STUDY OF HADRON-PHOTON COLLIDERS FOR SECONDARY BEAM GENERATION

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Abstract

We summarize the potentialities of combining two well developed technologies, which are advancing the frontiers of hadron colliders and of light sources, namely the hadron colliders for high energy physics, and the FELs for applied and fundamental science with light, towards the generation of secondary beams with unprecedented characteristics. The collision between their typical pulses of high energy protons and X-ray photons opens a collider scenario with potentials for luminosities in excess of 10^{38} $s^{-1}cm^{-2}$, adequate to generate TeV-class pion, muon, neutrino and photon beams with very high phase space densities. We report results based on Monte Carlo simulations of such a hadron-photon collider, aiming at qualifying the features of these secondary beams in view of experiments to be performed directly, or towards the design of a new kind of muon collider.

HADRON-PHOTON COLLIDER

Muon colliders represent a promising way to achieve the highest lepton-antilepton collision energies and precision measurements of the Higgs boson and for further study of its properties [1,2]. One of the main challenges of present muon collider design studies is the capture and 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. 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 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 [3,4]. 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, photon and neutrino beams via photoproduction in a highly relativistic Lorentz boosted frame. We propose an approach based on the collision of two counter-propagating beams of LHC/FCC like highly relativistic protons [5,6] and ultra-high brilliance FEL X-rays (energies between 3 and 20 keV, $10^{13}-10^{14}$ photons per pulse at MHz repetition rate [7,8]): such a Hadron-Photon Collider (HPC) permits to achieve extremely high luminosities in excess of 10^{38} $cm^{-2}s^{-1}$. In this collision scheme the energy of the X-ray photons observed by the proton in its own rest frame is much higher than the photon energy in the laboratory: this enables pion/muon photoproduction above the threshold with maximum efficiency, despite the keV energy of the colliding photon. Since the proton carries almost the total momentum of the system, the secondary beams are highly Lorentz boosted and collimated within a narrow forward angle of the same order of the proton beam diffraction angle given by its transverse normalized emittance (few mm·mrads).

SCHEME AND RELEVANT REACTIONS

For the head-on collision between an ultra-relativistic proton and a photon of energy respectively E_{pr} and E_{ph} in the laboratory frame (LAB), the energy E'_{ph} of the colliding photon in the proton rest frame is given by

$$E'_{ph} = (1 - \underline{\beta} \cdot \underline{e}_k)\, \gamma\, E_{ph} \simeq 2\, \gamma\, E_{ph} \qquad (1)$$

where $\underline{\beta}$ is the velocity of the proton, $\underline{e}_k$ is the direction of propagation of the photon, $\gamma = E_{pr}/M_{pr}$ and $M_{pr} = 938$ MeV/c^2. If $E_{ph} \ll E_{pr}$, the CM Lorentz factor is

$$\gamma_{CM} = \frac{E_{tot}^{LAB}}{E_{CM}} \simeq \frac{E_{pr} + E_{ph}}{\sqrt{4\, E_{pr}\, E_{ph} + M_{pr}^2}}. \qquad (2)$$

Besides the pion, double pion and direct muon pair photoproduction, the main reactions in the energy range $E'_{ph} <$ 1200 MeV are electron-positron pair production and inverse Compton scattering. The total cross sections are summarized in Fig. 1.

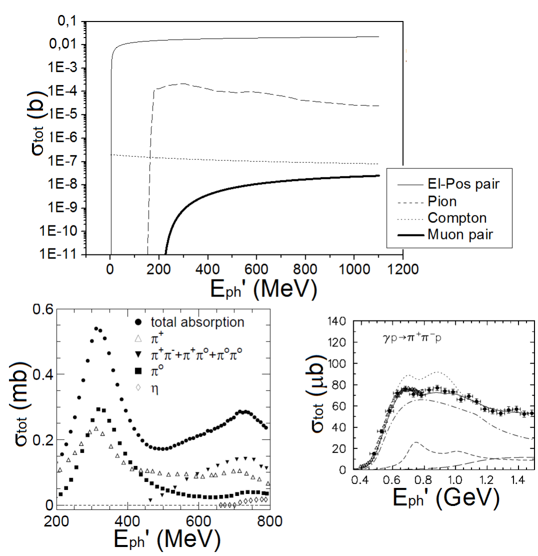

Figure 1: Total cross section σ_{tot} as a function of the photon energy E'_{ph} for different reactions: pion, double pion, electron/positron, muon pair photoproduction and inverse Compton scattering [9–12].

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LUMINOSITY, FLUX AND PHASE SPACES

The number of a certain kind of particle produced per second can be calculated as

$$\mathcal{N} = \mathcal{L} \cdot \sigma_{tot} = \frac{N_{pr} N_{ph} r}{4\pi\sigma_0^2} \cdot \sigma_{tot} \qquad (3)$$

where σ_{tot} is the total cross section for the considered reaction (see Fig. 1), $\mathcal{L}$ is the proton-photon collider luminosity, N_{pr} is the number of colliding protons in the bunch, N_{ph} is the number of photons carried by the radiation pulse, r the repetition rate of the collisions and σ_0 the effective spot size at the IP. Considering a FCC beam of $N_{pr} = 10^{11}$ and $\sigma_0 = 1.6\ \mu$m, $N_{ph} = 10^{14}$ and $r = 10$ MHz, we obtain $\mathcal{L} = 3.1 \cdot 10^{38}$ cm^{-2}s^{-1} and the expected number of events per second are specified in Table 1. In this case the dominant reaction is electron/positron pair production, but the proton beam is not affected since the e^-/e^+ energy is extremely low (see Fig. 2). Inverse Compton scattering does not substantially perturb the proton beam due to its very small cross section. The dominant proton beam loss rate is given by the pion production: at FCC it is of about $\sim 1.3 \cdot 10^{11}$ protons/s, twenty times higher than loss rate $\sim 6.8 \cdot 10^9$ protons/s foreseen for p-p operation. With an expected number of circulating proton bunches of about 3000, the proton beam life-time would be of about 1/2 hour, nearly equivalent to the one set by beam dynamics and instabilities in FCC ring.

Table 1: Number of particles (s^{-1}) at $E_{pr} = 50$ TeV, E_{ph} (keV) values reported in table and $\mathcal{L} = 3.1 \cdot 10^{38}$ cm^{-2}s^{-1}.

E_{ph} (keV)	$\mathcal{N}_{\pi^+}$ (s^{-1})	$\mathcal{N}_{\mu^-/\mu^+}$ (s^{-1})	$\mathcal{N}_{e^-/e^+}$ (s^{-1})
3	$6.8 \cdot 10^{10}$	$4 \cdot 10^5$	$5.4 \cdot 10^{12}$
5	$3.2 \cdot 10^{10}$	$1.2 \cdot 10^6$	$5.6 \cdot 10^{12}$
10	$3.1 \cdot 10^{10}$	$4.8 \cdot 10^6$	$6.5 \cdot 10^{12}$
12	$2.5 \cdot 10^{10}$	$5.6 \cdot 10^6$	$6.8 \cdot 10^{12}$

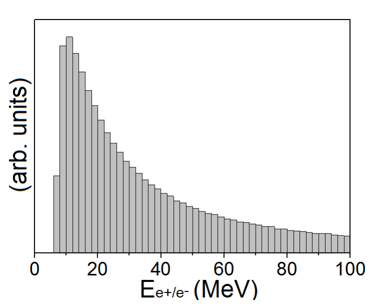

Figure 2: e^-/e^+ energy spectrum (MeV) for FCC protons at $E_{pr} = 50$ TeV and photons at $E_{ph} = 10$ keV colliding head-on. Homemade simulation code based on Geant4 differential cross sections.

By means of some homemade event generators and well-known codes such as Geant4 and Fluka [13,14], we simulate the secondary beams (see [15–18] for more datails) and we report in the following some examples. Our main purpose is to investigate the characteristics of the emitted muon beams: Fig. 3 shows the energy spectra of the muons produced by the reaction $p + \gamma \rightarrow p' + \mu^-\mu^+$ in case of a FCC like proton beam colliding with an FEL beam at 5, 10 and 12 keV. The 10 keV case, for example, exhibits a spectrum peaked around 0.5 TeV and a photocathode transverse normalized emittance (obtained disregarding the proton beam emittance) $\epsilon^{\mu}_{n-cath} = 0.83$ mm·mrad. The other possibility to obtain muons is from the decay of the generated pions via the single pion $p + h\nu \rightarrow n + \pi^+$ and the double pion $p + \gamma \rightarrow p' + \pi^-\pi^+$ production. Figure 4 represents the π^+ spectrum at the double pion cross section peak $E'_{ph} = 700$ MeV, corresponding in this case at $E_{pr} = 50$ TeV and $E_{ph} = 6.566$ keV. In the energy regimes under consideration, inverse Compton scattering off protons enables the production of very high energy γ rays (see [18]): an example is reported in Fig. 5.

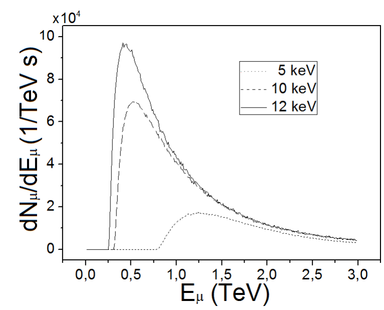

Figure 3: Number of muons per second in 10 GeV bins produced by FCC protons at $E_{pr} = 50$ TeV and photons $E_{ph} = 5$, 10, 12 keV colliding head-on. Homemade simulation code based on Geant4 differential cross sections.

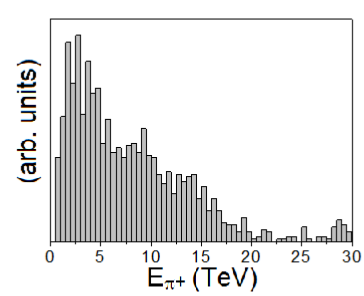

Figure 4: Spectrum of π^+ produced by FCC protons at $E_{pr} = 50$ TeV and photons at $E_{ph} = 6.566$ keV colliding head-on. Particles generated by Fluka and boosted to the LAB frame.

CONCLUSION

The combined operation of LHC/FCC with a X-ray Free Electron Laser, although not easy nor inexpensive to be implemented in reality, offers the great opportunity of conceiving a hybrid HPC, at an unprecedented luminosity exceeding 10^{38} s^{-1}cm^{-2}. The HPC is actually aimed not at producing events to study, but to generate secondary beams of unique characteristics, via a highly boosted Lorentz frame

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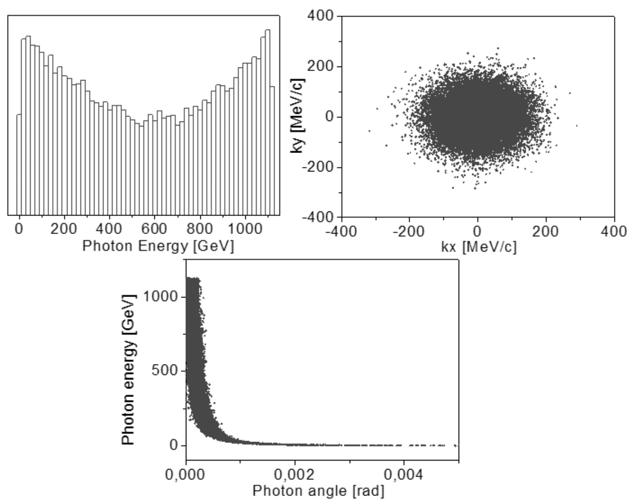

Figure 5: Scattered photons from LHC beam with $\epsilon_{n_x} = 2.5$ mm· mrad and photons at $E_{ph} = 6$ keV with $\sigma_0 = 5$ μm. Energy spectrum (GeV), transverse phase space (k_y vs k_x (MeV/c)) at the IP and energy (GeV) as a function of the emission angle θ (rad). Assuming $r = 100$ Hz and $\mathcal{L} = 6.36 \cdot 10^{31}$ cm^{-2}s^{-1}: total number of photons per second $\mathcal{N} = 10.62$. Simulation code: CMCC [16].

corresponding to a very relativistic moving center of mass reference frame. The phase space distributions of the secondary beam generated have outstanding properties of low transverse emittance and are collimated within very narrow forward angles with energies in the TeV range [15–18]. The main goal is the production of high quality muon beams. One option is given by the manipulation of charged pions of both signs, further decaying into muons and neutrino beams of similar characteristics in the phase space: the challenge is the large energy spread of the pion beams and the long range distance travelled by them before decay, at this energy. The potentialities in terms of muon and neutrino beams obtainable are impressive: although the number of muons and neutrinos per bunch would be low (a few thousands) their phase space distributions would be extremely high quality thanks to the large Lorentz boost of the primary proton-photon collision, giving rise to very small divergence angles for these beams. Another way to obtain muon beams is the 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. A possibility to partially compensate for the low efficiency of the process would be to collide lead ions in order to have a factor ~ 670 gain on the number of produced muons: around 10^8 muon pairs per second. In both scenarios, the long life of the high energy generated muons (in excess of 10 ms) may offer the opportunity to accumulate them in a storage ring so to achieve muon collider requested bunch intensities.

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