Proton laser scheme

conceptual study for a muon photocathode

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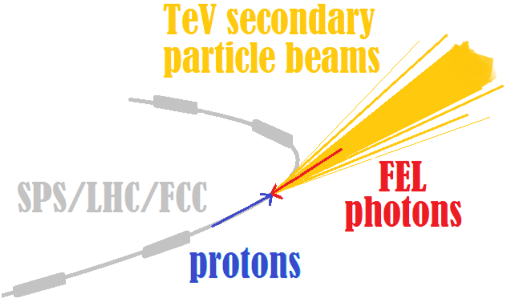
OUTLINE

Presentation outline:

- Introduction to the muon photocathode: Hadron-Photon Collider (HPC) scheme
- Kinematics of relavant reactions and description of event-generator codes to simulate the secondary beams
- Phase space and luminosity analysis in various scenarios
- Conclusion and considerations

INTRODUCTION: HPC SCHEME SKETCH

Conceptual study to generate TeV-class low emittance particle beams in highly Lorentz boosted frame by colliding high energy protons (SPS/LHC/FCC) and counterpropagating high brilliance keV photon beams (TCS/FEL)



Which are the advanteges of this scheme?
What happens in the collision of a ultra-relativistic proton beam and a counter-propagating high energy photon beam?

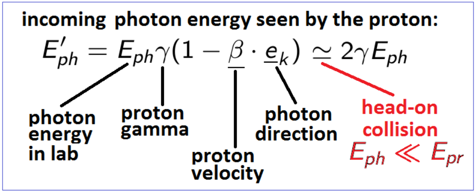
INTRODUCTION: ADVANTAGES OF HPC SCHEME

- TeV protons keV photons: very asymmetrical collision $\Rightarrow$

$$\gamma_{CM} = \frac{E_{tot}^{lab}}{E_{CM}} \simeq \frac{E_{pr} + E_{ph}}{\sqrt{4E_{pr}E_{ph} + M_{pr}^2}} \text{ close to } \gamma \text{ of protons} \Rightarrow$$

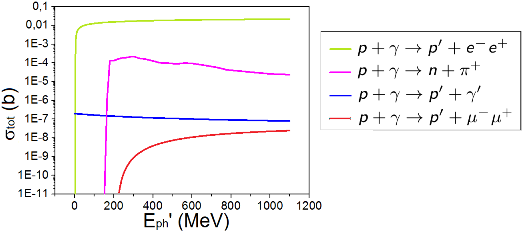
high Lorentz boost imparted to secondary beams:
high energy, very collimated and low transverse emittance

- energy of photons in protons rest frame much higher than in laboratory $\Rightarrow$
maximum efficiency above threshold even at keV photon energies



INTRODUCTION: MAIN REACTIONS

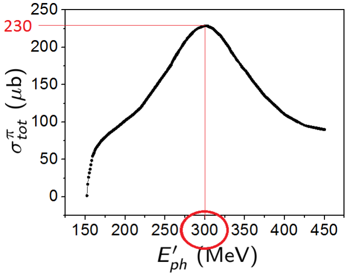
PRoton source	E_{pr} (TeV)	N_{pr}	σ_0 (μm)	PHoton source	E_{ph} (keV)	N_{ph}
SPS	0.4	$2 \cdot 10^{12}$	18	TCS	350	10^{8-9}
LHC	7	$2 \cdot 10^{11}$	7	FEL	$6-20$	10^{13}
FCC	50	10^{11}	1.6	FEL	$2-12$	10^{13-14}



Is it possibile to conceive a muon collider based on HPC?
What are the characteristics of the secondary
(pion, muon, neutrino, neutron, photon) beams ?
What is the impact of the collision on the proton beam features?

PION PRODUCTION: $p + \gamma \to \pi^+ + n$

E_{ph} value chosen to maximize Lorentz invariant total cross section of pion photo-production $p + \gamma \to n + \pi^+$



J. Phys. G: Nucl. Part. Phys. 18 (1992) 449–497.
Dieter Drechsel and Lothar Tiator

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

if head-on collision and $E_{ph} \ll E_{pr}$

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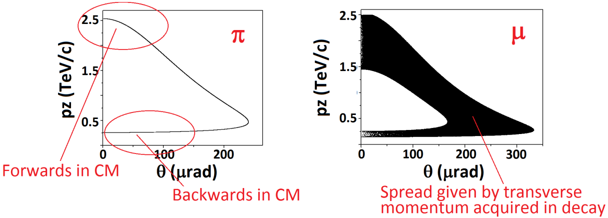
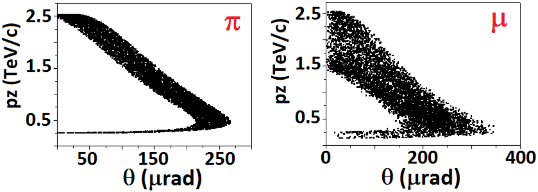
PION AND MUON PRODUCTION: $p + \gamma \rightarrow \pi^+ + n \rightarrow \mu^+ + \nu_\mu + n$

Homemade event-generator code: correct differential cross section for pion photo-production, no transport just event generation, all pions decay into muons. Example: results for $E_{pr} = 7$ TeV and $E_{ph} = 20$ keV, no proton beam emittance.



With proton emittance: enlargement of angular spread and momentum.



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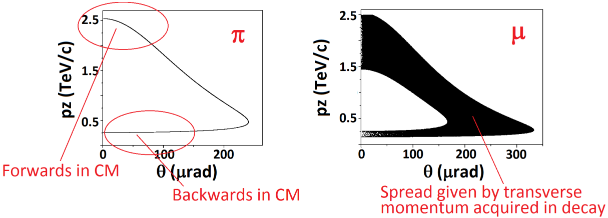

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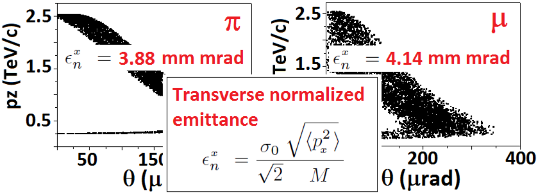
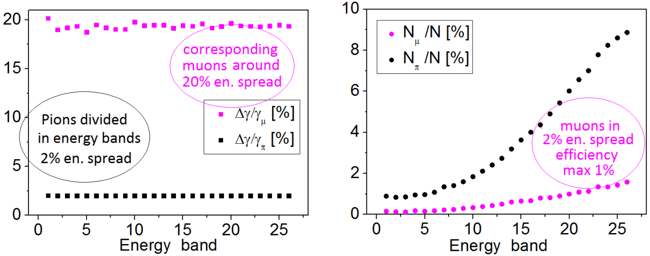


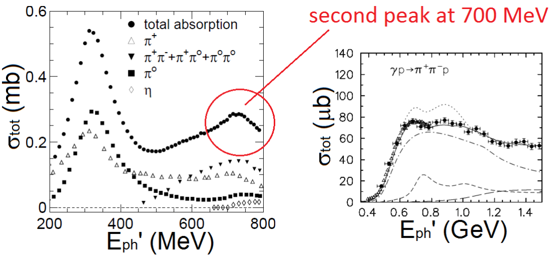
PION AND MUON PRODUCTION: $p + \gamma \to \pi^+ + n \to \mu^+ + \nu_\mu + n$

Pions have to run in a storage ring for a time sufficient to their decay into muons and the produced muons have to remain in the ring, i.e. only the muons produced within the acceptance of the ring survive.

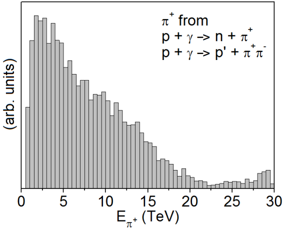
Example: $E_{pr} = 50$ TeV, $E_{ph} = 2.251$ keV and ring 2% en. spread acceptance.



PION PRODUCTION: $p + \gamma \rightarrow p' + \pi^- \pi^+$



Example: spectrum of π^+ by $E_{pr} = 50$ TeV and $E_{ph} = 6.566$ keV colliding head-on.



Particles generated in PRF by FLUKA and boosted to LAB

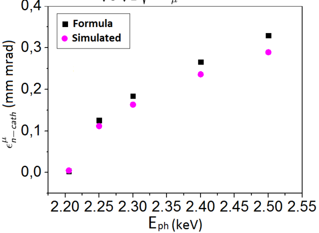
MUON PAIR PRODUCTION: $p + \gamma \to p' + \mu^- \mu^+$

Threshold photon energy in proton rest frame for pair production:

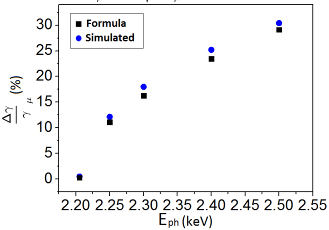
$$E'^{th}_{ph} = \frac{(2M_\mu + M_{pr})^2 - M_{pr}^2}{2M_{pr}} = 235 \text{ MeV}$$

Example: $E_{pr} = 50$ TeV $\Rightarrow E_{ph} = E'^{th}_{ph}/(2\gamma) = 2.2053$ keV.
Idea: close to muon production threshold to minimize emittance and energy spread.
Emittance very low but energy spread grows fast and it is hard to find correct differential cross section.
Homemade event generator based on flat differential cross section.

$$\epsilon^{\mu}_{n-cath} \le \frac{1}{\sqrt{3}}\frac{\sigma_0}{\sqrt{2}}\sqrt{\frac{M_{pr}^2}{4M_\mu^2}\left(\sqrt{1+X}-1\right)^2 - 1}$$

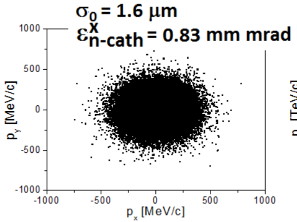


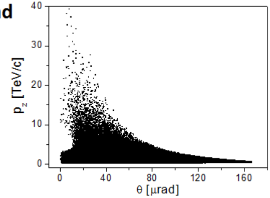
$$\frac{\Delta\gamma}{\gamma}_{\mu} = \frac{1}{\sqrt{3}}\sqrt{\frac{M_{pr}^2}{4M_\mu^2}\left(\sqrt{1+X}-1\right)^2 - 1}$$

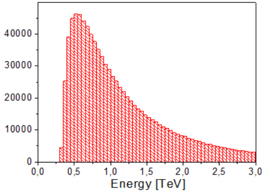


MUON PAIR PRODUCTION: $p + \gamma \to p' + \mu^- \mu^+$

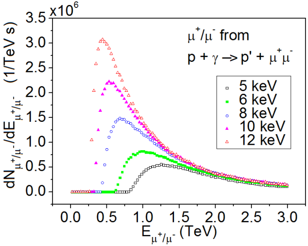
Next step: move from threshold in order to gain a lot in total cross section.
New code based on GEANT4 approach with correct differential cross section (calculation in PRF + Lorentz transformations to LAB)
Example: $E_{pr} = 50$ TeV, $E_{ph} = 10$ keV ($E'_{ph} = 1.066$ GeV)





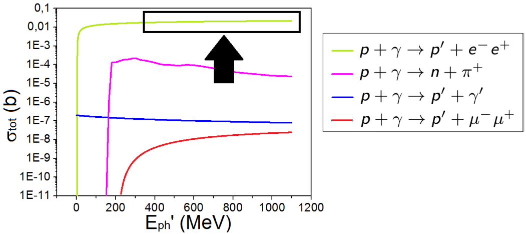


Example: $E_{pr} = 50$ TeV and various photon energies

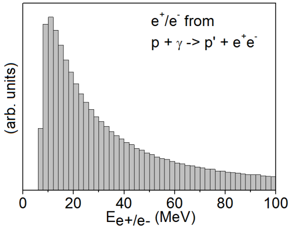


ELECTRON/POSITRON PRODUCTION: $p + \gamma \to p' + e^- e^+$

Electron/positron pair production is the most probable reaction.



Homemade simulation code based on Geant4 differential cross sections.
Example: $E_{pr} = 50$ TeV and $E_{ph} = 10$ keV colliding head-on.



LUMINOSITY AND FLUX

Example of FCC case: $E_{pr} = 50$ TeV, $\mathcal{N} = \mathcal{L} \cdot \sigma_{tot}$ and

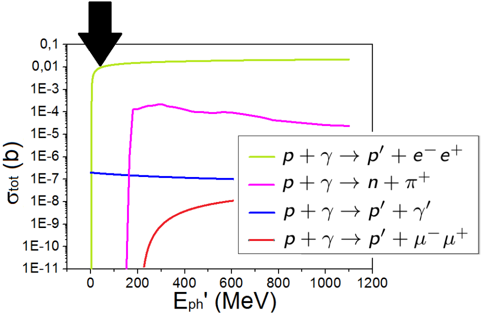
$$\mathcal{L} = \frac{N_{pr} N_{ph} r}{4\pi\sigma_0^2} = \frac{10^{11} \cdot 10^{14} \cdot 10^7}{4 \cdot \pi \cdot 1.6^2 \cdot 10^{-12}} = 3.1 \cdot 10^{38}\ \text{cm}^{-2}\text{s}^{-1}$$

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	$2.5 \cdot 10^{10}$	$5.6 \cdot 10^6$	$6.8 \cdot 10^{12}$

- Electron/positron pair production is the dominant reaction, but it does not affect the proton beam since in the energy range we considered here (300 MeV $< E'_{ph} < 1.1$ GeV) they are emitted at very low energy.
- Proton beam loss rate given by pion production at FCC 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.
- Direct muon pair production is not an issue for the proton beam.

LUMINOSITY AND FLUX

$p + \gamma \to p + e^+ + e^-$: positron beam production as main goal
close to threshold at the quasi top of total cross section,
below pion and muon production threshold



$$E'_{ph} \simeq 2\gamma E_{ph} = 3 \text{ MeV} \;\to\; \text{FEL needed}$$

•FCC $E_{ph} = 28$ eV $\quad N_{e^+/s} = \frac{10^{11}\;\, 10^{15}\;\, 10^{7}\;\, 0.01\;\, 10^{-30}}{4\pi(1.6\;\, 10^{-6})^2} = 3.1\; 10^{13} \quad \epsilon_n^x = 1.1\;\mu\text{m rad}$

•LHC $E_{ph} = 200$ eV $\quad N_{e^+/s} = \frac{2\;\, 10^{11}\;\, 10^{14}\;\, 10^{7}\;\, 0.01\;\, 10^{-30}}{4\pi(7\;\, 10^{-6})^2} = 3.24\; 10^{11} \quad \epsilon_n^x = 4.6\;\mu\text{m rad}$

CONCLUSION

- Combined operation of LHC/FCC with a X-ray Free Electron Laser: opportunity of conceiving a hybrid Hadron-Photon Collider at a luminosity exceeding 10^{38} $s^{-1}cm^{-2}$.
- Hadron-Photon Collider to generate secondary beams of unique characteristics, via a highly boosted Lorentz frame corresponding to a very relativistic moving center of mass reference frame: TeV-class secondary beams are produced with outstanding properties of low transverse emittance and collimation within narrow forward angles.
- Muon beams obtained by direct muon pair production or pion production and decay: quite low flux but outstanding phase space properties. 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.
- It would be interesting to evaluate the polarization of the emitted particles: schemes to produce polarized positrons using circularly polarized FEL light could be used for the generation of polarized muons.

Thank you for your attention!

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