Full Inverse Compton Scattering, Unruh photons and FICS relay in the cosmos

Can electrons emit photons of energy larger than their own?

255.5 keV photons can stop ANY relativistic electron

Luca Serafini, Vittoria Petrillo and Sanae Samsam
INFN-Milano and Università degli Studi di Milano

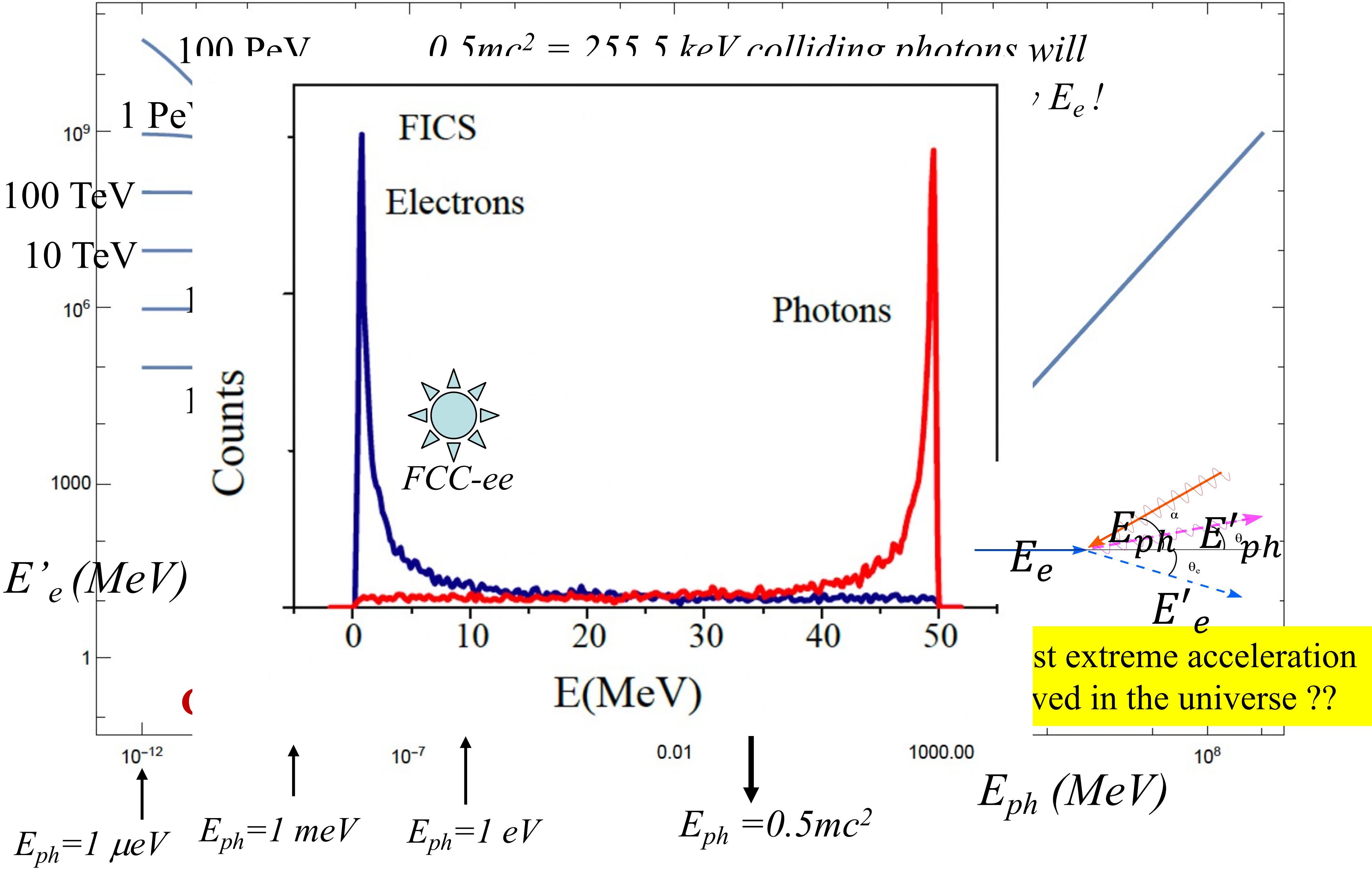
- ***Deep Recoil Inverse Compton Scattering revisited, how to stop (MeV's, GeV's, TeV's …) electrons in a single-collision event: a portal towards quantum gravity?***

- ***From Thomson back-scattering to FICS, total transfer of energy/momentum from an electron to a photon, and*** **how to generate 100 GeV photons at FCC-ee**

- ***Impacts in several fields: Plasma Physics (e^- / e^+ trapping in plasma mirrors), Astro-Physics (cosmic γ-ray sources), QED & Quantum Gravity (Unruh radiation and overcoming the Schwinger limit)***

Workshop on Other Science Opportunities @ FCC-ee, CERN, Nov. 28th, 2024

Full Inverse Compton Scattering: amazing power of 255.5 keV photons to stop ANY colliding electron



**hadronic threshold (E_{cm} < 600 MeV) with 255.5 keV photons ≈ 360 GeV*

Energy Budget towards γ-rays with high spectral density

- **25 GeV** electrons would be needed to generate
  2 MeV photons via ***synchrotron radiation***
  (highest spectral density S 10^{12} $s^{-1}eV^{-1}$, very small bdw 10^{-4})

- **850 MeV** electrons were used to ***Channeling Radiate***
  2 MeV γ-rays (high S 10^5-10^6 $s^{-1}eV^{-1}$, broad bdw 10 %)

- **350 MeV** e^-s are needed to ***Inverse Compton Scatter***
  2 MeV γ-rays (good S 10^4-10^5 $s^{-1}eV^{-1}$, small bdw 10^{-3})

- **3.5 MeV** electrons to ***bremsstrahlung***
  2 MeV γ-rays (poor S 1 $s^{-1}eV^{-1}$, very broad bandwidth)

- **2 MeV** e^-s to ***Symmetric Compton Scatter*** a photon target
  2 MeV γ-ray photons (S 10^4 $s^{-1}eV^{-1}$) **spectral purification!**

SYNCHR.

$$h\nu_c = \frac{3}{4\pi} \frac{eh}{m} \gamma^2 B$$

$$f \equiv \frac{h\nu_c}{\gamma m c^2} \qquad f = \frac{3}{2} \frac{\gamma c B}{E_{SCHW}} = \frac{3}{4} \frac{E_{ph-ERF}}{E_{SCHW}}$$

$$E_{SCHW} = \frac{2\pi m^2 c^3}{eh} \simeq 1.3 \cdot 10^{18} \frac{V}{m}$$

$$f_{ELETTRA} \simeq 10^{-6}$$

$$f = 1 \;@\; \gamma m c^2 = 1 \text{ PeV}$$

ICS

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1+X}$$

$$X \equiv \frac{4\gamma E_{ph}}{mc^2} = \frac{2E_{ph-ERF}}{mc^2}$$

$$f_{ICS} = \frac{E'_{ph}}{\gamma mc^2} \simeq \frac{X}{1+X}$$

$$\xrightarrow{X \ll 1} \propto X$$

$$\xrightarrow{X \gg 1} \propto 1 - \frac{1}{X}$$

$$f_{ICS}^{STAR} \simeq 10^{-3}$$

$$f_{ICS}^{ELI-NP} \simeq 10^{-2}$$

$$f_{ICS}\left(1\,\mathrm{GeV}\ \text{vs.}\ 1\,\mathrm{keV}\right) = 0.93$$

$$X = 15$$

PRL 115, 025504 (2015) PHYSICAL REVIEW LETTERS week ending 10 JULY 2015

Investigation of the Electromagnetic Radiation Emitted by Sub-GeV Electrons in a Bent Crystal

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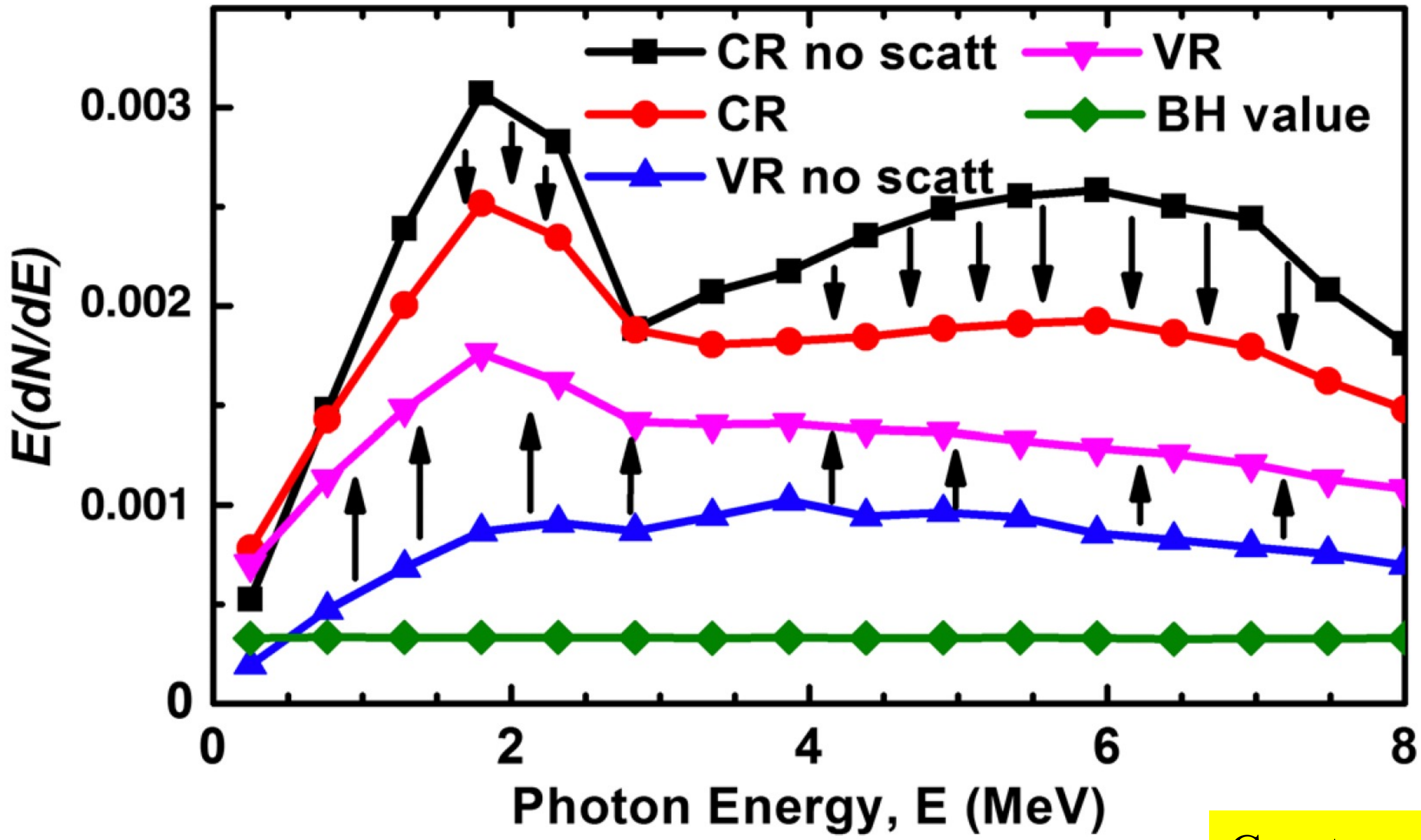
INFN Sezione di Ferrara and Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara Via Saragat 1, 44122 Ferrara, Italy

$f_{CHANN} \sim 1\%$

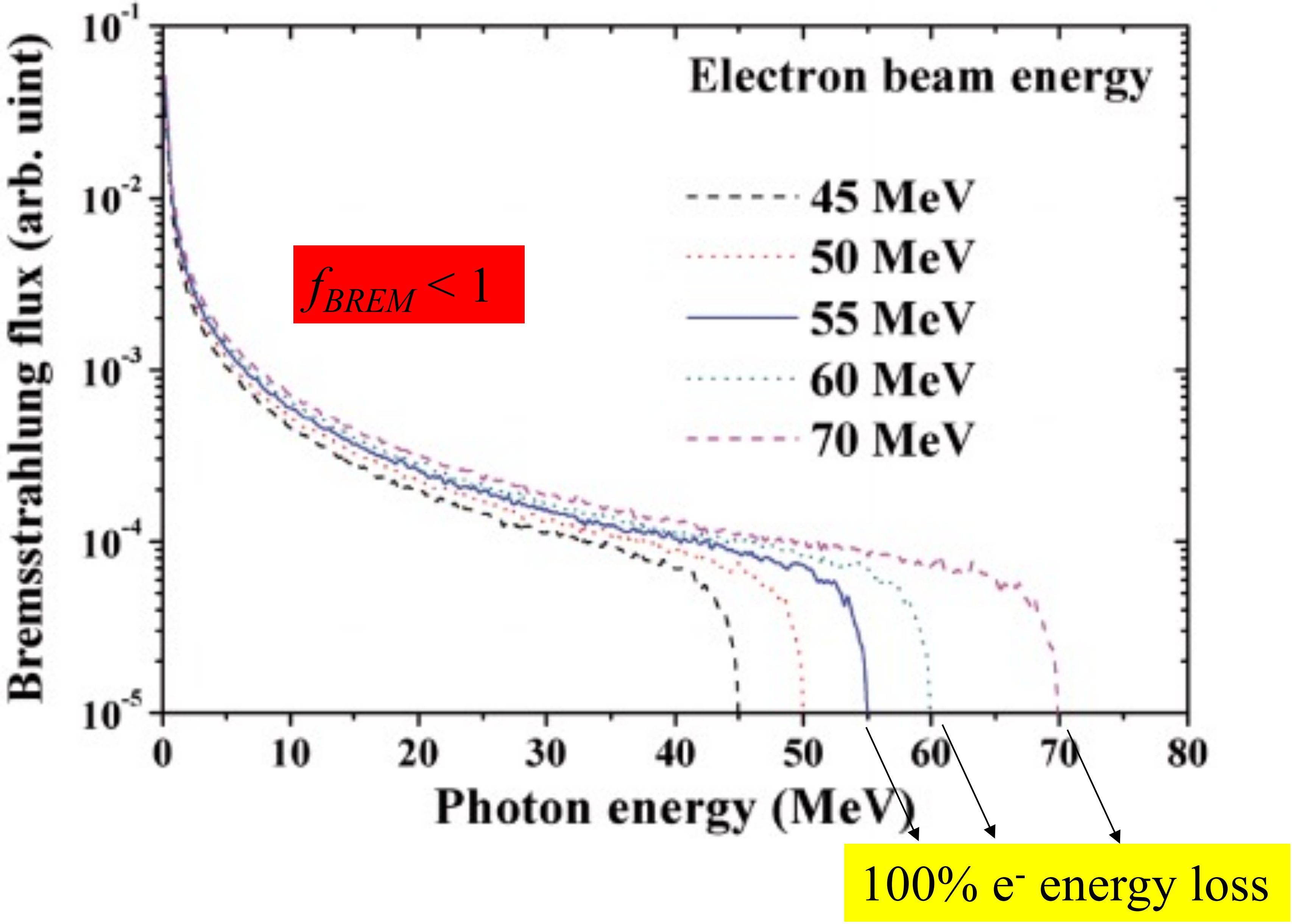


Courtesy L. Bandiera

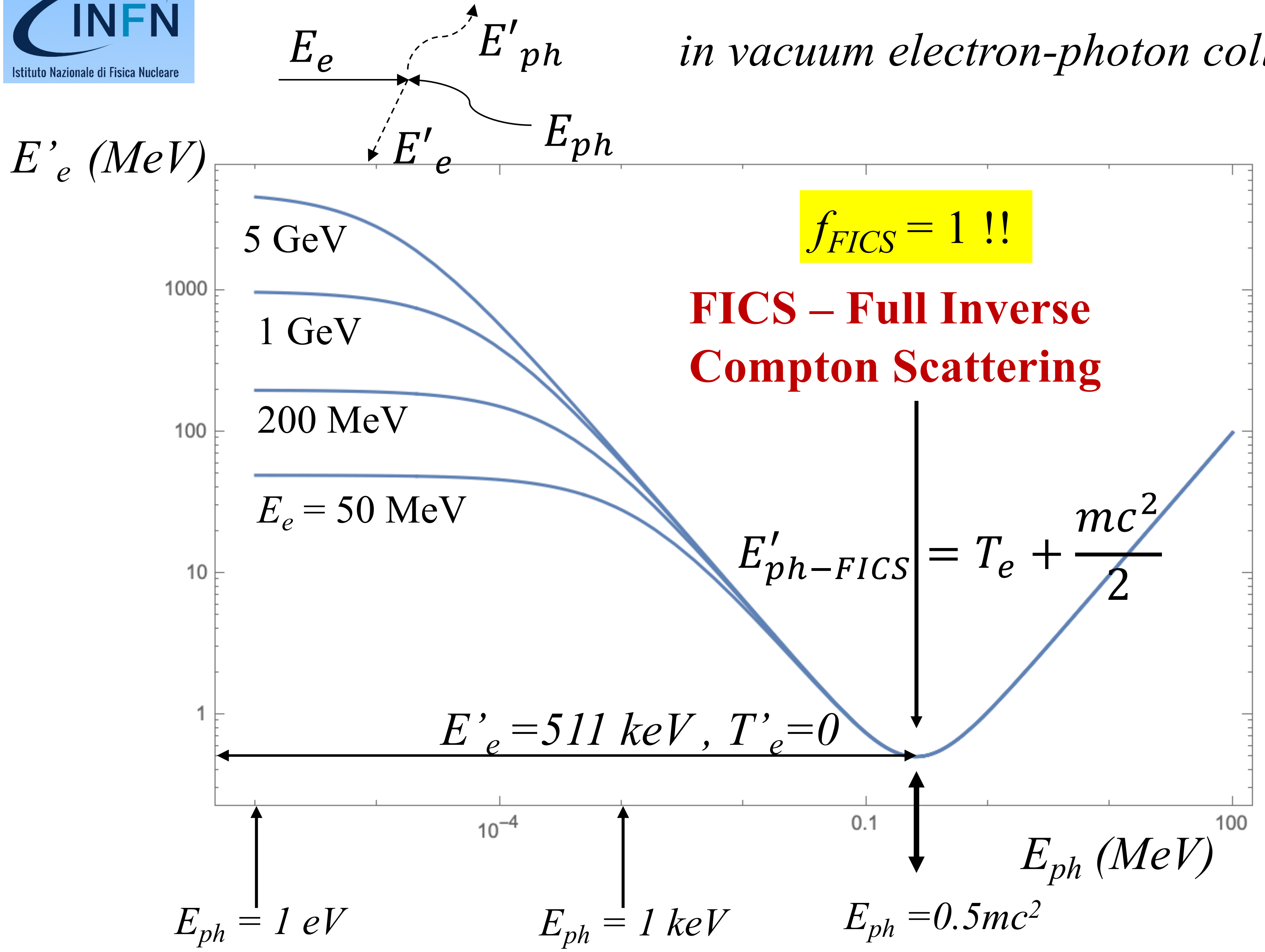
Bremsstrahlung is clearly not an option:

a) total electron energy loss not actually achievable

b) brilliance of bremsstrahlung sources is orders of magnitude smaller

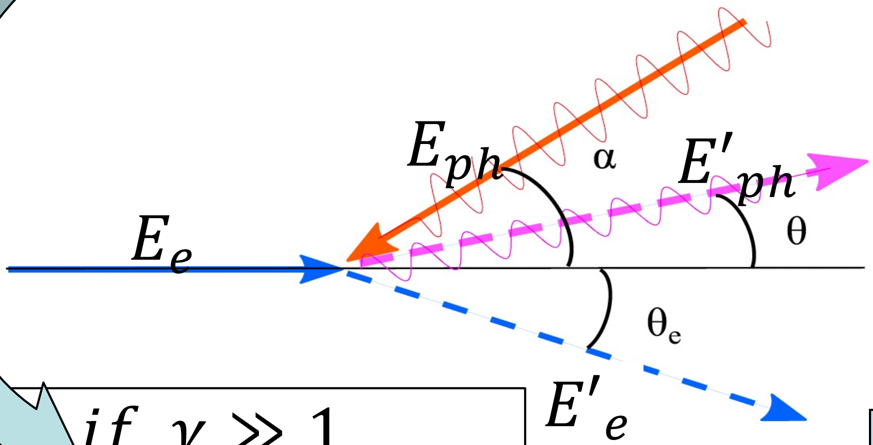


in vacuum electron-photon collision



General formula valid for ANY compton scattering

$$E'_{ph} = \frac{\gamma^2(1+\beta)}{\gamma^2(1-\beta\cos\theta)+\frac{X}{4}(1+\cos\theta)}E_{ph}$$



$X \equiv 4\gamma^2 E_{ph}/E_e$

$A \equiv \beta\gamma^2 - X/4 = \gamma^2(\beta - E_{ph}/E_e)$

if $\gamma \gg 1$

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1+X+\gamma^2\vartheta^2}$$

Fundamental Plasma Physics 7 (2023) 100026

Contents lists available at ScienceDirect

Fundamental Plasma Physics

journal homepage: www.elsevier.com/locate/fpp

ELSEVIER

Original research article

Symmetric Compton Scattering: A way towards plasma heating and tunable mono-chromatic gamma-rays

L. Serafini [a,b], A. Bacci [a,b], C. Curatolo [a,b], I. Drebot [a,b], V. Petrillo [a,c], A. Puppin [a,c], M. Rossetti Conti [a,b,*], S. Samsam [a,b]

$$E'_{ph} = \frac{4(\gamma^2+A)+X}{4(\gamma^2-A\cos\theta)+X}E_{ph}$$

$A=0$, *i.e.* Symmetric Compton Scattering cancels the $\gamma^2\theta^2$ correlation

An invariant view at Compton effect - 1

(any inertial ref. frame)

Simulation of inverse Compton scattering and its implications on the scattered linewidth

Phys. Rev. AB (2018) **21**, 030701

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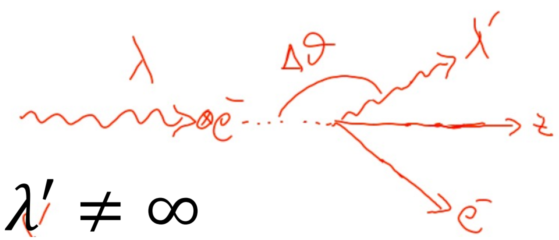
$$X = \frac{4\gamma\hbar\omega}{mc^2}$$

$$\omega'(\theta) = \frac{\omega(1+\beta)^2\gamma^2}{\gamma^2(1-\beta\cos\theta)(1+\beta) + \frac{X}{4}(1+\cos\theta)(1+\beta)}. \quad (3)$$

Arthur Compton, Nobel Prize 1927

$\beta = 0$

$\lambda' - \lambda = \frac{h}{mc}(1+\cos\Delta\vartheta)$



$\lambda' \neq \infty$

isolated e⁻ cannot absorb a photon

$A<0$ photon looses energy

$A=0$

$A>0$ electron looses energy

$\gamma \gg 1 \; ; \; \gamma^2 \gg \frac{X}{4}$

S.C.S.

FICS !

$$\beta\gamma^2 = \frac{X}{4}$$

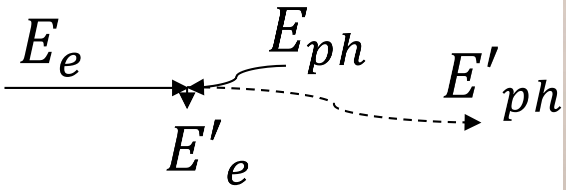
$$E'_{ph} = \beta E_e = \beta\gamma mc^2$$

$$E'_{ph} \neq f(\gamma^2\vartheta^2)$$

I.C.S.

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1 + X + \gamma^2\vartheta^2}$$

$$\lim_{X\to\infty} E'_{ph} = E_e$$



$$E'_e = mc^2$$

$$T'_e = 0$$

Let's focus on the "turning point" where electron starts to be back-scattered: FICS - Full Inverse Compton Scattering

$$\beta\gamma mc^2 - E_{ph} = 0 + E'_{ph}$$

FICS equations

$$\gamma mc^2 + E_{ph} = mc^2 + E'_{ph}$$

$$E_{ph} = \frac{mc^2}{2}\left(1 - (1-\beta)\gamma\right)$$

$$E'_{ph} = mc^2\left(\gamma\frac{1+\beta}{2} - \frac{1}{2}\right)$$

$$E_e = \gamma mc^2$$

$$E'_e = mc^2$$

FICS solutions

for any value of γ !

When $\gamma >> 1$ FICS solution becomes:

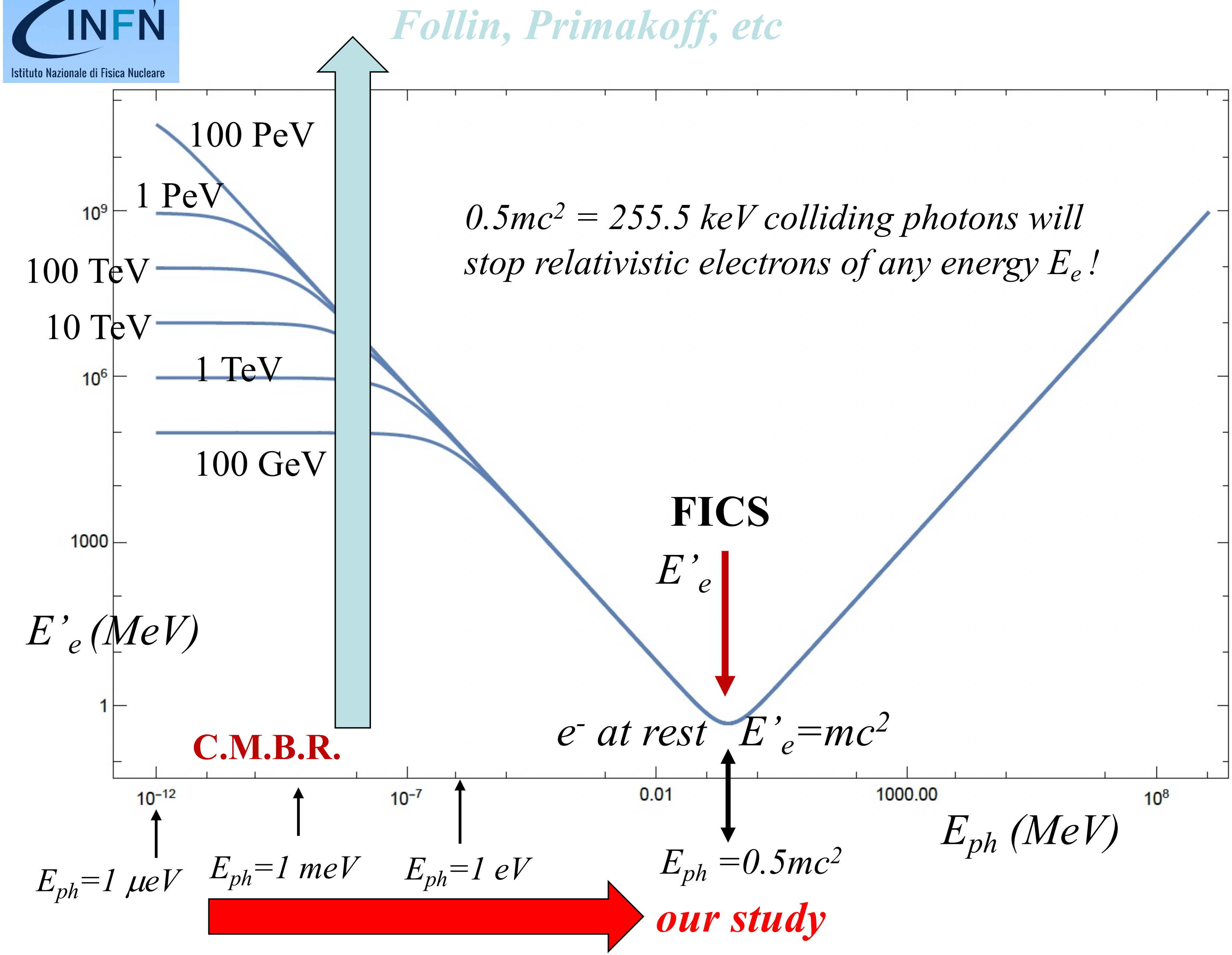
$$E_{ph} = \frac{mc^2}{2}\left(1 - \frac{1}{2\gamma}\right)$$

$$E'_{ph} = mc^2\left(\gamma - \frac{1}{2} - \frac{1}{4\gamma}\right)$$

$$E_e = \gamma mc^2$$

$$E'_e = mc^2$$

$mc^2/2$ photons can stop any relativistic electron !
The fractional energy loss of FICS is 100%



Follin, Primakoff, etc
100 PeV
1 PeV
100 TeV
10 TeV
1 TeV
100 GeV
10^9
10^6
1000
1
$0.5mc^2$ = 255.5 keV colliding photons will stop relativistic electrons of any energy E_e !
FICS
E'_e
E'_e (MeV)
C.M.B.R.
e^- at rest $E'_e=mc^2$
10^{-12}
10^{-7}
0.01
1000.00
10^8
E_{ph} (MeV)
E_{ph}=1 μeV
E_{ph}=1 meV
E_{ph}=1 eV
E_{ph} =$0.5mc^2$
our study

Good recap of the whole ICS history

PHYSICAL REVIEW ACCELERATORS AND BEAMS **27,** 080701 (2024)

From Compton scattering of photons on targets to inverse Compton scattering of electron and photon beams

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(Received 2 May 2024; accepted 1 August 2024; published 28 August 2024)

We revisit the kinematics of Compton scattering (electron-photon interactions producing electrons and photons in the exit channel) covering the full range of energy/momenta distribution between the two colliding particles, with a dedicated view to statistical properties of secondary beams that are generated in beam-beam collisions. Starting from the Thomson inverse scattering, where electrons do not recoil and photons are backscattered to higher energies by a Lorentz boost effect (factor $4\gamma^2$), we analyze three transition points, separating four regions. These are in sequence, given by increasing the electron recoil (numbers are for transition points and letters for regions): (a) Thomson backscattering, (1) equal sharing of total energy in the exit channel between electron and photon, (b) deep recoil regime where the bandwidth/energy spread of the two interacting beams are exchanged in the exit channel, (2) electron is stopped, i.e., taken down at rest in the laboratory system by colliding with an incident photon of $mc^2/2$ energy, (c) electron backscattering region, where incident electron is backscattered by the incident photon, and (3) symmetric scattering, when the incident particles carry equal and opposite momenta, so that in the exit channel they are backscattered with same energy/momenta, and (d) Compton scattering [*ála* Arthur Compton, see A. J. Compton, A quantum theory of the scattering of X-rays by light elements, Phys. Rev. **21**, 83 (1923)], where photons carry an energy much larger than the colliding electron energy. For each region and/or transition point, we discuss the potential effects of interest in diverse areas, like generating monochromatic gamma-ray beams in deep recoil regions with spectral purification, or possible mechanisms of generation and propagation of very high energy photons in the cosmological domain.

DOI: 10.1103/PhysRevAccelBeams.27.080701

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

beginning of the story – the photon, quantum of energy

THE

PHYSICAL REVIEW

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

By Arthur H. Compton

Abstract

The change in wave-length due to scattering.—Imagine, as in Fig. 1*A*,

...rays by light elements.
...uantum is scattered it
...ticular electron. This

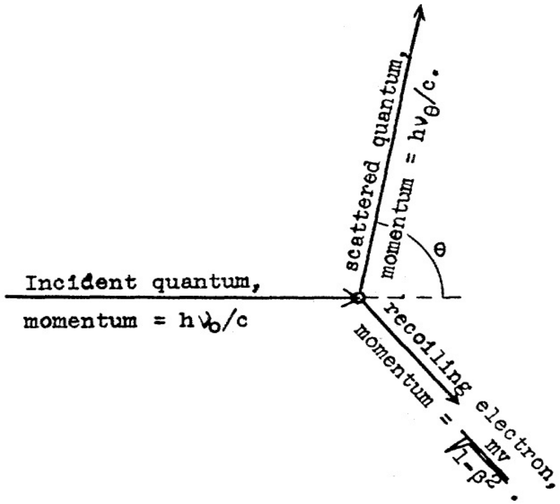


Fig. 1 A

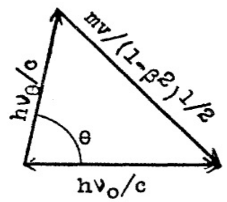
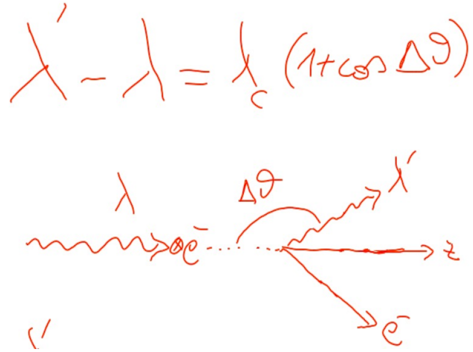


Fig. 1 B



$$E'_{ph} = \frac{E_{ph}}{1 + \frac{E_{ph}}{mc^2}(1+\cos\vartheta)}$$

angular correlation!

that an X-ray quantum of frequency ν_0 is scattered by an electron of mass m. The momentum of the incident ray will be $h\nu_0/c$, where c is

First physicists forced to think at Inverse Compton Scattering,
i.e. a mechanism by which electrons loose energy in favor to photons,
(opposite than direct Compton effect) were…

The developers of the Nuclear Bomb!
and, soon later,
first observers of cosmic rays in the upper atmosphere,
trying to figure out why there are many protons and very few electrons

Istituto Nazionale di Fisica Nucleare

AIP

PHYSICS TODAY

Manhattan Project astrophysics

After World War II, scientists applied the knowledge and experience they gained from nuclear weapons to nuclear astrophysics.

Michael Wiescher; Karlheinz Langanke

Check for updates

Physics Today **77** (3), 34–41 (2024);
https://doi.org/10.1063/pt.jksg.hage

of initiating nuclear fusion of the whole atmosphere!!!

an ignition could not be deemed impossible. The Trinity test took place in July 1945, and the atomic bombs were dropped on Hiroshima and Nagasaki shortly thereafter. Despite the bombs' tremendous damage, they did not set the atmosphere on fire.

Theory mitigates fear

The year after the test, Teller, his graduate student Emil Konopinski, and local technician Cloyd Marvin Jr wrote a classified Los Alamos National Laboratory report in which they summarized theoretical considerations on the possible ignition of the atmosphere by an atomic explosion.[1] The paper, declassified in 1979, argues that propagation of nuclear burning in the atmosphere is possible only if the energy gained from nuclear reactions is greater than the energy loss through the emitted gamma and beta radiation.

Konopinski, Teller, and Marvin considered the fusion of two ^{14}N nuclei as the most important energy-producing reaction, because ^{14}N is the dominant component in Earth's atmosphere. On the other hand, when compared to the stable oxygen-16 isotope, ^{14}N nuclei can easily be broken up. Therefore, the fusion of two ^{14}N atoms should lead mainly to a rearrangement of the nucleons by the nuclear force and produce a light fragment and a heavy fragment. Energetically, the most favorable result would be their breakup into alpha particles and a magnesium-24 nucleus.

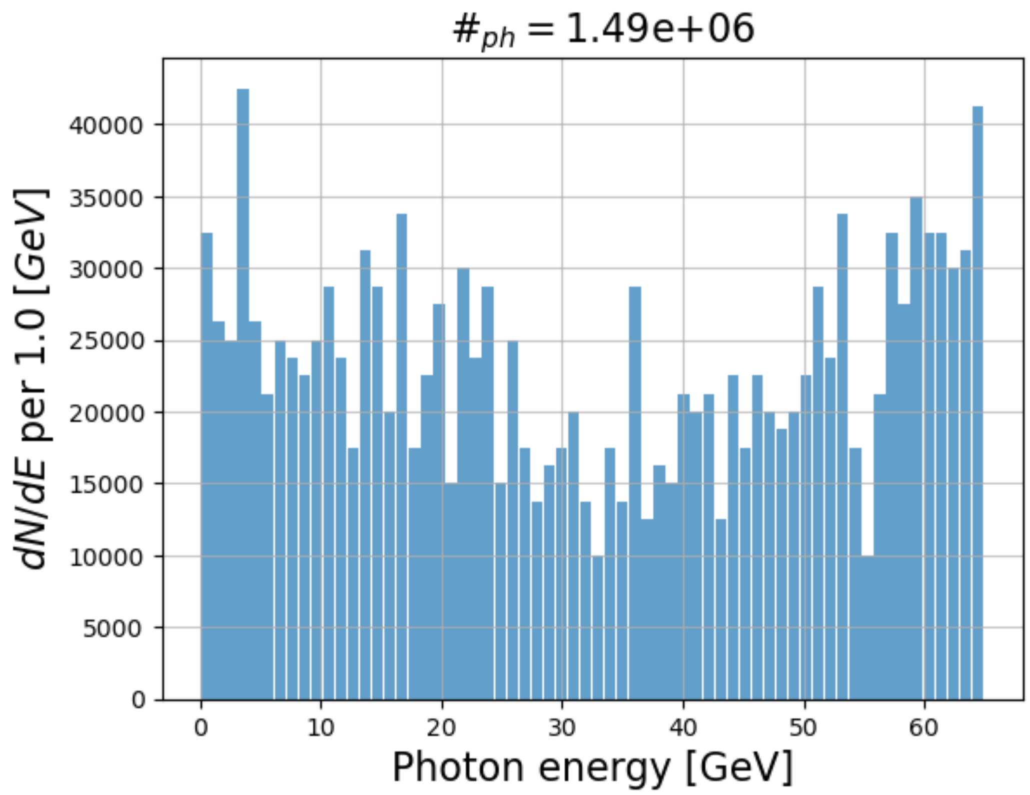
Up to 17.7 MeV of kinetic energy from the reaction can be

FIGURE 2. J. ROBERT OPPENHEIMER in typical postures—at the blackboard and with a cigarette. His goal as scientific director of the Manhattan Project was to develop a nuclear device that exploded from the fission of uranium-235 and plutonium-239. (Illustration by David McMacken.)

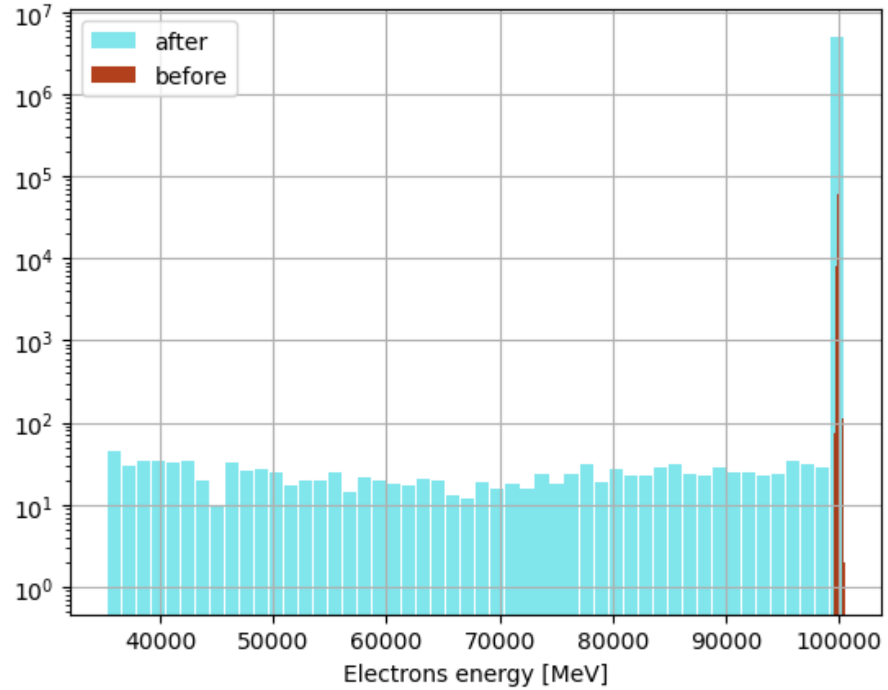
The electron gas cools by inelastic scattering and by emitting bremsstrahlung in the form of a continuous x-ray spectrum. Because the atmosphere is transparent to that radiation, it loses energy. Konopinski, Teller, and Marvin found that the rate of

FCC-ee
primary electron beam 100 GeV
primary photon beam: optical laser

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1+X}$$



$$X \equiv \frac{4\gamma E_{ph}}{mc^2} =$$
$$15.3\, E_e(MeV) E_{ph}(MeV)$$



X_{laser}=1.8

not negligible fraction of electrons
in the beam interact with laser

Workshop on Other Science Opportunities @ FCC-ee, CERN, Nov. 28th, 2024

Thanks to Illya Drebot

Largest value of recoil factor X achieved in experiments so far is *X=1.8* at SLAC in 1999

PHYSICAL REVIEW D, VOLUME 60, 092004

Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses

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C. Bula,¶ K. T. McDonald, and E. J. Prebys
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(Received 1 February 1999; published 8 October 1999)

We report on measurements of quantum electrodynamic processes in an intense electromagnetic wave, where nonlinear effects (both multiphoton and vacuum polarization) are prominent. Nonlinear Compton scattering and electron-positron pair production have been observed in collisions of 46.6 GeV and 49.1 GeV electrons of the Final Focus Test Beam at SLAC with terawatt pulses of 1053 nm and 527 nm wavelengths from a Nd:glass laser. Peak laser intensities of $\approx 0.5\times 10^{18}$ W/cm^2 have been achieved, corresponding to a value of ≈ 0.4 for the parameter $\eta = eE_{\mathrm{rms}}/m\omega_0 c$ and to a value of ≈ 0.25 for the parameter $\Upsilon_e = E^\star_{\mathrm{rms}}/E_{\mathrm{crit}} = eE^\star_{\mathrm{rms}}\hbar/m^2c^3$, where $E^\star_{\mathrm{rms}}$ is the rms electric field strength of the laser in the electron rest frame. We present data on the scattered electron spectra arising from nonlinear Compton scattering with up to four photons absorbed from the field. A convolved spectrum of the forward high energy photons is also given. The observed positron production rate depends on the fifth power of the laser intensity, as expected for a process where five photons are absorbed from the field. The positrons are interpreted as arising from the collision of a high-energy Compton scattered photon with the laser beam. The results are found to be in agreement with theoretical predictions. [S0556-2821(99)02519-9]

PACS number(s): 13.40.−f, 12.20.Fv, 13.10.+q, 42.65.−k

Colliding the XFEL photon beam (12 keV) with the 19.5 GeV electron beam would achieve *X=3585* !!!

FCC-ee

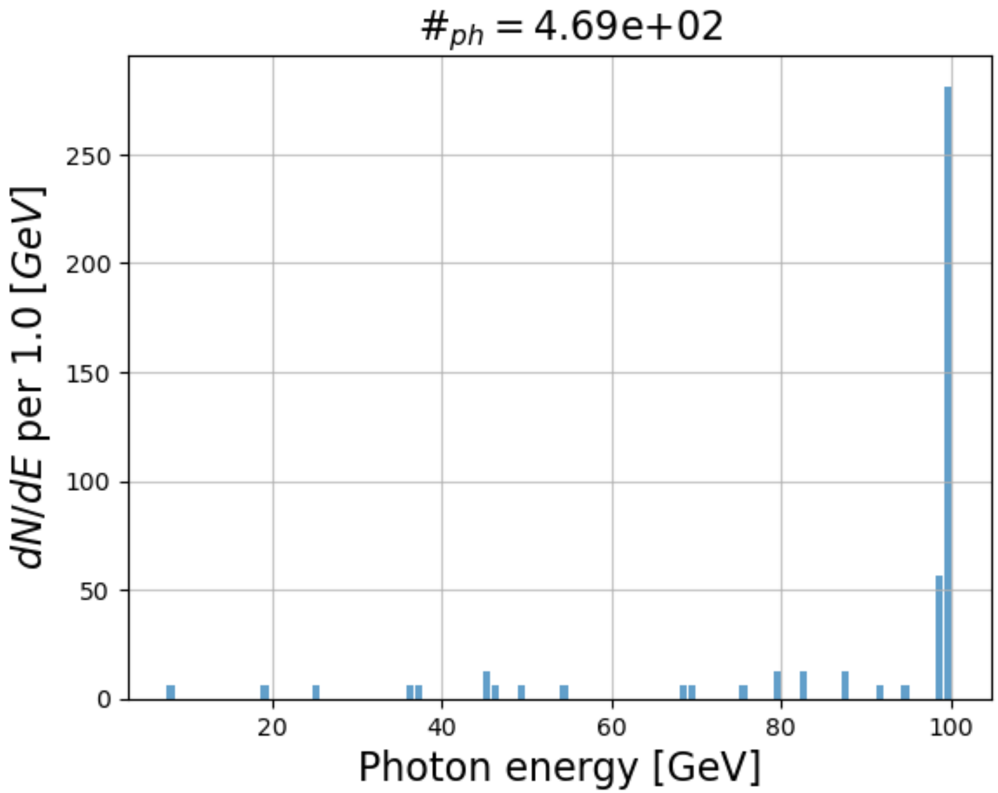
primary electron beam 100 GeV

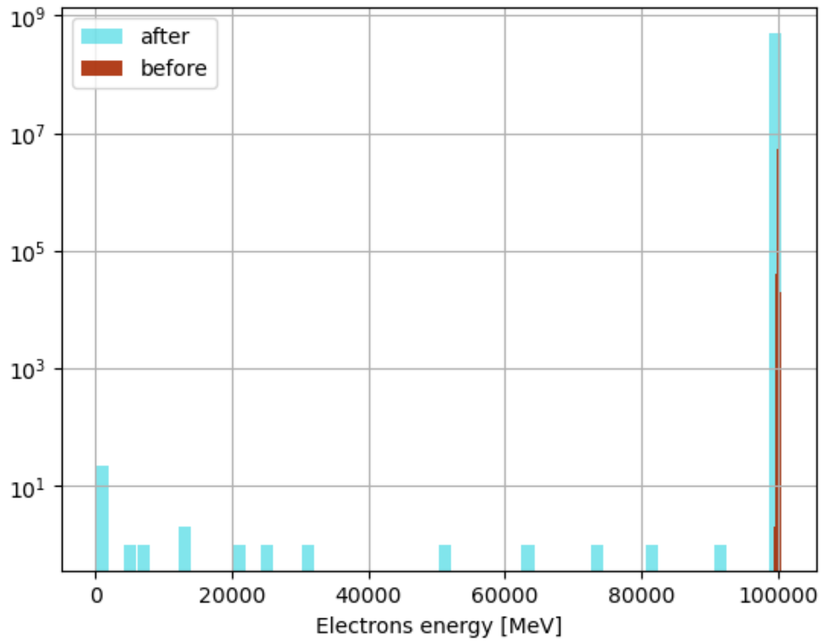
primary photon beam: 255.5 keV

Deep recoil Compton: X >> 1

$$E'_{ph} \sim \left(1 - \frac{1}{X}\right) E_e$$

$$X^{FICS} \equiv \frac{4\gamma E_{ph}}{mc^2} = 2\gamma$$





$X_{FICS} = 3.9 * 10^5$

Single particle energy extraction from the stored beam in the form of 100 GeV photons

Thanks to Illya Drebot

better statistics with 200 MeV e⁻

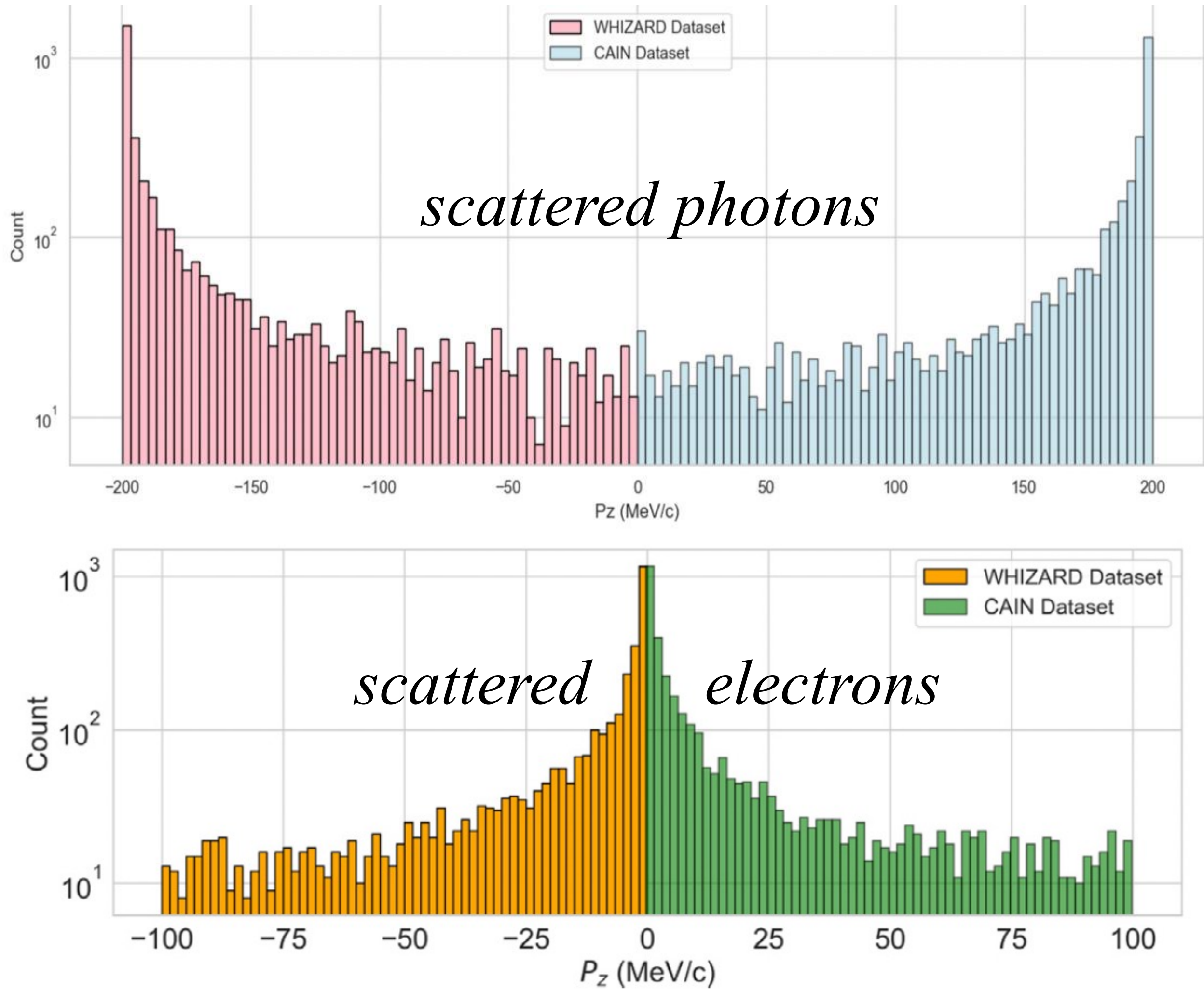


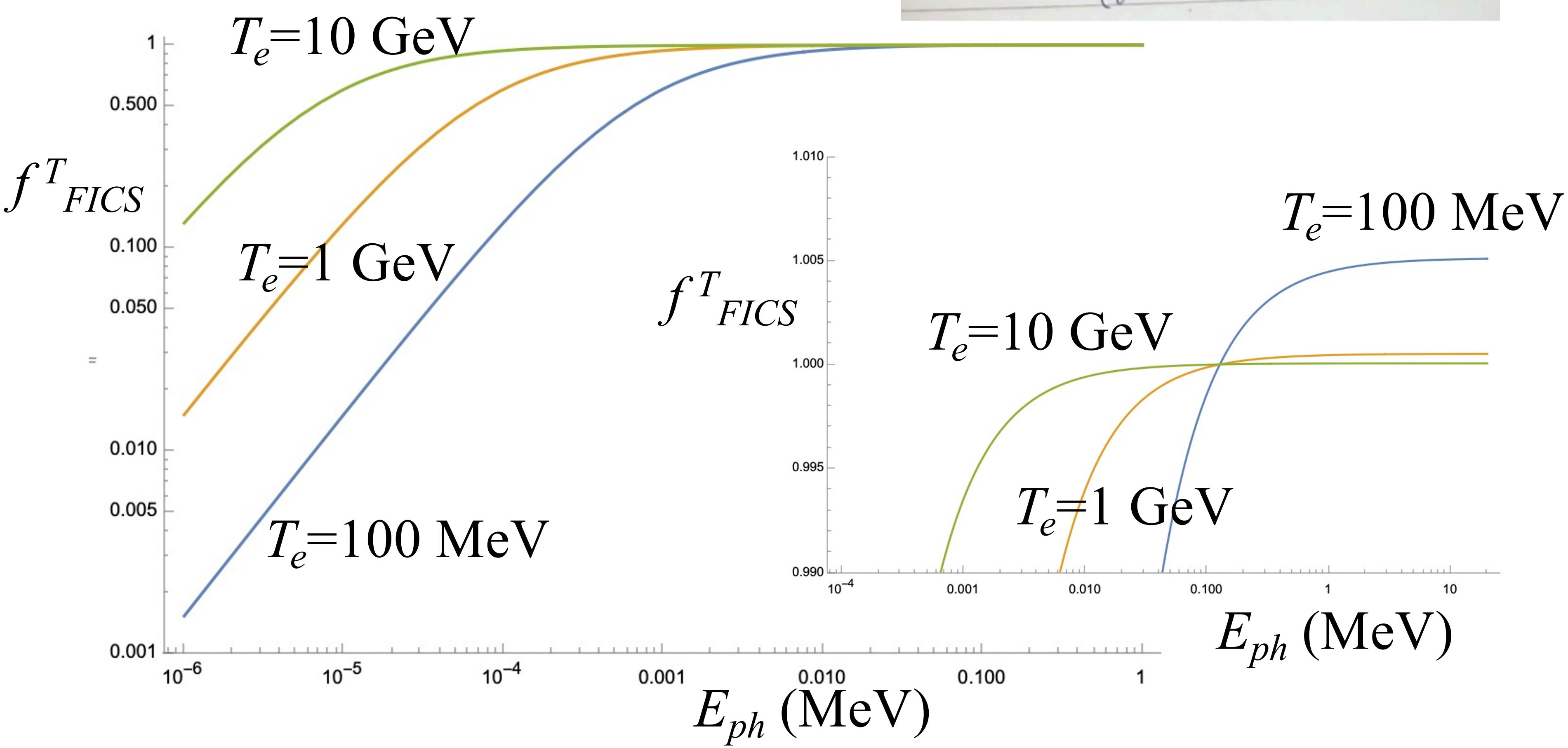
Fig. 13. Momentum Spectrum (P_z) in MeV/c of scattered photons and electrons following FICS Interaction. Top Panel: The momentum spectra of the scattered photons of an initial energy E_{ph} = 255.5 keV, comparing simulations from CAIN (blue) and WHIZARD (pink). The x-axis represents the longitudinal momentum (P_z) in MeV/c, and the y-axis represents the count on a logarithmic scale. Bottom Panel: The momentum spectra of scattered electrons on an initial energy E_e = 200 MeV, with simulations from CAIN (green) and WHIZARD (orange).

At FICS electrons emit photons with energy larger than T_e

$$E_{\mathrm{loss,FICS}} = \frac{E'_{ph} - E_{ph}}{T_e} = \frac{m_e c^2((\gamma - 1/2) - 1/2)}{m_e c^2(\gamma - 1)} = 1$$

$$\frac{E'_{ph}}{E_e} \approx \frac{m_e c^2(\gamma - 1/2)}{\gamma m_e c^2} = 1 - \frac{1}{2\gamma}$$

$$f^T_{FICS} \equiv \frac{E'_{Ph\text{-}FICS}}{(\gamma-1)mc^2} = 1 + \frac{1}{2\gamma}$$

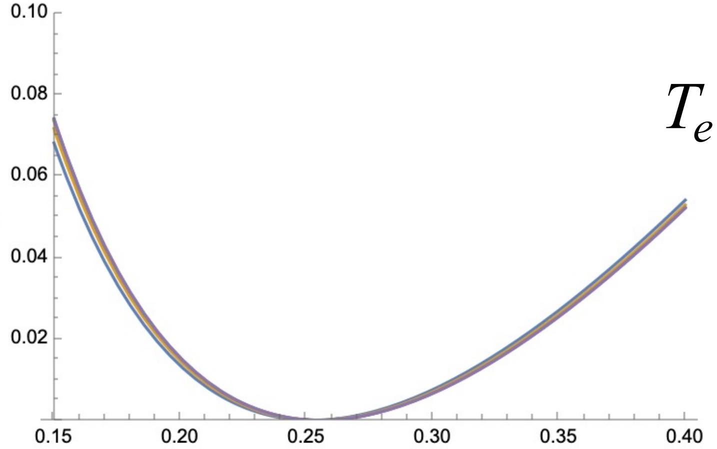


FICS has a shallow minimum: residual electron kinetic energy T'_e around FICS is small

```
In[26]:= Plot[{Tpe /. Ee → 20., Tpe /. Ee → 50., Tpe /. Ee → 200., Tpe /. Ee → 1000., Tpe /. Ee → 5000.},
  {Eph, 0.15, 0.4}, PlotRange → {0, 0.1}]
```

T'_e (MeV)

Out[26]=

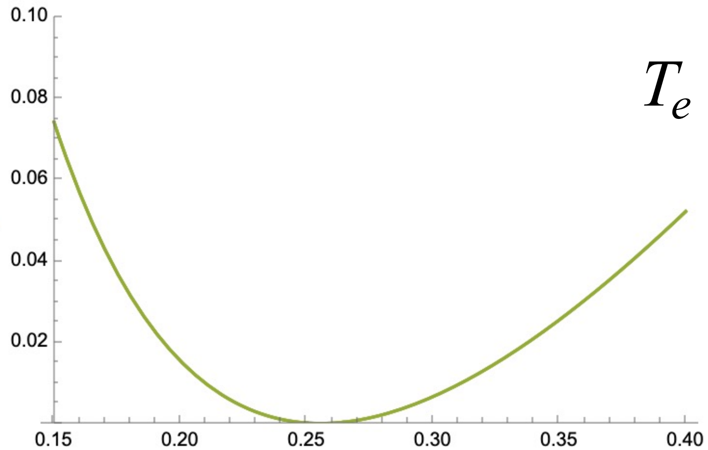


T_e = 20, 50, 200 (MeV), 1, 5 (GeV)

```
In[27]:= Plot[{Tpe /. Ee → 1. * 10 ^ 4, Tpe /. Ee → 1. * 10 ^ 5, Tpe /. Ee → 1. * 10 ^ 6, Tpe /. Ee → 1. * 10 ^ 9},
  {Eph, 0.15, 0.4}, PlotRange → {0, 0.1}]
```

T'_e (MeV)

Out[27]=



T_e = 10, 100 (GeV), 1 TeV, 1 PeV

The Unruh effect gives rise to a Planckian photon spectral distribution at a temperature

$$T = \frac{\hbar a}{2\pi k_B c}, \quad (91)$$

where a is the acceleration and k_B the Boltzmann con-

The **Unruh temperature**, sometimes called the Davies–Unruh temperature,[5] was derived separately by Paul Davies[3] and William Unruh[4] and is the effective temperature experienced by a uniformly accelerating detector in a vacuum field. It is given by[6]

$$T = \frac{\hbar a}{2\pi c k_B} \approx 4.06 \times 10^{-21}\ \mathrm{K \cdot s^2 \cdot m^{-1}} \times a,$$

where $\hbar$ is the reduced Planck constant, a is the proper uniform acceleration, c is the speed of light, and k_B is the Boltzmann constant. Thus, for example, a proper acceleration of $2.47 \times 10^{20}\ \mathrm{m \cdot s^{-2}}$ corresponds approximately to a temperature of 1 K. Conversely, an acceleration of $1\ \mathrm{m \cdot s^{-2}}$ corresponds to a temperature of 4.06×10^{-21} K.

Black-hole $a=10^{10}$ $T=4.1 \cdot 10^{-11}\ K$

Plasma acceleration (100 GV/m) $a=1.8 \cdot 10^{22}$ $T=74\ K$

?? ***how about FICS*** ??

PRL 97, 121302 (2006) PHYSICAL REVIEW LETTERS week ending 22 SEPTEMBER 2006

Signatures of the Unruh Effect from Electrons Accelerated by Ultrastrong Laser Fields

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(Received 18 April 2006; revised manuscript received 23 June 2006; published 22 September 2006; publisher error corrected 22 September 2006)

We calculate the radiation resulting from the Unruh effect for strongly accelerated electrons and show that the photons are created in pairs whose polarizations are perfectly correlated. Apart from the photon statistics, this quantum radiation can further be discriminated from the classical (Larmor) radiation via the different spectral and angular distributions. The signatures of the Unruh effect become significant if the external electromagnetic field accelerating the electrons is not too far below the Schwinger limit and might be observable with future facilities. Finally, the corrections due to the birefringent nature of the QED vacuum at such ultrahigh fields are discussed.

Probably $a_{laser} = 10^{23\text{-}25}$

Unruh radiation during FICS and SCS

$$a_{FICS} = \frac{\Delta v}{\Delta t} = \frac{c-0}{\frac{1}{\nu'_{ph}}} = \frac{c}{\frac{h}{E'_{ph}}} \overset{FICS}{\simeq} \frac{cE_0}{h}$$

$$a_{FICS}\,(m/s^2) = 7.3 \cdot 10^{28} * E_e(MeV)$$

$$T_{Unruh\text{-}FICS}\,(K) = 3.1 \cdot 10^{8} * E_e(MeV)$$

$$T_{Unruh\text{-}FICS}\,(MeV) = 0.026 * E_e(MeV)$$

going from 100 MeV up to 2 GeV electrons the Unruh photons at FICS would cover the 2.6 – 52 MeV range (easy detection in vacuum with low background)

$$a_{SCS} = 2 \cdot a_{FICS}$$

but *E_{ph} must be = E_e in SCS, while in FICS E_{ph} = 255.5 keV*

The electrons performing Compton scattering in the FICS condition undergo a state transition with a longitudinal momentum change by a quantity almost equal to its initial value. Their velocity, in turn, changes by a factor $\Delta v \simeq v_0$, $v_0 \simeq c$ being the electron velocity before the scattering. The typical time duration of this transition can be evaluated by applying the Tamm-Mandelstam criterion [14]:

$$\Delta E \Delta t \simeq h$$

In the cases presented previously,

$$\Delta E = E_e - E_e' \simeq E_e - m_e c^2$$

and the deceleration time turns out to be:

$$\Delta t \simeq \frac{h}{E_e - m_e c^2}$$

leading to:

$$a \simeq \frac{c\,(E_e - m_e c^2)}{h}$$

a_{FICS} $(m/s^2) = 7.3 \cdot 10^{28} * E_e(MeV)$

$T_{Unruh\text{-}FICS}$ $(K) = 3.1 \cdot 10^{8} * E_e(MeV)$

$T_{Unruh\text{-}FICS}$ $(MeV) = 0.026 * E_e(MeV)$

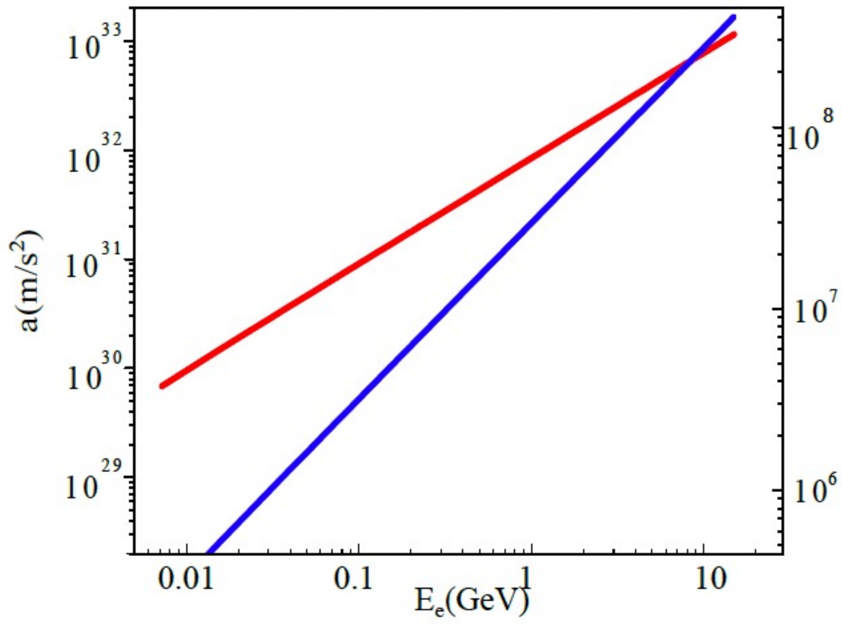


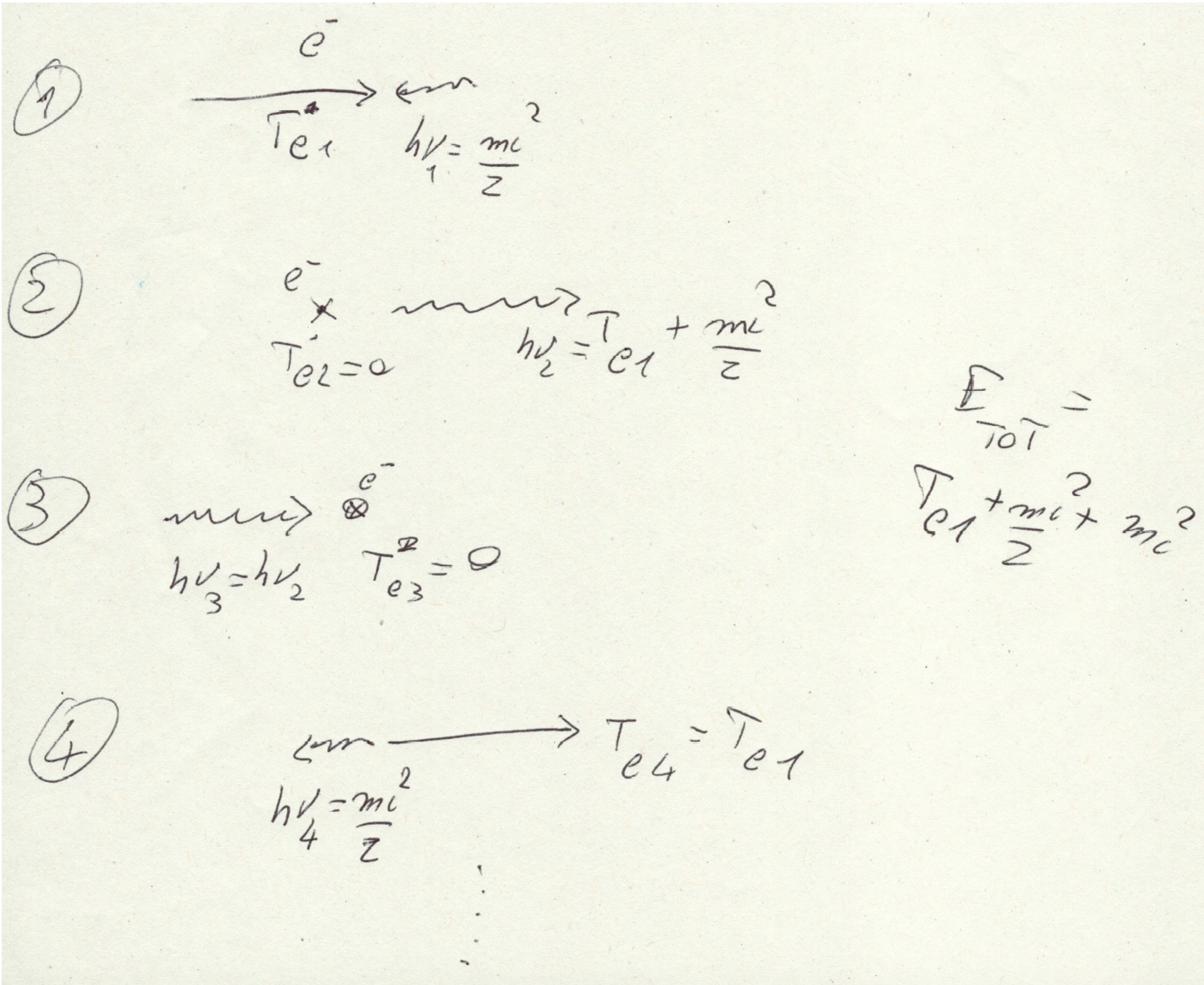
Figure 15: Acceleration in m/s^2 of the electrons (red) and temperature in eV (blue) of the Unruh thermal bath as function of the initial electron energy (GeV)

FICS Relay in the cosmo - a possible mechanism to propagate very high energy electrons in the universe

FICS

Direct Compton

FICS, etc, etc



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Grazie per l'attenzione
Thanks for your attention

Nuclear Instruments and Methods in Physics Research A 1069 (2024) 169964

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ELSEVIER

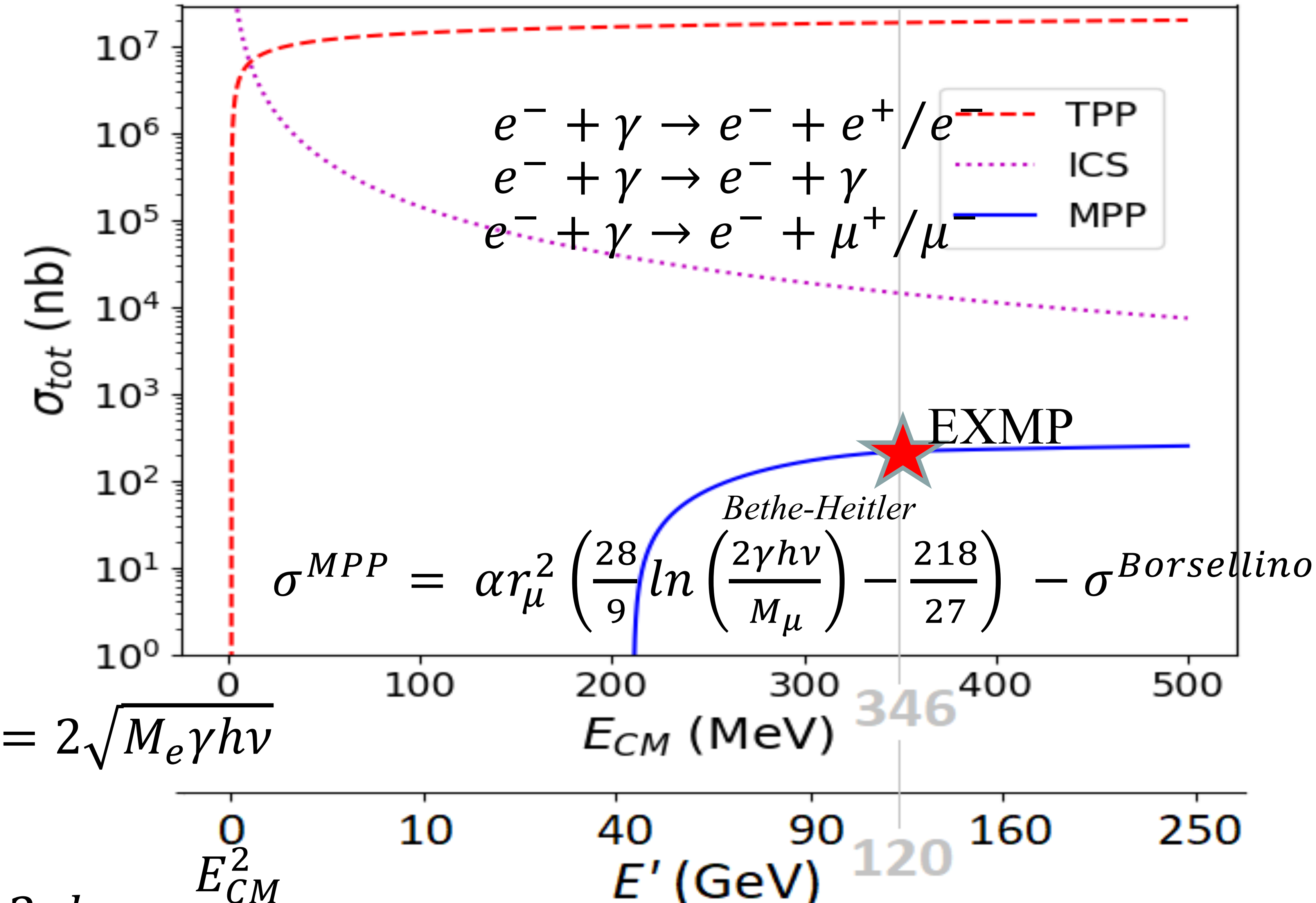
Full Length Article

Full inverse Compton Scattering: Total transfer of energy and momentum from electrons to photons

L. Serafini [a], V. Petrillo [a,b,*], S. Samsam [a]

[a] *INFN-Milano and LASA, Via G. Celoria 16, Milan, 20133, Italy*
[b] *University of Milan, Via G. Celoria 16, Milan, 20133, Italy*

Total cross-section for MPP (muon pair production), Bethe-Heitler: fraction of a μbarn at photon energies > 100 GeV onto electrons at rest



$$E_{CM} = 2\sqrt{M_e \gamma h\nu}$$

$$E' = 2\gamma h\nu = \frac{E_{CM}^2}{2M_e} \quad E_{CM-FICS} = 2M_e\sqrt{0.5\gamma}$$

$E_{CM\text{-}FICS\text{-}FCCee}$=320 MeV

Large Recoil in MPP damps the normalized emittance of the secondary generated muon beam

applied sciences

MDPI

Article

Electrons and X-rays to Muon Pairs (EXMP)

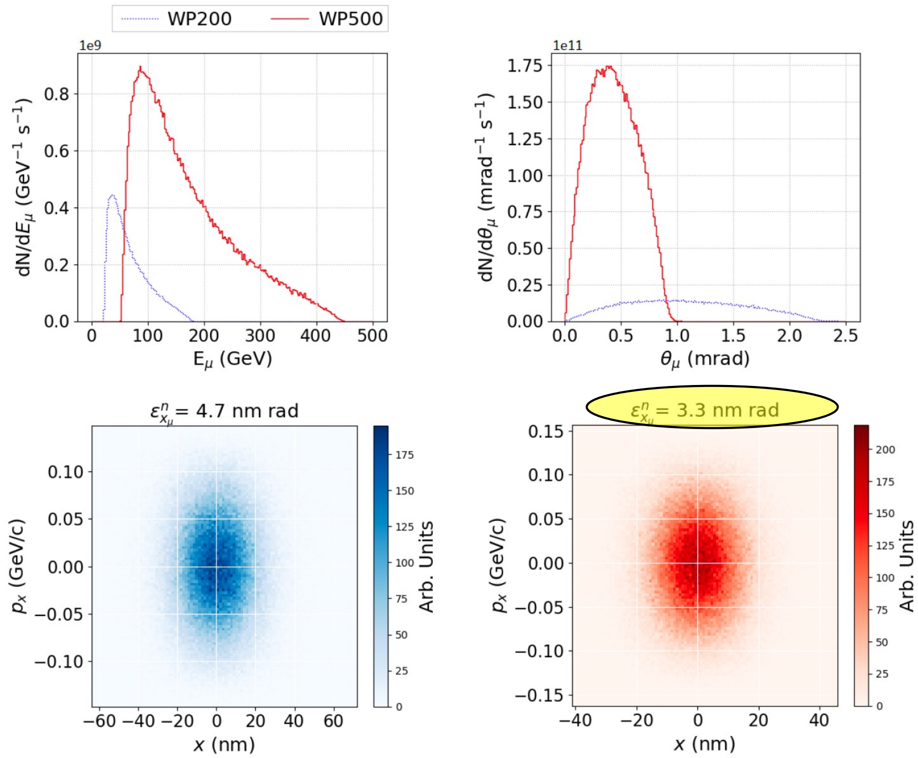
Camilla Curatolo * and Luca Serafini

INFN Sezione di Milano, via Celoria 16, 20133 Milan, Italy; luca.serafini@mi.infn.it
* Correspondence: camilla.curatolo@mi.infn

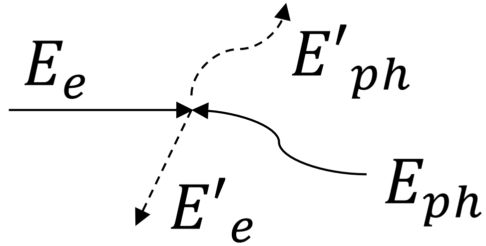
muon beam norm. emittance

$$\epsilon_\mu^n \simeq \frac{2}{3}\sigma_0\left(\frac{M_e}{2M_\mu}\sqrt{X}-1\right)+\frac{\epsilon_e^n}{\sqrt{X}}$$

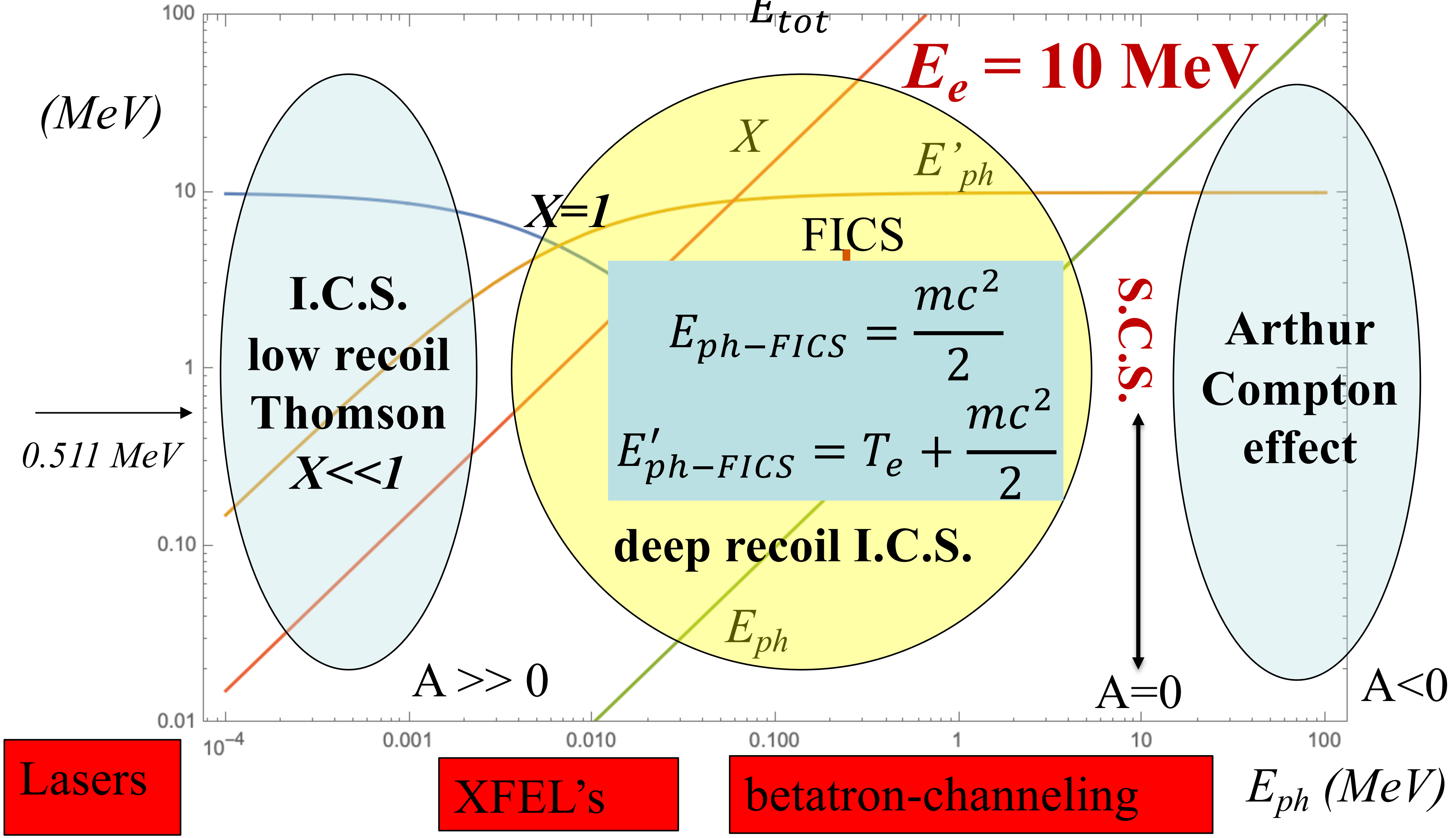
cmp. MAP norm. emitt. **2.5·10^4** *nm·rad after ionization cooling*



$X = 4 E_e E_{ph} / (mc^2)^2$ $\quad A = \beta\gamma^2 - X/4$



$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1+X} \qquad E'_e = \underbrace{E_e + E_{ph}}_{E_{tot}} - \frac{4\gamma^2 E_{ph}}{1+X}$$



$$f^{T}_{ICS} \equiv \frac{E'_{ph}}{(\gamma-1)mc^2}$$

if $\gamma \gg 1$ $\quad f^{T}_{ICS} \simeq \frac{X}{1+X}\left(1+\frac{1}{\gamma}\right)$

if $X \gg 1$ $\quad f^{T}_{ICS} \simeq 1 - \frac{1}{X} + \frac{1}{\gamma}$

$f^{T}_{ICS} < 1$ if $X < \gamma$, i.e. $E_{ph} < \frac{mc^2}{4}$

A simple yet fundamental question:

"Why do I need **150 Mega-electronVolt electrons** to generate **350 kilo-electronVolt photons**" ??
(STAR biased…)

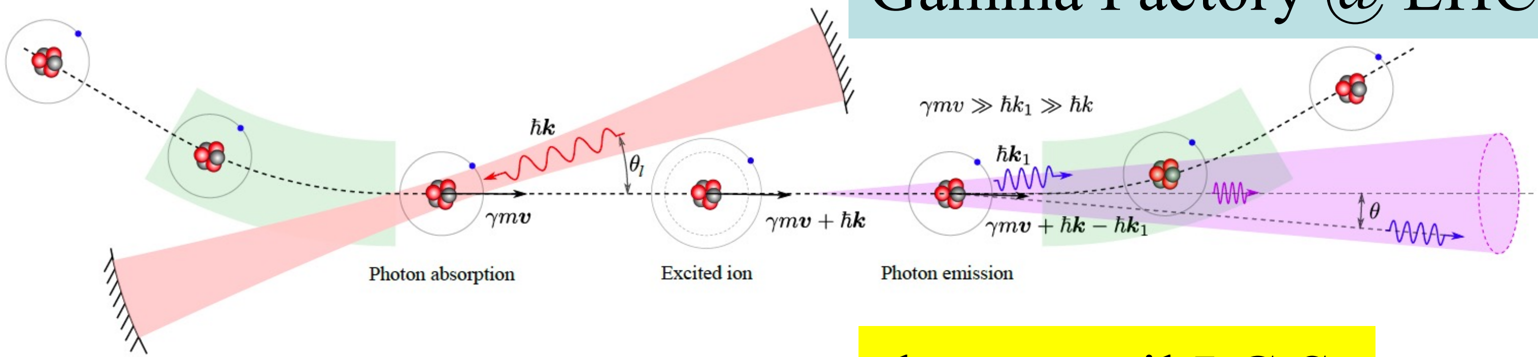
(not to mention a storage ring based light source where a GeV electron beam radiates tens keV photons)

How to transfer maximum energy from an electron to a photon…

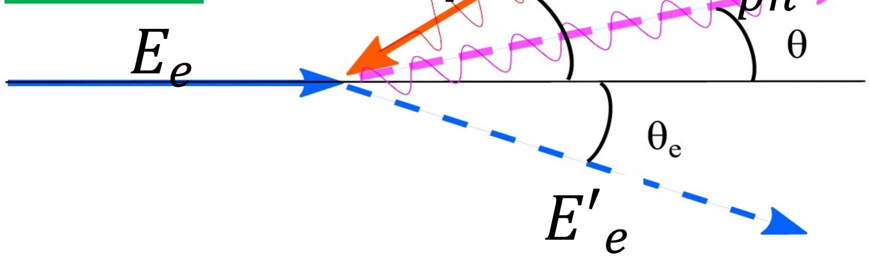
Collisional radiation

(quantum nature of light essential: Inverse Compton Scattering, Deep Recoil ICS for e+ or μ^+, μ^- secondary beam generation, Relativistic Rayleigh Scattering)

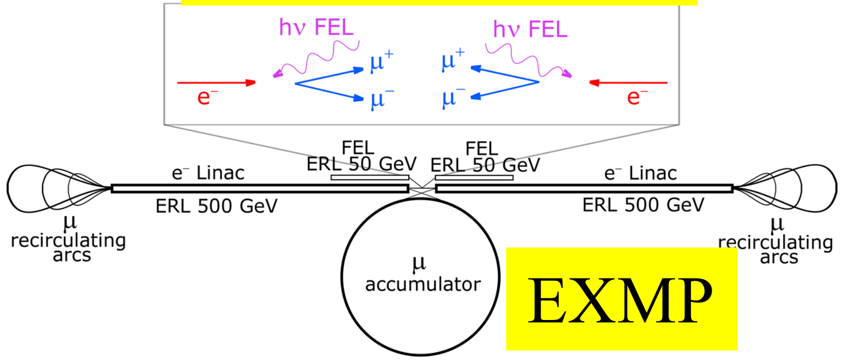
Gamma Factory @ LHC



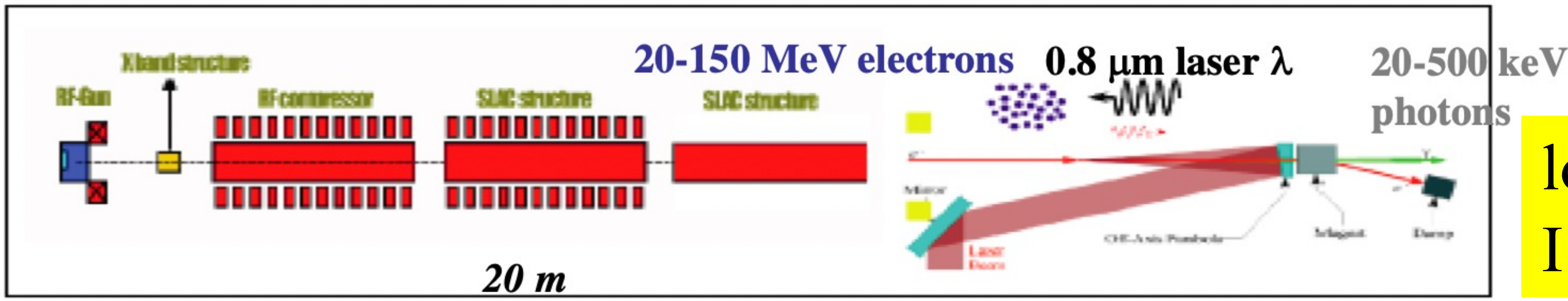
I.C.S.



deep recoil I.C.S.



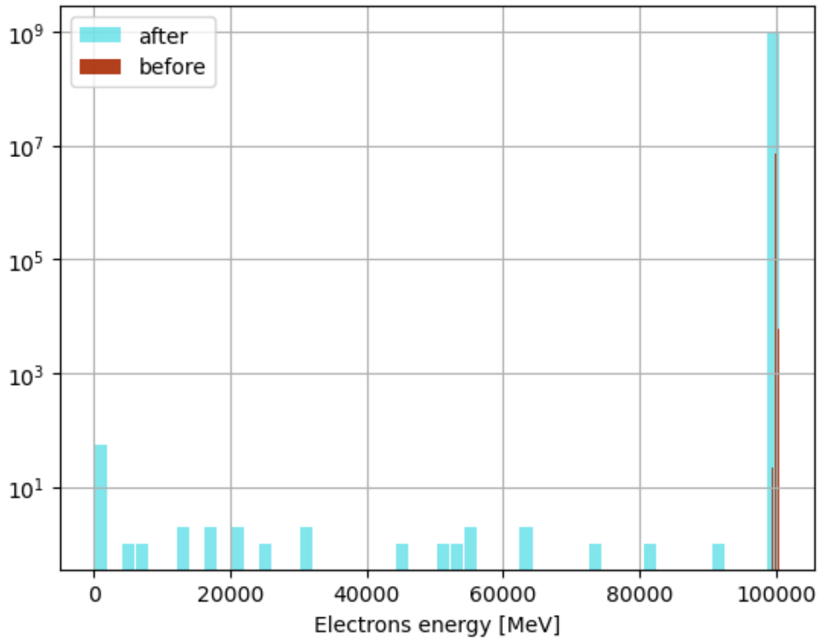
EXMP



low recoil I.C.S. - STAR

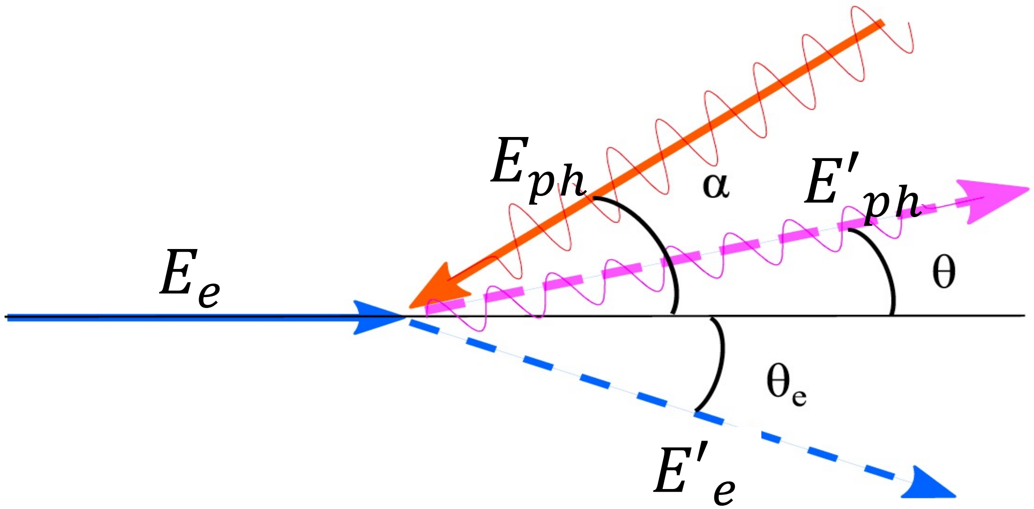
255.5 keV 10^12 photons

```
### Electrons beam parameteres

n_macro=1e8; # Number of macroparticles
chargebunch = 1e-9; # Charge per electrons bunch [C] pico->10^-
12 femto->10^-15
beam_energy_MeV=100e3; # initial beam energy MeV
energy_spread=0.1e-2; # initial relative energy spread (not in
[%])

norm_emit_x=1e-6; # Normalised emittance x [m rad]
norm_emit_y=1e-6; # Normalised emittance н [m rad]
sigma_e_x=1e-6; # horizontal electron beam size [m]
sigma_e_y=1e-6; # vertical electron beam size [m]
bunch_length=1e-12*3e8; # initial bunch length [m]



### LASER parameteres
angle_deg=0; # in degree
pulseE=0.0361095; #laser puse energy [J]
sigLrx=10; #/2; % given in [mu m] micro meter like
sigLry=10; #/2; % given in [mu m] micro meter like
laserwl=0.00549819; # laser wavelenth [nm] nano meters
sigt=1; #pulse length [ps]
```



The $\gamma^2\theta^2$ issue/disease

All radiation originated by a Lorentz Boost associated to relativistic emitting particles (electrons, heavy ions) is intrinsically poli-chromatic because of $\gamma\theta$ correlation (energy boost of scattered photons depends on scattering angle, at $\theta=1/\gamma$ photon energy is 50% of max photon energy at $\theta=0$) of single electron spectrum (on top of inhomogeneous effects)



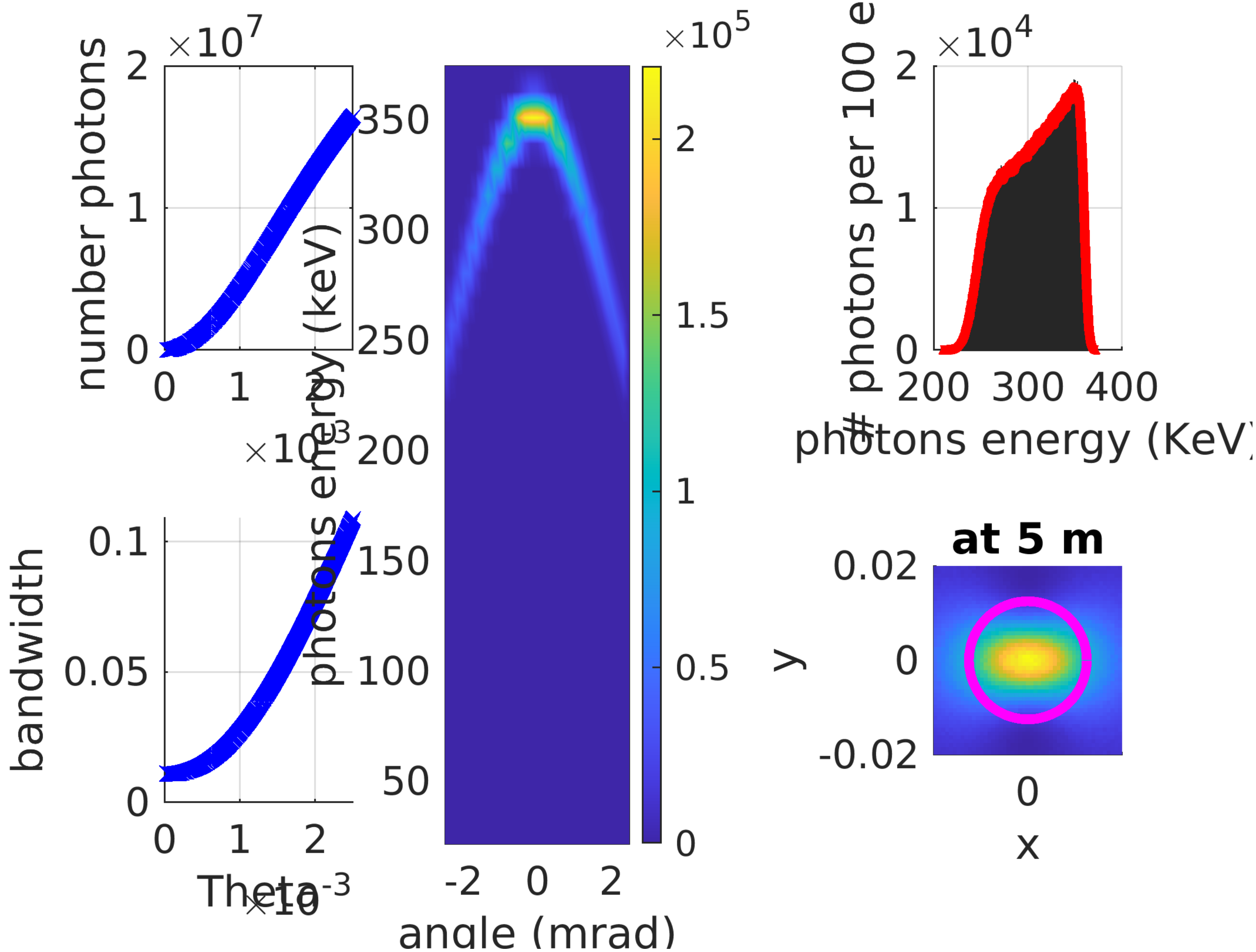
$$E_e = \gamma m c^2$$

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1 + X + \gamma^2\vartheta^2}$$

$$X \equiv \frac{4\gamma E_{ph}}{mc^2} = \frac{2E_{ph}^{ERF}}{mc^2}$$

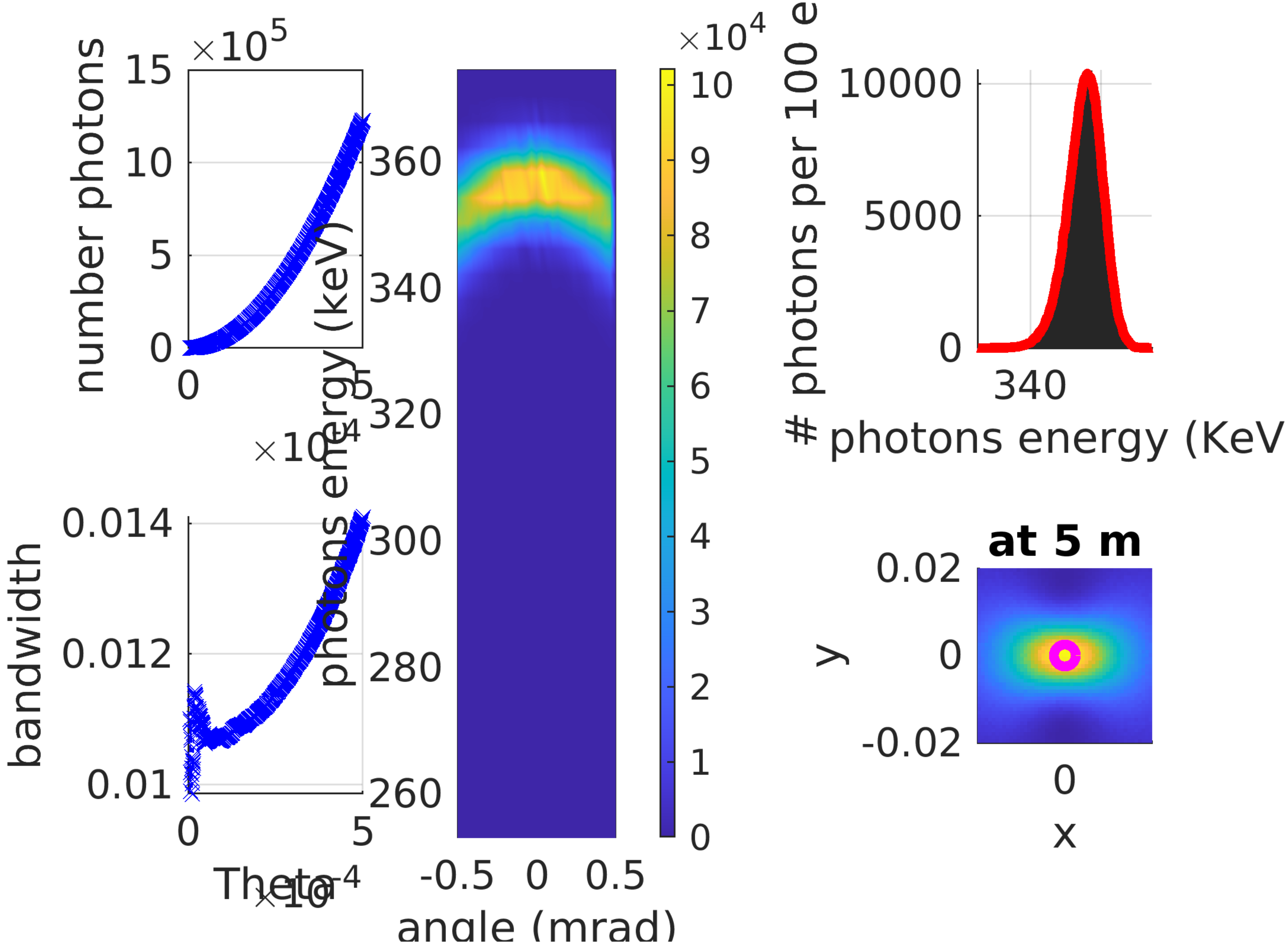
True for all kinds of Undulatory and Collisional radiation (bremsstrahlung, wiggler/betatron, synchrotron, RRS, ICS), while resonant or amplified radiation (undulators, FELs), that are diffraction limited thanks to their beam quality, are not (or only partially) affected

WP 140 MeV



Courtesy I. Drebot

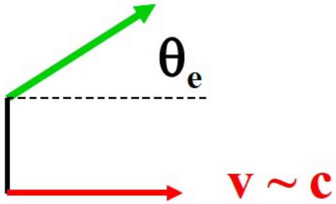
WP 140 MeV



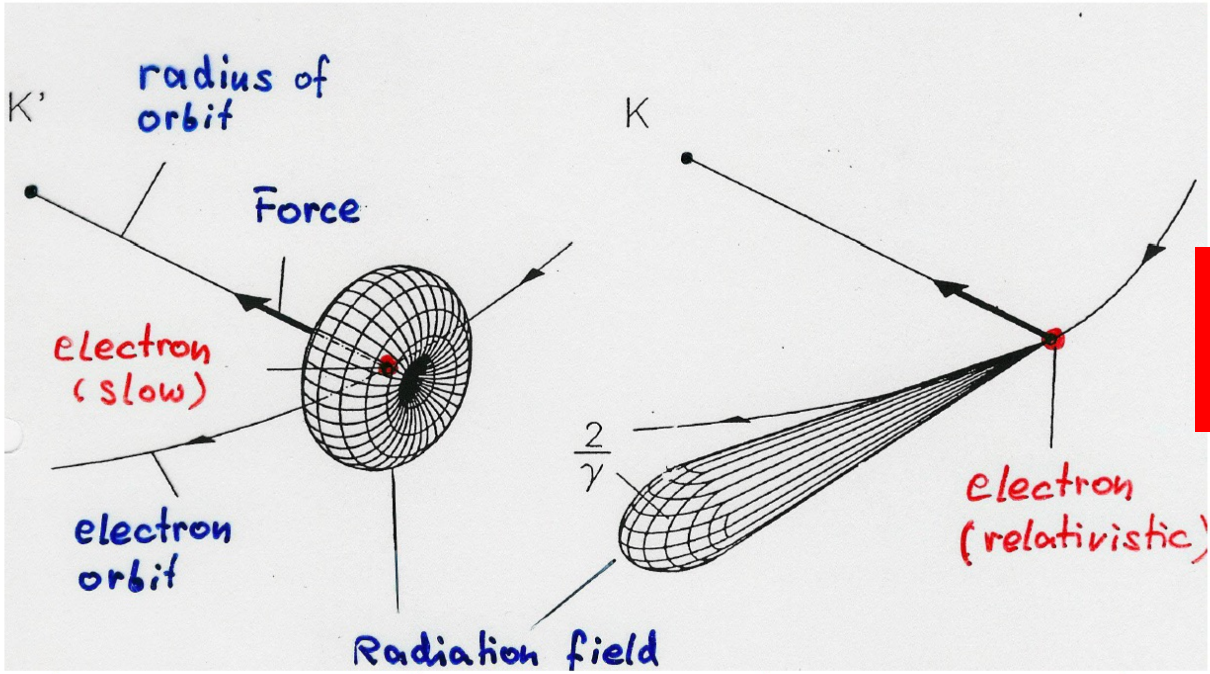
Courtesy I. Drebot

Also synchrotron radiation is affected by the $\gamma^2\theta^2$ red shift

Radiation is emitted into a narrow cone



$$\theta = \frac{1}{\gamma} \cdot \theta_e$$



Lorentz boost

v << c

v ≈ c

Courtesy L. Rivkin

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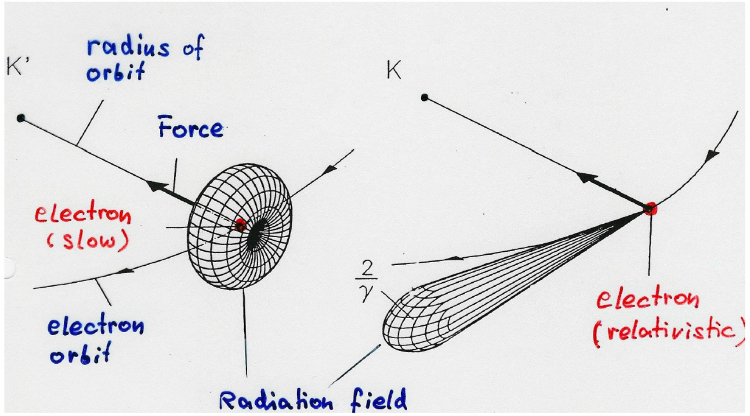
All spontaneous undulatory X/γ Radiation Sources (keV, MeV, GeV…) are affected by the angular correlation

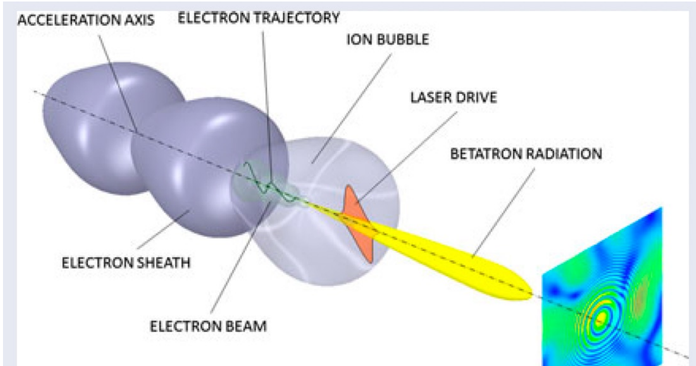
Spontaneous undulatory radiation (synchrotron, wiggler, *betatron*, *channeling*, *bremsstrahlung*)



v << c

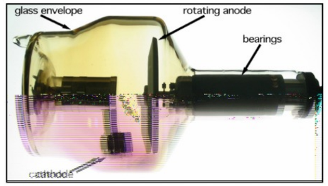
v ≈ c

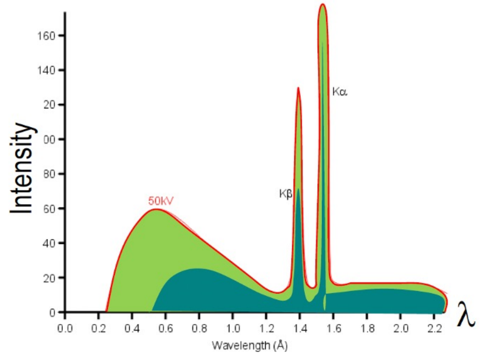
$$E_X = f(\gamma^2\vartheta^2)$$



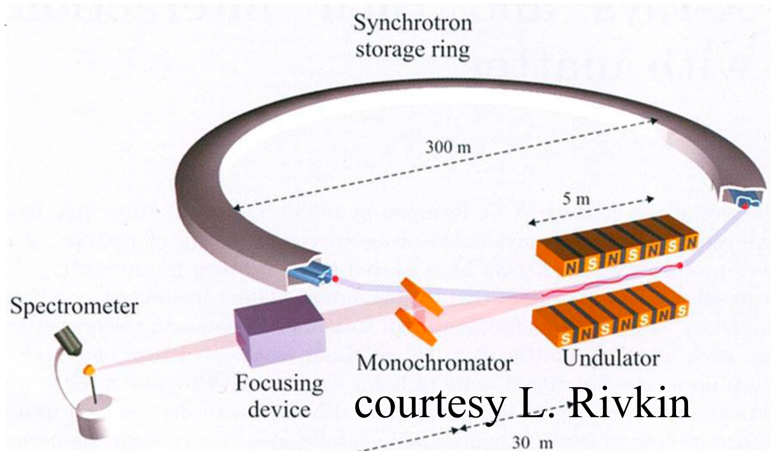
courtesy B. Paroli, M. Potenza

Rotating Anode Tube





Resonant/amplified undulatory radiation (undulator, FEL)



courtesy L. Rivkin

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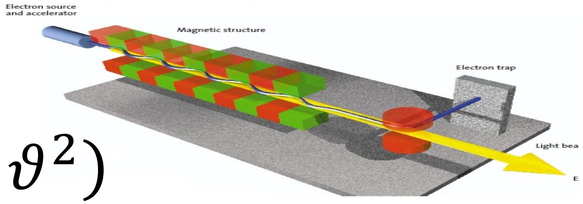
Optics Communications

Volume 50, Issue 6, 15 July 1984, Pages 373-378

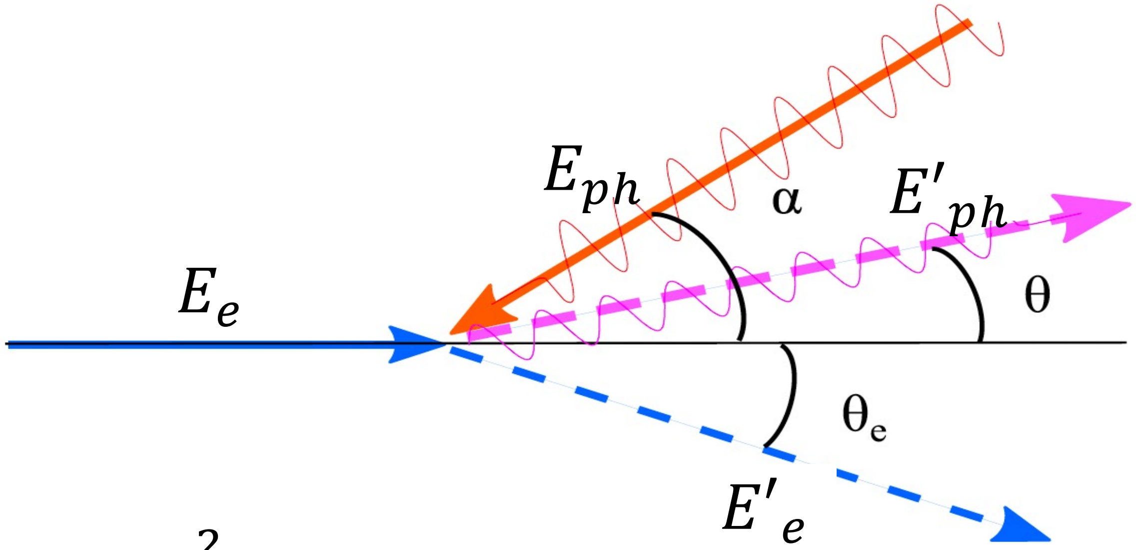
Collective instabilities and high-gain regime in a free electron laser

R. Bonifacio *, C. Pellegrini, L.M. Narducci



$$E_X \neq f(\gamma^2\vartheta^2)$$

General Compton Scattering geometry between an incident electron E_e and a photon E_{ph} at a collision angle α, photon E'_{ph} scattering angle θ and electron E'_e scattering angle θ_e



$$E_e = \gamma m c^2$$

a) $\gamma = 1$ *Direct Compton effect* Energy/momentum transferred from photon to e-

b) $\gamma \gg 1$ *Inverse Compton* Energy/momentum transferred from e- to photon

We are not considering in this study non-linear effects due to photon (laser) pulse intensity

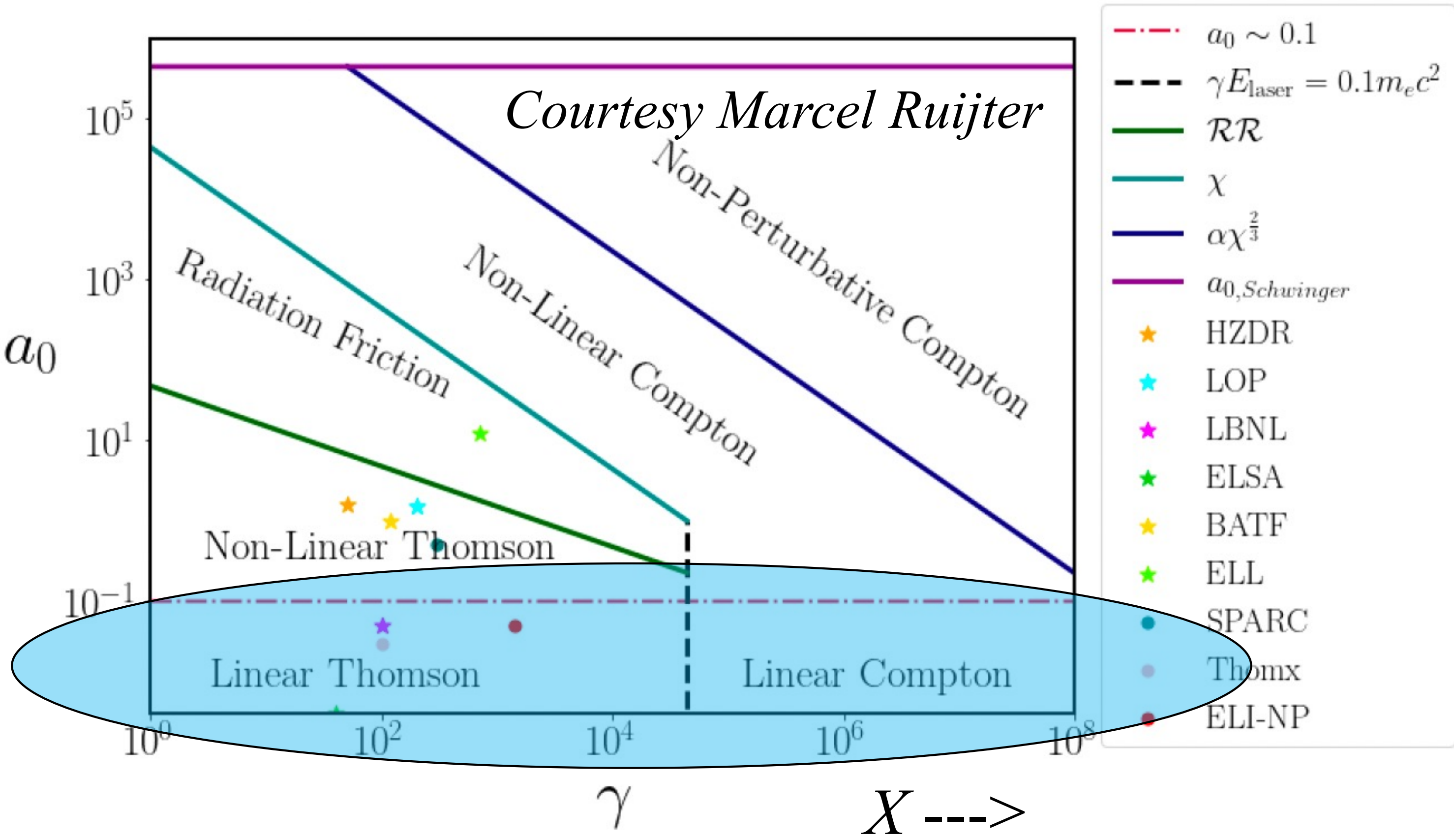
$$a_{0,\text{linear}} = \frac{q}{mc^2}\sqrt{\frac{c}{4\pi}}\frac{\lambda}{2\pi}\sqrt{2I_{\text{peak}}}$$

$$= 0.85\lambda[\mu\text{m}]\sqrt{\frac{I_{\text{peak}}[\frac{\text{W}}{\text{cm}^2}]}{10^{18}}}$$

$$a_{0,\text{circular}} = \frac{q}{mc^2}\sqrt{\frac{c}{4\pi}}\frac{\lambda}{2\pi}\sqrt{I_{\text{peak}}}$$

no collective multi-photon effects
only single electron-photon interaction
(à la Klein-Nishina, linear QED)

Deep Recoil ICS
FICS



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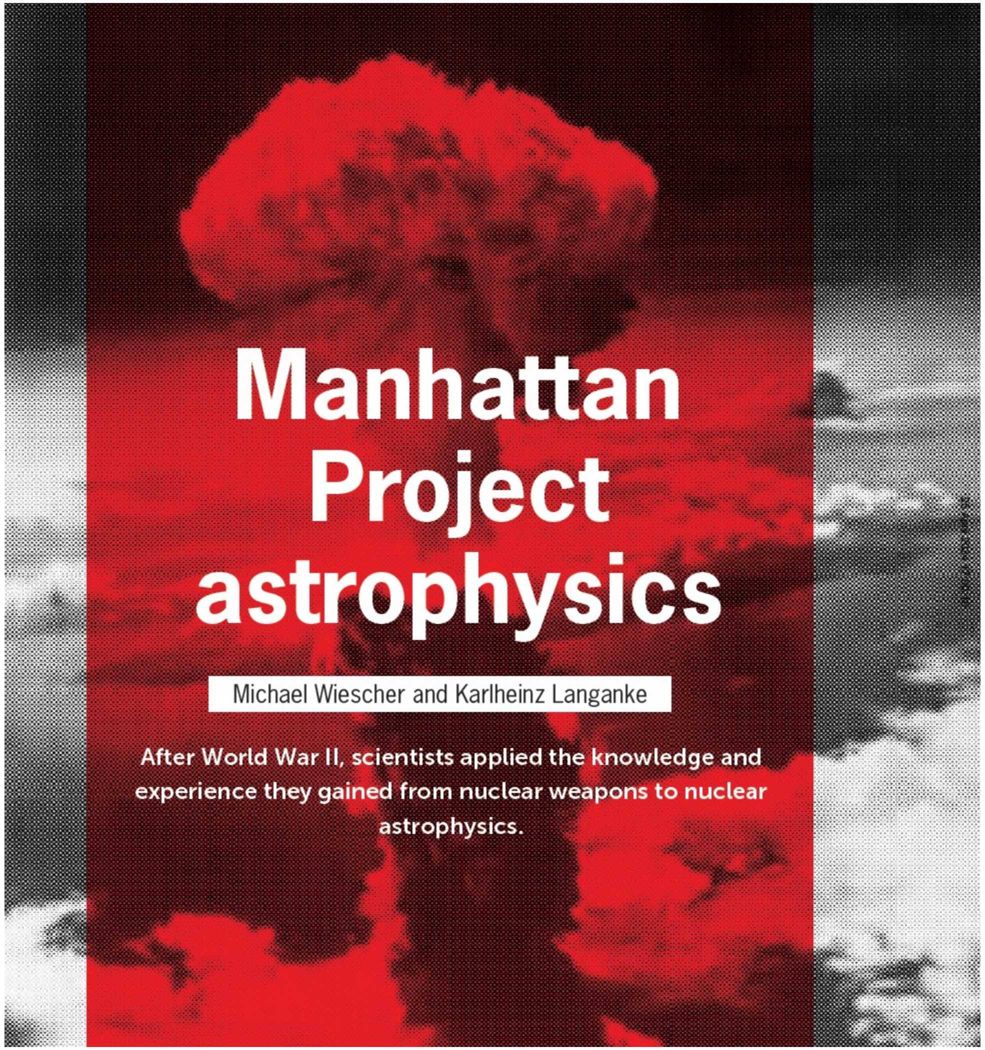
A. Compton 1923 - Direct Compton effect

First consideration and study of Inverse Compton Scattering….

During the development of the nuclear bomb!

The Manhattan Project

Will the back-scattered photons, by hot electrons of the plasma created in the initial stage of the nuclear bomb explosion, release energy from the fire-ball decreasing its temperature???



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gen content. Of even more concern were the tests of 20-megaton thermonuclear weapons (so-called hydrogen bombs), and scientists even considered the possibility of the fusion of ^{16}O atoms in ocean water.[2] Their explosions would increase the sudden energy release by up to three orders of magnitude. The uncertainties in the initial crude energy release and cooling calculations required experimental verification.

Experiment confirms theory

To experimentally clarify the troubling situation, a dedicated accelerator was built at Oak Ridge National Laboratory in the early 1950s, which made it possible to measure fusion cross sections for $^{14}N + ^{14}N$, $^{16}O + ^{16}O$, and other reactions of medium-heavy nuclei.[3] Alexander Zucker, one of the young scientists who was to measure the effective cross sections and who would later be director of Oak Ridge, noted that for security reasons he and other experimentalists were not

... data.
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well below the Coulomb barrier, and the likelihood of fusion is low.

The Oak Ridge fusion tests were not confined to nitrogen and oxygen nuclei; they also included tests on light isotopes such as deuterium and tritium and were meant to inform Teller's plans and ideas for developing the "Super," his label for a thermonuclear weapon based on fusion. The idea for the fusion bomb based on the fusion of deuterium and tritium

fire-ball becomes transparent to photons, that can take energy off the fire-ball, limiting the maximum temperature down to a "safe" level

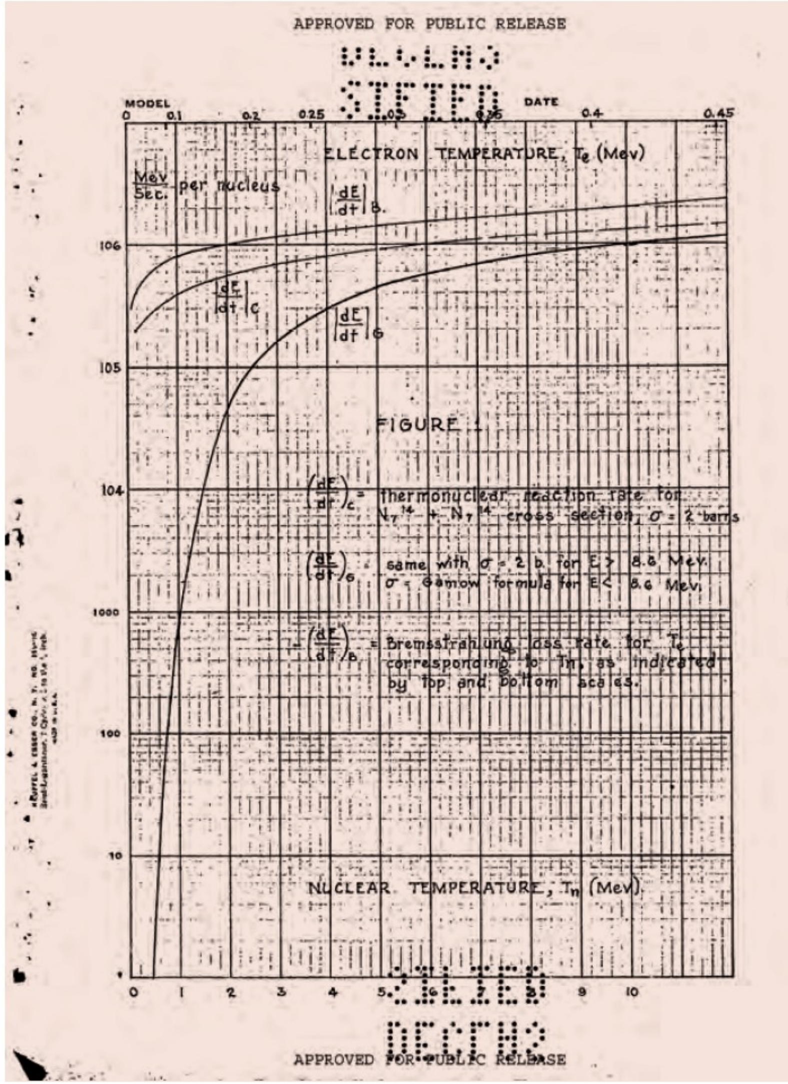

FIGURE 3. A CRITICAL PLOT of the rate of energy production as a function of temperature (in megaelectron volts), from the originally classified 1946 Los Alamos report *Ignition of the Atmosphere with Nuclear Bombs*.[1] Three curves characterize the energy-transport conditions for different temperatures in the nuclear fireball. The $(dE/dt)_C$ curve shows the reaction rate for the fusion of two nitrogen-14 nuclei when a constant cross section is assumed. The $(dE/dt)_G$ curve shows the $^{14}N + ^{14}N$ fusion reaction rate when the cross section is assumed to rapidly decrease at low energies, as predicted by George Gamow. And the $(dE/dt)_B$ curve shows the radiative energy loss through x-ray emission, as predicted by Arthur Compton. (From ref. 1.)

25 April 2024 17:00:10

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A. Compton 1923 - Direct Compton effect

- J. Follin 1947 - Inverse Compton Scattering
  *first published (non classified) study on ICS**

PROPAGATION OF COSMIC RAYS THROUGH

INTERSTELLAR SPACE

Thesis by

James Wightman Follin, Jr.

Second motivation to study ICS in the late '40s was understanding why electrons are almost missing in cosmic rays bombarding the upper atmosphere

In Partial Fulfilment of the Requirements for the

Degree of Doctor of Philosophy

Both directions (nuclear bomb and astrophysics) were looking for a mechanism capable to transfer maximum energy from the electrons to the photons

California Institute of Technology

Pasadena, California

1947

* *but unknown and not credited in the whole literature on ICS*

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Publication referenced by everybody in ICS community as the first published paper on ICS

PHYSICAL REVIEW VOLUME 73, NUMBER 5 MARCH 1, 1948

Interaction of Cosmic-Ray Primaries with Sunlight and Starlight*

E. FEENBERG AND H. PRIMAKOFF
Washington University, St. Louis, Missouri

(Received November 20, 1947)

This paper discusses collision processes between cosmic-ray primaries (protons and electrons) and the thermal photons of sunlight and starlight. In particular, electron-positron pair production and Compton scattering in interplanetary, intragalactic, and intergalactic space are treated in detail. It is found that the number of collisions between primary particles and thermal photons in single traversals energetic scattered photons. The same statement holds for the primary protons even on an intergalactic scale. On the other hand, energetic primary electrons may experience a sufficient number of Compton collisions in intergalactic space (travel time of the order 2×10^9 years) to eliminate them effectively from the cosmic radiation reaching the neighborhood of the earth.

* The research described in this paper was supported in part by contract N60RI-117, U.S. Navy Department.

[1] T. H. Johnson, Rev. Mod. Phys. **11**, 208 (1939); M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **59**, 615 (1941); **59**, 930 (1941).

[2] Collisions between high energy photons, considered as cosmic-ray primaries, and thermal photons, with resultant electron-positron pair creation have been considered by G. Breit and J. A. Wheeler, Phys. Rev. **46**, 1087 (1934); **45**, 134 (A) (1934). Extensive calculations similar to the present have been carried out by J. W. Follin, Bull. Am. Phys. Soc. July 11, 1947, Abstract D5. Through the courtesy of Dr. J. R. Oppenheimer, we have seen a manuscript copy of Dr. Follin's paper.

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First idea by Milburn: use electron accelerators to perform Inverse Compton Scattering in the laboratory vs. the cosmos

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)

Compton scattering by starlight quanta has been postulated by Feenberg and Primakoff to be a mechanism for the energy degradation of high-energy electrons in interstellar space.[1] We shall discuss here the possibility of observing this phenomenon directly in the laboratory by scattering a multi-GeV electron beam against the intense flux of visible photons produced by a typical laser. It will be shown that using existing laser systems and electron accelerators, one may expect to obtain of the order of several thousand collimated high-energy scattered photons during each accelerator pulse, and that these quanta retain to a high degree the polarization of the original beam of optical photons.

The kinematic formulas for Compton scattering on moving electrons are given by Feenberg and Primakoff.[2] We shall consider the special case of an extreme-relativistic electron of energy $E = \gamma mc^2$, $\gamma = 1/(1-\beta^2)^{1/2} \gg 1$, incident head-on upon a beam of photons of energy $k_i = (1-3)$ eV propagating in the opposite direction. An observer moving with the incident electron will see a photon of energy $k_0 = 2\gamma k_i$. In Table I are listed for various laboratory electron energies, E, the corresponding values of k_i tabulated in terms

The approximation fails only near $x = 1$, for which $k_f = k_i$ is required. However, for large $\gamma = E/mc^2$ the bulk of the scattered photons is folded back and emerges in the laboratory in the direction of motion of the incident electron, making angles with that direction given by $\theta = 2\tan(\frac{1}{2}\theta) = (1/\gamma) \times \cot(\frac{1}{2}\theta_0)$. Thus for 1-GeV electrons, all photons having $23° < \theta_0 < 180°$ will end up within 0.0025 radian of the electron direction. We shall confine our discussion to these high-energy quanta. The

Table I. Energy, λ, polarization, and cross section for highest energy photons produced by ruby-laser photons scattered on electrons of energy E. The quantity $\sigma_{1/2}$ is the cross section for higher half of k_f spectrum.

E (GeV)	λ	$(k_f)_{max}$ (MeV)	P_{max}	$\sigma_{1/2}$ (mb)
1.02	0.014	28	1.00	320
2.92	0.040	216	1.00	310
4.16	0.057	426	0.99	300
4.60	0.063	515	0.99	290
5.11	0.070	628	0.99	290
5.48	0.075	715	0.99	290
5.84	0.080	806	0.99	280

PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 020702 (2016)

Narrow-band GeV photons generated from an x-ray free-electron laser oscillator

Ryoichi Hajima[1,*] and Mamoru Fujiwara[1,2]
[1]*Quantum Beam Science Center, Japan Atomic Energy Agency, Tokai, Naka, Ibaraki 3191195, Japan*
[2]*Research Center for Nuclear Physics, Osaka University, Mihogaoka 10-1, Ibaraki 5670047, Japan*
(Received 17 July 2015; published 16 February 2016)

We propose a scheme to generate narrow-band GeV photons, γ-rays, via Compton scattering of hard x-ray photons in an x-ray free-electron laser oscillator. Generated γ-rays show a narrow-band spectrum with a sharp peak, ~0.1% (FWHM), due to large momentum transfer from electrons to photons. The γ-ray beam has a spectral density of ~10^2 ph/(MeV s) with a typical set of parameters based on a 7-GeV electron beam operated at 3-MHz repetition, Such γ-rays will be a unique probe for studying hadron physics. Features of the γ-ray source, flux, spectrum, polarization, tunability and energy resolution are discussed.

DOI: 10.1103/PhysRevAccelBeams.19.020702

$$\Sigma_{TH} = 670\ mbarn\ 0-recoil$$

Deep Recoil
and its 2 benefits:
spectral purification
and
suppression of $\gamma^2\theta^2$ desease

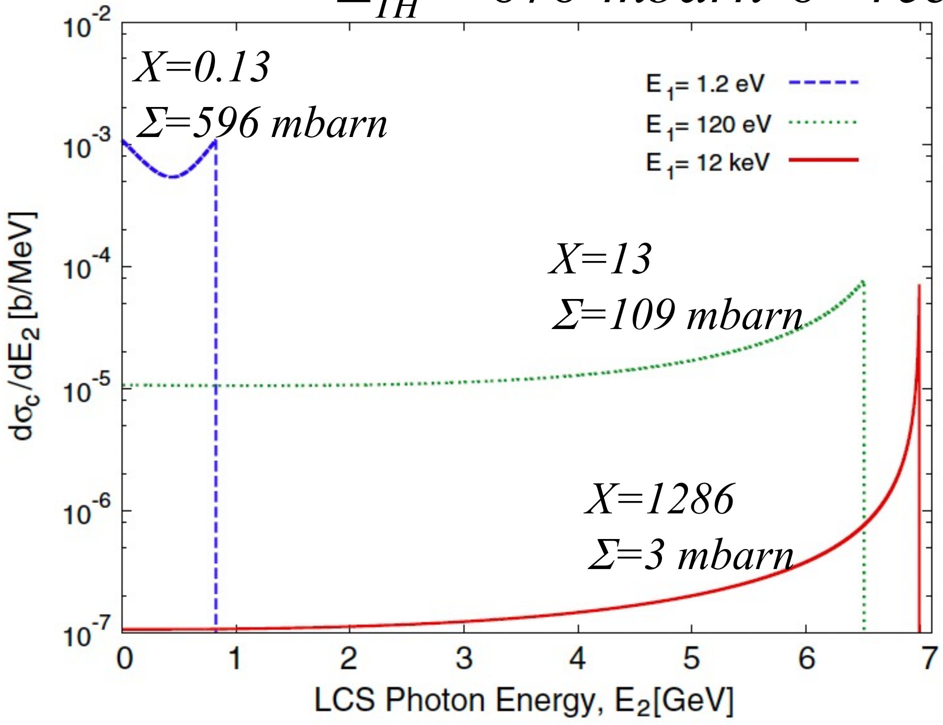


FIG. 3. Energy-differential cross section of Compton scattering for 7 GeV electrons and laser photons at three different energies of 1.2 eV, 120 eV and 12 keV.

Inverse Compton Scattering of photons on relativistic electrons, $\theta < 1/\gamma$

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1+\gamma^2\vartheta^2 + X}$$

$$X = \frac{4E_{ph}E_e}{(mc^2)^2}$$

Thomson limit: X << 1

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1+\gamma^2\vartheta^2}$$

$$E'_{ph}\left(\vartheta = \frac{1}{\gamma}\right) = 2\gamma^2 E_{ph} = \frac{E'_{ph}(\vartheta=0)}{2}$$

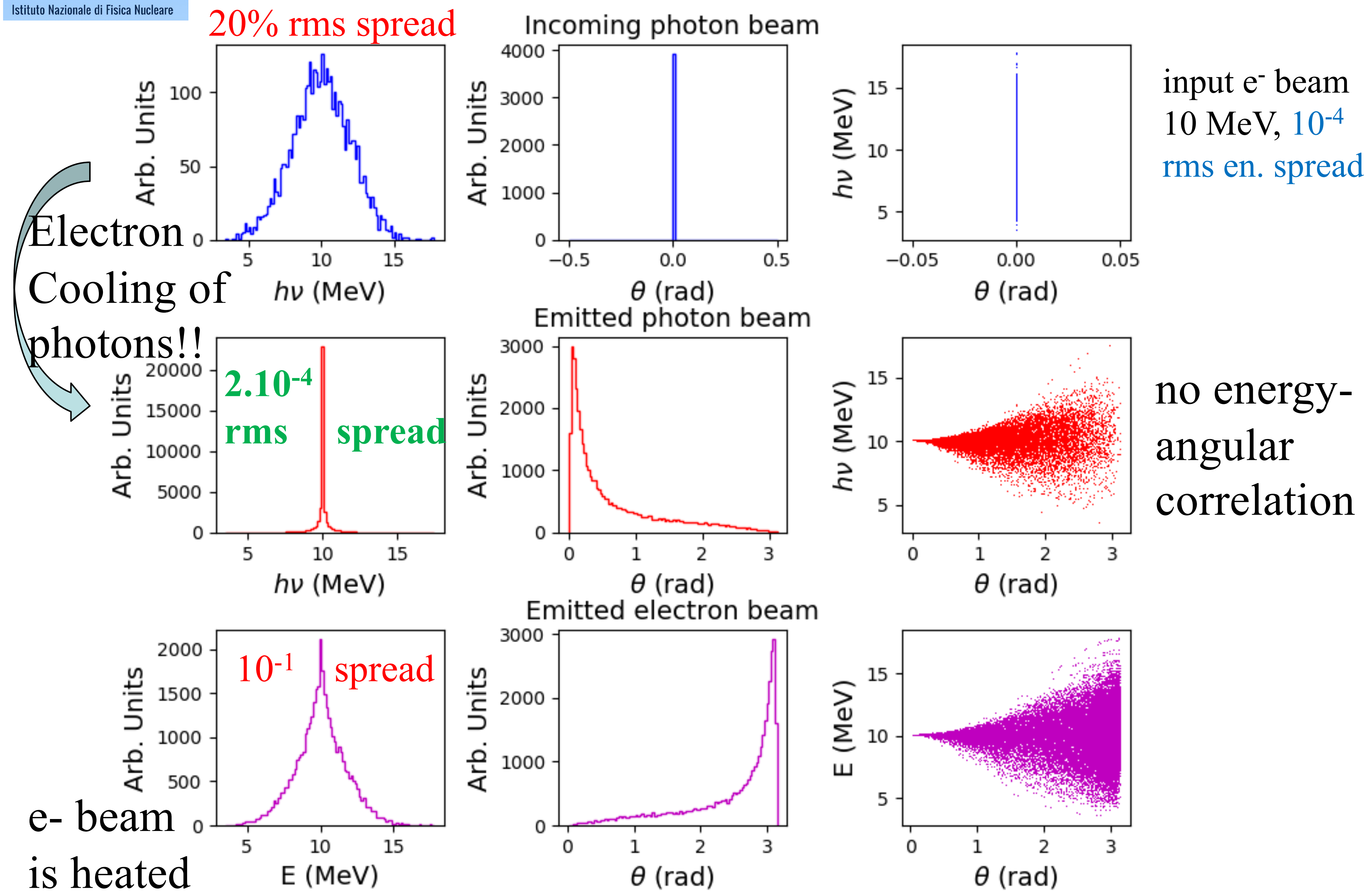
Deep recoil Compton: X >> 1

$$E'_{ph} \sim \left(1 - \frac{1}{X} - \frac{\gamma^2\vartheta^2}{X}\right) E_e$$

$$E'_{ph}\left(\vartheta = \frac{1}{\gamma}\right) \sim \left(1 - \frac{2}{X}\right) E_e$$

$$note\ that\ \ E_{cm} = mc^2\sqrt{1+X}\,, \qquad if\ X \gg 1 \Rightarrow X \sim \left(\frac{E_{cm}}{mc^2}\right)^2$$

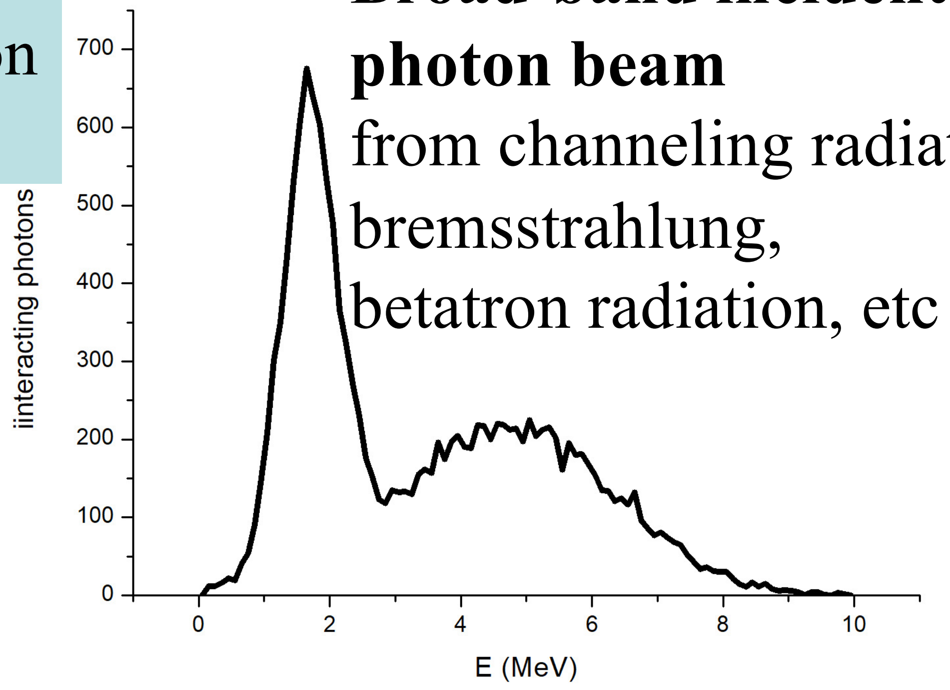
Previous Seminars: 1) Cooling of Photons in Symmetric Compton Scattering (S.C.S.)



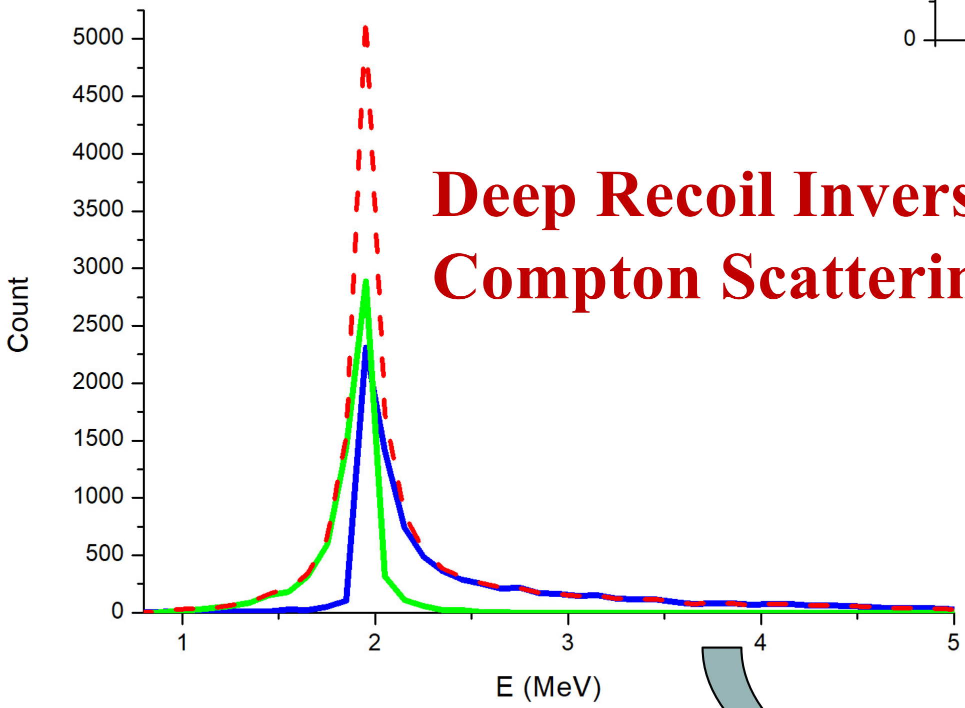
C. Curatolo - Whizard

Previous Seminars:
2) Spectral Purification
in deep recoil I.C.S.

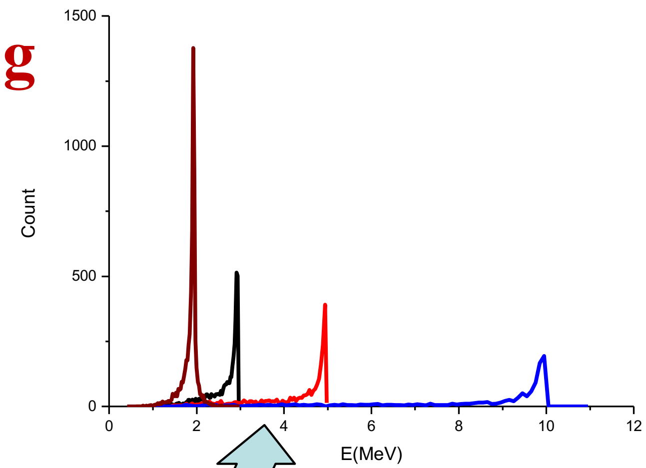
Broad-band incident photon beam
from channeling radiation,
bremsstrahlung,
betatron radiation, etc



spectral purification

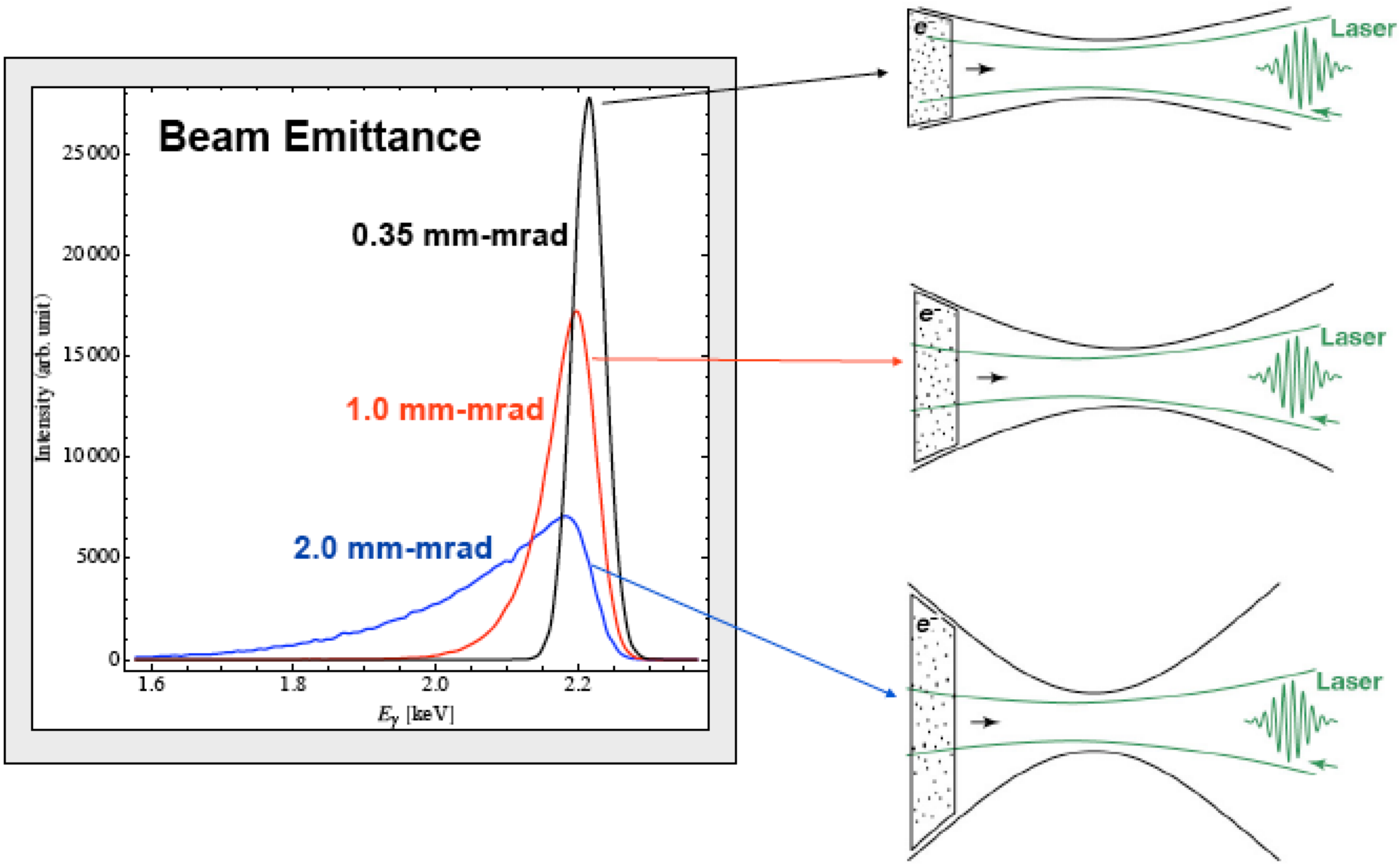


Deep Recoil Inverse Compton Scattering



tunability

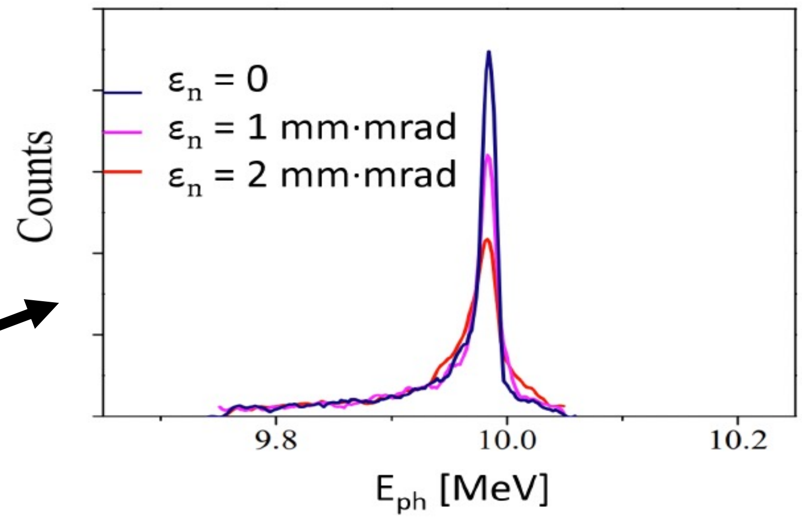
Lorentz boosted radiation (synchrotron, ICS, FEL, etc) is strongly affected by the emittance of the electron beam



Courtesy C. Barty - LLNL

Deep Recoil suppresses the $\gamma^2\theta^2$ disease and the bandwidth broadening effect due to electron beam emittance according to *Petrillo-Serafini criterion*

$$\begin{cases} bw \geq \dfrac{2\varepsilon_n^2}{\sigma_x^2} \\ S_d \propto \dfrac{\langle I_e \rangle U_{las}}{\varepsilon_n^2 E_x} \end{cases}$$



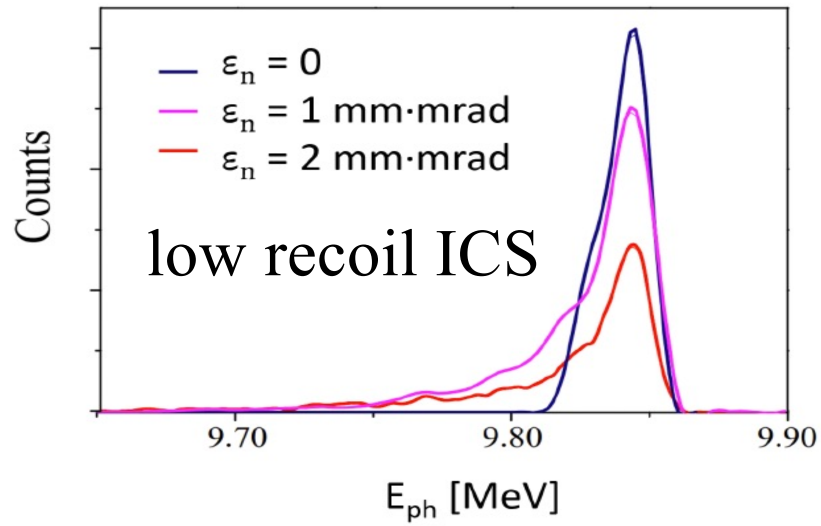
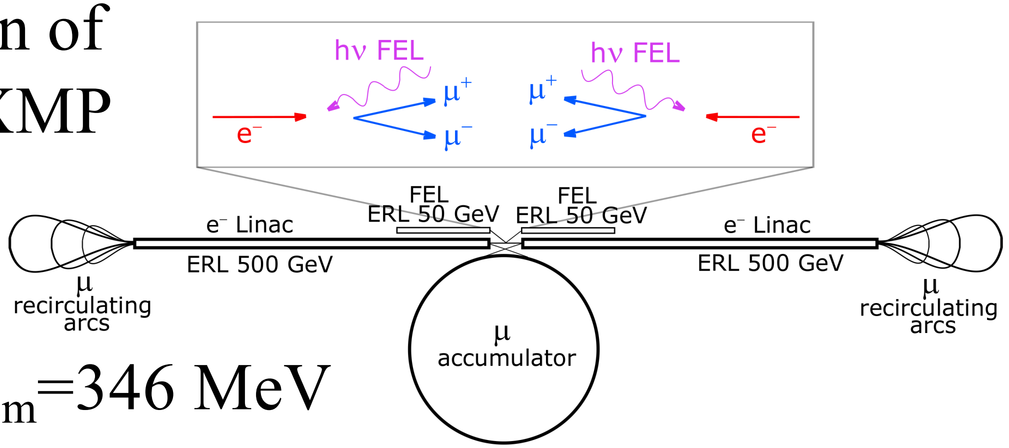


Figure 4: Bandwidth dependence on electron beam emittance. Comparison between SCS and ICS. Upper window: electron energy 10 MeV, incident photon energy 10 MeV with 20% relative bandwidth, emitted photon energy 10 MeV, interaction rms spot size 10 μm, normalized emittance 0 mm·mrad,1 mm·mrad, 2 mm·mrad. Lower window: electron energy 659 MeV, incident photon energy 1.5 eV ($5 \cdot 10^{-4}$ relative bandwidth), collimation angle= 50 μrad, emitted photon energy about 10 MeV, interaction rms spot size 10 μm, normalized emittance 0 mm·mrad, 0.17 mm·mrad, 0.25 mm·mrad

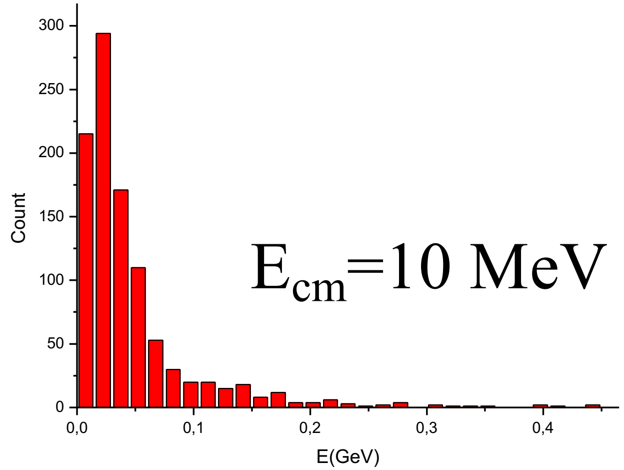
Ultra-low emittance positron beams from deep recoil electron-photon collider: 5 GeV ERL vs. 5 keV FEL, X=391

up to $10^{13\text{-}14}$ e^+/s at 50 MeV within 5% en. spread

Son of EXMP



E_{cm}=346 MeV

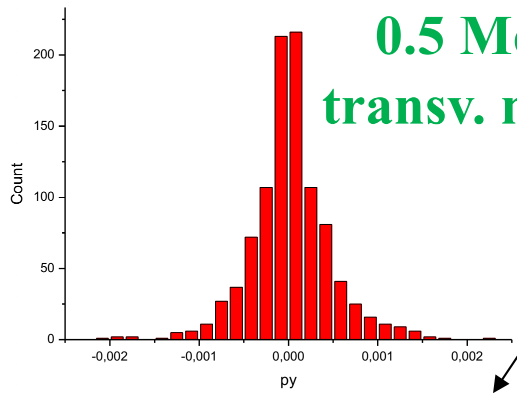


E_{cm}=10 MeV

Table 4: Future Positron Collider Projects [53, 59, 61–66].

Project	CLIC	ILC	LHeC (pulsed)	LEMMA	CEPC	FCC-ee
Final e^+ energy [GeV]	190	125	140	45	45	45.6
Primary e^- energy [GeV]	5	128** (3*)	10	–	4	6
Number of bunches per pulse	352	1312 (66*)	10^5	1000	1	2
Required charge [10^{10} e^+/bunch]	0.4	3	0.18	50	0.6	2.1
Horizontal emittance $\gamma\epsilon_x$ [μm]	0.9	5	100	–	16	24
Vertical emittance $\gamma\epsilon_y$ [μm]	0.03	0.035	100	–	0.14	0.09
Repetition rate [Hz]	50	5 (300*)	10	20	50	200
e^+ flux [10^{14} e^+/second]	1	2	18	10–100	0.003	0.06
Polarization	No/Yes***	Yes/(No*)	Yes	No	No	No

* The parameters are given for the electron-driven positron source being under consideration.
** Electron beam energy at the end of the main electron linac taking into account the looses in the undulator.
*** Polarization is considered as an upgrade option.



0.5 MeV/c rms transv. momentum

0.5-1*10^{-7} m·rad rms norm. transv. emittance with round beam (no-cooling)

V. Petrillo, A. Puppin – Whizard

FICS - Full Inverse Compton Scattering - how to achieve 10^{30} m/s^2 acceleration to sense Unruh radiation

Nuclear Instruments and Methods in Physics Research A 1069 (2024) 169964

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Full Length Article

Full inverse Compton Scattering: Total transfer of energy and momentum from electrons to photons

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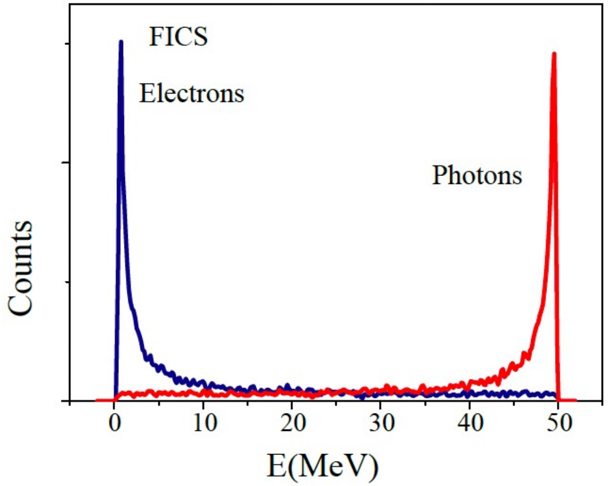
[a] INFN-Milano and LASA, Via G. Celoria 16, Milan, 20133, Italy

[b] University of Milan, Via G. Celoria 16, Milan, 20133, Italy



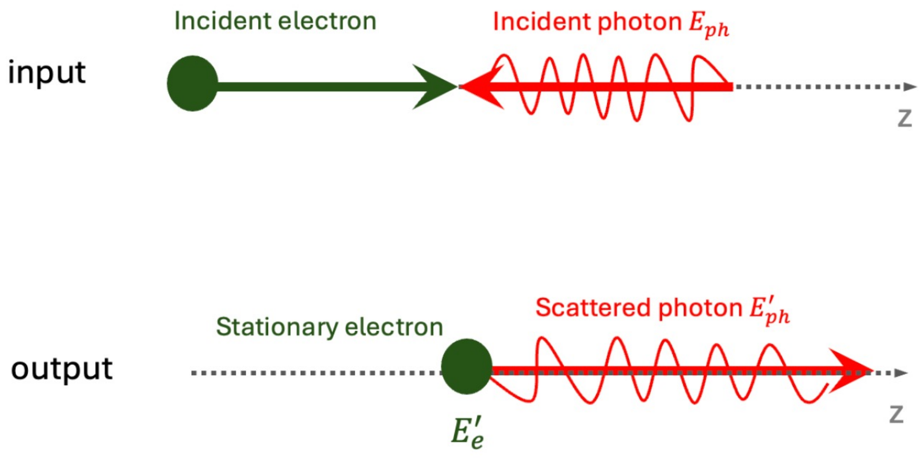
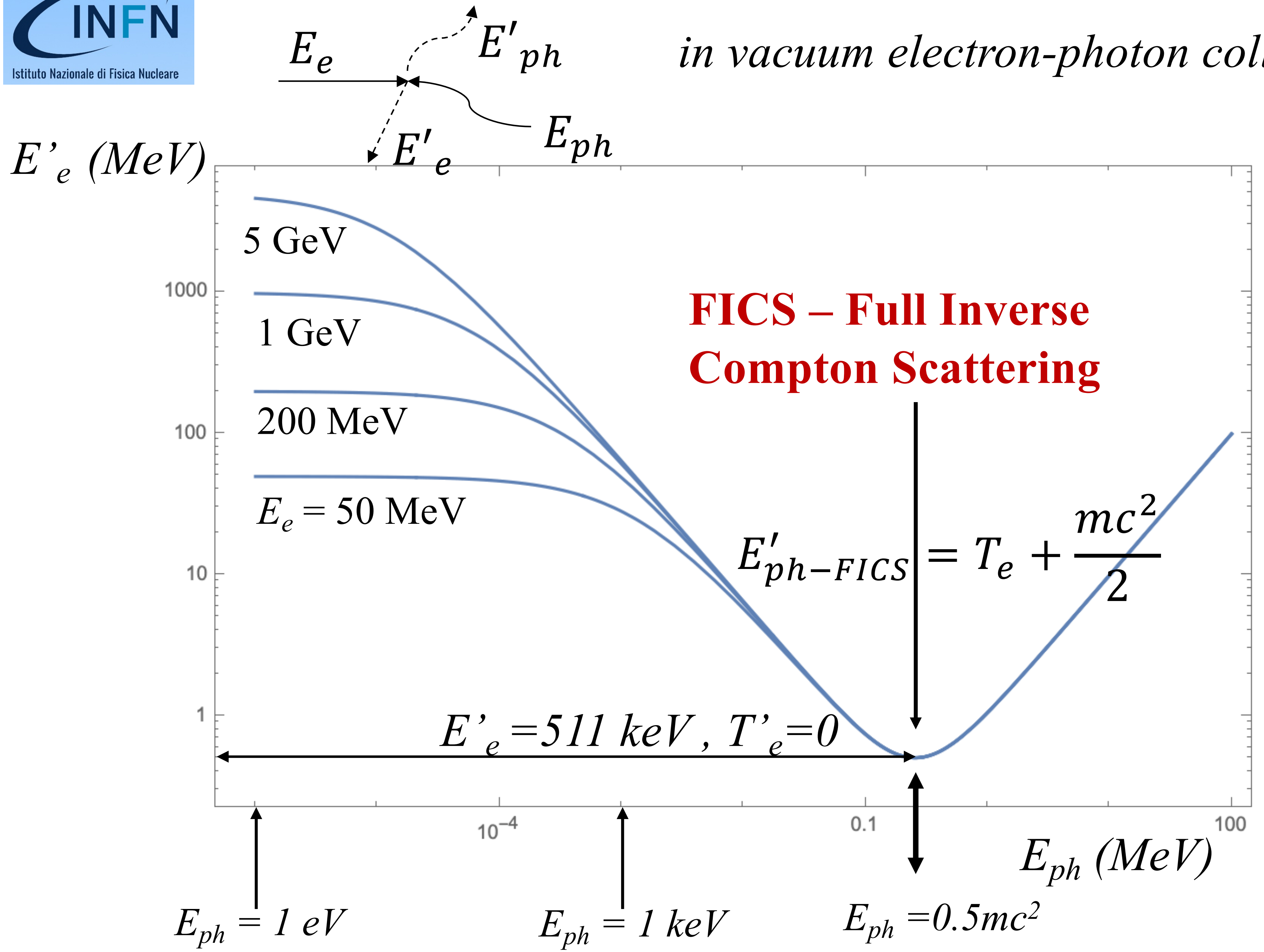


FIG. 5: Full Inverse Compton Scattering (FICS). Left: energy distribution, right: angular distribution. Red: scattered photons, blue:scattered electrons.$E_{ph} = 255.5keV$, E_e=50 MeV, $bw_{ph} = 5\%$

V. Petrillo, ad-hoc developed Montecarlo code for linear QED *in vacuum electron-photon collision*



From Feenberg-Primakoff

4. COMPTON SCATTERING IN PROTON-PHOTON AND ELECTRON-PHOTON COLLISIONS

We shall now discuss those collisions of the primary cosmic-ray protons and electrons with thermal photons which result in Compton scattering. In the primary rest frame the photon energies ϵ^* and ϵ'^* before and after scattering, and the scattering angle χ^* are connected by the relation,[32]

$$\epsilon'^* = \frac{\epsilon^*}{1+\frac{(\epsilon^*)^2}{Mc^2}(1-\cos\chi^*)}. \tag{45}$$

Correspondingly, in the earth's frame,[33]

$$\epsilon' = \gamma\epsilon'^*(1-\beta\cos\theta'^*)$$

lisions, N_s^c, and the average energy loss, ΔE_s^c, experienced by a primary falling radially from infinity through the sun's radiation field to the orbit of the earth ($\theta \cong 0$). It is convenient to distinguish two extreme cases: "rest-frame non-relativistic" and "rest-frame extreme relativistic," depending on whether $\epsilon^* = \gamma\epsilon(1+\beta\cos\theta)$ is $\ll Mc^2$ or $\gg Mc^2$ for $\epsilon \cong 2.7\ kT$. An equivalent statement is

$$u_c = \left.\frac{(Mc^2)^2}{EkT}\right] \begin{array}{l} \gg 1 \ \text{("rest-frame non-relativistic"} \\ \quad E \ll 2\times 10^{18}\ \text{ev-protons;} \\ \quad E \ll 5\times 10^{11}\ \text{ev-electrons)} \\ \ll 1 \ \text{("rest-frame extreme relativistic").} \end{array} \tag{54}$$

In the "rest-frame non-relativistic" case one

From Follin

3.2. Theory of the Interaction of Electrons and Photons

The interaction of electrons with radiation is just Compton scattering in the coordinate system moving with the electrons but the treatment is more complicated since large energy transfers can take place so that fluctuations are important. Hence, we must compute the probability for various fractional energy losses for all values of the energy. Similar considerations hold for the interactions of photons. The situation is further complicated by the fact that high energy electrons generate photons and high energy photons generate electrons so that a sort of "cosmic cascade" ensues.

If we now consider a photon $\underline{\gamma}$ in the moving coordinate system incident along the negative $\underline{z}$ - axis and assume a Compton scattering, then the energy of the scattered photon is given by

$$\gamma' = \frac{\gamma}{1 + \gamma(1 - \cos\theta)}, \tag{3.18}$$

$$d\phi = \frac{1}{2}\left(\frac{e^2}{mc^2}\right)^2 (1-\delta)^2\left\{\frac{1}{1-\delta} + \left[1-\frac{\delta}{\gamma(1-\delta)}\right]^2 + 1-\delta\right\}\frac{dz}{d\delta}\,d\delta$$

(3.25)

$$= \frac{1}{2}\left(\frac{e^2}{mc^2}\right)^2\left\{\frac{1}{1-\delta} + 1-\delta - \frac{2\delta}{\gamma(1-\delta)} + \frac{\delta^2}{\gamma^2(1-\delta)^2}\right\}d\delta,\quad 0 \leq \delta \leq \frac{2\gamma}{1+2\gamma}.$$

It may be seen that there is a large probability of large fractional energy loss since $(1-\delta)$ occurs in the denominator. An idea of the order of magnitude of the cross section may be obtained from the following table.

TABLE 5

The Values of δ and $d\phi$ from (3.23) and (3.25)

	γ \ θ	0	$\pi/4$	$\pi/2$	$3\pi/4$	π
δ	0.1	0	.028	.091	.146	.167
	1.0	0	.227	.50	.63	.80
	10.	0	.745	.91	.945	.952
$d\phi \times 10^{26} cm^2$	0.1	80.0	60.4	40.4	61.2	84.8
	1.0	8.00	6.28	6.00	10.32	13.32
	10.	0.80	1.28	4.04	7.04	8.44

PHYSICAL REVIEW ACCELERATORS AND BEAMS **27,** 080701 (2024)

From Compton scattering of photons on targets to inverse Compton scattering of electron and photon beams

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(Received 2 May 2024; accepted 1 August 2024; published 28 August 2024)

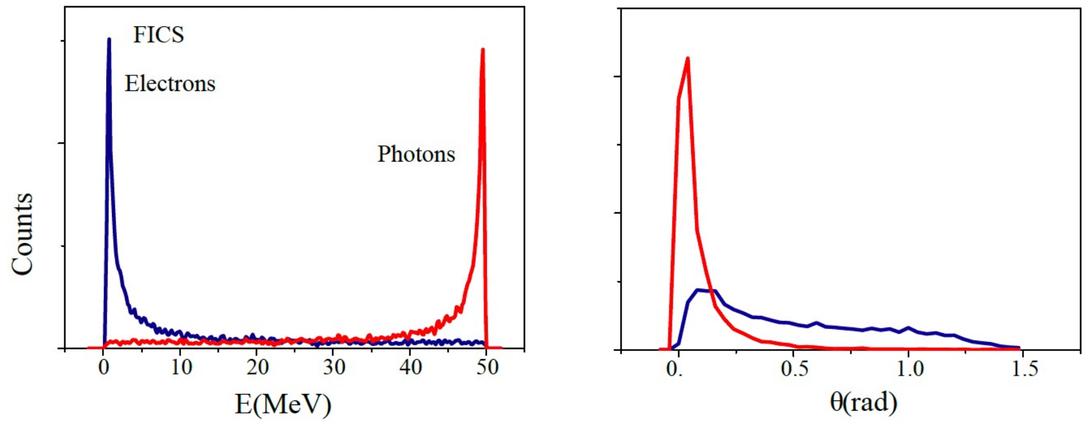


FIG. 5: Full Inverse Compton Scattering (FICS). Left: energy distribution, right: angular distribution. Red: scattered photons, blue:scattered electrons.$E_{ph} = 255.5 keV$, E_e=50 MeV, $bw_{ph} = 5\%$

residual electron kinetic energy T'_e at FICS with 511./2. keV photons instead of

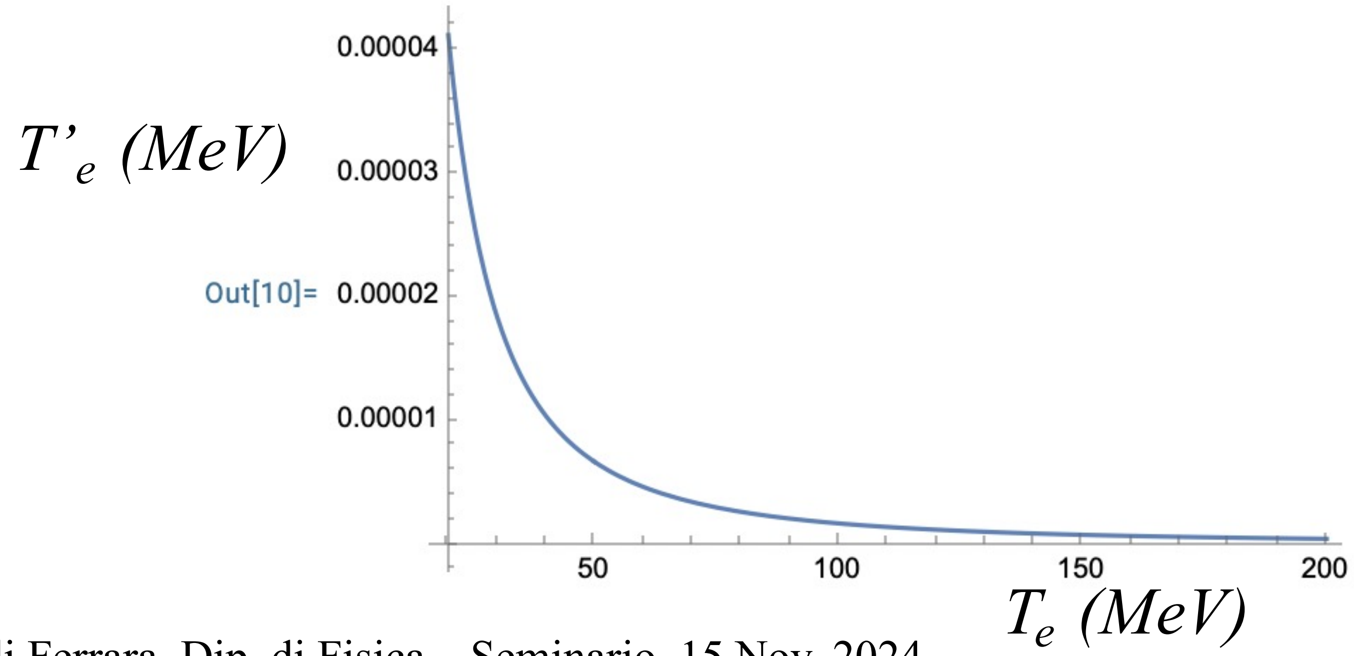
$$E_{ph} = \frac{mc^2}{2}\left(1 - (1-\beta)\gamma\right)$$

```
In[9]:= Tpefics = Tpe /. Eph → 0.511 / 2.
```

$$\text{Out[9]=}\ -0.2555 + \text{Ee} - \frac{0.2555\left(1 + \sqrt{1 - \frac{0.261121}{\text{Ee}^2}}\right)\text{Ee}}{0.511 + \left(1 - \sqrt{1 - \frac{0.261121}{\text{Ee}^2}}\right)\text{Ee}}$$

```
In[10]:= Plot[Tpefics, {Ee, 20., 200.}, PlotRange → All]
```

Out[10]=



SCHWINGER

$$E_{SCH} = \frac{2\pi m^2 c^3}{e h}$$

$$E_{Z\text{-}FICS} = \frac{T_e(eV)}{\frac{hc}{E'_{ph}}} = \frac{(\gamma-1)\, mc^2/e}{\frac{hc}{\frac{mc^2}{2}\left((1+\beta)\gamma-1\right)}}$$

$$E_{Z\text{-}FICS} = \frac{E_{SCH}}{4\pi}(\gamma-1)\left((1+\beta)\gamma-1\right)$$

Direct Compton $\gamma=1$, $\beta=0$, $X = 4E_{ph}/mc^2$

$$E'_{ph-min} = \frac{E_{ph}}{1+2E_{ph}/mc^2} \qquad if \quad E_{ph} \gg mc^2 \quad E'_{ph-min} = \frac{mc^2}{2}$$

Very energetic photons are scattered back at 255 keV
and electrons pushed to $E_{ph} + 0.5mc^2$

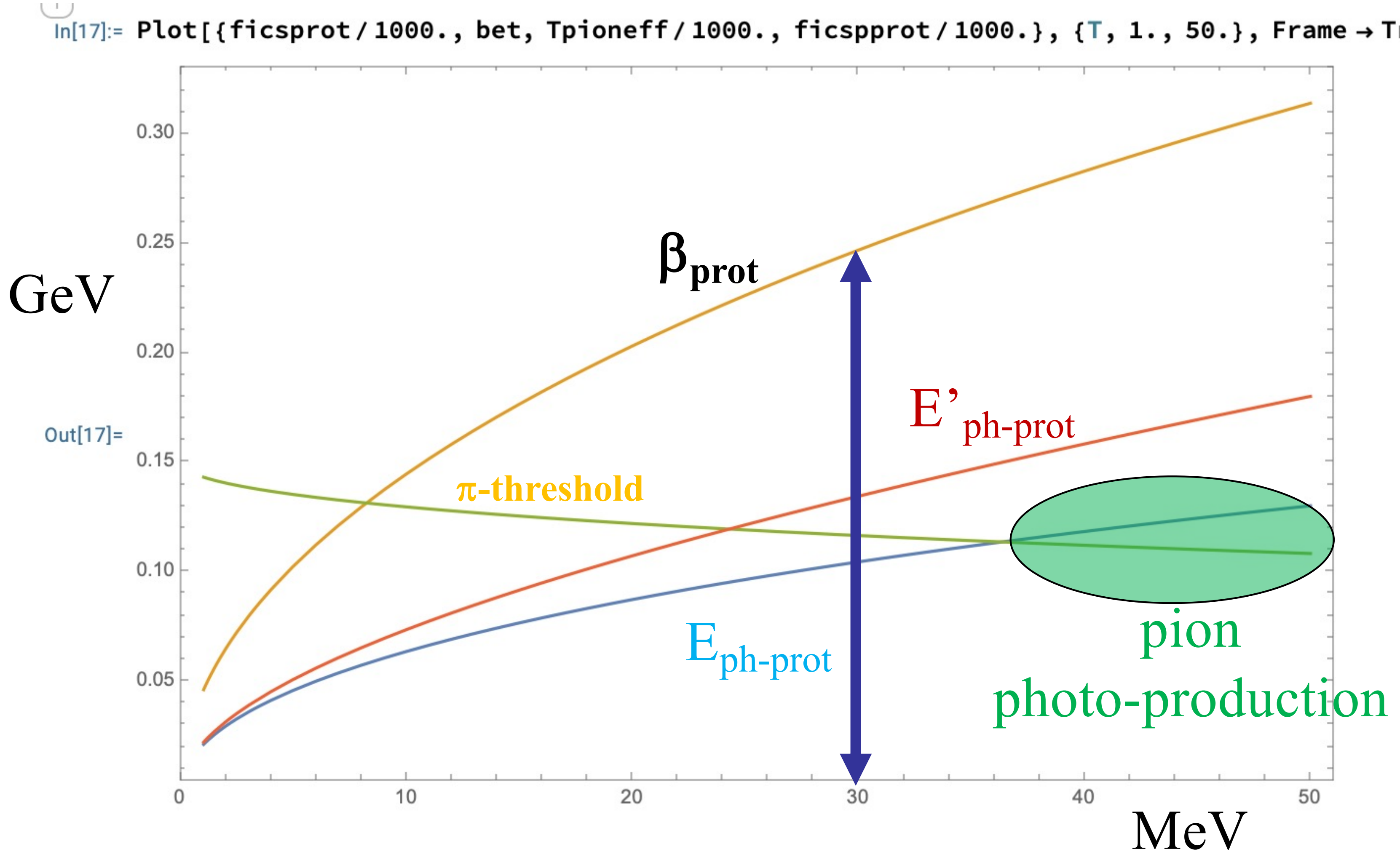
$$E'_{e-max} = mc^2 + E_{ph} - E'_{ph-min} \;, if \; E_{ph} \gg mc^2 \; E'_{e-max} = E_{ph} + \frac{mc^2}{2}$$

So FICS is the time reversal of Compton scattering at infinitely large recoil

kinematics is similar for any particle interacting with photons (protons, μ, neutrinos? $h\nu_{inc}=0.5*m_pc^2$ ***- next step in progress…)***

It’s unbelievable how much you don’t know about
the game you’ve been playing all your life”
Mikey Mantle (big baseball player of the past, after Danilo Babusci INFN-LNF)

Stopping Protons with photons
Relativistic protons require 938/2 MeV photons



electrons do not have internal degree of freedom (apart from spin) while protons do have - protons can act as detectors of Unruh thermal photon bath (they can "click") - but protons cannot be driven to strong accelerations by intense lasers… FICS is the only way??

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https://doi.org/10.1140/epjc/s10052-024-12849-9

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Measuring Unruh radiation from accelerated electrons

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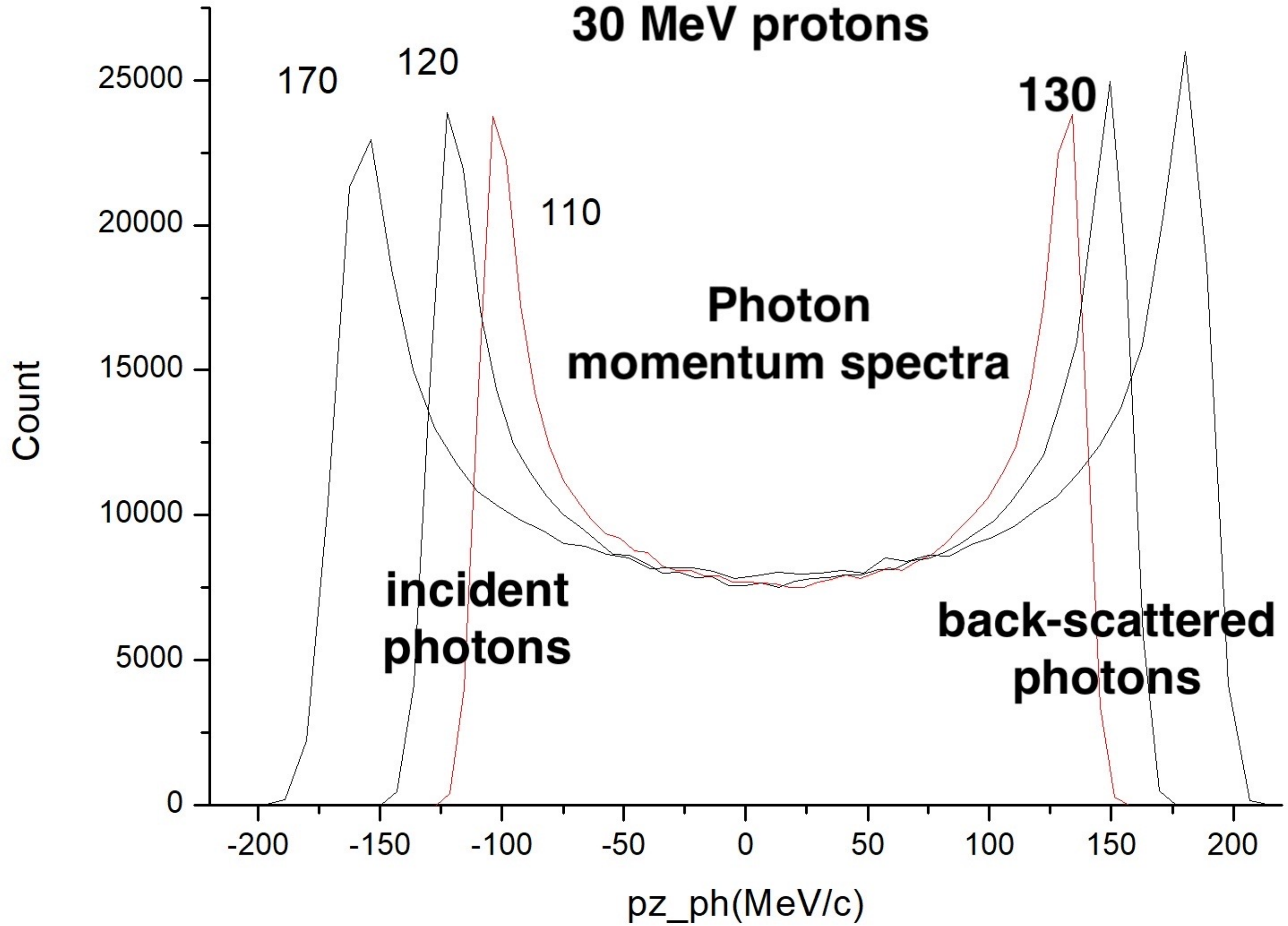
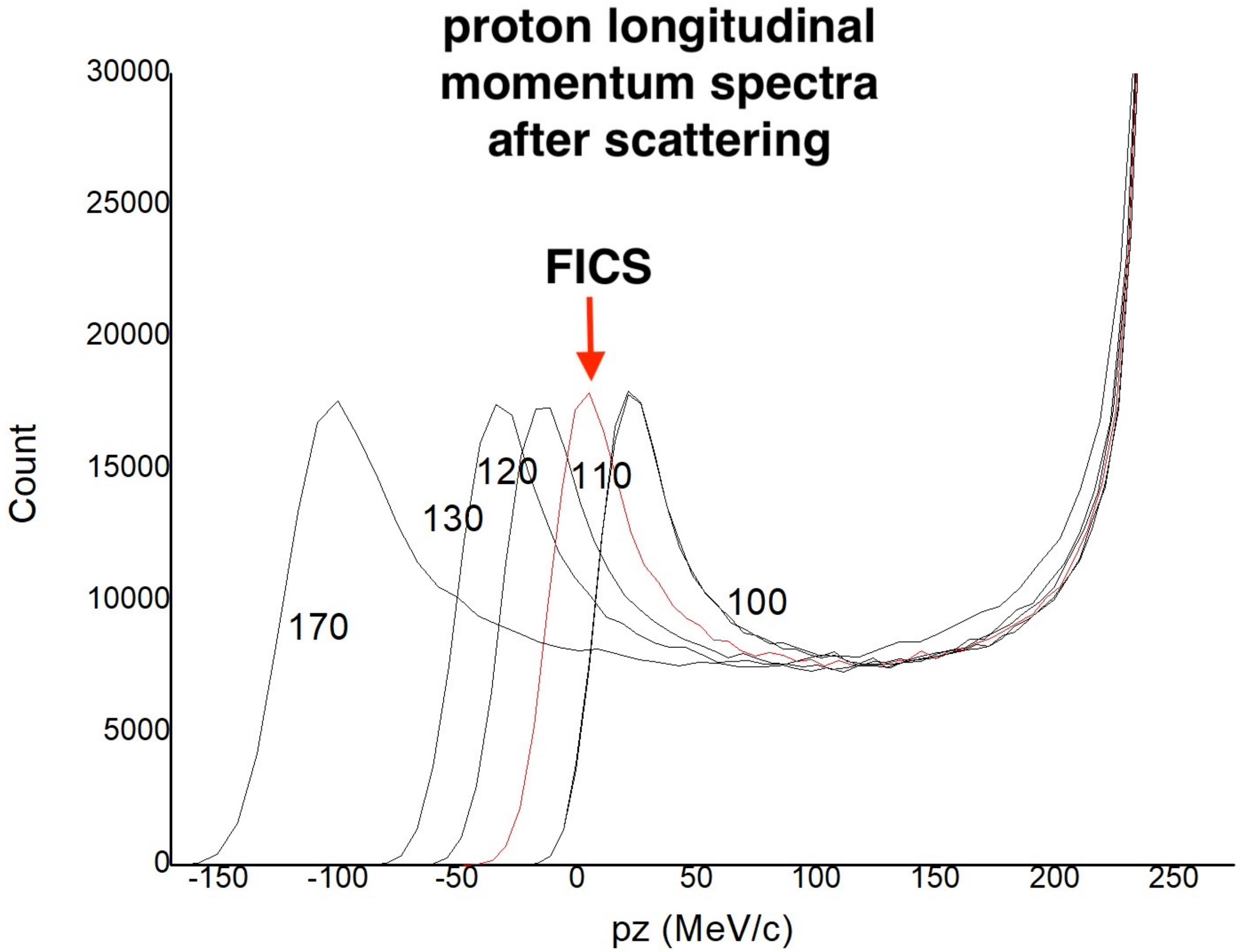
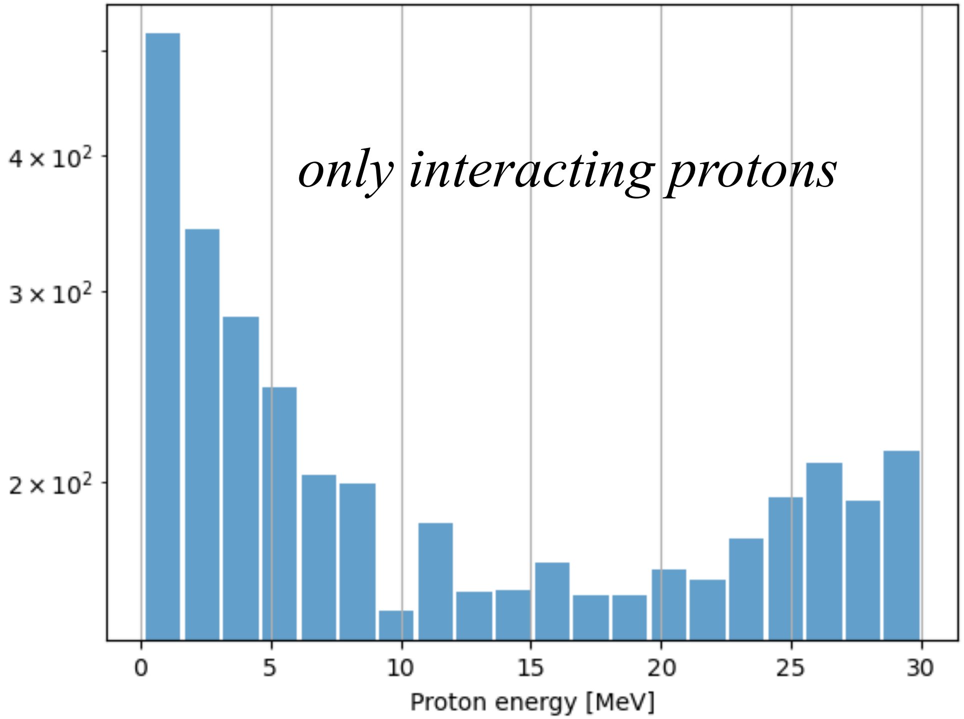
Received: 13 March 2024 / Accepted: 23 April 2024

30 MeV protons vs. photon beams of different energies (110, 120, 170 MeV)

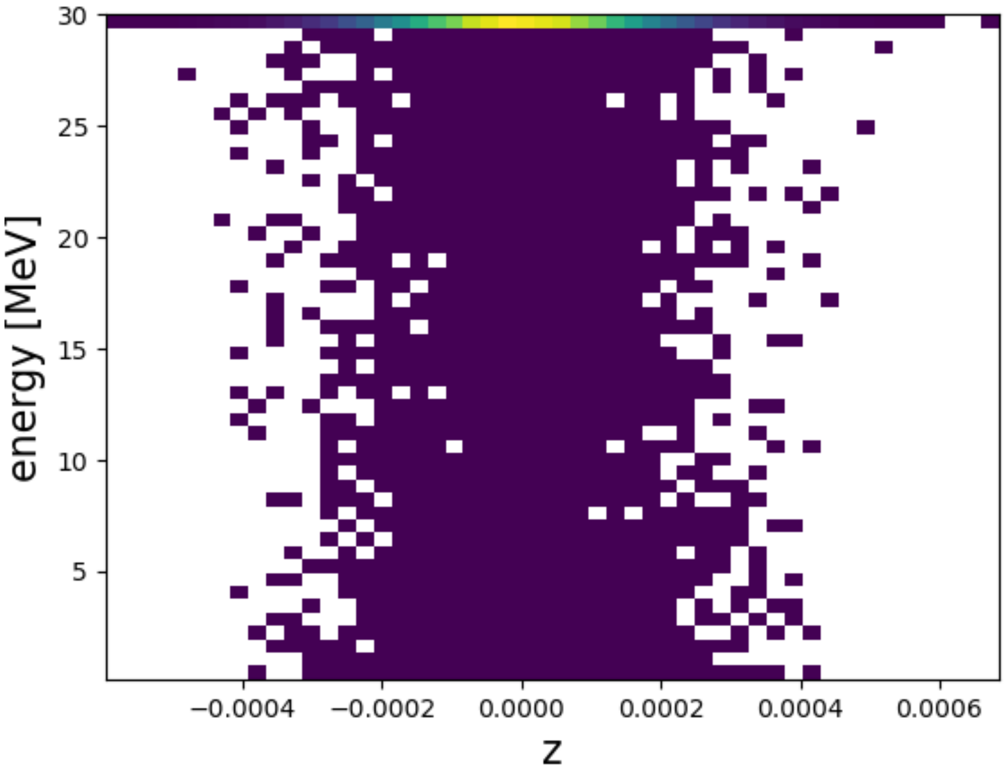



proton longitudinal
momentum spectra
after scattering
FICS
Count
30000
25000
20000
15000
10000
5000
0
170
130
120
110
100
-150
-100
-50
0
50
100
150
200
250
pz (MeV/c)

Checked with CAIN modified for protons (I. Drebot, A. Bacci)



primary proton beam
+
interacting protons



in FICS there is a clear experimental signature of the specific scattering event: since electrons transfer almost entirely their kinetic energy to the photons, there will be a highly collimated photon beam propagating in the direction of the incoming beam of electrons with energy spectrum peaked at the value of the incoming electron beam kinetic energy, which is a unique indication of FICS.

We asked Chat-GPT again (Oct. 26th 2024), after recommending her/him/it reading our 2 papers

10.1103/PhysRevAccelBeams.27.080701
https://doi.org/10.1016/j.nima.2024.169964

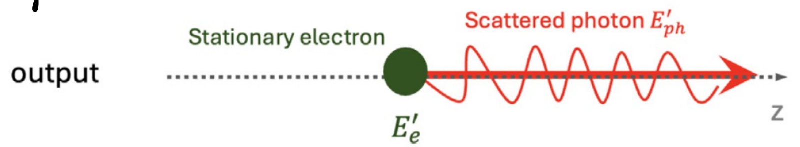
Now that Full Inverse Compton Scattering (FICS) demonstrates that total energy transfer from an electron to a photon is theoretically possible, it shifts our understanding of photon-electron interactions, especially at high energies.
This interaction is unique because the electron can stop completely and transfer all its kinetic energy to the photon in a controlled, head-on setup.
This level of energy transfer efficiency has significant implications, potentially enabling precise photon energy boosts and offering new applications in particle accelerators and high-energy astrophysics.

Grazie per l'attenzione

Nuclear Inst. and Methods in Physics Research, A 1069 (2024) 169964

Full Inverse Compton Scattering

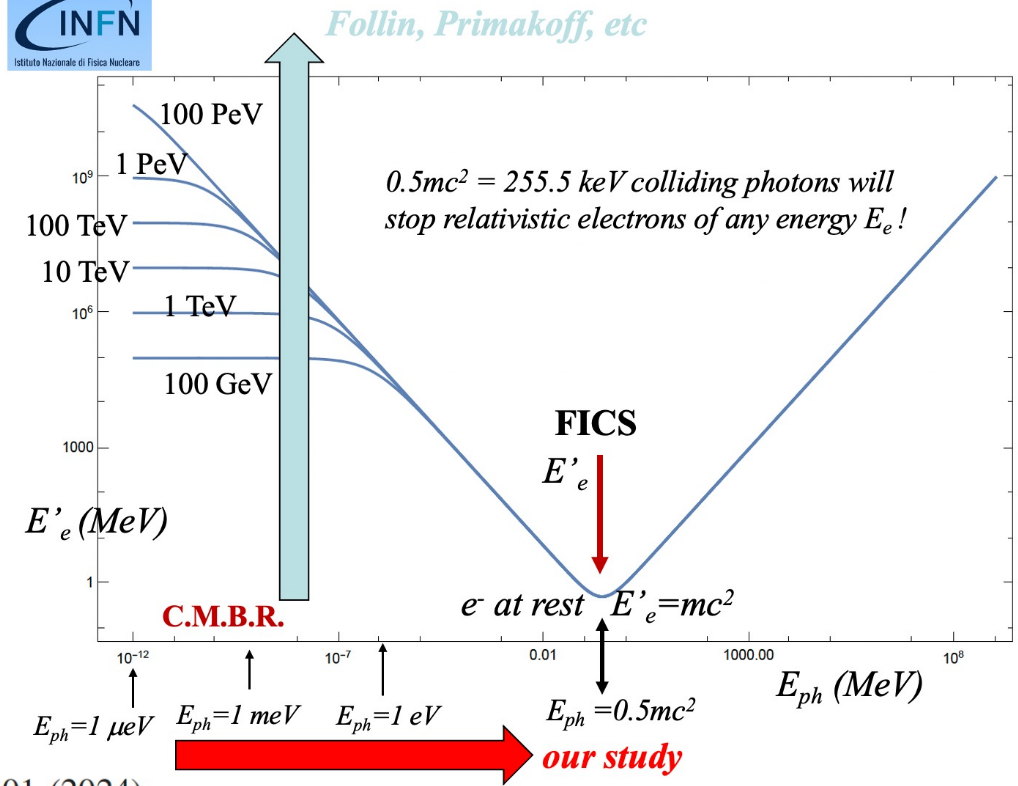
$\gamma >> 1$ $\quad T_e \;;\; E_{ph} = 0.5mc^2$



$$T'_e = 0 \;;\; E'_{ph} = T_e + 0.5mc^2$$

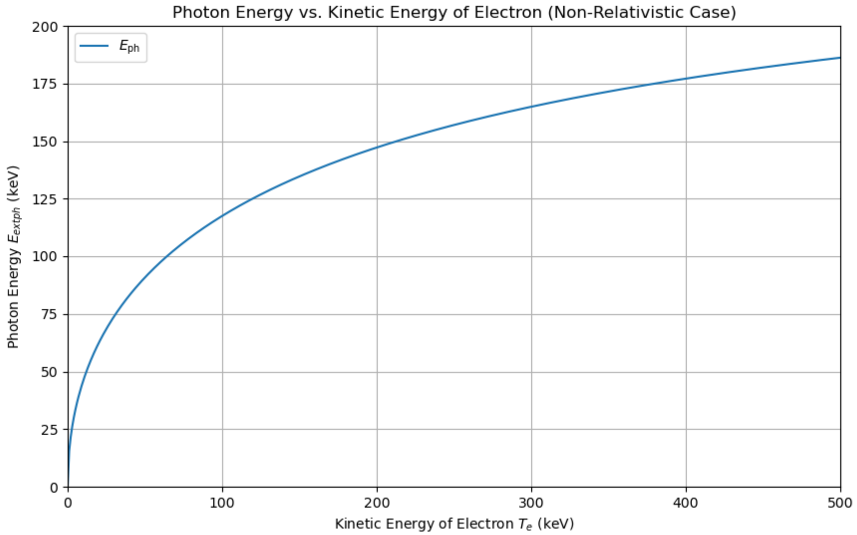
Can electrons emit photons of energy larger than their own?

Impacts in several fields: Plasma Physics (e^- / e^+ trapping in plasma mirrors), Astro-Physics (cosmic γ-ray sources), QED & Quantum Gravity (Unruh radiation and overcoming the Schwinger limit), measuring neutrino mass?



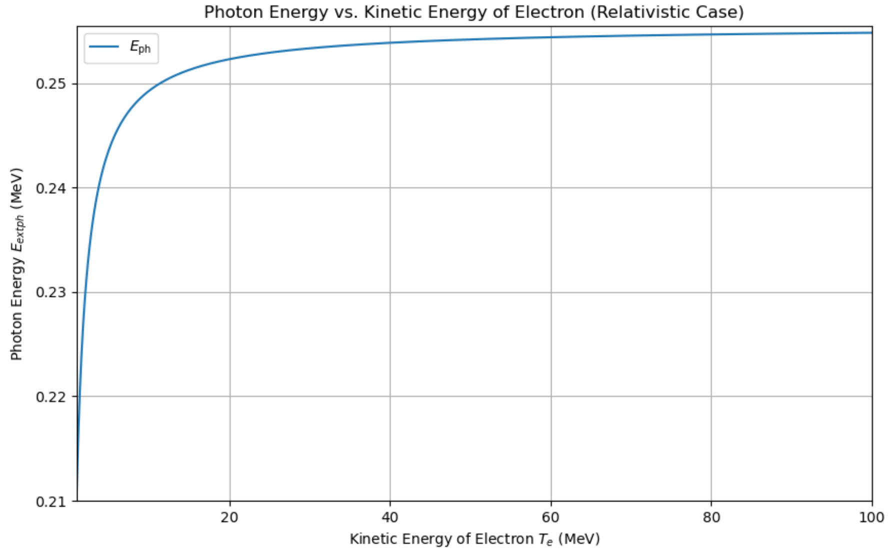
Fundamental Plasma Physics 7 (2023) 100026
PHYSICAL REVIEW ACCELERATORS AND BEAMS **27**, 080701 (2024)

$$E_{ph}^{FICS}(T_e \leq 500\ keV)$$

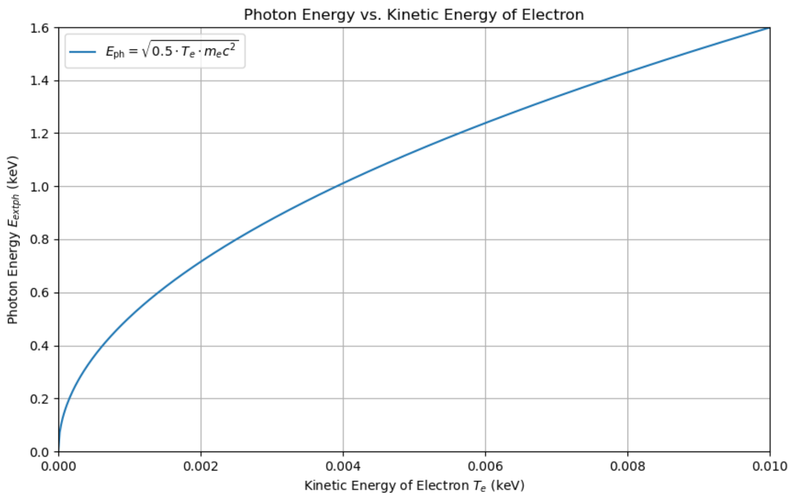


$$E_{ph}^{FICS}(T_e \leq 100\ MeV)$$

$$\frac{mc^2}{2}$$

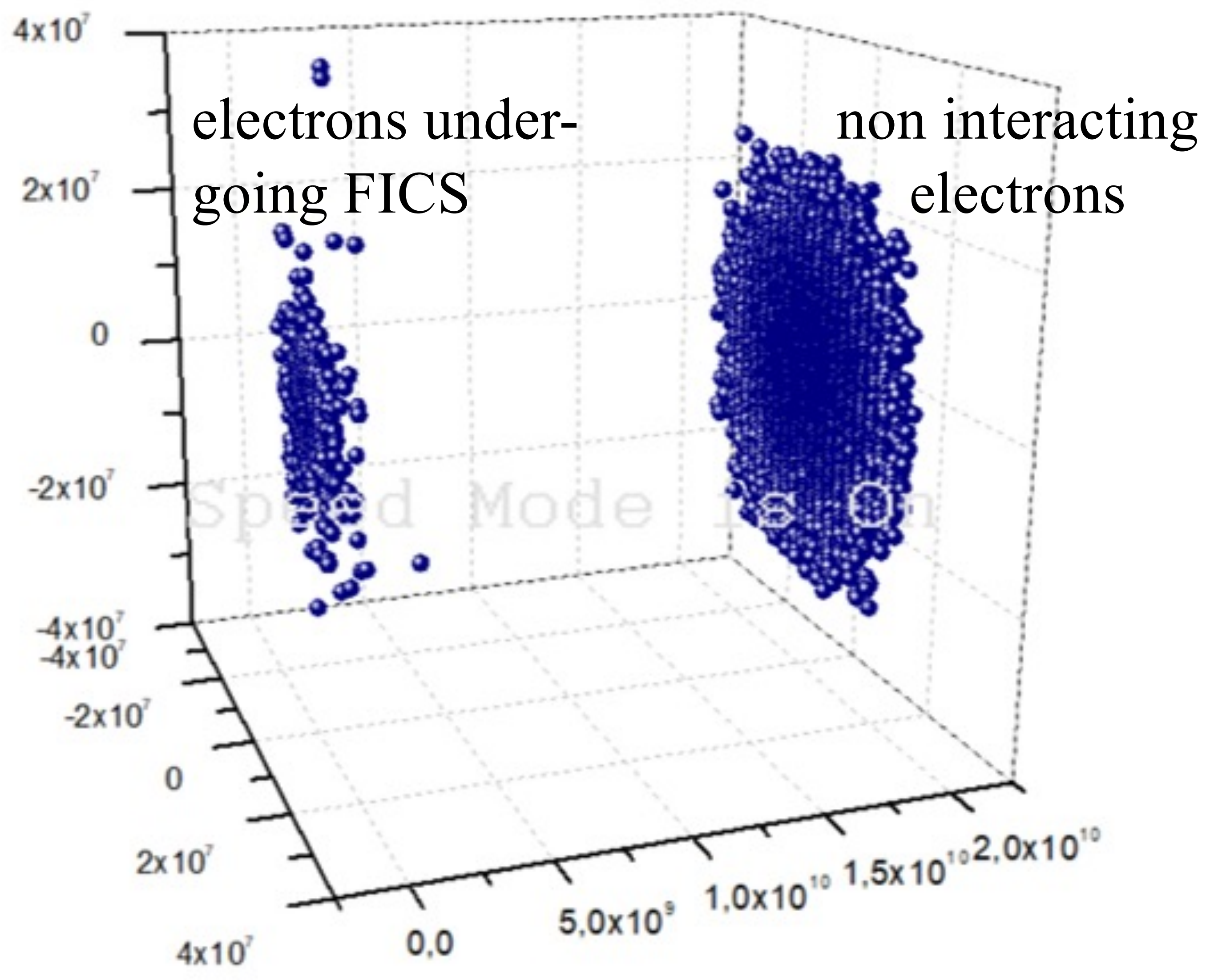


$$E_{ph}^{FICS}(T_e \leq 10\ eV)$$

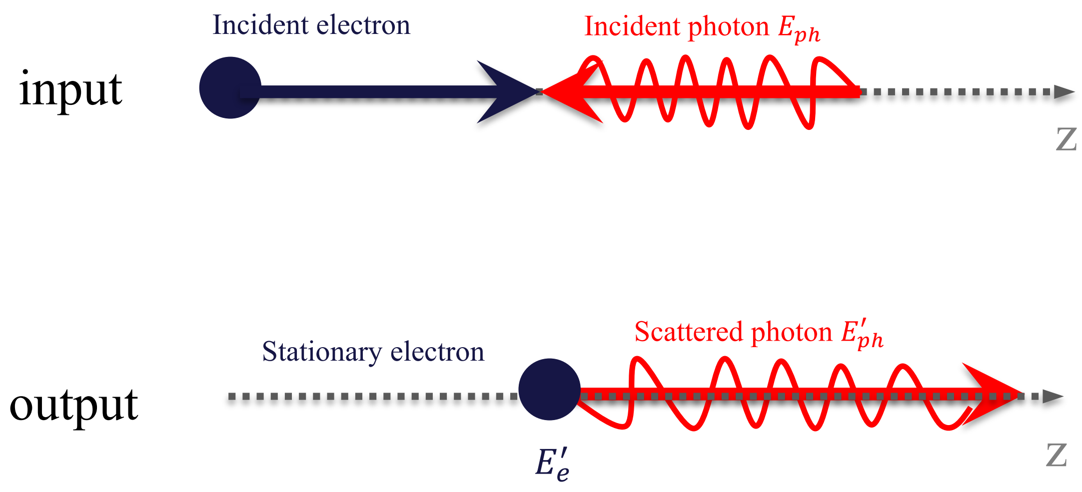


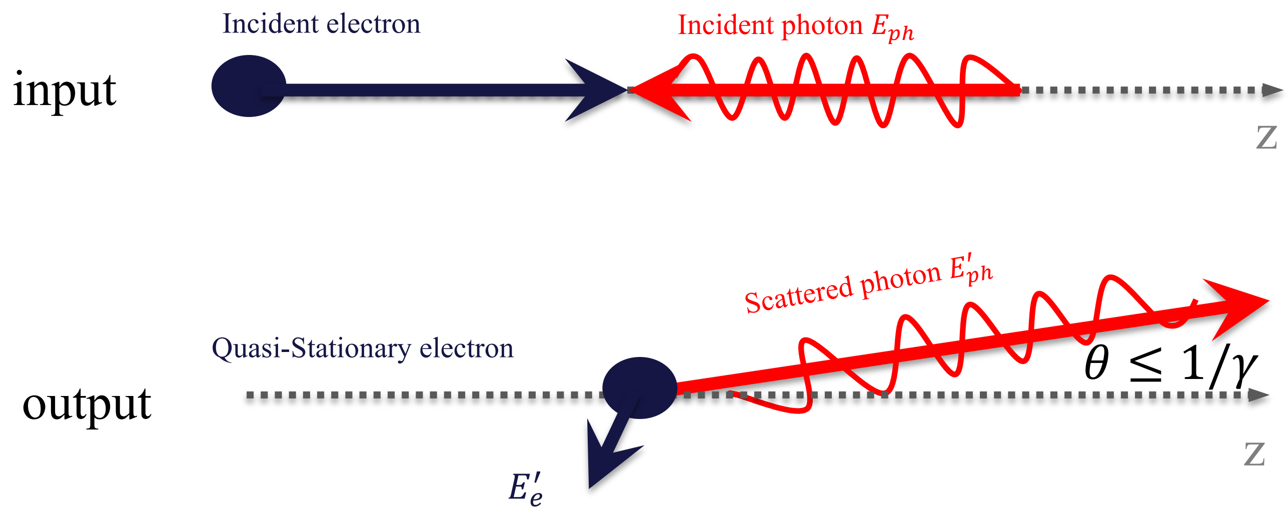
$E_e = 200\ MeV$; E_{ph}=255.5 keV

electron momenta distribution after FICS



FICS lay-out


input
Incident electron
Incident photon E_{ph}
z
output
Stationary electron
Scattered photon E'_{ph}
E'_e
z


input
Incident electron
Incident photon E_{ph}
z
output
Quasi-Stationary electron
Scattered photon E'_{ph}
$\theta \leq 1/\gamma$
E'_e
z

$$T_e' = (\gamma - 1)m_e c^2 + E_{ph}^{FICS} - \frac{\gamma(1+\beta)E_{ph}^{FICS} m_e c^2}{(1-\beta cos\theta)\gamma m_e c^2 + (1+cos\theta)E_{ph}^{FICS}} \quad (21)$$

After scattering, the kinetic energy T_e' of the electron (valide for $\gamma \gg 1$ and $\theta \approx \frac{1}{\gamma}$) is given by:

$$T_e' = \frac{m_e c^2}{2}\gamma^2\theta^2 \quad (22)$$

For a small angle θ, where $cos\theta \approx 1 - \frac{\theta^2}{2}$, T_e' simplifies to the following form:

$$T_e' = m_e c^2 \frac{4\gamma^2 - 4\gamma - 1}{8\gamma^2 - 4\gamma} \quad (23)$$

As γ approaches infinity, T_e' converges to:

$$T_e'^{FICS} \xrightarrow{\gamma\to\infty} \frac{m_e c^2}{2} \quad (24)$$

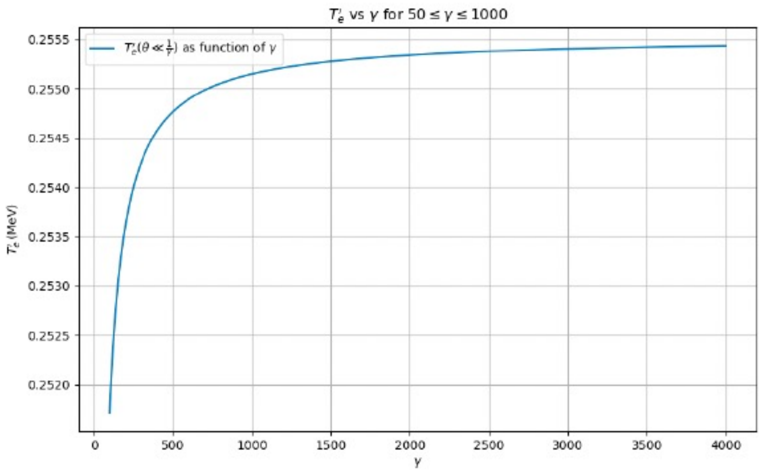


Figure 6: Kinetic energy of the scattered electron T_e' as function of the Lorentz factor

β (T_e=255 keV) = 0.75

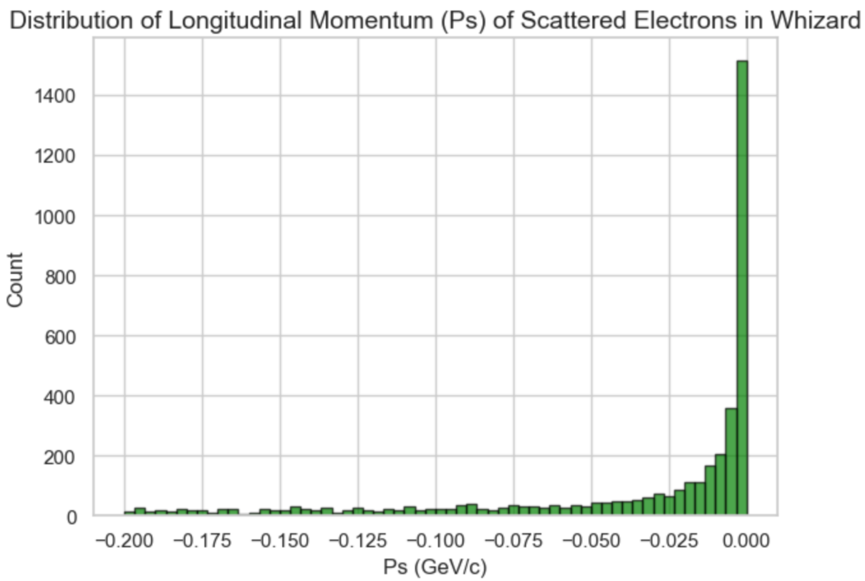
electrons undergoing FICS with photons back-scattered between $\theta=0$ and $\theta=1/\gamma$ have $\beta < 0.75$

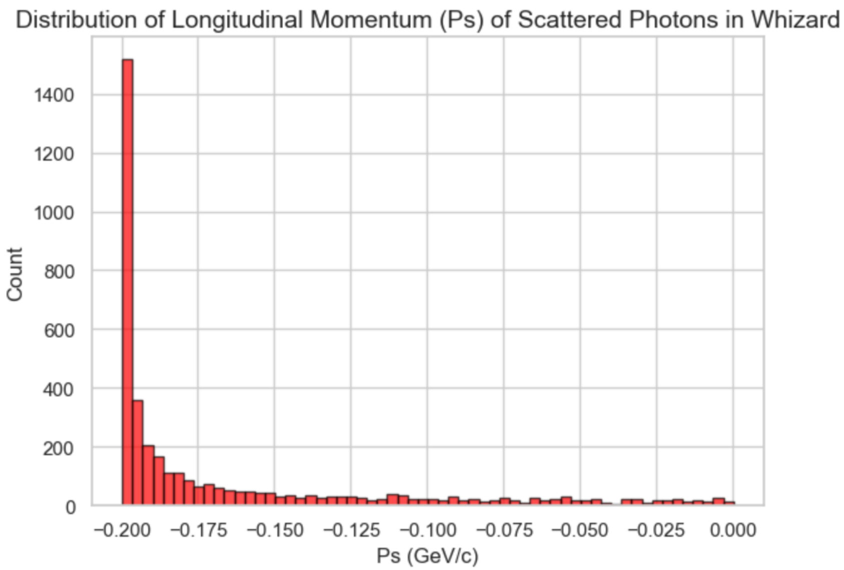
back-scattered photons in FICS have energy E'_{ph} in the range

$$E'_{ph}(\theta=0) = E_e(1-1/2\gamma) \quad ; \quad E'_{ph}(\theta=1/\gamma) = E_e(1-1/\gamma)$$

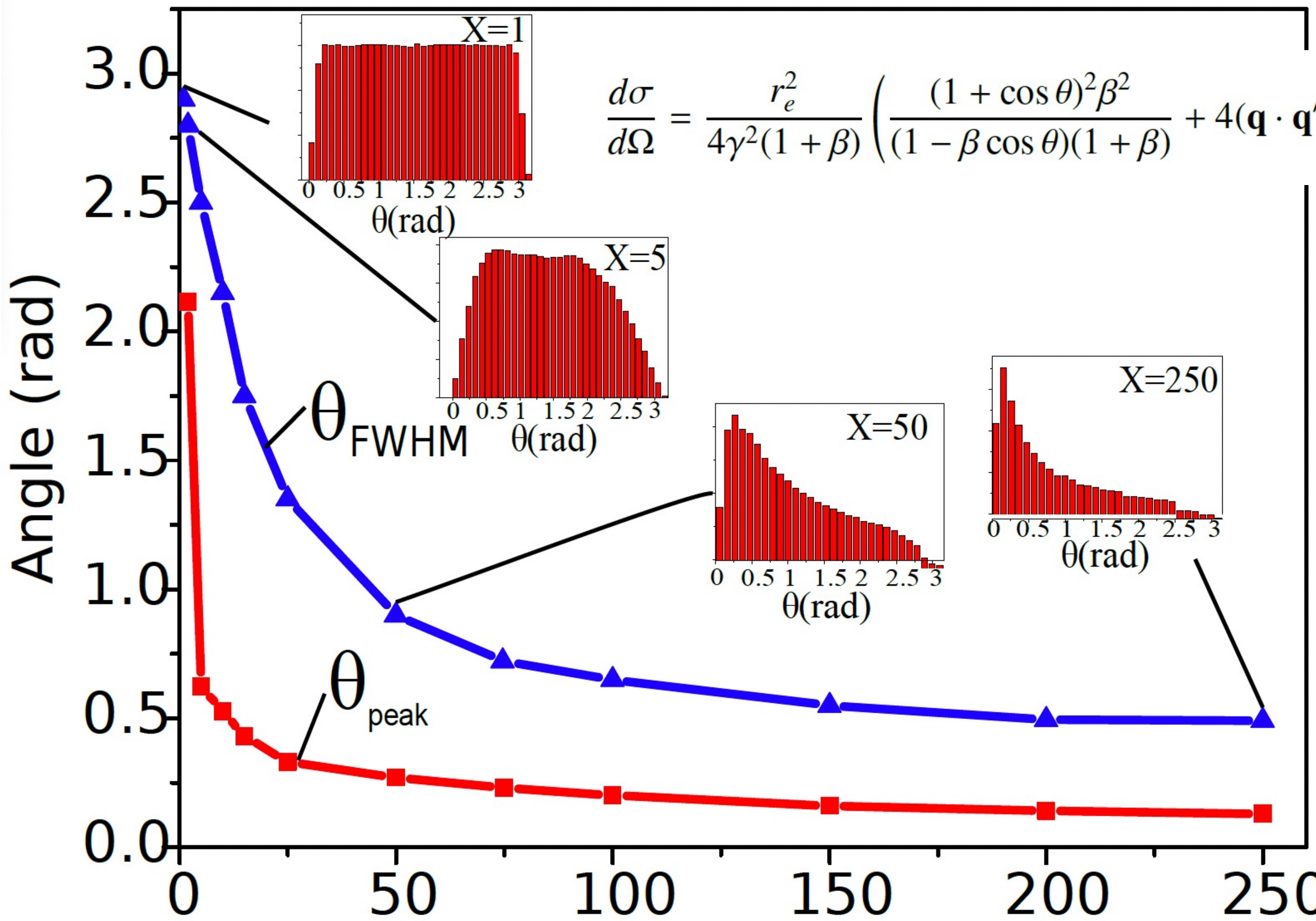
to be compared with low recoil ICS, where

$$E'_{ph}(\theta=0) = 4\gamma^2 E_{ph} \quad ; \quad E'_{ph}(\theta=1/\gamma) = 2\gamma^2 E_{ph}$$


Distribution of Longitudinal Momentum (Ps) of Scattered Electrons in Whizard
Count
Ps (GeV/c)


Distribution of Longitudinal Momentum (Ps) of Scattered Photons in Whizard
Count
Ps (GeV/c)

S.C.S. Spectra at different recoil factors X
back-scattering of the photon is most likely in deep recoil



$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{4\gamma^2(1+\beta)}\left(\frac{(1+\cos\theta)^2\beta^2}{(1-\beta\cos\theta)(1+\beta)} + 4(\mathbf{q}\cdot\mathbf{q}')\right)$$

if an electron/photon interaction occurs in deep recoil it must be back-scattering

$$f^{FICS} = \frac{6.25}{4.2} \frac{(1 + \sqrt[3]{X}\frac{\Psi^2}{3})\Psi^2}{(1 + (1 + \frac{X}{2})\Psi^2)(1 + \Psi^2)} \cdot \frac{\sigma_T}{\sigma} \tag{28}$$

where $\Psi \approx \frac{\gamma\theta}{\sqrt{1+X}}$ is the acceptance angle, σ is the unpolarized Compton cross section and σ_T ia the Thomson cross section [9].

Taking the fact that $\frac{\sigma_T}{\sigma} = \frac{4X}{lnX+\frac{1}{2}}$, $X \gg 1$, $\gamma \gg 1$ and $\theta \leq \frac{1}{\gamma}$, Eq.28 simplifies to the following form:

$$f^{FICS}(\theta = \frac{1}{\gamma}) \approx \frac{4}{lnX + \frac{1}{2}} \tag{29}$$

Taking into consideration that the recoil X for FICS is equal to 2γ (see Tab. 1 in Ref. [3]). Eq. 29 can be written as:

$$f^{FICS}(X = 2\gamma) = \frac{4}{\ln\gamma + 1.19} \tag{30}$$

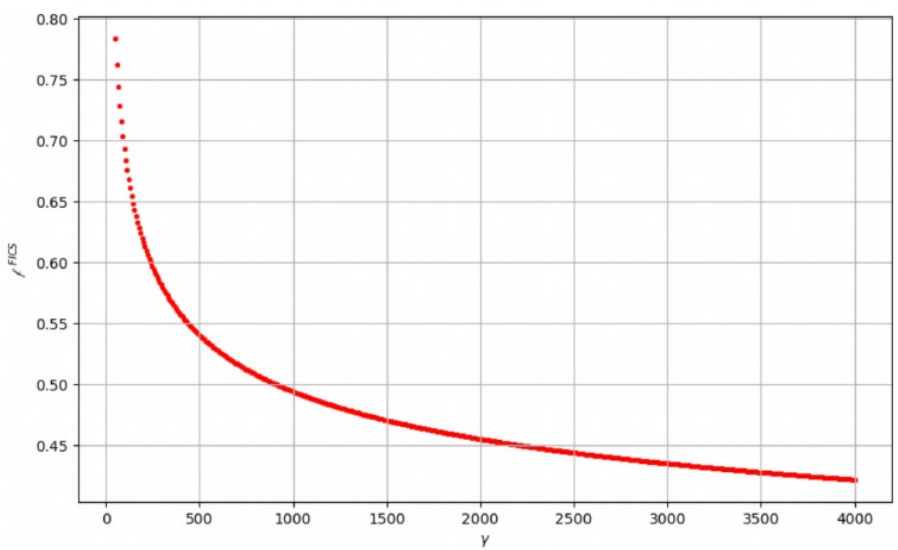


Figure 7: FICS fraction factor $f^{FICS} = \frac{\mathcal{N}^{\Psi}}{\mathcal{N}}$ as function of the Lorentz factor γ.

Volume 4, number 3 PHYSICS LETTERS 1 April 1963

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8) R.M.Hill and C.F.Bruce, Australian J. Phys. 15 (1962)194.

* * * * *

Almost at the same time as Arutyunian and co-workers

THE COMPTON EFFECT ON RELATIVISTIC ELECTRONS AND THE POSSIBILITY OF OBTAINING HIGH ENERGY BEAMS

F. R. ARUTYUNIAN and V. A. TUMANIAN
Physical Institute of the State Committee of the Council of Ministers of the USSR for the Use of Atomic Energy

Received 20 February 1963

A characteristic feature of the Compton effect on relativistic electrons is the appearance of photons with energies exceeding those of the primary photons. As a result, even when light photons are scattered on extremely relativistic electrons, the energies of the scattered photons will be of the same order of magnitude as those of the electrons. This feature may possibly be exploited for obtaining high energy γ-ray beams in electron accelerators. An important point to be mentioned is that the characteristics of such γ-beams will significantly differ from those obtained by bremsstahlung.

In the Compton effect involving moving electrons

Of course in order to obtain γ-beams by the method considered here high photon fluxes will be required. A high intensity photon source that should be feasible is the laser. At present ruby lasers seem to be the most reliable.

For ruby laser photons ($\lambda = 6943$ Å) scattered on 6 GeV electrons one gets $\omega_{2\ max.} = 848$ MeV. This effect rapidly grows with increase of the electron energy. Thus for the same ruby lasers and $\epsilon_1 = 40$ and 500 GeV the maximal energy is correspondingly $\omega_{2\ max.} \sim 21$ and 497 GeV.

Of course if lasers emitting shorter wave lengths or other sources of high energy photons be employed,

Volume 13, number 4 PHYSICS LETTERS 15 December 1964

First measured ICS – 500 MeV

COMPTON EFFECT ON MOVING ELECTRONS

O. F. KULIKOV, Y. Y. TELNOV, E. I. FILIPPOV and M. N. YAKIMENKO
Lebedev Physical Institute, Moscow University, Moscow, USSR

Received 3 November 1964

Until recent times only the Compton effect on electrons at rest has been investigated. The electron acceleration technique having being improved, there arises the possibility of investigating the scattering of photons by electrons moving with speeds near to the speed of light. New powerful sources of photon-lasers make possible the scattering of visible photons on electrons, moving in an orbit of a cyclic accelerator.

telescope tube (T) which was used while positioning the laser beam. A photomultiplier is installed beyond the telescope's ocular. The signals from the photomultiplier are proportional to the energy of the light. Gamma-quanta of scattered radiation, passing through the glass plate (G), the lens (L), the turning mirror (TM) and the collimator (C) (diameter 15 mm) cause scintillation in the crystal of NaI. This is registered by the photo-

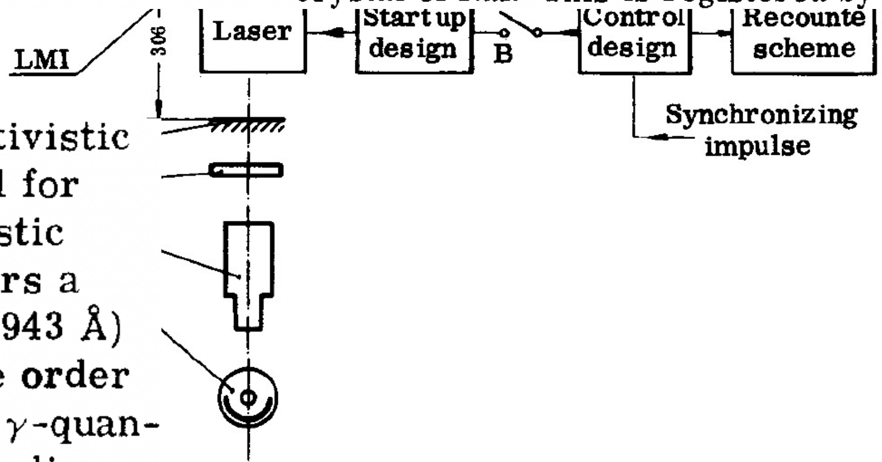

Fig. 1

The thoery of Compton's effect on relativistic electrons [1] has been considered in detail for interactions of laser photons with relativistic electrons [2 - 4]. According to these authors a head-on collision of laser radiation (γ = 6943 Å) with relativistic electrons of energy of the order of 500 MeV, will cause the appearance of γ-quanta of energy near 6.75 MeV, moving in the direction of motion of electrons.

Second measured ICS – 6 GeV

PHYSICAL REVIEW VOLUME 138, NUMBER 6B 21 JUNE 1965

High-Energy Photons from Compton Scattering of Light on 6.0-GeV Electrons*

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Department of Physics, Tufts University, Medford, Massachusetts

AND

MIRCEA FOTINO
Cambridge Electron Accelerator, Harvard University, Cambridge, Massachusetts
(Received 28 January 1965; revised manuscript received 1 March 1965)

Compton scattering of optical photons on 6.0-GeV electrons has been observed at the Cambridge Electron Accelerator. A giant-pulsed ruby-laser burst of 0.2 J, impinging upon a 2-mA circulating electron current, was observed to yield about 8 scattered photons per pulse. These photons acquire, through a twofold Doppler shift, energies of hundred of MeV, and are expected to retain to a high degree the polarization of the laser beam. The observed yield is compatible with predictions based upon the theory of Compton scattering.

THE scattering of optical photons from a laser on extreme-relativistic electrons has been predicted[1–3] to yield a high-energy output photon beam which preserves to a high degree the polarization of the incident light beam. Photons of energy up to 0.85 GeV are expected from the interaction of 6943-Å quanta from

mercial laser cavity, a cylindrical reflector, together with and parallel to a single flash lamp.[5] The optical pumping energy was normally between 750 and 850 J. Total measured output energies were typically about 0.2 J appearing in two or three giant pulses, each about 30 nsec wide and 200–300 nsec apart. Electrical pulses de-

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 044701 (2011)

Theoretical and simulation studies of characteristics of a Compton light source

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and DFELL, Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308, USA
(Received 25 January 2011; published 21 April 2011)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 050703 (2011)

Design of narrow-band Compton scattering sources for nuclear resonance fluorescence

F. Albert,* S. G. Anderson, D. J. Gibson, R. A. Marsh, S. S. Wu, C. W. Siders, C. P. J. Barty, and F. V. Hartemann

Lawrence Livermore National Laboratory, NIF and Photon Science, 7000 East Avenue, Livermore, California 94550, USA
(Received 20 December 2010; published 13 May 2011)

Reviews of Accelerator Science and Technology
Vol. 3 (2010) 147–163

DOI: 10.1142/S1793626810000440

World Scientific
www.worldscientific.com

Many studies in the literature on electron-photon beam collisions collective/statistical properties (phase spaces, etc)

Compton Sources of Electromagnetic Radiation*

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Relevance of recoil in electron-photon beam-beam collisions

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 080701 (2017)

Analytical description of photon beam phase spaces in inverse Compton scattering sources

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(Received 9 March 2017; published 3 August 2017)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **21,** 030701 (2018)

Simulation of inverse Compton scattering and its implications on the scattered linewidth

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[2]*Department of Physics, Center for Accelerator Science, Old Dominion University, Norfolk, Virginia 23529, USA*
[3]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
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Istituto Nazionale di Fisica Nucleare

applied sciences

MDPI

Article

Electrons and X-rays to Muon Pairs (EXMP)

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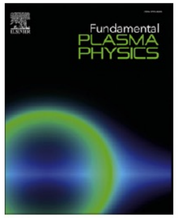

Original research article

Check for updates

Symmetric Compton Scattering: A way towards plasma heating and tunable mono-chromatic gamma-rays

L. Serafini [a,b], A. Bacci [a,b], C. Curatolo [a,b], I. Drebot [a,b], V. Petrillo [a,c], A. Puppin [a,c], M. Rossetti Conti [a,b,*], S. Samsam [a,b]

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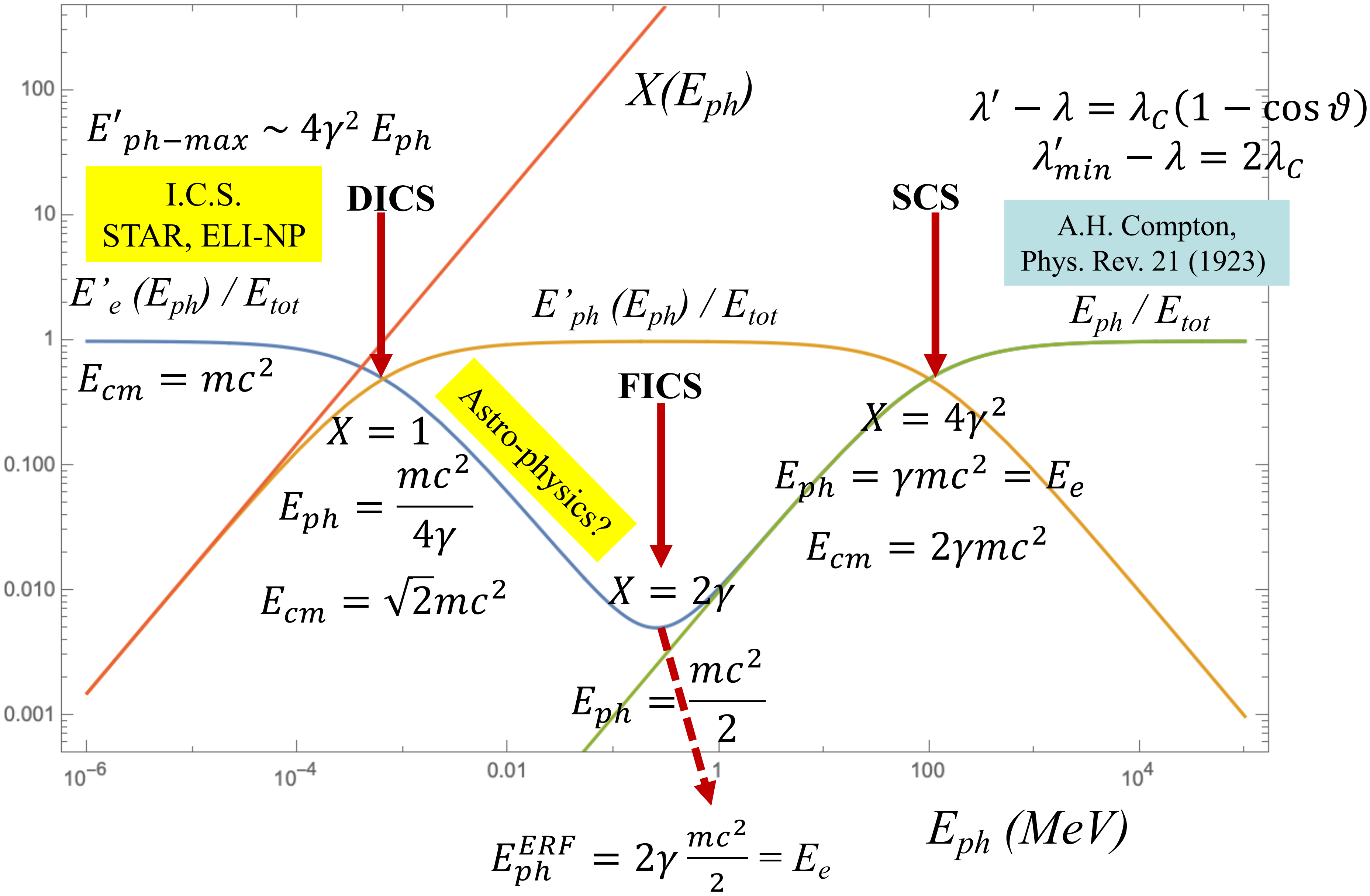
Istituto Nazionale di Fisica Nucleare

$$\frac{E'_{ph}}{E_{tot}} = \frac{X}{(1+X)(1+\frac{X}{4\gamma^2})}$$

$$\frac{E'_{e}}{E_{tot}} = 1 - \frac{X}{(1+X)(1+\frac{X}{4\gamma^2})}$$

All quantities normalized to the total energy $E_{tot} = E_e + E_{ph}$

E_e = 100 MeV



Grazie per l'attenzione

If you ask Chat-gpt :
“can an electron transfer its total kinetic energy to a photon?”
It will answer “no” - a wrong (or not updated) answer

The mechanism of total energy transfer from an electron to a photon, where the electron essentially stops and transfers all its kinetic energy to a photon, is not typically described within the framework of conventional Compton scattering. However, such an extreme scenario can be considered in specific contexts:

1. **Inverse Compton Scattering**: Inverse Compton scattering is a process where a high-energy electron transfers part of its energy to a low-energy photon, resulting in a higher-energy photon. However, the electron does not typically come to a complete stop; it just loses some of its energy.
2. **Photon Emission in Strong Fields**: In extremely strong electromagnetic fields, such as those generated by intense laser pulses, the dynamics can be different. The interaction of an electron with a strong electromagnetic field can lead to significant energy transfer through a process known as non-linear Compton scattering or non-linear Thomson scattering. Here, the electron can emit high-energy photons and lose a substantial amount of its kinetic energy.
3. **Bremsstrahlung in Extreme Fields**: When electrons decelerate rapidly in the presence of strong electromagnetic fields, they can emit radiation (bremsstrahlung). If the deceleration is extreme, the electron can lose a large fraction of its kinetic energy to the emitted photon(s).
4. **Quantum Effects and Pair Production**: In extremely high-energy environments, quantum electrodynamics (QED) effects become significant. An electron interacting with a high-intensity photon field could potentially transfer a large fraction of its energy to photons, but this process might also involve phenomena like pair production (e.g., electron-positron pairs).

This was done in June 2024

Courtesy S. Sanae

V. Petrillo, ad-hoc developed Montecarlo code for linear QED
1) low recoil 2) DICS (X=1) 3) deep recoil (X=8)

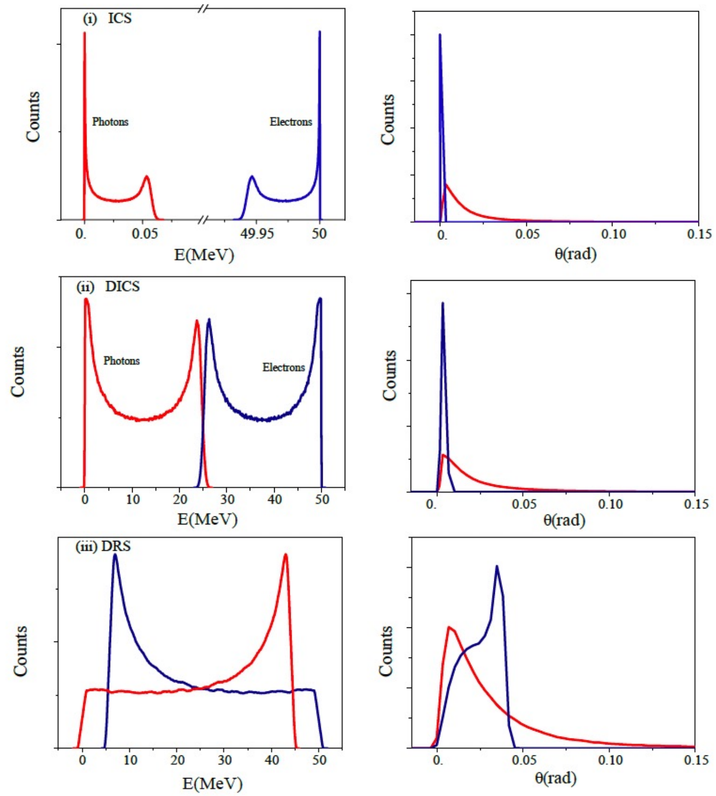


FIG. 4: (i) Inverse Thomson Scattering (ITS). Left: energy distribution, right: angular distribution. Red: scattered photons, blue:scattered electrons. E_{ph}=1.5 eV, E_e=50 MeV, $bw_{ph} = 5\%$. (ii) Democratic Inverse Compton Scattering (DICS). E_{ph}=1.3 keV, $E_e = 50 MeV$, $bw_{ph} = 5\%$. (iii) Deep Recoil Scattering (DRS). E_{ph}=10 keV, E_e=50 MeV, $bw_{ph} = 5\%$.

V. Petrillo, ad-hoc developed Montecarlo code for linear QED

1) electron back-scattering (X=12.000) 2) SCS (X=40.000) 3) Direct Compton ($X=1.2 \cdot 10^5$)

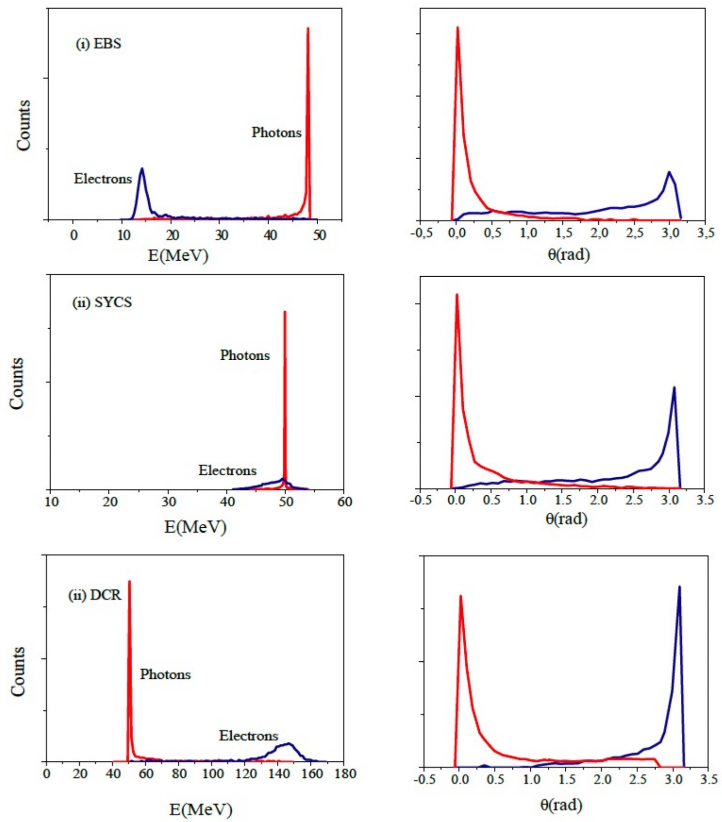


FIG. 6: (i) Electron Back-Scattering (EBS). Left: energy distribution, right: angular distribution. Red: scattered photons, blue:scattered electrons. $E_{ph} = 15MeV$, $E_e = 50MeV$, $bw_{ph} = 5\%$.(ii) Symmetric Compton Scattering (SYCS): $E_{ph} = 50$ MeV, E_e=50 MeV, $bw_{ph} = 5\%$. (iii) Relativistic Direct Compton Scattering: E_{ph}=150 MeV, E_e=50 MeV, $bw_{ph} = 5\%$

$$
\begin{cases}
E_{ph} = \dfrac{mc^2}{2}\left(1 - (1-\beta)\gamma\right) \\[2ex]
E'_{ph} = mc^2\left(\gamma\,\dfrac{1+\beta}{2} - \dfrac{1}{2}\right) \\[2ex]
E_e = \gamma mc^2 \\[2ex]
E'_e = mc^2
\end{cases}
$$

Spectral Purification of incident Channeling Radiation
Compact, sustainable, mono-chromatic gamma-ray source

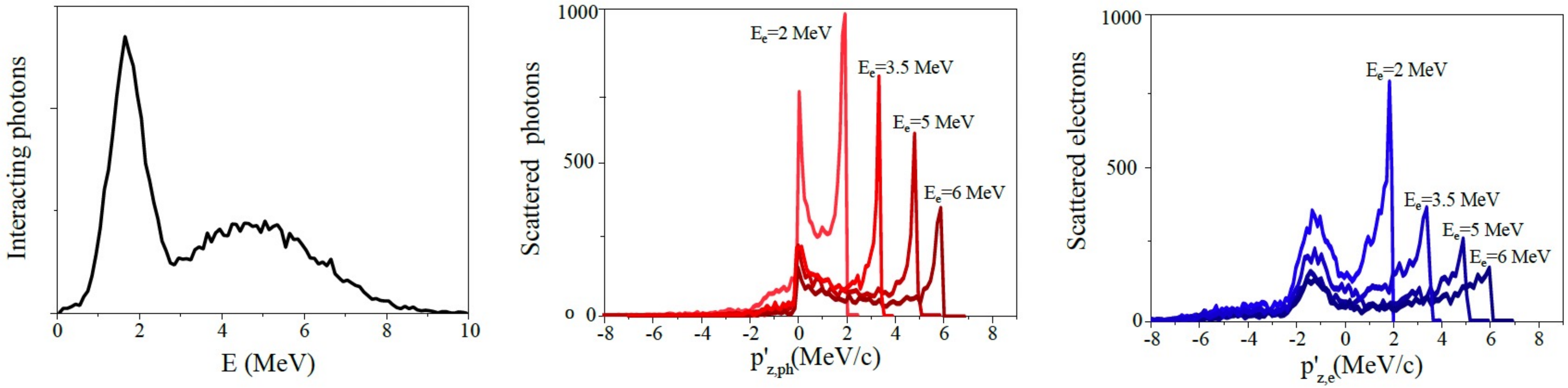


FIG. 8: Left window: Spectrum of the incident photon similar to channelling radiation in crystals, with colliding electron beams of energy $E_e = 2MeV, 3.5MeV, 5MeV$, and $6MeV$. Central window: Momentum spectrum of scattered photons. Right window: Momentum spectrum of scattered electrons

Deep recoil cancels the $\gamma^2\theta^2$ disease/correlation, therefore strongly decreases the dependence of the back-scattered photon beam bandwidth on the electron beam transverse emittance

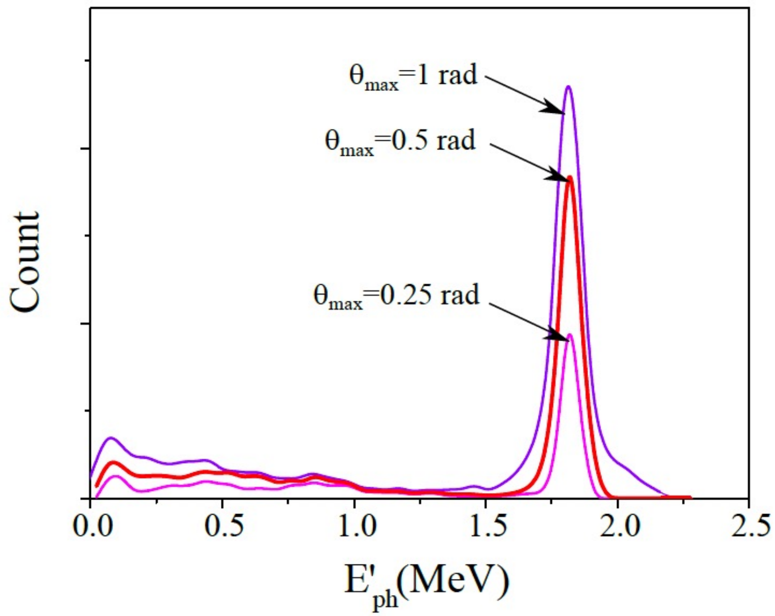


FIG. 9: Collimated energy spectrum. $E_e = 1.9MeV$, curve magenta:$\theta_{max} = 0.25rad$, red:$\theta_{max} = 0.5rad$,blue: $\theta_{max} = 1rad$

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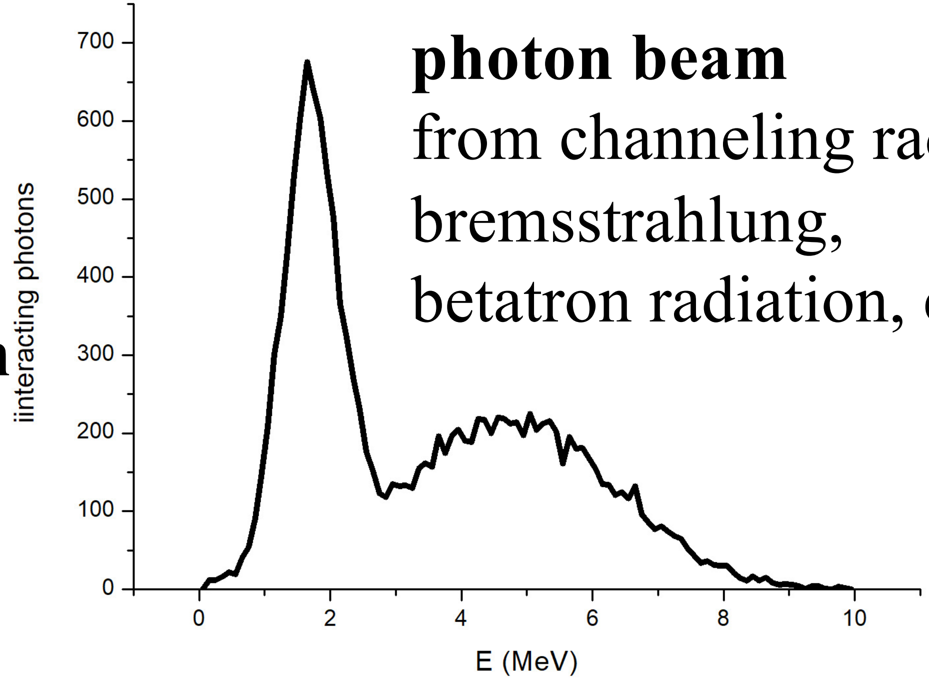
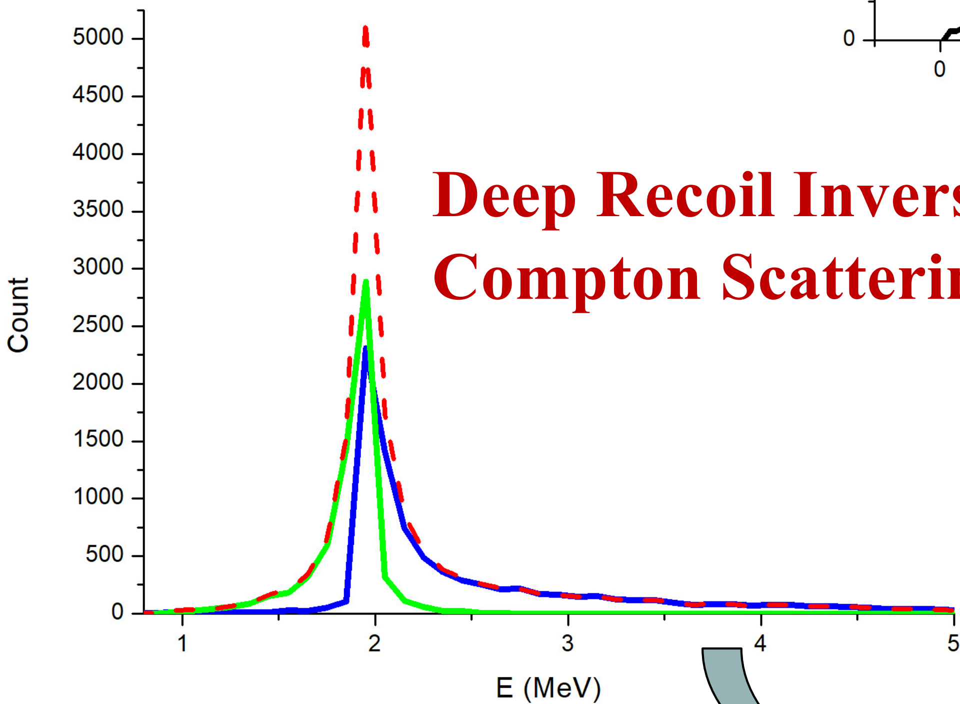
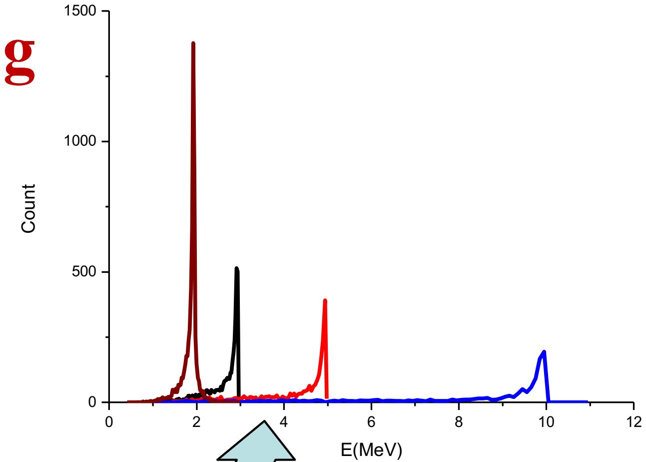
Broad-band incident photon beam
from channeling radiation, bremsstrahlung, betatron radiation, etc



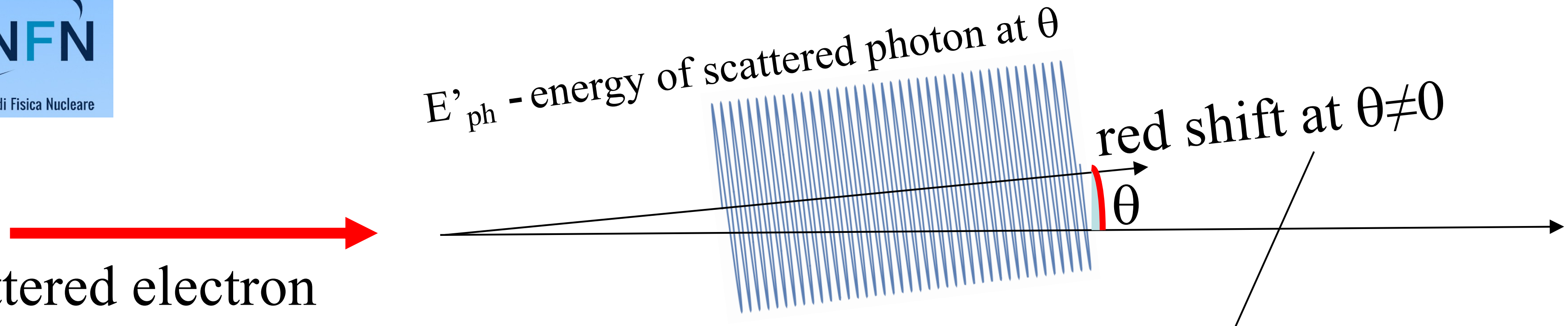
spectral purification

Deep Recoil Inverse Compton Scattering





tunability



scattered electron

$E'_e = \gamma mc^2 + E_{ph} - E'_{ph}$

$$E'_{ph}(\theta) = \frac{4E_{ph}\gamma^2}{1 + X + \gamma^2\theta^2}$$

$$X = \frac{4E_eE_{ph}}{\dots} = \frac{4\gamma E_{ph}}{\dots} = 4\gamma^2\frac{E_{ph}}{\dots}$$

All I.C.S. X/γ ray Sources work at X<1 and A » 1

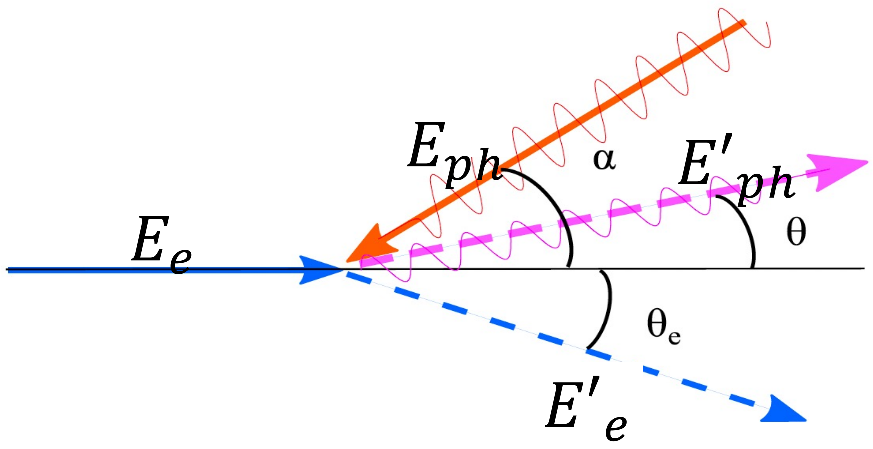
STAR (350 keV) $X_{STAR} < 2.6 \cdot 10^{-3}$ $A_{STAR} > 10^4$

ELI-NP (20 MeV) $X_{ELI-NP} < 0.026$ $A_{ELI-NP} > 2.4 \cdot 10^5$

X = recoil … n seen

by the ele … d to mc^2

$$E'_{ph} = \frac{\gamma^2(1+\beta)}{\gamma^2(1-\beta\cos\theta) + \frac{X}{4}(1+\cos\theta)} E_{ph}$$



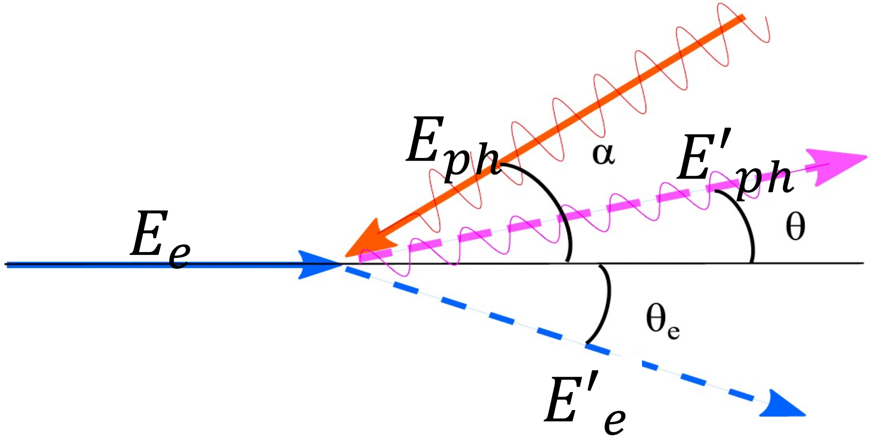
$X \equiv 4\gamma^2 E_{ph}/E_e$

$A \equiv \beta\gamma^2 - X/4 = \gamma^2(\beta - E_{ph}/E_e)$

$$E'_{ph} = \frac{4(\gamma^2+A)+X}{4(\gamma^2 - A\cos\theta)+X} E_{ph}$$

A=*0* , *i.e.* Symmetric Compton Scattering cancels the $\gamma^2\theta^2$ correlation

Let's consider the condition of maximum energy/momentum transfer between electron and photon, *i.e.* $\theta = 0$



$$E'_{ph} = \frac{\gamma^2(1+\beta)}{\gamma^2(1-\beta\cos\theta)+\frac{X}{4}(1+\cos\theta)}E_{ph}$$

$\theta = 0$

$$E'_{ph} = \frac{2\gamma^2}{\gamma^2(1-\beta)+\frac{X}{2}}E_{ph}$$

θ = 0 corresponds to:
maximum energy of back-scattered photon E'_{ph-max}
and
minimum energy of electron after scattering E'_{e-min}

$$E'_{ph-max} = \frac{4\gamma^2 E_{ph}}{1+X}$$

Thomson limit: X << 1

$$E'_{ph-max} = 4\gamma^2 E_{ph}$$

Deep recoil Compton: X >> 1

$$E'_{ph-max} \sim \left(1 - \frac{1}{X}\right) E_e$$

$$E_{TOT} = E_e + E_{ph} = E'_{e-min} + E'_{ph-max}$$

$$E'_{e-min} = E_e + E_{ph} - E'_{ph-max} = E_e + E_{ph} - \frac{4\gamma^2 E_{ph}}{1+X}$$

All quantities normalized to the total energy $E_{tot} = E_e + E_{ph}$

E_e = 100 MeV

$$\frac{E'_{ph}}{E_{tot}} = \frac{X}{(1+X)(1+\frac{X}{4\gamma^2})}$$

$$\frac{E'_e}{E_{tot}} = 1 - \frac{X}{(1+X)(1+\frac{X}{4\gamma^2})}$$

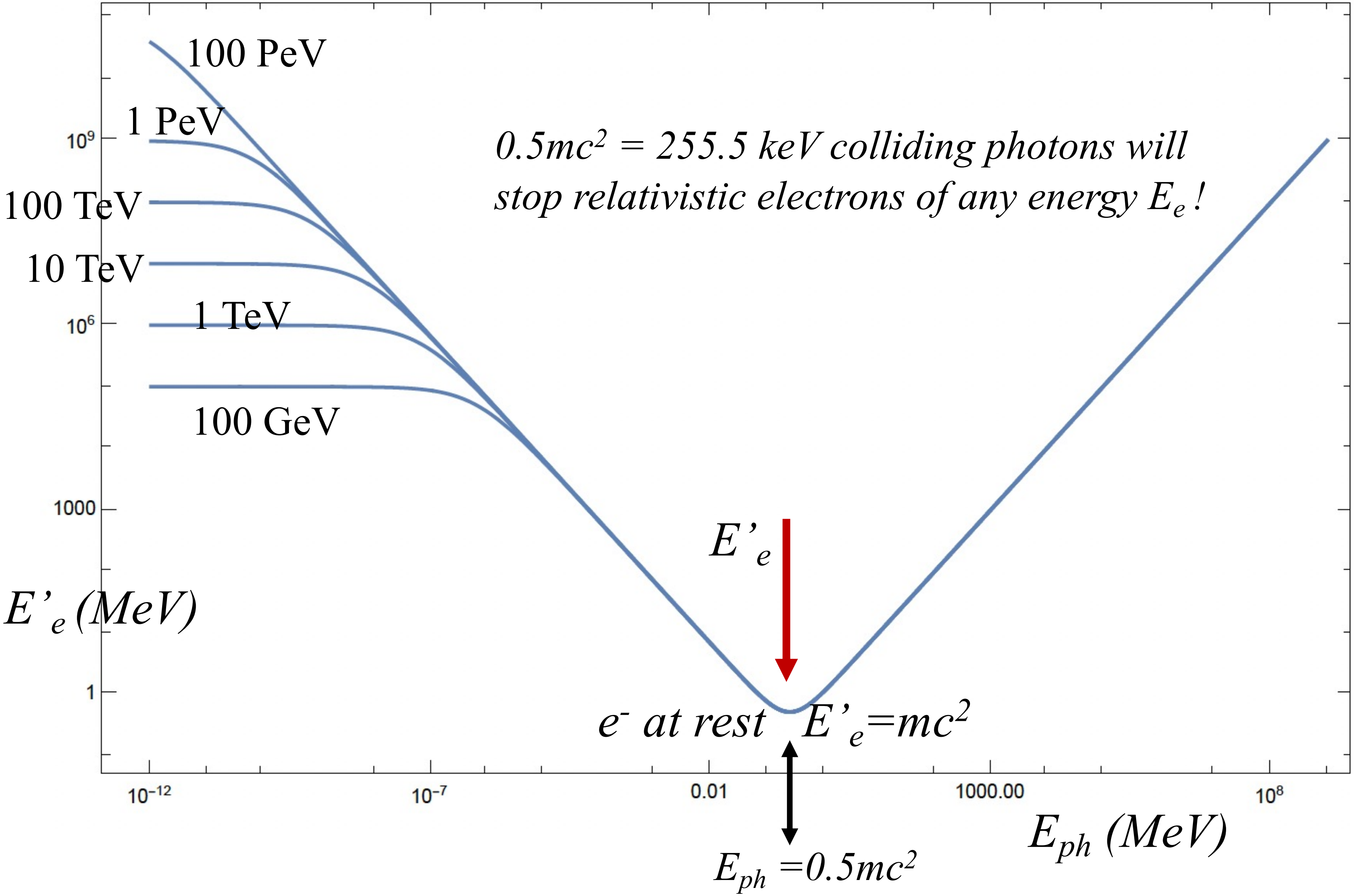
when recoil X is large electron swaps with photon,
maximum energy loss by the electron in favour to the photon

$$E'_{ph-max} = \frac{4E_{ph}{E_e}^2/(mc^2)^2}{1 + 4E_{ph}E_e/(mc^2)^2}$$

$$if\ \gamma \gg 1 \qquad E'_{e-min} \approx E_e \frac{1 + (1 + X)\, E_{ph}/E_e}{1 + X}$$

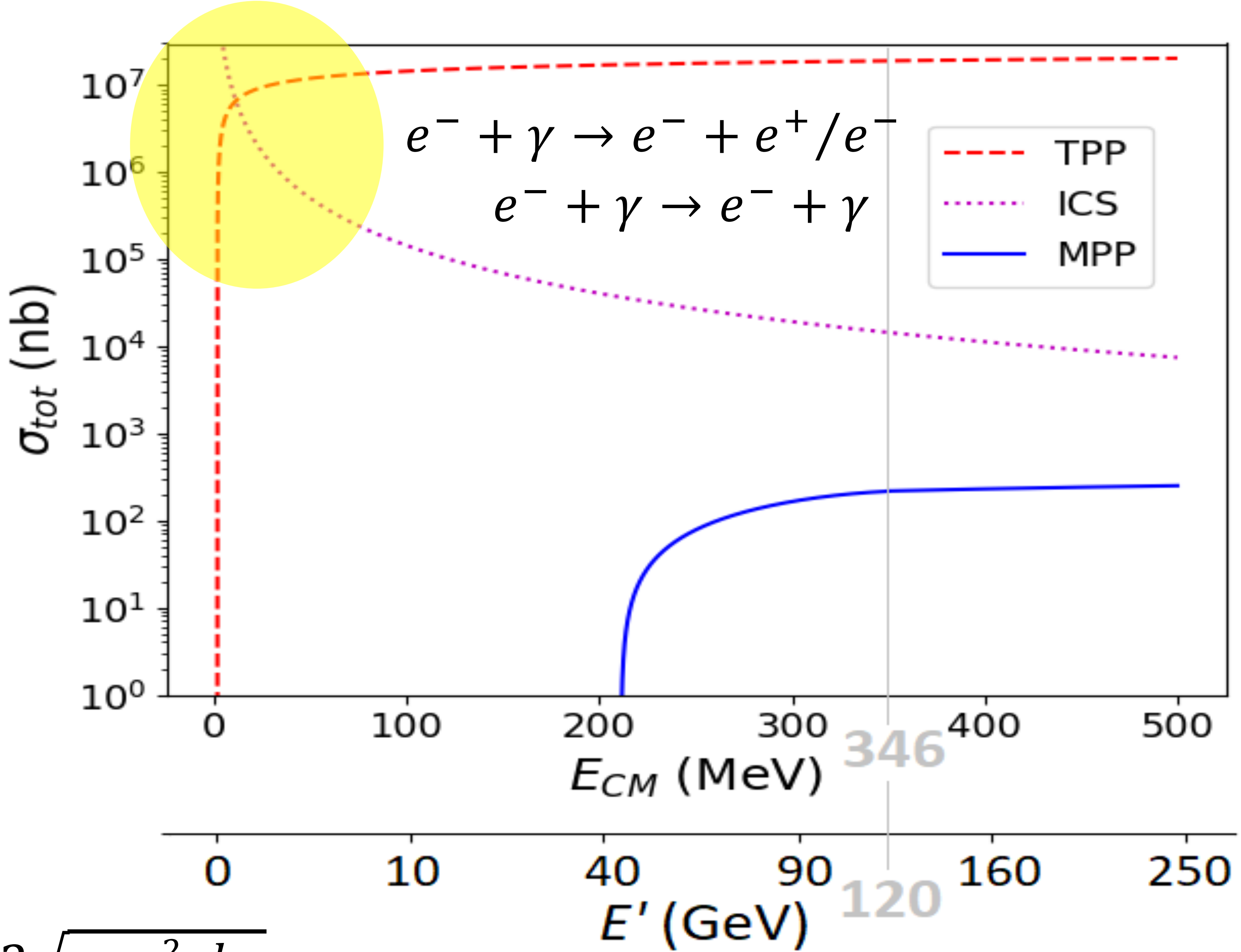
X<<1: $E'_{e-min} \approx E_e$

X>>1: $E'_{e-min} \approx E_{ph}$



*hadronic threshold ($E_{cm} < 600$ MeV) with 255.5 keV photons ≈ 360 GeV

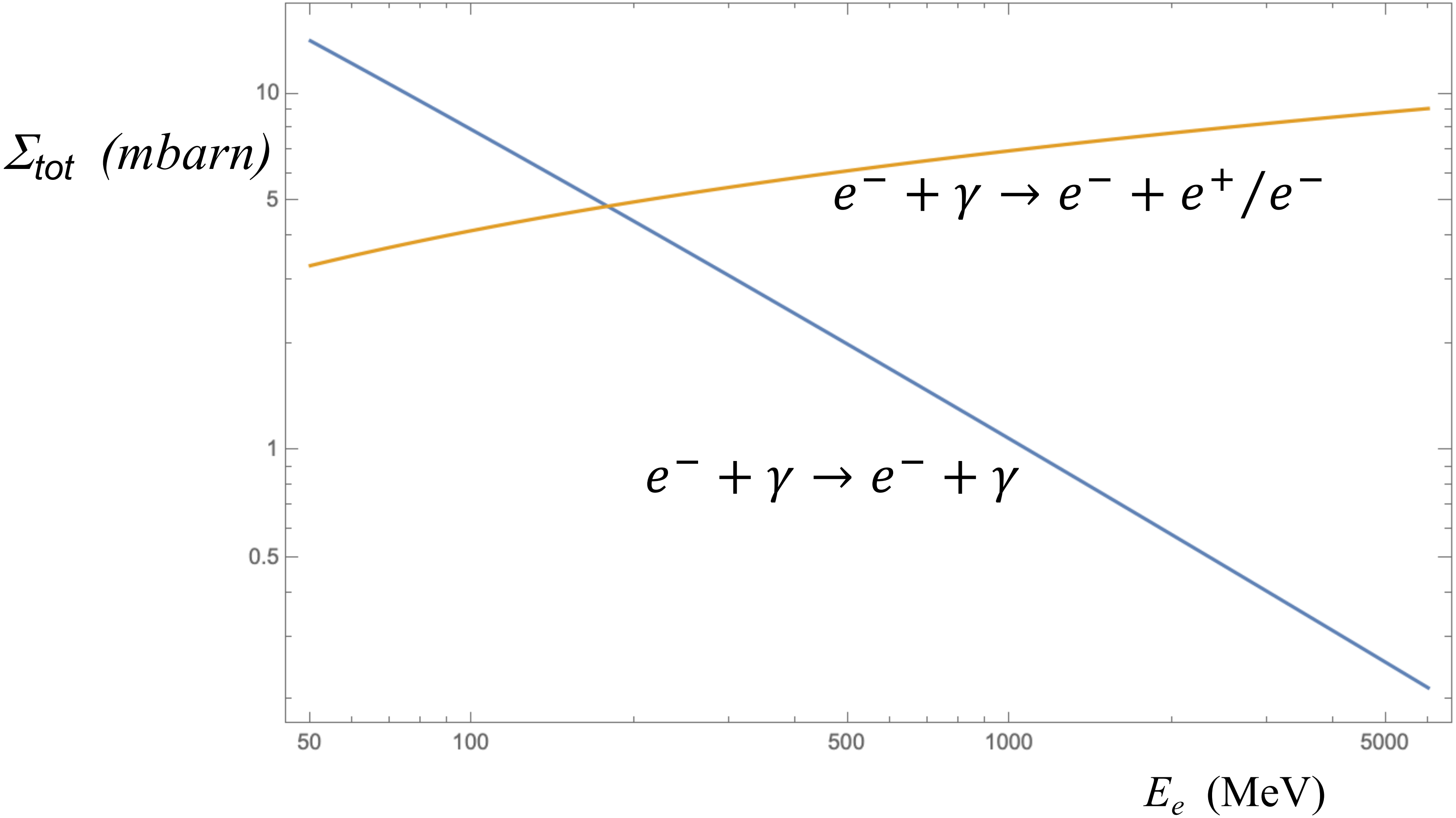
Total cross-section for QED (e,γ) reactions



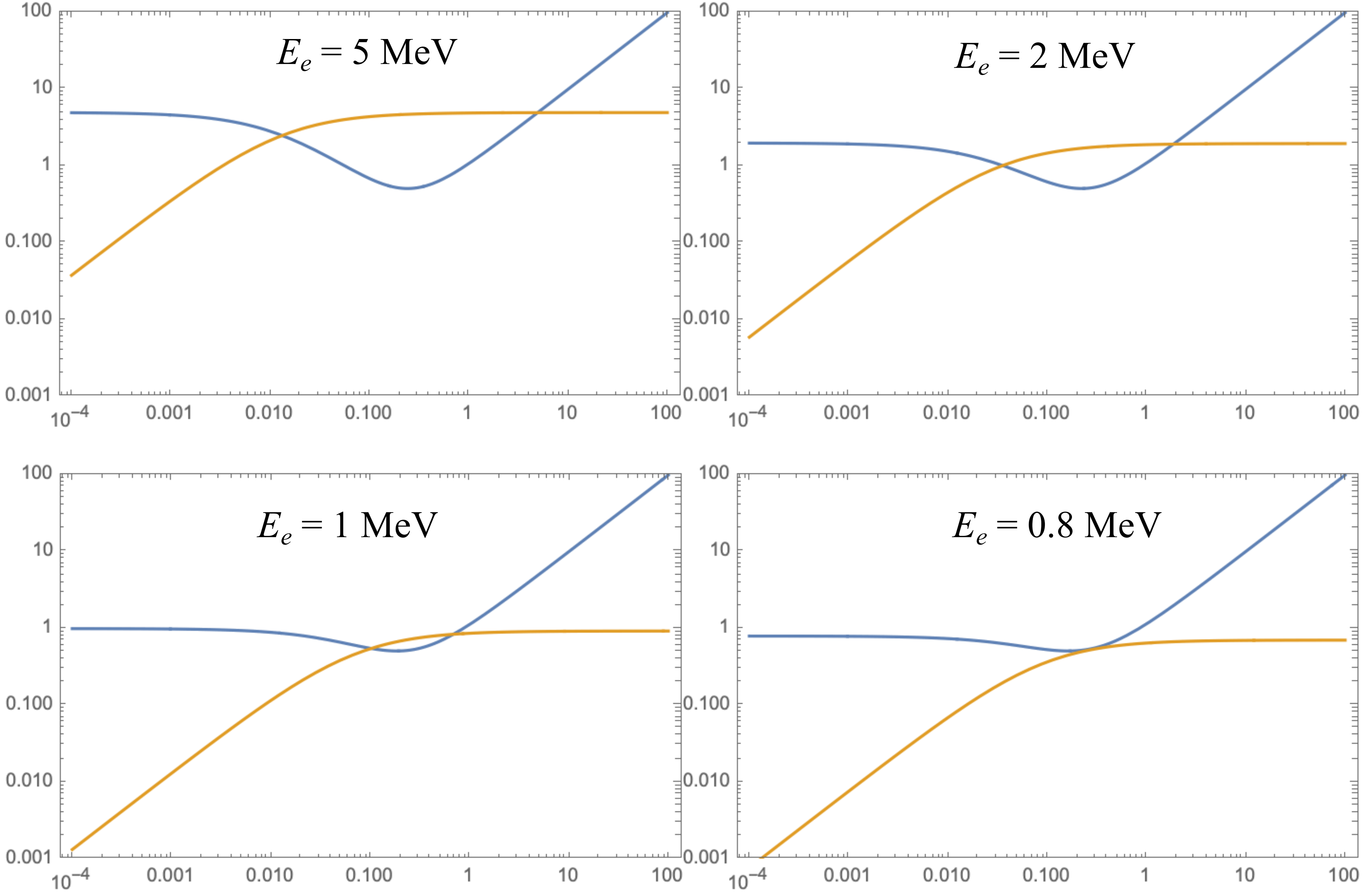
$$E_{CM} = 2\sqrt{m_e c^2 \gamma h\nu}$$

Total cross-sections for Compton and Bethe-Heitler

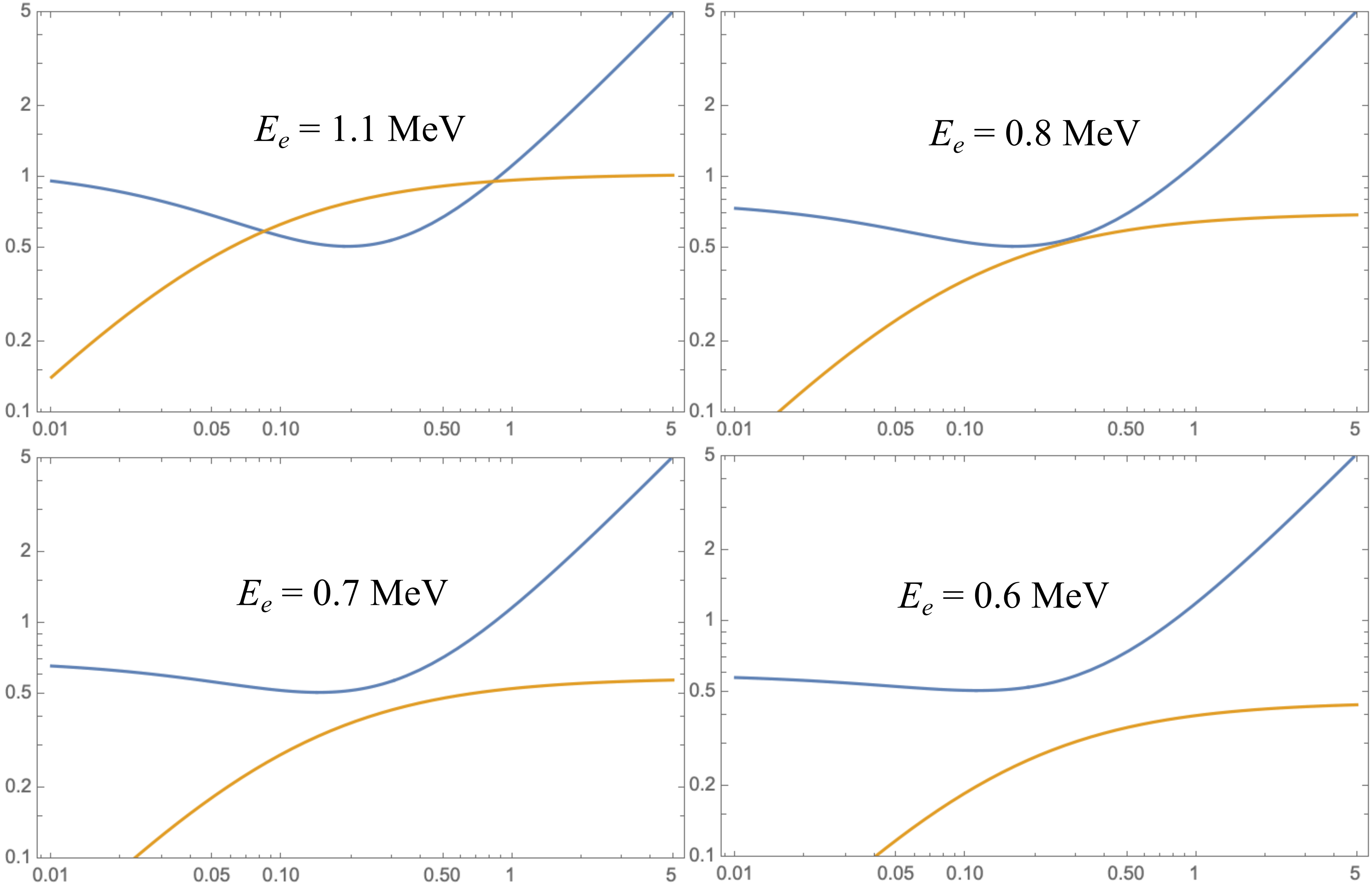
$E_{ph} = 255.5$ *keV* $(E_e$ *from 50 MeV to 5 GeV*$)$



FICS low relativistic



FICS very low relativistic



Large Recoil in ICS damps the effect of large bandwidth incident photon beams onto the bandwidth of scattered photons

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 080701 (2017)

Analytical description of photon beam phase spaces in inverse Compton scattering sources

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[2]*Università degli Studi di Milano, via Celoria 16, 20133 Milano, Italy*
(Received 9 March 2017; published 3 August 2017)

equivalent to FELs Kim-Pellegrini crit. on 3D inhomogeneous effects on photon bandwidth

$$\frac{\Delta E_{\rm ph}}{E_{\rm ph}} \simeq \sqrt{\left[\frac{\Psi^2/\sqrt{12}}{1+\Psi^2}+\frac{\bar{P}^2}{1+\sqrt{12}\bar{P}^2}\right]^2+\left[\left(\frac{2+X}{1+X}\right)\frac{\Delta\gamma}{\gamma}\right]^2+\left(\frac{1}{1+X}\frac{\Delta E_L}{E_L}\right)^2+\left(\frac{M^2\lambda_0}{2\pi w_0}\right)^4+\left(\frac{a_0^2/3}{1+a_0^2/2}\right)^2}$$

collimation angle

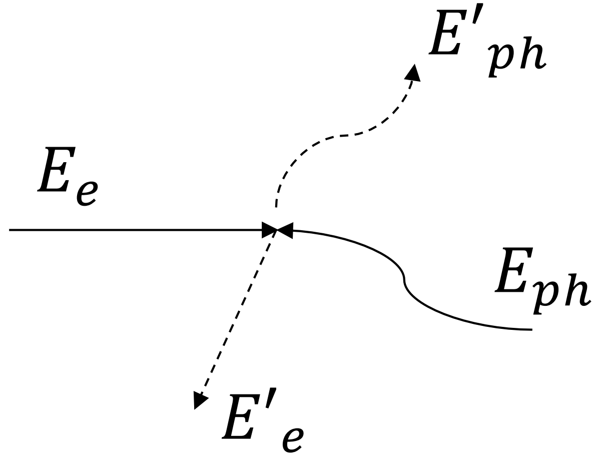
beam emittance

beam en. spread

incident photons en. spread

diffraction

non linearity



$X \equiv 4\gamma^2 E_{ph}/E_e$

$A \equiv \beta\gamma^2 - X/4 = \gamma^2(\beta - E_{ph}/E_e)$

$$E'_{ph} = \frac{4(\gamma^2+A)+X}{4(\gamma^2 - A\cos\theta)+X} E_{ph}$$

I.C.S. low recoil $X << 1$

$A \sim \beta\gamma^2 \sim \gamma^2 - 1/2$

$$E'_{ph-max} \sim 4\gamma^2 E_{ph}$$

I.C.S. deep recoil $X >> 1$

$A \sim \beta\gamma^2 - X/4 \sim \gamma^2 - 1/2 - X/4$

$$E'_{ph-max} \sim \frac{4\gamma^2}{1+X} E_{ph} \sim \left(1 - \frac{1}{X}\right) E_e$$

S.C.S. $(A = 0)$ ***or***

quasi-SCS $(|A| << 1)$

$$E'_{ph-max} \sim E_{ph}\left(1 + \frac{2A}{(1+\beta)\gamma^2}\right)$$

$$E'_{e-min} \sim E_e - E_{ph}\frac{2A}{(1+\beta)\gamma^2}$$

D.C. $\gamma = 1, \ \beta = 0, \ A = -X/4$

$$E'_{ph-min} = \frac{1}{1+X/2} E_{ph} = \frac{1}{1-2A} E_{ph}$$

Direct Compton $\gamma = 1$, $\beta = 0$, $X = 4E_{ph}/mc^2$

$$E'_{ph-min} = \frac{E_{ph}}{1 + 2E_{ph}/mc^2} \quad if \quad E_{ph} \gg mc^2 \quad E'_{ph-min} = \frac{mc^2}{2}$$

Very energetic photons are scattered back at 255 keV
and electrons pushed to $E_{ph} + 0.5mc^2$

$$E'_{e-max} = mc^2 + E_{ph} - E'_{ph-min} \;, if \; E_{ph} \gg mc^2 \; E'_{e-max} = E_{ph} + \frac{mc^2}{2}$$

General Formula expressed in terms of energies of primary colliding particles, valid for any γ, A, X, θ

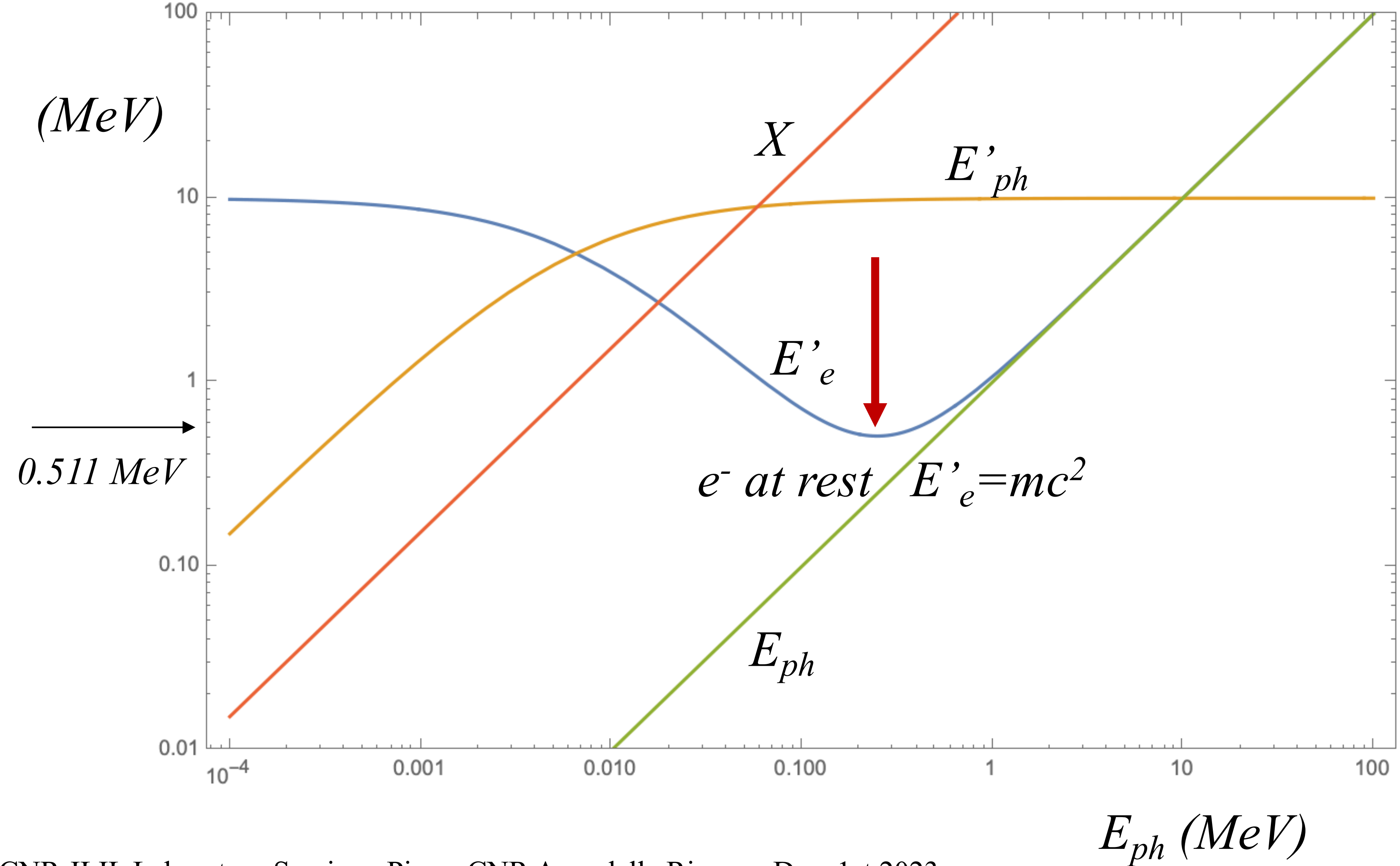
$$E'_{ph} = \frac{(1+\beta)\,E_{ph}E_e}{(1-\beta\cos\theta)\,E_e + (1+\cos\theta)\,E_{ph}}$$

$$E'_{ph-max} = \frac{(1+\beta)E_{ph}E_e}{(1-\beta)E_e + 2E_{ph}}$$

$$X = 4\, E_e E_{ph} /(mc^2)^2$$

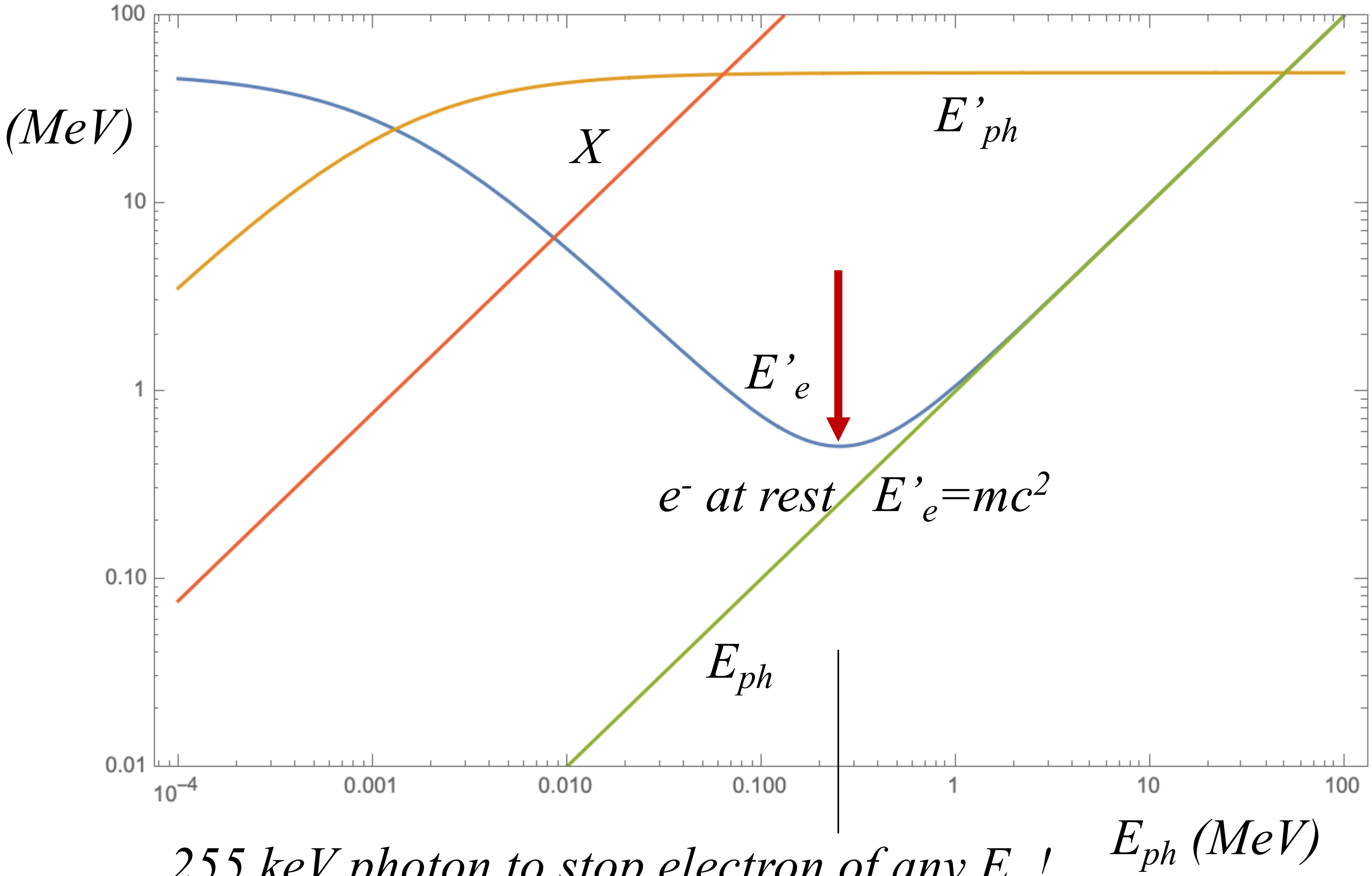
$$E'_{ph-max} = \frac{(1+\beta)E_{ph}E_e}{(1-\beta)E_e + 2E_{ph}}$$

E_e = 10 MeV



$$E'_{ph-max} = \frac{(1+\beta)E_{ph}E_e}{(1-\beta)E_e + 2E_{ph}}$$

$E_e = 50$ MeV



255 keV photon to stop electron of any E_e !

$$E'_{ph-max} = \frac{(1+\beta)E_{ph}E_e}{(1-\beta)E_e + 2E_{ph}}$$

$$E'_{e-min} = E_e + E_{ph} - E'_{ph-max} = E_e + E_{ph} - \frac{(1+\beta)E_{ph}E_e}{(1-\beta)E_e + 2E_{ph}}$$

$$E'_{ph-max} = \frac{4E_{ph}{E_e}^2/(mc^2)^2}{1 + 4E_{ph}E_e/(mc^2)^2}$$

$$if\ \gamma \gg 1 \qquad E'_{e-min} \approx E_e \frac{1 + (1+X)\, E_{ph}/E_e}{1+X}$$

X<<1 → $E'_{e-min} \approx E_e$

X>>1 → $E'_{e-min} \approx E_{ph}$

$$if\ E_{ph} = \frac{mc^2}{2} - (1-\beta)E_e \quad \Longrightarrow \quad E'_{e-min} = mc^2$$

255 keV photon to stop electron of any E_e !

$$if\ E_{ph} = \frac{mc^2}{2} - (1-\beta)E_e \quad \Longrightarrow \quad E'_{e-min} = mc^2$$

$$if\ \gamma \gg 1\ \ and\ \ E_{ph} = \frac{mc^2}{2}\left[1 - \frac{1}{\gamma}\right] \quad \Longrightarrow \quad E'_{e-min} = mc^2$$

If the incident photon energy is given by $E_{ph} = \frac{mc^2}{2}\left[1 - \frac{1}{\gamma}\right]$

any relativitic electron (i.e. $\gamma >> 1$) will be stopped in a head-on collision with such a photon

255 keV photons will stop electrons of any E_e as far as $\gamma >> 1$

$$E_{ph} = \frac{mc^2}{2}\left[1 - \frac{1}{2\gamma}\right]$$ to stop any (relativistic) electron

Incidentally, the condition is almost the same needed to make the total energy in the lab ref. frame (LAB) equal to the total energy in the electron rest frame (ERF)

LAB total energy $E_{LAB} = \gamma mc^2 + E_{ph}$

ERF total energy $E_{ERF} = mc^2 + 2\gamma E_{ph}$

$$E_{LAB} = E_{ERF}$$

if

$$E_{ph} = \frac{mc^2}{2}\frac{2\gamma - 2}{2\gamma - 1} \xrightarrow[\gamma\to\infty]{} \frac{mc^2}{2}$$

Generalization to any Collision Angle α , $\alpha = \pi$ *head-on*

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17,** 020706 (2014)

Dual color x rays from Thomson or Compton sources

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Each electron, characterized by normalized velocity $\underline{\beta}_i$ forming an angle θ_i with the z axis, scatters photons with frequency ν_p given by

$$\nu_p = \nu_0 \frac{1 - \underline{e}_k \cdot \underline{\beta}_i}{1 - \underline{n} \cdot \underline{\beta}_i + \frac{h\nu_0}{mc^2\gamma_i}(1 - \underline{e}_k \cdot \underline{n})}, \qquad (1)$$

where ν_0 is the frequency of the incident laser photon, $\underline{e}_k$ the unit vector of its direction, $\underline{n}$ is the direction of the scattered photon, h the Planck constant and γ_i the electron Lorentz factor before the scattering. The last term in the

$$E'_{ph} = \frac{4\gamma^2(1 - \beta\cos\alpha)}{4\gamma^2(1 - \beta\cos\theta) + X(1 - \cos\alpha\cos\theta + \sin\alpha\sin\theta)} E_{ph}$$

$\alpha = \pi$, *head-on* $\Rightarrow$ $$E'_{ph} = \frac{\gamma^2(1 + \beta)}{\gamma^2(1 - \beta\cos\theta) + \frac{X}{4}(1 + \cos\theta)} E_{ph}$$

in agreement with Eq.3 in *N. Ranjan et al.*, **PRAB 21**, 030701 (2018)

$$E'_{ph} = \frac{4\gamma^2(1-\beta\cos\alpha)}{4\gamma^2(1-\beta\cos\theta)+X(1-\cos\alpha\cos\theta+\sin\alpha\sin\theta)}E_{ph}$$

$$if\ \gamma \gg 1\ \ and\ \ \beta \approx 1-\frac{1}{2\gamma^2}\ and\ \theta \ll 1$$

$$E'_{ph} = \frac{4\gamma^2\left(\frac{1-\cos\alpha}{2}\right)}{1+\gamma^2\theta^2+X\left(\frac{1-\cos\alpha}{2}\right)}E_{ph}$$

$$if\ \theta = 0 \quad E'_{ph} = E'_{ph-max} \qquad E'_{ph-max} = \frac{4\gamma^2\left(\frac{1-\cos\alpha}{2}\right)}{1+X\left(\frac{1-\cos\alpha}{2}\right)}E_{ph}$$

in agreement with Eq.1 in *I. Drebot et al.*, ***EPL* 120**, 14002 (2017)

$$E'_{ph-max} = \frac{4\gamma^2 \left(\frac{1-\cos\alpha}{2}\right)}{1 + X\left(\frac{1-\cos\alpha}{2}\right)} E_{ph}$$

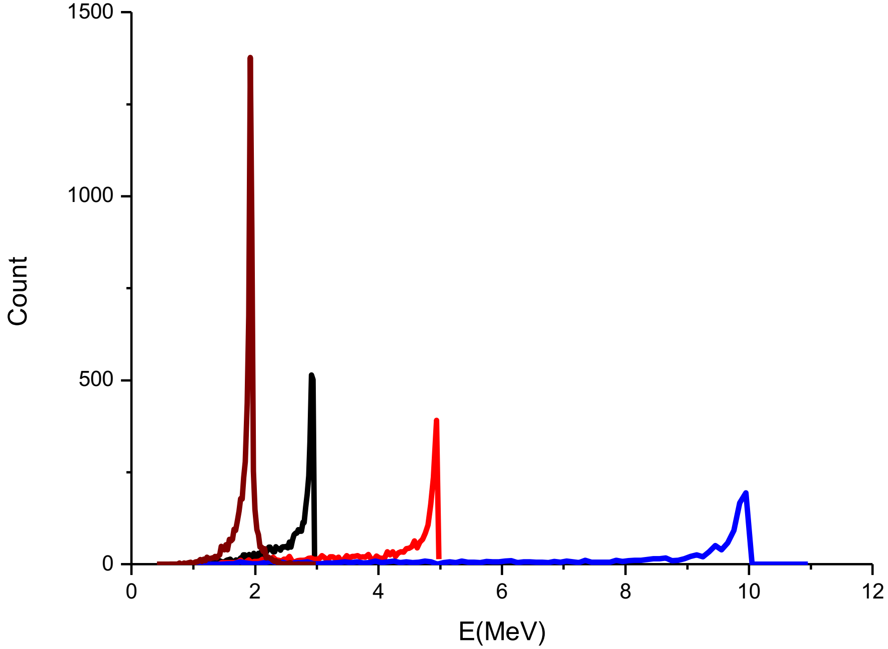
$X << 1 \Rightarrow$ $$E'_{ph-max} = 4\gamma^2 \left(\frac{1-\cos\alpha}{2}\right) E_{ph}$$

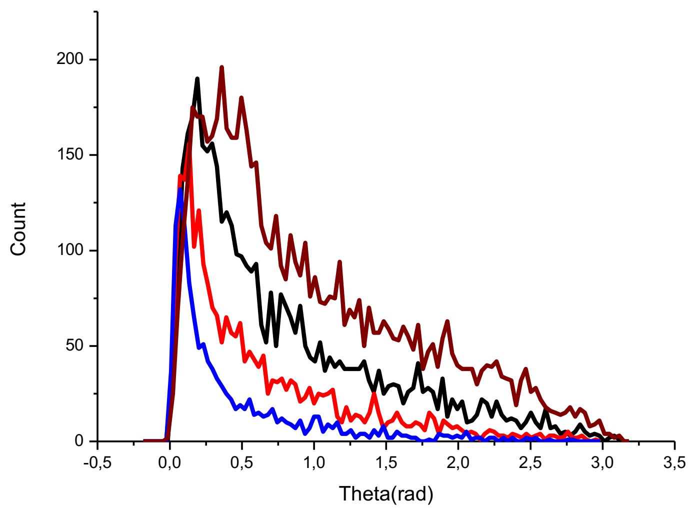
$\alpha = \pi$, *head-on* $\Rightarrow$ $$E'_{ph-max} = \frac{4\gamma^2}{1+X} E_{ph}$$

$\alpha = \pi/2$, $X << 1 \Rightarrow$ $$E'_{ph-max} = 2\gamma^2 E_{ph}$$

$X >> 1 \Rightarrow$ $$E'_{ph-max} = \frac{4\gamma^2}{X} E_{ph} = E_e \quad \forall\alpha \;\; !!$$

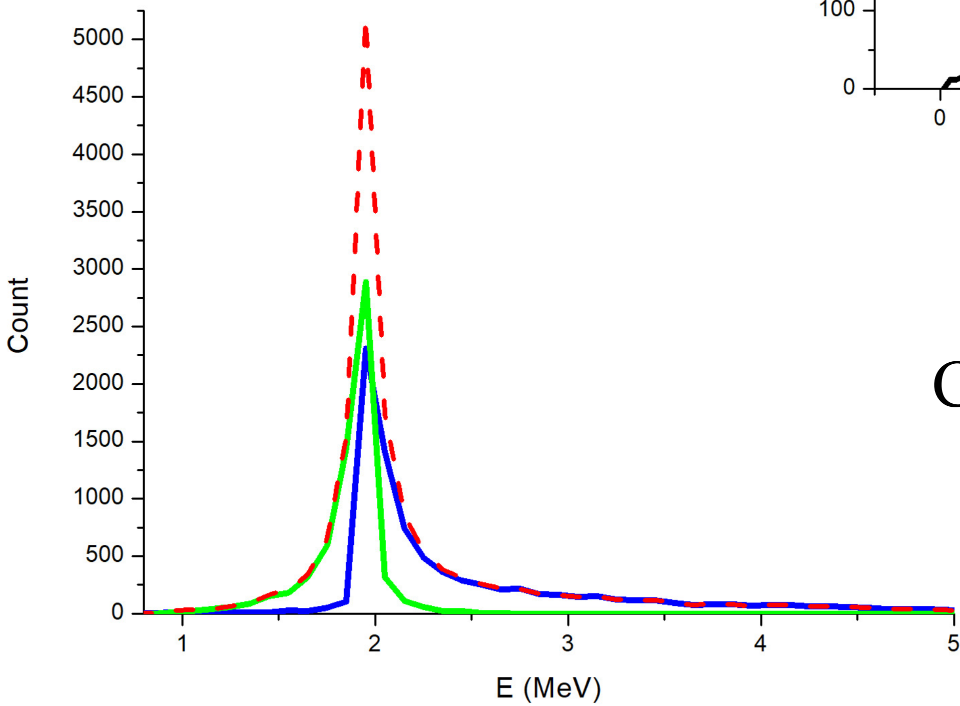
Colliding a gaussian distributed (20% rms spread) broad-band radiation beam, representing the first peak of channeling spectrum at 2 MeV, with a low energy (variable) electron beam (2,3,5,10 MeV)

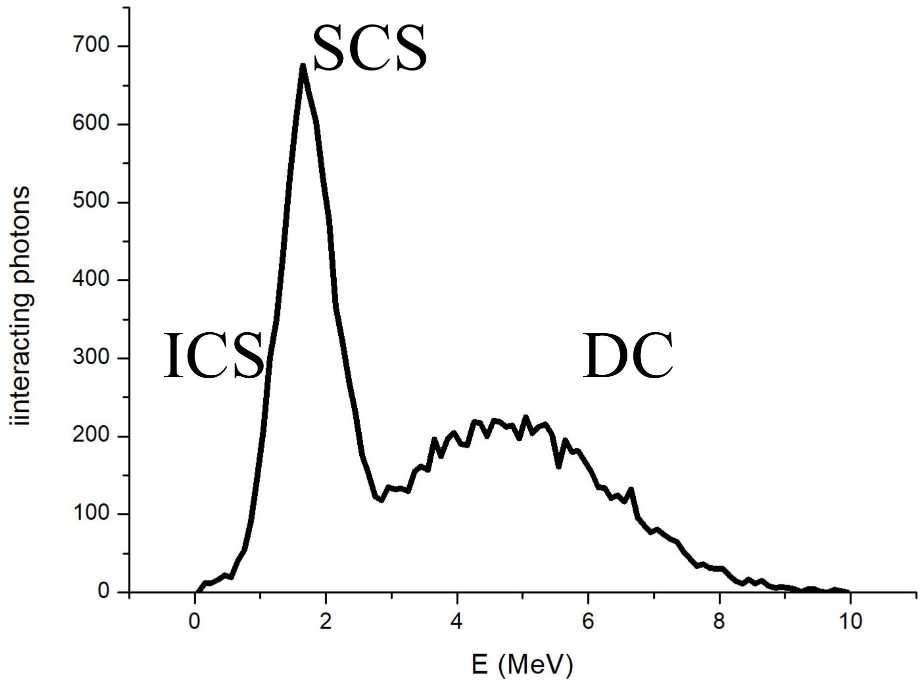




Mono-chromatization, Tunability

Colliding the full spectrum





Spectral purification
Compton Scattering across SCS

ELSEVIER

Optics Communications

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Collective instabilities and high-gain regime in a free electron laser

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