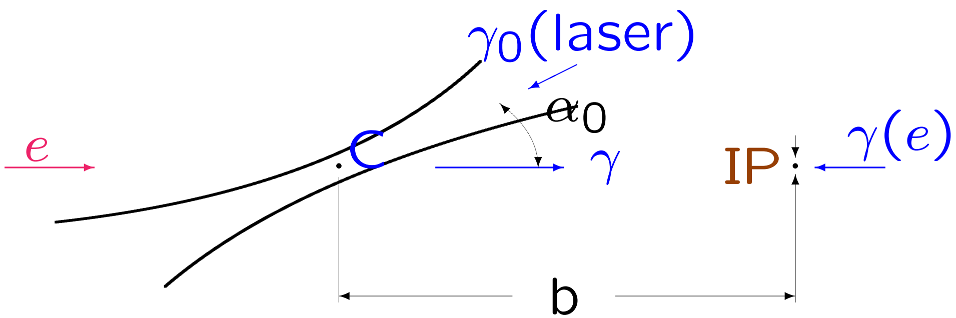
Physical problems for Photon Colliders

Ilya F. Ginzburg
Sobolev Inst. of Mathematics, SB RAS
and Novosibirsk State University
Novosibirsk, Russia

Photon Collider

— specific mode of Linear Collider

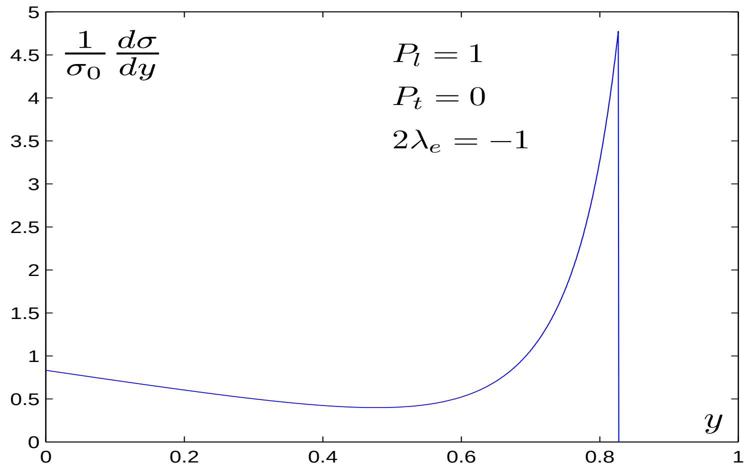
The focused laser flash meet the electron bunch of LC in the conversion point C at small distance b before interaction point IP.

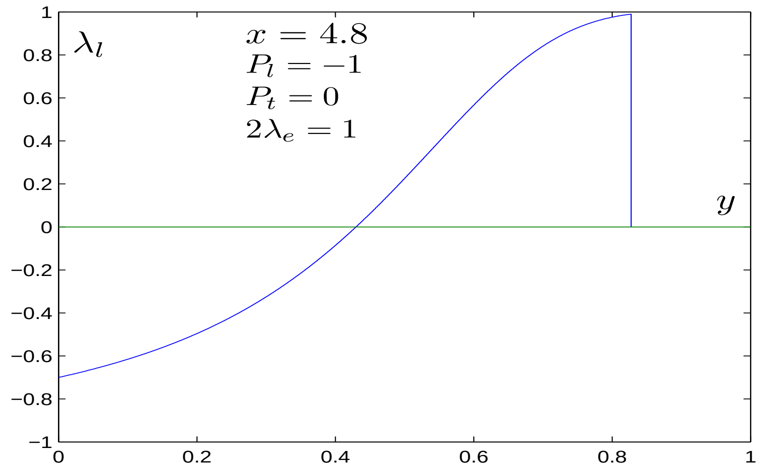


In C a laser photon scatters on high–energy electron taking from it a large portion of energy. Scattered photons travel along the direction of the initial electron with angular spread $\sim 1/\gamma_e \equiv m_e c^2/E$, they are focused in the IP. Here they collide with opposite electron ($e\gamma$ collider) or photon ($\gamma\gamma$ collider).

The laser flash with energy of a few Joules and length of a few mm is sufficient.

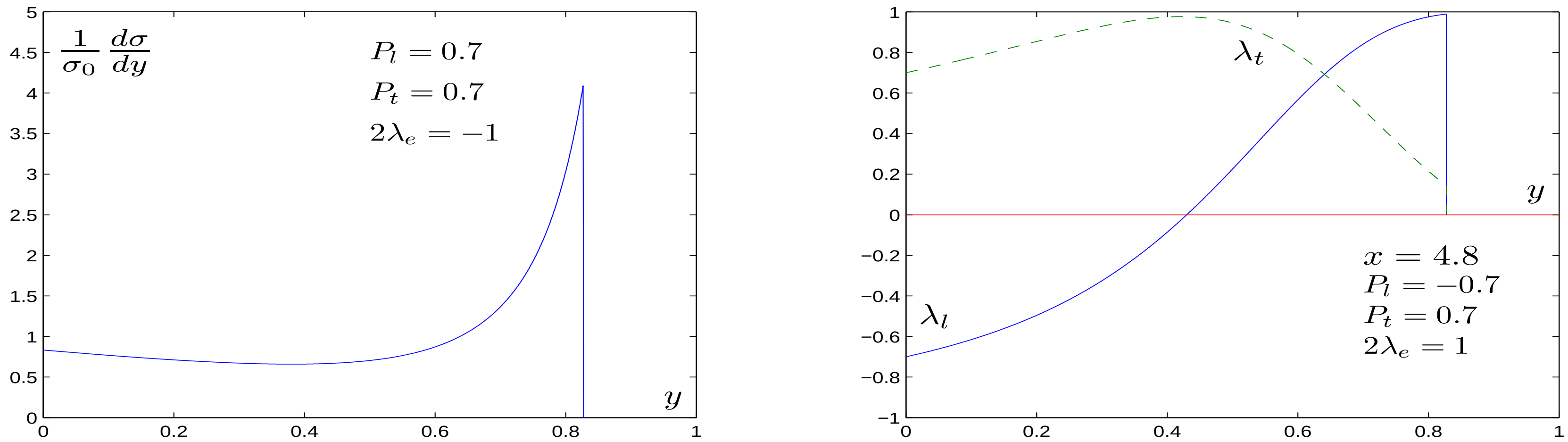
The energy spectrum of obtained photon beam is concentrated near its upper bound. If E_e – electron energy and $x = 4E_e\omega_0/(m^2c^4)$, then $\omega_{max} = E_e x/(x+1)$. The optimal value $x = 4.8$. Spectrum become more sharp with suitable choice of polarizations of initial electrons and laser photons. This beam is strongly polarized.



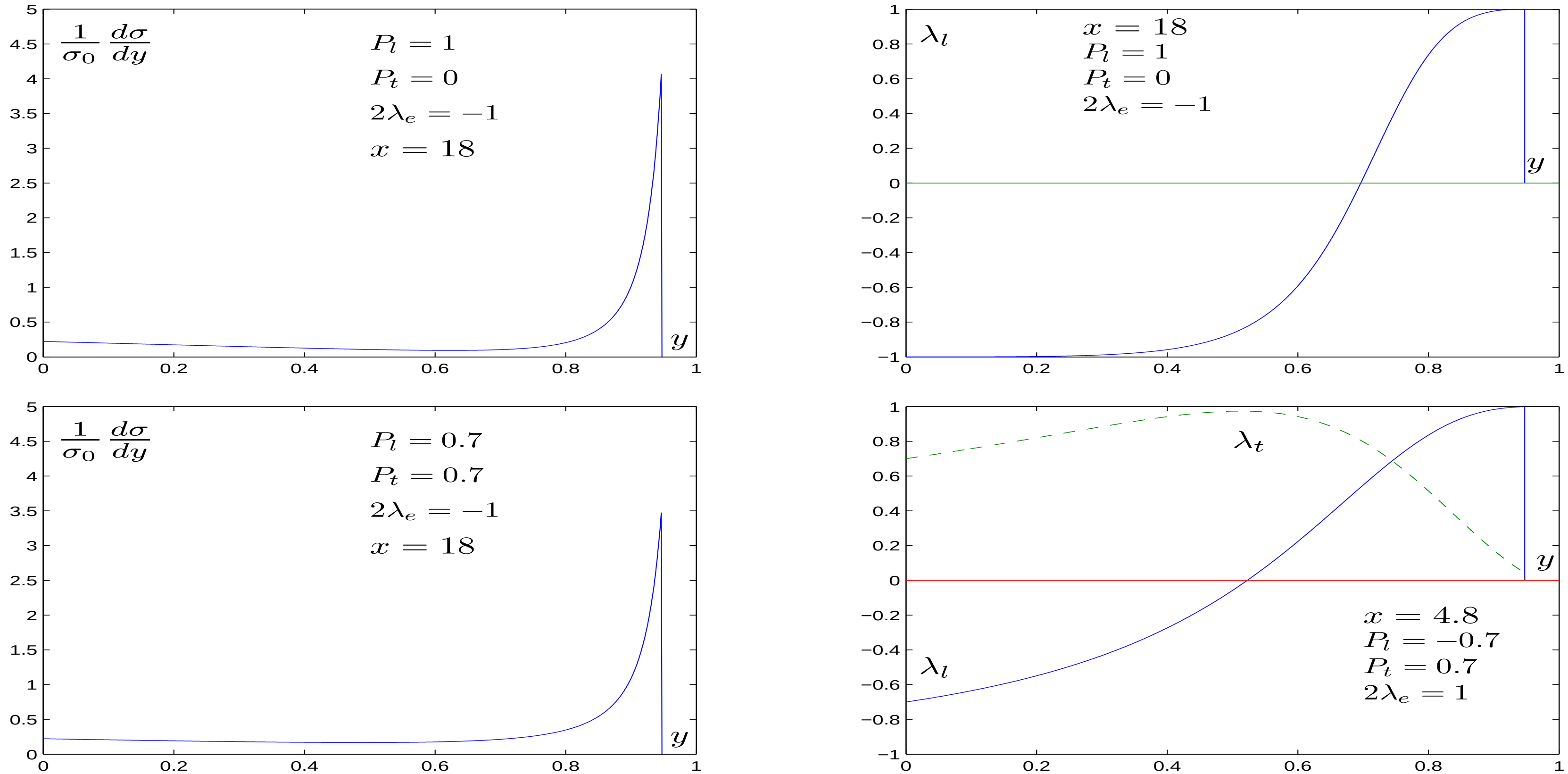


$y = \omega/E_e$, λ_e – electron longitudinal polarization, P_l and P_t – degrees of laser circular and transverse polarizations, resp.

The case with circular and transverse polarization of laser photon is also useful providing high enough degree of transverse polarization of high energy photons



With growth of x spectra become sharper and more longitudinally polarized.



The real picture is more complex.

(*i*) When photons with energy $\omega < \omega_{max}$ propagate from collision point C to interaction point IP, they distribute over the wider area reducing $\gamma\gamma$ luminosity in its soft part.

(*ii*) The low energy part of spectra is increased due to multiple rescatterings of electron on the other laser photons.

(*iii*) The nonlinear QED effects also modify spectra.

(*iv*) At $x > 4.8$ some fraction of produced photons disappear in the collision with laser photon, $\gamma\gamma_0 \to e^+e^-$.

In practice, the luminosity/polarization spectra will be measured during operations with high precision.

Photon Collider at ILC-I

■ Characteristic photon energy $E_{\gamma\,max} \approx 0.8 E_e$.

■ For high energy peak $(E_{\gamma 1,2} > 0.7 E_{\gamma max})$, separated well from low energy part of spectrum

- Luminosity $\mathcal{L}_{\gamma\gamma} \approx \mathcal{L}_{ee}/3$, $\mathcal{L}_{e\gamma} \approx \mathcal{L}_{ee}/4$ with $\int \mathcal{L}_{\gamma\gamma} dt$, $\int \mathcal{L}_{e\gamma} dt \approx 200 \div 150$ fb^{-1}/year (TESLA)
- Mean energy spread $< \Delta E_\gamma > \approx 0.07 E_{\gamma max}$.
- Mean photon helicity $< \lambda_\gamma > \approx 0.95$, with easily variable sign.

□ More suitable for some physical studies looks case with 70% circular polarization and 70% linear polarization.

■ The total additional cost is estimated as $\sim 10\%$ from that of LC.

Photon Collider at CLIC. Two variants:

- Laser conversion with IR laser or FEL to have $x = 4.8$
- Laser conversion with 1 eV photons (the same as for ILC1) but with conversion coefficient 0.15 (preferable for me).

■ Characteristic photon energy $\boxed{E_{\gamma\, max} \approx 0.95 E_e}$.

■ For high energy peak ($E_{\gamma 1,2} > 0.7 E_{\gamma max}$), separated well from low energy part of spectrum

- Luminosity $\mathcal{L}_{\gamma\gamma} \approx (0.1 \div 0.05)\mathcal{L}_{ee}$, $\mathcal{L}_{e\gamma} \approx (0.3 \div 0.2)\mathcal{L}_{ee}$ with $\int \mathcal{L}_{\gamma\gamma} dt$, $\int \mathcal{L}_{e\gamma} dt \sim 100$ fb^{-1}/year
- Mean energy spread $\boxed{< \Delta E_\gamma > \approx 0.03 E_{\gamma max}}$.

(The same as in e^+e^- mode with beamstrahlung and ISR)

- Mean photon helicity $< \lambda_\gamma > \approx 0.95$, with easily variable sign.

□ More suitable for physical studies looks case with

70% circular polarization and 70% linear polarization.

Main question:

What new can be studied at PLC after

- about 10 years of work of LHC with higher beam energy,
- perhaps, few years of work of e^+e^- LC with slightly larger beam energy and luminosity.

Detail studies of some separate questions can be found in TESLA TDR and other books.

Topics:

1. QCD and hadron physics.
2. Higgs physics
3. New particles
4. Gauge boson physics
5. Large angle $\gamma\gamma \to \gamma\gamma$ scattering and exotics.

1. QCD and hadron physics

1-1. Photon structure function is unique object of QCD, calculable at large enough Q^2 without additional phenomenological parameters (Witten). It can be measured here in $e\gamma$ mode) with high accuracy, since photon target with its energy and polarization here are practically known.

Range of accessible virtualities of photon is limited from **below** by details of set-up.

The region of electron transverse momenta above 50 GeV ($M_Z/2$) can be studied well, providing opportunity to study effect of Z-boson exchange and $\gamma^* - Z$ interference. The manipulation with beam polarizations will be important instrument here.

1-2. The other studies like those at HERA are possible here.

2. Higgs physics
Three directions:

2-1. Let earlier observations discover Higgs boson, similar to that in SM (SM-like scenario).

How to state whether we deals with SM Higgs boson or some other realization of Higgs sector (e.g. 2HDM). What can we know about properties of this realization.

2-2. Even if Higgs mechanism works, physical Higgs boson can not be discovered at LHC, e^+e^- LC if the self-interaction of basic Higgs field is so strong that elementary Higgs particle disappear. That is the case of strong $W_L W_L$ interaction.

How to obtain signals of this strong interaction at energy, lower than necessary for formation of corresponding resonances?

2-3. If more than one scalar, like Higgs boson, will be observed, it will be strong argument in favor of more complex Higgs sector, like 2HDM or somewhat else. It is necessary to measure properties of these scalars, including coupling to fermions, gauge bosons and self-couplings with the best accuracy, to find what model is realized and (in particular) to know what variant of history of Universe was realized in the past (see my report later).

2-1. How to state whether we deals with SM Higgs boson or some other realization of Higgs sector (e.g. 2HDM)

LHC can measure Higgs couplings to particles only with very low precision, typically 10-20%.

The e^+e^- LC will improve these results up to 5-10%, sometimes better.

The PLC can improve them further to about 2%.

Here, measuring the $h\gamma\gamma$ $(hZ\gamma)$ couplings is very promising since:

□ In $\mathcal{SM}$, these couplings appear only at the loop level $\Rightarrow$ the S/B for new signals is better than for the processes allowed at tree level.

□ All fundamental charged particles contribute to these couplings. The whole structure of theory influences these vertices.

□ The expected accuracy in the measurement of the two-photon width is $\sim$ 2% at $M_h \leq$ 150 GeV and $\int \mathcal{L} dt =$ 30 fb^{-1} (by 5 times lower than the anticipated annual luminosity)

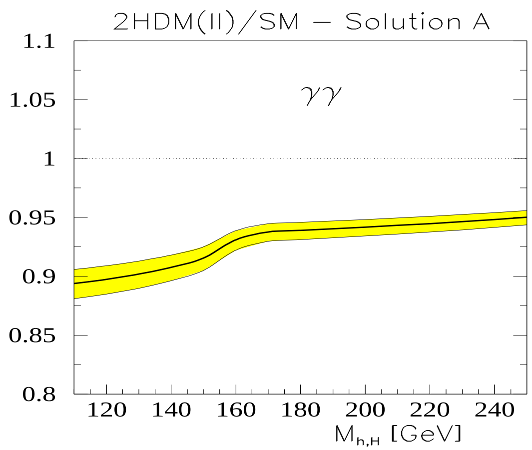
G. Jikia, S. Söldner-Rembold, *Nucl. Phys. B (Proc. Suppl.)* **82** (2000) 373; M. Melles, W.J. Stirling, V.A. Khoze,*Phys. Rev.* **D61**(2000) 054015.

Example – distinguishing $\mathcal{SM}$ /2$\mathcal{HDM}$

The simplest extension of Higgs sector is 2$\mathcal{HDM}$ with the Model II for the Yukawa coupling (the same is realized in $\mathcal{MSSM}$). It contains two Higgs doublet fields ϕ_1 and ϕ_2 with v.e.v.'s $v\cos\beta$ and $v\sin\beta$. The physical sector contains charged scalars $H^{\pm}$ and three neutral scalars h_i with no definite $\mathcal{CP}$ parity. In the $\mathcal{CP}$ conserving case these $h_i \Rightarrow$ 2 scalars h, H $(M_h < M_H)$ and a pseudoscalar A.

The $\mathcal{SM}$ – like scenario means that the coupling constants squared (measured at LHC and e^+e^- LC) are close to the $\mathcal{SM}$ value within anticipated precision, not coupling constants themselves. In the 2$\mathcal{HDM}$ this scenario can be realized by many ways.

The models can be distinguished via measurement of the $\gamma\gamma$ width of the observed SM-like Higgs boson. (I.G., M. Krawczyk, P. Olsen).



The ratio of $\Gamma(h \to \gamma\gamma)$ to its SM value for typical class of realization of SM-like scenario. The bands reflect the anticipated uncertainty of future measurements.

The deviation from $\mathcal{SM}$, given by contributions of heavy charged Higgs bosons for a natural set of parameters, is about 10% (compare with anticipated 2% accuracy).
For other sets these deviations are even larger.

Possible CP violation

In many extensions of Higgs model (e.g. in 2HDM) observable neutral Higgs bosons H_i have generally no definite CP and effectively

$$\mathcal{L}_{\gamma\gamma H} = G_\gamma^{SM} \left[g_\gamma H F^{\mu\nu} F_{\mu\nu} + i\tilde{g}_\gamma H F^{\mu\nu} \tilde{F}_{\mu\nu} \right]; \quad g_\gamma \sim \tilde{g}_\gamma \sim 1\,.$$

Here $F^{\mu\nu}$ and $\tilde{F}^{\mu\nu} = \varepsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}/2$ are standard electromagnetic field strengths. The relative effective couplings g and $\tilde{g}$ are described with standard triangle diagram $H\gamma\gamma$, they are expressed with known equations via masses of charged fermions and W, and mixing parameters (parameters of 2HDM potential). They are generally complex ($b\bar{b}$ –loop).

(I.F.G., I.P. Ivanov, *Eur. Phys. J.* **C 22** (2001) 411-421)

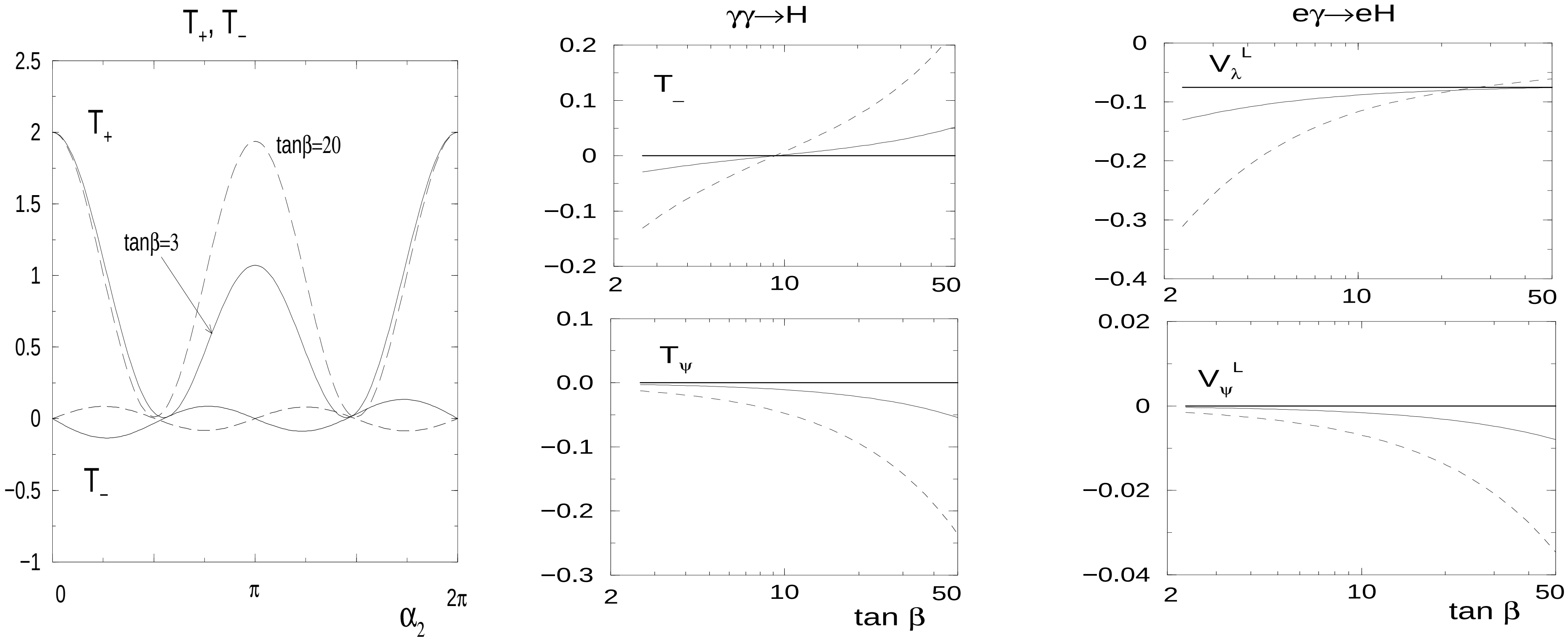
Total production cross section varies strong with variation of circular λ_i and linear ℓ_i polarizations of photon beams and the angle ψ between linear polarization vectors:

$$\sigma(\gamma\gamma \to H) = \sigma_{np}^{SM} \times$$
$$\times \Big[|g_\gamma|^2 (1 + \lambda_1\lambda_2 + \ell_1\ell_2 \cos 2\psi) + |\tilde{g}_\gamma|^2 (1 + \lambda_1\lambda_2 - \ell_1\ell_2 \cos 2\psi) +$$
$$+ 2Re(g_\gamma^* \tilde{g}_\gamma)(\lambda_1 + \lambda_2) + 2Im(g_\gamma^* \tilde{g}_\gamma)\ell_1\ell_2 \sin 2\psi \Big] \,.$$

It is useful to study

$$T_+ = \left.\frac{\sigma(\lambda_i) + \sigma(-\lambda_i)}{\sigma_{np}^{SM}}\right|_{\ell_i=0} \propto (1 + \lambda_1\lambda_2)(|g_\gamma|^2 + |\tilde{g}_\gamma|^2)\,;$$
$$T_- = \frac{\sigma(\lambda_i) - \sigma(-\lambda_i)}{\sigma_{np}^{SM}} \propto (\lambda_1 + \lambda_2) Re(g_\gamma \tilde{g}_\gamma^*)\,;$$
$$T_\psi = \frac{\sigma(\ell_i, \psi = \pi/4) - \sigma(\ell_i, \psi = -\pi/4)}{\sigma_{np}^{SM}} \propto \ell_1\ell_2 Im(g_\gamma \tilde{g}_\gamma^*)\,.$$

Standard calculation of vertexes in the 2HDM at different parameters of model gives typical dependencies



$\lambda_1 = \lambda_2 = \pm 1,\ \ell_1 = \ell_2 = 0.9$

Effects are strong and well measured.

2-2. Strong interaction in Higgs sector via charge asymmetry in $e\gamma \to eWW$

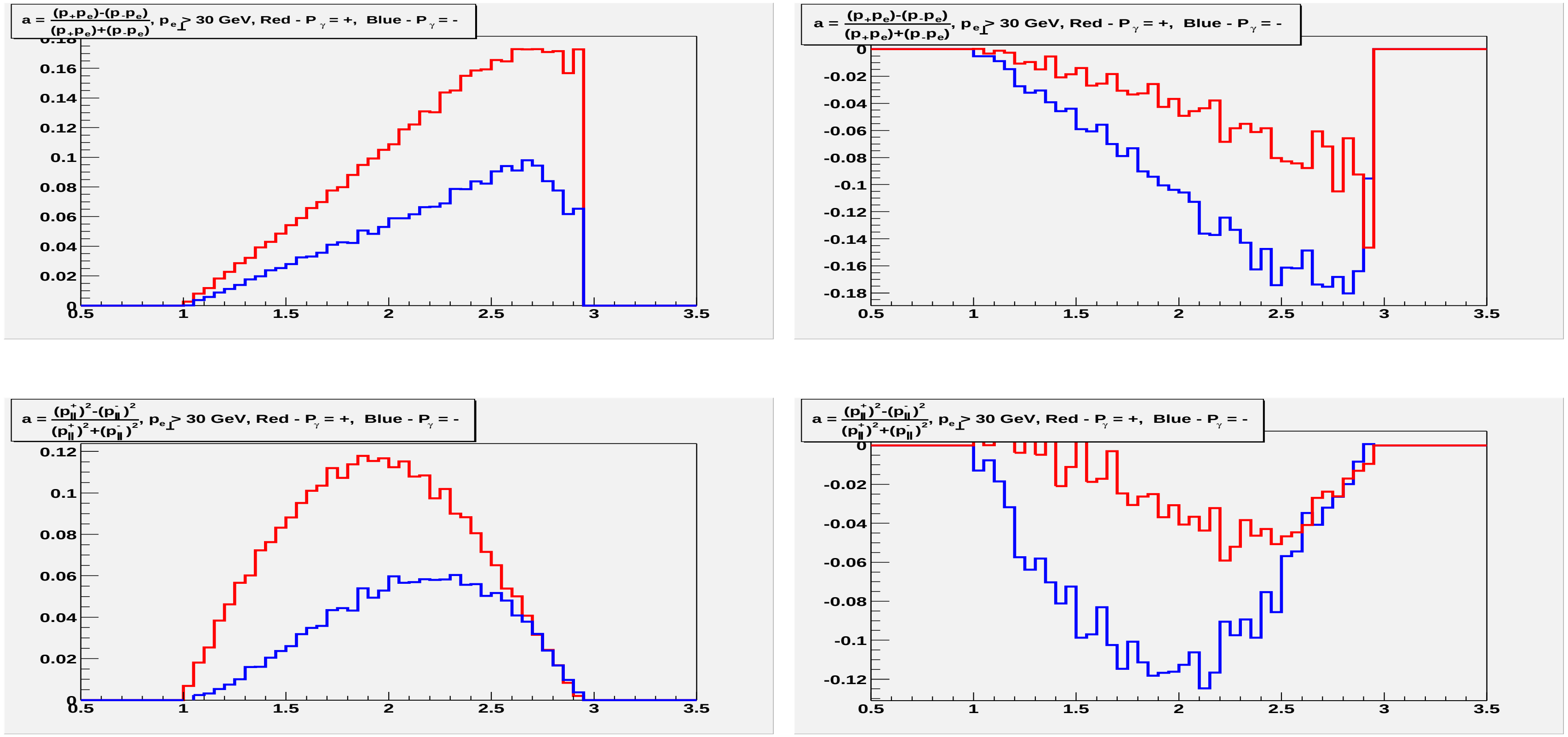
The diagrams of the process are subdivided into three types,

a) $e \to e\gamma^*(Z^*) \otimes \boxed{\gamma + \gamma^*(Z^*) \to WW}$, subprocess is modified by strong interaction in Higgs sector (denoted 2-gauge).

b) $e\gamma \to e\gamma^*(Z^*) \otimes \boxed{\gamma^*(Z^*) \to WW}$, subprocess is modified by strong interaction in Higgs sector (denoted 1-gauge).

c) $\gamma \oplus \boxed{e \to W\nu \to We}$

Interference of 2-gauge and 1- gauge diagrams result in charge asymmetry of produced W due to different C-parity of final WW system in contributions with γ and due to indefinite C-parity for contributions with Z^*.



SM: in variables $v_1 = \frac{\langle (p^+ - p^-) p_e \rangle}{\langle (p^+ + p^-) p_e \rangle}$ (up), $v_2 = \frac{\langle (p_\parallel^+)^2 - (p_\parallel^-)^2 \rangle}{\langle (p_\parallel^+)^2 + (p_\parallel^-)^2 \rangle}$ (down), complete (left) and without 1-gauge contribution (right).

High sensitivity to interrelation 2-gauge and 1-gauge contributions $\Rightarrow$ to the phase of strong Higgs interaction under interest.

2-3. If more than one scalar, like Higgs boson, will be observed

One must to know what type of Higgs sector is realized.

Let it is 2HDM.

Than complete set of observable particles includes 3 neutrals h_1, h_2, h_3 (generally with no definite CP parity) and charged Higgs $H^{\pm}$.
After discovery all of them it would be necessary do determine parameters of model. They can be expressed via masses, couplings to gauge bosons and some fermions and three triple couplings like $H^+H^-h_i$ plus one quartic coupling like $H^+H^-H^+H^-$ (K. Kanishev).
The measuring of these triple and quartic couplings at PLC looks preferable for obtaining of complete set of parameters of model.
The information of this set will give also information about way of evolution of phase states of earlier Universe
(I.F.G. I. Ivanov, K. Kanishev)

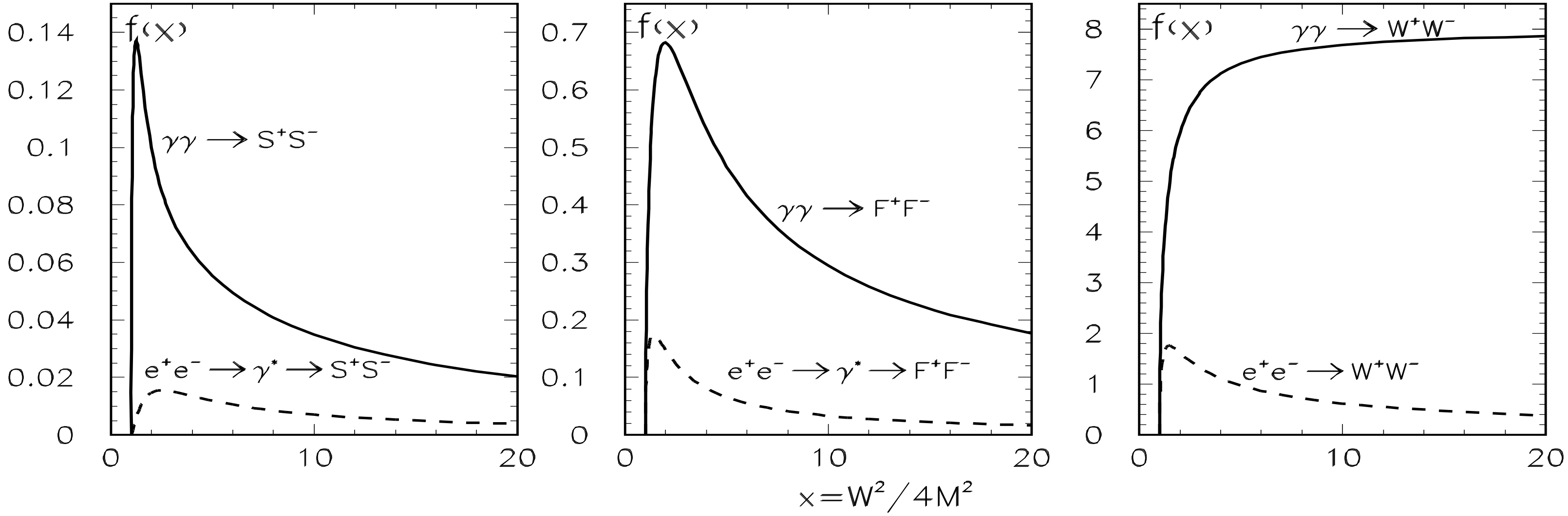
3. New particles

New charged particles will be discovered at LHC and in e^+e^- mode of LC. We expect their decay for final states with invisible particles (like LSP in MSSM).

• How to measure with reasonable accuracy masses, decay modes and spin of these new particles?

In these problems the $\gamma\gamma$ production provides essential advantages compared to e^+e^- collisions and LHC.

The cross section of the pair production $\gamma\gamma \to P^+P^-$ ($P = S$ – scalar, $P = F$ – fermion, $P = W$ – gauge boson) not far from the threshold is given by QED with reasonable accuracy.



$\sigma(\gamma\gamma \to P^+P^-)/[\pi\alpha^2/M_P^2]$, nonpolarized photons,

and $\sigma(e^+e^- \to \gamma^* \to P^+P^-)/[\pi\alpha^2/M_P^2]$

• These cross sections decreases slowly with energy growth
$\Rightarrow$ one can study these processes relatively far from the threshold where the decay products are almost non-overlapping.

• Near the threshold $f_P \propto (1+\lambda_1\lambda_2 \pm \ell_1\ell_2 \cos 2\phi)$ with $+$ sign for $P=S$ and $-$ sign for $P=F$. This polarization dependence provides the opportunity to determine spin of produced particle P.

• The polarization of produced fermion or vector P depends on the initial photon helicity. At the P decay this polarization $\Rightarrow$ the momentum distribution of decay products. E.g., for the SM processes like $\gamma\gamma \to \mu^+\mu^- + neutrals$ (obtained from muon decay modes of $\gamma\gamma \to WW$, $\gamma\gamma \to \tau^+\tau^-$, etc.) muons should exhibit charge asymmetry linked to the polarization of initial photons – see slides below.
These studies can help to understand the nature of candidates for Dark Matter particles.

■ The possible $\not{C}P$ in the $P\gamma$ interaction can be seen as a variation of cross section with changing the sign of both photon helicities.

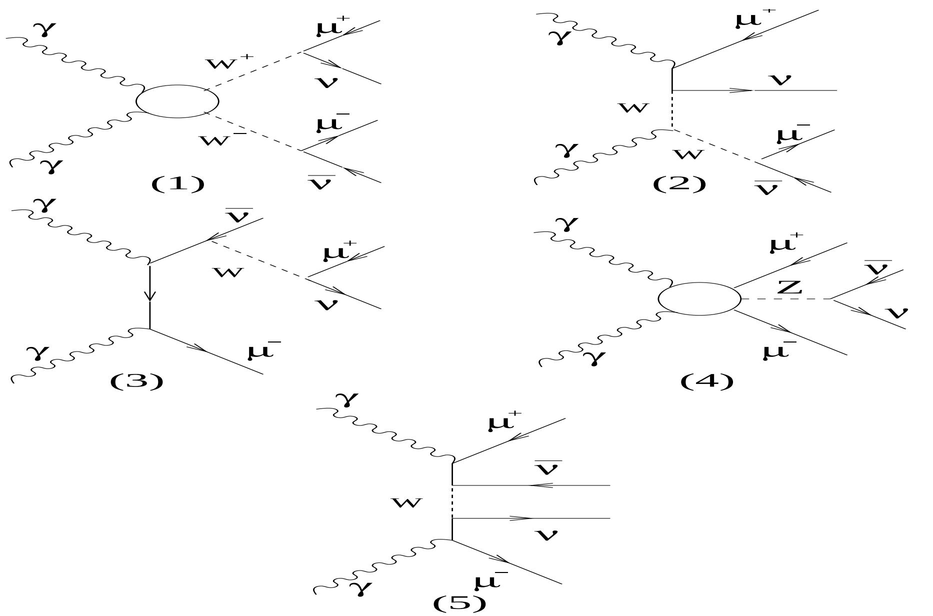
Charge asymmetry in processes $\gamma_\uparrow\gamma_\uparrow \to \mu^+\mu^-\nu_\mu\bar{\nu}_\mu$, $\gamma_\uparrow\gamma_\uparrow \to W^\pm\mu^\mp\nu$

D.A. Anipko, M. Cannoni, I.F. G., K.A. Kanishev, A.V. Pak, O. Panella

Phys. Rev. **D 78** (2008) 093009

That is huge effect in SM. It can be used for the study of CP nonconservation in New Physics processes.

In SM process is described by shown diagrams and effect appears due to P nonconservation in the W-decay.



We used CalcHEP for calculations.

For each observed particle:

- Cut in escape angle θ

$$\pi - \theta_0 > \theta > \theta_0 \ \text{ with } \theta_0 = 10\, mrad,$$

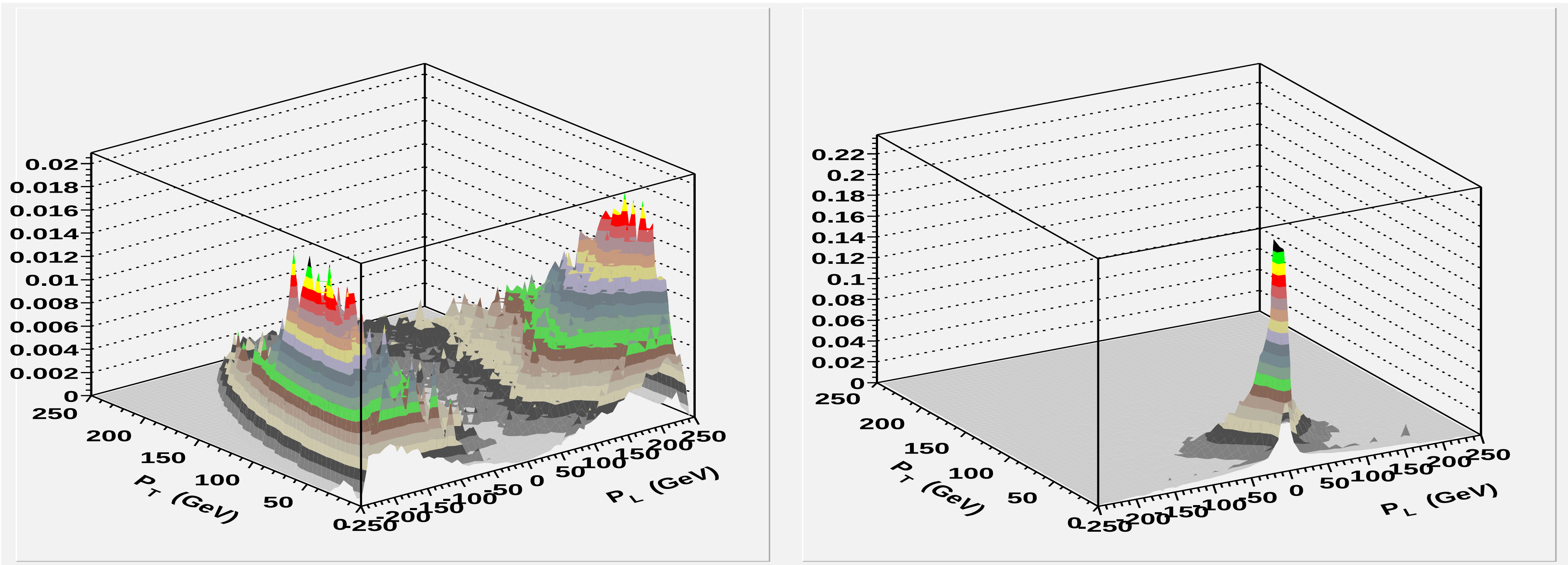
- Cut in transverse momentum $p_\perp$:

$$p_\perp > p^c_{\perp\mu} \ \text{ with } p^c_{\perp\mu} = 10 \text{ GeV.}$$

These simultaneous cuts allow to eliminate many backgrounds.

Difference between distributions of positive and negative muons in $\gamma_{\boldsymbol{\lambda_1}}\gamma_{\boldsymbol{\lambda_2}} \to \boldsymbol{W\mu\nu}$.

Example: Both photons are left polarized: $\gamma_-\gamma_-$.



Negative μ distribution. Positive μ distribution.

4. Multiple production of SM gauge bosons and higher orders of SM

The high energy **PLC** — single place in future accelerator program where one can measure these processes with high enough accuracy

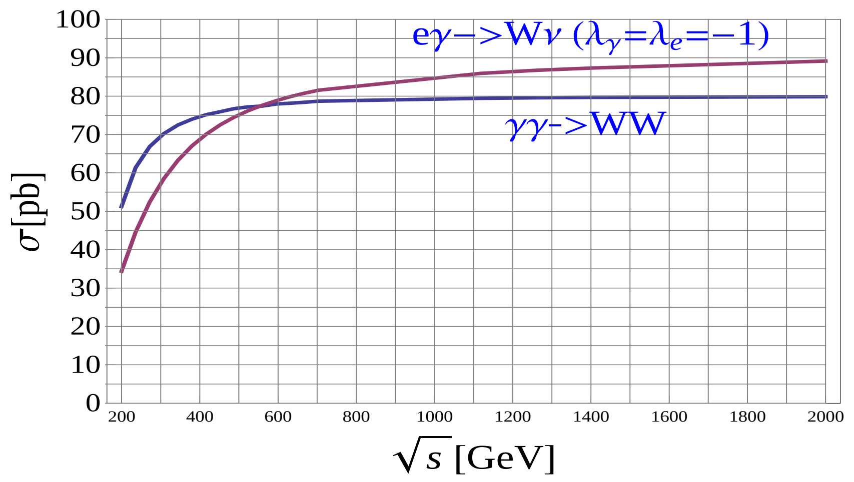
Why interesting?

- High sensitivity to details of SM
- High sensitivity to New Physics via set of anomalous parameters of W and Z interactions
- Fundamental problems of QFT

The most ambitious goal is to find deviations from prediction of $\mathcal{SM}$, obliged by New Physics (and described by anomalies in Effective Lagrangian). There are many anomalies relevant to the gauge boson interactions. Each process react for a number of anomalies. Large variety of processes accessible at Photon colliders allows to separate anomalies from each other.

2-nd order processes

Cross sections provide about 10^7 events per year.



Practically independent on polarization. (Distributions of observables strongly depend on polarization – see above.)

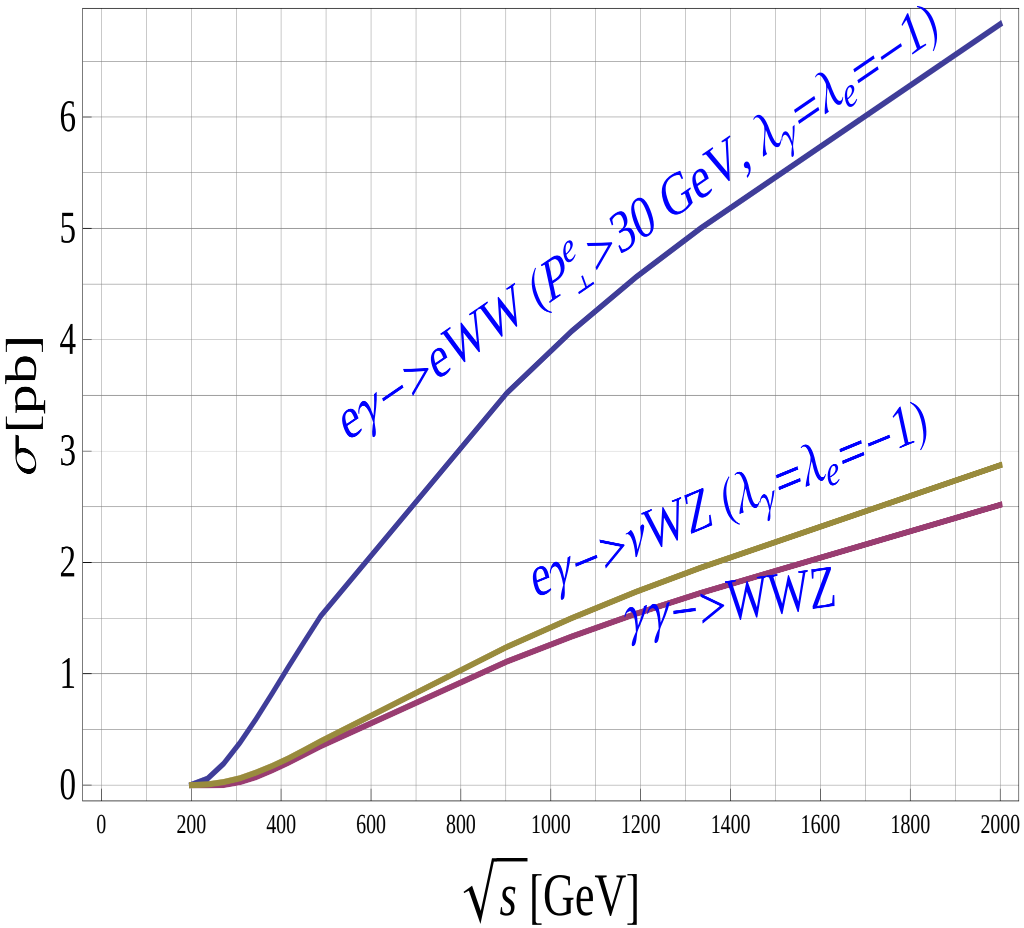
Accuracy enough for study of 2-loop corrections.

The two–loop radiative corrections to $\gamma\gamma \to W^+W^-$ and $e\gamma \to \nu W$ should be considered. They are measurable and sensitive to the problems

(i) construction of S–matrix of theory with unstable particles;

(ii) gluon corrections like Pomeron exchange between quark components of W's.

3-rd order processes

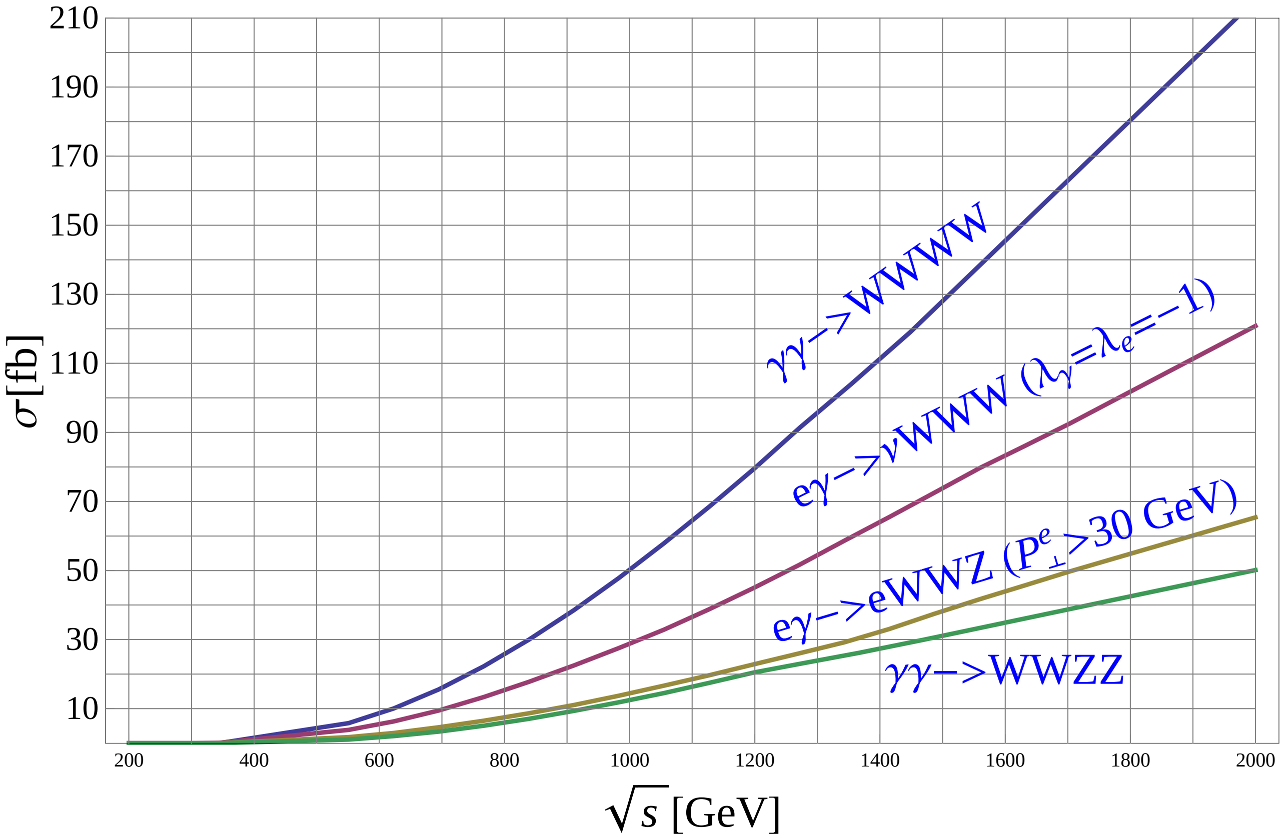


Total cross section $\sigma_{e\gamma\to eWW} \simeq dn_\gamma \otimes \sigma_{\gamma\gamma\to WW}$. At large enough transverse momentum of scattered electron this factorization is violated. So that we present $\sigma_{e\gamma\to eWW}$ only for $p_{\perp e} > 30$ GeV. It allow to separate contribution of $\gamma Z \to WW$ subprocess.

For definiteness, we put $M_H = 140$ GeV

4-th order processes

Cross sections are high enough to study these processes with 1% precision.



5. Large angle high energy photons for exotics

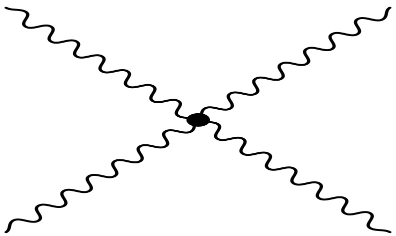
Different exotic models of New Physics - large extra dimensions, point-like monopole, unparticles have common signature – the cross section for $\gamma\gamma \to \gamma\gamma$ production grows with energy as ω^6, these photons are produced almost isotropically. Future observations either give limits for scales of these exotics or allow to see these effects via recording large $p_\perp \sim 0.5 \div 0.7 E_e$ photons.

All these models seem hardly probable to ME

Common features

All these exotics at modern energies can be treated as an effective point-like interaction with typical interaction of form

$$L \propto \frac{F^{\mu\nu} F^{\alpha\beta} F_{\rho\sigma} F_{\phi\tau}}{\Lambda^4}, \quad (\Lambda^2 \gg s/4).$$



In different models different orders of field indices are realized.

Λ is characteristic mass scale. It is large enough to don't contradict modern data. In my notations, it accumulate other coefficients.

In all cases s, t and $u-$ channels are essential.

Matrix element (in the photon c.m.s.):

- gauge invariance provides factor ω for each photon leg;
- to make this factor dimensionless it should be written as $\omega/\Lambda \Rightarrow$ amplitude $\mathcal{M} \propto (\omega/\Lambda)^4 = s^2/(2\Lambda)^4$ (choice of normalization of Λ).

The cross section

$$\sigma_{tot} = \frac{1}{32\pi s}\left(\frac{s}{4\Lambda^2}\right)^4, \qquad \frac{d\sigma}{dp_\perp^2} = \sigma_{tot}\Phi\left(\frac{p_\perp^2}{s}\right)\frac{2dp_\perp^2}{\sqrt{s(s-4p_\perp^2)}}$$

with smooth and model dependent function $\Phi(p_\perp^2/s)$ and

$$\int \Phi\left(\frac{p_\perp^2}{s}\right)\frac{2dp_\perp^2}{\sqrt{s(s-4p_\perp^2)}} = 1\,.$$

For large extra dimensions and monopoles entire s dependence is given by mentioned $s^4/(2\Lambda)^8$, for unparticles additional factor $(s/4\Lambda^2)^\delta$ is added.

Extra dimensions

H. Davoudiasi, K. Cheung,... 1998 – 2000 $\to$

In this case point corresponds exchange by heavy KK excitations (via stress-energy tensor).

$$\mathcal{M}_{\gamma\gamma\to\gamma\gamma} \propto \langle\frac{T_{ab}T^{ab}}{\Lambda^4}\rangle \approx \frac{F^{\mu\nu}F_{\nu\alpha}F^{\alpha\beta}F_{\beta\mu}}{\Lambda^4} \; + \; permutations\,,$$

T_{ab} – stress-energy tensor.

After averaging over polarizations for tensorial KK excitations

$$\Phi \propto 2\left(1-\frac{p_\perp^2}{\hat{s}}\right)^2 = \frac{(3+\cos^2\theta)^2}{8} = \frac{\hat{s}^4+\hat{t}^4+\hat{u}^4}{2\hat{s}^4}$$

At ILC1 energies interference with $\gamma\gamma\to WW$ is essential $\Rightarrow$ $\gamma\gamma\to WW$ is better for discovery.

At $E_e = 1$ TeV the $\gamma\gamma\to\gamma\gamma$ process dominates.

Point–like Dirac monopole.

I.F.G., S.L.Panfil (1983), I.F.G., A.Shiller (1998-2000)

This monopole existence would explain mysterious quantization of an electric charge. There is no place for it in modern theories of our world but there are no precise reasons against its existence.

Let M is monopole mass. At $s \ll M^2$ the electrodynamics of monopoles is expected to be similar to the standard QED with effective perturbation parameter $g\sqrt{s}/(4\pi M)$. The effect is described by monopole Heisenberg, Euler-like loop $\Rightarrow$ it is calculated within QED). The details of angular and polarization distributions depend strong on spin of monopole J.

After averaging over polarizations the cross section is given the same eq. as for extra dimensions with $\Lambda = (M/n)a_J$, where quantity a_J is determined by the monopole spin J,

$$a_0 = 0.177,\ a_{1/2} = 0.125,\ a_1 = 0.069.$$

Unparticles (H.Georgi, 2007).

In this case point corresponds exchange via heavy unparticle $\mathcal{U}$ – object, describing particle scattering via propagator which has no poles at real axis, correspondent to particles. This propagator behaves (in the scalar case) as $(-p^2)^{d_U-2}$ where scalar dimension d_u is not integer or half-integer. The interaction carried by unparticle has form $\frac{F^{\mu\nu}F_{\mu\nu}\mathcal{U}}{\Lambda^{2d_U}}$ with some phase factor. For matrix element it gives (C.F. Chang et al.)

$$\mathcal{M} = \frac{F^{\mu\nu}F_{\mu\nu}F^{\rho\tau}F_{\rho\tau}}{\Lambda^{4d_U}}(-P^2)^{d_U-2} + \textit{permutations}.$$

$$|\mathcal{M}|^2 = C\frac{s^{2d_U} + |t|^{2d_U} + |u|^{2d_U} + \cos(d_u\pi)[(s|t|)^{d_U} + (s|u)^{d_U}] + (tu)^{d_U}}{\Lambda^{4d_U}}$$

Discovery limits

Tevatron D0	175 GeV
LHC	2 TeV
$\gamma\gamma$ (100 fb^{-1})	$3E_e$
e^+e^- LC (1000 fb^{-1})	$2E_e$

THE END