BINP - IHEP Seminar 2019

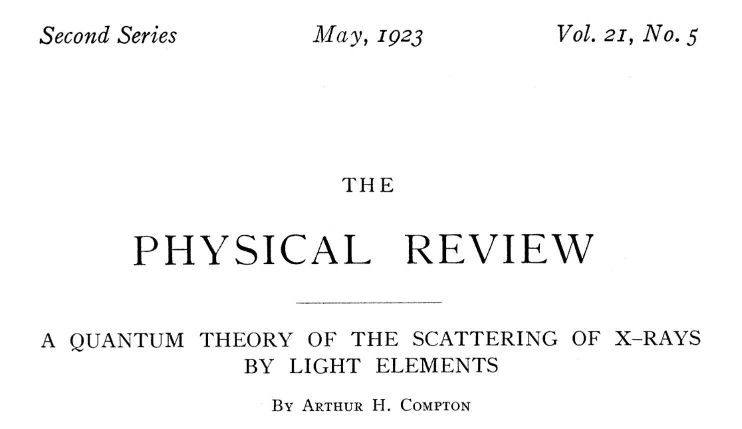
Inverse Compton Scattering at Budker INP: experiments & prospects

Nickolai Muchnoi

Budker INP SB RAS

December 27, 2019. Novosibirsk, Russian Federation.

Compton Effect

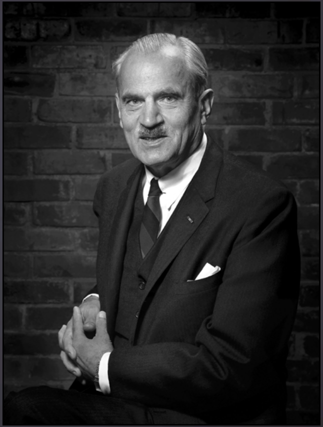

Second Series *May, 1923* *Vol. 21, No. 5*

THE

PHYSICAL REVIEW

A QUANTUM THEORY OF THE SCATTERING OF X-RAYS BY LIGHT ELEMENTS

By Arthur H. Compton

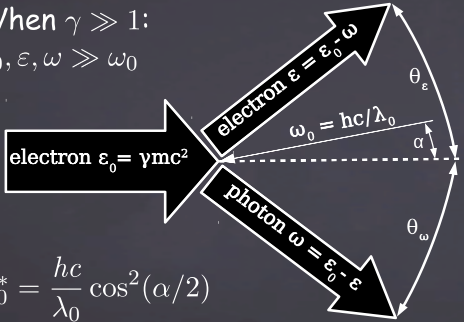


$\lambda_\theta - \lambda_0 = \lambda_c(1 - \cos\theta)$. Compton wavelength $\lambda_c = \frac{h}{mc} = 1.43 \cdot 10^{-12}$ m

Compton Effect

When $\gamma \gg 1$:

$\varepsilon_0, \varepsilon, \omega \gg \omega_0$



$$\omega_0^* = \frac{hc}{\lambda_0} \cos^2(\alpha/2)$$

Universal scattering parameter:

$$u = \frac{\omega}{\varepsilon} = \frac{\theta_\varepsilon}{\theta_\omega} = \frac{\omega}{\varepsilon_0 - \omega} = \frac{\varepsilon_0 - \varepsilon}{\varepsilon}$$

is in the range

$$0 \le u \le \kappa, \text{ where } \kappa = \frac{4\omega_0^* \varepsilon_0}{(mc^2)^2}.$$

$\kappa \simeq 1.53$ for $\varepsilon_0 = 100$ GeV and $\omega_0^* = 1$ eV

Scattering energies:

$$\max(\omega) = \kappa \cdot \varepsilon_0/(1+\kappa)$$
$$\min(\varepsilon) = \varepsilon_0/(1+\kappa)$$

Scattering angles:

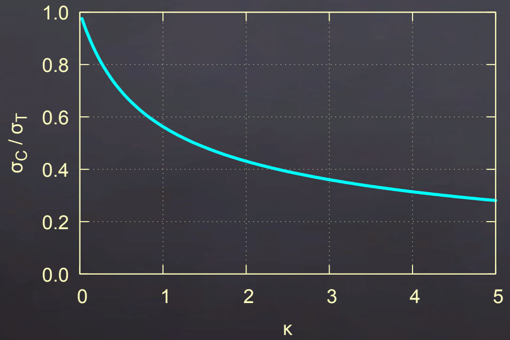
$$\theta_\omega = \frac{1}{\gamma}\sqrt{\frac{\kappa}{u} - 1}; \quad \theta_\varepsilon = \frac{u}{\gamma}\sqrt{\frac{\kappa}{u} - 1}.$$

$\max(\theta_\varepsilon) = 2\omega_0^*/mc^2$ ($\simeq 10$ urad for green light).

Scattering Cross Section

$$\sigma_C = \frac{2\pi r_e^2}{\kappa}\left(\left[1 - \frac{4}{\kappa} - \frac{8}{\kappa^2}\right]\log(1+\kappa) + \frac{1}{2}\left[1 - \frac{1}{(1+\kappa)^2}\right] + \frac{8}{\kappa}\right) \xrightarrow{\kappa \ll 1} \sigma_T(1-\kappa),$$

where $\sigma_T = \frac{8}{3}\pi r_e^2 = 0.665 \cdot 10^{-24}$ [cm^2] is the Thomson cross section.



Über die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac.

Von **O. Klein** und **Y. Nishina** in Kopenhagen.

(Eingegangen am 30. Oktober 1928.)

Auf Grund der neuen, von Dirac entwickelten relativistischen Quantendynamik wird die Intensität der Comptonstreustrahlung berechnet. Das Resultat zeigt Abweichungen von den entsprechenden Dirac-Gordonschen Formeln, die von der zweiten Größenordnung hinsichtlich des Verhältnisses der Energie des primären Lichtquants zu der Ruheenergie des Elektrons sind.

Soon After the Invention of Lasers

PHYSICAL REVIEW LETTERS

VOLUME 10 — 1 FEBRUARY 1963 — NUMBER 3

ELECTRON SCATTERING BY AN INTENSE POLARIZED PHOTON FIELD*

Richard H. Milburn
Department of Physics, Tufts University, Medford, Massachusetts
(Received 26 December 1962)

SOVIET PHYSICS JETP — VOLUME 17, NUMBER 6 — DECEMBER, 1963

THE COMPTON EFFECT ON RELATIVISTIC ELECTRONS AND THE POSSIBILITY OF PRODUCING BEAMS OF HARD γ RAYS

F. R. ARUTYUNYAN and V. A. TUMANYAN
Physics Institute of the Georgian Atomic Energy Commission, Erevan
Submitted to JETP editor January 22, 1963
J. Exptl. Theoret. Phys. (U.S.S.R.) **44**, 2100-2103 (June, 1963)

After Another 6-7 Years

VOLUME 23, NUMBER 9 PHYSICAL REVIEW LETTERS 1 SEPTEMBER 1969

TOTAL AND PARTIAL PHOTOPRODUCTION CROSS SECTIONS AT 1.44, 2.8, AND 4.7 GeV [*]

J. Ballam, G. B. Chadwick, R. Gearhart, Z. G. T Guiragossián, P. R. Klein,
A. Levy,[†] M. Menke, J. J. Murray, P. Seyboth,[‡] and G. Wolf[§]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

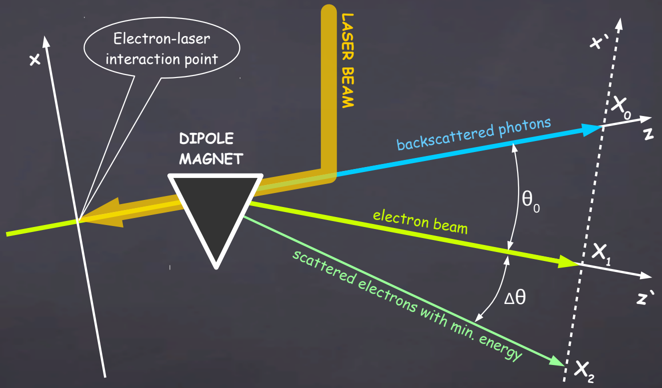
C. K. Sinclair
Tufts University, Medford, Massachusetts

and

H. H. Bingham, W. B. Fretter, K. C. Moffeit, W. J. Podolsky, M. S. Rabin,
A. H. Rosenfeld, and R. Windmolders[‖]
Department of Physics and Lawrence Radiation Laboratory, University of California, Berkeley, California 94720
(Received 27 June 1969)

A nearly monochromatic high-energy photon beam produced by Compton backscattering of ruby laser light has been used to study photoproduction in a hydrogen bubble chamber. The total hadronic γp cross sections at 1.44, 2.8, and 4.7 GeV are found to be 145.1 ± 5.7, 131.3 ± 4.3, and 124.2 ± 3.9 μb, respectively. Partial cross sections are presented also.

Conventional Setup



Laser Beam Propagation

Light intensity in the focused laser beam:

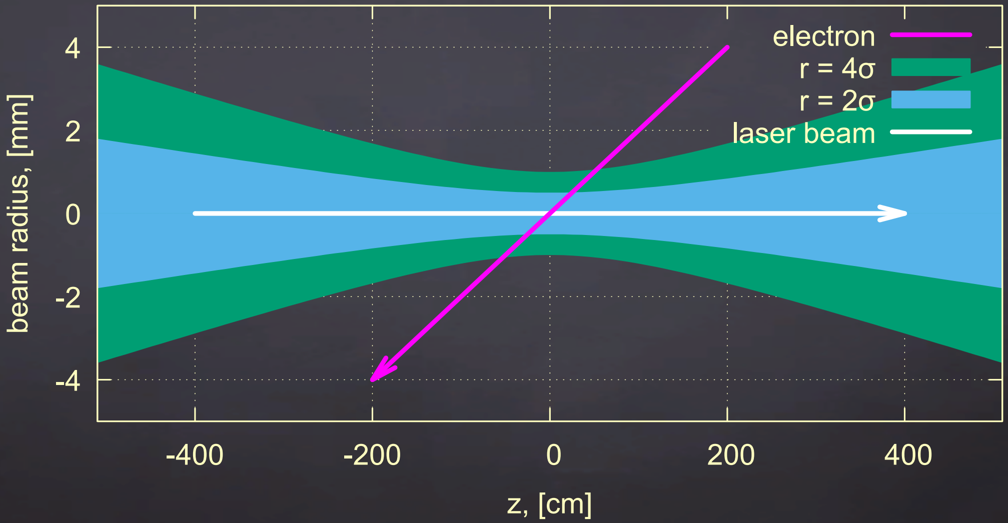
$$I(r, z) = \frac{P}{2\pi\sigma(z)^2} \exp\left(-\frac{r^2}{2\sigma(z)^2}\right) \left[\mathrm{W/cm^2}\right], \text{ where}$$

- z - beam axis, r - distance from beam axis, P [W] - radiation power,
- $\sigma(z) = \sigma_0\sqrt{1 + (z/z_R)^2}$ - beam radius at the intensity level of $1/e$,
- σ_0 - beam radius at the waist ($z = 0$),
- $z_R = 4\pi\sigma_0^2/\lambda$ - Rayleigh length, $I_0(z_R) = I_0(0)/2$.

Radiation power: $P \equiv \frac{dE}{dt} = h\nu\frac{dN}{dt}$ that makes $\rho_\parallel \equiv \frac{dN}{dz} = \frac{P\lambda}{hc^2}$ $\left[\mathrm{cm}^{-1}\right]$.

Laser Beam Propagation

$\lambda = 0.532$ µm, $\sigma_0 = 250.0$ µm, $Z_R = 147.6$ cm, $\theta = 0.34$ mrad, $\alpha = 2.0$ mrad



Scattering Probability

Consider an electron ($v/c \simeq 1$) moving on axis towards the laser beam ($\alpha = 0$). The photon target density is:

$$\rho_\perp = \frac{\rho_\parallel}{\pi\sigma_0^2}\int_{-\infty}^{\infty}\frac{dz}{1+(z/z_R)^2} = \frac{4P}{hc^2}\int_{-\infty}^{\infty}\frac{dx}{1+x^2} = \frac{2P}{\hbar c^2}\ [\text{cm}^{-2}]\,.$$

The probability of Thomson scattering for the electron

$$W = \rho_\perp\sigma_T = \frac{P}{P_c},\ \text{where } P_c = \frac{\hbar c^2}{2\sigma_T} \simeq 0.7\cdot 10^{11}\ [\text{W}]$$

does not depend on the laser wavelength λ nor the waist size σ_0.

Electron beam current of 1 mA ($1.6\cdot 10^{16}$ [electrons/s]) and 1 W of laser power can provide the flux of $\simeq 2\cdot 10^5$ backscattered photons/s.

CERN Courier Volume 39 No.6, 1999

"The Graal of Particle Physics" (p.24)

Physics with photon beams

Project name	Ladon *	Taladon†	ROKK-1‡	ROKK-2	ROKK-1M	LEGS§	Graal‖	LEPS¶
Location	Frascati		Novosibirsk			Brookhaven	Grenoble	Harima
Storage ring	Adone	Adone	VEPP-4	VEPP-3	VEPP-4M	NSLS	ESRF	SPring-8
Energy defining method	collimation	internal tagging	tagging	tagging	tagging	external tagging	internal tagging	internal tagging
Electron energy (GeV)	1.5	1.5	1.8–5.5	0.35–2.0	1.4–5.3	2.5	6.04	8
Photon energy (eV)	2.45	2.45	2.34–2.41	2.41–2.53	1.17–3.51	3.53	3.53	3.5
Gamma-ray energy (MeV)	5–80	35–80 variable	100–960 simultaneous	140–220	100–1200	180–320	550–1470	500–2400
Energy resolution (%)	1.4–10	5	–	1.5	–	2	1.1	1.25
FWHM (MeV)	0.07–8	4–2	1.5–2	4	–	6	16	30
Electron current (A)	0.1	0.1	0.2	0.2	0.1	0.2	0.2	0.1
Gamma intensity (s^{-1})	10^5	5×10^5	2×10^5	2×10^6	2×10^6	4×10^6	2×10^6	107
Date of operation	1978	1989	1982	1987	1993	1987	1996	1999

The ROKK-xx facilities were created in Novosibirsk by G. Ya. Kezerashvili.

Common feature of installations – non-specialized storage rings & lasers.

LbyL scattering evidence (13 events)

ARTICLES

PUBLISHED ONLINE: 14 AUGUST 2017 | DOI: 10.1038/NPHYS4208

nature physics

OPEN

Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

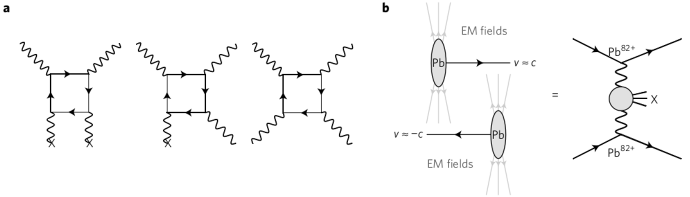


Figure 1 | Diagrams illustrating the QED LbyL interaction processes and the equivalent photon approximation. a, Diagrams for Delbrück scattering (left), photon splitting (middle) and elastic LbyL scattering (right). Each cross denotes external field legs, for example, an atomic Coulomb field or a strong background magnetic field. **b**, Illustration of an ultra-peripheral collision of two lead ions. Electromagnetic interaction between the ions can be described as an exchange of photons that can couple to form a given final state X. The flux of photons is determined from the Fourier transform of the electromagnetic field of the ion, taking into account the nuclear electromagnetic form factors.

Non-linear QED studies at ROKK-1M

VOLUME 89, NUMBER 6 PHYSICAL REVIEW LETTERS 5 AUGUST 2002

Experimental Investigation of High-Energy Photon Splitting in Atomic Fields

Sh. Zh. Akhmadaliev, G. Ya. Kezerashvili, S. G. Klimenko, R. N. Lee, V. M. Malyshev, A. L. Maslennikov, A. M. Milov, A. I. Milstein, N. Yu. Muchnoi, A. I. Naumenkov, V. S. Panin, S. V. Peleganchuk, G. E. Pospelov, I. Ya. Protopopov, L. V. Romanov, A. G. Shamov, D. N. Shatilov, E. A. Simonov, V. M. Strakhovenko, and Yu. A. Tikhonov

Budker Institute of Nuclear Physics, Novosibirsk, 630090, Russia

(Received 18 February 2002; published 19 July 2002)

Data analysis of an experiment in which photon splitting in atomic fields was observed is presented. The experiment was performed at the tagged photon beam of the ROKK-1M facility at the VEPP-4M collider. In the energy region of 120–450 MeV, statistics of 1.6×10^9 photons incident on the BGO target was collected. About 400 candidate photon-splitting events were reconstructed. Within the attained experimental accuracy, the experimental results are consistent with the calculated exact atomic-field cross section. The predictions obtained in the Born approximation differ significantly from the experimental results.

PHYSICAL REVIEW C VOLUME 58, NUMBER 5 NOVEMBER 1998

Delbrück scattering at energies of 140–450 MeV

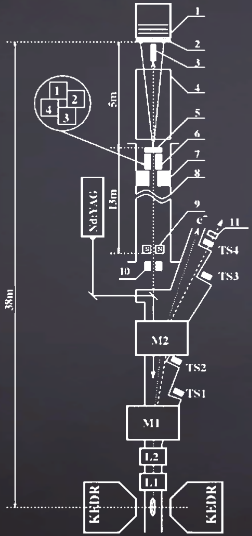
Sh. Zh. Akhmadaliev, G. Ya. Kezerashvili, S. G. Klimenko, V. M. Malyshev, A. L. Maslennikov, A. M. Milov, A. I. Milstein, N. Yu. Muchnoi, A. I. Naumenkov, V. S. Panin, S. V. Peleganchuk, V. G. Popov, G. E. Pospelov, I. Ya. Protopopov, L. V. Romanov, A. G. Shamov, D. N. Shatilov, E. A. Simonov, and Yu. A. Tikhonov

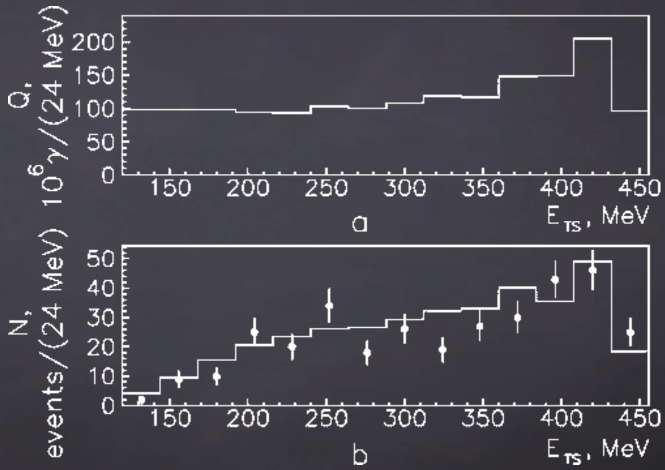
Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

(Received 29 June 1998)

The differential cross section of Delbrück scattering is measured on a bismuth germanate ($Bi_4Ge_3O_{12}$) target at photon energies 140–450 MeV and scattering angles 2.6–16.6 mrad. A good agreement with the theoretical results, obtained exactly in a Coulomb field, is found. [S0556-2813(98)02411-X]

Photon Splitting

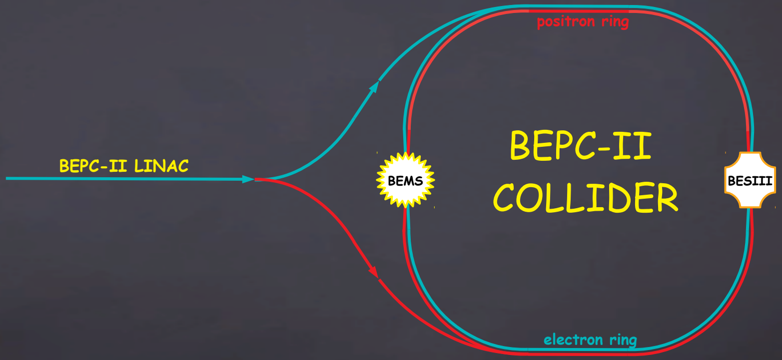




In total 418 ± 20 photon splitting events observed.

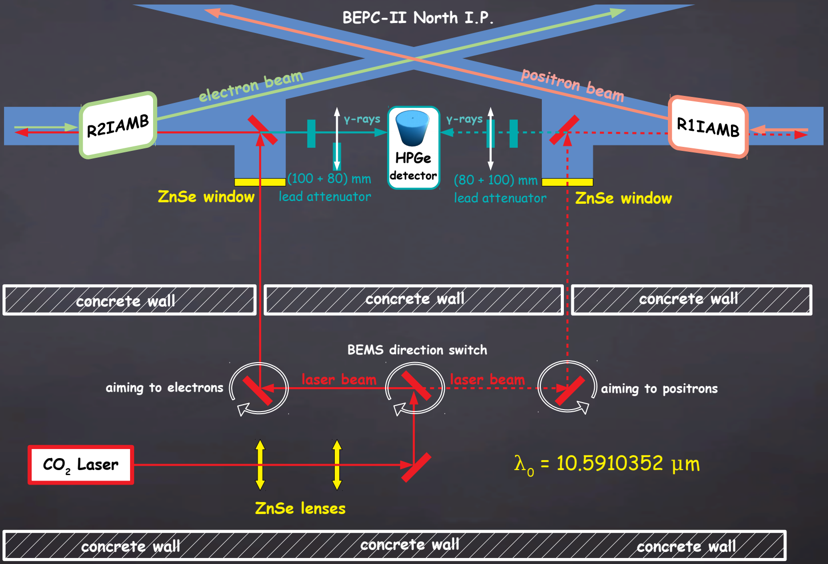
$e^{\pm}$ Beam Energy Measurement

VEPP-4M (2005-2011) ∘ BEPC-II (2010-now) ∘ VEPP-2000 (2012-now)



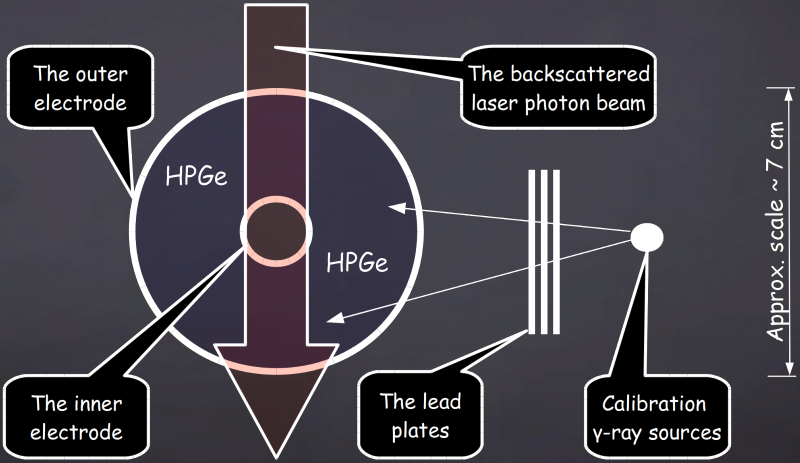
- SR losses: $E_{\text{ip}} = E_{\text{BEMS}} + 4.75 \cdot 10^{-6} \left(E_{\text{BEMS}}\right)^4$ [GeV]
- IP angle: $E_{\text{cm}} = 2\cos(0.011)\sqrt{E_{\text{ip}}^{e^+}\ E_{\text{ip}}^{e^-}}$

Beam Energy Measurement System (BEMS)



$\lambda_0 = 10.5910352\ \mu m$

HPGe detector

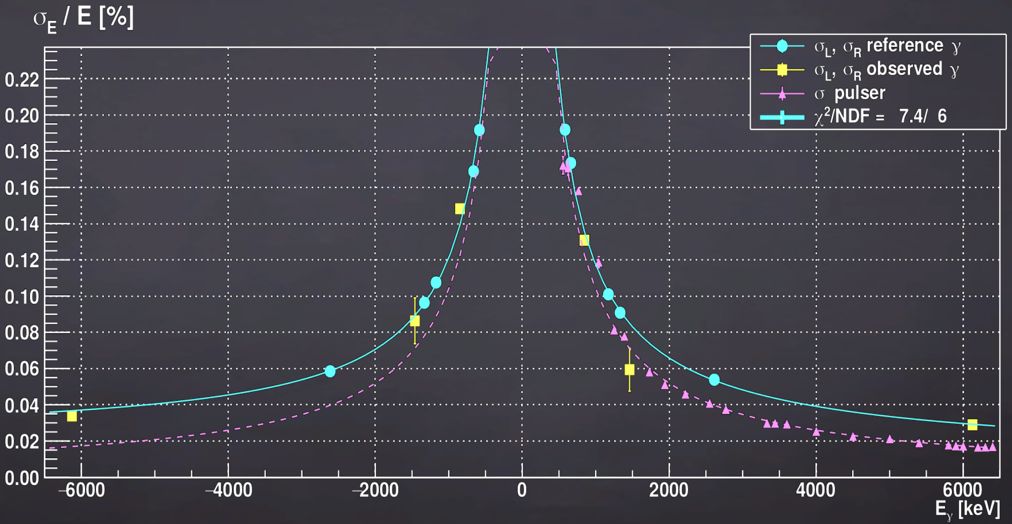


HPGe Scale Calibration

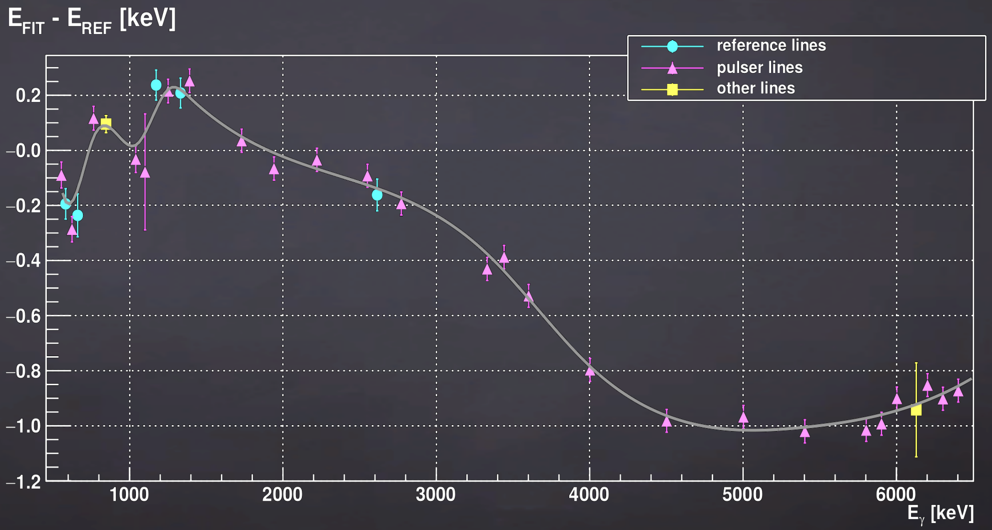
Source	γ-rays energies, keV	Reference *
^{137}Cs	661.657 ± 0.003	vol.4, 2008
^{60}Co	1173.228 ± 0.003 1332.492 ± 0.004	vol.4, 2008
^{228}Ac (^{232}Th)	911.209 ± 0.006	vol.6, 2011
^{212}Bi (^{232}Th)	727.330 ± 0.030 1620.740 ± 0.010	vol.2, 2004
^{208}Tl (^{232}Th)	583.187 ± 0.002 860.560 ± 0.030 2614.511 ± 0.010	vol.2, 2004

* Table of Radionuclides, Bureau International des Poids et Mesures
https://www.bipm.org/en/publications/scientific-output/monographie-ri-5.html

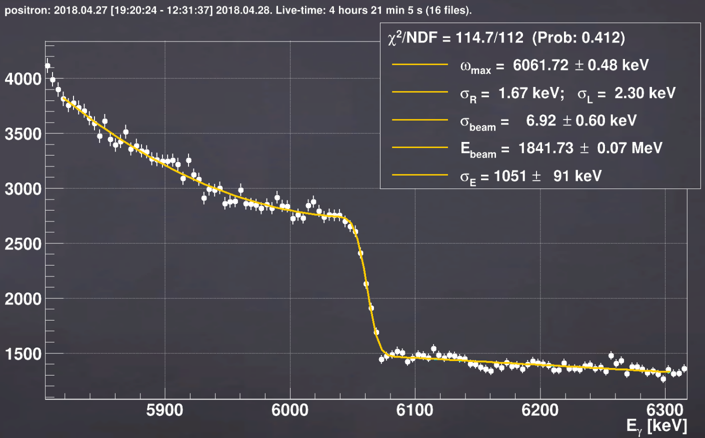
HPGe Energy Resolution



Energy Scale Calibration



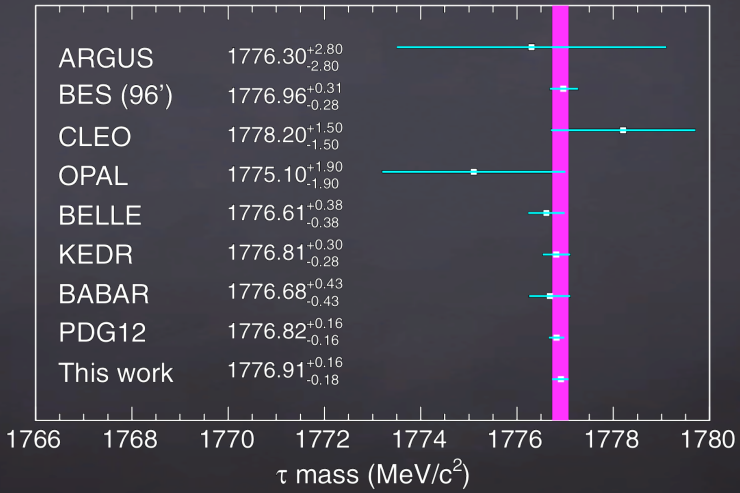
The Edge of the Compton Spectrum



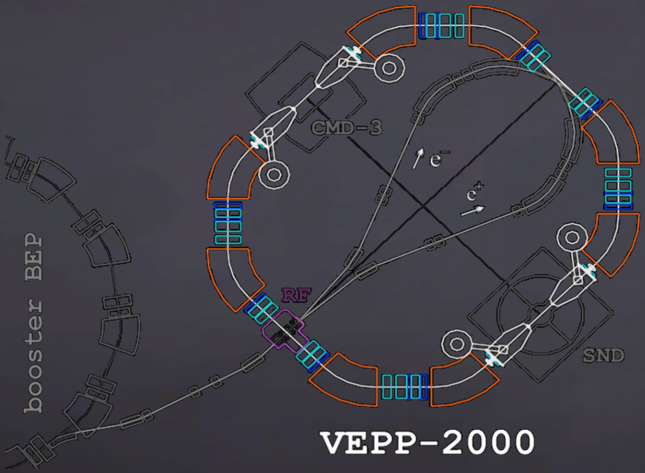
$$E_{\text{beam}} = \frac{\omega_{\text{max}}}{2}\left(1 + \sqrt{1 + \frac{m^2}{\omega_0 \omega_{\text{max}}}}\right) \qquad (\omega_0 = 0.11706523 \text{ eV})$$

PHYSICAL REVIEW D 90, 012001 (2014)

"Precision measurement of the mass of the τ lepton"



VEPP-2000 e^+e^- collider at BINP



Circumference:

$$P = 24.4 \text{ m}$$

C. m. s. energy:

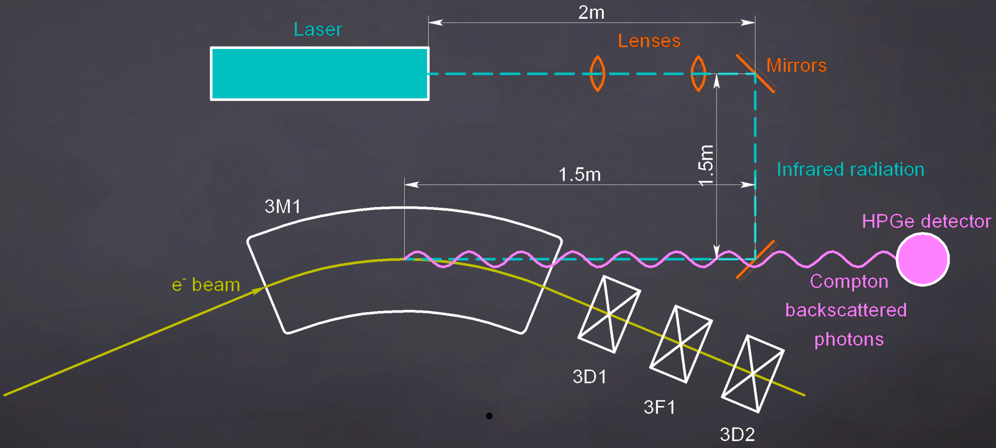
$$E = 200 - 2000 \text{ MeV}$$

Luminosity / i.p.:

$$L = 10^{32} \text{ cm}^{-2}\text{s}^{-1}$$

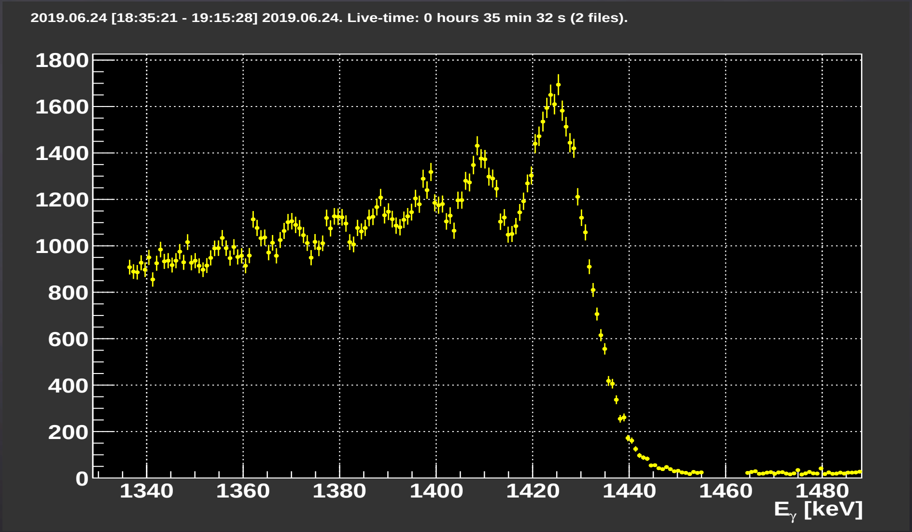
Could not find a free straight section for laser i.p.!

BEMS for VEPP-2000

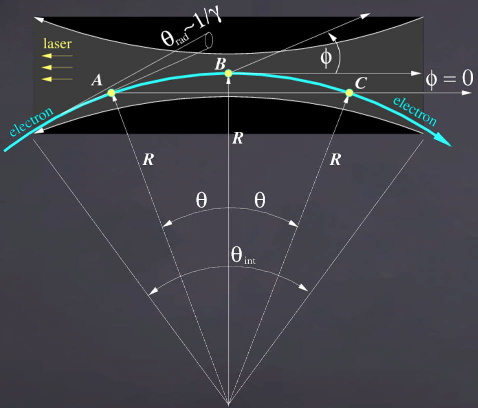


Beam orbit radius in 3M1 dipole: $R = 140$ cm

Spectrum $\varepsilon_0 = 640$ MeV, $\lambda_0 = 5.426463$ um



Interference



$\theta_{int} \gg \theta_{rad}$: take only $\phi = 0$

Time for electron $A \to B \to C$: $t_e = \dfrac{2R\theta}{\beta c}$

Time for photon $A \to C$: $t_\gamma = \dfrac{2R\sin\theta}{c}\cos\psi$

Phase advance: $\Delta\Phi = 2\pi c\left[\dfrac{t_e}{\lambda} - \dfrac{t_\gamma}{\lambda} - \dfrac{2t_e}{\lambda_0}\right]$

λ_0 - laser wavelength. Since $\theta, \psi, 1/\gamma \ll 1$

$$\Delta\Phi \simeq \frac{\omega R}{c}\left[\theta\left(\frac{1}{\gamma^2} - \frac{4\omega_0}{\omega} + \psi^2\right) + \frac{\theta^3}{3}\right].$$

For 1 MeV photon $\lambda = 1.24 \cdot 10^{-12}$ m. For $R = 140$ cm, $E = 1$ GeV,

$\Delta\Phi = 2\pi$ when $\theta \simeq 0.1/\gamma$ and $\overline{AC} \simeq 0.1$ mm $\simeq 10^8\lambda$!

Energy spectrum

$$\frac{d\dot{N}_\gamma}{d\omega\ d\psi} \propto \omega^{1/3}\,\mathrm{Ai}^2(x),$$ where

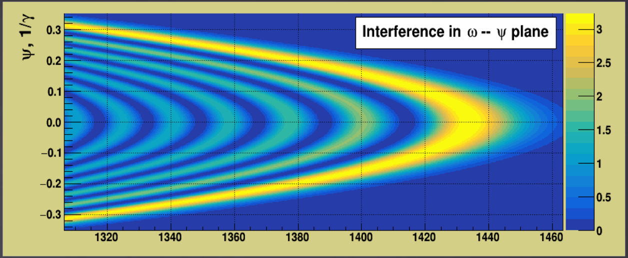
$$x = \left[\frac{\omega R}{2\hbar c}\right]^{2/3}\left[\frac{1}{\gamma^2} - \frac{4\omega_0}{\omega} + \psi^2\right].$$

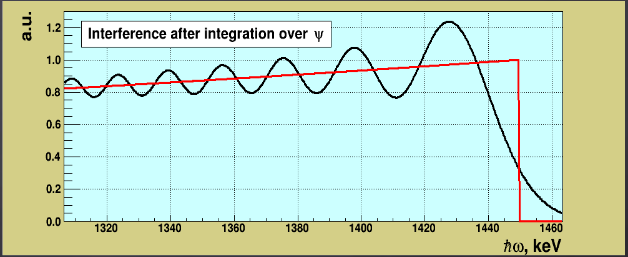
$$\frac{d\sigma}{d\omega} = \frac{d\sigma_{KN}}{d\omega}\int_z^\infty \mathrm{Ai}(x)\,dx,$$ where

$$z = (u/\chi)^{2/3}(1-\kappa/u),$$ where

$$\chi = \gamma\frac{B}{B_c},\ u = \frac{\omega}{\varepsilon_0 - \omega},\ \kappa = 4\frac{\varepsilon_0\omega_0}{m^2c^4}$$

$$B_c = \frac{m^2c^2}{\hbar e} = 4.414\cdot 10^9\ [\mathrm{T}]$$

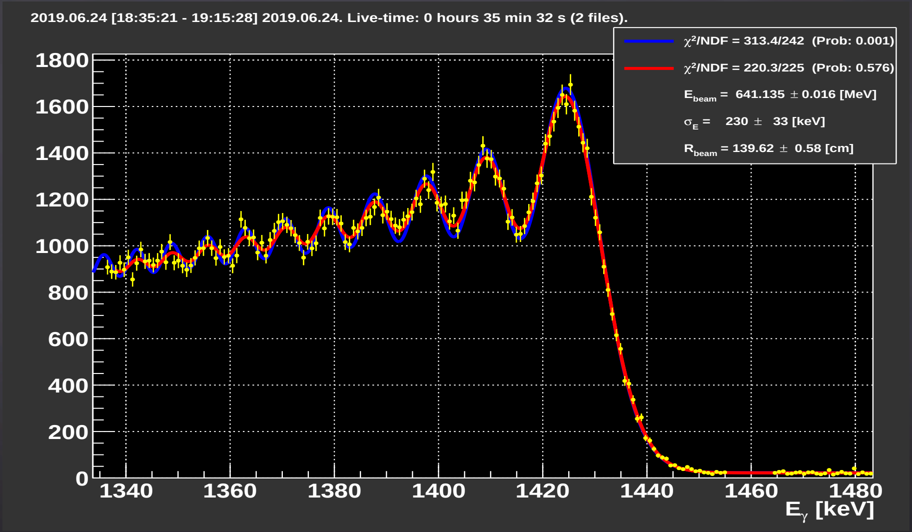




$\omega_0 = 0.117$ eV; $\varepsilon_0 = 900$ MeV; $R = 140$ cm

$$\mathrm{Ai}(x) = \frac{1}{\pi}\int_0^\infty \cos\left(xt + \frac{t^3}{3}\right)dt$$

Test of the theory



Evidence of Interference

PRL **110,** 140402 (2013) PHYSICAL REVIEW LETTERS week ending 5 APRIL 2013

Backscattering of Laser Radiation on Ultrarelativistic Electrons in a Transverse Magnetic Field: Evidence of MeV-Scale Photon Interference

E. V. Abakumova, M. N. Achasov, D. E. Berkaev, V. V. Kaminsky, N. Yu. Muchnoi,*
E. A. Perevedentsev, E. E. Pyata, and Yu. M. Shatunov
Budker Institute of Nuclear Physics Siberian Branch of the Russian Academy of Sciences and Novosibirsk State University, 630090 Novosibirsk, Russia
(Received 3 November 2012; published 2 April 2013)

adp annalen der physik

Article

Compton Scattering and Induced Compton Scattering in a Constant Electromagnetic Field

Dr. J. Herrmann, Dr. V. Ch. Zhukovskii

First published: 1972 | https://doi.org/10.1002/andp.19724820405 | Citations: 2

Prospects for the Future

Eur. Phys. J. Special Topics **228**, 261–623 (2019)

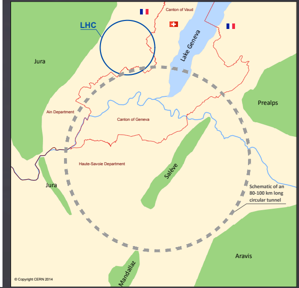
https://doi.org/10.1140/epjst/e2019-900045-4

THE EUROPEAN PHYSICAL JOURNAL
SPECIAL TOPICS

Regular Article

FCC-ee: The Lepton Collider

Future Circular Collider Conceptual Design Report Volume 2



This report contains the description of a novel research infrastructure based on a highest-luminosity energy frontier electron-positron collider (FCC-ee) to address the open questions of modern physics. It will be a general precision instrument for the continued in-depth exploration of nature at the smallest scales, optimised to measure precisely the properties of the Higgs boson, the Z and W bosons, the top quark and the Higgs coupling to the Z.

FCC-ee will provide unprecedented sensitivity to signs of new physics appearing either in the form of small deviations from the Standard Model or as rare decay processes.

Excerpts from FCC-ee CDR

- Beam energy calibration by Resonant Depolarization is the basis for the precise measurements of the Z and W masses with a precision of $\sim$100 keV and $\sim$500 keV correspondingly.
- Compton polarimeters – positive experience of LEP, HERA, SLD
- About 200 polarized pilot bunches/ring will not collide – just used for frequent beam energy measurements by RD.
- It is impossible to use RD at higher beam energies since the increased energy spread make the spin resonances too strong, reducing the asymptotic polarization to an unacceptably small value.
- E_{cm} near the $e^+e^- \to t\bar{t}$ threshold will be measured by the final state reconstruction of $e^+e^- \to W^+W^-, ZZ, Z\gamma$ events and from the knowledge of the W and Z masses.

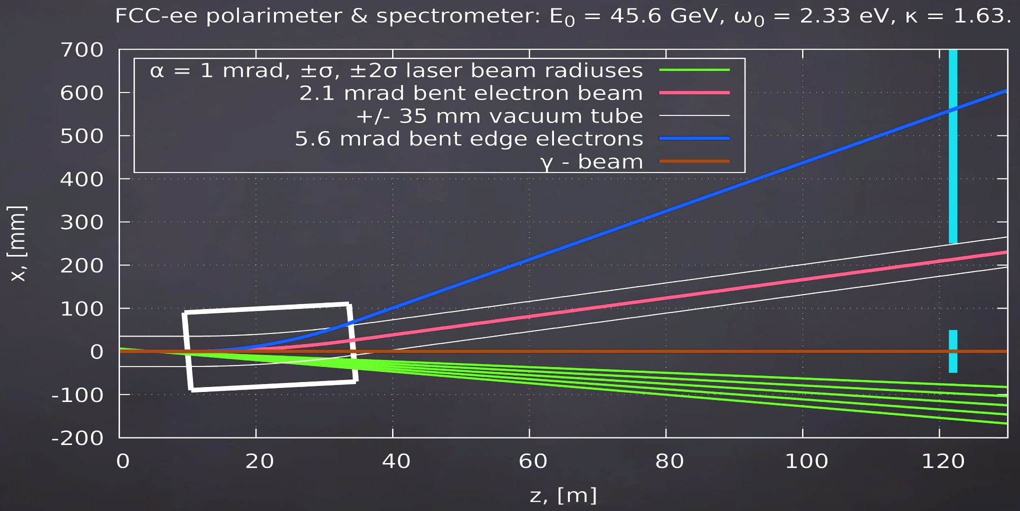
Compton Scattering cross section

for circular polarization of light $\xi_{\circlearrowright} = \pm 1$ depends on both longitudinal $\zeta_{\circlearrowright}$ and transverse $\zeta_{\perp}$ polarizations of the electron:

$$
\begin{aligned}
d\sigma_0 &= \frac{r_e^2}{\kappa^2(1+u)^3}\left(\kappa(1+(1+u)^2) - 4\frac{u}{\kappa}(1+u)(\kappa-u)\right) \, du\, d\varphi, \\
d\sigma_{\parallel} &= \frac{\xi_{\circlearrowright}\zeta_{\circlearrowright} r_e^2}{\kappa^2(1+u)^3} \, u(u+2)(\kappa-2u) \, du\, d\varphi, \\
d\sigma_{\perp} &= -\frac{\xi_{\circlearrowright}\zeta_{\perp} r_e^2}{\kappa^2(1+u)^3} \, 2u\sqrt{u(\kappa-u)}\cos(\varphi-\phi_{\perp}) \, du\, d\varphi.
\end{aligned}
$$

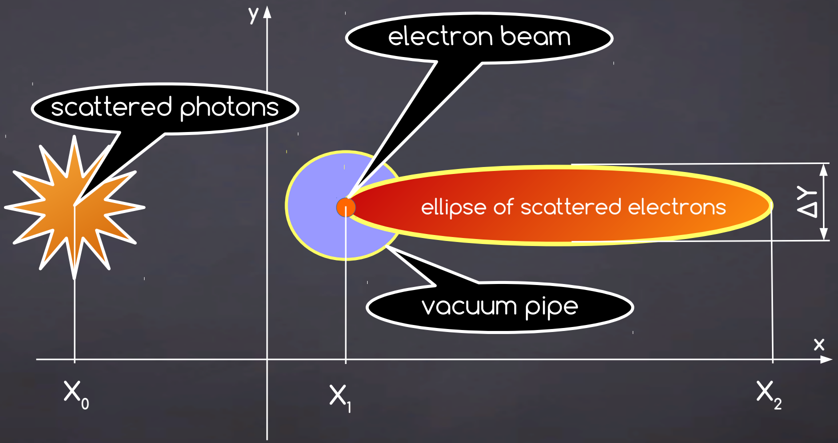
For vertical electron (beam) polarization $\phi_{\perp} = \pi/2$

FCC-ee Polarimeter: x-z plane



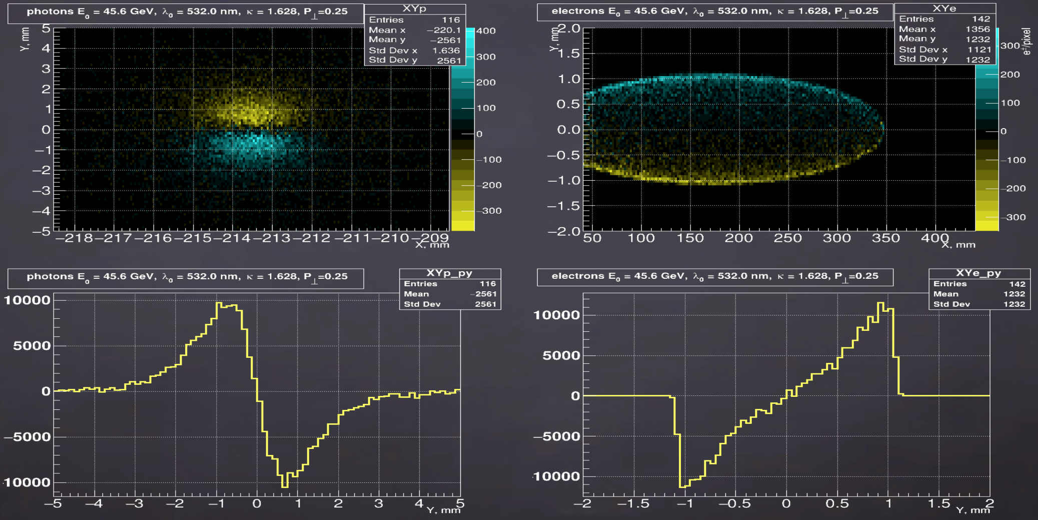
Blue bars – 2D silicon pixel detectors for scattered electrons & photons.

FCC-ee Polarimeter: x-y plane

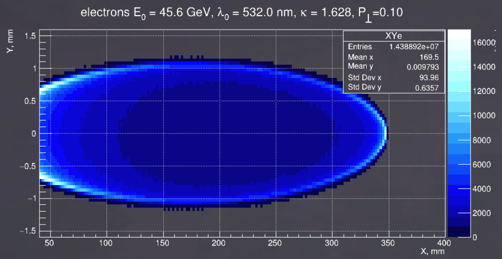


Direct beam energy measurement: $E = \frac{(mc^2)^2}{4\omega_0} \cdot \frac{X_2 - X_1}{X_1 - X_0}$

Scattered γ & e: The Difference



Fit: cross section & emittance



χ^2/NDF = 6356.7/6129 | Prob = 0.0208

X_0 = -213.538 ± 0.000 mm

X_1 = -000.008 ± 0.010 mm

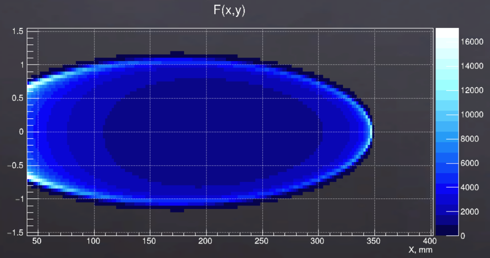
X_2 = 0347.631 ± 0.003 mm

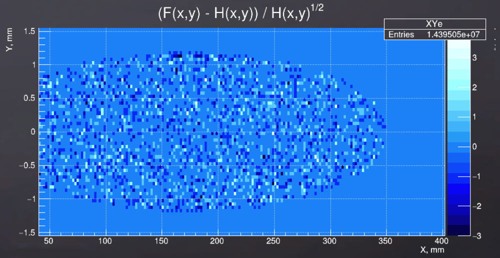
σ_x = 194.8 ± 4.4 μm

σ_y = 23.69 ± 0.02 μm

E_{beam} = 45.6032 ± 0.0035 GeV.

$P_\perp$ = 0.0997 ± 0.0016





Laser parameters

- λ_0 = 532 nm, waist σ_0 = 0.25 mm, z_R = 148 cm, divergence θ = 0.169 mrad.
- Interaction angle α = 1.0 mrad (horizontal crossing).
- Laser pulse: E_L = 1 mJ, τ_L=5 ns, f = 3 kHz, P_L = 80 kW, $\langle P_L \rangle$ = 3 W.
- Beam electron energy E_{beam} = 45.6 GeV, cross section $R_\times$ $\simeq$50%.
- Scattering probability $W = P_L/P_c \cdot R_\times \cdot \eta(R_L, R_A) \simeq 7 \cdot 10^{-8}$.
- $N_e = 10^{10}$ e$^\pm$/bunch: $\dot{N}_\gamma = f \cdot N_e \cdot W \simeq 2 \cdot 10^6$ s^{-1}.

Summary on FCC-ee polarimeter

- Detecting both scattered photons & electrons increases the reliability of beam polarization measurement.
- Polarimeter provides $\simeq 1$ % / s accuracy for $\zeta_\perp$.
- The beam energy spectrometer option does not require mandatory neither the B-field measurement nor the BPMs data:
  - statistical precision $\Delta E/E \simeq 100$ ppm / 10 sec;
  - systematic effects estimation requires further studies: yet no limitations;
  - test of the approach does not require high beam energy and should be performed with low emittance beam at low energy.
- Polarimeter allows to measure beam sizes & positions.

Summary

- On the eve of the centenary of its discovery the Compton effect continue to find new applications in contemporary physics.
- Strange as it may seem, the observed phenomena are not always predictable and obvious.
- Beam Energy Measurement System for BES-III experiment is a positive example of the collaboration between BINP & IHEP.

Thank You for Your Attention!