A. Drutskoy,
LPI, Moscow

co-authors: E. Vasenin and S. Zenchuk

An opportunity to measure $\mathcal{B}(Z \to \nu_e \bar{\nu}_e)$ with high accuracy at CEPC.



The 2026 International Workshop on the High-Energy Circular Electron-Positron Collider (CEPC2026)

Shanghai, October 22 - 26, 2026.

The talk is devoted to possible method of $\mathcal{B}(Z \to \nu_e \bar{\nu}_e)$ measuring using only single high-energy photon reconstructed in ECAL calorimeter , with no other clusters or tracks detected in event.

As of today, $\mathcal{B}(Z \to \nu_e \bar{\nu}_e)$ has not been experimentally measured.
The method of measurement of this value is proposed for the first time.
The branching fraction is sensitive to BSM scenarios, including the seesaw mechanism, lepton universality violation and some others.

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$Z \to$ *invisible*: current experimental and theoretical status

Two methods of Z boson invisible decay branching fraction measurements:

1. Direct: from process $e^+e^- \to \gamma$ + *invisible* (less precise; LHC – missing E,P,M)
2. Indirect: $\Gamma_{inv} = \Gamma_Z - \Gamma_{hadrons} - \Gamma_{leptons}$ (PDG: $\mathcal{B}(Z \to inv.) = (20.000 \pm 0.055)\%$)

Within SM the Z decay width for each active neutrino can be precisely calculated.

Using this SM values and indirectly measured Γ_{inv}, number of neutrinos was obtained:

LEP combined analysis 2006 : $N\nu$ = 2.9840 ± 0.0082

Improved analysis in 2020, PDG 2026 : $N\nu$ = 2.9963 ± 0.0074

Introducing one sterile neutrino mixed with active ones results in non-unitarity of the PMNS matrix. Correction corresponds to sum of mixing elements.

Seesaw mechanism

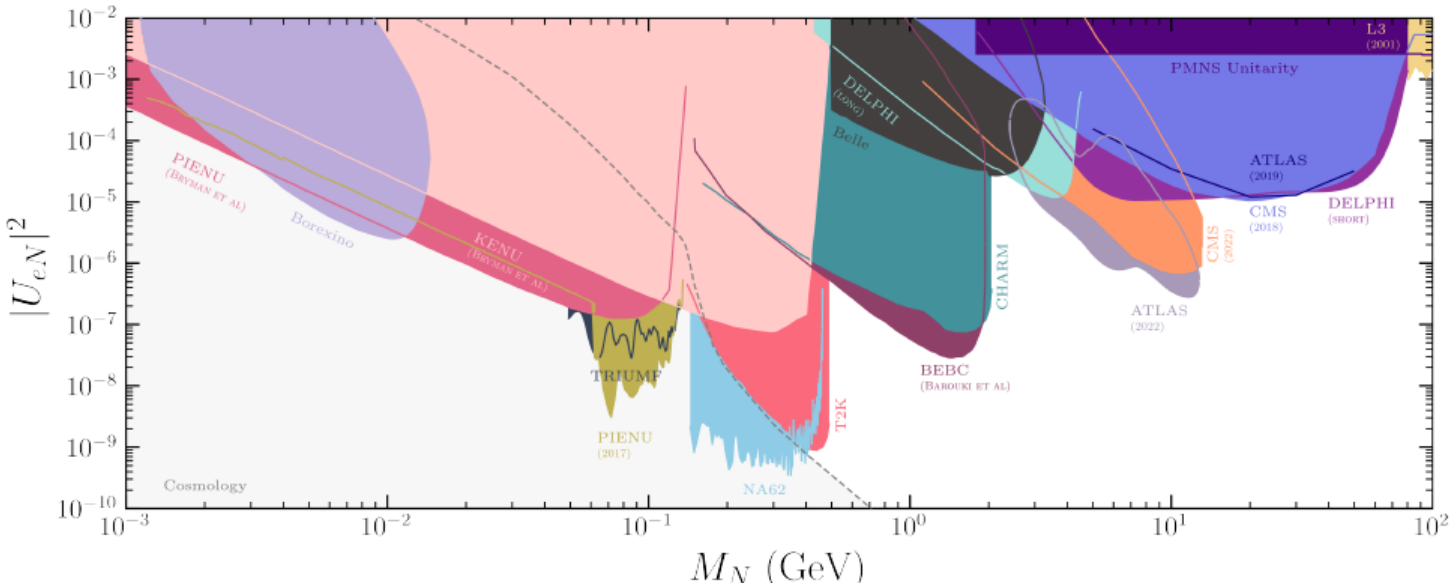
$$\varepsilon^2 = \sum_{\alpha=e,\mu,\tau} |U_{\alpha 4}|^2$$

Then invisible Z width: $\Gamma_{inv} = \Gamma_0(3 - 2\varepsilon^2 + \varepsilon^4) + \Gamma_4\varepsilon^4 + 2\,\Gamma_{40}\,\varepsilon^2(1 - \varepsilon^2)$ + Γ_{BSM}

Γ_0 – decay to two light neutrinos, Γ_4 - two heavy, Γ_{40} – light-heavy

If $\Gamma_0 = \Gamma_4 = \Gamma_{40}$ ⇨ $\Gamma_{inv} = 3\,\Gamma_0$ - restoration of SM value $N\nu = 3$ for $m_{NHL} < m_Z$

Current experimental limits on sterile neutrino mixing



There are relatively strong limits of 10^{-4} or stronger on mixing element for sterile neutrino mass region from 1 MeV to 100 GeV.

Very weak constrains on mixing elements for sterile neutrino mass region below 1 MeV.

There is a room for deviations from SM for experimental values $N\nu$ and $\mathcal{B}(Z \to \nu_e \bar{\nu}_e)$.

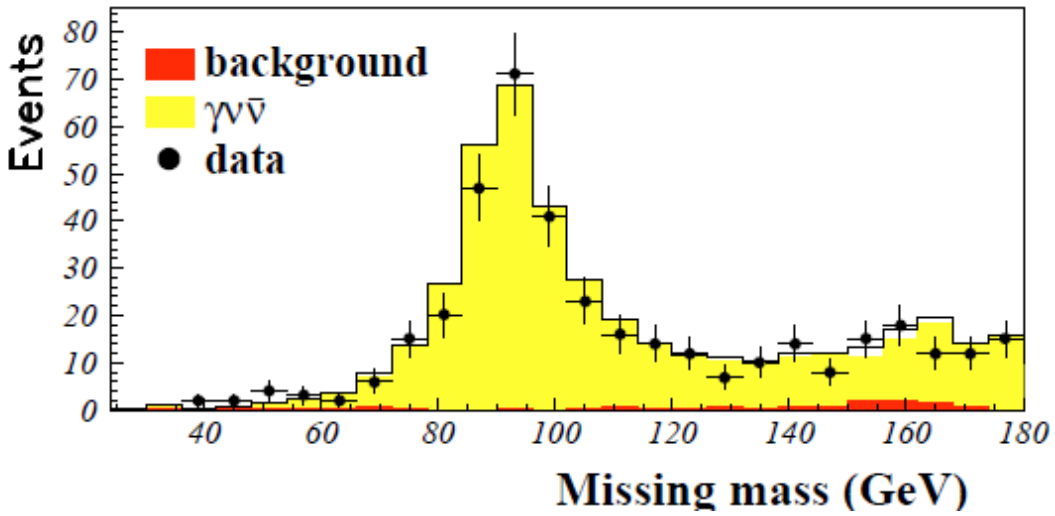
As example, if sterile neutrino M < 1 MeV and sterile-active mixing element ~ 10^{-1} - 10^{-3}.

!!! We propose method of experimental measurement $\mathcal{B}(Z \to inv.)$ and $\mathcal{B}(Z \to \nu_e \bar{\nu}_e)$, not only test of seesaw theory and additional sterile (right-handed) neutrinos.

Earlier results from LEP

The DELPHI Collaboration (submitted to the HEP'99 Conference)

Process: $e^+e^- \rightarrow \gamma$ + *invisible particles.* Recoiling mass against detected photon for the events at 189 GeV in all three calorimeters. Integrated luminosity is 158 pb^{-1}.



Selections: only high-energy photon is detected, no additional clusters in calorimeters, no tracks in trackers.

We assume full data sample expected at CEPC of 5.6 ab^{-1}, about 35,000 times larger.

Recoil (missing) mass to photon depends on photon energy, but not on photon angle.

Simulation procedure

Signal: $e^+e^- \to \gamma + \nu\bar{\nu}$

MC: Whizard 3 (arXiv:2004.14486)
+ Delphes (CEPC card)

E_{CM} = 240 GeV $\mathcal{L}_{int}$ = 5.6 ab^{-1}

$$\mathcal{B}(Z \to \nu_e \bar{\nu}_e) = \kappa^2 \times \mathcal{B}(Z \to \nu_e \bar{\nu}_e)_{SM}$$

$$\mathcal{B}(Z \to \nu\bar{\nu}) = \mathcal{B}(Z \to \nu\bar{\nu})_{SM}$$

$$\mathcal{L} = \frac{e}{4 \cdot \cos\theta_W \cdot \sin\theta_W} \times \Big[\kappa\, \bar{\nu}_e \gamma_\mu (1-\gamma_5) \nu_e + \sqrt{1 - \frac{1-\kappa^2}{2}}\, \bar{\nu}_\mu \gamma_\mu (1-\gamma_5) \nu_\mu + \sqrt{1 - \frac{1-\kappa^2}{2}}\, \bar{\nu}_\tau \gamma_\mu (1-\gamma_5) \nu_\tau \Big] Z^\mu$$

SM ➔ $\kappa = 1$

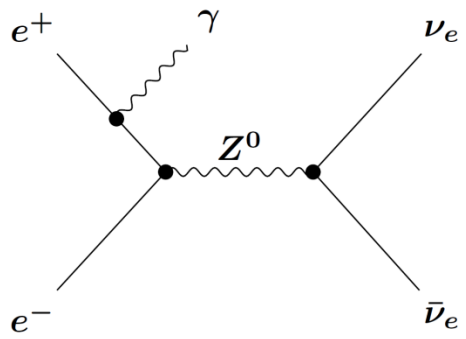
We modified SM Lagrangian to vary coupling of Z boson with electron neutrinos, but compensated for this by changing respectively couplings with muon and tau neutrinos so as to keep invisible Z width unchanged.
Alternatively, we can vary all three couplings simultaneously using a single parameter, that will change the invisible Z width. These two effects can be well separated experimentally (will be explained below).

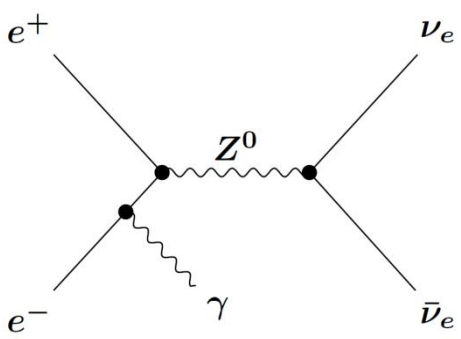
Preselection:

1. Energetic photon with E > 10 GeV
2. No other photons in ECAL with parameters Pt > 0.5 GeV, E > 2 GeV, $|\cos\theta| < 0.99$
3. No tracks in tracker and objects in HCAL calorimeter in angular region $|\cos\theta| < 0.99$

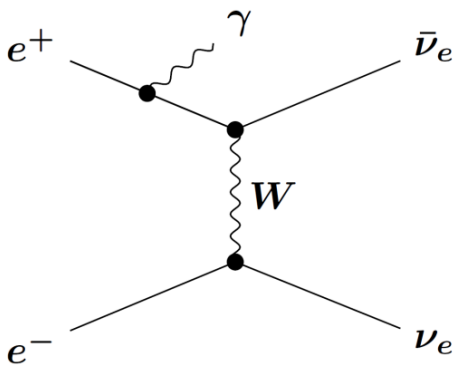
Signal diagrams

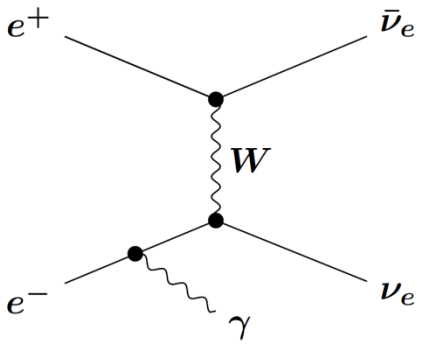
s-channel

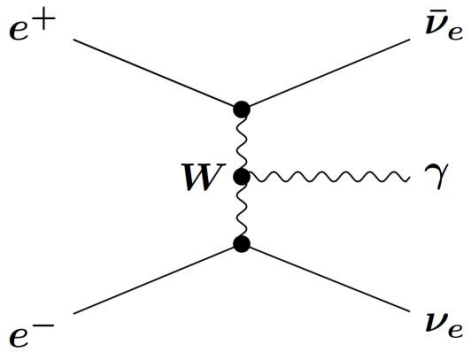




t-channel

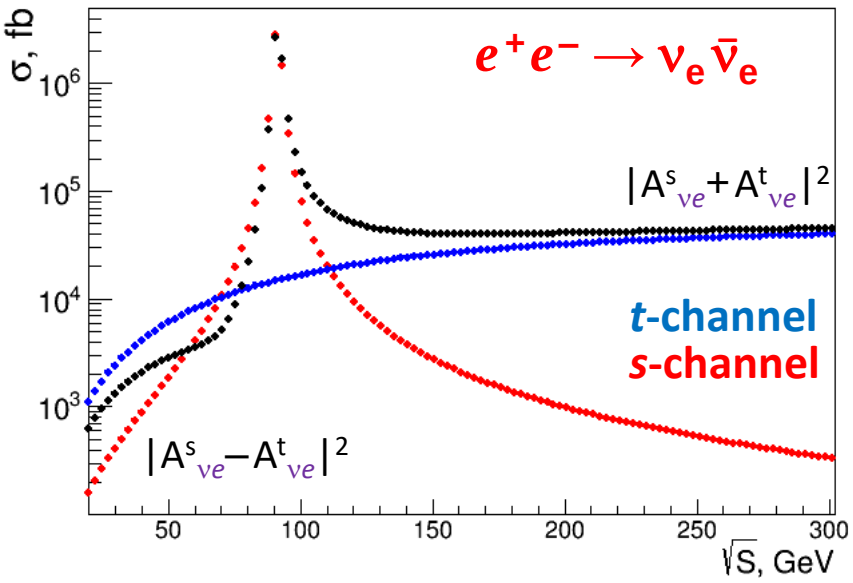


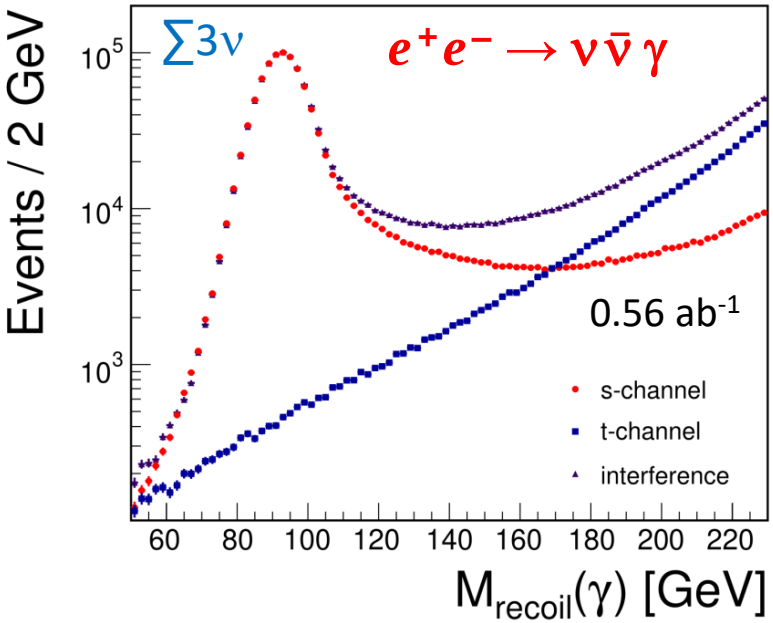




Last diagram is important at very high photon energy.

General idea





Born cross section of $e^+e^- \to \nu_e\bar{\nu}_e$ as a function of CM energy is shown (left).

Interference (relative phase) of *s*- and *t*-channel amplitudes changes smoothly from negative to positive with $\sqrt{S}$.

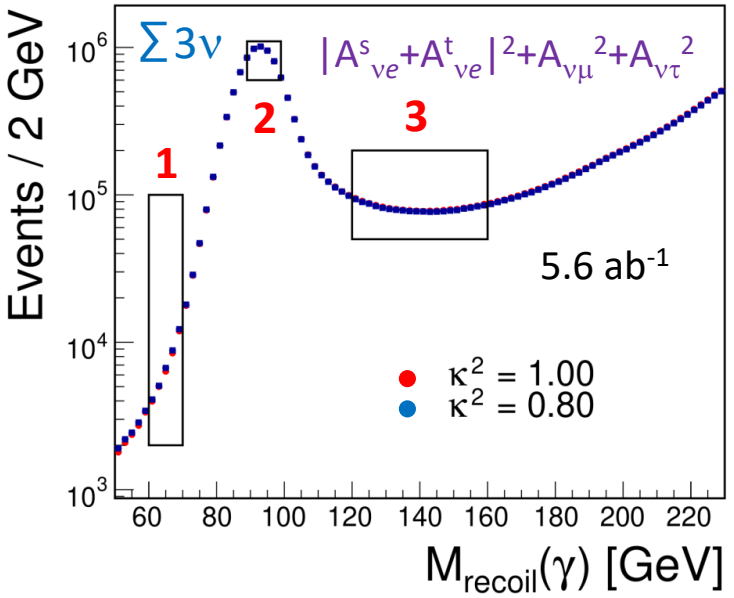
Due to very large cross sections, the effect can be also tested in recoil mass to γ (right). It works like energy scan, where cross section is convolved with probability of (ISR) photon production with fixed energy.

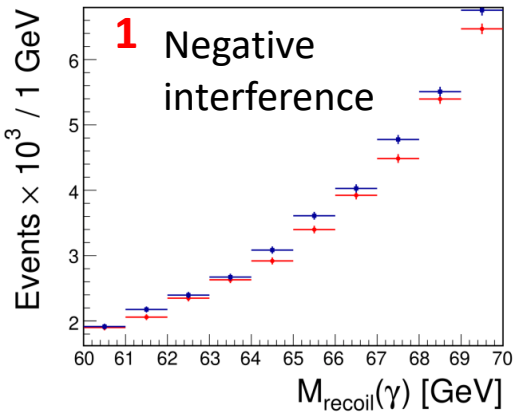
Signal shape with interference

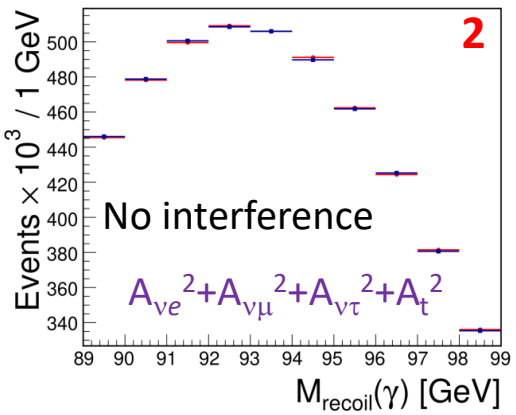
Relative phase of s-channel is changing from -π to 0 from left to right. Sum of 3 neutrinos.

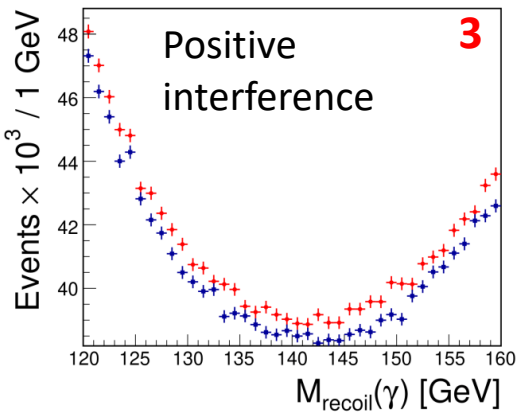
Interference is sensitive to κ^2 assuming Lagrangian given above.

Using this effect we can measure branching fraction $\mathcal{B}(Z \to \nu_e \bar{\nu}_e)$, as its deviation from SM value.

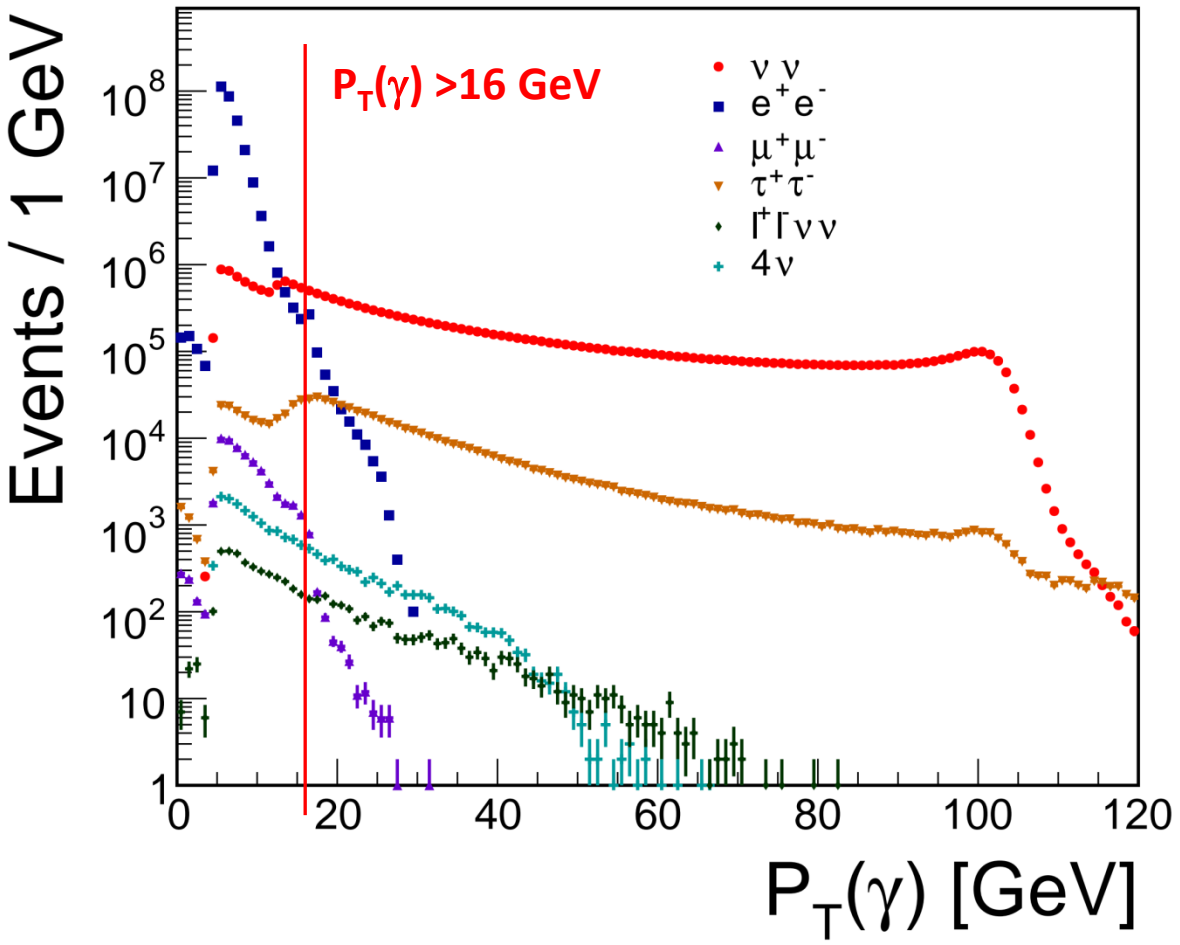








Background suppression



Studied backgrounds:

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

$e^+e^- \to \mu^+\mu^-\gamma$

$e^+e^- \to \tau^+\tau^-\gamma$

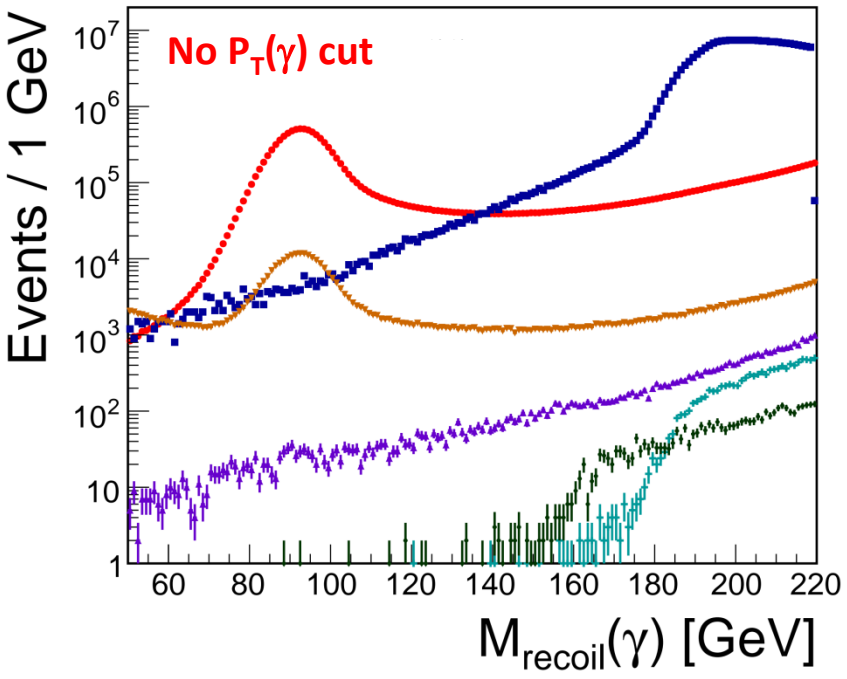
$e^+e^- \to \ell\ell\nu\nu\gamma$

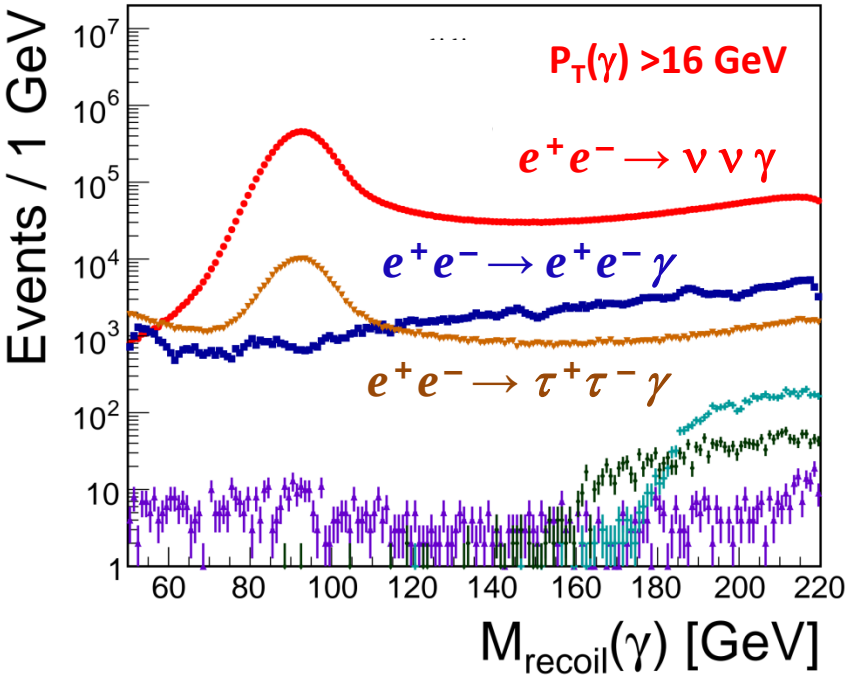
$e^+e^- \to 4\nu\gamma$

Large $e^+e^-\gamma$ background, which can be effectively suppressed.

To reduce backgrounds significantly cut **$P_T(\gamma)$ >16 GeV** is applied.

Backgrounds suppression





Studied backgrounds:

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

$e^+e^- \to \mu^+\mu^-\gamma$

$e^+e^- \to \tau^+\tau^-\gamma$

$e^+e^- \to \ell\ell\nu\nu\gamma$

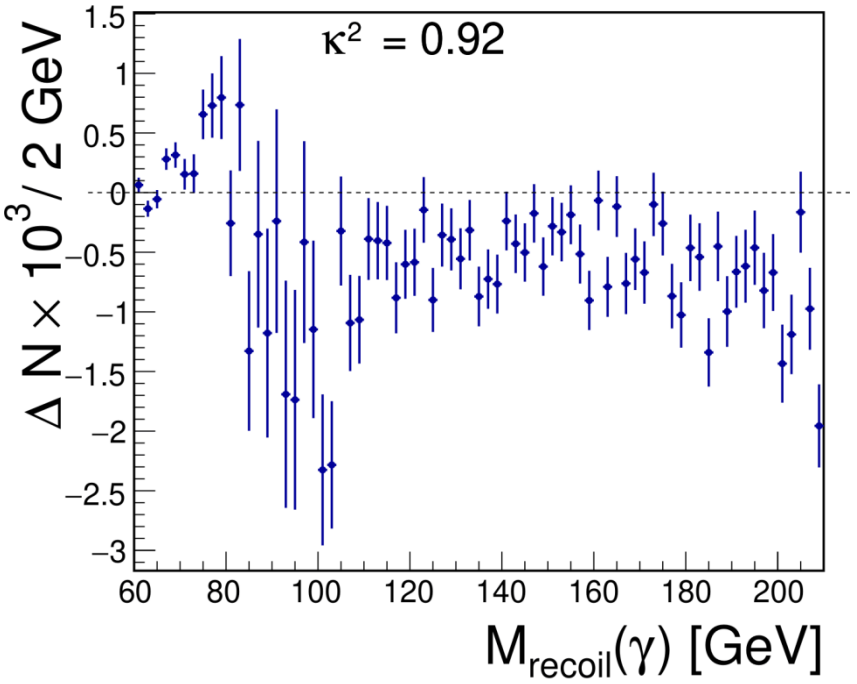
$e^+e^- \to 4\nu\gamma$

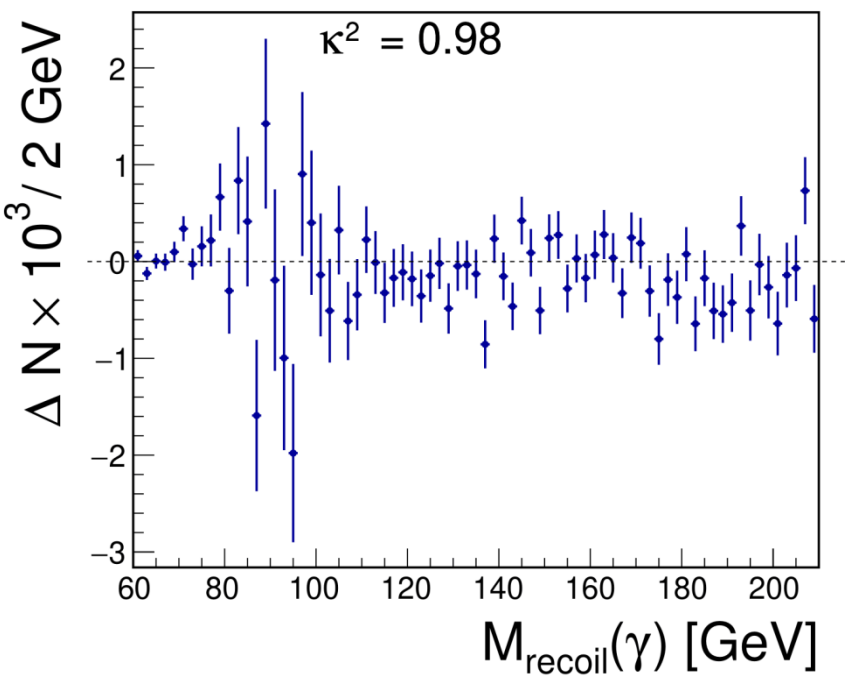
All backgrounds can be reduced to < 8 % of signal, except low mass region.

Region chosen for analysis: 60 – 210 GeV

All remaining backgrounds are taken into account in calculations of signal significance shown below.

Examples of difference in event numbers relative to SM

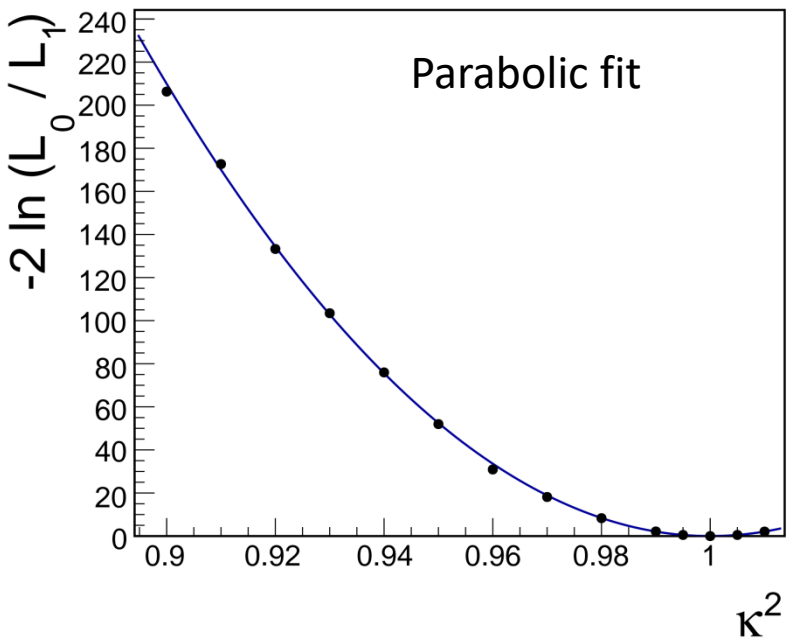


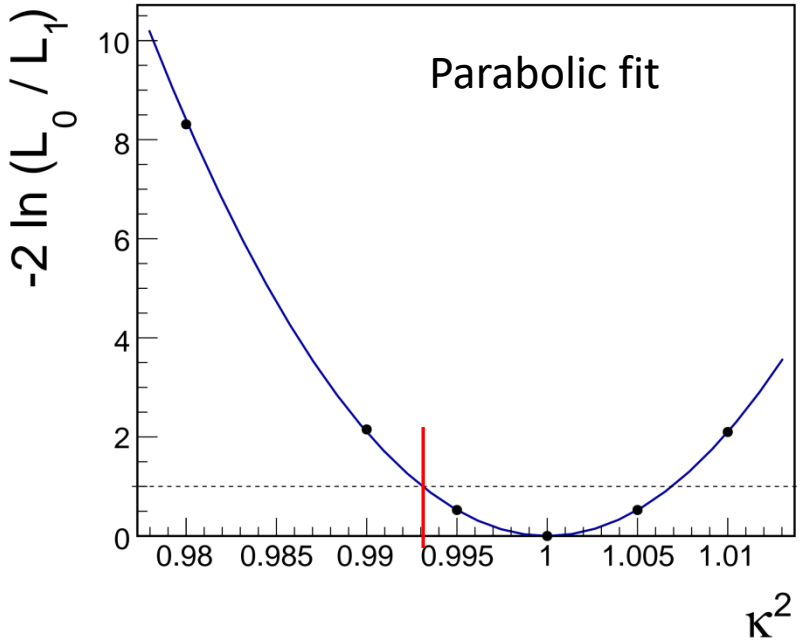


Difference in event yields between SM (κ^2 = 1) and fixed κ^2 in recoil mass distributions.

Points are higher than zero level before Z mass and lower after Z mass.
Difference from zero is already seen for κ^2 deviated from SM at a few % level.

Signal significance





Significance = $-2 \ln (\mathcal{L}_0/\mathcal{L}_1)$

$\mathcal{L}_{0/1} = \prod_i^{bin} Poiss\ (\mu_i^{0/1}, N_i(\kappa^2))$

Binned likelihood method, fit range for $M_{recoil}(\gamma)$: 60 – 210 GeV

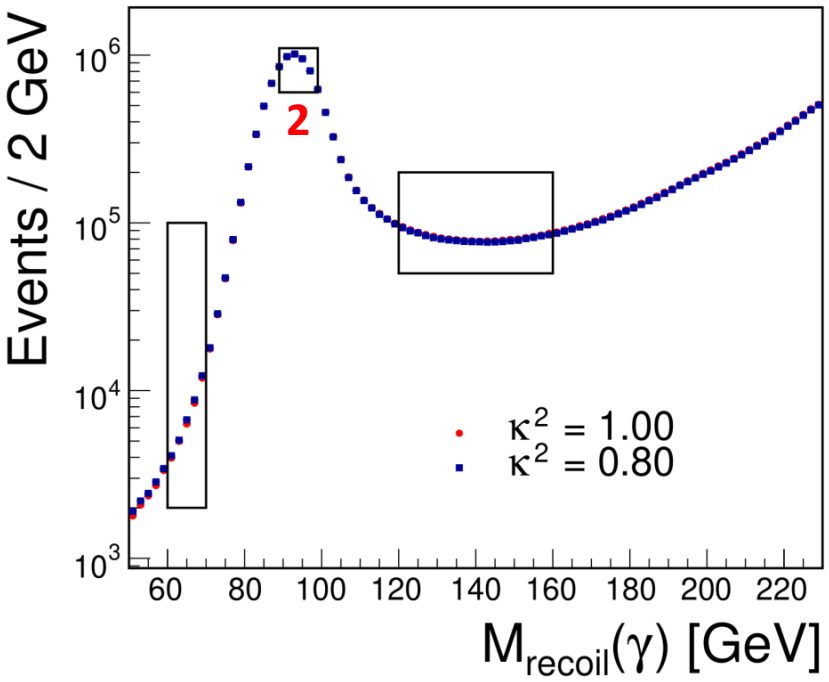
$N_i(\kappa^2)$: MC distribution obtained for fixed κ^2 assuming 5.6 ab^{-1}

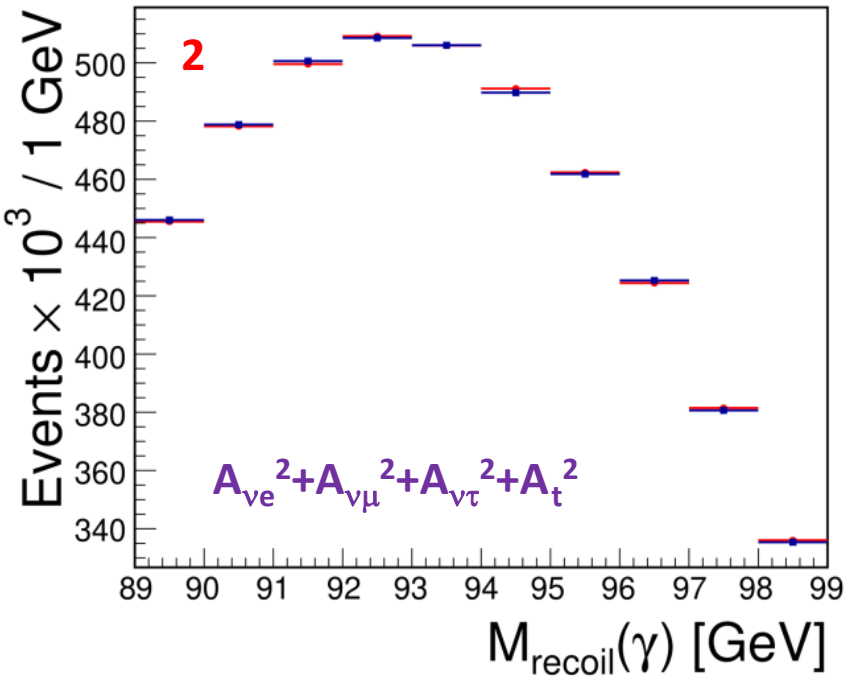
$\mu_i^{0/1}$: expected MC distributions for hypothesis 0 and 1 for very large samples

Hypothesis 0 : $\kappa^2 = 1$; hypothesis 1 : $\kappa^2 = \kappa_{fit}^2$ obtained from best fit to $N_i(\kappa^2)$.

1σ corresponds to κ^2 interval [0.993, 1.007] or $\pm$ 0.007 around 1.

Opportunity to measure $N\nu$





Number of events in Z peak region depends on $\mathcal{B}(Z \to inv.)$ but does not depend on κ.
Full number of events in this region is approximately 10^7 for 5.6 ab^{-1}. Respectively we can estimate relative accuracy of $\mathcal{B}(Z \to inv.)$ measurement as 3×10^{-4}.
Current accuracy is $N\nu = 2.9963 \pm 0.0074$, it means relative accuracy of ~ 2.5×10^{-3}.

$\mathcal{B}(Z \to \nu_e \bar{\nu}_e)$ and $\mathcal{B}(Z \to inv.)$ can be measured independently (wings and peak of Z).

Conclusions

We propose a method of $\mathcal{B}(Z \to \nu_e \bar{\nu}_e)$ measurement. Using this method we can measure $\mathcal{B}(Z \to \nu_e \bar{\nu}_e)$ with relative accuracy of ± 0.007 assuming integrated luminosity of 5.6 ab^{-1} and CEPC reference detector.

Systematic uncertainties are not estimated, but they can be well controlled using $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to e^+e^-\gamma$ processes.

Independently of $\mathcal{B}(Z \to \nu_e \bar{\nu}_e)$ measurement, $\mathcal{B}(Z \to inv.)$ can be directly measured with relative accuracy of about 3 x 10^{-4} with 5.6 ab^{-1}. It is an order of magnitude better, than LEP indirect measurement. Indirect method in CEPC can give best accuracy.

Proposed method can be used at lower and higher CM energy.

The most general task : to search for any deviation from SM.

Table 10.4: Partial and total Z decay widths [in MeV]. The results are derived from Table 10.3 and the corresponding covariance matrices [139,215]. The results in the second column are derived without the assumption of lepton universality, while lepton universality is assumed in the third column. The SM predictions are given in the fourth column.

Quantity	Value	Value (universal)	Standard Model
$\Gamma_{e^+e^-}$	83.87 ± 0.12	83.942 ± 0.085	83.983 ± 0.018
$\Gamma_{\mu^+\mu^-}$	83.95 ± 0.18	83.941 ± 0.085	83.982 ± 0.018
$\Gamma_{\tau^+\tau^-}$	84.03 ± 0.21	83.759 ± 0.085	83.793 ± 0.018
Γ_{inv}	498.9 ± 2.5	500.5 ± 1.5	501.605 ± 0.048
$\Gamma_{u\bar{u}}$	—	—	299.88 ± 0.16
$\Gamma_{c\bar{c}}$	300.3 ± 5.3	300.0 ± 5.2	299.80 ± 0.16
$\Gamma_{d\bar{d}}, \Gamma_{s\bar{s}}$	—	—	382.82 ± 0.12
$\Gamma_{b\bar{b}}$	377.4 ± 1.3	377.0 ± 1.2	375.90 ± 0.20
Γ_{had}	1744.8 ± 2.6	1743.2 ± 1.9	1741.21 ± 0.65
Γ_Z	2495.5 ± 2.3	2495.5 ± 2.3	2494.56 ± 0.73