View on Future Accelerators/Concepts

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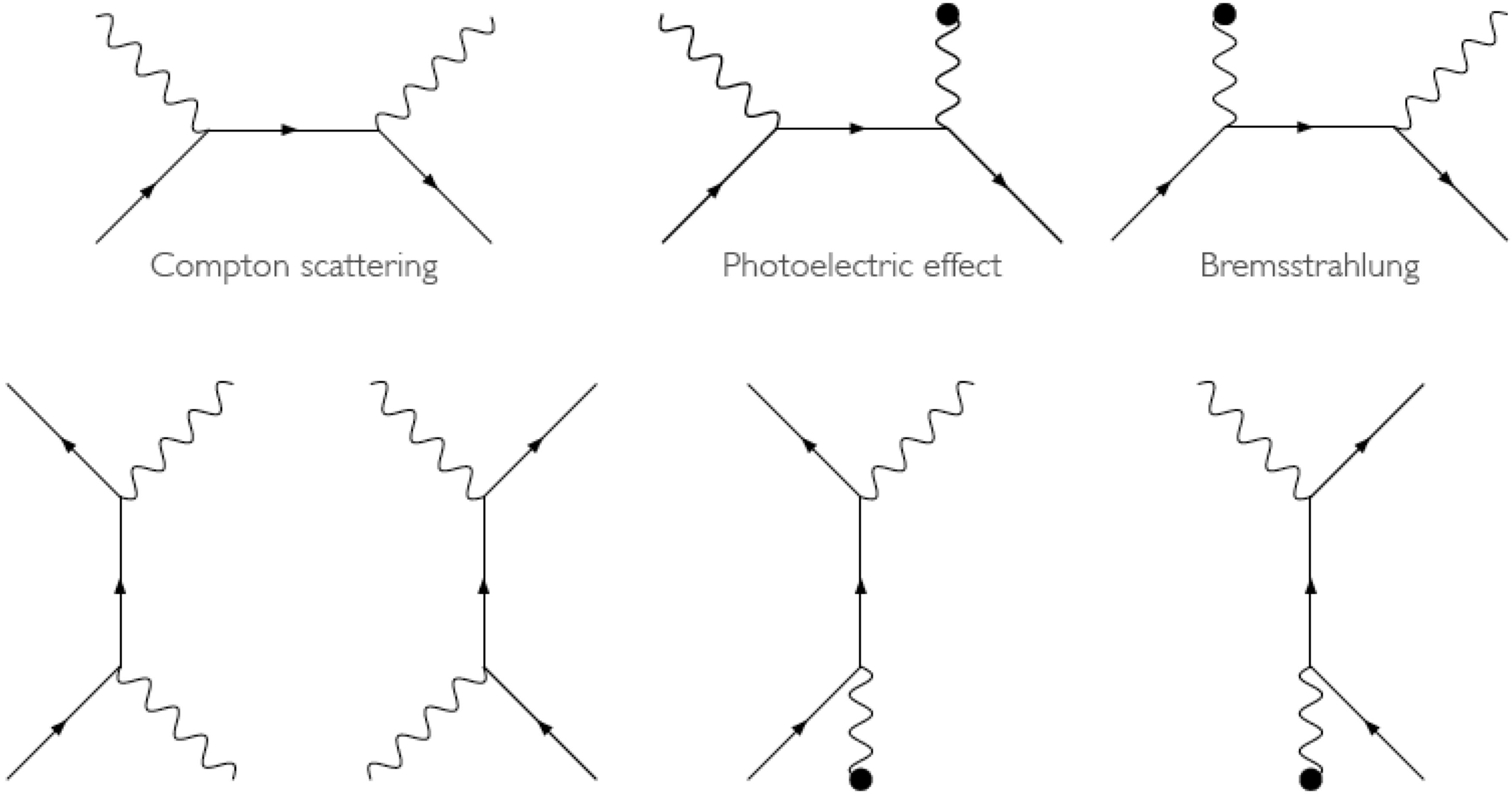
- **Going Big/Going Small:**

  Fundamental High Energy Physics/Applications oriented
- **An example of Going Small with present technology to perform Fundamental QED Physics: the low energy gamma-gamma collider (MeV c.m.) – doing HEP with a photon machine**
- **An example of Going Big for Hybridization: combining diff. technologies/machines for new beam sources (muons, neutrinos, etc.) and collider scenarios. The hadron-photon collider, merging FEL's with LHC (two genetically different animals with record performances in their own evolutionary chain)**

The simplest interactions between light and matter: the basics of QED



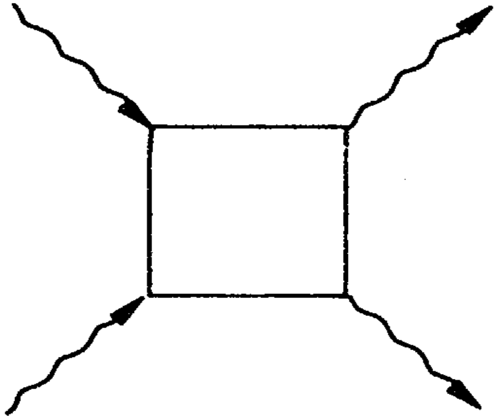
Compton scattering — Photoelectric effect — Bremsstrahlung

Dirac annihilation — Breit-Wheeler pair production — Single photon annihilation — Bethe-Heitler pair production

Feymann tree-level diagrams, all imply interaction e.m. field - el. charge

Courtesy Oliver Pike

Photon-photon scattering is a probe into the structure of the vacuum of QFT



Feymann fermion loop diagram

The QFT vacuum holds the key to the understanding of renormalization in QFTs.

Different vacua are possible, and the observation of photon-photon scattering would provide important clues on the actual structure of the QFT vacuum.

Photon-photon scattering at low energy is very difficult to observe, the total cross-section is extremely small. The total unpolarized scattering cross section predicted by QED is

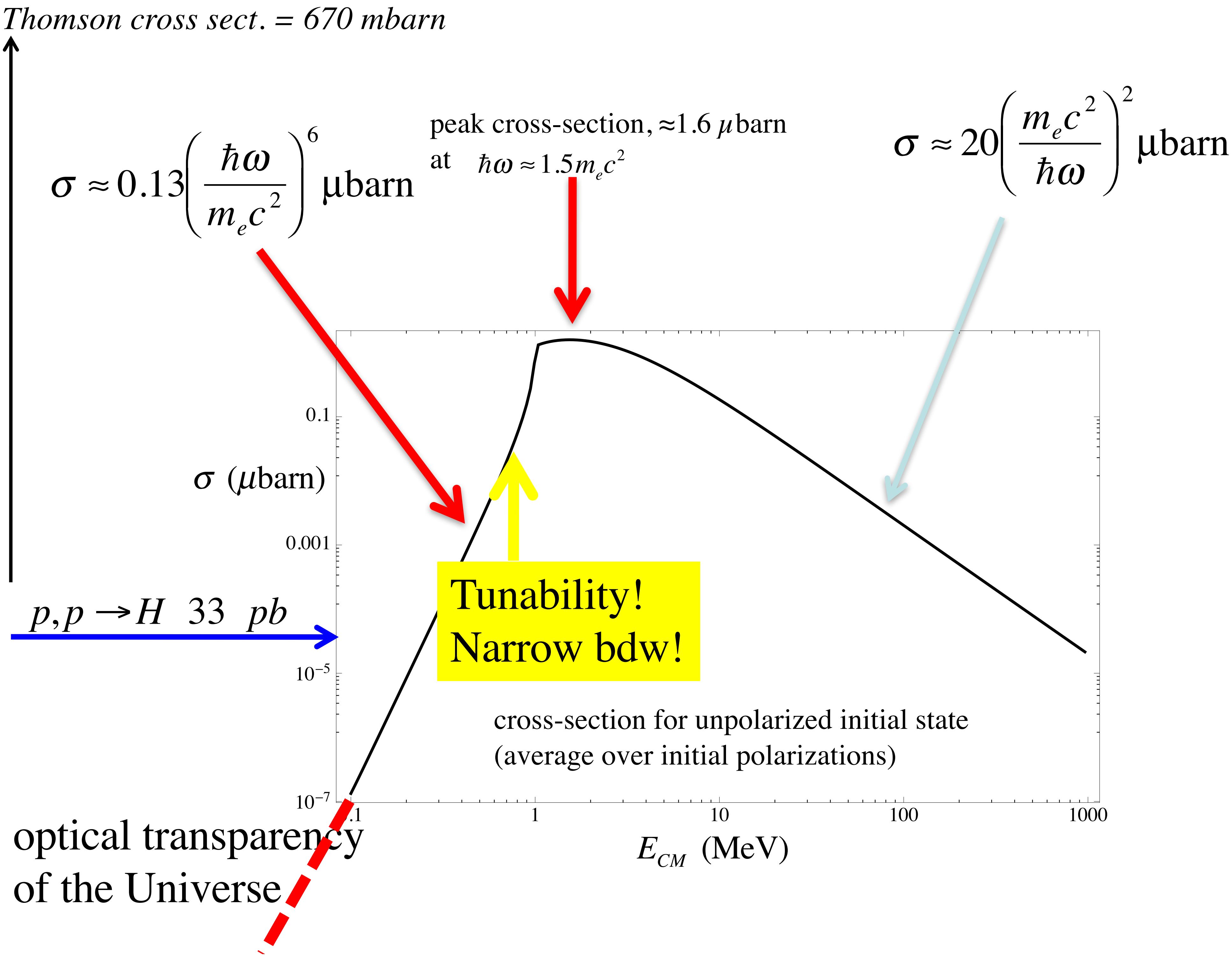
$$\sigma_{\gamma\gamma}^{(QED)} = \frac{973\mu_0^2(\hbar\omega)^6}{20\pi\hbar^4 c^4} A_e^2$$

Where

$$A_e = \frac{2\alpha^2 \lambda\!\!\!^{-}{}_e^3}{45\mu_0 m_e c^2} \approx 1.32\ 10^{-24}\mathrm{T}^{-2}$$

This evaluates to a very small number with low energy (≈ 1 eV) photons, however it increases as the sixth power of photon energy.

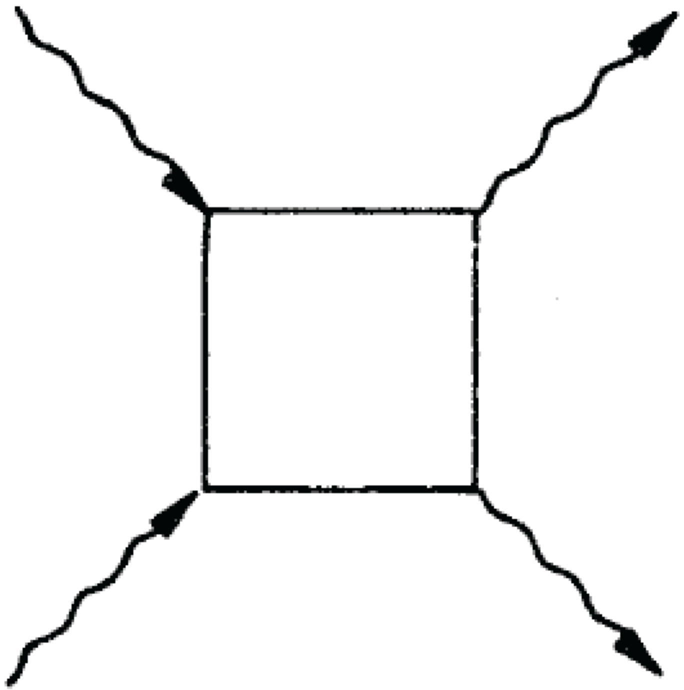
Focus: Future Frontiers in Accelerators, Scharbeutz (D), Dec. 2016



Thomson cross sect. = 670 mbarn
$\sigma \approx 0.13\left(\frac{\hbar\omega}{m_e c^2}\right)^6$ μbarn
peak cross-section, ≈1.6 μbarn
at $\hbar\omega \approx 1.5 m_e c^2$
$\sigma \approx 20\left(\frac{m_e c^2}{\hbar\omega}\right)^2$ μbarn
0.1
σ (μbarn)
0.001
$p,p \rightarrow H$ 33 pb
Tunability!
Narrow bdw!
10^{-5}
cross-section for unpolarized initial state
(average over initial polarizations)
10^{-7}
0.1
1
10
100
1000
E_{CM} (MeV)
optical transparency
of the Universe

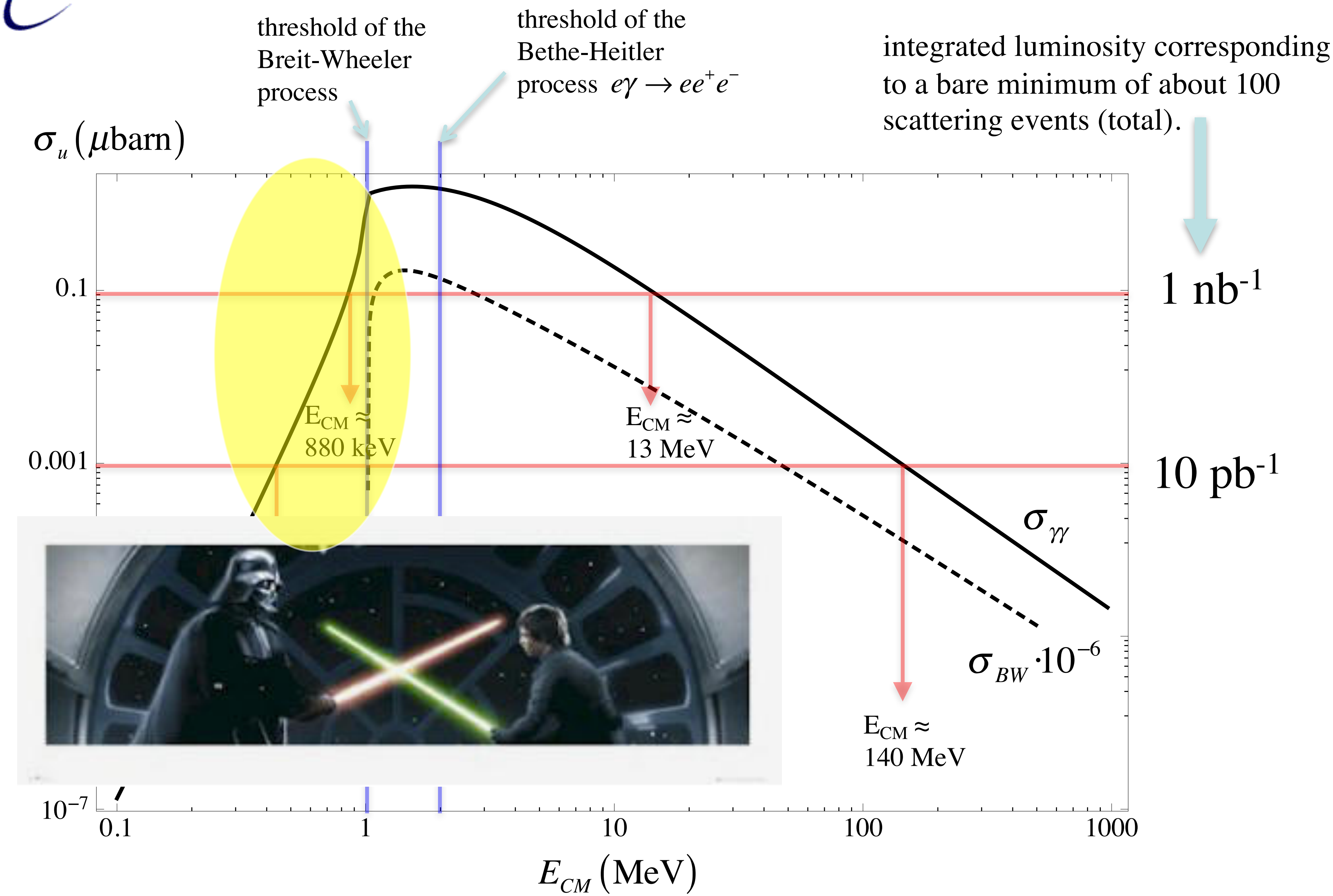
The cosmological constant problem is related to the zero-point energy, i.e., to the fluctuations of quantum vacuum, and therefore also to the renormalization procedure in QFT.

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



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

All the involved photons are real particles



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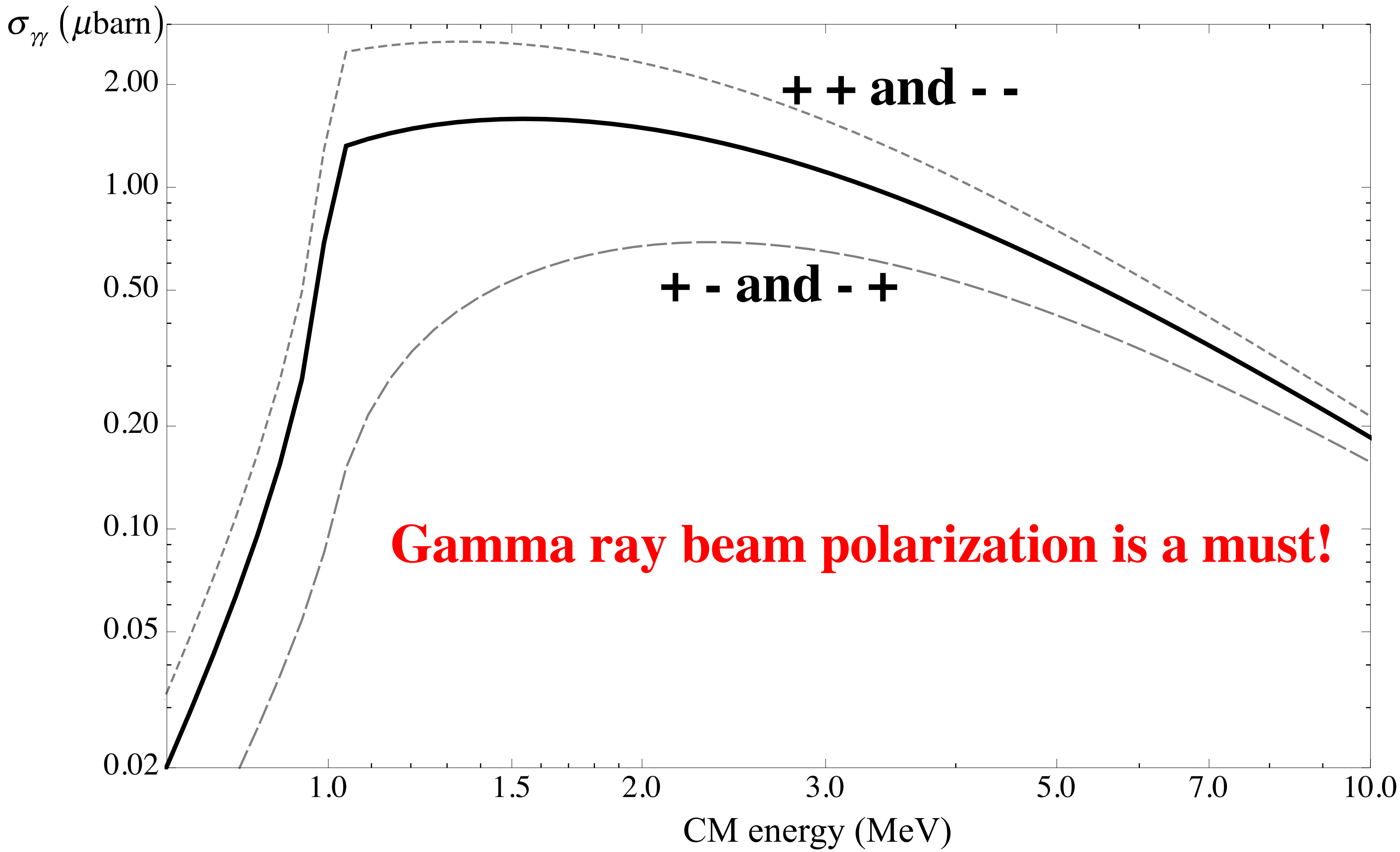
Unpolarized and (circularly) polarized initial photons.

The scattering of polarized photons yields additional information



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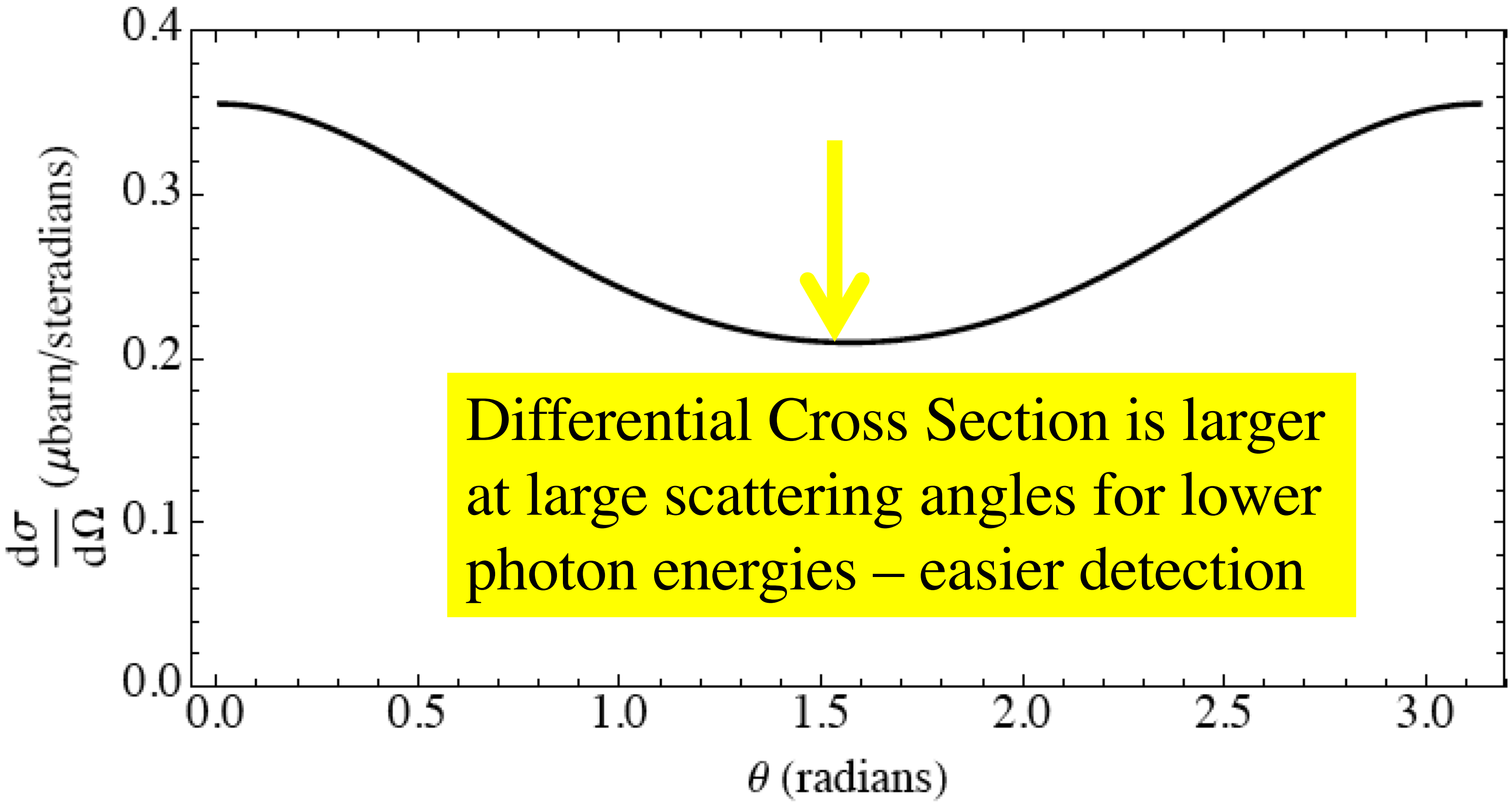
Differential cross-section at ECM = 1.6 MeV (peak)



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

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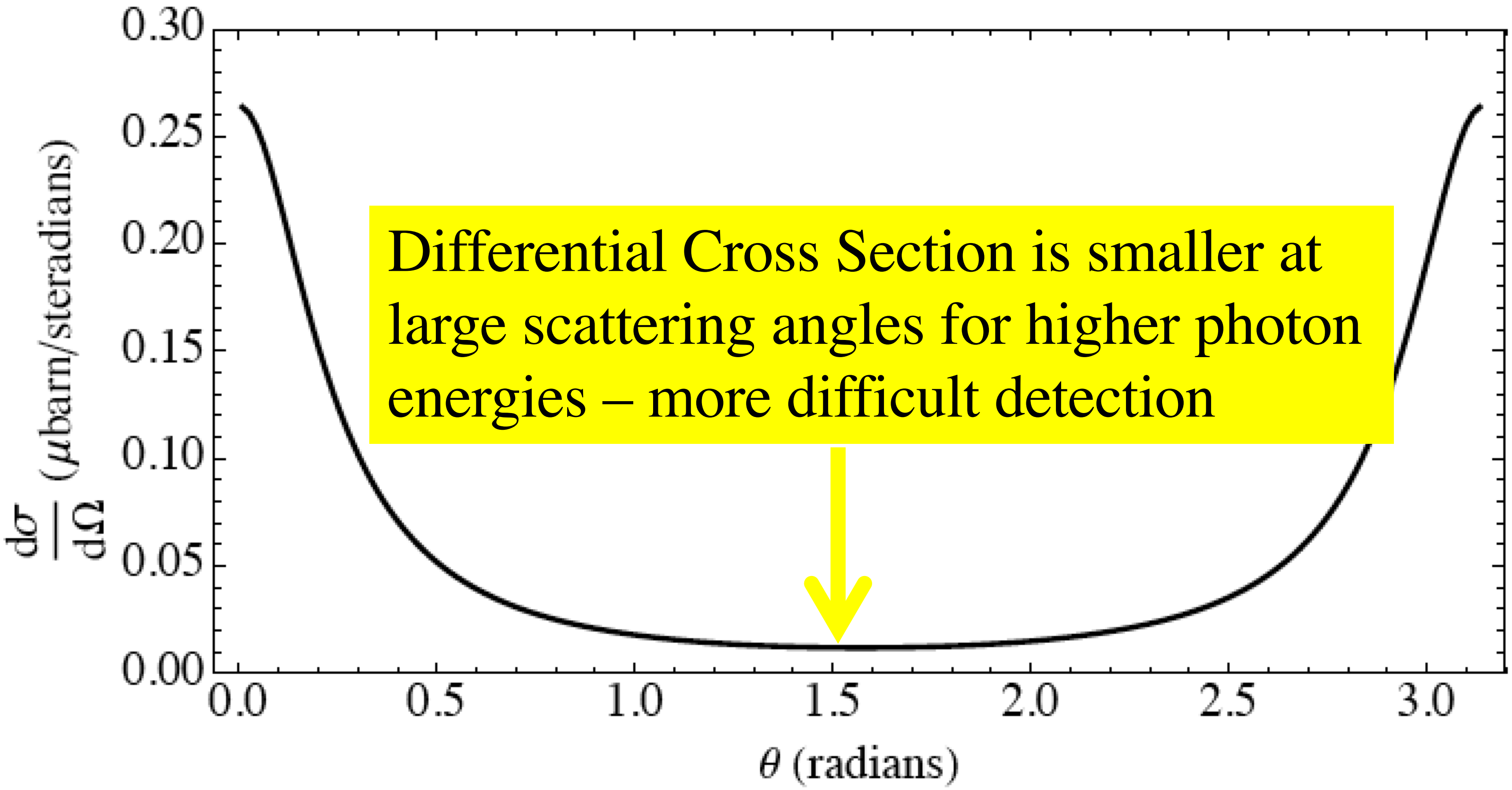
Differential cross-section at ECM = 10 MeV



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

Focus: Future Frontiers in Accelerators, Scharbeutz (D), Dec. 2016

We evaluated the event production rate of several schemes for photon-photon scattering, based on *ultra-intense lasers*, *brehmstralhung machines*, *Nuclear Photonics gamma-ray machines*, etc, in all possible combinations: collision of 0.5 MeV photon beams is the only viable solution to achieve 1 $nbarn^{-1}$ in a reasonable measurement time.

1)Colliding 2 ELI-NP 10 PW lasers under construction (ready in 2018), $h\nu=1.2$ *eV*, *f=1/60 Hz*, we achieve (E_{cm}=3 eV): $L_{SC}=6.10^{45}$, cross section= 6.10^{-64}, events/sec=10^{-19}
2)Colliding 1 ELI-NP 10 PW laser with the 20 MeV gamma-ray beam of ELI-NP-GBS we achieve (E_{cm}=5.5 keV): $L_{SC}=6.10^{33}$, cross section=10^{-41}, events/sec = 10^{-8}

3) Colliding a high power Brehmstralhung 50 keV X-ray beam (unpolarized, 100 kW on a mm spot size) with ELI-NP-GBS 20 MeV gamma-ray beam (E_{cm}=2 MeV) we achieve: $L_{SC}=6.10^{22}$, cross section=1 μbarn, events/s = 10^{-8}

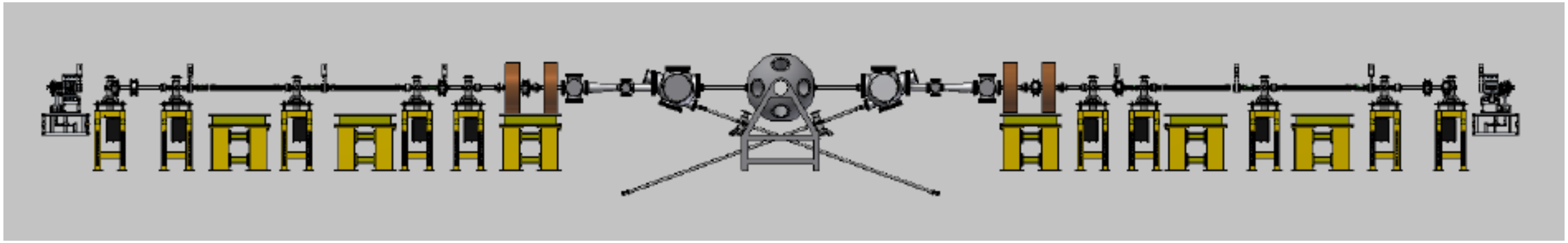
4) **Colliding 2 gamma-ray 0.5 MeV beams, carrying 10^{9} photons per pulse at 100 Hz rep rate, with focal spot size at the collision point of about 2 μm, we achieve: $L_{SC}=2.10^{26}$, cross section = 1 μbarn, events/s=2.10^{-4}, events/day=18, 1 nanobarn^{-1} accumulated after 3.2 months of 5/24 machine running.**

5) Colliding 2 LCLS-2 10 keV 10^{13} photons at 1 MHz we would achieve: $L_{SC}=8.10^{38}$, cross section=1 atto-barn, events/s = 8.10^{-4}

A Photon-Photon Scattering Machine based on twin Photo-Injectors and Compton Sources

- Mono-chromatic High Brilliance micron-spot psec Gamma Ray beams are needed for pursuing Photon-Photon scattering experiments at high luminosity ⇒ scaling laws
- Similar to those generated by Compton (back-scattering) Sources for Nuclear Physics/Photonics
- (mini) Colliders similar to γ–γ colliders, but at low energy (in the 0.5-2 MeV range): issue with photon beam diffraction!
- Best option: twin system of X-band 200 MeV photo-injectors with Compton converters and amplified *J-class* ps lasers (ELI-NP-GBS/STAR) – single bunch no laser re-circulation

A MeV-class Photon-Photon Scattering Machine based on twin Photo-Injectors and Compton Sources



- γ-ray beams similar to those generated by Compton Sources for Nuclear Physics/Photonics
- issue with photon beam diffraction at low energy!
- Best option: twin system of high gradient *X-band* 200 *MeV* photo-injectors with *J-class ps* lasers (ELI-NP-GBS)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 093401 (2016)

Compton sources for the observation of elastic photon-photon scattering events

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We present the design of a photon-photon collider based on conventional Compton gamma sources for the observation of elastic $\gamma\gamma$ scattering. Two symmetric electron beams, generated by photocathodes and accelerated in linacs, produce two primary gamma rays through Compton backscattering with two high energy lasers. The elastic photon-photon scattering is analyzed by start-to-end
photocathodes to the detector. A new Monte Carlo code has been developed *ad hoc* f
QED events. Realistic numbers of the secondary gamma yield, obtained by using the
or approved Compton devices, a discussion of the feasibility of the experiment an
background are presented.

DOI: 10.1103/PhysRevAccelBeams.19.093401

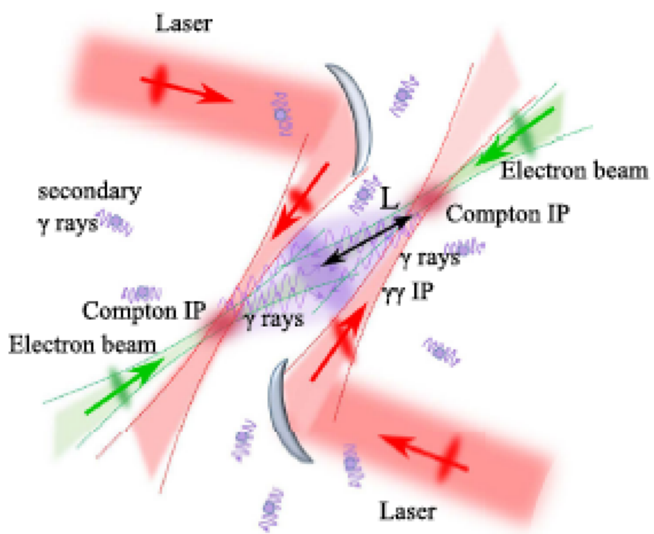

FIG. 1. Scheme of the $\gamma\gamma$ interaction. Two lasers (in red) impinge on two electron beams (in green) in two interaction points (Compton IP), generating primary gamma rays (in violet). The primary gamma rays interact in the $\gamma\gamma$ IP, generating secondary gammas.

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Q2 Study of photon–photon scattering events

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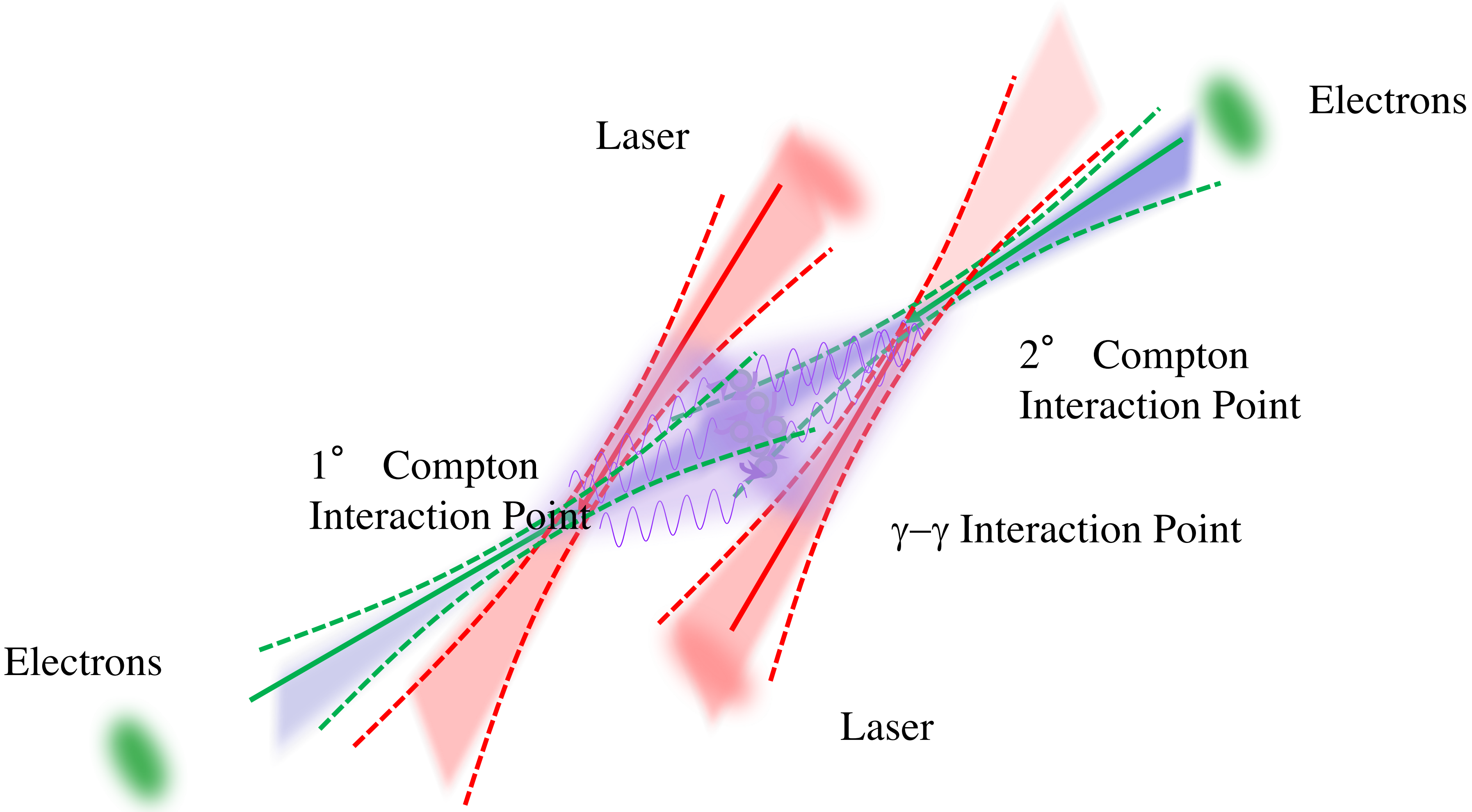
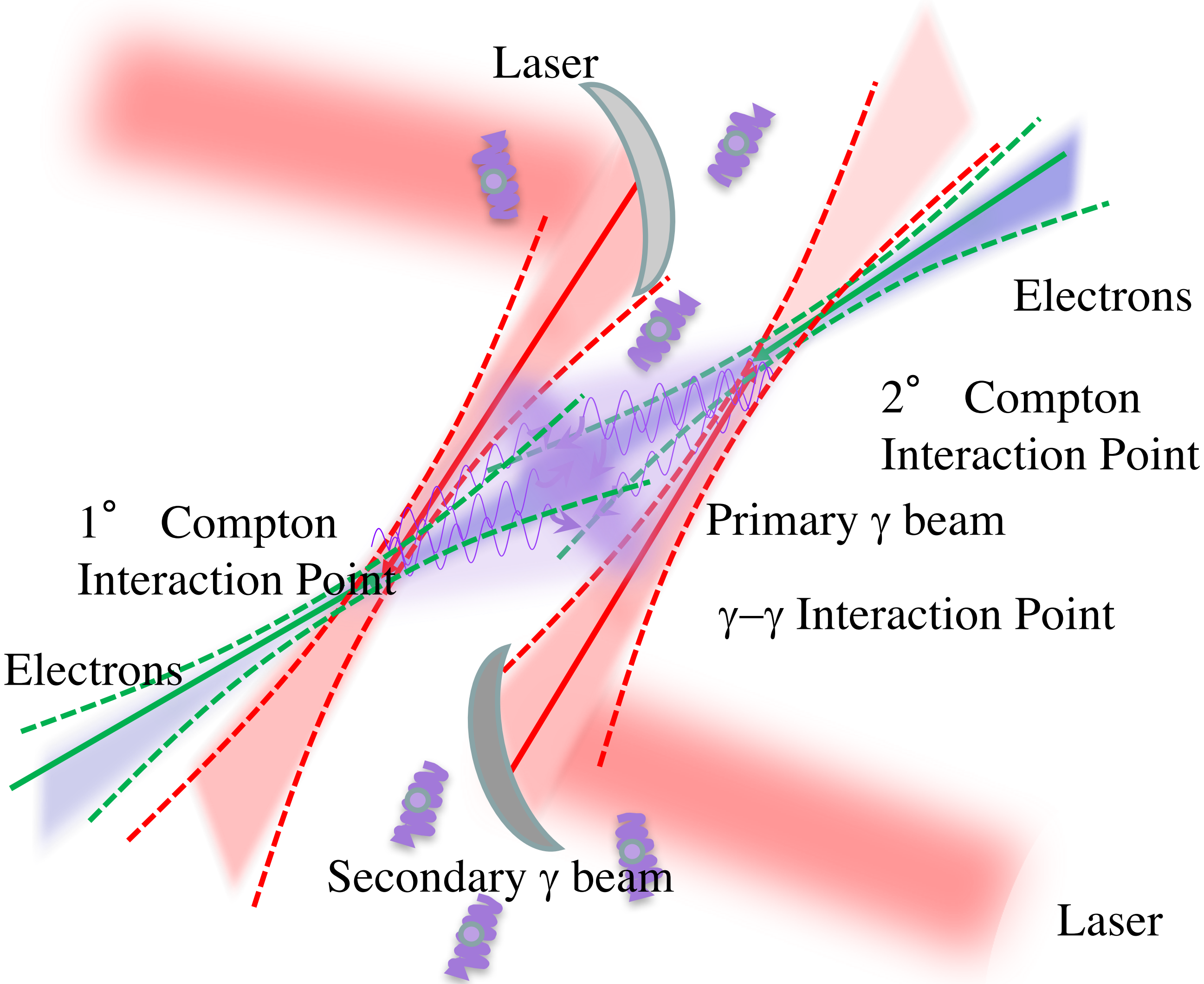
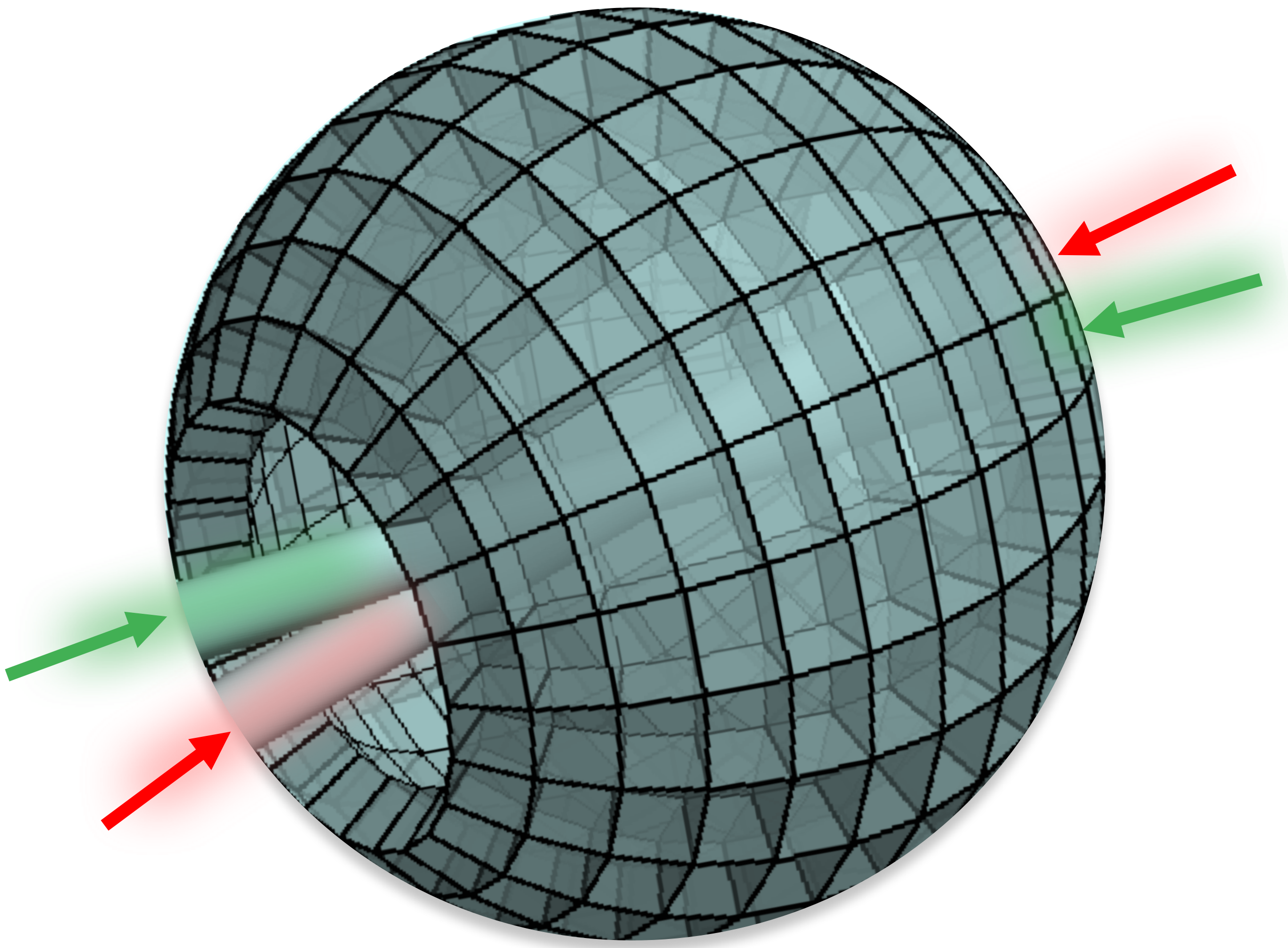
ABSTRACT

We present the design of a photon–photon collider based on conventional Compton gamma sources for the observation of secondary $\gamma\gamma$ production. Two symmetric electron beams, generated by photocathodes and accelerated in linacs, produce two primary gamma rays through Compton back scattering with two high energy lasers. Tuning the system energy to the energy of the photon–photon cross section maximum, a flux of secondary gamma photons is generated. The process is analyzed by start-to-end simulations from the photocathodes to the propagation of the QED photons towards the detector. The new Monte Carlo code 'Rate Of Scattering Events' (ROSE) has been developed *ad hoc* for the counting of the QED events. Realistic numbers of the secondary gamma yield, referring to existing or approved set-ups and a discussion of the feasibility of the experiment are presented. Q3


Laser
Electrons
2° Compton
Interaction Point
1° Compton
Interaction Point
γ–γ Interaction Point
Electrons
Laser


Laser
Electrons
2° Compton
Interaction Point
Primary γ beam
1° Compton
Interaction Point
γ–γ Interaction Point
Electrons
Secondary γ beam
Laser



Focus: Future Frontiers in Accelerators, Scharbeutz (D), Dec. 2016

TABLE I. Parameters of the Compton sources.

$\sqrt{s}$	÷2.4 eV, 2 MeV
Electron energy E_e	250 MeV
Normalized emittance $\varepsilon_{n,x/y}$ end linac	0.36 mm mrad
Normalized emittance $\varepsilon_{n,x/y}$ in the focus	0.8–2.1 mm mrad
Electron energy spread $\Delta E_e/E_e$	0.7×10^{-4}
Charge Q	250 pC
Transverse electron width σ_e	1–4 μm
Laser wavelength λ	1 μm
Laser waist w	10 μm
Laser length	1 ps
Laser energy E_L	1 J
Photon energy $E_{1,2}$	<1 MeV
Transverse photon beam dimension σ_r	1–4 μm
Repetition rate f	100 Hz

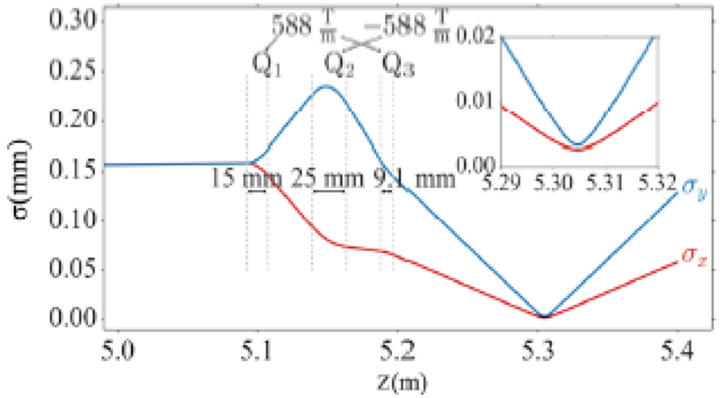


FIG. 7. Focusing stage of the electron beam. Rms transverse σ_x, σ_y dimensions vs the beam line coordinate z. Q_1, Q_2, Q_3 represent the focusing gradients of the quadrupoles. In the inner window, the detail of the focus.

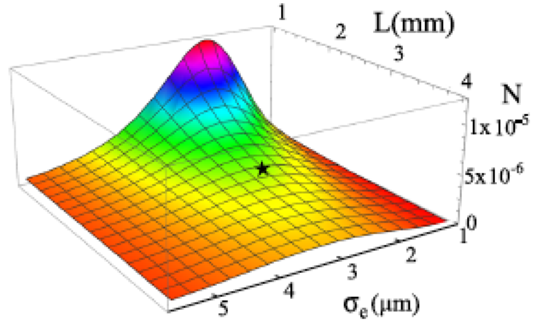


FIG. 5. Single shot number of events N as function of the rms transverse dimension of the electrons and of the distance L between Compton and $\gamma\gamma$ IP.

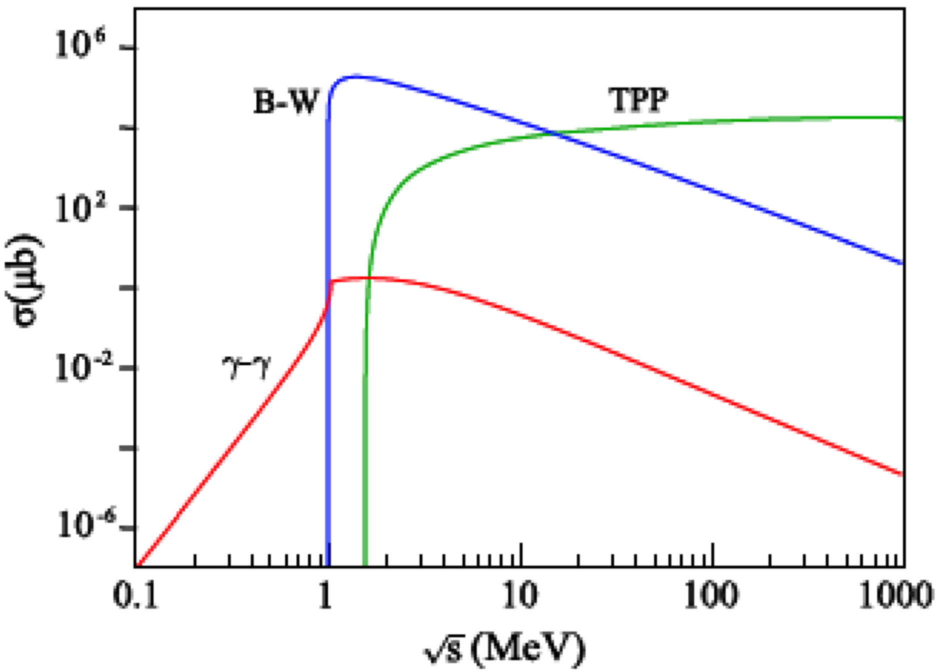


FIG. 14. Comparison between $\gamma\gamma$, Breit-Wheeler and TPP cross sections.

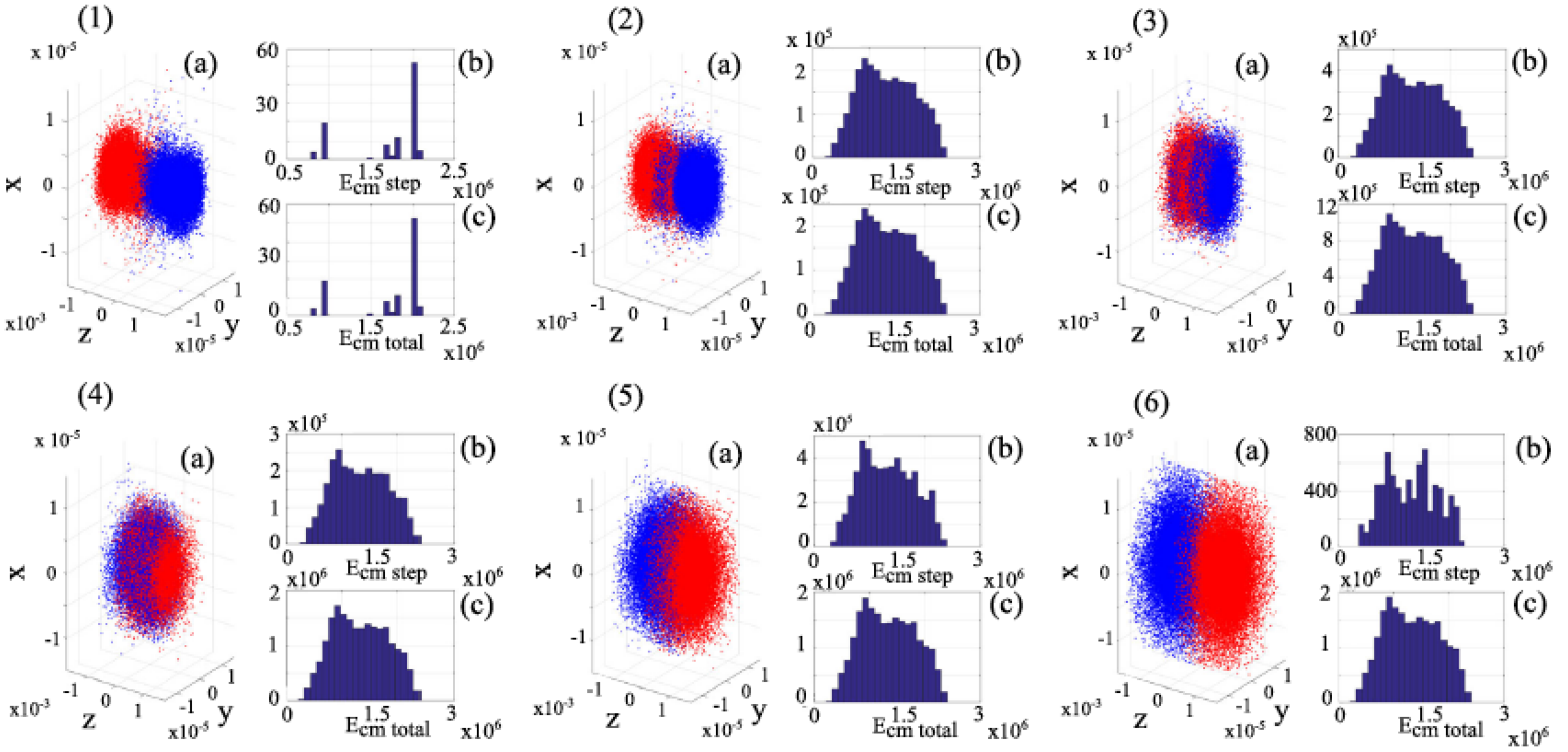


FIG. 11. Superposition of the beams in space at various instants (a) and instantaneous (b) and time averaged (c) center of mass energy dispersion. (1) $t = 0$ ps. (2) $t = 0.2$ ps. (3) $t = 0.4$ ps. (4) $t = 0.6$ ps. (5) $t = 0.8$ ps. (6) $t = 1$ ps.

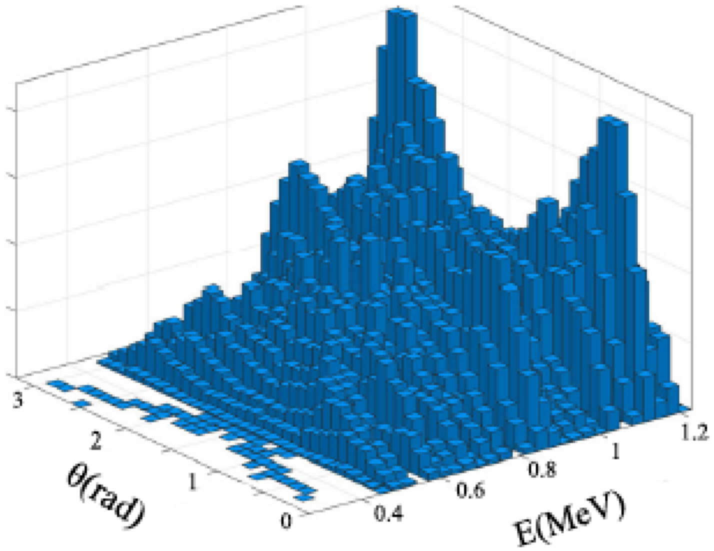


FIG. 12. Distribution of the $\gamma\gamma$ events in the laboratory as a function of the energy of the secondary particles $E = E_{3,4}$ and of the zenith angle θ.

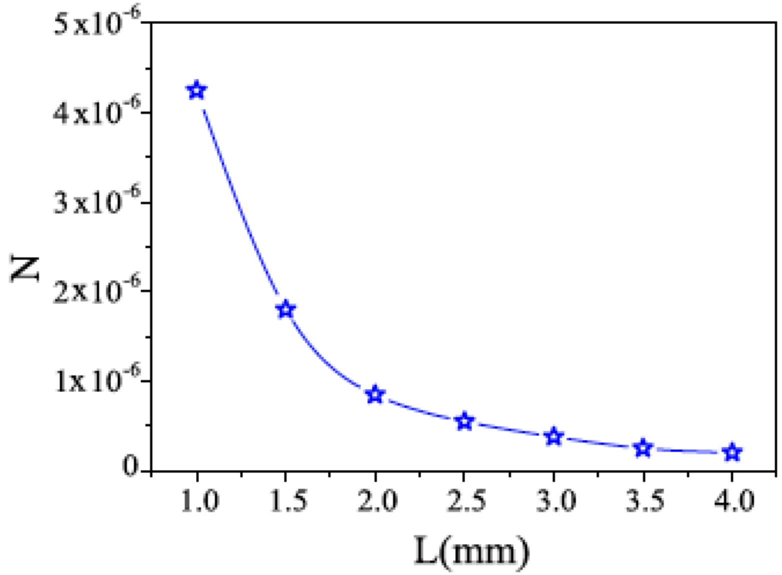


FIG. 13. $\gamma\gamma$ event rate.

Luminosities of Colliders involving Photon Beams at various c.m. energy

- **Compton Sources:** ***$L=10^{35}$ $cm^{-2}s^{-1}$*** **at 1-100 keV c.m. energy (ELI-NP-GBS like)**
- ***γ–γ*** **colliders for photon-photon scattering experiment and Breit-Wheeler:** ***$L=10^{26}$ $cm^{-2}s^{-1}$*** **at 0.5-2 MeV c.m. energy**
- **Photon–photon collider with 2x10 PW ELI Laser (most powerful of this decade):** ***$L=10^{45}$ $cm^{-2}s^{-1}$*** **at 3 eV c.m. energy**
- **LHC proton (7 TeV) – XFEL photon (20 keV) collider : ultimate Luminosity (10^{12} p 100ns, TW-FEL* as for LCLS-II SC-CW)** ***$L=10^{38}$ $cm^{-2}s^{-1}$*** **at 1.2 GeV c.m. energy**

**C.Pellegrini et al.,*
PRSTAB **15**, 050704 (2012)

Is it of any interest?

production of
low emittance
$\pi/\mu/\nu/$ beams…

Let's try to use LHC proton beam as a Relativistic Pion Photo-cathode (and see what happens...)

I. INTRODUCTION

Let us consider the collision between a proton and a counter-propagating photon of energy respectively E_p and $h\nu$ in the laboratory frame (LAB). The energy $h\nu'$ of the colliding photon in the proton rest frame is given by (relativistic Döppler effect)

$$h\nu' = h\nu\gamma(1 - \underline{\beta} \cdot \underline{e_k}) \quad (1)$$

where $\underline{\beta}$ is the velocity of the proton, $\underline{e_k}$ is the direction of propagation of the photon, $\gamma = E_p/M_p$ and $M_p = 938$ MeV/c^2. For an ultra-relativistic proton colliding head-on with a photon, the formula simplifies in $h\nu' \simeq 2\gamma h\nu$. The energy available in the center of mass (CM) of the proton-photon system is

$$E_{CM} = \sqrt{P^2} = \sqrt{2E_p h\nu - 2(\underline{p_p} \cdot \underline{k}) + M_p^2} \quad (2)$$

where $P = \{E_p + h\nu, \underline{p_p} + \underline{k}\}$. Assuming $h\nu << E_p$,

$$\gamma_{CM} = \frac{E_{tot}^{LAB}}{E_{CM}} \simeq \frac{E_p + h\nu}{\sqrt{4E_p h\nu + M_p^2}}. \quad (3)$$

Once we define the parameter representing the recoil of the proton in the collision as

$$\Delta_p \equiv 4\gamma h\nu/M_p, \quad (4)$$

we can write $E_{CM} \simeq M_p\sqrt{1+\Delta_p}$ and $\gamma_{CM} \simeq \gamma/\sqrt{1+\Delta_p}$. Natural units $c = \hbar = 1$ have been adopted and $*$ denotes the particles' momenta and energies in their CM reference frame.

Our studies regarding the secondary beams generated in the proton-photon collision are reported in [1–3]. In this article we analyze in details the $p + \gamma \to p_s + \gamma_s$ reaction. In particular we will consider the interaction of a high intensity FEL beam at $h\nu = 6$ keV and the SPS and LHC proton beams. We will consider the FCC case in a future work since $h\nu'$ is large enough to require a description taking into account the quark structure of the proton. The collider specifications are reported in Table I.

The great advantage given by the use of protons instead then electrons is the low value of the recoil parameter Δ_p at the same laboratory energies.

Table I: Collider performances: $N_{ph} = 10^{13}$ photons at $h\nu = 6$ keV from FEL.

Protons	E_p [TeV]	N_{pr}	γ	γ_{CM}	Δ_p	$h\nu'$ [MeV]
SPS	0.4	10^{12}	426	424	0.01	5.11
LHC	7	$2 \cdot 10^{11}$	7462	6838	0.19	89.55
FCC	50	10^{11}	53304	34670	1.36	639.65

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RELEVANT REACTIONS

$\mathbf{p} + \mathbf{h}\nu \rightarrow \mathbf{p}' + \mu^-\mu^+$	Best way to produce both signs muons. Threshold energy: $h\nu'^{th} = 235$ MeV.

$$p + h\nu \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu$$

$$\left.\begin{array}{l} p + h\nu \rightarrow p' + e^-e^+ \\ p + h\nu \rightarrow p' + h\nu' \end{array}\right\} \text{ side effects}$$

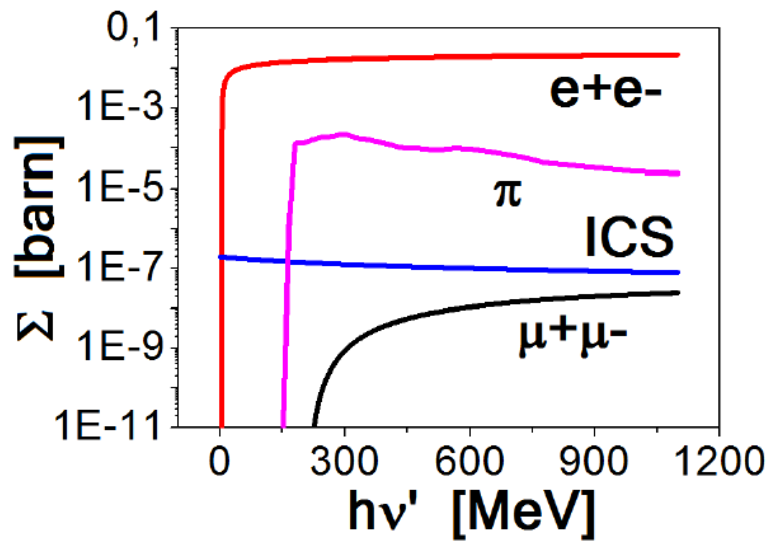

Figure 4: Total cross sections of relevant reactions.

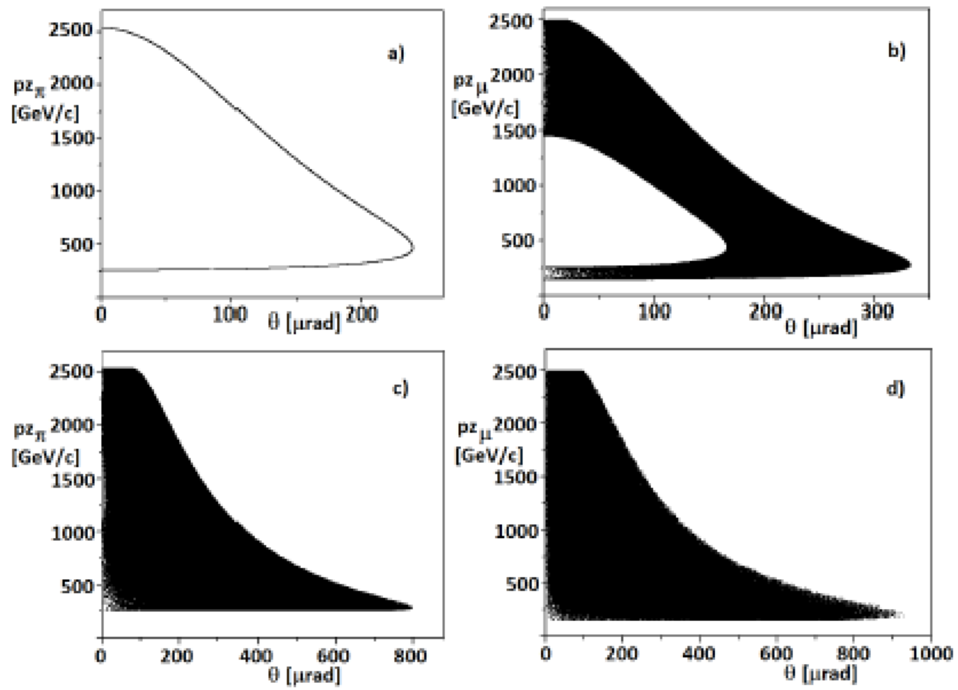

Figure 1: Pion and muon longitudinal momentum [GeV/c] as a function of θ [μrad], without (top) and with (bottom) transverse emittance of the incoming proton beam (case LHC).

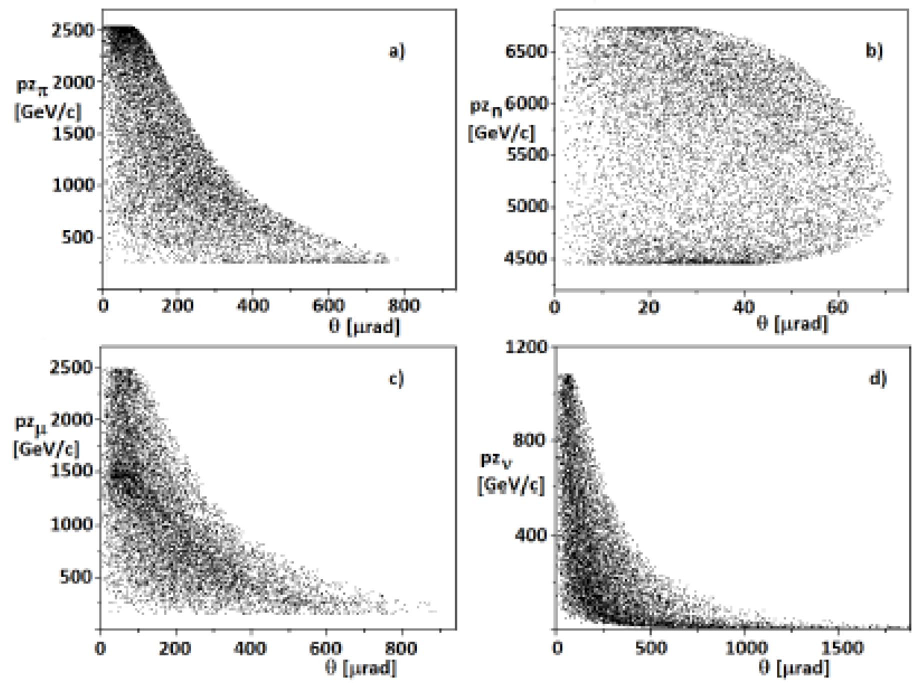

Figure 2: Pion, neutron, muon and neutrino longitudinal momentum [GeV/c] as a function of θ [μrad] (case LHC).

Thanks to large Lorentz boost and small LHC beam emitance

very highly collimated beams of TeV-class neutrons, neutrinos, photons

direct muon-pair production

MUON PAIR PRODUCTION: PHASE SPACES, EMITTANCE AND ENERGY SPREAD CONSIDERATIONS

Close to MPP energy threshold

$$\sqrt{\langle\left(\frac{p_\mu}{M_\mu}\right)^2\rangle} = \frac{1}{\sqrt{3}}\sqrt{\frac{M_p^2}{4M_\mu^2}\left(\sqrt{1+\Delta_p}-1\right)^2-1}$$

$$\epsilon^{\mu}_{n-cath} \le \frac{\sigma_0}{\sqrt{2}}\sqrt{\langle\left(\frac{p_\mu}{M_\mu}\right)^2\rangle} \quad (1) \qquad \text{and} \qquad \frac{\Delta\gamma}{\gamma}_\mu = \sqrt{\langle\left(\frac{p_\mu}{M_\mu}\right)^2\rangle} \quad (2)$$

where p_μ, M_μ are momentum, mass of muon, $\Delta_p \equiv 4\gamma h\nu/M_p$ and we assumed a uniform distribution of momenta in transverse phase space.
Homemade event generator code based on flat differential cross section, some examples reported below: transverse normalized emittance values are very low, but energy spread ones increase extremely fast.

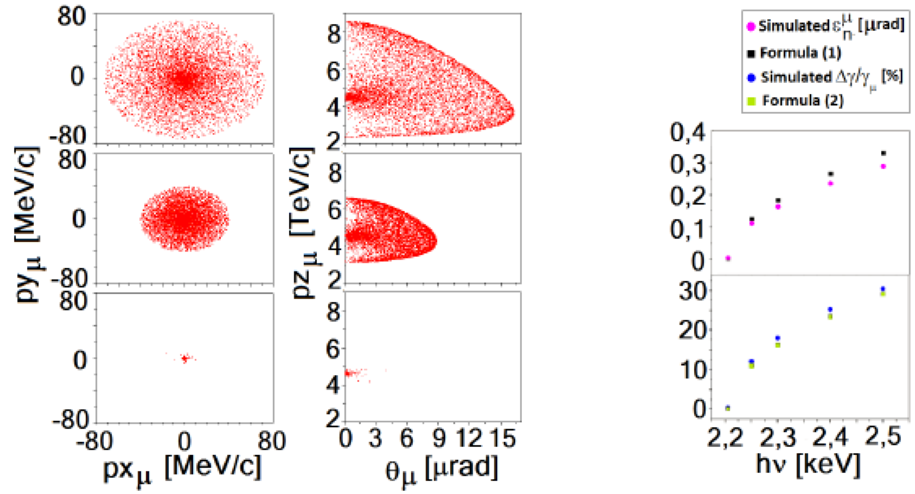

Figure 1: $E_p = 50$ TeV, no proton beam emittance. Left: muon beam phase speces at $h\nu = 2.5$ a), 2.3 b), 2.2053 c) keV. Right: simulated vs theoretical muon beam emittance and energy spread as function of $h\nu$ [keV].

Away from MPP energy threshold

Homemade event generator code based on correct differential cross section. The spectrum is peaked: opportunity to select a high number of muons around the energy peak value to reduce energy spread.

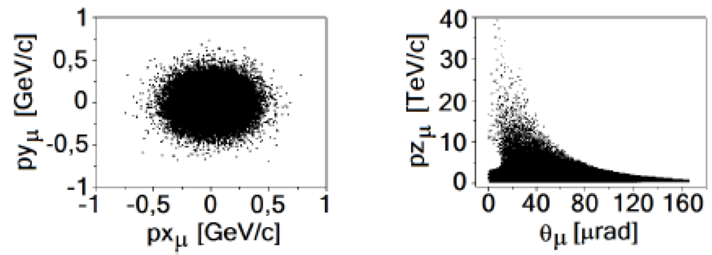

Figure 2: Phase spaces of muons for $E_p = 50$ TeV and $h\nu = 10$ keV. Here $\epsilon_n^\mu = 0.83$ [mm·mrad].

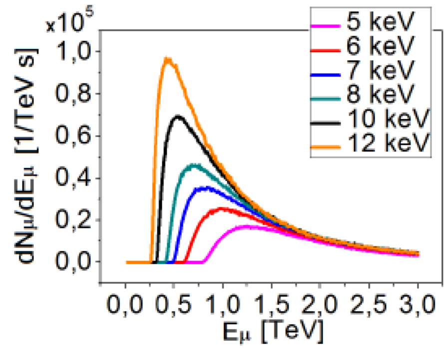

Figure 3: Muons/s within 10 GeV bandwidth, $E_p = 50$ TeV and h$\nu = 5, 6, 7, 8, 10, 12$ keV.

Table 2: Rate of events per second for $E_p = 50$ TeV, $\mathcal{L} = 3.1 \cdot 10^{38}$ cm^{-2}s^{-1} and various photon beam energies.

$h\nu$ [keV]	$\mathcal{N}_\pi$ [s^{-1}]	$\mathcal{N}_{\mu^-\mu^+}$ [s^{-1}]	$\mathcal{N}_{e^-e^+}$ [s^{-1}]
1.43	$1.86 \cdot 10^{10}$	0	$4.5 \cdot 10^{12}$
2.21	$3.72 \cdot 10^{10}$	$1.25 \cdot 10^4$	$5 \cdot 10^{12}$
3	$6.5 \cdot 10^{10}$	$4 \cdot 10^5$	$5.4 \cdot 10^{12}$
10	$8.6 \cdot 10^9$	$4.8 \cdot 10^6$	$6.5 \cdot 10^{12}$
12	$6.8 \cdot 10^9$	$5.6 \cdot 10^6$	$6.8 \cdot 10^{12}$

e^+/e^- pair production doesn't burn the proton beam thanks to very small proton recoil (within LHC energy spread)

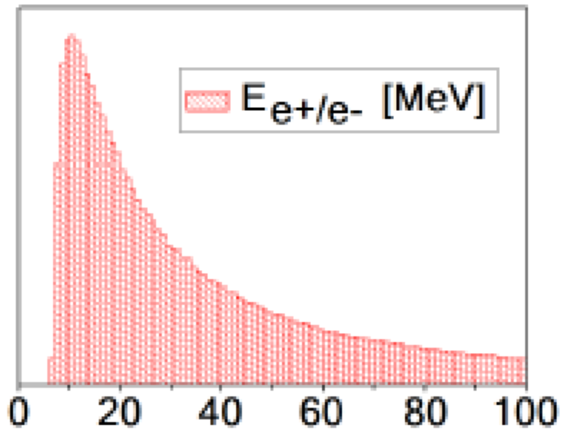

Figure 5: e^-e^+ energy spectrum [MeV] for $E_p = 50$ TeV and $h\nu = 10$ keV.

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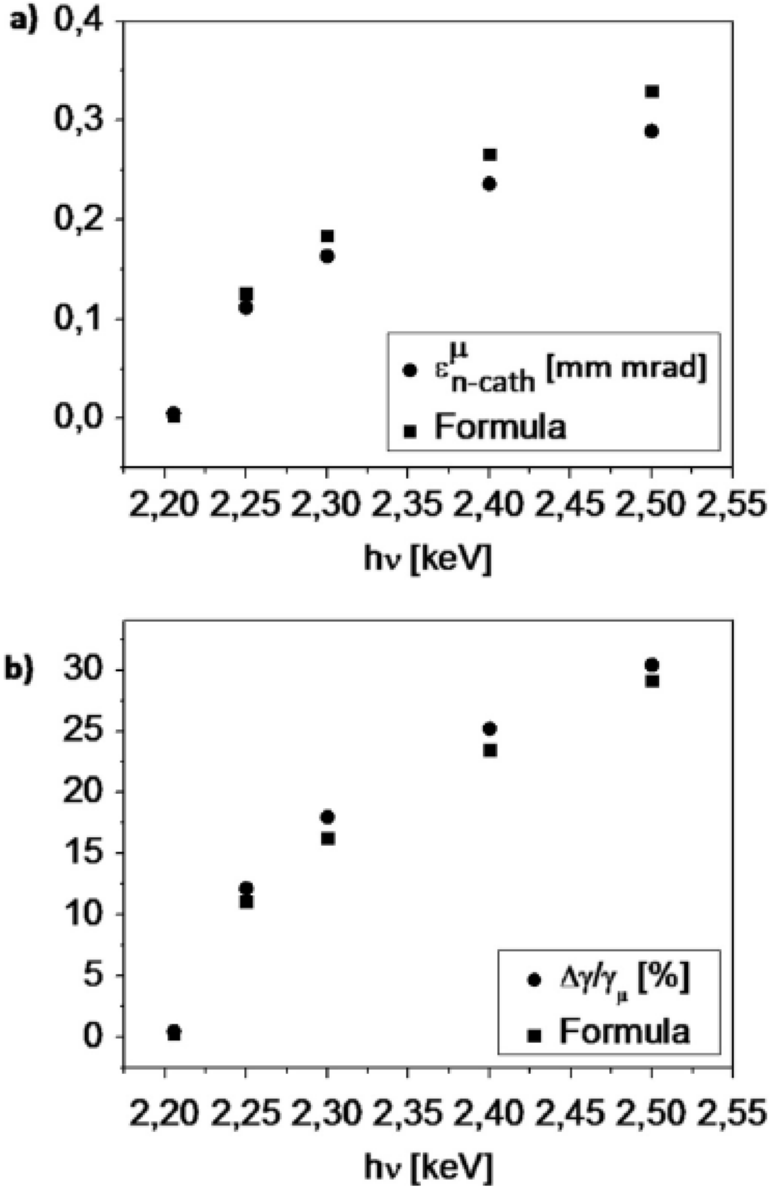

Fig. 3. Graph a): Simulated emittance of μ^- beam (dots) and Formula (8) (squares) as a function of $h\nu$ [keV]. Graph b): Relative energy spread of $\mu-$ beam [%] (dots) and Formula (9) (squares) vs photon energy [keV]. No proton beam emittance.

2.2. Direct muon pair production

Let us now consider the direct muon pair production via $p + h\nu \rightarrow p' + \mu^-\mu^+$. Fig. 2 shows the phase spaces of the muon produced by the collision of protons at $E_p = 50$ TeV and photons at different energies around the threshold value.

The thermal normalized emittance of the muon beams, due to the collision transverse temperature, can be written as

$$\epsilon^{\mu}_{n-cath} \leq \frac{1}{\sqrt{3}} \frac{\sigma_0}{\sqrt{2}} \sqrt{\frac{M_p^2}{4M_\mu^2}\left(\sqrt{1+\Delta_p} - 1\right)^2 - 1} \tag{8}$$

where σ_0 is the proton beam spot size at the interaction point (assuming a uniform distribution of momenta in the transverse phase space of the muon beams). The values of the normalized transverse emittance for $E_p = 50$ TeV and several photon energies are reported in Fig. 3a): the emittance in this cases is purely thermal (no proton beam emittance). The simulated values (dots) are compared to the ones given by Formula (8) (squares). In case the proton beam emittance is considered, the total transverse normalized emittance ϵ^{μ} is such that $\epsilon_1 < \epsilon^{\mu}_n < \epsilon_2$ where $\epsilon_1 = \sqrt{(\epsilon^{\mu}_{n-cath})^2 + (\epsilon^{p'}_n)^2}$ and $\epsilon_2 = \epsilon^{\mu}_{n-cath} + \epsilon^{p'}_n$. We can evaluate the rms energy spread of the muon beams as

$$\left.\frac{\Delta\gamma}{\gamma}\right|_{\mu} = \frac{1}{\sqrt{3}} \sqrt{\frac{M_p^2}{4M_\mu^2}\left(\sqrt{1+\Delta_p} - 1\right)^2 - 1}\,. \tag{9}$$

The simulated relative energy spread values are reported in Fig. 3b) (dots) in comparison to the values of the analytical expression (9) (squares).

We need a 10-20% acceptance storage ring (issue shared with P.Raimondi's scheme of e^+/e^- -> mu^+/mu^-)

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Conclusion

- Combined operation of LHC/FCC with a X-ray Free Electron Laser: opportunity of conceiving a hybrid HPC at a luminosity exceeding 10^{38} $s^{-1}cm^{-2}$.
- HPC aimed to generate secondary beams of unique characteristics, via a highly boosted Lorentz frame corresponding to a very relativistic moving CM reference frame. Secondary beams have outstanding properties of low transverse emittance and collimation within very narrow forward angles.
- Best opportunity to obtain muon beams is direct muon pair production: despite the very low cross section value, the critical steps represented by the production of charged pions of both signs and the storage and selection of the pions would be overcome. The long life of the high energy generated muons (in excess of ms) offers the opportunity to accumulate them in a storage ring so to achieve muon collider requested bunch intensities.

References

L. Serafini, C. Curatolo and V.Petrillo, *Low emittance pion beams generation from bright photons and relativistic protons*, `arXiv:1507.06626v2`, (2015)

C. Curatolo, *PhD Thesis: High brilliance photon pulses interacting with relativistic electron and proton beams*, `https://air.unimi.it/handle/2434/358227`, (2016)

C. Curatolo, F. Broggi and L. Serafini, *Phase space analysis of secondary beams generated in hadron-photon collisions*, in press on Nucl. Instr. Meth. Phys. Res. A.

INFN

Low emittance pion beams generation from bright photons and relativistic protons

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(Dated: July 11th, 2015)

Present availability of high brilliance photon beams as those produced by X-ray Free Electron Lasers in combination with intense TeV proton beams typical of the Large Hadron Collider makes it possible to conceive the generation of pion beams via photo-production in a highly relativistic Lorentz boosted frame: the main advantage is the low emittance attainable and a TeV-class energy for the generated pions, that may be an interesting option for the production of low emittance muon and neutrino beams. We will describe the kinematics of the two classes of dominant events, i.e. the pion photo-production and the electron/positron pair production, neglecting other small cross-section possible events like Compton and muon pair production. Based on the phase space distributions of the pion and muon beams we will analyze the pion beam brightness achievable in three examples, based on advanced high efficiency high repetition rate FELs coupled to *LHC* or Future Circular Collider (*FCC*) proton beams, together with the study of a possible small scale demonstrator based on a Compton Source coupled to a Super Proton Synchrotron (*SPS*) proton beam.

I. INTRODUCTION

One of the main challenges of present muon collider design studies is the capture/cooling stage of muons after generation by intense GeV-class proton beams impinging on solid targets: this mechanism produces pions further decaying into muons and neutrinos. As extensively analyzed in Ref. [1, 2], the large emittance of the generated pion beams, which is mapped into the muon beam, is mainly given by the mm-size beam source at the target (i.e. the proton beam focal spot size) and by Coulomb scattering of protons and pions propagating through the target itself, inducing large transverse momenta which in turns dilute the phase space area. Recently the option to use hundreds of MeVs photons to make muon pairs via photo-production in a solid target was analyzed in Ref. [3], with the aim of getting a smaller source spot size, avoiding as well the proton beam scattering effects. This scheme is promising in terms of low emittance of the muon beams at the source, but unfortunately it turns out that the low energy of the generated muons and the transport process into the high field solenoid system induces an irreversible emittance growth. Therefore the small source emittance of muons produced in the Bethe-Heitler process does not compensate its very low efficiency [4].

We propose in this paper a different approach, still based on photon beams, enabled by the present availability of outstanding TeV-class high intensity proton beams and ultra-high brilliance X-ray photon beams obtained by advanced X-ray Free Electron Lasers: although these

Their combined capability of producing ultra-high phase space density particle beams is the base of our strategy for generating low emittance pion, muon and neutrino beams, using collisions between two counter-propagating beams of highly relativistic protons and ultra-high intensity photons. The extremely high luminosity achievable by such a collider (10^{38} cm^{-2}s^{-1}) can compensate for the low efficiency of the pion photo-production which has a total cross section of $\simeq$ 220 μbarn with 300 MeV photons, much smaller than GeV-proton based pion production ($\simeq$ 20 mbarn).

There are two crucial aspects in such a collision scheme. The first is the much higher energy of the X-ray photons observed by the proton in its own rest frame: this enables pion photo-production above the threshold with maximum efficiency, despite the keV energy of the colliding photon. The second deals with the proton carrying almost the total momentum of the system, which makes it the source of highly Lorentz boosted secondary beams collimated within a narrow forward angle of the same order of the proton beam diffraction angle given by its transverse emittance (tens of μrads). In this sense the mechanism for pion production described in the following represents sort of a relativistic pion photo-cathode. A similar approach has been proposed and discussed in Ref. [6] although based on a multi-photon production of pion and muon pairs, which is a much lower efficiency process.

We considered two examples of TeV proton beams: an upgraded *LHC* beam carrying up to 10^{12} protons per

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ELSEVIER

Phase space analysis of secondary beams generated in hadron–photon collisions

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A R T I C L E I N F O

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Hadron–photon collider
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A B S T R A C T

Present availability of high brilliance photon beams in combination with intense TeV hadron beams makes it possible to conceive the generation of low emittance TeV-class energy pion/muon beams via photoproduction in a highly relativistic Lorentz boosted frame. We analyze the secondary beams brightness achievable by the coupling of advanced high efficiency high repetition rate FEL pulses and Large Hadron Collider or Future Circular Collider hadron beams. The phase space distributions of the pion and muon beams are obtained by means of an event generator code and the characteristics, such as emittance and energy spread, are benchmarked against analytical expressions.

1. Hadron–photon collider

Muon colliders represent a promising way to achieve the highest lepton–antilepton collision energies and precision mea-

deals with the proton carrying almost the total momentum of the system, which makes it the source of highly Lorentz boosted secondary beams collimated within a narrow forward angle of the same order of the proton beam diffraction angle given by its

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Production of TeV-class photons via Compton back-scattering on proton beams of a keV high brilliance FEL

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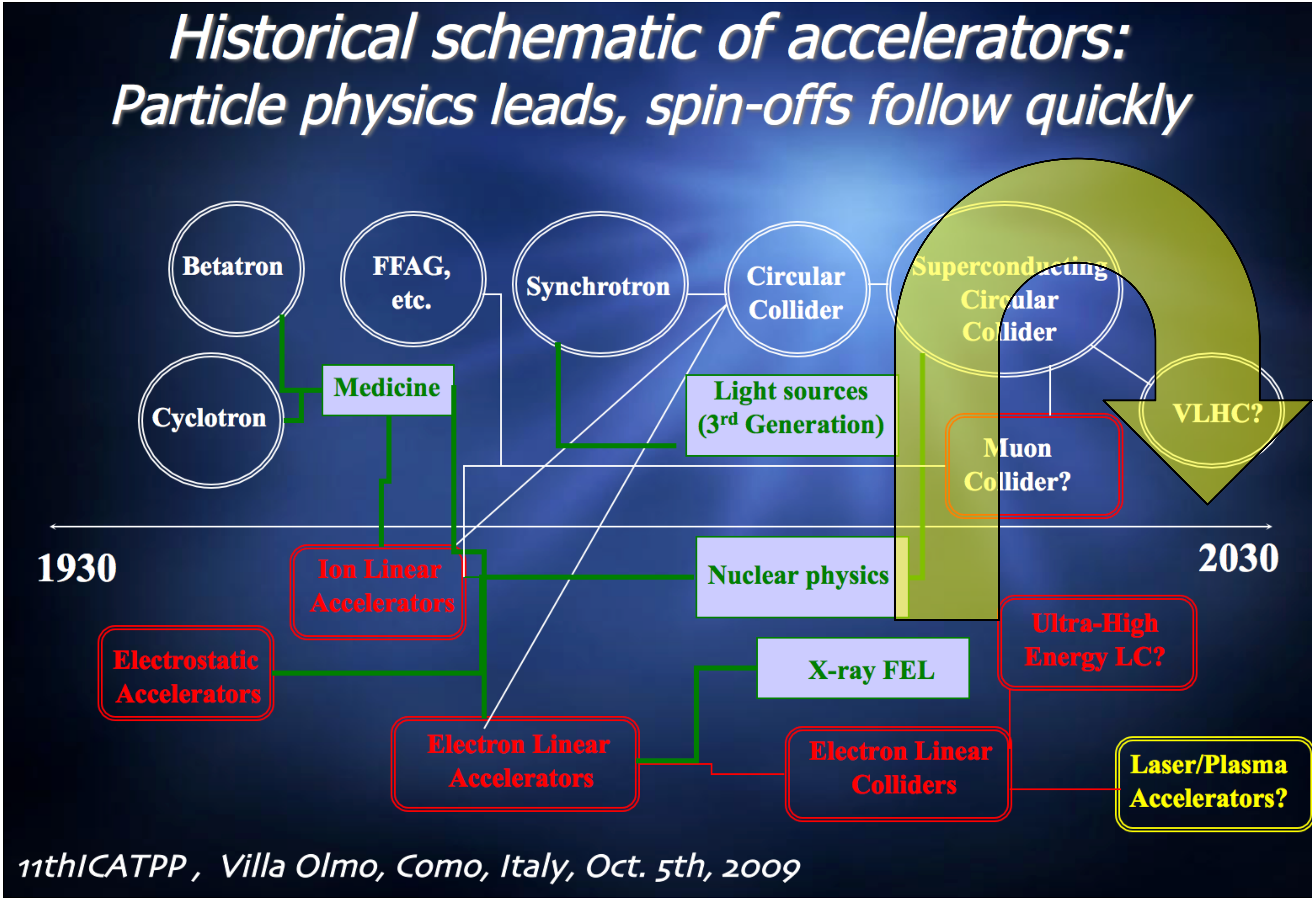
(Dated: December 5, 2016)

Present availability of high brilliance photon beams as those produced by X-ray Free Electron Lasers in combination with intense TeV proton beams like those available at SPS, LHC or in the future at FCC, makes possible to conceive the production of TeV-class photons by Compton back-scattering of keV photons carried by the FEL radiation pulse. We present here the study of spectra and fluxes of the TeV-class photons, which are collimated in the typical $1/\gamma$ forward angle with respect to the propagation of the proton beam (γ is the proton beam relativistic factor). Using a room-temperature Linac based X-ray FEL, similar to LCLS or a more compact version based on X-band RF cavities, delivering FEL radiation pulses at 100 Hz up to 6 keV photon energy (implying a Linac electron beam energy in the $5-8$ GeV range), fluxes of tens photons/s are achievable. It is also shown that a proper control of proton beam emittance and focusing at the interaction point is crucial to assure a reasonable energy spread of the photons emitted within an angle smaller than $1/\gamma$. Moreover, due to the reasonably small proton recoil, the back-scattering is actually in the Thomson regime, so the polarization of the back-scattered photons is at all similar to the polarization of the incident FEL beam (that is typically linear, but could be made circular too) even using unpolarized protons. The life-time of the proton beam circulating in the main ring is not affected at all by the interaction with the FEL beam due to the small number of Compton back-scattering events generated (maximum of 1 per bunch collision).

We might need to look for a syncretism between our two religions... (photon science / energy frontier)



Once we define the parameter representing the recoil of the proton in the collision as

$$\Delta_p \equiv 4\gamma h\nu / M_p, \quad (4)$$

$$\begin{cases} k_z^{max} = k_z(\theta^* = 0) = \dfrac{4\gamma^2 h\nu}{1+\Delta_p} \\ k_z^{min} = k_z(\theta^* = \pi) = -h\nu. \end{cases} \quad (7)$$

Incidentally, at very small angles in the CM, the corresponding laboratory angle is $\theta = \theta^* \sqrt{1+\Delta_p}/2\gamma$, and the photon momentum at small angles around the proton propagation axis (back-scattering close to the Compton edge) is given by

$$k_z = \frac{4\gamma^2 h\nu}{1+\Delta_p}\left(1 - \frac{\gamma^2\theta^2}{1+\Delta_p}\right) \quad (8)$$

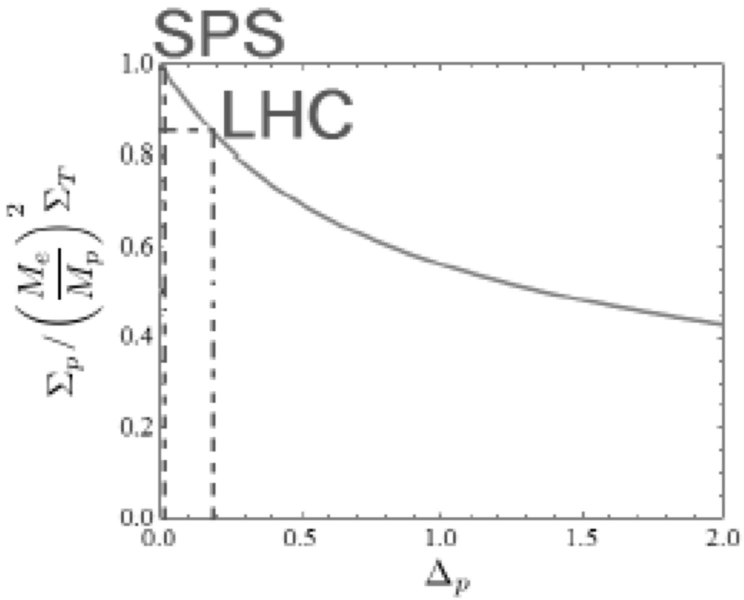


Figure 2: Total Compton cross section Σ_p normalized by the total Thomson cross section for protons $\left(\frac{M_e}{M_p}\right)^2 \Sigma_T$ as a function of the recoil parameter Δ_p.

Polarized TeV photons with LHC

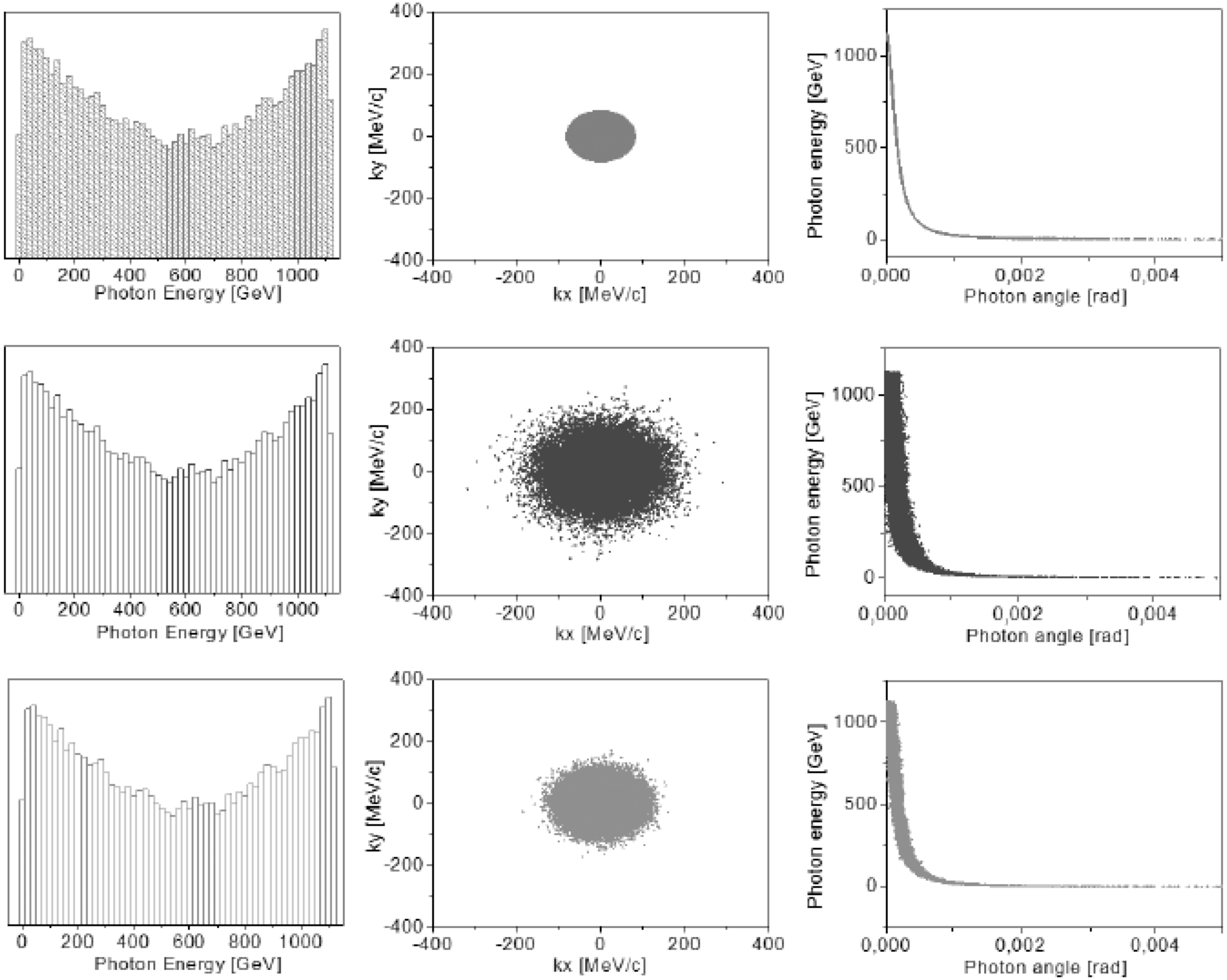


Figure 4: Analysis of the scattered photons in LHC case: $E_p = 7$ TeV and $h\nu = 6$ keV. Energy spectrum [GeV] in the first column, transverse phase space (k_y vs k_x [MeV/c]) at the IP in the second column and energy [GeV] as a function of the emission angle θ [rad] in the third column.
Top line: $\sigma_p = \sigma_L = 5$ μm. No proton beam emittance.
Middle line: $\sigma_p = \sigma_L = 5$ μm and $\epsilon_{n_x} = 2.5$ mm·mrad.
Bottom line: $\sigma_p = \sigma_L = 10$ μm and $\epsilon_{n_x} = 2.5$ mm·mrad.

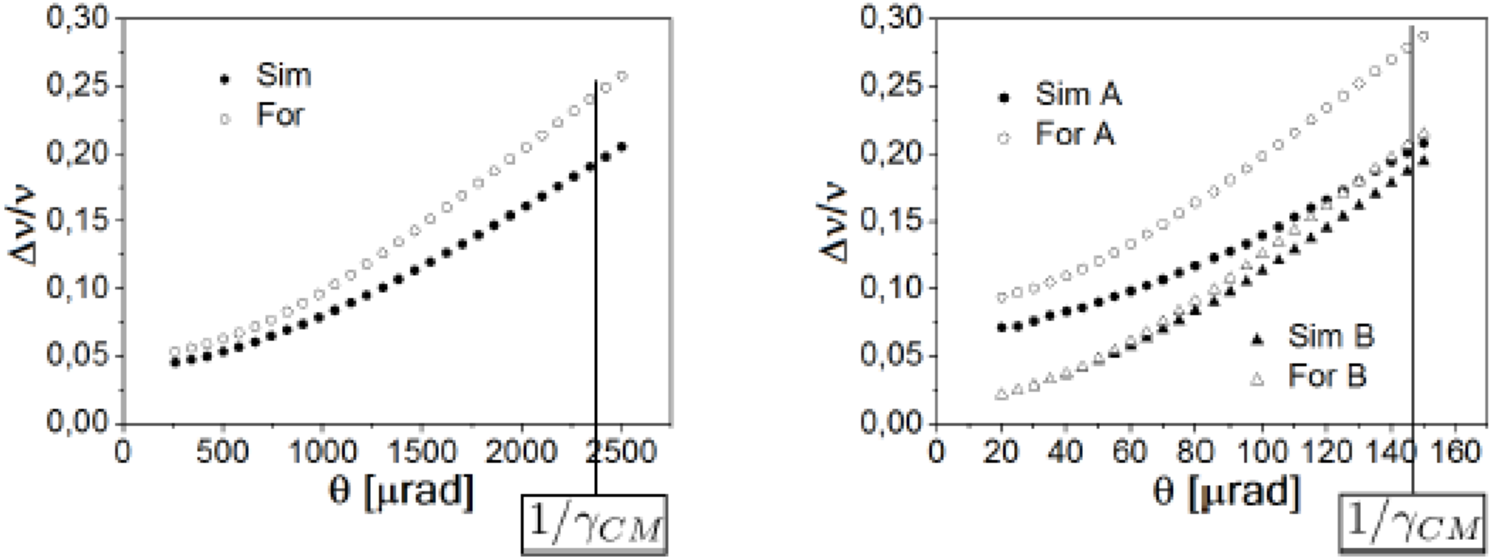


Figure 5: Relative bandwidth of the emitted photons $\Delta\nu/\nu$ as a function of the emission angle θ [μrad]: SPS case with $\sigma_p = \sigma_L = 15$ μm and $\epsilon_{n_x} = 2.5$ mm·mrad (left) and LHC case with $\sigma_p = \sigma_L = 10$ μm and $\epsilon_{n_x} = 2.5$ mm·mrad for subcase A, $\epsilon_{n_x} = 1$ mm·mrad for subcase B (right). Simulation results vs analytical formula eq. (12).

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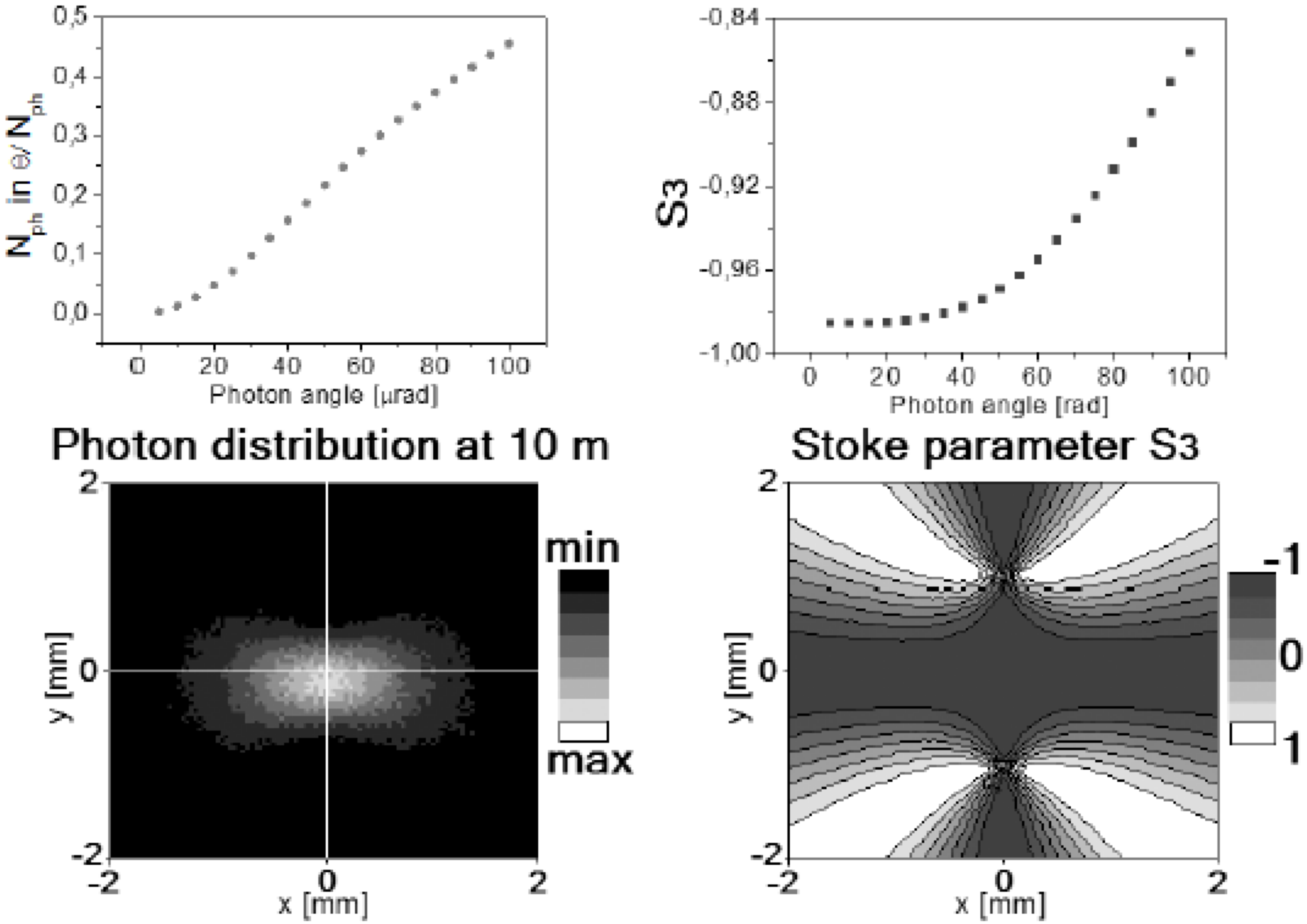

Figure 7: LHC case: $E_p = 7$ TeV and $h\nu = 6$ keV with $\sigma_p = \sigma_L = 5$ μm, no proton beam emittance, unpolarized protons and FEL 100% linearly polarized along y axis. Top line: number of photons in the emission angle normalized on the total number of emitted photons as a function of the emission angle [μrad] (left) and Stokes parameter S_3 as a function of the emission angle [μrad] (right). Bottom line: photon distribution on a screen perpendicular to the proton beam axis at 10 meters from the interaction point (max intensity in white and min in black, x and y in [mm]) (left) and Stokes parameter S_3 value on the same screen (right).

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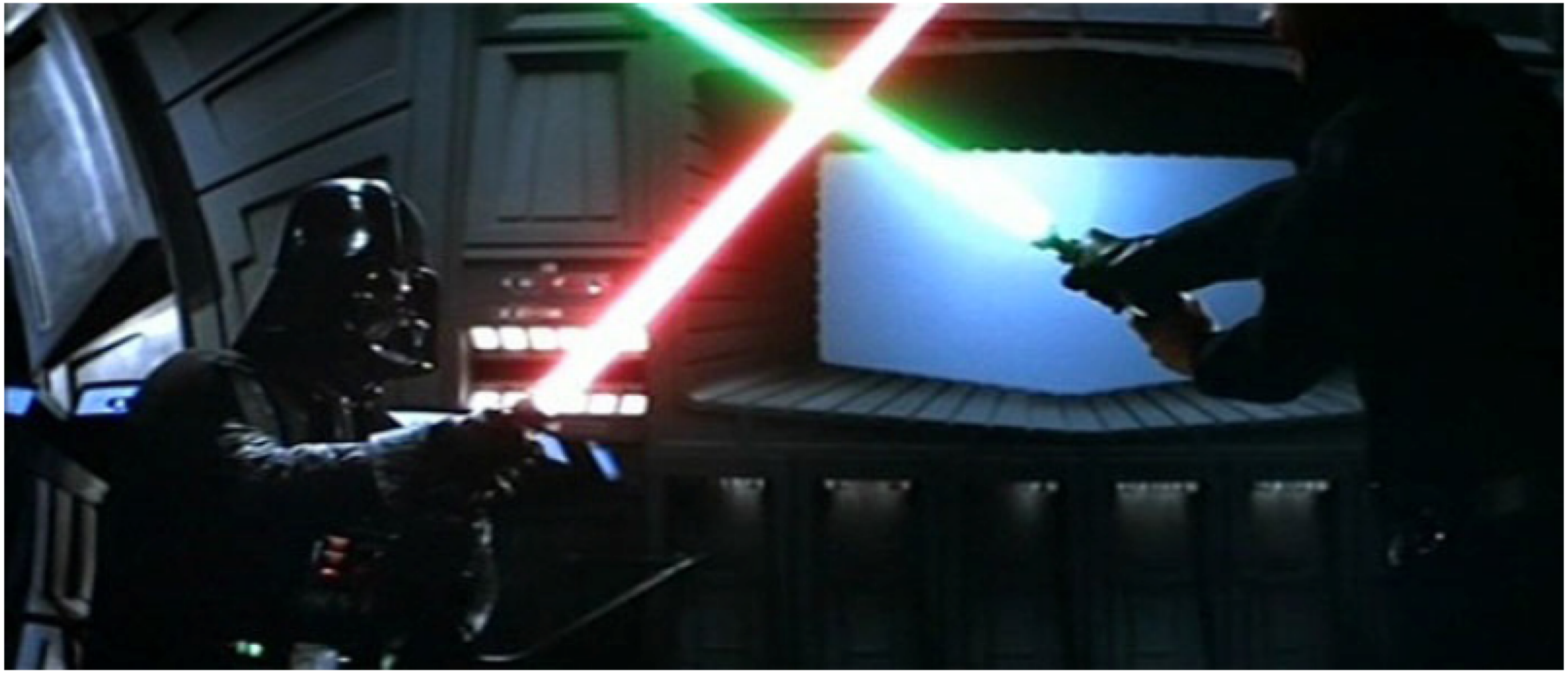
Dipartimento di Fisica

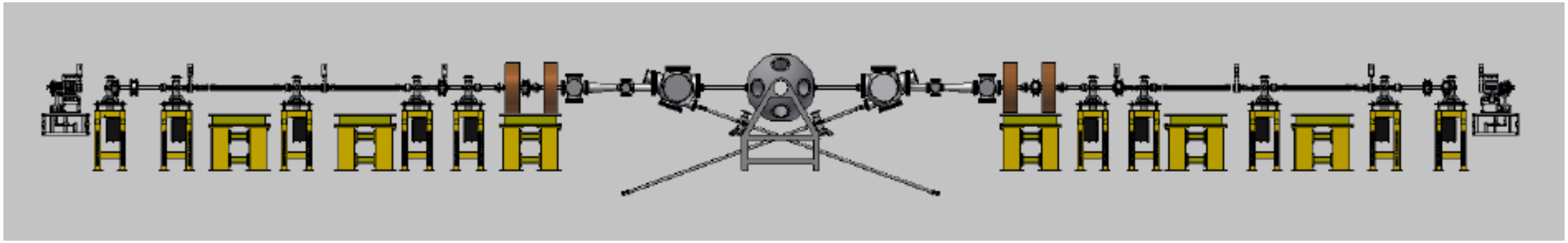


The scattering of light by light

Davide Micieli

SPARC-LAB Upgrade, INFN-LNF, Nov. 12th 2015

Strawman Design of Photon-Photon Scattering machine based on X-Band SLAC RF Photo-Injector + SLAC new X-band (Tantawi-Dolgashev) RF cavities + J-class Yb:Yag 100 Hz collision laser (Amplitude/ELI-NP-GBS&EuroGammaS)

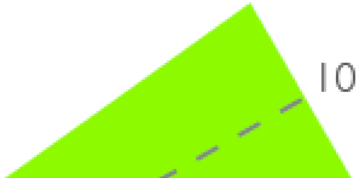


1) Electron beam operation in single bunch – focusability to 3 micron spot size at Compton Interaction Point
2) Pointing stability at 2 Compton Sources
3) Control Moeller scattering of counter-propagating electrons

SLAC E-144 experiment: first sign of positron production in light-by-light scattering

Multi-photon
Breit-Wheeler process

$\gamma + n\gamma_0 \rightarrow e^+e^-$



10^{18} Wcm^{-2} laser

PHYSICAL REVIEW D, VOLUME 60, 092004

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

C. Bamber,* S. J. Boege,† T. Koffas, T. Kotseroglou,‡ A. C. Melissinos, D. D. Meyerhofer,§ D. A. Reis, and W. Ragg‖
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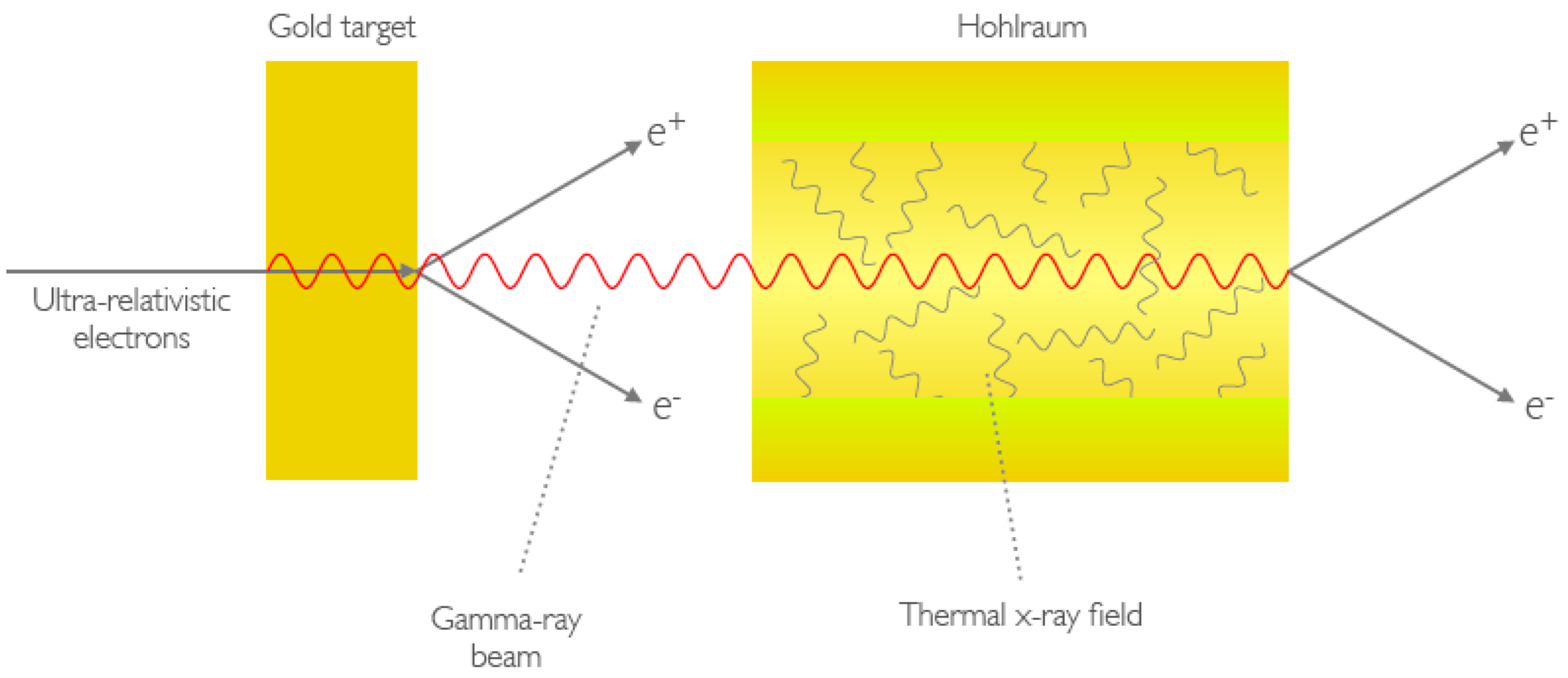
(Received 1 February 1999; published 8 October 1999)

- Recently shown that, on average, n = 6.44 laser photons were absorbed.

Burke et al., *PRL* **79**, 1626 (1997)
Hu & Müller, *PRL* **107**, 090402 (2010)

Courtesy Oliver Pike

A photon-photon collider in a vacuum hohlraum: a new HEP experiment using HEDP facilities



Pike et al., *Nature Photonics* **8**, 434 (2014)

Courtesy Oliver Pike

Gamma Gamma collider @ FACET

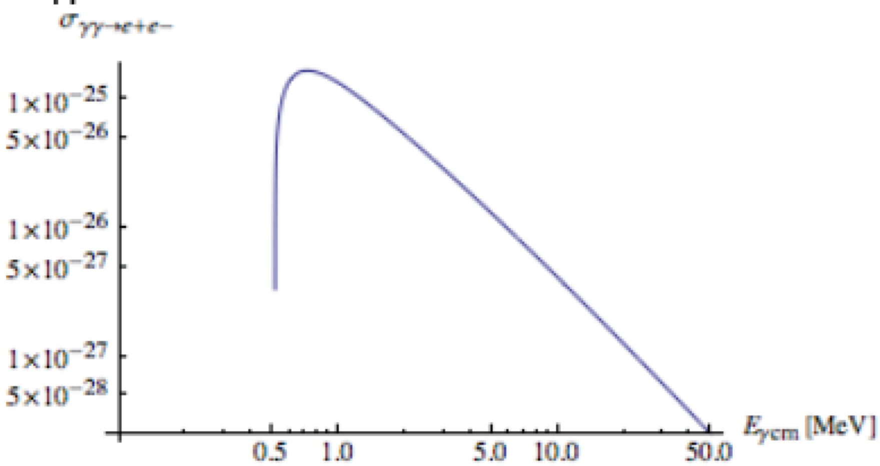
$E_e = 4GeV$

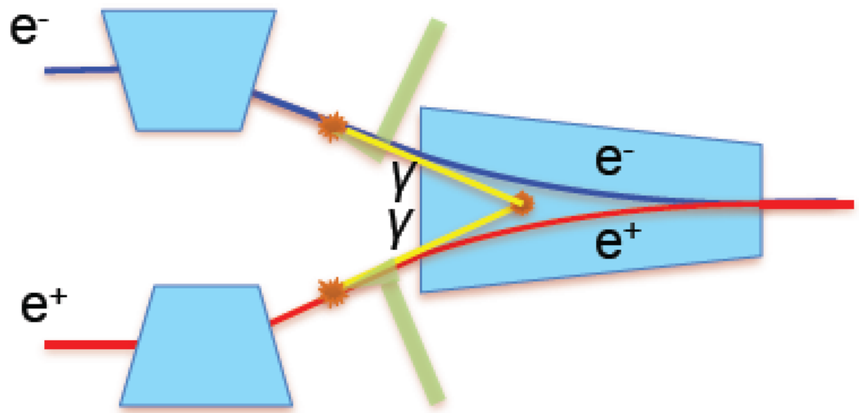
$E_\gamma \sim 30$ MeV, $\alpha \sim 0.05$

$E_{\gamma cm} \sim 1.5$ MeV

$L \sim 5x10^{22}\ cm^{-2}\ sec^{-1}$

$\sigma_{\gamma\gamma\text{->}e+e-} \sim 10^{-25} cm^2$ @ 1.5MeV

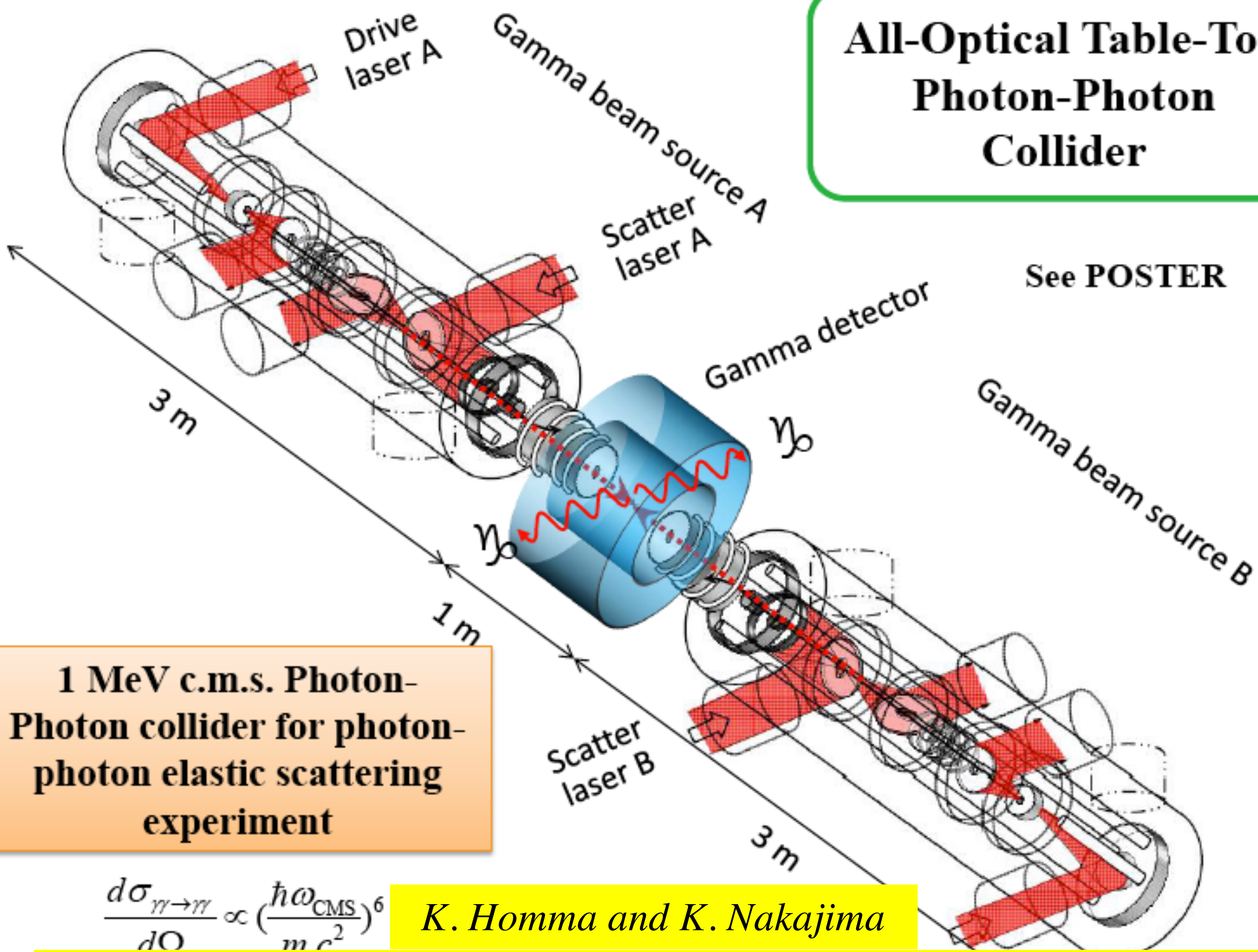




Will focus on technology research for gamma gamma collider.

Will test for the first time ability to generate e^+e^- pairs with real (not virtual) photons

This would be the first pair creation test using real photons



All-Optical Table-Top Photon-Photon Collider

See POSTER

1 MeV c.m.s. Photon-Photon collider for photon-photon elastic scattering experiment

$$\frac{d\sigma_{\gamma\gamma\to\gamma\gamma}}{d\Omega} \propto \left(\frac{\hbar\omega_{CMS}}{mc^2}\right)^6$$

K. Homma and K. Nakajima

https://www.izest.polytechnique.edu/izest-home/izest-events/09-2014-izest-eli-np-conf-extreme-light-new-horizon-paris-france/slides/slides-317952.kjsp?RF=1412352802227

- **At present Nuclear Photonics and Photo-Nuclear Physics are done with Compton Sources, producing gamma ray beams by Compton back-scattering of Laser Beams by high brightness GeV-class electron beams (incoherent sources)**
- **2 Main Figures of Merit: Spectral Density and Bandwidth, within the typical Photon Energy Range of interest (1-20 MeV)**
- **Spectral Density = #Photons/s·eV (bremsstrahlung SD=1, ELI-NP-GBS SD=$5\cdot10^{3}$, ERL based new designs aim at SD=10^{5})**
- **Bandwidth = $\Delta\nu/\nu$ (bremsstrahlung=30%, ELI-NP-GBS=$5\cdot10^{-3}$, ERL based new designs aim at $1\cdot10^{-3}$) FELs operate routinely at $5\cdot10^{-4}$!! Can they get down to $5\cdot10^{-5}$? Is it crucial? Yes, the magic number – the nuclear physicist' dream is $\Delta\nu$ = 100 eV (single nuclear state excitation, below pure Ge detector en. res.)**

Formulas for photon scattering Luminosity extensively tested vs. ELI-NP-GBS simulations

$$L_{sc} = \frac{\left(N_{\gamma-shot}^{bw}\right)^2}{4\pi\sigma_{sc}^2} f_{RF}\delta_\phi \qquad \sigma_{sc} \approx \{!\} \;\; \sigma_S = \frac{\sigma_x w_0}{\sqrt{4\sigma_x^2 + w_0^2}}$$

$$N_\gamma^{bw} = 1.4\cdot 10^9 \frac{U_L[J]Q[pC]f_{RF}\delta_\phi}{h\nu[eV]\left(\sigma_x^2[\mu m] + \frac{w_0^2[\mu m]}{4}\right)} \cdot \frac{\gamma\theta}{\sqrt{2}}$$

$$Assumptions: \;\; weak \;\; diffraction \;\; c\sigma_t < \;\; Z_0 \equiv \frac{\pi w_0^2}{\lambda}$$

$$and \;\; \sigma_{z-el} < \;\; \beta_0 \equiv \frac{\gamma\sigma_0^2}{\varepsilon_n} \quad and \;\; ideal \;\; time-space \;\; overlap$$

$$implies: \;\; \sigma_t < \;\; a \;\; few \;\; psec \;\;\; \sigma_{z-el} < \;\; 300 \;\; \mu m$$

$$L_{sc} = 6.2\cdot 10^{25} \frac{U_L^2[J]Q^2[pC]f_{RF}\delta_\phi^3}{h\nu^2[eV]\sigma_x^2[\mu m]w_0^2[\mu m]\left(\sigma_x^2[\mu m]+\frac{w_0^2[\mu m]}{4}\right)}\cdot\frac{\gamma^2\theta^2}{2}$$

$$Source\ \ size\ \ \sigma_S = \frac{\sigma_x w_0}{\sqrt{4\sigma_x^2+w_0^2}}\quad Photon\ \ emittance\ = \ \varepsilon_{\gamma 0} = \sigma_S\cdot\frac{\theta}{\sqrt{2}}$$

$$Diffraction\ \ \sigma_\gamma(z) = \sigma_S\sqrt{1+\frac{z^2}{\beta^{*2}}}\quad diffr.\ length\ \ \beta^* \equiv \frac{\sigma_S^2}{\varepsilon_{\gamma 0}} = \frac{\sqrt{2}\sigma_S}{\theta}$$

$$\beta^* \approx (ph - ph\ \ scatt) \approx 3\gamma\sigma_S$$

Formula for L_{sc} is valid if distance between 2 Compton conversion IP's is smaller than β^*

Example $\gamma=300$ $\sigma_S=3\ \mu m$ $\beta^*=1\ mm$