photon-photon scattering as a test of QED at IRIDE

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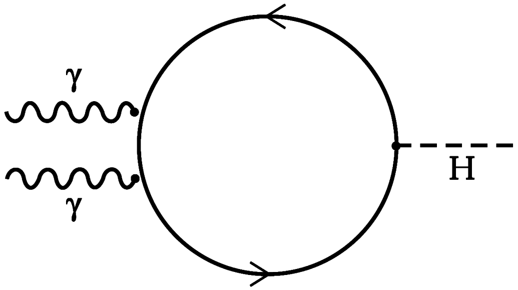
There is no doubt that photon-photon colliders are an important option at high energy



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.

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 preparation for a higher energy complex, while still providing a rich testing ground for QED, and, more generally, QFT.

The *huge* unsolved problem of QFT:
QFT vacuum and 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

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

A HUGE ENERGY DENSITY !!!

Contribution of each degree of freedom $\pm\frac{\hbar\omega}{2}$ ⇒ $\frac{3}{8\pi^2}\frac{(\hbar\omega_{max})^4}{(\hbar c)^3}$

When we take the Planck energy as the ultraviolet cutoff

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

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

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

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

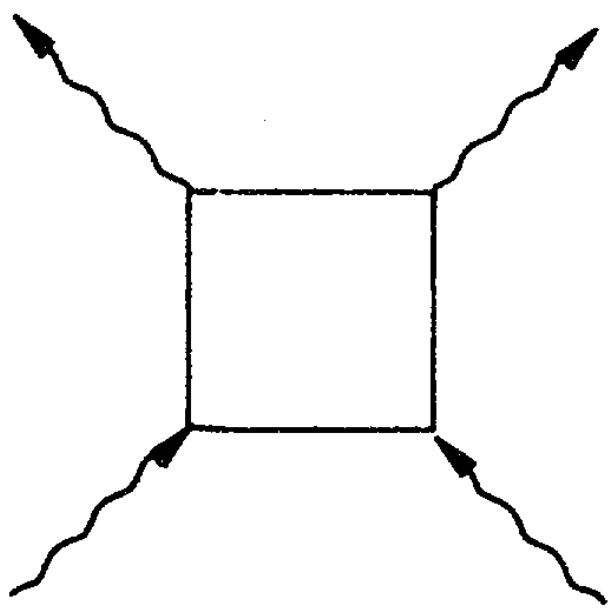
In 1975 Bruno Zumino suggested that supersymmetry would solve the problem (Nucl. Phys. B89 (1975) 535):

same number of fermionic and bosonic degrees-of-freedom, hence complete cancellation of vacuum energy contributions.

However, Zumino himself noted that 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.

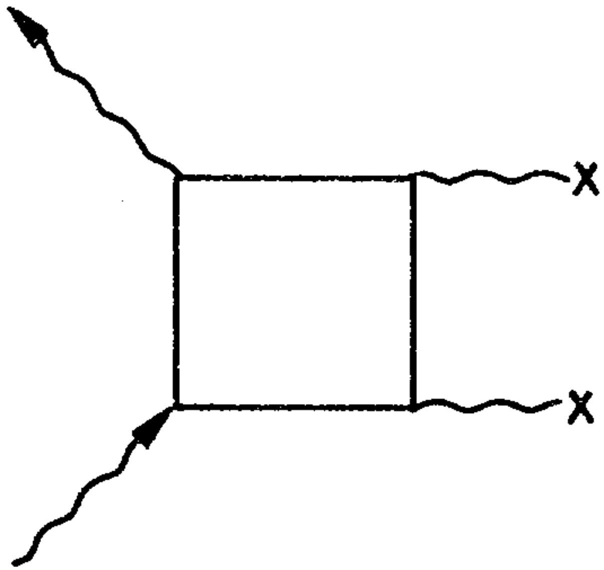
The cosmological constant problem is related to the zero-point energy, i.e., to the fluctuations of quantum vacuum, and therefore also to the renormalization procedure in QFT.

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



This is the first nonvanishing diagram: there are no tree-level diagrams

All the involved photons are real particles



Delbrück scattering as the leading correction to Compton scattering off nuclei

The diagram is very much like the one in photon-photon scattering, however this is basically a correction to a lower-order process and two photons are virtual

First observed in 1973 by Jarlskog and collaborators

PHYSICAL REVIEW D VOLUME 8, NUMBER 11 1 DECEMBER 1973

Measurement of Delbrück Scattering and Observation of Photon Splitting at High Energies

G. Jarlskog* and L. Jönsson
University of Lund, Lund, Sweden

S. Prünster, H. D. Schulz, H. J. Willutzki, and G. G. Winter
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
(Received 18 June 1973)

The differential cross section for Delbrück scattering has been measured at photon energies between 1 and 7 GeV and scattering angles between 1 and 3 mrad on copper, silver, gold, and uranium targets. The results confirm the predictions of quantum electrodynamics, if the exchange of a very large number of photons with the nucleus (Coulomb correction) is taken into account. At momentum transfers of a few MeV/c, the Coulomb correction for uranium results in a reduction of the cross section by a factor between 3 and 5 as compared to the prediction of lowest-order relativistic perturbation theory. The photon-splitting process has been experimentally detected at the same energies and angles. Estimates of the cross section are given.

Thus, one might argue that since Delbrück scattering is observed, and the total cross-section turns out right, then the description of QED vacuum is correct and complete.

However this inference is incorrect: Delbrück scattering is just a correction to a more complex process, it is an individual term in a perturbative expansion.

By contrast, photon-photon scattering is an independent process.

Here we must recall the message of R. Peierls (see R. Peierls: *Models, hypotheses and approximations*, New directions in physics (ed. N. Metropolis, D. N. Kerr & G. S. Rota), 95-105, New York: Academic Press, (1987).)

"... Another old example was pointed out to me by Steve Weinberg. In the 1930's quantum electrodynamics was in trouble because of the infinities that affected the calculation of any quantity beyond its leading order, and we therefore had the feeling that we could not meaningfully talk about any corrections to the leading term. ... the horrors affecting any attempt to calculate higher-order terms led to the feeling that there were no such corrections. ... It was only when Lamb's experiments established the shift beyond any possible doubt that theoreticians realized that there was a correction"

Thus we should not be misled by unsupported preconceptions about the theory: and here the processes are sufficiently different, and the prize at stake (the understanding of QED vacuum) is so high, that we should feel compelled to measure photon-photon scattering.

How could the QED vacuum be any different?

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.

An important feature of the BI Lagrangian is that vacuum does not become birefringent with a strong background magnetic field.

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)

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Vol. 95, pp. 12776–12778, October 1998
Physics

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Field theory: Why have some physicists abandoned it?

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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.

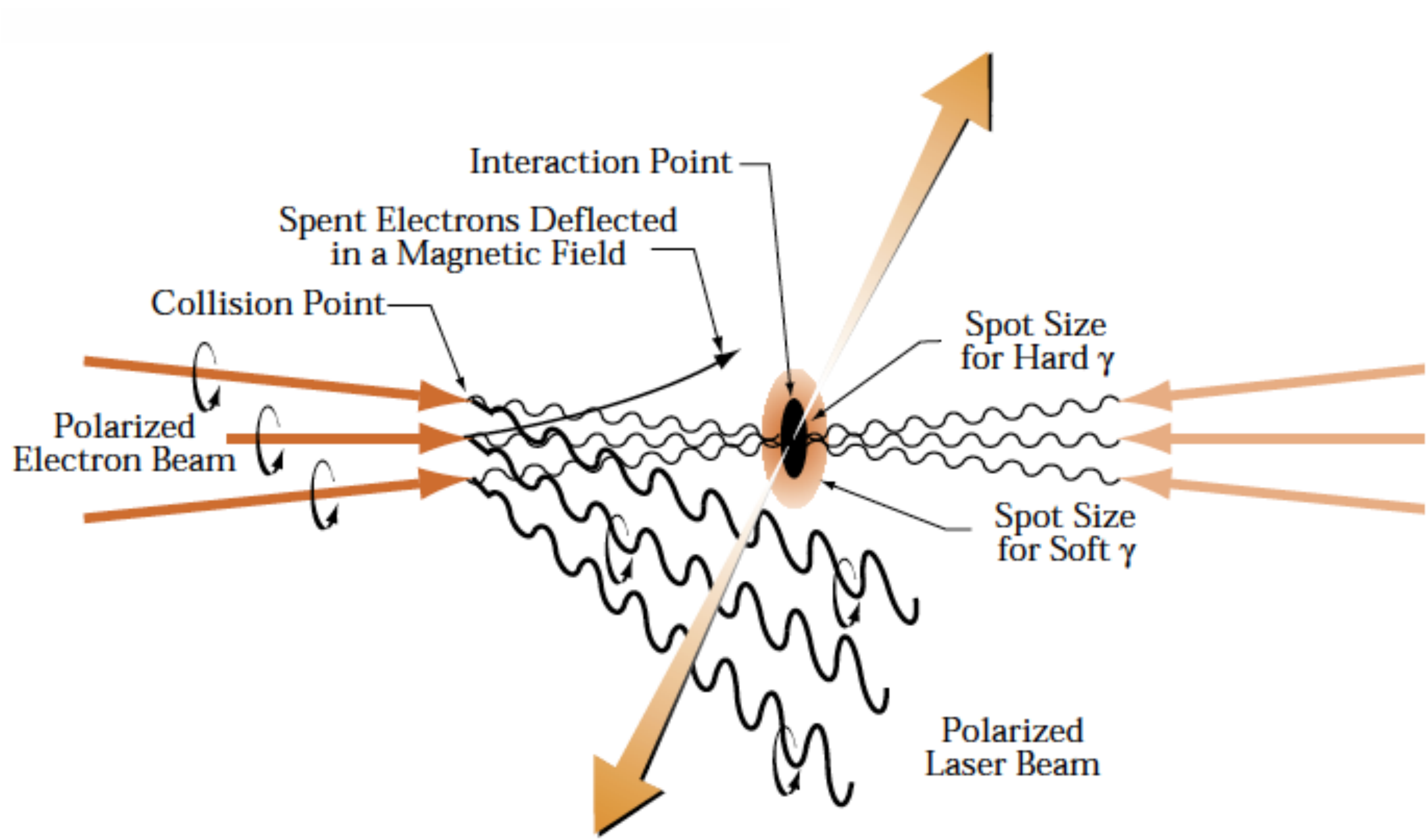
... The construction of physically successful quantum field theories makes use of symmetry for yet another reason. Quantum field theory models are notoriously difficult to solve and also explicit calculations are beset by infinities.

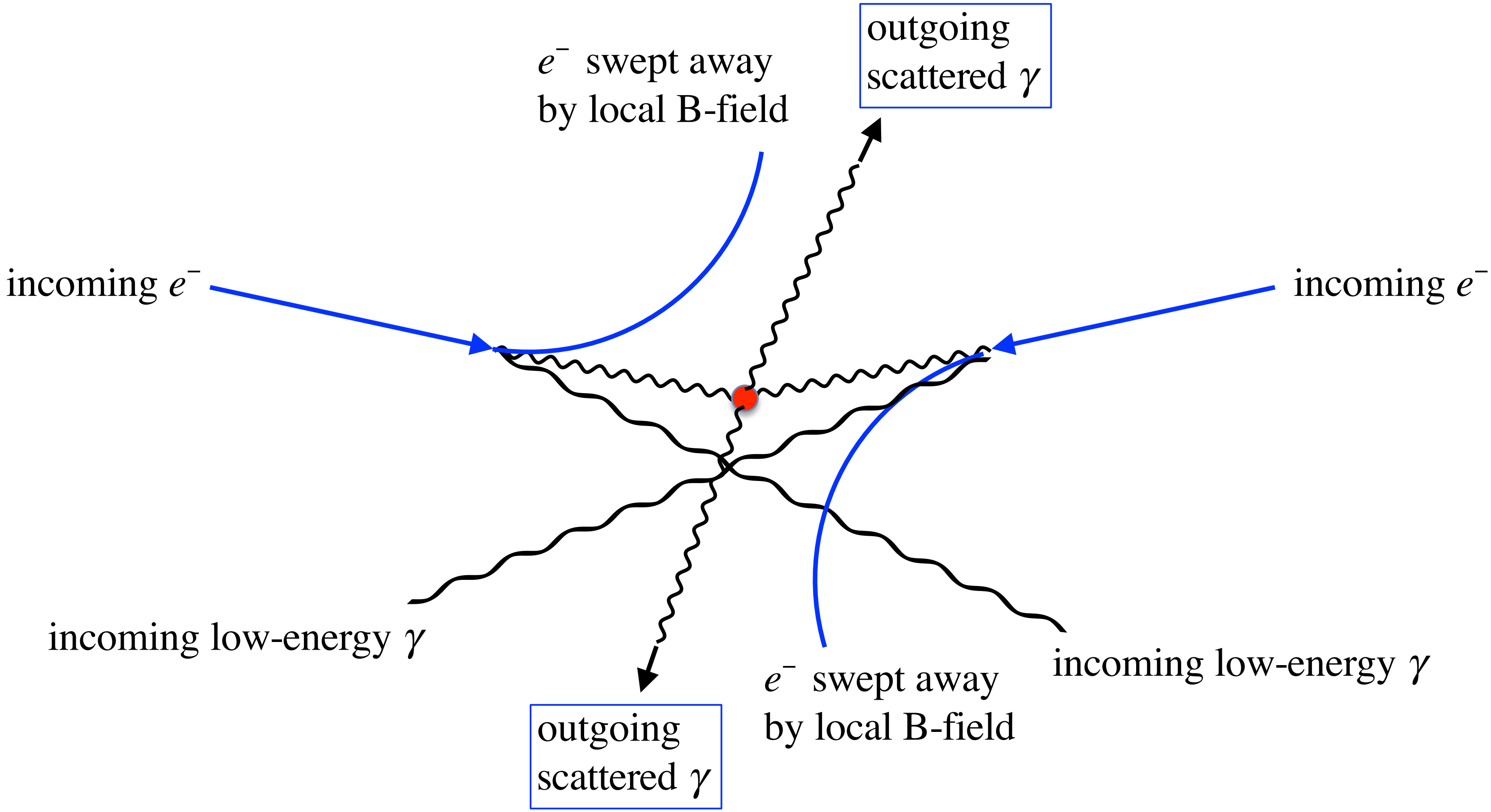
Thus far we have been able to overcome these two obstacles only when the models possess a high degree of symmetry, which allows unraveling the complicated dynamics and taming the infinities by renormalization. Our present-day model for quarks, leptons, and their interactions exemplifies this by enjoying 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 ...

Back to experiment: a possible experimental layout with Compton-backscattered gamma's

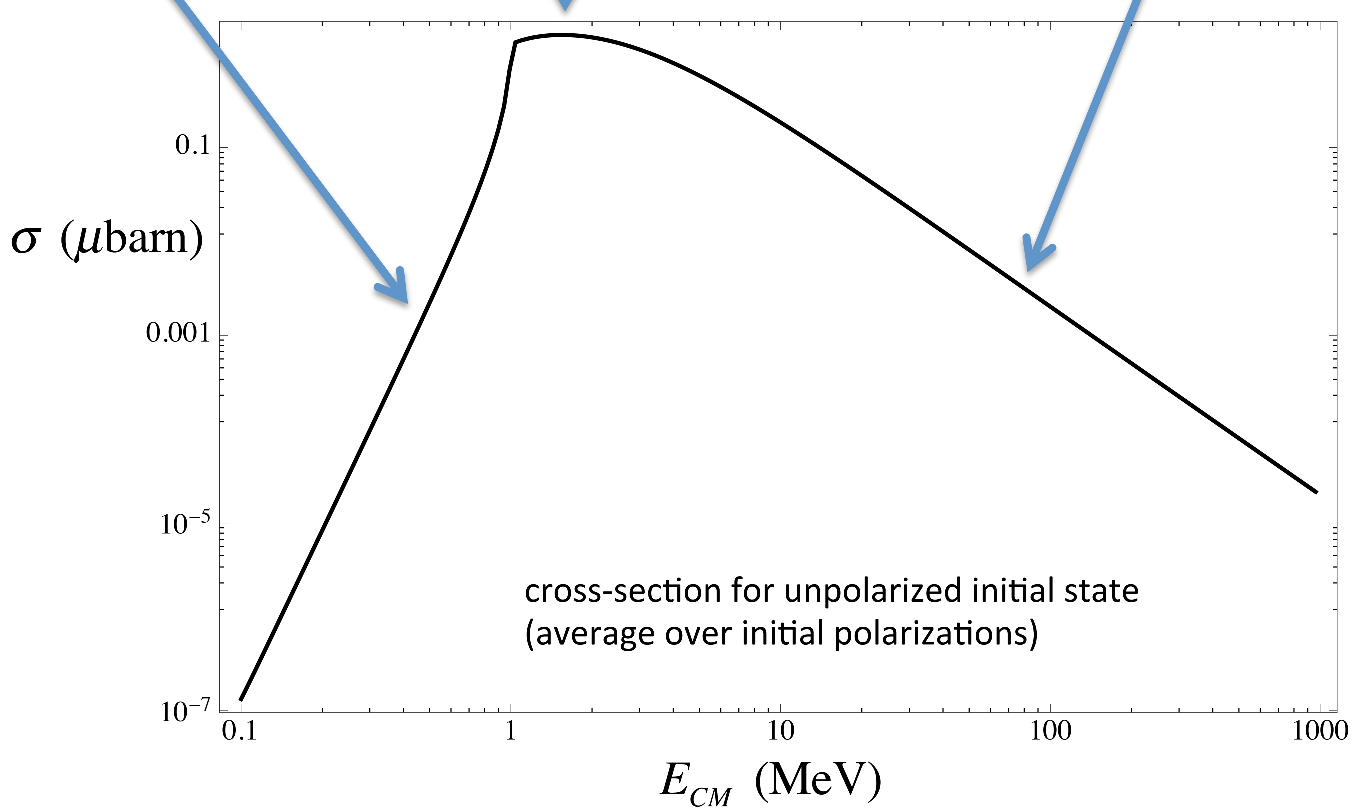



e^- swept away
by local B-field
outgoing
scattered γ
incoming e^-
incoming e^-
incoming low-energy γ
e^- swept away
by local B-field
incoming low-energy γ
outgoing
scattered γ

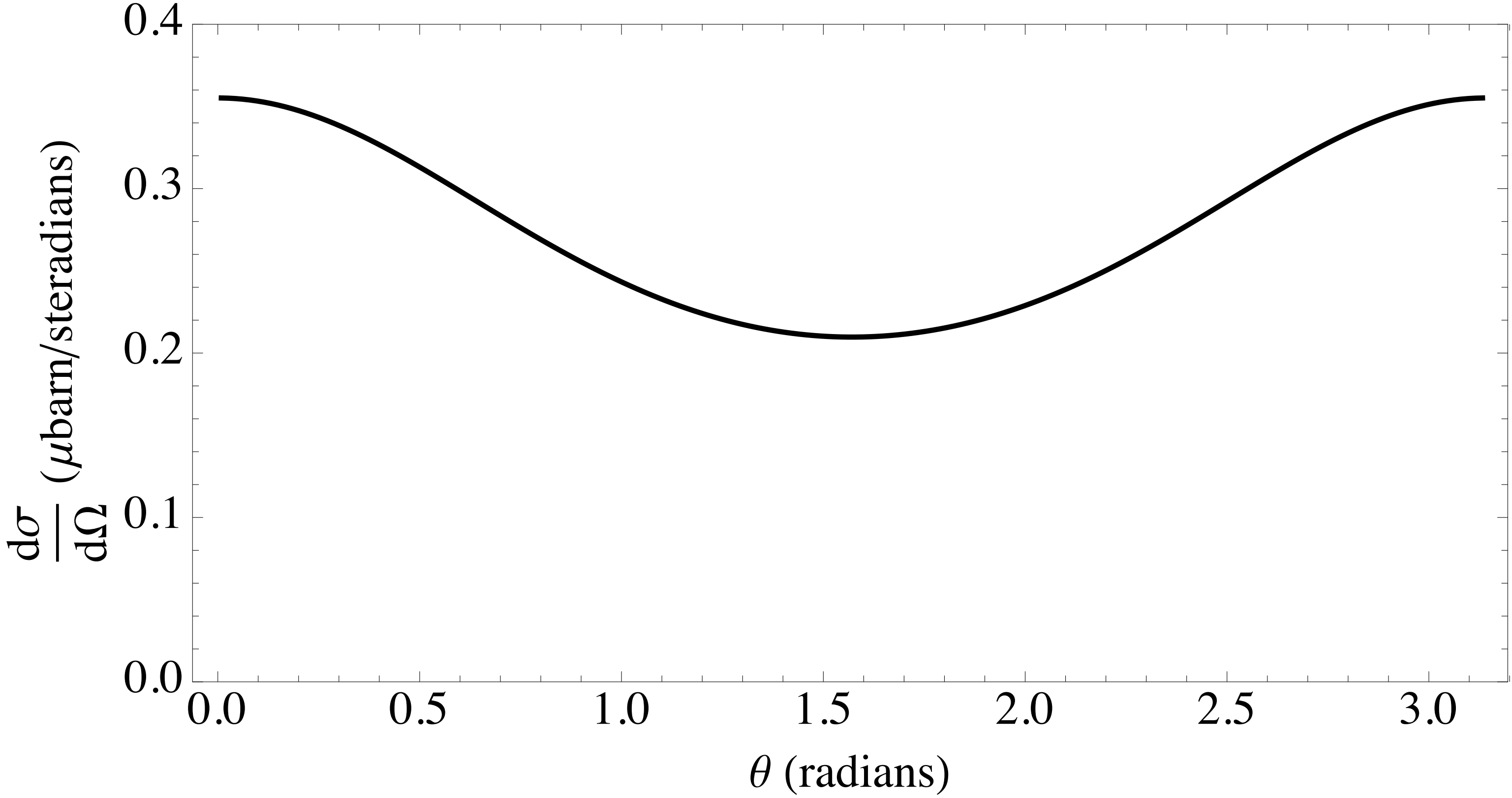
$$\sigma \approx 0.13\left(\frac{\hbar\omega}{m_e c^2}\right)^6 \mu\text{barn}$$

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

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

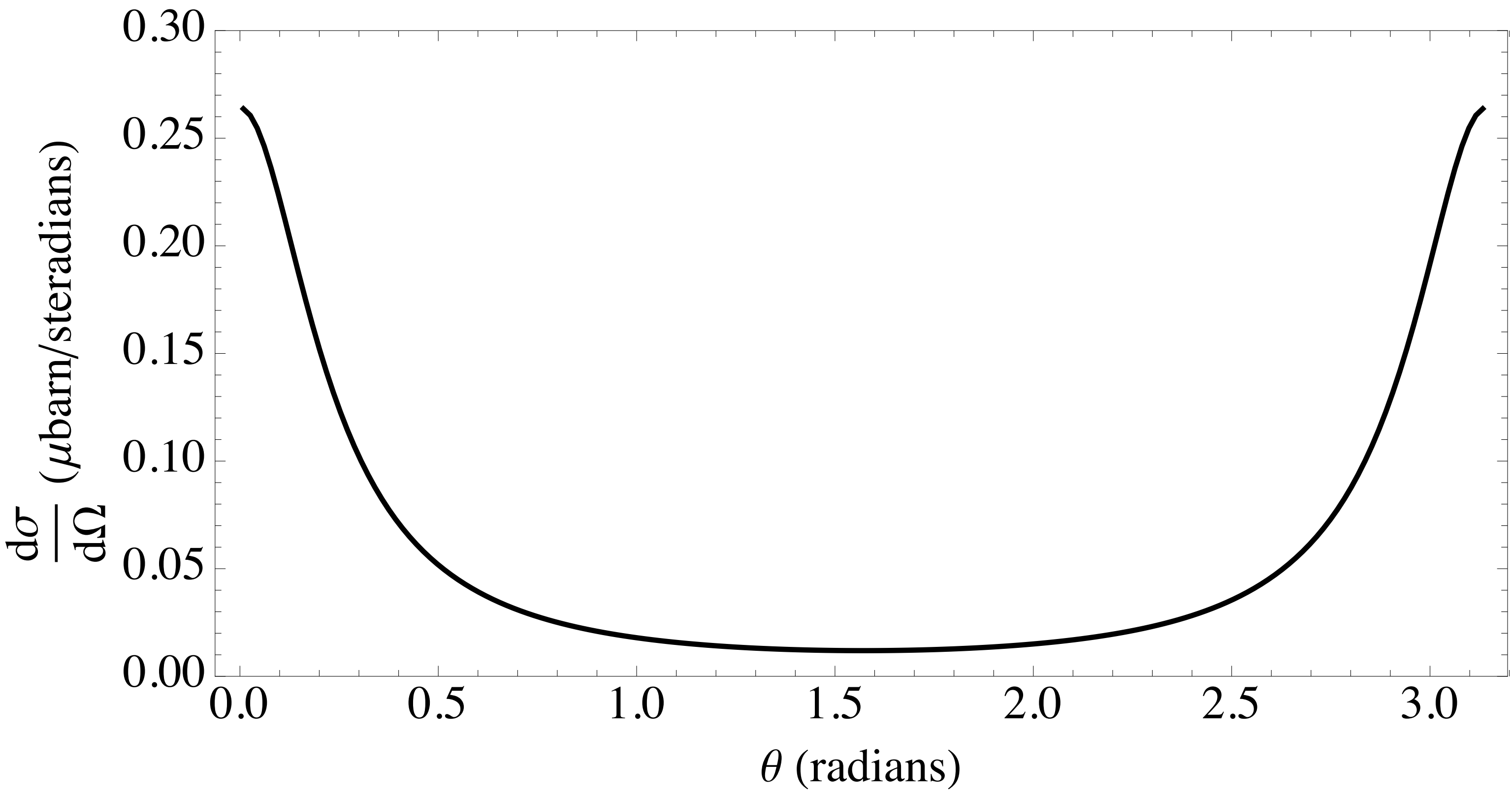


Differential cross-section at ECM = 1.6 MeV (peak)



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

Differential cross-section at ECM = 10 MeV



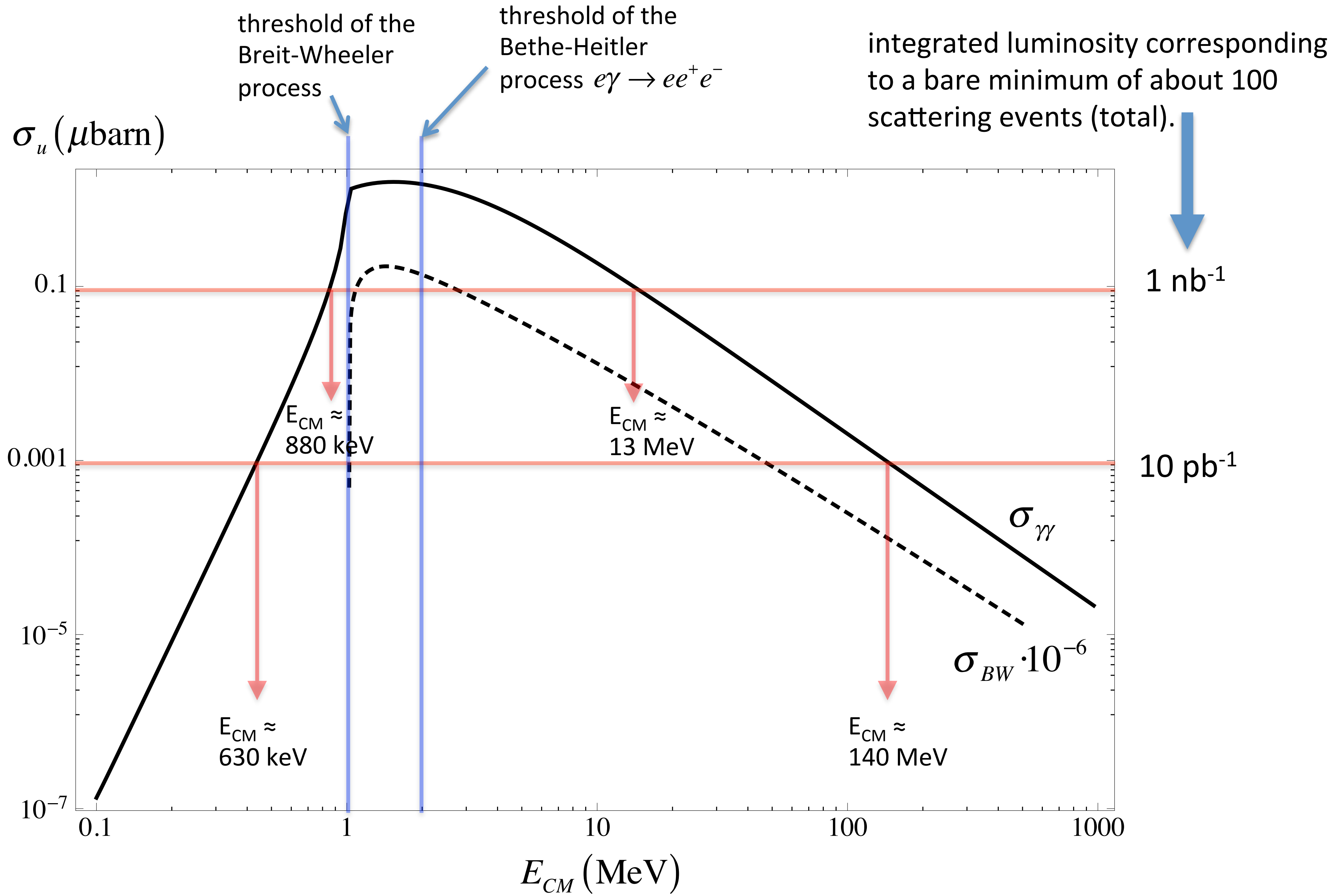
$$\left.\frac{d\sigma}{d\Omega}\right|_{\theta=0} \approx \frac{\alpha^2}{\pi^2} r_0^2 \left(\frac{\hbar\omega}{mc^2}\right)^2 \left(\ln\frac{\hbar\omega}{mc^2}\right)^4$$

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

Beam requests:

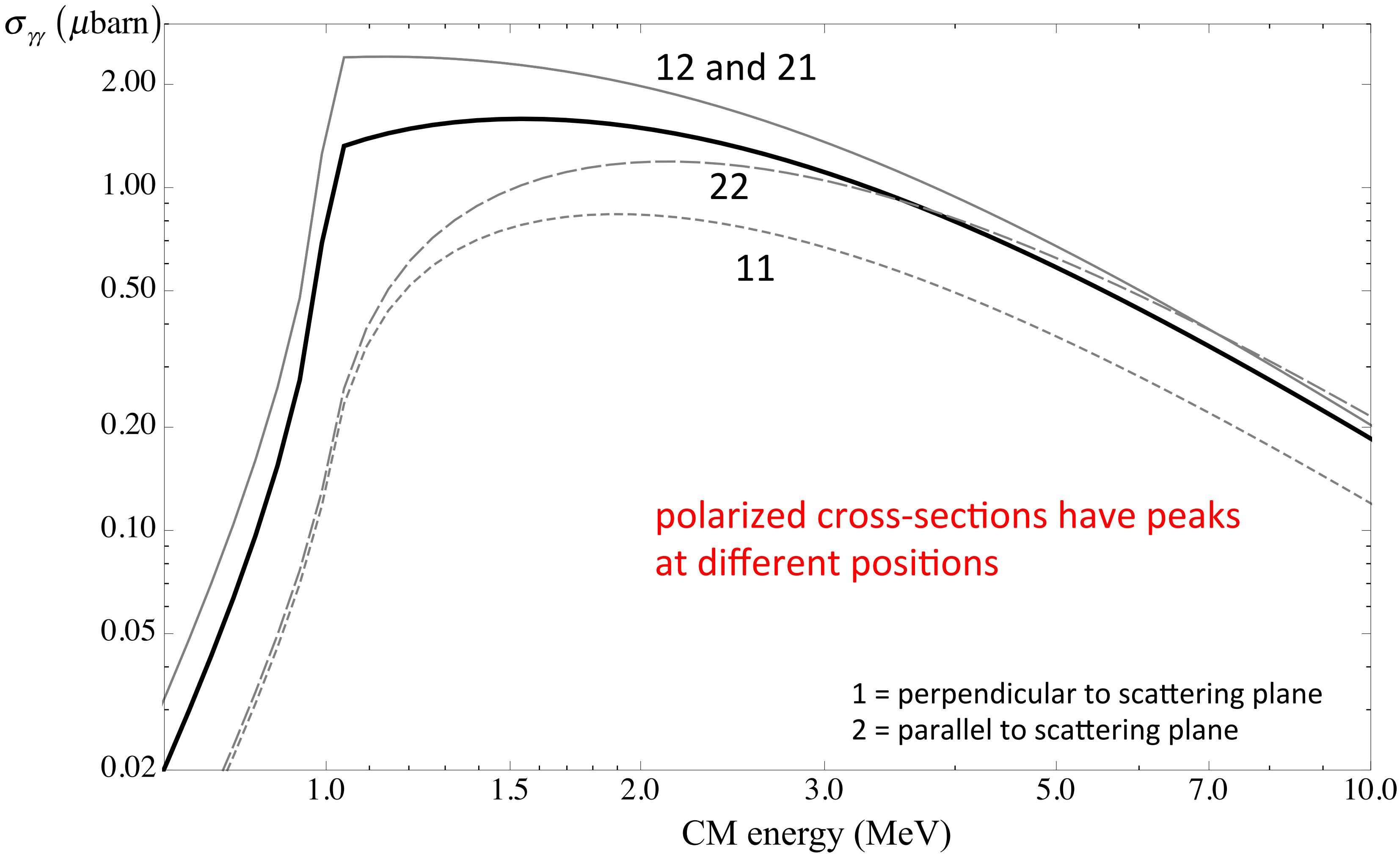
- high gamma-gamma luminosity
- tuneable beam energy (0.7 MeV – 2 MeV)
- polarized photon beams (circular polarization is better, linear polarization OK)
- good beam quality (small energy spread, small collision angle)
- variable beam polarization
- low machine background

"High luminosity"



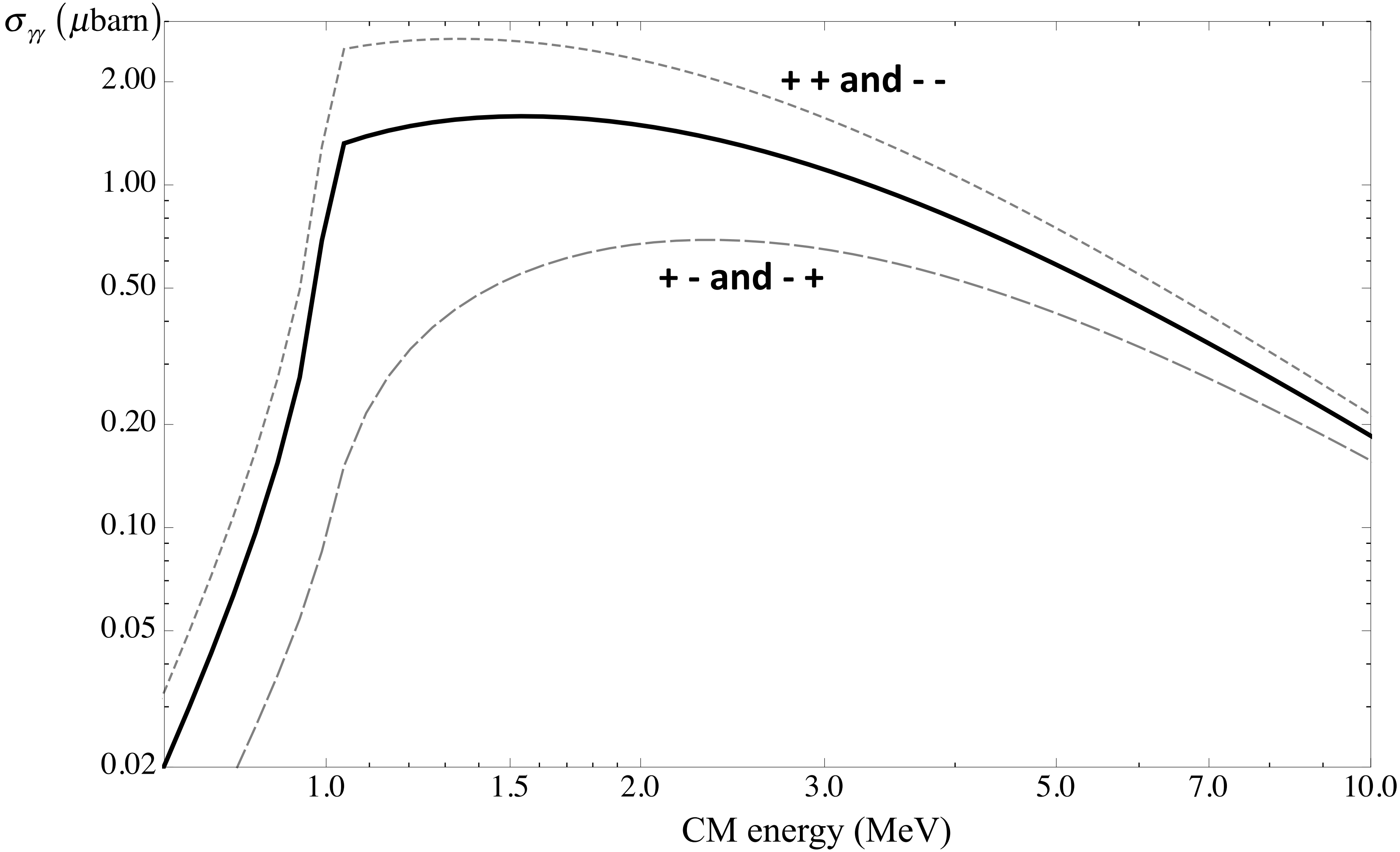
"Tuneable beam energy"

Unpolarized and (linearly) polarized initial photons

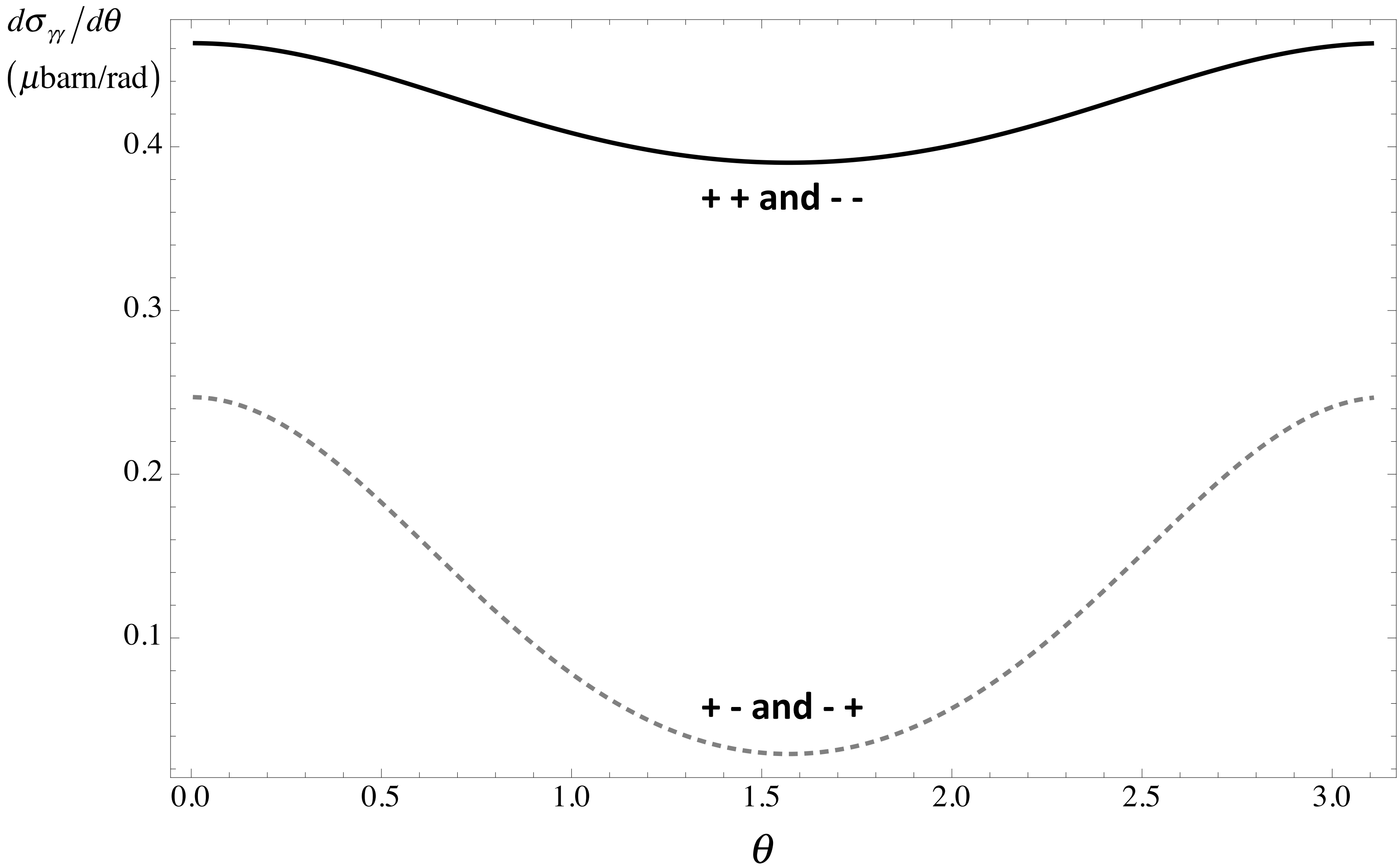


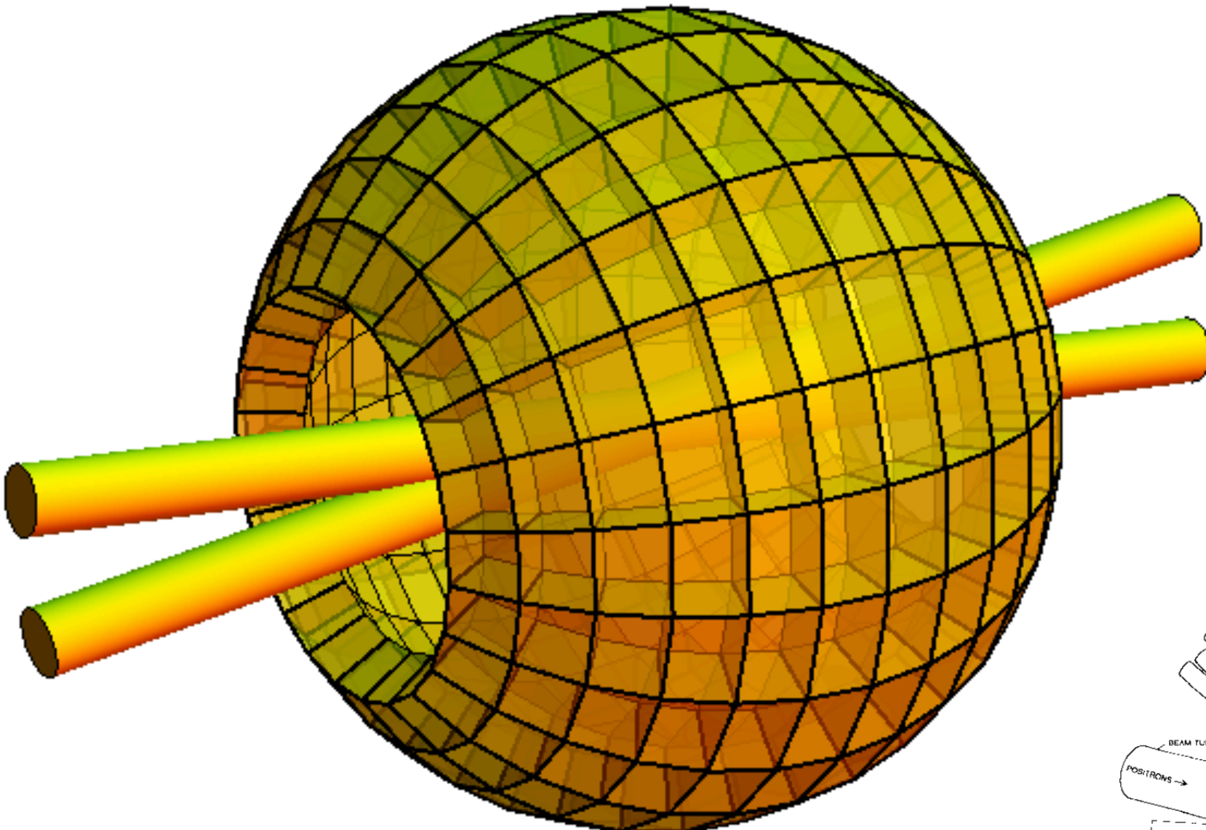
“Polarized photon beams”

Unpolarized and (circularly) polarized initial photons

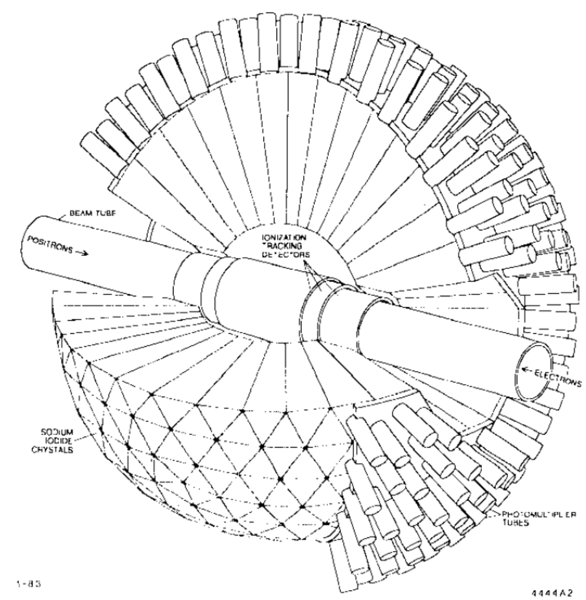


Differential cross-sections for different circular polarizations at 1.6 MeV CM energy





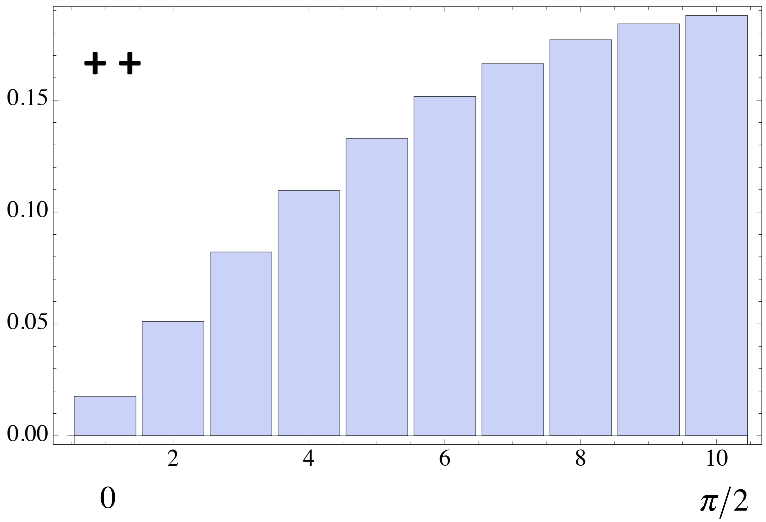
PET-like, segmented detector



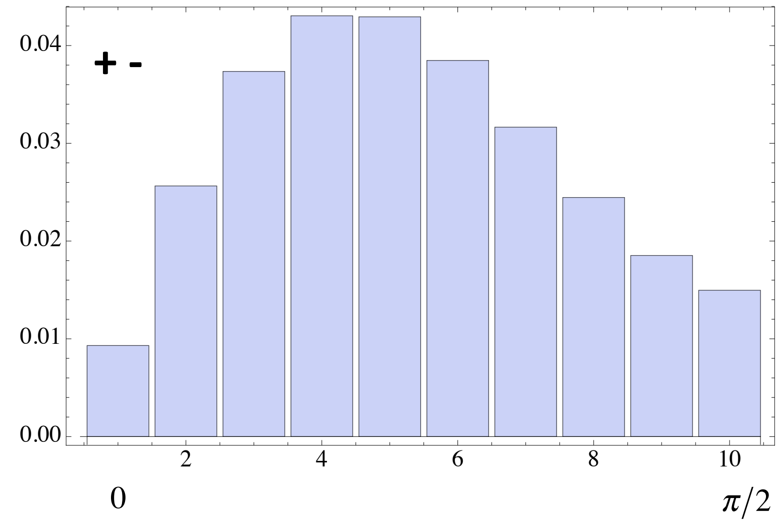
... somewhat similar to Crystal Ball

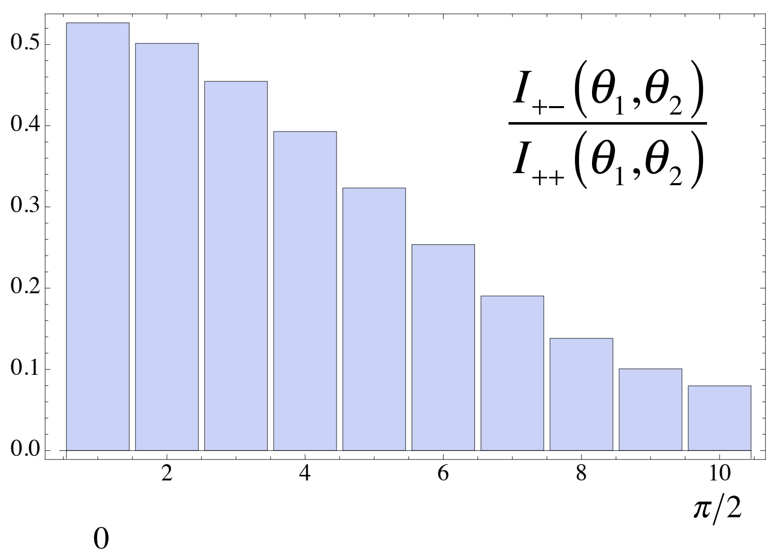
Event rate calculation (at 1.6 MeV CM)

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



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





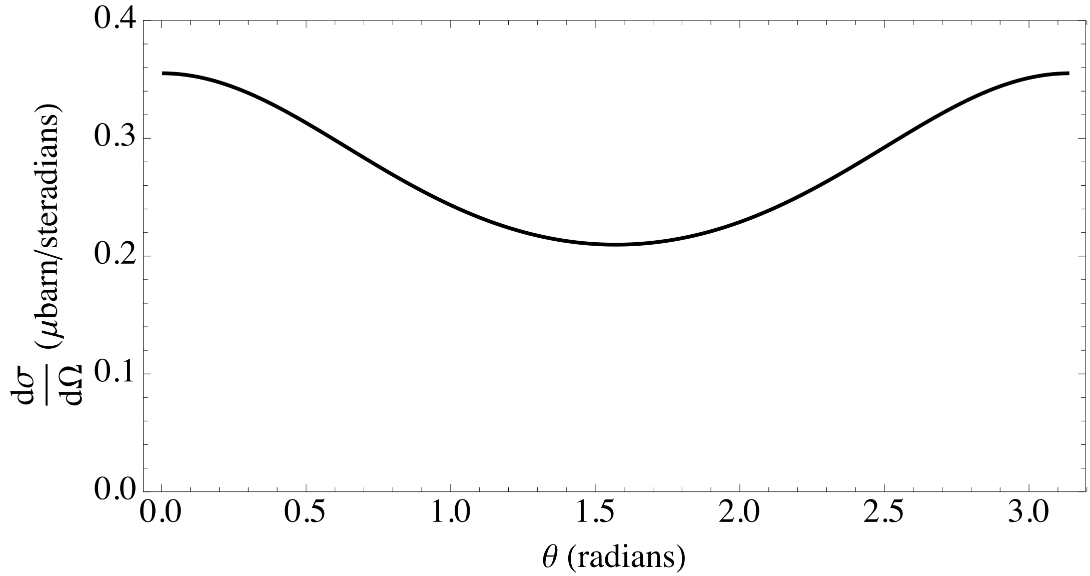
At least 13 events in the last bin for I_{+-}

(cross-section ≈ 0.015 μbarn)

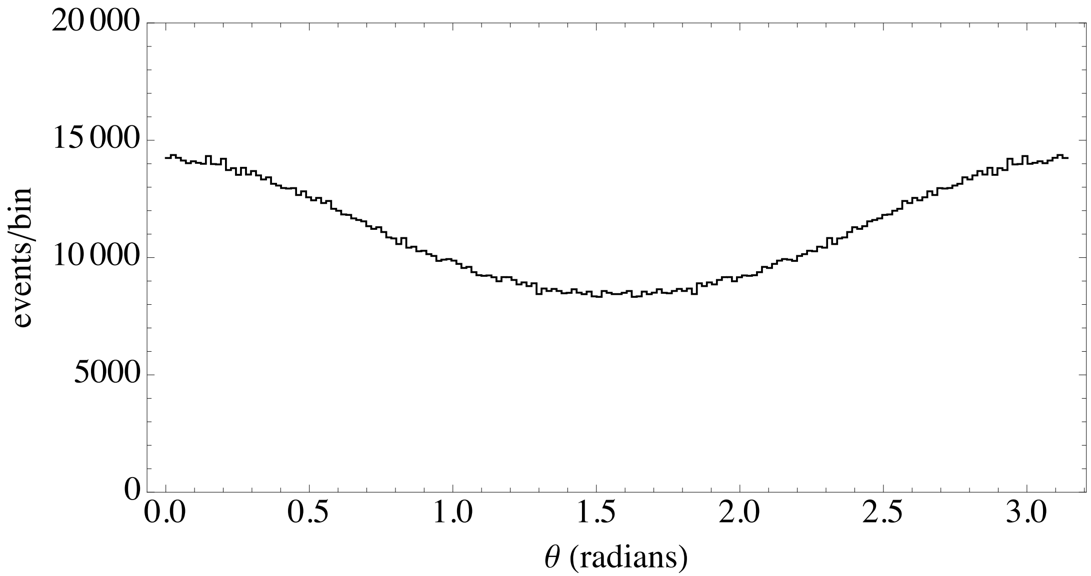
THEN, Luminosity must be

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

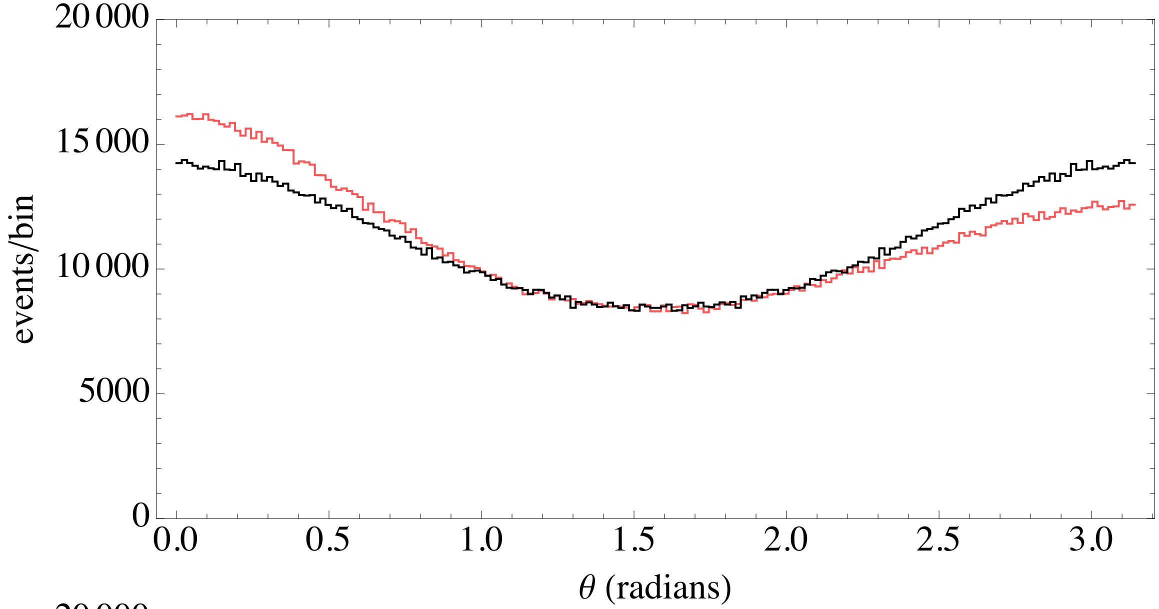
"Good beam quality"



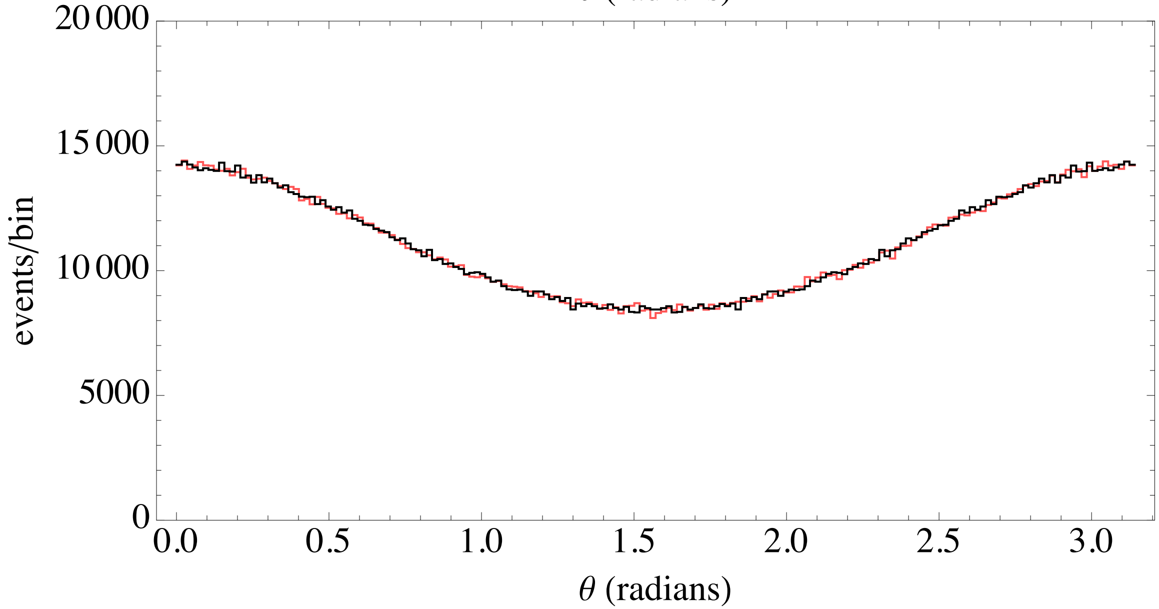
"exact" differential cross-section



MC simulation

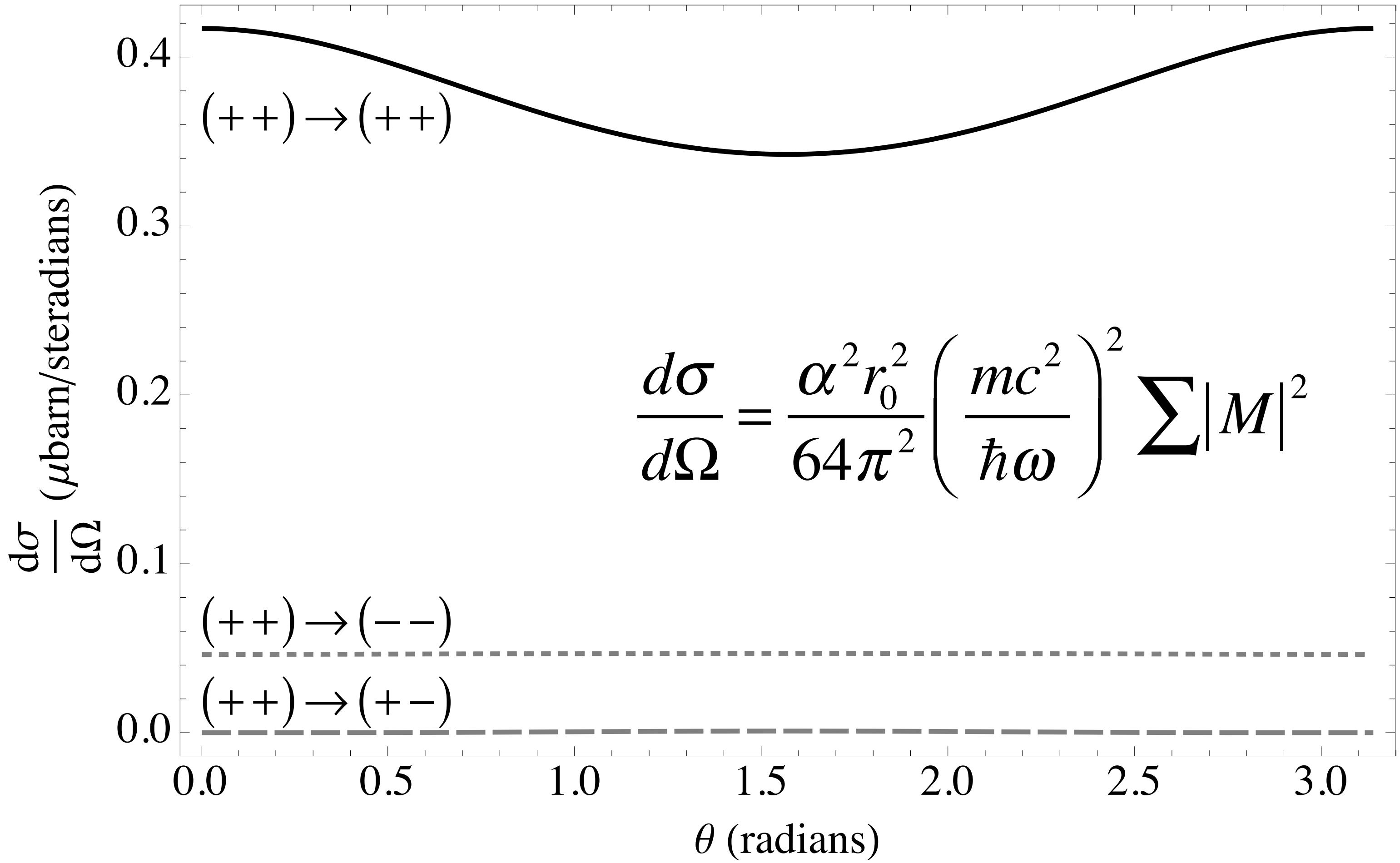


MC simulation, systematic energy imbalance (E_1 = 0.9 MeV; E_2 = 0.7 MeV) and small energy spread (uniform, ±1%)

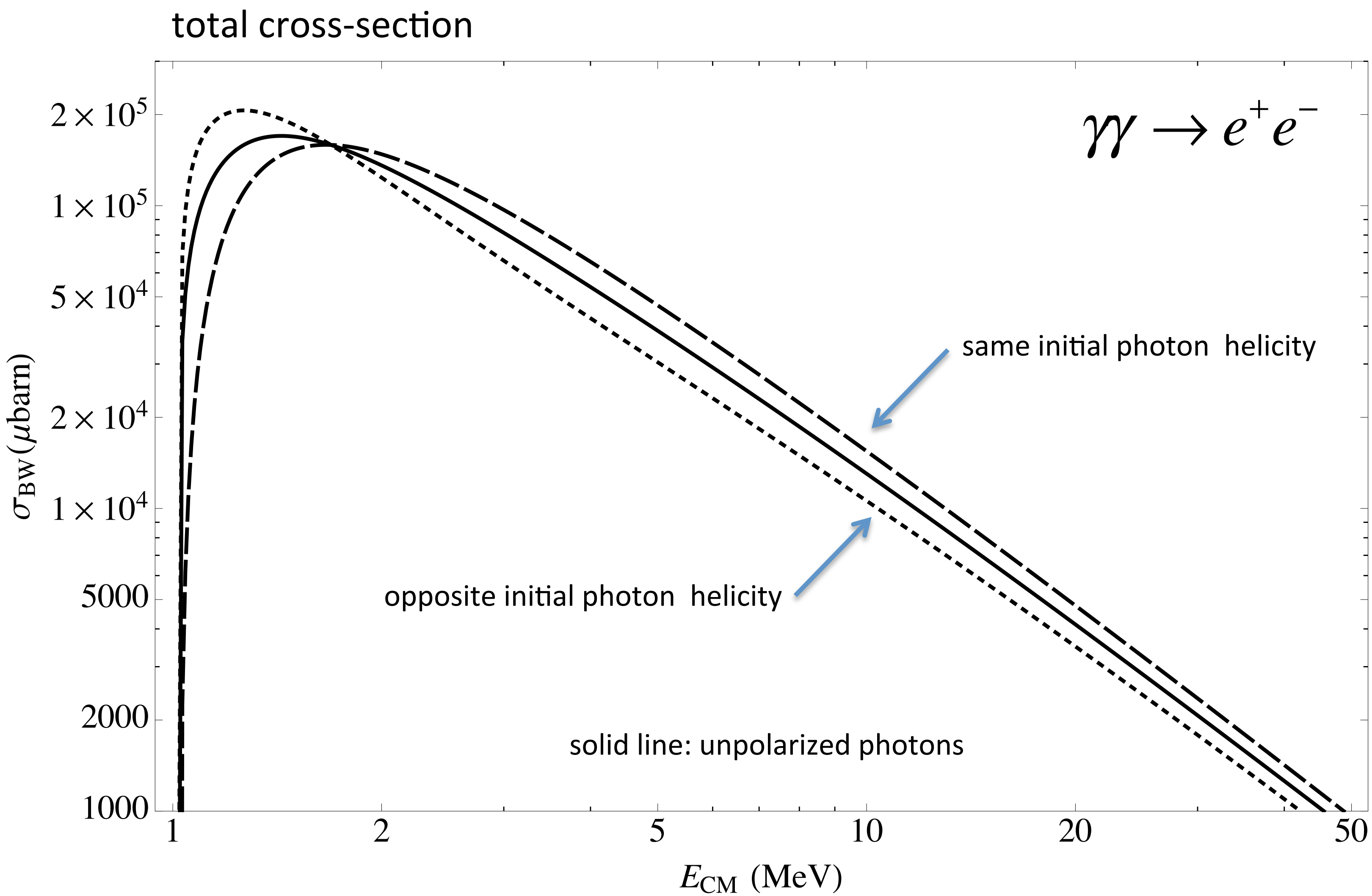


MC simulation, no systematic imbalance and larger energy spread (uniform, ±10%)

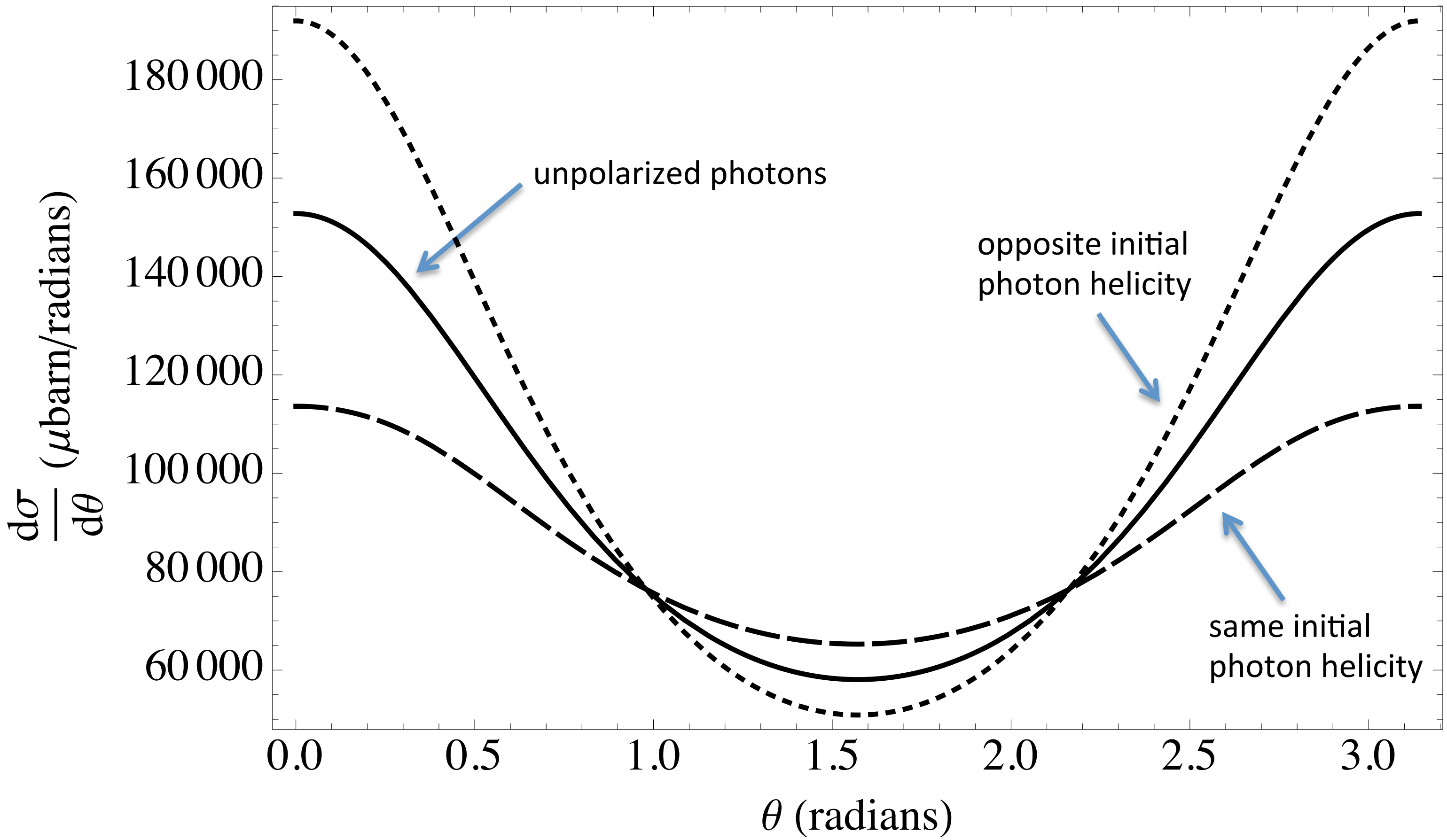
“Variable beam polarization”



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



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



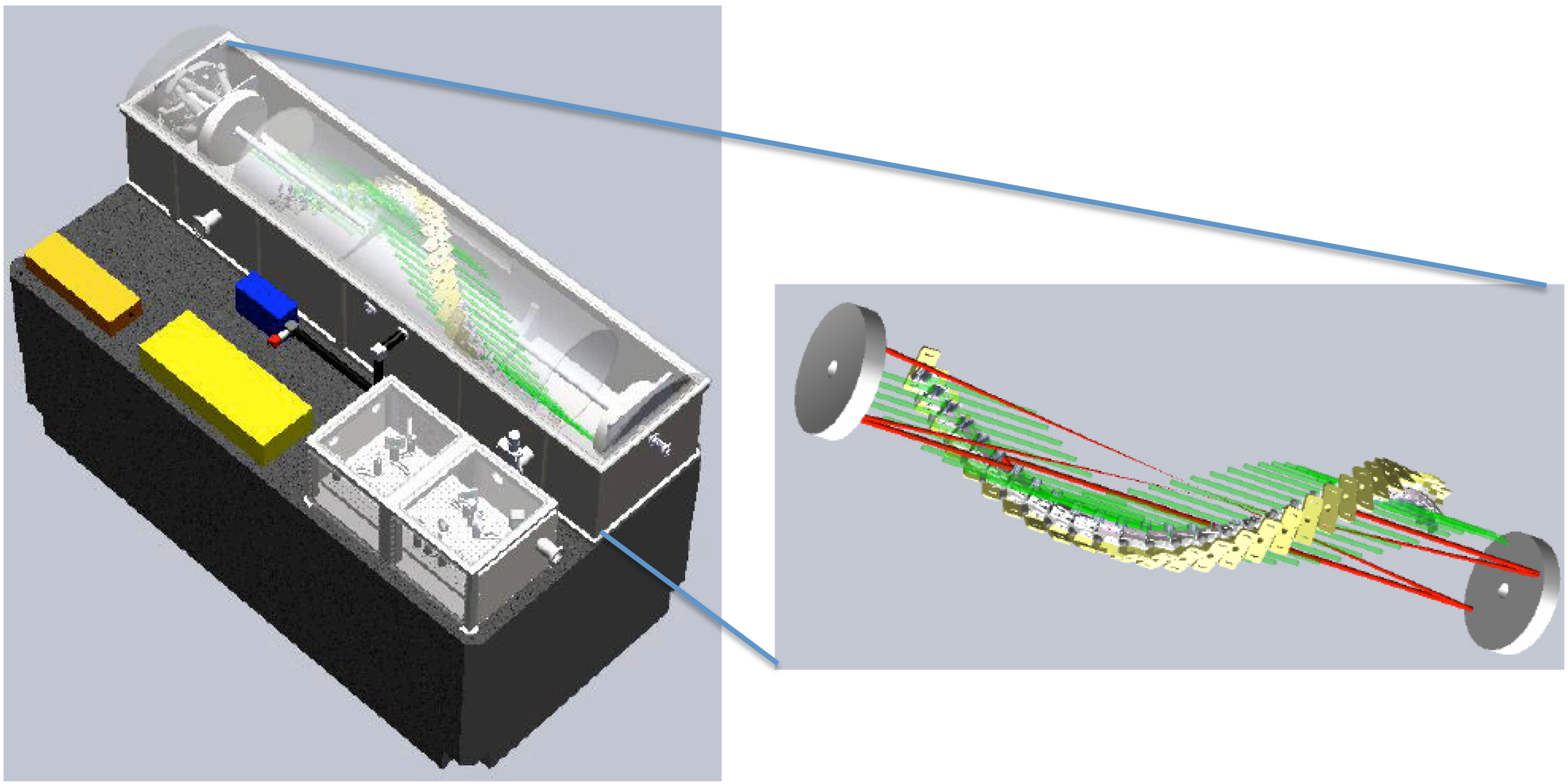
E_γ (MeV)	0°-10°	10°-20°	20°-30°	30°-40°	40°-50°	50°-60°	60°-70°	70°-80°	80°-90°
0.55	7.963	23.59	38.32	51.60	62.96	72.09	78.89	83.35	85.55
0.60	12.63	37.12	59.35	78.09	92.64	103.0	109.8	113.7	115.5
0.65	16.10	46.82	73.31	93.69	107.5	115.8	120.0	121.8	122.3
0.70	18.84	54.09	82.69	102.4	113.7	118.7	119.9	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.

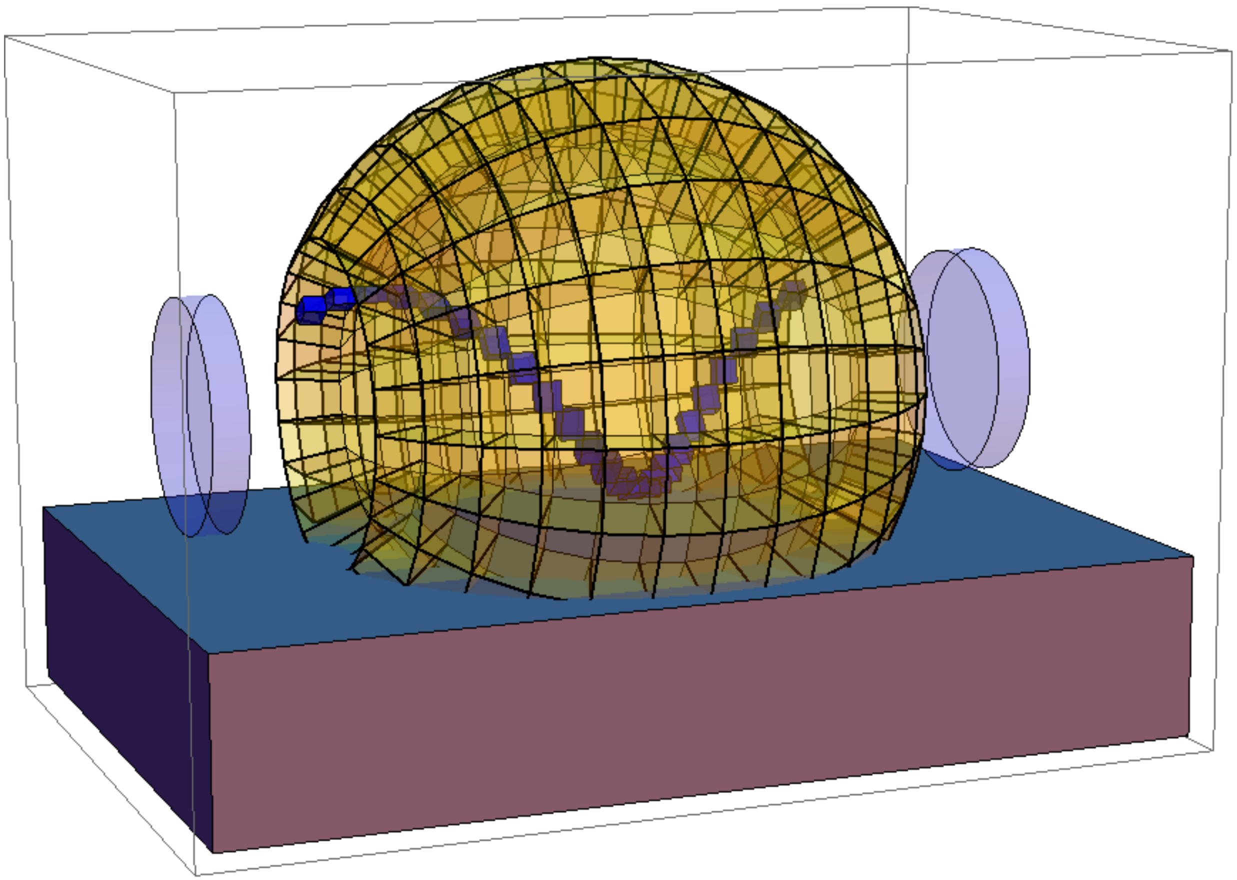
Challenging experimental set-up

Given the existing machine constraints, it seems that a sufficient luminosity can only be reached with an optical recirculator, as in ELI



Schematic view of the re-circulator mounted on a thermal controlled table. The small box contains the laser beam injection control and the synchronization system.

Possible layout of the detector on the optical table that supports the laser recirculator



- mirror-mirror distance ≈ 2.40 m
- 24 recirc. mirrors, 7 cm long
- inner ball radius ≈ 0.8 m
- outer ball radius ≈ 1 m

Several choices for the detector tecnology.

We need
- e/gamma discrimination
- good angular resolution
- good photon energy resolution

Moreover
- decide detector technology
- set up MC simulation
- optimize detector size and positioning

... 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. ...