Two Photon Physics at CEPC energies

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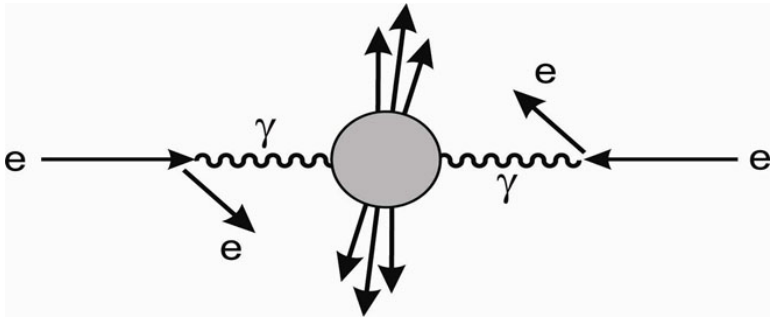
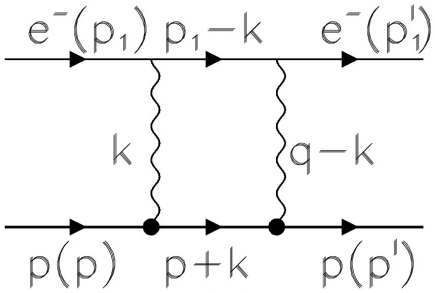
What are two photon processes about?

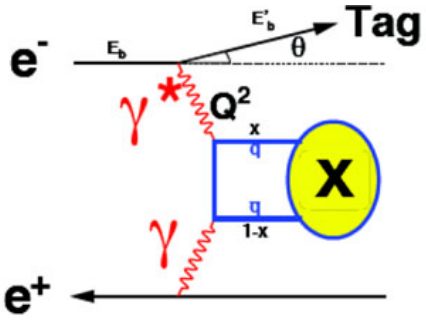
Process in consideration: $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-X$



- electron and positron radiate photons approximately in beam direction
- bulk of radiated photons are almost real
- the main process in consideration is $\gamma\gamma \to X$, X is final state containing leptons, mesons, other hadrons.
- Do not mess with the two-photon exchange process, which is connected with Feynman Diagram of type:



Key feature of two photon processes



- The cross-section of the 2γ process is factorized in two parts, one of which is cross section of $\gamma\gamma \to X$ process:

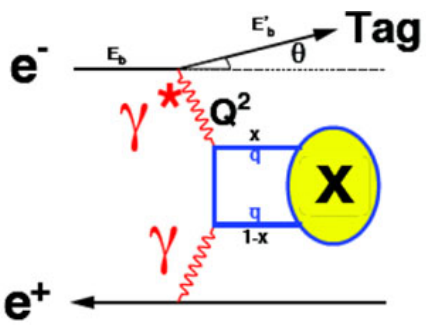
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{64\pi^4} \frac{(E^2 + E_1^2)(E^2 + E_2^2)}{E^4(E - E_1)(E - E_2)\sin^2\frac{\theta_1}{2}\sin^2\frac{\theta_2}{2}} \sigma_{\gamma\gamma\to X}$$

- 2γ process is enhanced with the energy of initial particles:

$$\sigma(e^+e^- \to e^+e^-X) \approx \alpha^4 \log^2(\frac{E}{m_e}), \qquad \sigma(e^+e^- \to X) \approx \frac{\alpha^2}{E}$$

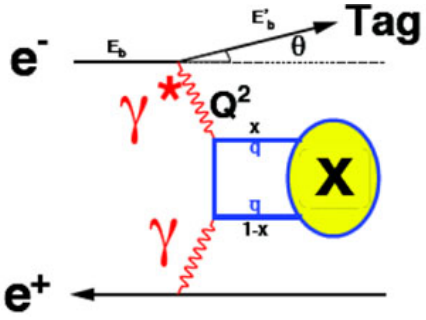
- The enhancement is due to the poles in photon propagators ($Q^2 \to 0$). As a consequence, almost all photons with small virtualities, lepton scattering angle is very small, invariant mass W of final state X tends to small values

Possible kinematics set-ups



- Notag events: collisions of quasi-real photons (low Q^2).
  - A lot of statistics
  - but it is difficult to reconstruct the exact kinematics due to non-tagged scattered leptons
- Single-tag events: collision of a quasi-real photon with a highly virtual one. One beam particle detected in the calorimeter
  - Moderate statistics
  - one of Q^2 is measurable due to tagged scattering lepton (positron or electron)
- Double-tag: 2 high-virtuality photons, both beam particles detected,
  - Scarce statistics
  - event kinematics fully reconstructed

2γ and initial state radiation process



- For notag events the 2γ process and processes with emission of photon form initial electron or positron in detector have similar signature, but at low invariant mass W of final state X below 120 GeV, the contribution of ISR is negligible compared to the 2γ
- Two γ process cross section (x_i is the photon energy fraction):

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{64\pi^4} \frac{(E^2 + E_1^2)(E^2 + E_2^2)}{E^4 x_1 x_2 E^2 \sin^2 \frac{\theta_1}{2} \sin^2 \frac{\theta_2}{2}} \sigma_{\gamma\gamma \to X(s x_1 x_2)}$$

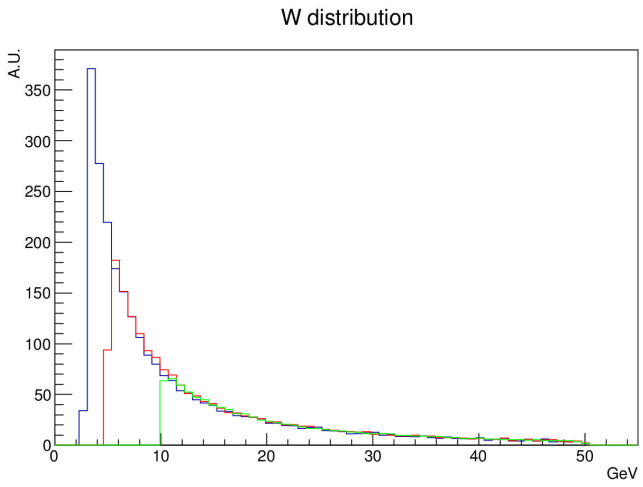
- Initial state radiation process (x_i is lepton energy fraction):

$$\frac{d\sigma}{d\Omega} = D(x_1, \beta) D(x_2, \beta) \sigma_{ee \to X}(s x_1 x_2)$$

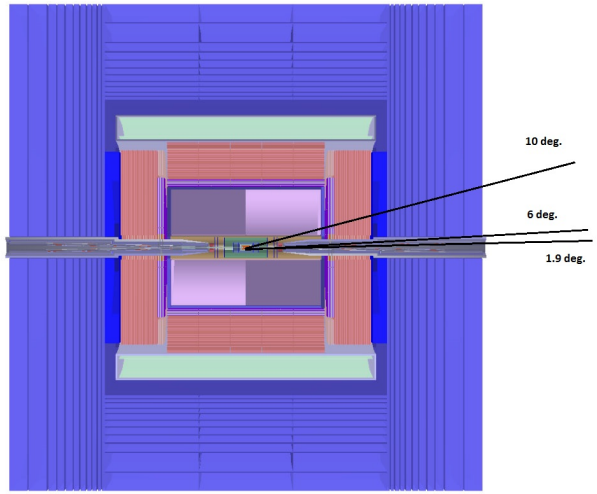
$$D(x, \beta) = 2\beta(1 - x)^{2\beta - 1}(1 + \frac{3}{2}\beta) - \beta(1 + x) \approx \frac{1 + x^2}{1 - x}$$

Event simulation

- for simulation was used event generator Galuga (G.A. Schuler, arXiv:hep-ph/9611249)
  - no equivalent photon approximation utilization (could lead to the wrong shapes for the energy and momentum distributions of the hadronic system in single and double tag set-ups)
  - virtuality and polarization of 2 photon is taken into account.
- We consider several cases, where invariant mass of 2γ final state is cutted at 3/5/ 10 GeV <W< 50 GeV
- Cuts over scattered lepton are defined at 10 degrees, 6 degrees (min angle for the detector) and 1.9 degree for luminosity detector utilization



Different cuts over W mass



Detector design concept (from CEPC conceptual design report)

Integrated luminosity of $\gamma\gamma$ *collisions*

Simulation over CEPC energy (240 GeV) for 2γ luminosity per 5 ab^{-}1 of ee luminosity

- No tag and single tag (nb^{-1}):

Energy Cut	No Tag	S Tag 10	S Tag 6
3	2.6×10^8	1.1×10^5	3.6×10^4
5	1.8×10^8	$1. \times 10^5$	3.3×10^4
10	$1. \times 10^8$	8.5×10^4	2.8×10^4

- Double tag (nb^{-1}):

Energy Cut	D Tag 6	D Tag 6-1.9	D Tag 1.9-1.9
3	2.8×10^1	3.9×10^2	2.1×10^3
5	2.4×10^1	3.6×10^2	1.8×10^3
10	1.9×10^1	2.8×10^2	1.3×10^3

Simulation is done over cases: the minimal angle of scattering lepton is 10 or 6 degrees (detection in the main device) and 1.6 degrees for detection in small angle luminosity calorimeter (double tag event).

Why 2γ physic is interesting?

Figure 8.9
Summary of gamma-gamma collider golden modes

Reaction	Remarks
$\gamma\gamma \to h^0 \to b\bar{b}$	SM/MSSM Higgs, $M_{h^0} < 160$ GeV/c^2
$\gamma\gamma \to h^0 \to WW(^*)$	SM Higgs, 140$< M_{h^0} <$ 190 GeV/c^2
$\gamma\gamma \to h^0 \to ZZ(^*)$	SM Higgs, 180$< M_{h^0} <$ 350 GeV/c^2
$\gamma\gamma \to h^0 \to \gamma\gamma$	SM Higgs, 120$< M_{h^0} <$ 160 GeV/c^2
$\gamma\gamma \to h^0 \to tt$	SM Higgs, $M_{h^0} >$ 350 GeV/c^2
$\gamma\gamma \to H, A \to b\bar{b}$	MSSM heavy Higgs, interm. $\tan\beta$
$\gamma\gamma \to \tilde{f}\bar{\tilde{f}},\ \tilde{\chi}_i^+\tilde{\chi}_i^-$	large cross sections
$\gamma\gamma \to \tilde{g}\tilde{g}$	measurable cross sections
$\gamma\gamma \to H^+H^-$	large cross sections
$\gamma\gamma \to S[\tilde{t}\bar{\tilde{t}}]$	$\tilde{t}\bar{\tilde{t}}$ stoponium
$e\gamma \to \tilde{e}^-\tilde{\chi}_1^0$	$M_{\tilde{e}^-} < 0.9 \times 2E_0 - M_{\tilde{\chi}_1^0}$
$\gamma\gamma \to \gamma\gamma$	non-commutative theories
$e\gamma \to eG$	Extra Dimensions
$\gamma\gamma \to \phi$	Radions
$e\gamma \to \tilde{e}\tilde{G}$	superlight gravitons
$\gamma\gamma \to W^+W^-$	anom. W interactions, extra dimensions
$e\gamma^- \to W^-\nu_e$	anom. W couplings
$\gamma\gamma \to 4W/(Z)$	WW scatt., quartic anom. W,Z
$\gamma\gamma \to t\bar{t}$	anomalous top quark interactions
$e\gamma^- \to \bar{t}b\nu_e$	anomalous Wtb coupling
$\gamma\gamma \to$ hadrons	total $\gamma\gamma$ cross section
$e\gamma^- \to e^-X,\ \nu_eX$	NC and CC structure functions
$\gamma g \to q\bar{q},\ c\bar{c}$	gluon in the photon
$\gamma\gamma \to J/\psi\, J/\psi$	QCD Pomeron

Table are taken form ILC white paper, https://arxiv.org/pdf/1310.0763.pdf

Simulation over CEPC energy (240 GeV) for charmonium production events for luminosity 5ab^{-1}

- No tag and single tag events:

name	No Tag	S Tag 10	S Tag 6
η_c	$1. \times 10^9$	5.3×10^5	1.7×10^5
χ_{c_0}	$2. \times 10^8$	6.5×10^4	2.2×10^4
χ_{c_1}	$7. \times 10^6$	4.4×10^4	1.1×10^4
χ_{c_2}	9.5×10^7	3.1×10^4	9.8×10^3
$\eta_{c_D}(3840)$	2.6×10^6	2.5×10^3	7.8×10^2
$\eta_c(2S)$	2.4×10^8	2.1×10^5	6.4×10^4

The minimal angle of scattering lepton is 10 or 6 degrees (detection in the main device) and 1.6 degrees for detection in small angle luminosity calorimeter.

- Double tag events:

name	D Tag 6	D tag 10	D Tag 6-1.9	D Tag 1.9-1.9
η_c	7.6×10^2	7.8×10^1	1.2×10^4	8.6×10^4
χ_{c_0}	6.3×10^1	6.1	$9. \times 10^2$	8.3×10^3
χ_{c_1}	1.7×10^2	1.8×10^1	2.4×10^3	1.7×10^4
χ_{c_2}	5.4×10^1	5.2	7.2×10^2	6.7×10^3
$\eta_{c_D}(3840)$	5.7×10^{-1}	$5. \times 10^{-2}$	2.5×10^1	1.5×10^2
$\eta_c(2S)$	4.1×10^2	4.2×10^1	$6. \times 10^3$	4.1×10^4

bottomonium production events for luminosity 5ab^{-1}

- No tag and single tag events:

name	No Tag	S Tag 6	S Tag 10
$\eta_b(9400)$	1.3×10^6	1.4×10^4	3.9×10^3
χ_{b_0}	9.6×10^4	5.2×10^2	1.4×10^2
χ_{b_1}	3.9×10^3	5.1×10^2	1.3×10^2
χ_{b_2}	8.3×10^4	4.9×10^2	1.2×10^2
$\eta_{b_D}(10150)$	7.9×10^2	9.9	2.8
$\eta_b(9980)$	4.6×10^5	5.8×10^3	1.6×10^3

For estimation of detected particles we put efficiency about 10 %.

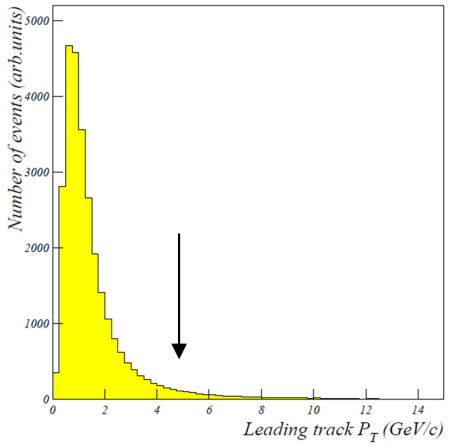
Measurements in notag set-up could be estimated only after exact parameters of detector will be known

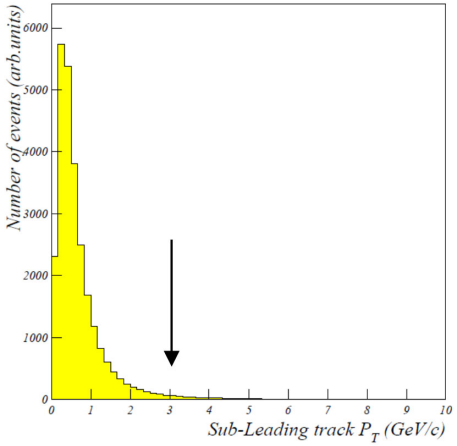
- Double tag events:

name	D Tag 6	D Tag 6-1.9	D Tag 1.9-1.9
$\eta_b(9400)$	1.1×10^2	$1. \times 10^3$	3.6×10^3
χ_{b_0}	2.7	$3. \times 10^1$	1.5×10^2
χ_{b_1}	6.6	5.3×10^1	1.4×10^2
χ_{b_2}	3.4	3.4×10^1	1.6×10^2
$\eta_{b_D}(10150)$	2.3×10^{-2}	4.3×10^{-1}	1.8
$\eta_b(9980)$	4.9×10^1	4.4×10^2	1.5×10^3

Anomalous magnetic moment of the τ lepton

- Anomalous magnetic moments of electron and muon (a_e and a_μ) are known with astonishing precision of 10^{-12} and 10^{-9}
- a_τ is known only at 10^{-2} level (LEP2), the magnetic moment of τ lepton has been measured via the cross-section $ee \to ee\gamma\gamma \to ee\tau\tau$ of untagged events

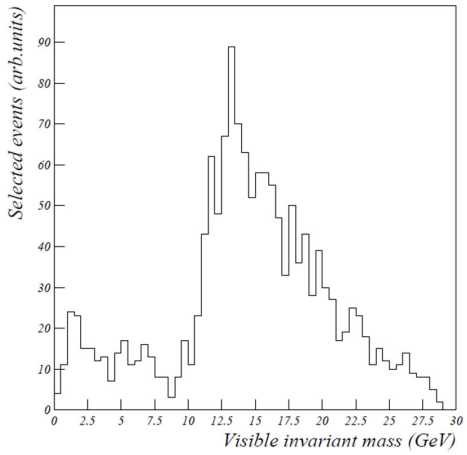




- 570 pb will provide 3×10^9 events with 5 ab^{-1}, or 165×10^6 events in eμ final state
- We assume extremely severe kinematic cuts: P_T above 5 GeV for the leading track, and 3 GeV for the second track
- Tracks with θ>20 degrees, total energy E<30 GeV to remove annihilation events

Estimation of sensitivity

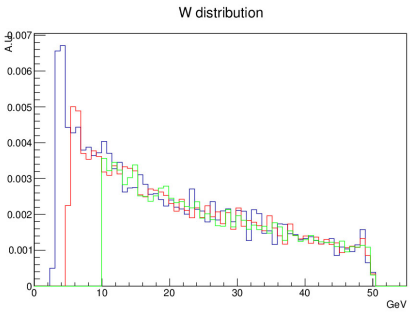
- Selection efficiency: 0.42 % (at LEP: 15-20%).
- Number of events at CEPC: 700K with statistical error at permille level.
- Systematics:
  - tracking 0.15% per track;
  - PID 0.15% per track;
  - luminosity: 0.1%;
  - trigger efficiency: 0.1%
- Total systematics: 0.5%

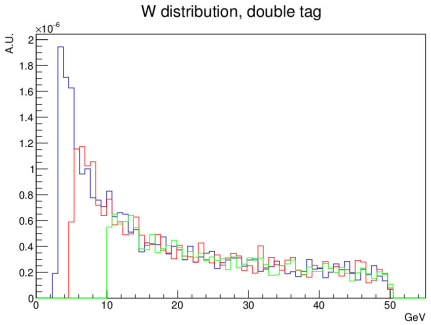


- DELPHI measurement: $\pm 4\%$
- CEPC will improve magnetic moment by order of magnitude

Photon structure function $F_2^\gamma(x, Q^2)$

- Hadronic structure function in single-tag
- Most difficult part is the reconstruction of the hadronic invariant mass W
- Required complicated unfolding procedure, detailed understanding of the detector





- No tag and single tag events:

Energy Cut	No Tag	S Tag 10	S Tag 6
3	9.1×10^{10}	4.1×10^{7}	1.3×10^{7}
5	6.4×10^{10}	3.8×10^{7}	1.2×10^{7}
10	3.8×10^{10}	3.2×10^{7}	$1. \times 10^{7}$

- Double tag events:

Energy Cut	D Tag 6	D Tag 6-1.9	D Tag 1.9-1.9
3	$1. \times 10^{4}$	1.4×10^{5}	7.5×10^{5}
5	$9. \times 10^{3}$	1.3×10^{5}	6.5×10^{5}
10	7.5×10^{3}	1.2×10^{5}	$5. \times 10^{5}$

Conclusion

- we make an conservative estimation for number of events of 2γ processes at CEPC at $\sqrt{s}$=240 GeV and consider "must-have" processes
-
  - charmonium production
  - botomonium production
  - anomalous magnetic moment of τ lepton
  - proton structure function
- we show that 2γ and ISR process detection is severe sensitive to small angle detection. Luminosity calorimeter at small angles is necessary for efficient data taking
- more exotic and modern processes could be measured:
  - Belle collaboration detection $\gamma\gamma \to X(3915) \to \Omega + J/\Psi$
  - BESIII collaboration measurement mode $Z_c(3900) \to \Omega + J/\Psi$
  - CEPC cold remeasure X(3915) with higher accuracy