(low-energy) photon-photon collider

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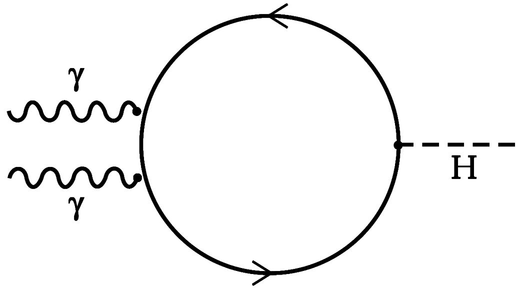
There is no doubt that photon-photon colliders are an important option at high energy



Feynman diagram for two photon decay of the Higgs boson. The loop can be of any charged elementary particles whose mass is generated via the Higgs mechanism.

Nuclear Physics B (Proc. Suppl.) 184 (2008) 271–286

Introduction to the Photon Collider

V.I. Telnov [a]

Reaction	Remarks
$\gamma\gamma \to h^0 \to b\bar{b}$	$M_{h^0} < 160$ GeV
$\gamma\gamma \to h^0 \to WW(WW^*)$	$140 < M_{h^0} < 190$ GeV
$\gamma\gamma \to h^0 \to ZZ(ZZ^*)$	$180 < M_{h^0} < 350$ GeV
$\gamma\gamma \to h^0 \to \gamma\gamma$	$M_{h^0} < 150$ GeV
$\gamma\gamma \to H, A \to b\bar{b}$	*MSSM* heavy Higgs
$\gamma\gamma \to H\tau^+\tau^-$	$\tan\beta$ in SUSY sector
$\gamma\gamma \to \tilde{f}\bar{\tilde{f}},\ \tilde{\chi}_i^+\tilde{\chi}_i^-,\ H^+H^-$	SUSY particles
$\gamma\gamma \to S[\tilde{t}\bar{\tilde{t}}]$	$\tilde{t}\bar{\tilde{t}}$ stoponium
$\gamma e \to \tilde{e}^-\tilde{\chi}_1^0$	$M_{\tilde{e}^-} < 0.9 \times 2E_0 - M_{\tilde{\chi}_1^0}$
$\gamma e \to \tilde{\nu}_e\tilde{\chi}_1^\pm \to \tilde{\nu}_e\tilde{\nu}_\mu\mu$	sneutrino production
$\gamma e \to \nu W^+ \to W^+W^-l^+$	Majorana neutrino
$\gamma\gamma \to W^+W^-$	anom. W inter., extra dim.
$\gamma e^- \to W^-\nu_e$	anom. W couplings
$\gamma\gamma \to WW + WW(ZZ)$	strong WW scattering
$\gamma\gamma \to t\bar{t}$	anom. t-quark interact.
$\gamma e^- \to \bar{t}b\nu_e$	anom. Wtb coupling
$\gamma\gamma \to$ hadrons	total $\gamma\gamma$ cross section
$\gamma e^- \to e^-X$ and $\nu_e X$	struct. functions
$\gamma g \to q\bar{q},\ c\bar{c}$	gluon distr. in the photon
$\gamma\gamma \to J/\psi\, J/\psi$	QCD Pomeron

Table 1
Gold-plated processes at PLC

$$\sigma = \frac{\pi\alpha^2}{M^2} f(x); \qquad x = \frac{s}{4M^2}$$

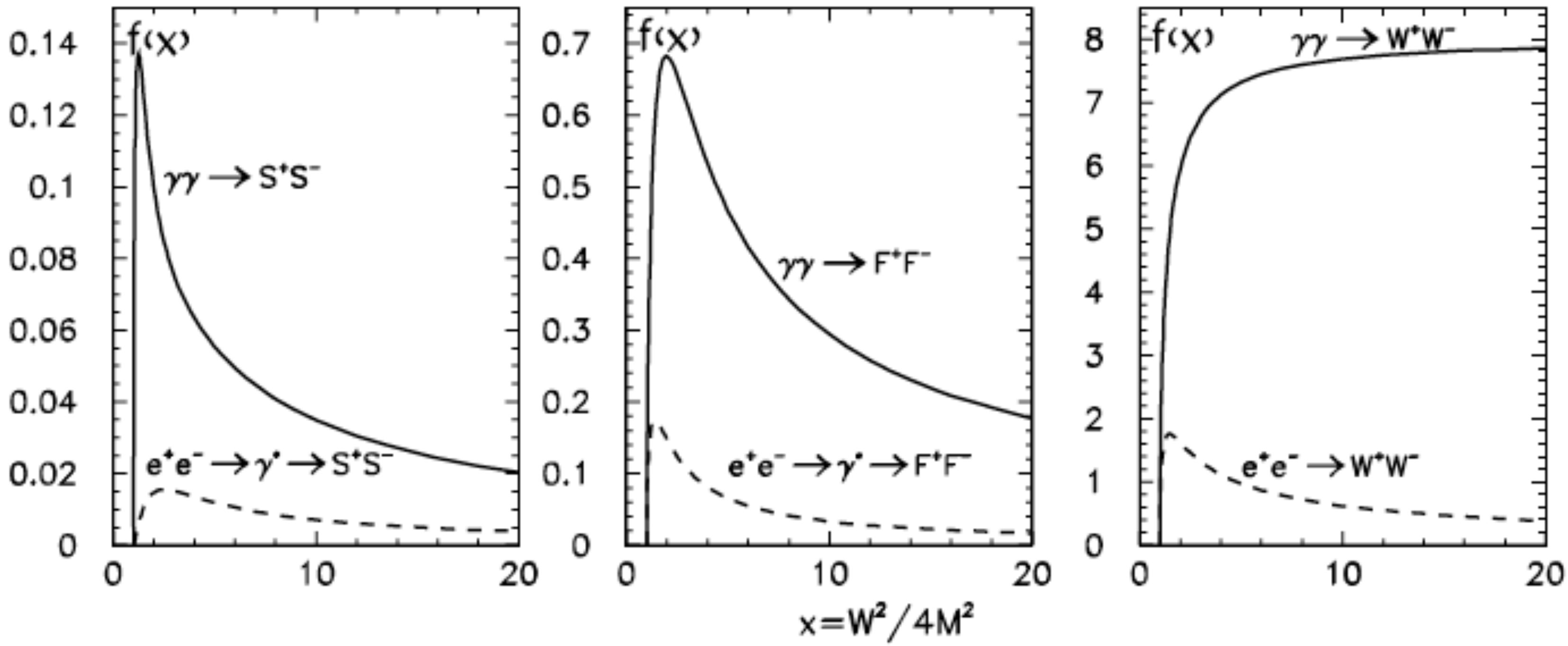


Figure 1.1.3: *Comparison between cross sections for charged pair production in unpolarised e^+e^- and $\gamma\gamma$ collisions. S (scalars), F (fermions), W (W bosons); $\sigma = (\pi\alpha^2/M^2)f(x)$, M is the particle mass, W is the invariant mass (c.m.s. energy of colliding beams), $f(x)$ are shown. Contribution of Z boson for production of S and F in e^+e^- collisions was not taken into account, it is less than 10%*

Given the present value of the Higgs mass, a 80+80 GeV photon-photon collider would suffice for a very rich physics program.

However, for all its potential, a high-energy photon-photon collider has not yet been built.

A low-energy photon-photon collider could lead to the necessary technology developments and prepare the ground for a higher energy complex, while still providing a rich testing ground for QED, and, more generally, QFT.

Unsolved problem of QFT: the cosmological constant problem

Contributions to vacuum energy density (*zero point energy*) from elementary fields

Bosons (spin 1 particles):

- photon: 2 polarizations
- gluons: 8 types of gluons, 2 polarizations
- Ws and Z bosons: 3 bosons, 3 polarizations (massive force carriers)

total: 27 boson degrees of freedom

Fermions (spin 1/2 particles):

- 6 massive quark fields, 2 polarizations
- 3 massive lepton fields, 2 polarizations
- 3 neutrino fields

total: 21 fermion degrees of freedom

A HUGE ENERGY DENSITY !!!

fermionic d.o.f.'s give a negative contribution

Contribution of each degree of freedom

$$\pm \frac{\hbar\omega}{2} \Rightarrow \frac{3}{8\pi^2}\frac{(\hbar\omega_{\max})^4}{(\hbar c)^3}$$

When we take the Planck energy as the ultraviolet cutoff

$$\ell_P = \sqrt{\frac{\hbar G}{c^2}} \approx 1.6 \cdot 10^{-35}\,\mathrm{m} = 1.6 \cdot 10^{-20}\,\mathrm{fm}$$

$$\mathrm{E}_P = \frac{\hbar c}{\ell_P} \approx 10^{19}\,\mathrm{GeV}$$

$$u = \frac{3(\hbar\omega_{\max})^4}{8\pi^2(\hbar c)^3} \approx \frac{3(10^{19}\ \mathrm{GeV})^4}{8\pi^2(0.2\,\mathrm{GeV\cdot fm})^3} \approx 5 \cdot 10^{76}\,\mathrm{GeV\cdot fm^{-3}}$$

A HUMONGOUS NUMBER !!!
About 10^{78} times larger than the nuclear energy density

Eventually, it turns out that there is a 120 orders-of-magnitude discrepancy with the estimated energy density of interstellar vacuum

Nuclear Physics B89 (1975) 535–546

SUPERSYMMETRY AND THE VACUUM

Bruno ZUMINO
CERN, Geneva

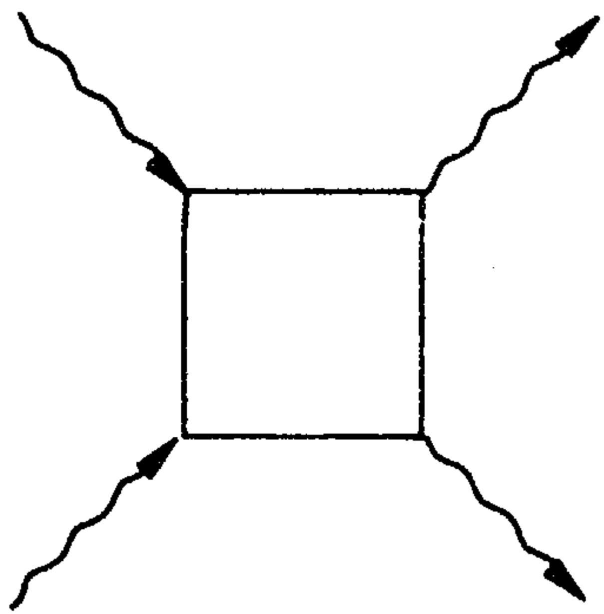
Received 28 October 1974

It is shown that, in a supersymmetric theory, the sum of all vacuum diagrams vanishes identically as a consequence of compensations among contributions involving different fields of the supermultiplet. This means that the zero-point energy-momentum density is zero to all orders in the supersymmetric interaction. In an external gravitational field no cosmological term is induced through the vacuum polarization of the matter fields. The situation when supersymmetry is spontaneously broken, or softly broken is also discussed.

However, the problem of a high energy density of vacuum would still persist at low energy, even in a supersymmetric world, because of low-energy supersymmetry breaking.

The cosmological constant problem is related to the zero-point energy, i.e., to the fluctuations of quantum vacuum, and therefore also to the renormalization procedure in QFT.

Photon-photon scattering directly probes the fluctuations of quantum vacuum.



At low energy the 4-photon interaction can also be described by a phenomenological Lagrangian.

The class of effective Lagrangians that satisfy basic QFT constraints can be parameterized as follows

$$\mathcal{L} = -\mathcal{F} + c_1\mathcal{F}^2 + c_2\mathcal{G}^2$$

$$\mathcal{F} = \frac{1}{4}F_{ab}F^{ab} = \frac{1}{2}\left(\mathbf{B}^2 - \mathbf{E}^2\right)$$

$$\mathcal{G} = \frac{1}{4}F_{ab}\tilde{F}^{ab} = -\mathbf{E}\cdot\mathbf{B}$$

and the QED Euler, Heisenberg and Weisskopf (EWH) Lagrangian has

$$c_1 = \frac{8\alpha^2}{45m^4}; \qquad c_2 = \frac{14\alpha^2}{45m^4}$$

Another member of this class is the Born-Infeld Lagrangian (originally introduced to solve the divergence of electron EM self-energy)

$$\mathcal{L}_{BI} \approx \frac{1}{2}\left\{\left(\mathbf{E}^2 - \mathbf{B}^2\right) + \frac{1}{4b^2}\left[\left(\mathbf{E}^2 - \mathbf{B}^2\right)^2 + 4\left(\mathbf{E}\cdot\mathbf{B}\right)^2\right]\right\}$$

Notably, the BI Lagrangian surfaces in low-energy extrapolations of string theories.

Photon-photon scattering

(first complete calculation by Karplus and Neuman in 1950-51, further refinements by De Tollis and collaborators in the following years)

$$G_{\mu\nu\lambda\sigma}{}^{(\kappa)}(k^{(1)}, k^{(2)}, k^{(3)}, k^{(4)})$$

electromagnetic polarization tensor

$$G_{\mu\nu\lambda\sigma}{}^{(\kappa)}(k^{(1)}, k^{(2)}, k^{(3)}, k^{(4)}) = G_{\mu\nu\lambda\sigma}{}^{(\kappa)}(-k^{(1)}, -k^{(2)}, -k^{(3)}, -k^{(4)})$$

the EM pol. tensor is completely symmetric with respect to indices and momenta and is divergenceless and P-invariant

$$G_{\mu\nu\lambda\sigma} = \lim_{M\to\infty}\left[G_{\mu\nu\lambda\sigma}{}^{(\kappa)} - G_{\mu\nu\lambda\sigma}{}^{(M)}\right]$$

tensor must be regularized

Differential cross-section

$$\sigma_s(\theta, \phi; \omega) = \frac{\alpha^4}{4\pi^2\kappa^2}\frac{1}{16\omega^2}\left| e_\mu{}^{\lambda_1} e_\nu{}^{\lambda_2} e_\lambda{}^{\lambda_3 *} e_\sigma{}^{\lambda_4 *} \right.$$

$$\left. G_{\mu\nu\lambda\sigma}(\mathbf{p}, \omega; -\mathbf{p}, \omega; -\mathbf{q}, -\omega; \mathbf{q}, -\omega) \right|^2$$

Polarization dependent amplitude

$$M_{\lambda_1\lambda_2\lambda_3\lambda_4}(\theta, \omega) = \tfrac{1}{4} e_\mu{}^{\lambda_1} e_\nu{}^{\lambda_2} e_\lambda{}^{\lambda_3 *} e_\sigma{}^{\lambda_4 *}$$

$$G_{\mu\nu\lambda\sigma}(\mathbf{p}, \omega; -\mathbf{p}, \omega; -\mathbf{q}, -\omega; \mathbf{q}, -\omega)$$

For $\hbar\omega \leq 0.7 m_e c^2$, the differential photon-photon scattering cross-section is

$$\frac{d\sigma}{d\Omega} = \frac{139\alpha^4}{(180\pi)^2}\frac{\omega^6}{m^8}\left(3+\cos^2\theta\right)^2$$

This cross-section is derived from a genuine non-linear QED effect (loop) and its value is critically dependent on the regularization procedure.

The importance of regularization has recently been emphasized by the a couple of wrong preprints, that claimed that the photon-photon cross section is actually

$$\frac{d\sigma_{\mathrm{FK}}}{d\Omega} = \frac{\alpha^4}{(12\pi)^2\omega^2}\left(3+2\cos^2\theta+\cos^4\theta\right)$$

(see N. Kanda, arXiv:1106.0592, and T. Fujita and N. Kanda, arXiv:1106.0465, and the refutation by Y. Liang and A. Czarnecki, arXiv:1111.6126)

Why this discrepancy?

- The origin of the error lies in neglecting the regularization-renormalization of the scattering amplitudes
- Kanda and Fujita argued that there is no need of regularization-renormalization because the unrenormalized amplitudes are finite
- However the regularization-renormalization process breaks the symmetry of the QED Lagrangian, and cannot be neglected even in this finite case
- Although the issue is not quite clear, it can be conjectured that this is associated to the ABJ chiral anomaly (see R. Jackiw, arXiv:hep-th/9903044v1)

... this takes us deep into the heart of QFT's

- Quantum anomalies are related to the topological properties of space: there is a deep connection with the Atiyah-Singer index theorem (where the index is closely related to the winding number and therefore to the connectivity of space, see also t'Hooft, PRL **37** (1976) 8)

- A derivation of the chiral anomaly by means of path integrals (Fujikawa, PRL **42** (1979) 1195; PRD **21** (1980) 2848; PRD **22** (1980) 1499; PRL **44** (1980) 1733; PRD **23** (1981) 2262) further indicates a connection with quantum paths

- A recent paper by Bender and Hook ("Quantum tunneling as a classical anomaly", J. Phys. A: Math. Theor. 44 (2011) 372001) further points to an intriguing connection of anomalies with paths and with the nature of space

- A tantalizing hint: the Green-Schwartz mechanism cancels anomalies in string theory (Phys. Lett. **B149** (1984) 117)

Proc. Natl. Acad. Sci. USA
Vol. 95, pp. 12776–12778, October 1998
Physics

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Field theory: Why have some physicists abandoned it?

ROMAN JACKIW

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Contributed by Roman Jackiw, August 10, 1998

... these shortcomings are actually symptoms of a deeper lack of understanding that has to do with symmetry and symmetry breaking. Physicists mostly agree that ultimate laws of Nature enjoy a high degree of symmetry, that is, the formulation of these laws is unchanged when various transformations are performed.

... , we must also recognize that actual, observed physical phenomena rarely exhibit overwhelming regularity. Therefore, at the very same time that we construct a physical theory with intrinsic symmetry, we must find a way to break the symmetry in physical consequences of the model. ...

... Progress in physics can frequently be seen as the resolution of this tension.

... The construction of physically successful quantum field theories makes use of symmetry for yet another reason. Quantum field theory models are notoriously difficult to solve and also explicit calculations are beset by infinities.

Thus far we have been able to overcome these two obstacles only when the models possess a high degree of symmetry, which allows unraveling the complicated dynamics and taming the infinities by renormalization. Our present-day model for quarks, leptons, and their interactions exemplifies this by enjoying a variety of chiral, scale/conformal, and gauge symmetries. But to agree with experiments, most of these symmetries must be absent in the solutions.

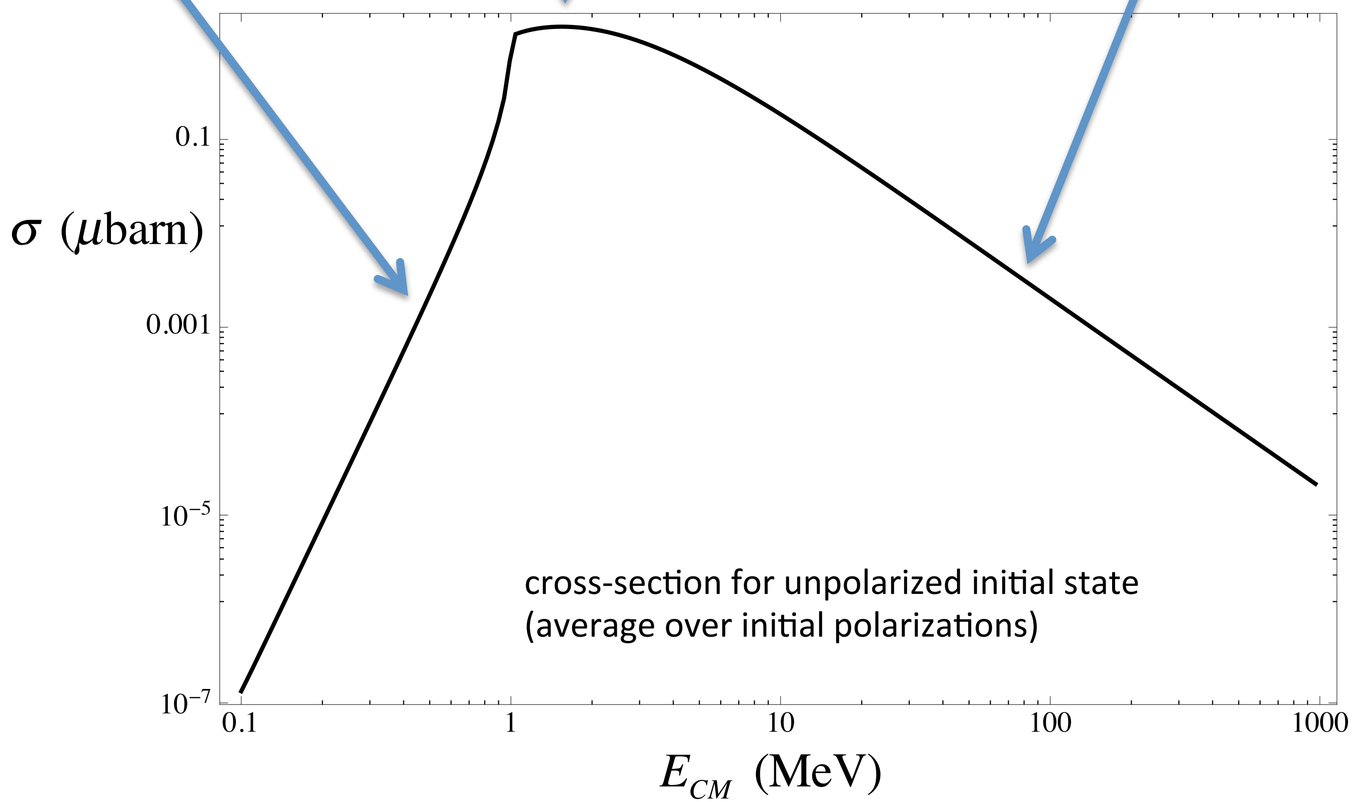
At present we have available two mechanisms for achieving this necessary result. One is spontaneous symmetry breaking, which relies on energy differences between symmetric and nonsymmetric solutions: the dynamics may be such that the nonsymmetric solution has lower energy than the symmetric one, and the nonsymmetric one is realized in Nature while the symmetric solution is unstable.

The second mechanism is anomalous or quantum mechanical symmetry breaking, which uses the infinities of quantum theory to effect a violation of the correspondence principle: the symmetries that appear in the model before quantization disappear after quantization, because the renormalization procedure— needed to tame the infinities and well define the theory— cannot be carried out in a fashion that preserves the symmetries ...

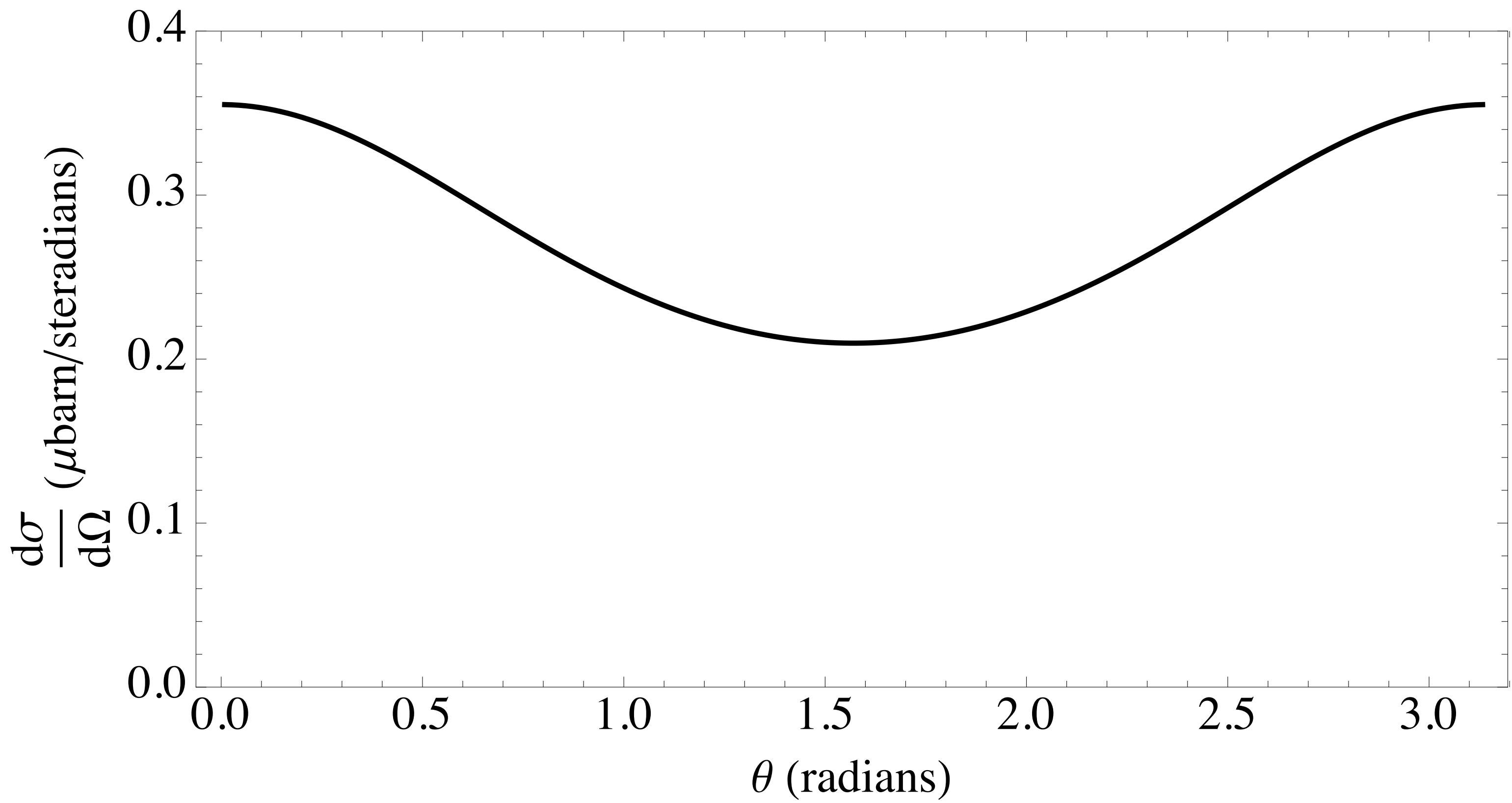
$$\sigma \approx 0.13\left(\frac{\hbar\omega}{m_e c^2}\right)^6 \mu\text{barn}$$

peak cross-section, ≈1.6 μbarn at $\hbar\omega \approx 1.5 m_e c^2$

$$\sigma \approx 20\left(\frac{m_e c^2}{\hbar\omega}\right)^2 \mu\text{barn}$$

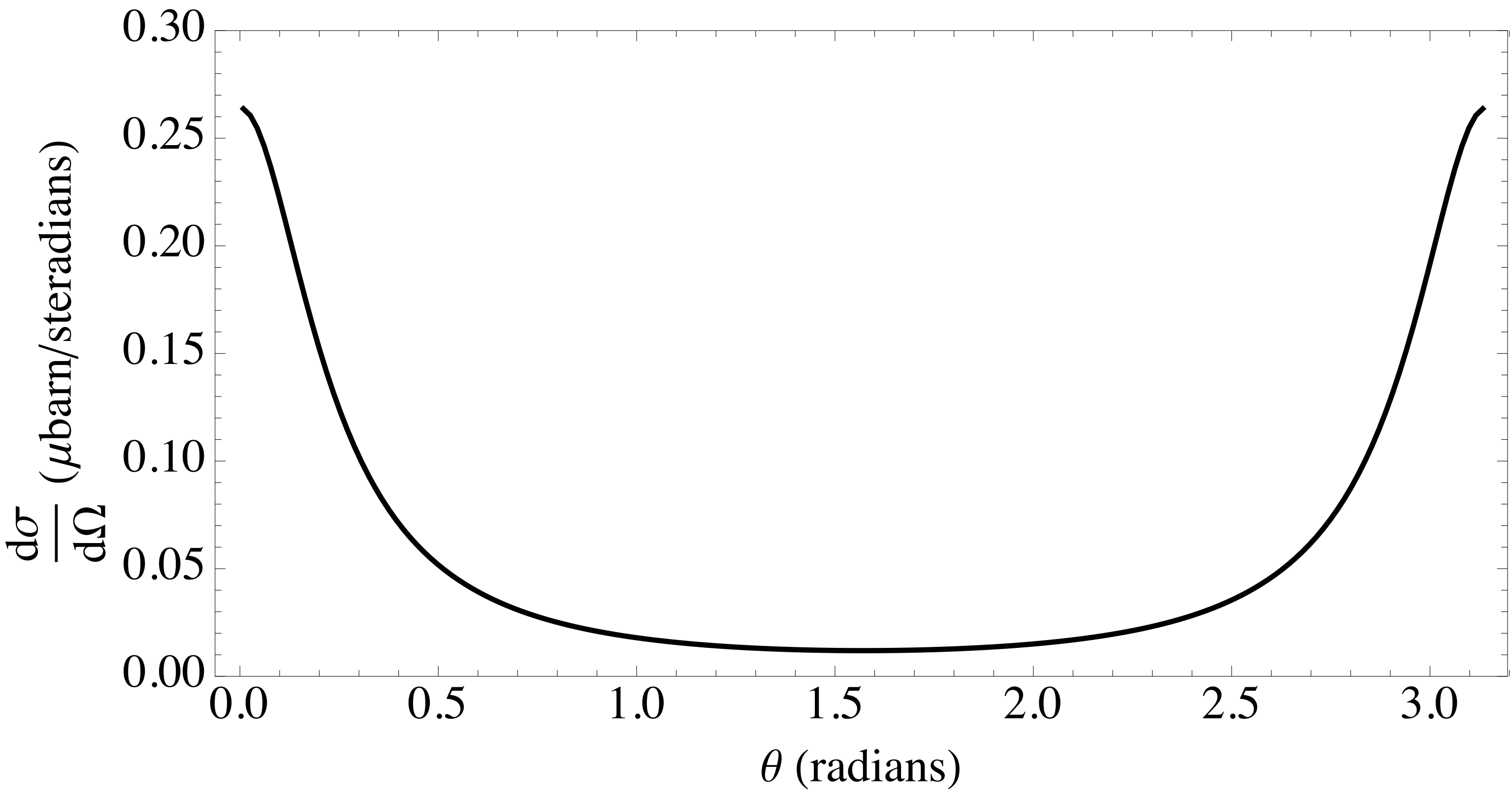


Differential cross-section at ECM = 1.6 MeV (peak)



$$\frac{d\sigma}{d\Omega} \approx \frac{139}{(180\pi)^2} \alpha^2 r_0^2 \left(\frac{\hbar\omega}{mc^2} \right)^6 \left(3 + \cos^2\theta\right)^2$$

Differential cross-section at ECM = 10 MeV

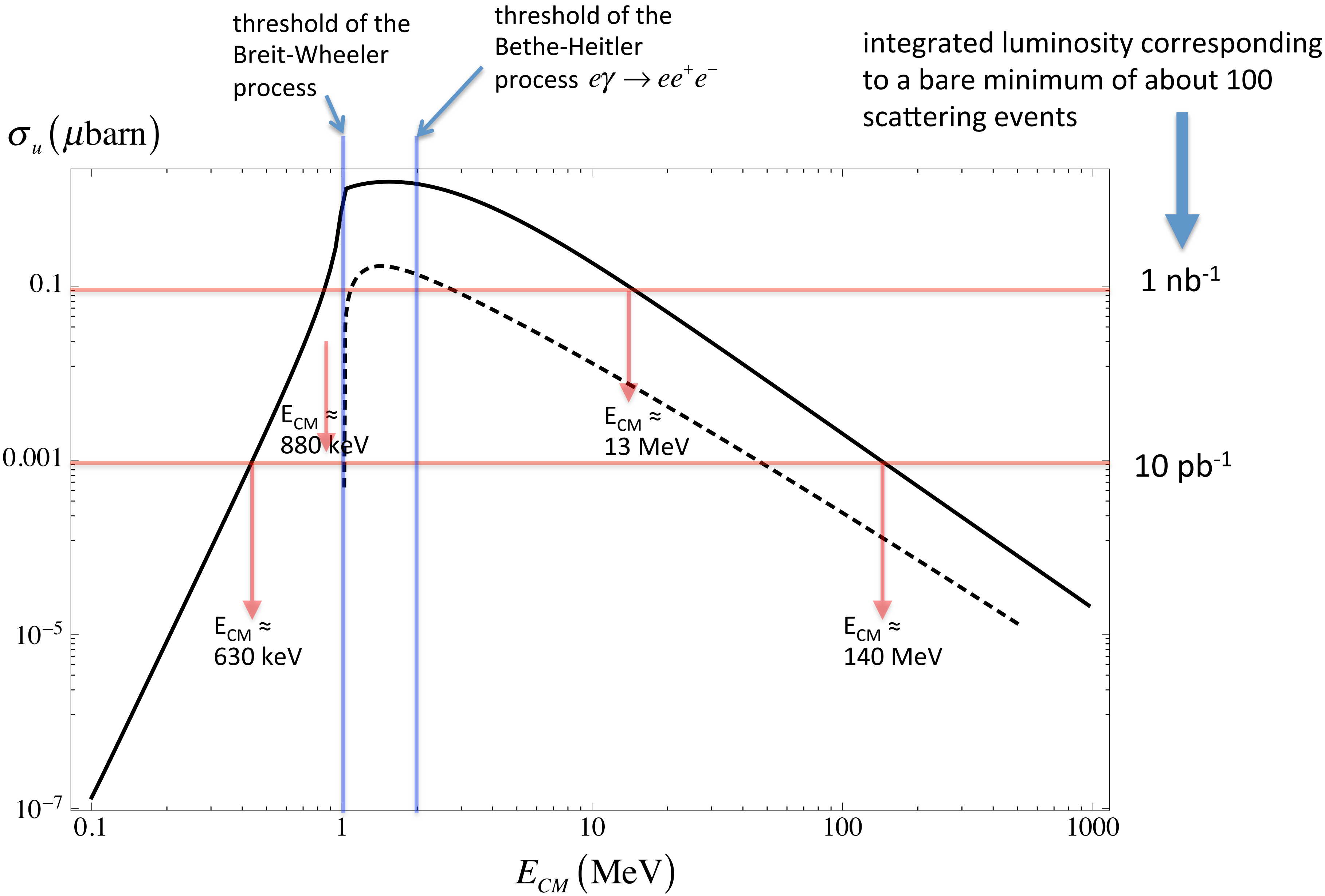


$$\left.\frac{d\sigma}{d\Omega}\right|_{\theta=0} \approx \frac{\alpha^2}{\pi^2} r_0^2 \left(\frac{\hbar\omega}{mc^2}\right)^2 \left(\ln\frac{\hbar\omega}{mc^2}\right)^4 \qquad \left.\frac{d\sigma}{d\Omega}\right|_{\theta=\pi/2} \approx \frac{\alpha^2}{\pi^2} r_0^2 \left(\frac{\hbar\omega}{mc^2}\right)^2$$

Beam requests:

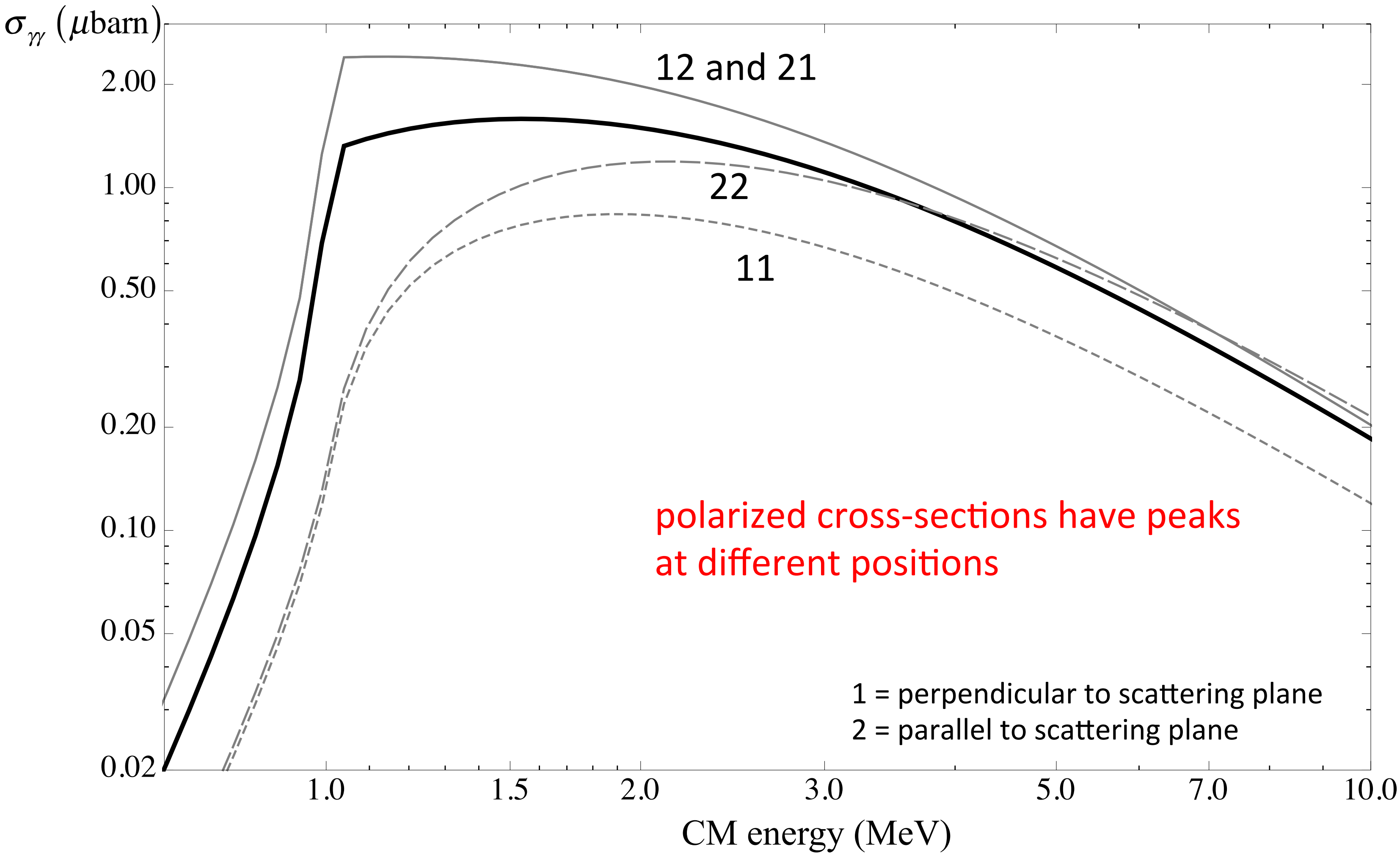
- high luminosity
- tuneable beam energy
- polarized photon beams (circular polarization is better, linear polarization OK)
- good beam quality (small energy spread, small collision angle)
- variable beam polarization
- low machine background

"High luminosity"



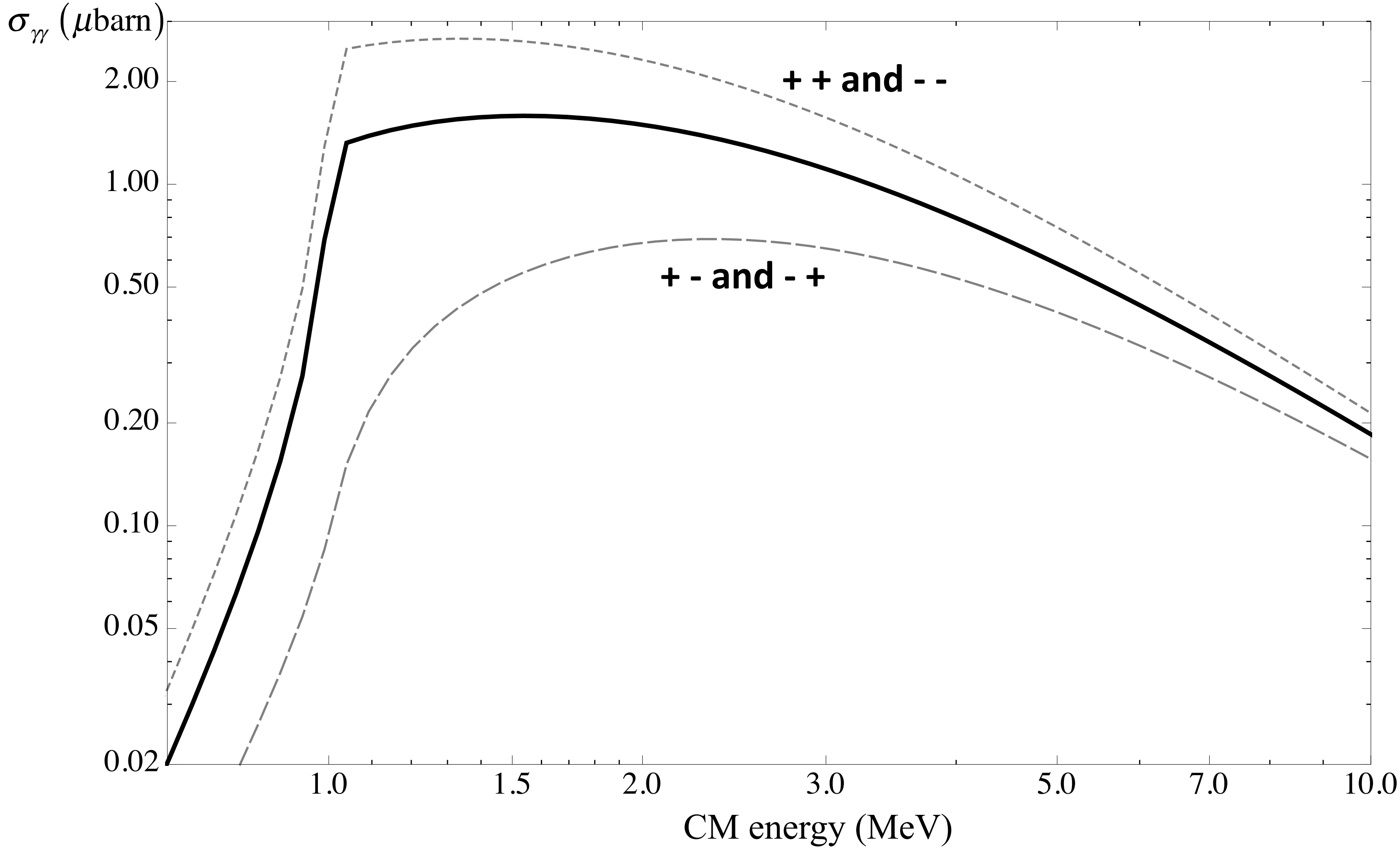
“Tuneable beam energy”

Unpolarized and (linearly) polarized initial photons

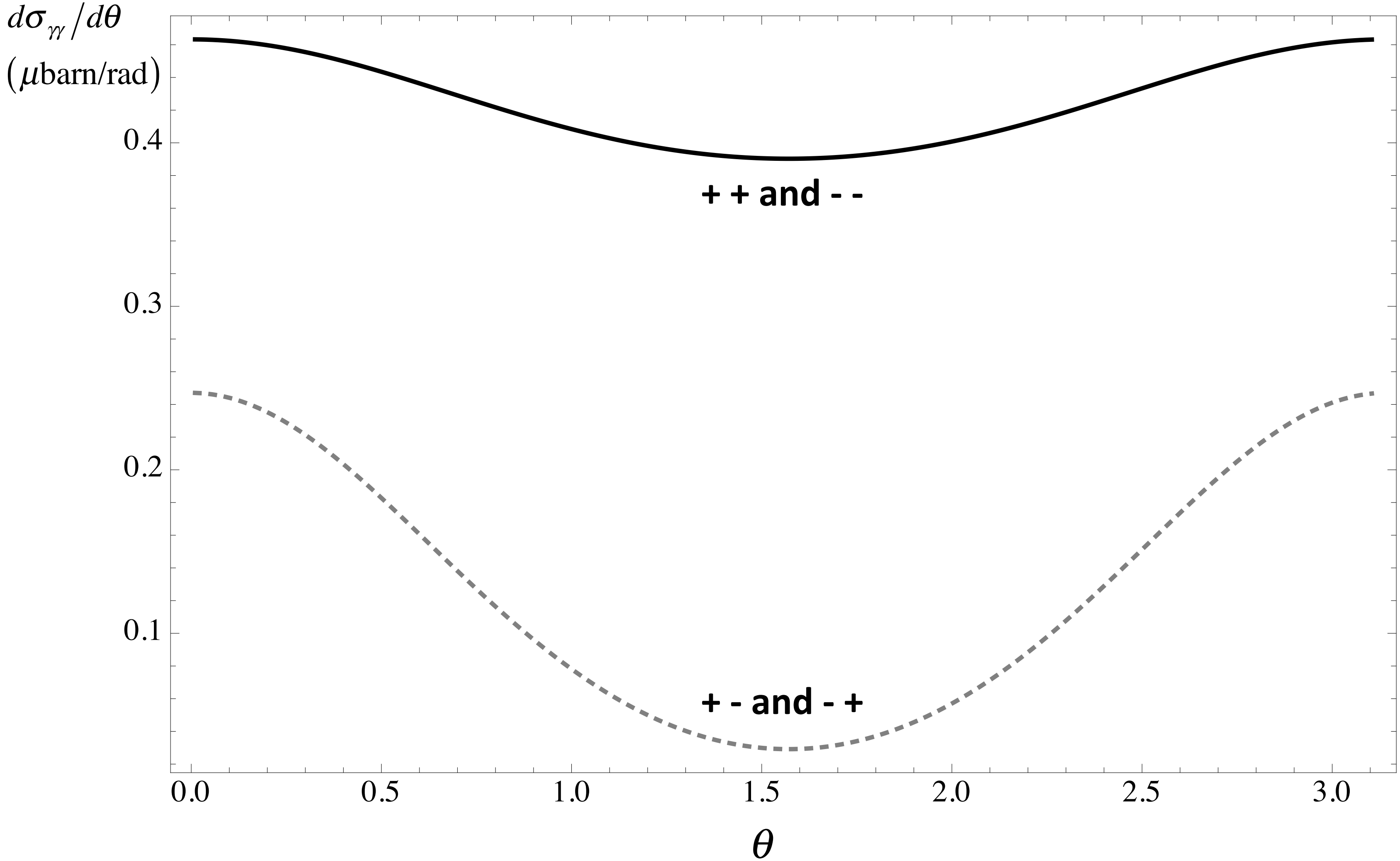


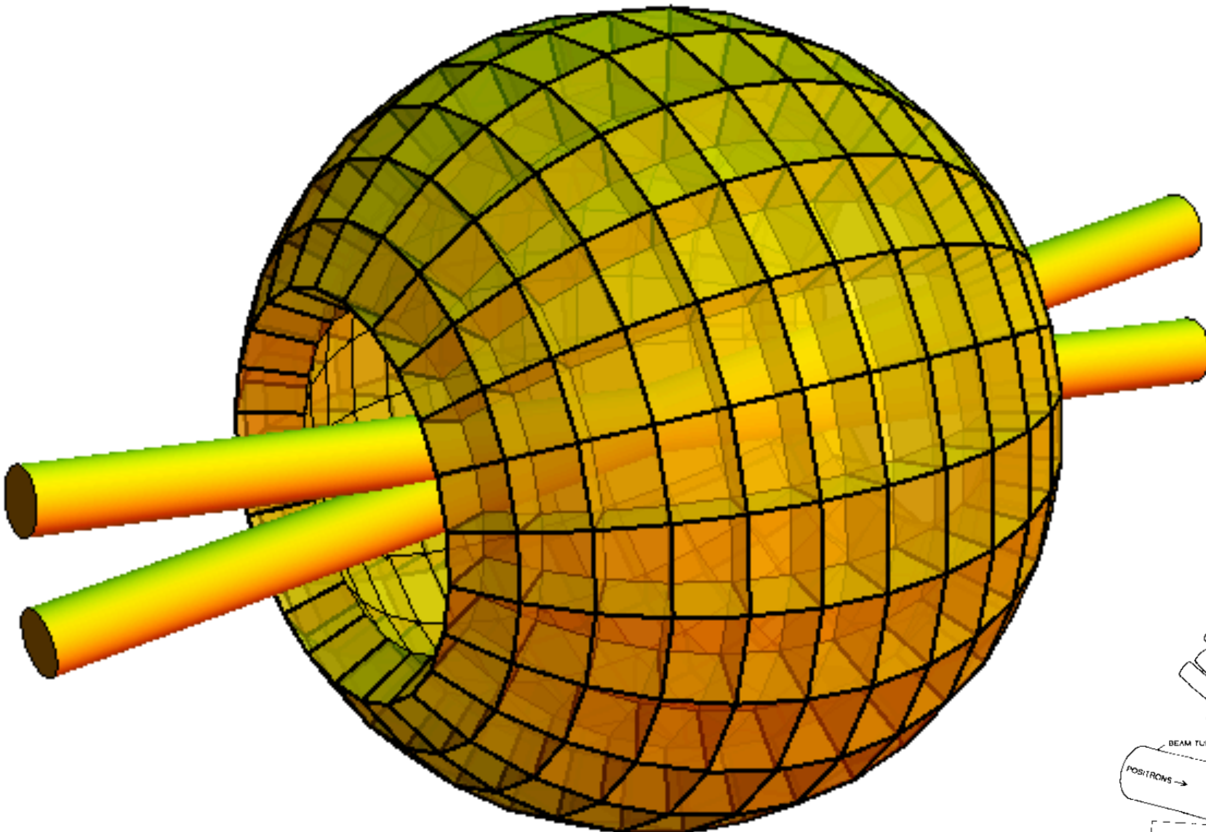
“Polarized photon beams”

Unpolarized and (circularly) polarized initial photons

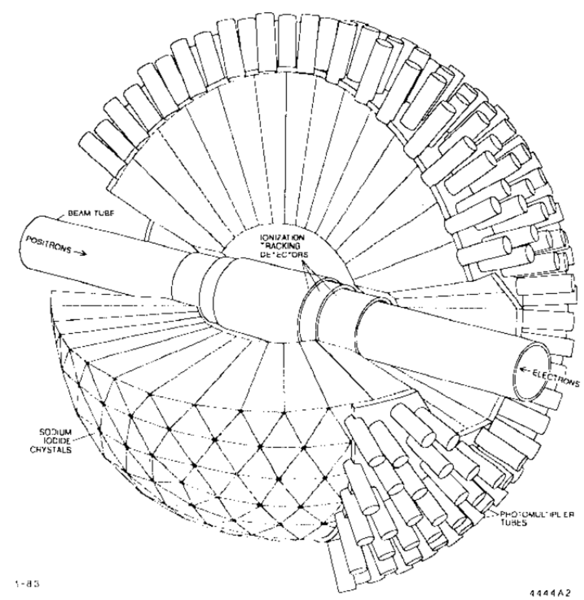


Differential cross-sections for different circular polarizations at 1.6 MeV CM energy





PET-like, segmented detector

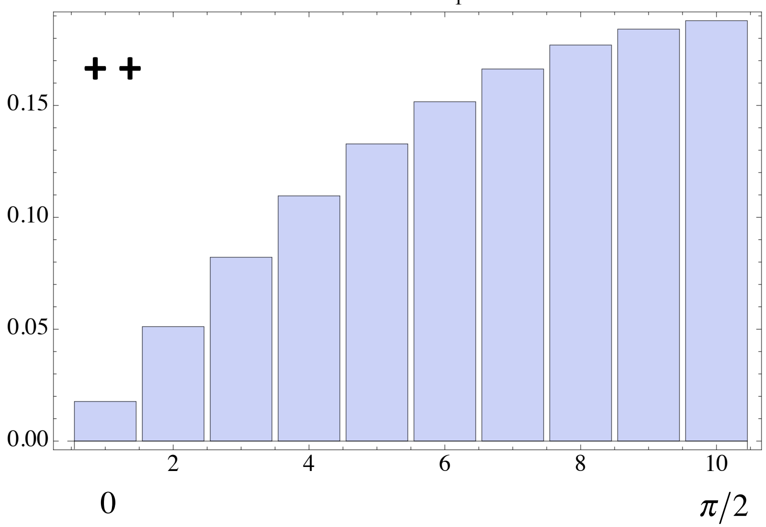


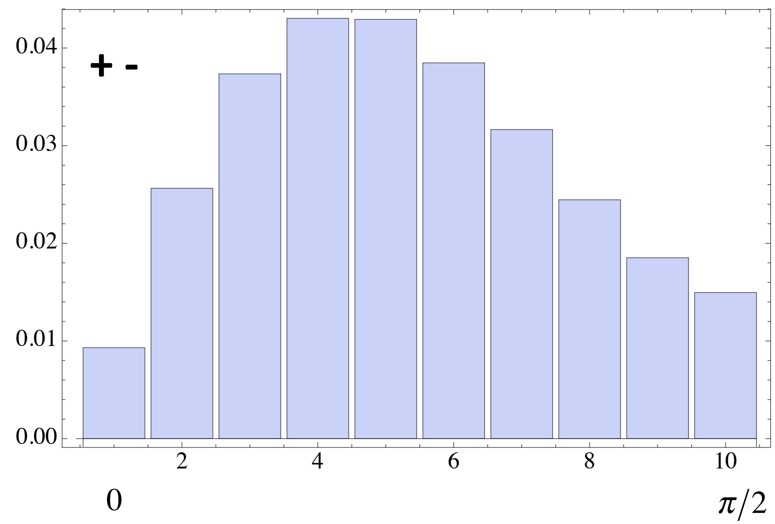
... somewhat similar to Crystal Ball

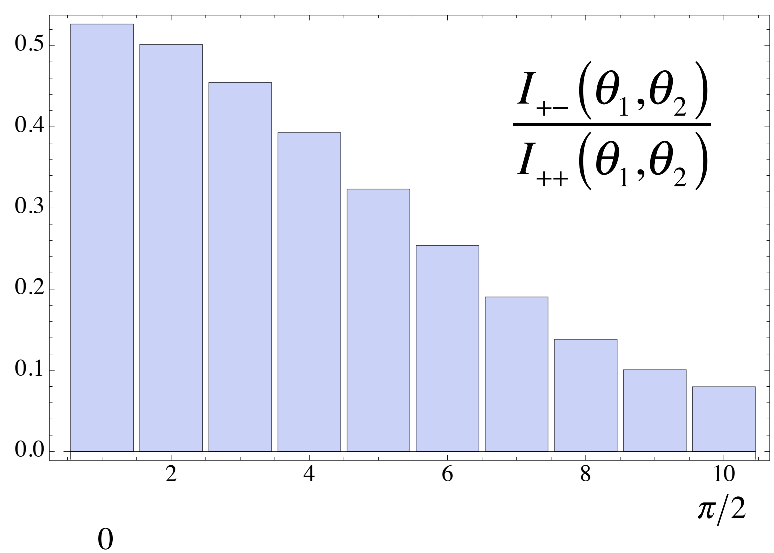
Event rate calculation (at 1.6 MeV CM)

$$I_{++}(\theta_1,\theta_2) = \int_0^{2\pi} d\varphi \int_{\theta_1}^{\theta_2} \sin\theta\, d\theta \frac{d\sigma_{++}}{d\Omega}$$

$$I_{+-}(\theta_1,\theta_2) = \int_0^{2\pi} d\varphi \int_{\theta_1}^{\theta_2} \sin\theta\, d\theta \frac{d\sigma_{+-}}{d\Omega}$$







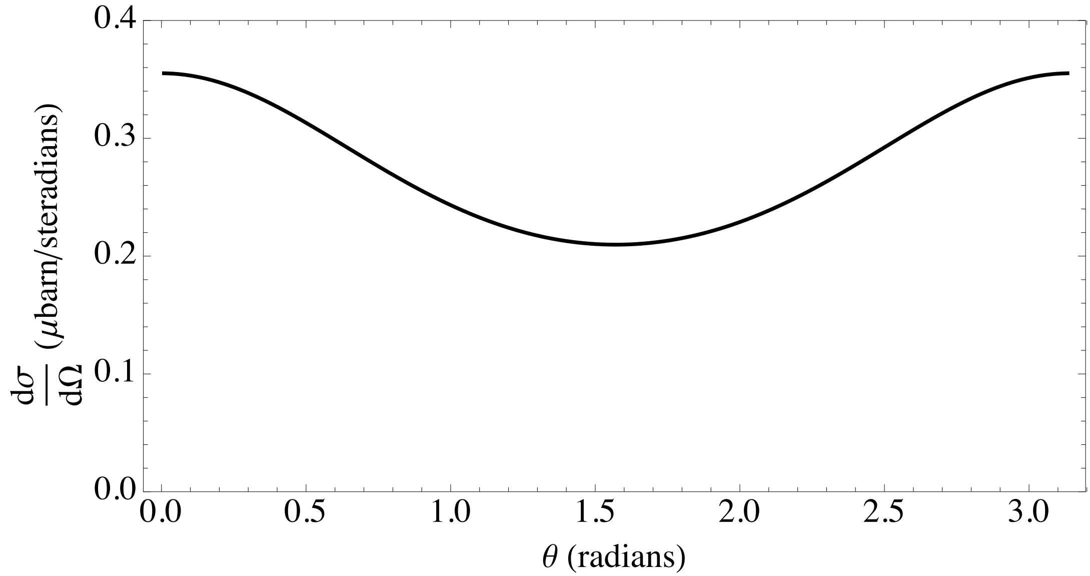
At least 13 events in the last bin for I_{+-}

(cross-section ≈ 0.015 μbarn)

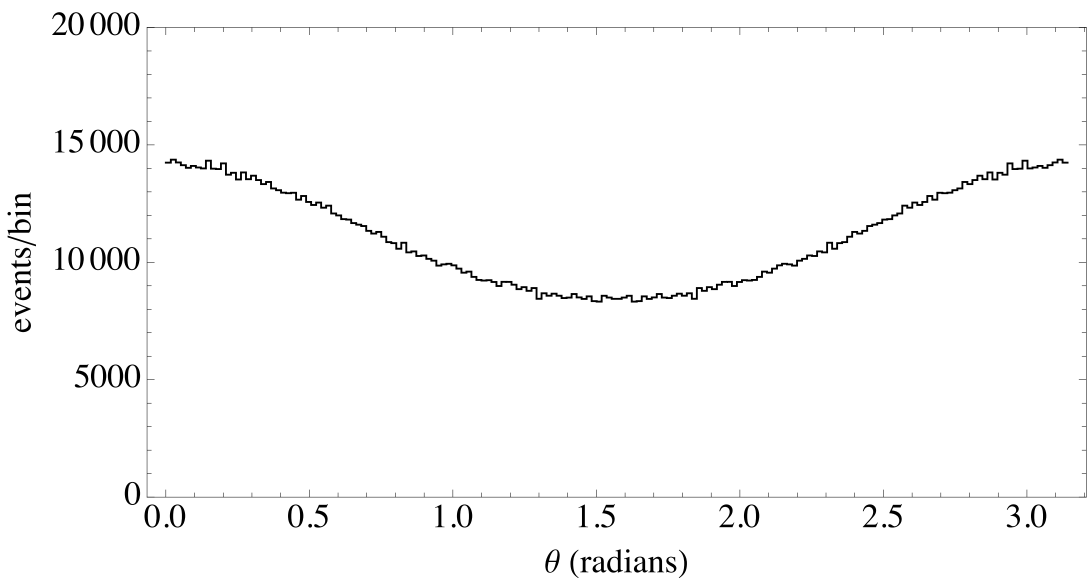
THEN, Luminosity must be

$$L\Delta t \approx \frac{N}{\sigma} \geq \frac{13}{15\,\mathrm{nbarn}} \approx 0.87\ \mathrm{nbarn}^{-1}$$

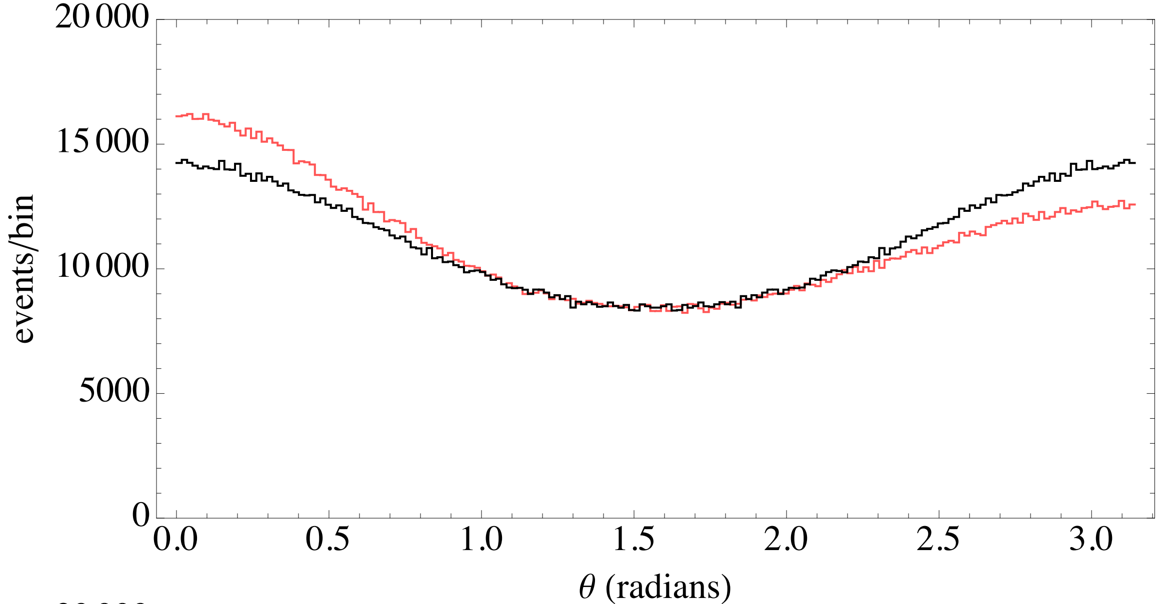
"Good beam quality"



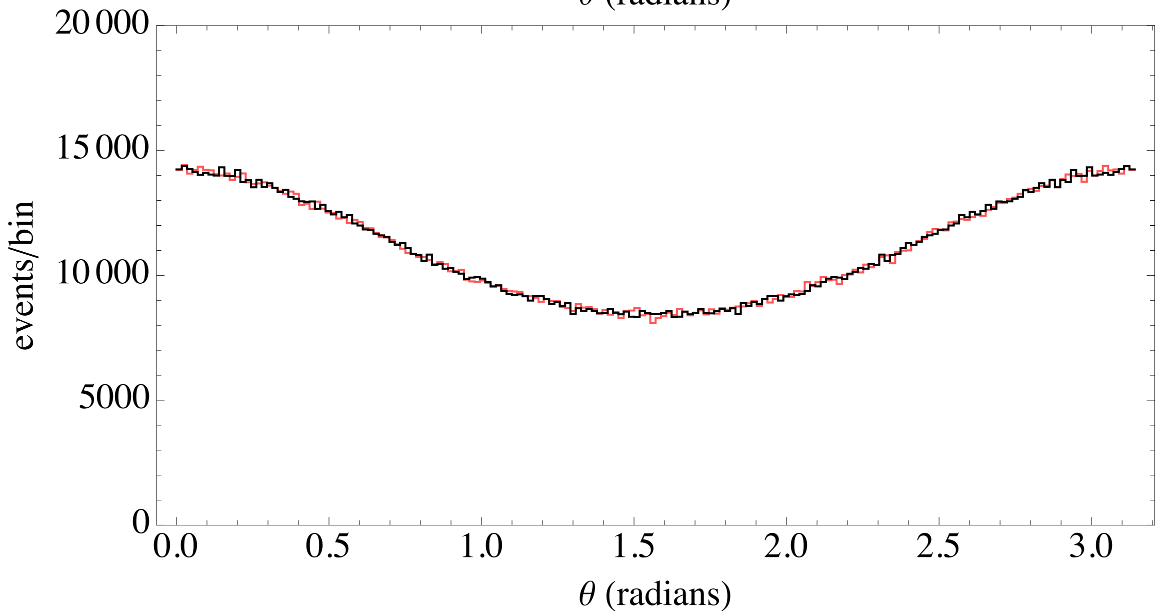
"exact" differential cross-section



MC simulation

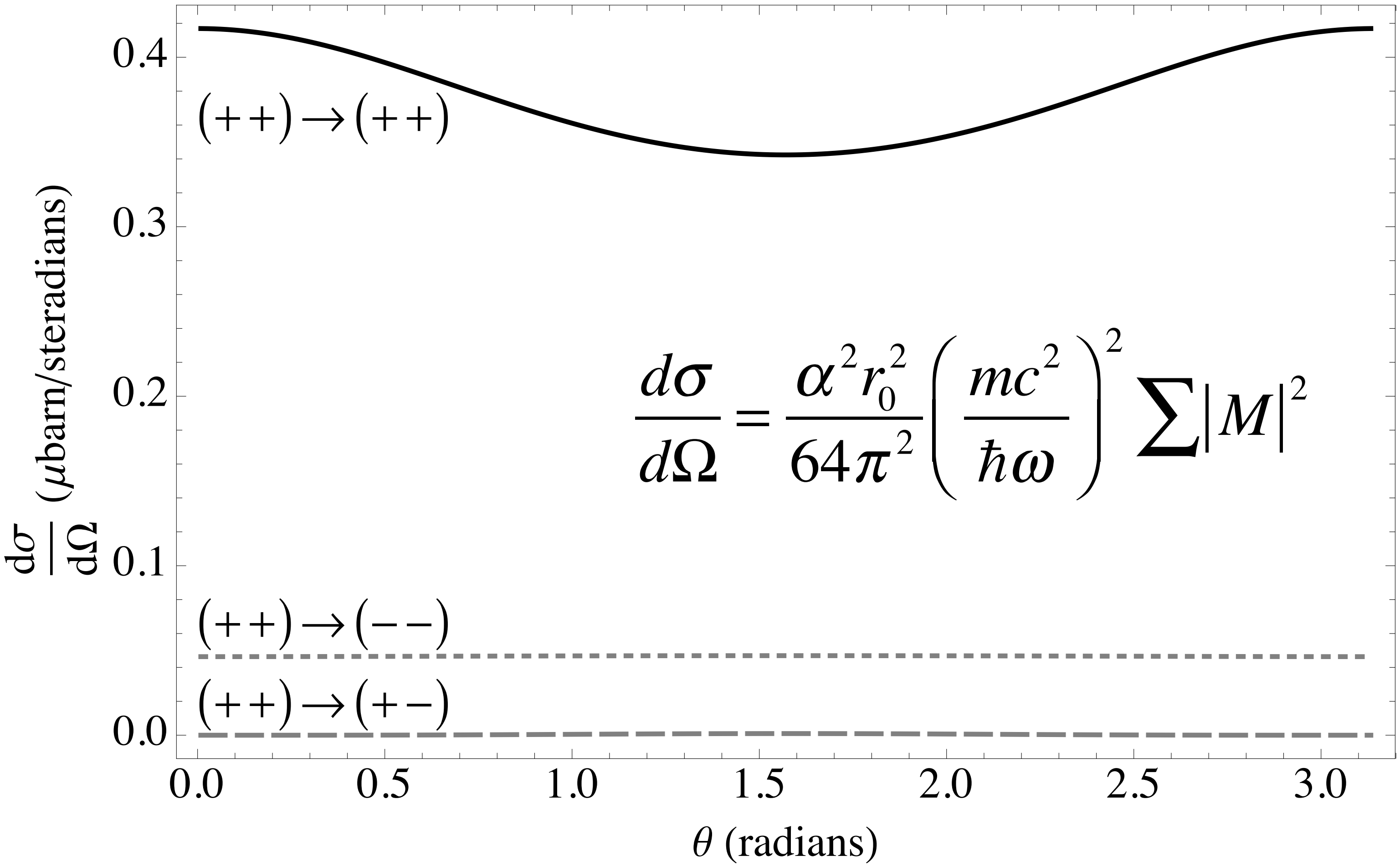


MC simulation, systematic energy imbalance (E_1 = 0.9 MeV; E_2 = 0.7 MeV) and small energy spread (uniform, ±1%)

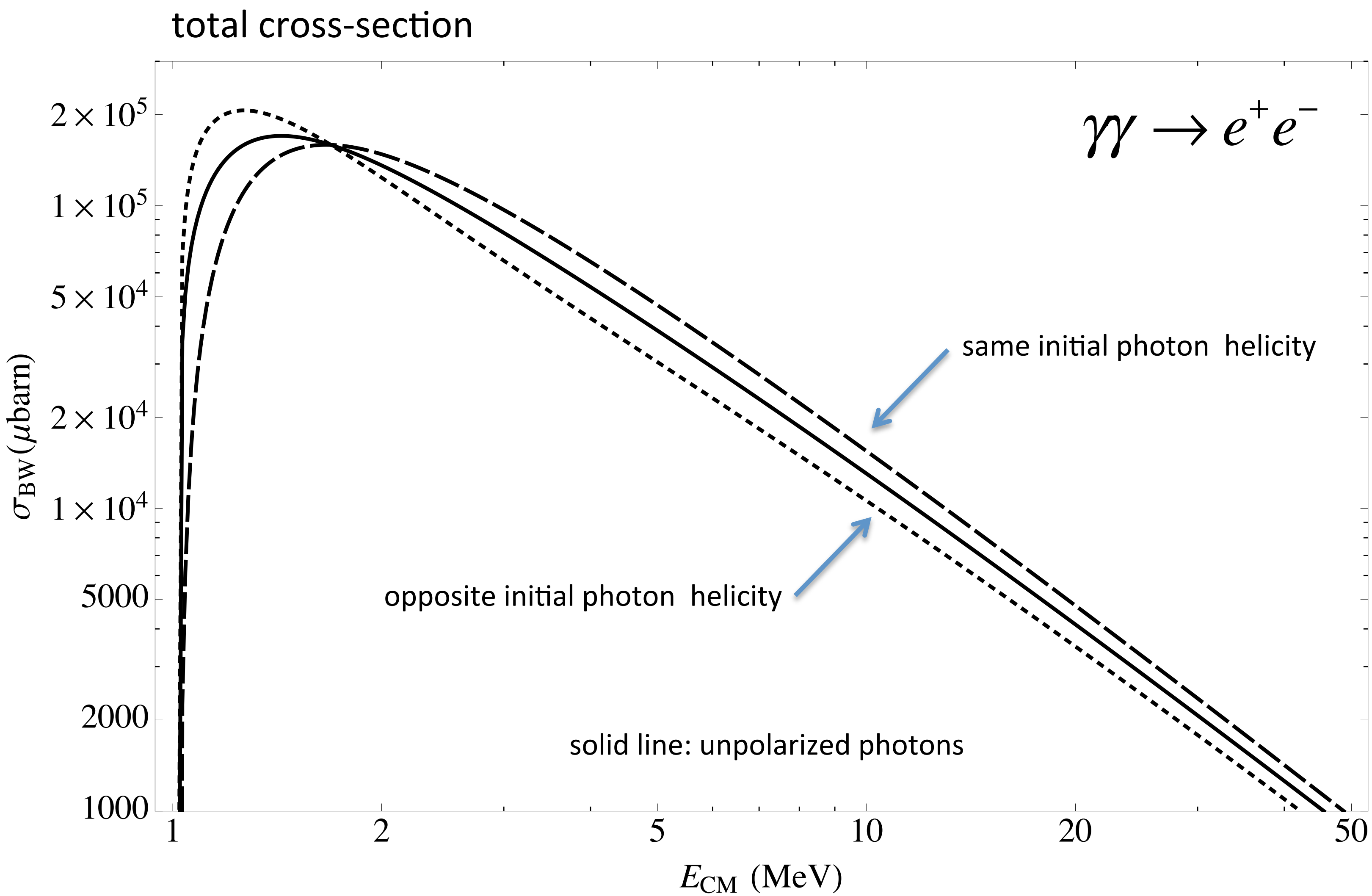


MC simulation, no systematic imbalance and larger energy spread (uniform, ±10%)

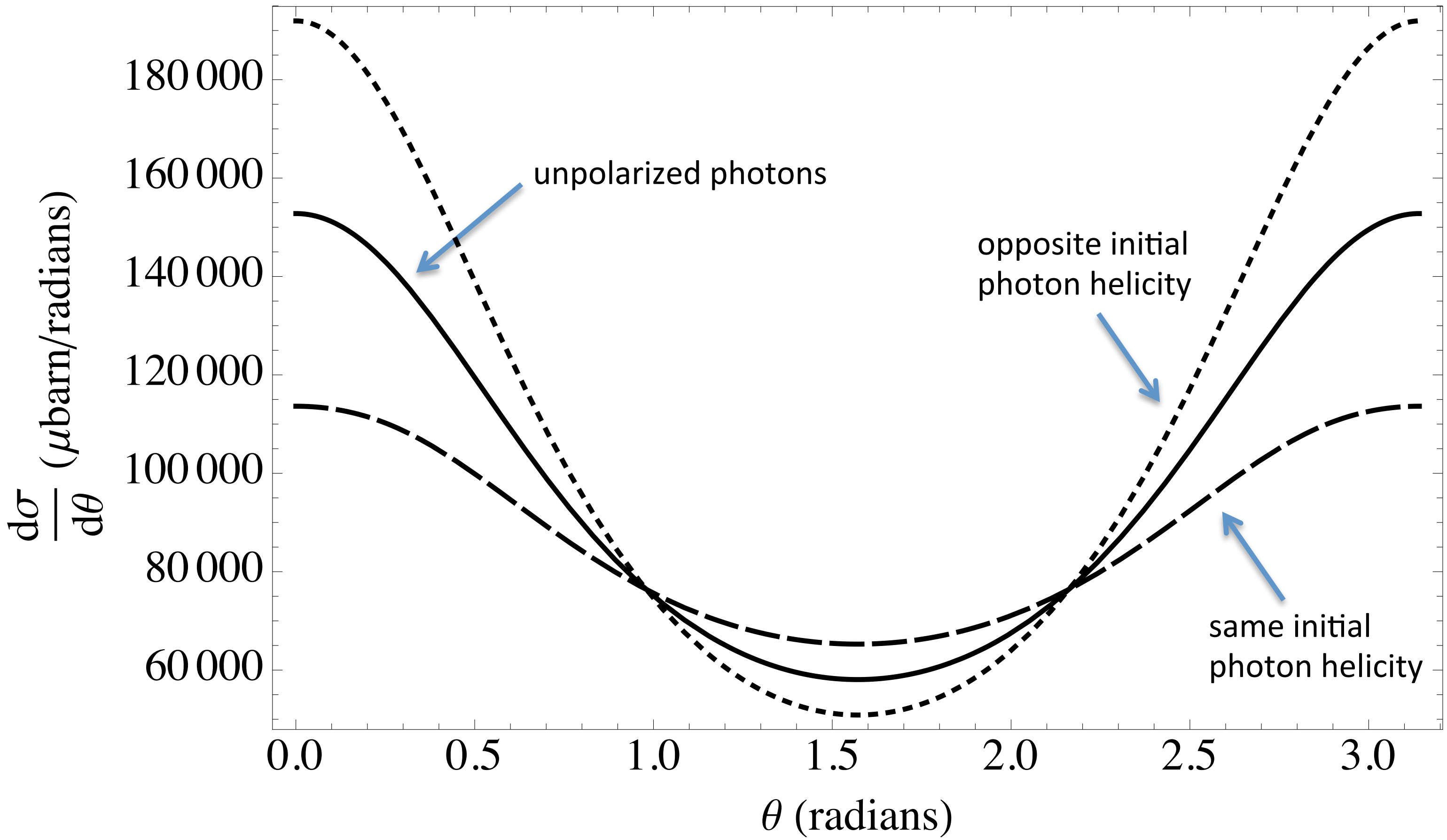
"Variable beam polarization"



Background from the Breit-Wheeler process (straighforward process, however still unobserved!)



Differential cross-sections for different circular polarizations at 1.6 MeV CM energy



E_γ (MeV)	0°-10°	10°-20°	20°-30°	30°-40°	40°-50°	50°-60°	60°-70°	70°-80°	80°-90°
0.55	7.963	23.59	38.32	51.60	62.96	72.09	78.89	83.35	85.55
0.60	12.63	37.12	59.35	78.09	92.64	103.0	109.8	113.7	115.5
0.65	16.10	46.82	73.31	93.69	107.5	115.8	120.0	121.8	122.3
0.70	18.84	54.09	82.69	102.4	113.7	118.7	119.9	119.4	118.9
0.75	21.04	59.56	88.77	106.6	114.6	116.2	114.7	112.5	111.0
0.80	22.84	63.66	92.41	107.6	112.3	111.0	107.3	103.8	101.7
0.85	24.30	66.67	94.23	106.5	108.1	104.4	99.22	94.79	92.32
0.90	25.51	68.81	94.69	104.0	103.0	97.43	91.16	86.17	83.47
0.95	26.51	70.27	94.15	100.6	97.38	90.49	83.52	78.22	75.41
1.0	27.33	71.16	92.87	96.78	91.70	83.85	76.47	71.03	68.20

Background events from the Breit-Wheeler process (events) with unpolarized initial photons in the same 10° angular bins specified earlier. Here the number of background event rate (Hz) has been estimated for the machine luminosity 10^{28} cm^{-2} s^{-1}.

We need a detector with photon/electron discrimination to reject these background events.

... R. Jackiw, reversed conclusions ...

... Today we do not know whether the impasse within field theory is due to a failure of imagination or whether indeed we have to present fundamental physical laws in a new framework, thereby replacing the field theoretic one, which has served us well for over 100 years.

... On previous occasions when it appeared that quantum field theory was incapable of advancing our understanding of fundamental physics, new ideas and new approaches to the subject dispelled the pessimism. ...

Con mio grande compiacimento, nel maggio del 2004 ho rimesso piede in Siberia, a Novosibirsk ... [c'era] Pief Panofski che, con l'età, era divenuto quasi affettuoso. ... Intorno, i più giovani, ignari dell'incessante fluire del tempo, cercano di farsi avanti con idee innovative, che mostrino a quei resti umani che li stanno a sentire quanta strada è stata fatta dopo di loro. ... Pief [Panofski] ed io ci guardiamo smarriti di fronte a un ragazzotto che propone un gamma-gamma collider, macchina inverosimile: ma bisogna accordare fiducia. ...

Carlo Bernardini, *Fisica Vissuta* (2006), Cap. 11