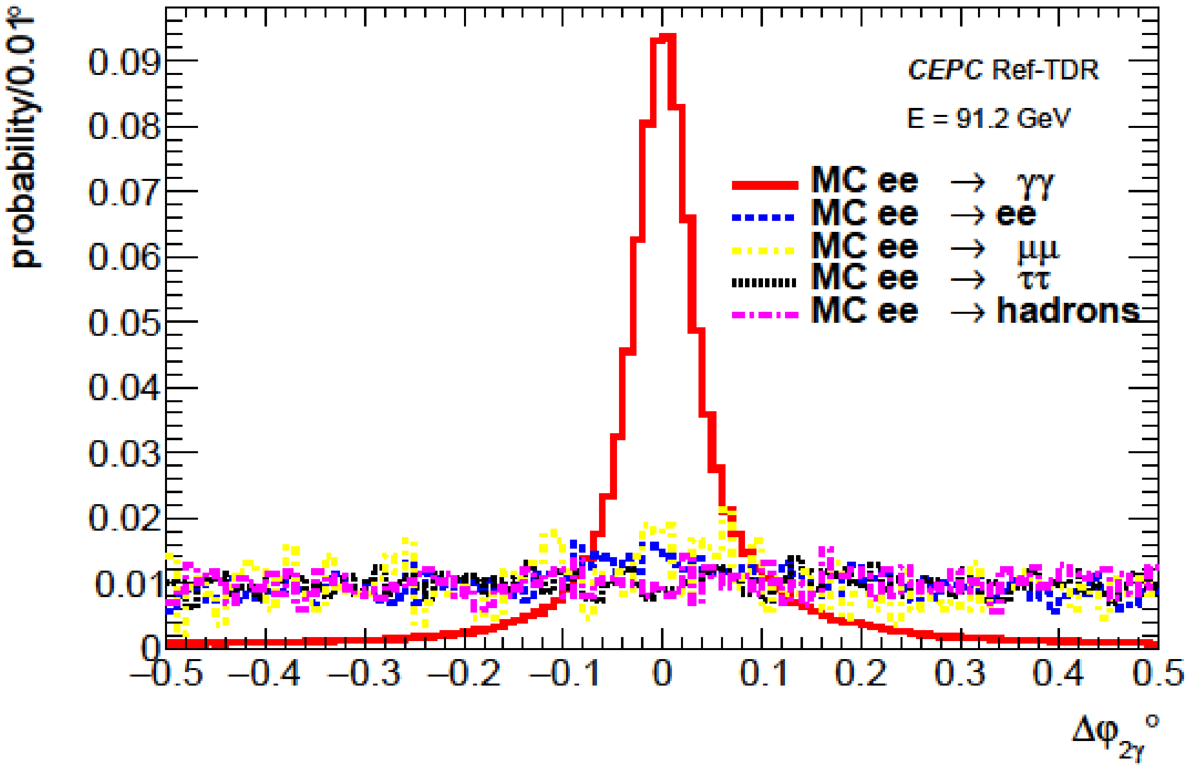


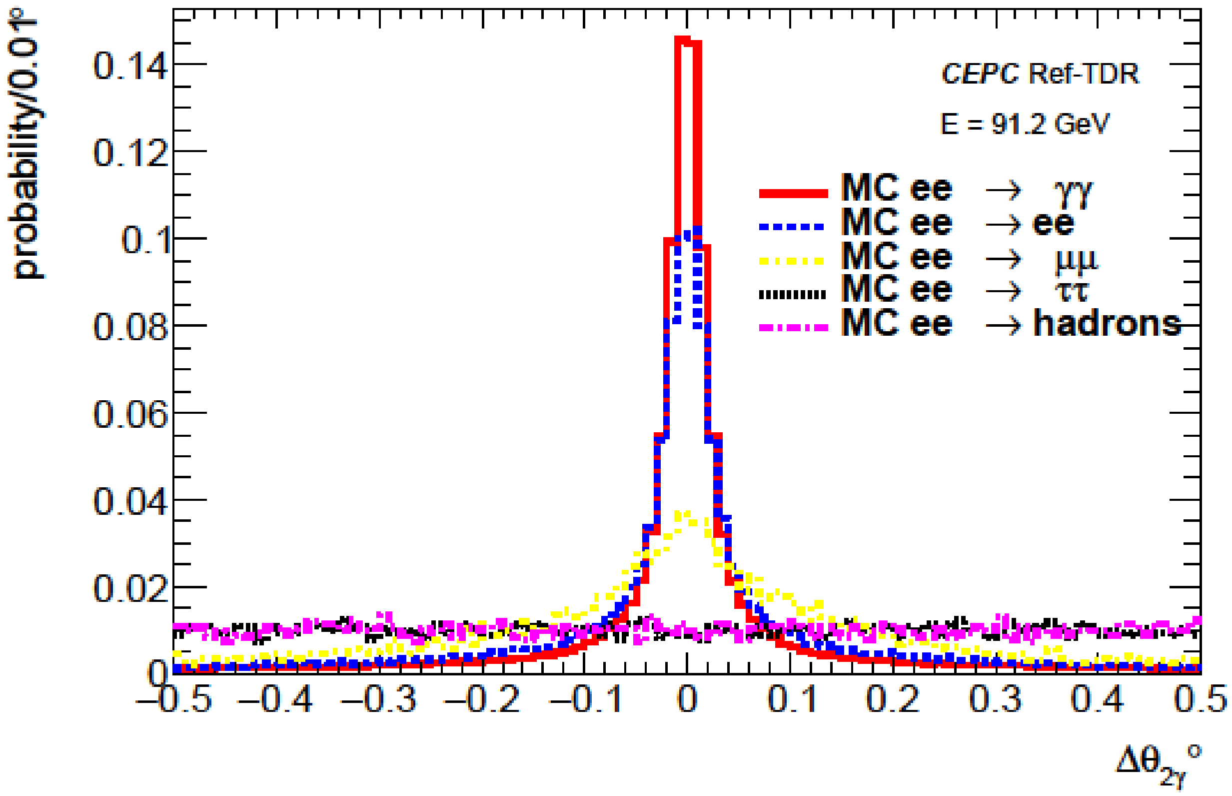
γγ final state could be separated with total energy deposition at electromagnetic calorimeter. e^+e^- final state should have close Ecal energy deposition.

$$\text{HcalTotNorm} = \frac{\sum E_{Hcal}}{\sum E_{Hcal} + \sum E_{Ecal}}$$

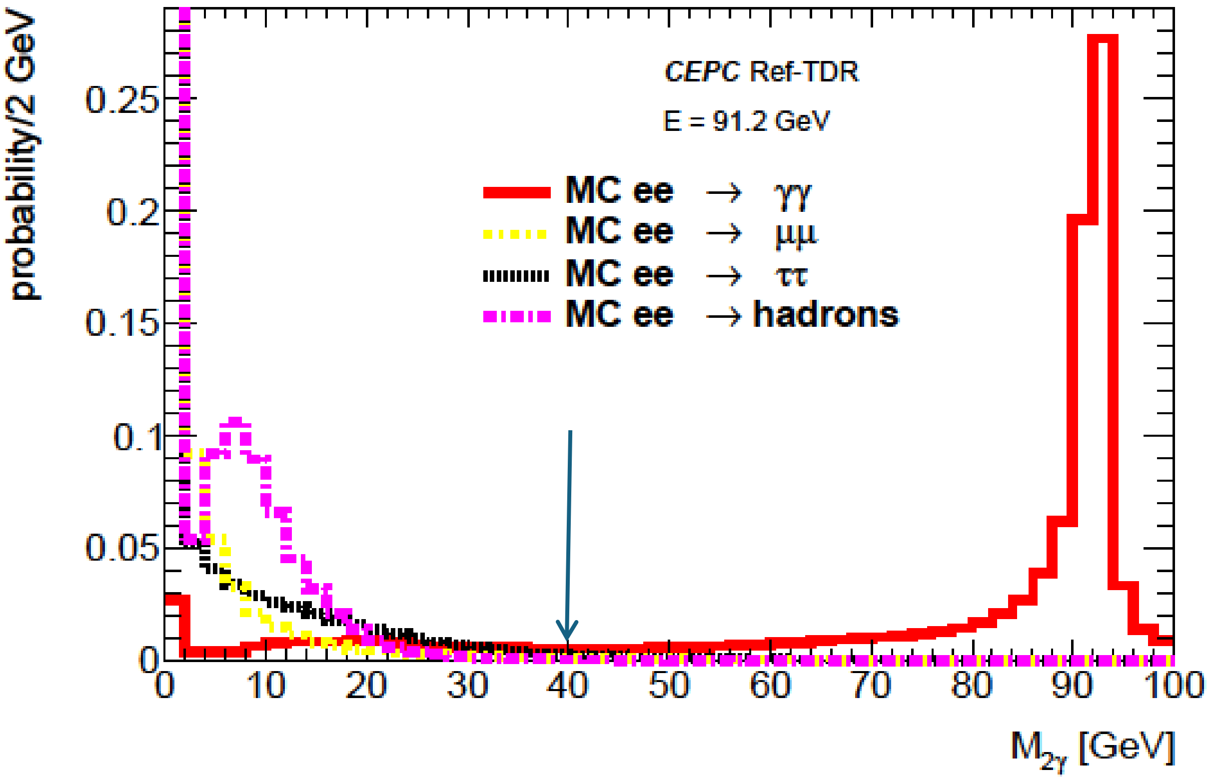
Normalized hadronic leakage could be used to suppress muons, hadrons, taus.

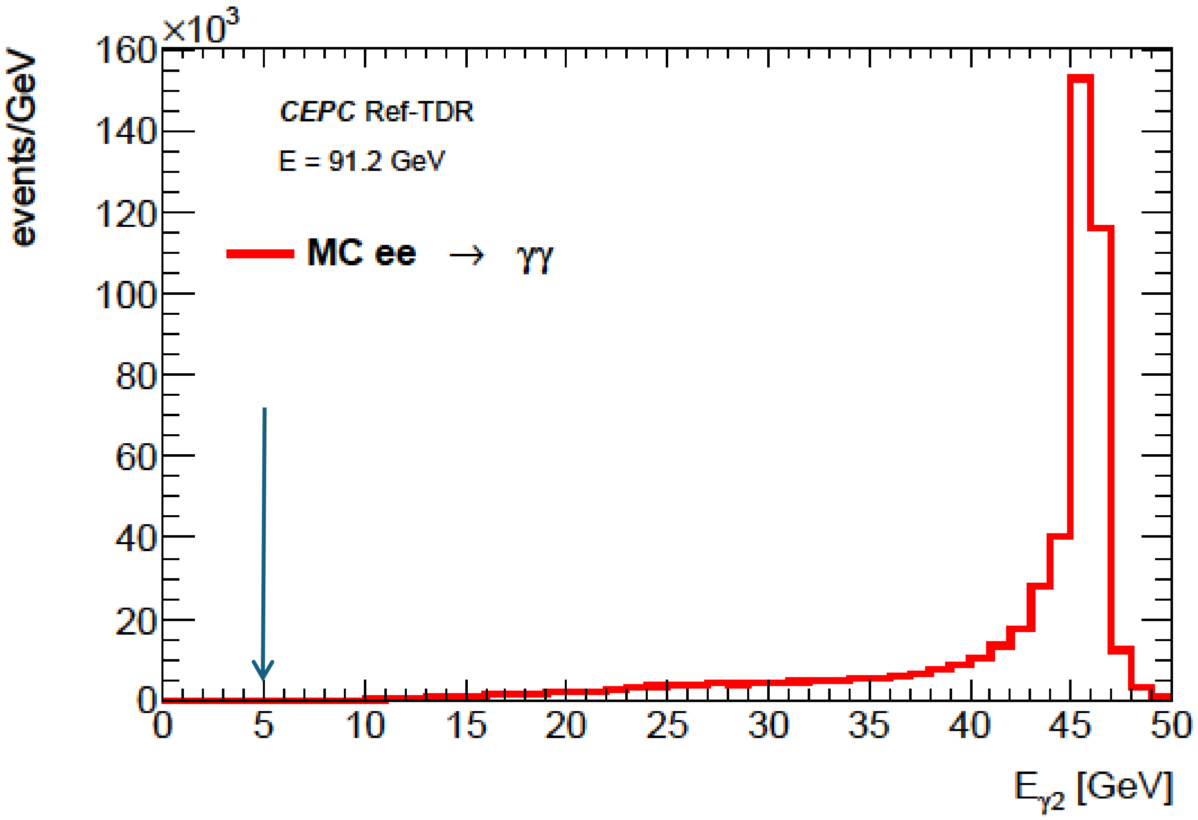
Selections: collinearity





Selections: 2γ invariant mass, and energy of the second energetic photon

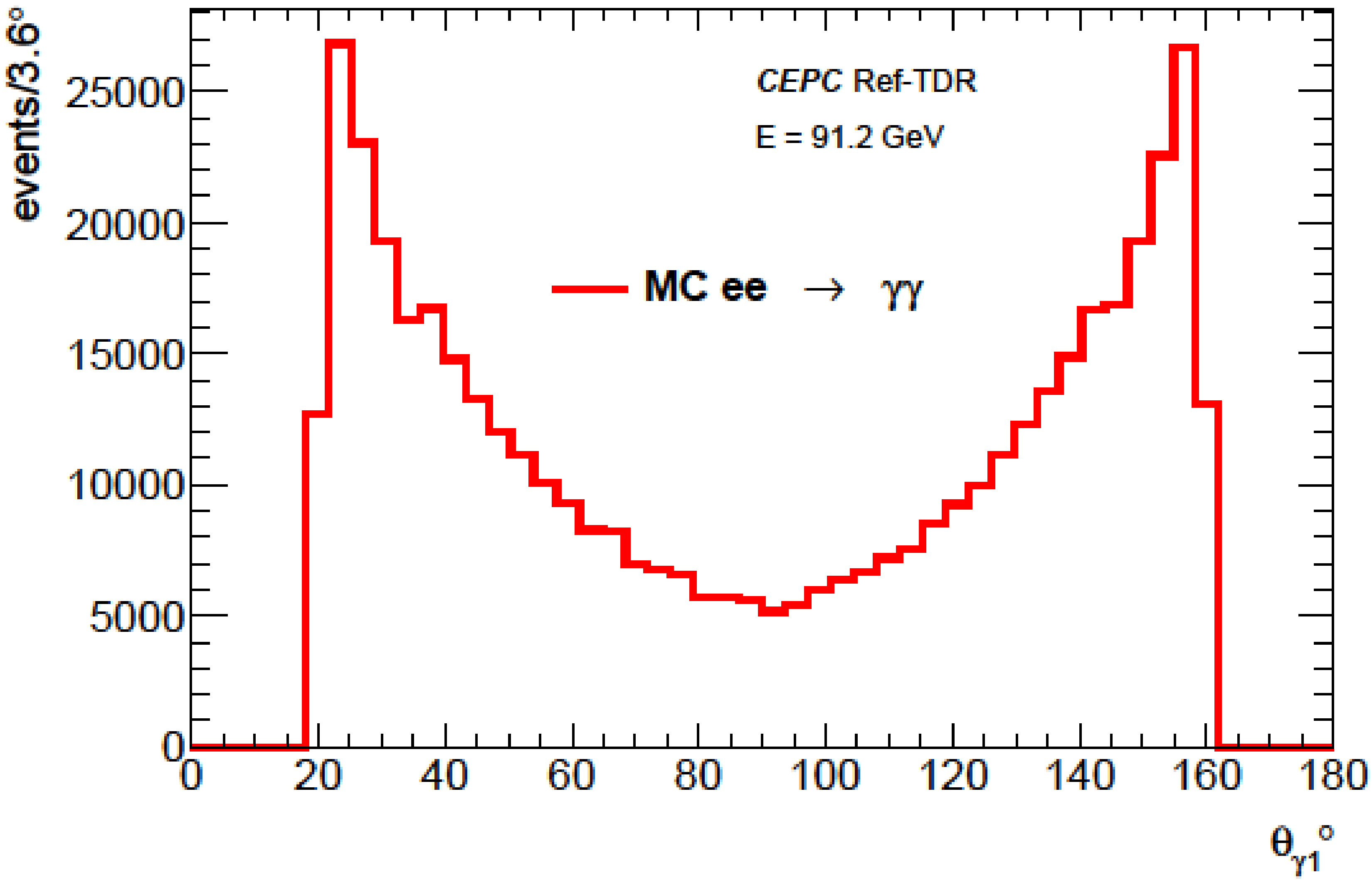




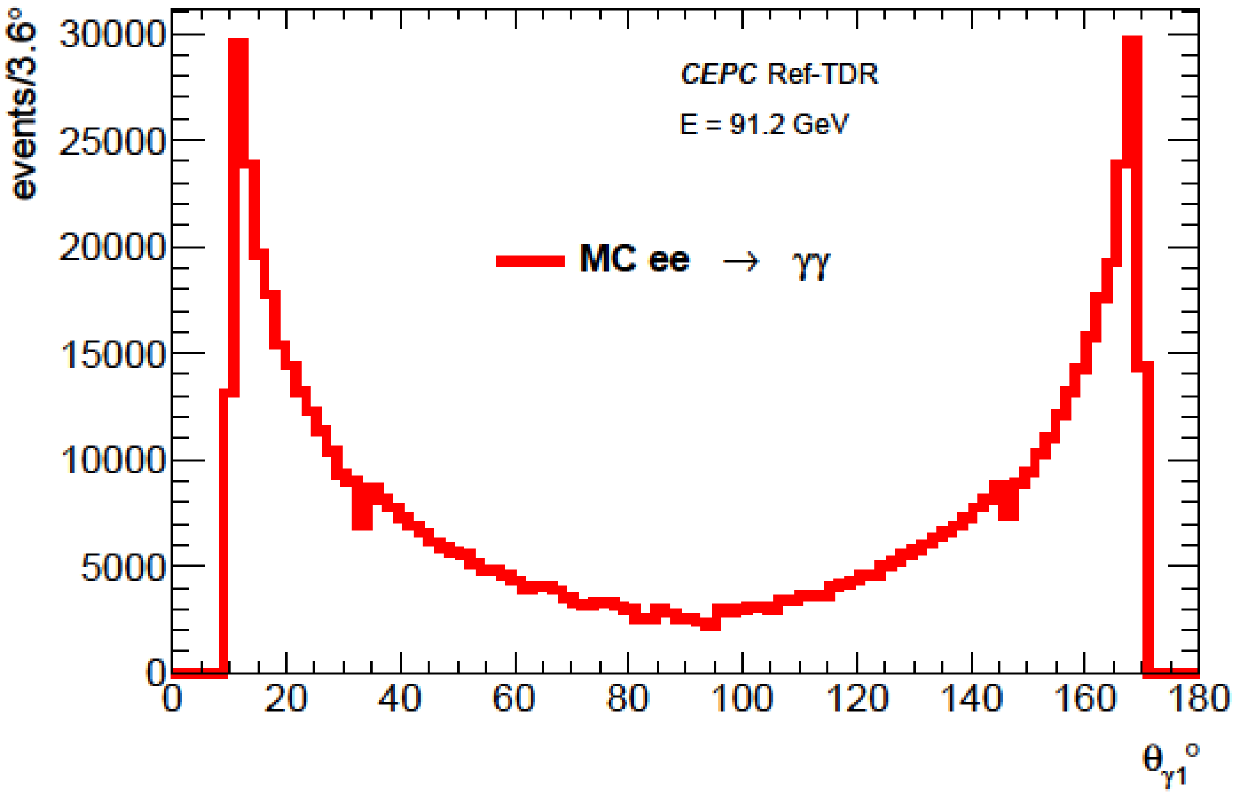
At E = M_Z invariant mass of 2 photons allow to select **ee → γγ.**

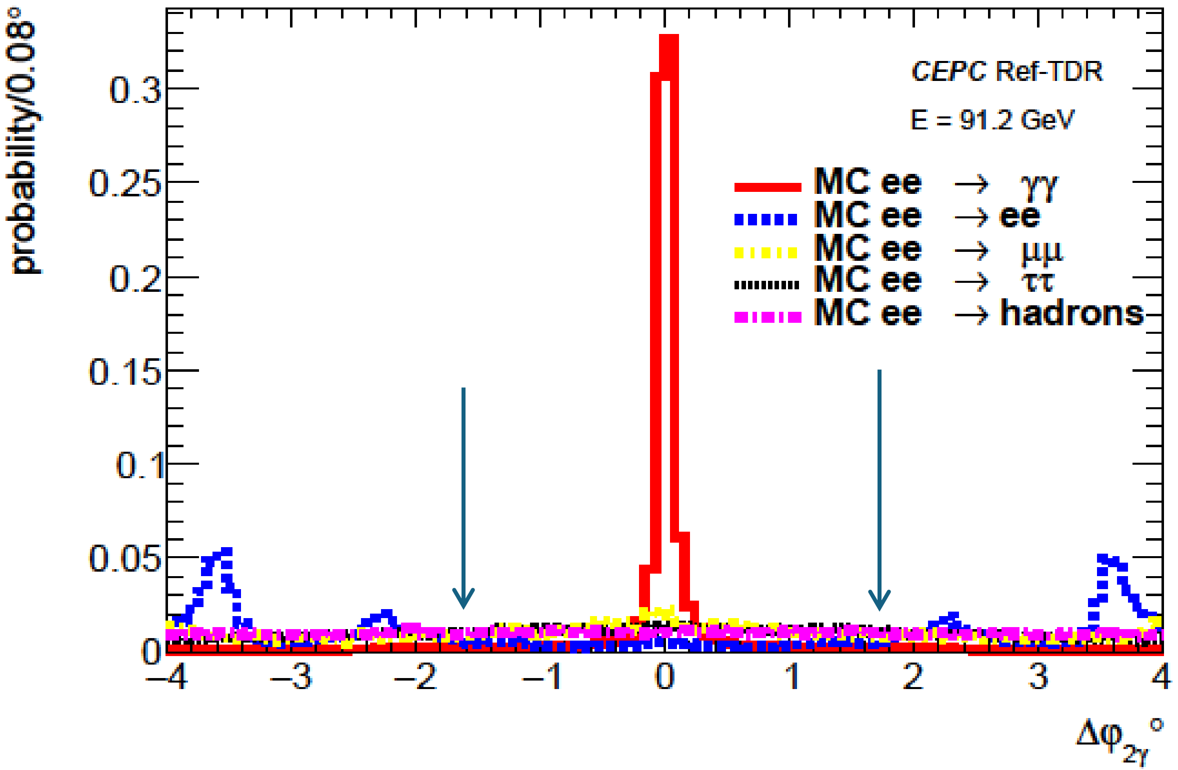
Minimal photon energy is used to calculate number of neutral particles.

Angular distribution for $ee \to \gamma\gamma$ process.



Relaxed selection 10<θ<170°





If we want to increase statistics by using 10<θ<170° selection then 10^{-4} contamination from the ee → ee process appears.

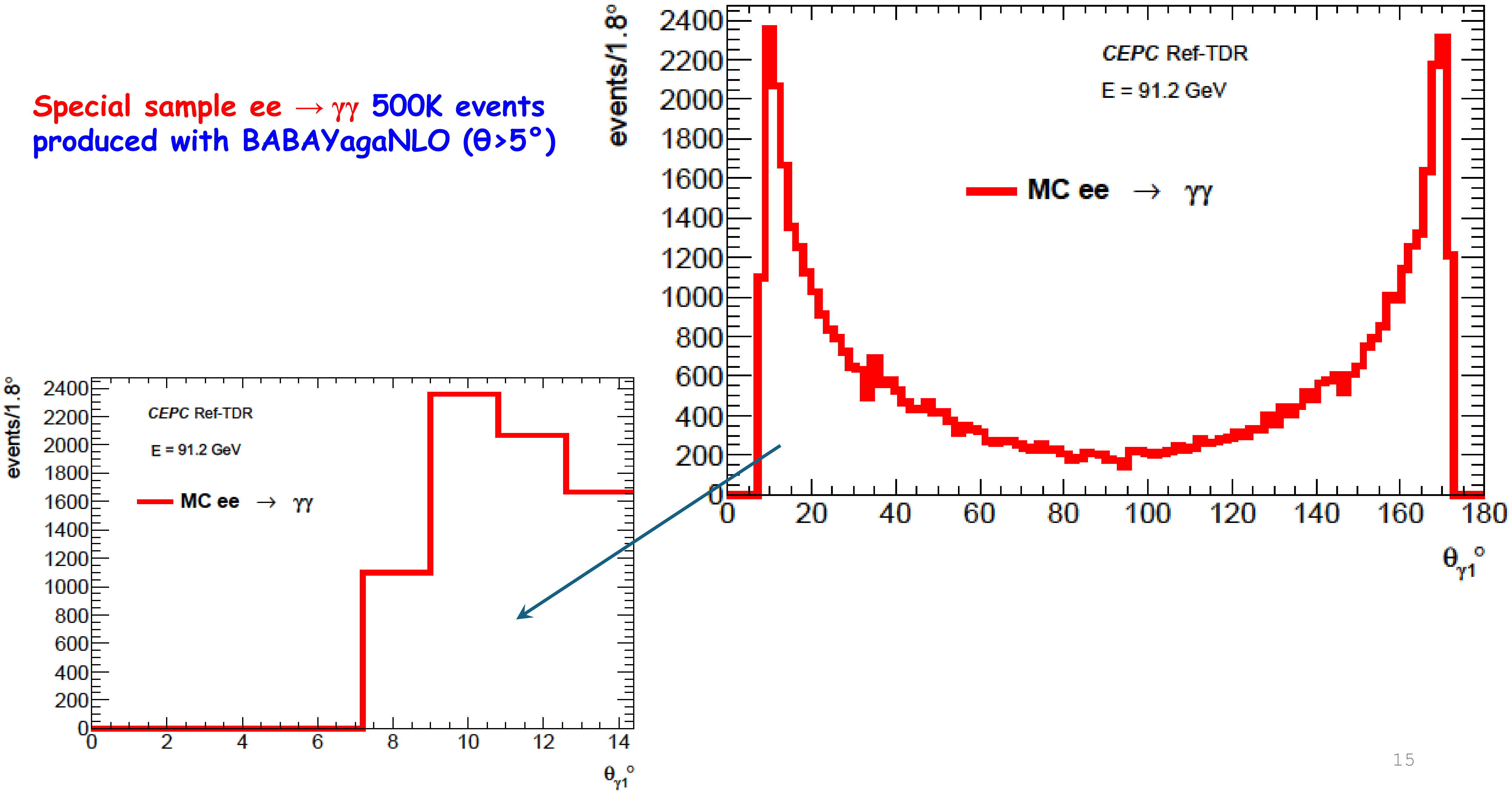
To suppress this ee → ee background the condition **abs($\Delta\varphi_{2\gamma}$) <1.75** could be used. In this case:

ee → γγ 688081 events selected from 1M (~69% efficiency)

ee → ee 0 events selected from 200k (without abs($\Delta\varphi_{2\gamma}$) <1.75 2 events selected)

Relaxed selection 5<θ<175°

Special sample ee $\rightarrow \gamma\gamma$ 500K events
produced with BABAYagaNLO (θ>5°)



Possible systematical uncertainty sources

1. Theoretical total cross section should be known with accuracy 10^{-4}
2. γ – conversion should be studied with data
3. Detector acceptance at small angles (10-20°), beam spot position and width
4. Scale and resolution of the electromagnetic calorimeter, trigger efficiency
5. Backgrounds (are expected to be small: 0 events passed the selection criteria, and several cuts as Ecal, $\Delta\varphi$, $\Delta\theta$ are not used yet)

Comparison with $ee \to ee$ could be used to check the systematical uncertainty. Systematical uncertainty reduction is expected if the main detector is used for process under study and for normalization process.

$ee \to \gamma\gamma$ cross section dependence on energy (line shape) could be used to control background.

Rare Z Decays and New Physics with $e^+e^- \to \gamma\gamma$

Forbidden decay $Z\to\gamma\gamma$ and rare decays $Z\to\pi^0\gamma$, $Z\to\eta\gamma$ were searched at LEP. This was done with Z-line shape (Fig.2).

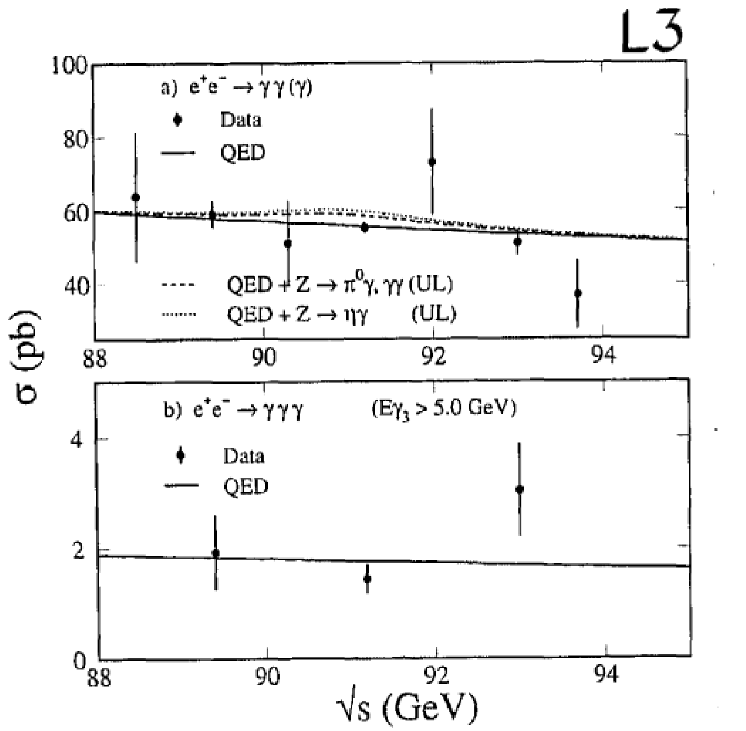


Fig. 2. Comparison of the total cross sections between the data and the QED prediction as a function of center of mass energy. In (a) upper limits (UL), at 95% CL, on the rare and forbidden processes are also shown.

$$\mathrm{BR}(Z\to\pi^0\gamma/\gamma\gamma) < 5.2\times10^{-5}$$

$$\mathrm{BR}(Z\to\eta\gamma) < 7.6\times10^{-5}.$$

Deviation from SM predictions:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda_\pm} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm Born} \pm \frac{\alpha^2 s}{2\Lambda_\pm^4}(1+\cos^2\theta)\,.$$

$\Lambda_+ > 431$ (GeV)

$\Lambda_- > 339$ (GeV)

Short range exponential deviation

$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda'} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm Born} + \frac{s^2}{32\pi}\frac{1}{\Lambda'^6}\,.$$

$\Lambda_7 > 880$ (GeV)

$\Lambda_8 > 24.3$ (GeV)

Contact interaction (dimension 7 and 8 operators)

$$\left(\frac{d\sigma}{d\Omega}\right)_{M_s} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm Born} - \frac{\alpha s}{2\pi}\frac{\lambda}{M_s^4}(1+\cos^2\theta) + \frac{s^3}{16\pi^2}\frac{\lambda^2}{M_s^8}(1-\cos^4\theta)\,,\quad \lambda=\pm1\,.$$

$\lambda = +1$: $M_s > 868$ (GeV)

$\lambda = -1$: $M_s > 1108$ (GeV)

Extra spatial dimensions

$$\left(\frac{d\sigma}{d\Omega}\right)_{e^*} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm Born} + \frac{\alpha^2}{16}\frac{f_\gamma^4}{\Lambda^4}s\sin^2\theta\left[\frac{p^4}{(p^2-M_{e^*}^2)^2}+\frac{q^4}{(q^2-M_{e^*}^2)^2}\right] - \frac{\alpha^2}{2s}\frac{f_\gamma^2}{\Lambda^2}\left[\frac{p^4}{(p^2-M_{e^*}^2)}+\frac{q^4}{(q^2-M_{e^*}^2)}\right],$$

Exited electron $M_{e^*} > 366$ (GeV)

Summary

1. ee → γγ luminosity measurement with main detector is possible at CEPC.
2. Theoretical uncertainty could be decreased to the level 10^{-5} if NNLO calculations will be available
3. The backgrounds are expected to be small
4. Resolutions of the detector systems are well enough for precision ee → γγ study
5. Rare Z decays and New Physics could be searched with $e^+e^- \to \gamma\gamma$

MC samples

We using CEPCSW tdr25.3.3, all MC is for E = 91.2 GeV

ee → γγ 1M events produced with BABAYagaNLO (θ>10°) and converted to stdhep:
/cefs/higgs/alexey/Converter/gg_cepc_E91_stdhep/

Reco level output: /cefs/higgs/alexey/SamplesProd/E91_gg/Reco/

MiniTree /cefs/higgs/alexey/TestNt/Init.C

ee → ee 200k events is taken from:
/cefs/higgs/zhagkl/stdhep/E91.2/2fermions/E91.2.Pe1e1.e0.p0.whizard195/

ee → μμ 1M events from /cefs/higgs/wanjiawei/work/E91_e2e2/Reco/

ee → ττ 200k events /cefs/higgs/wanjiawei/work/E91_e3e3/Reco/

ee → bb 100k events /cefs/higgs/wanjiawei/work/E91_bb.e0.p0/Reco/

ee → cc 100k events /cefs/higgs/wanjiawei/work/E91_cc.e0.p0/Reco/