TeV muon beams photoproduction with Hadron-Photon Colliders based on high efficiency FELs

Camilla Curatolo, Francesco Broggi, Luca Serafini

INFN Milan, Italy

camilla.curatolo@mi.infn.it

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Conceptual study to generate
TeV low emittance muon beams
in highly Lorentz boosted frame
by colliding TeV protons (LHC/FCC) and
high brilliance keV photon beams (FEL)

OUTLINE

- Introduction to Hadron-Photon Collider

- Kinematics of relavant reactions and description of event-generator codes to simulate the secondary beams

- Phase space and luminosity analysis in various scenarios

INTRODUCTION

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· TeV protons keV photons: very asymmetrical collision

$$\gamma_{CM} = \frac{E_{tot}^{lab}}{E_{CM}} \simeq \frac{E_p + h\nu}{\sqrt{4E_p h\nu + M_p^2}}$$

close to γ of protons $\rightarrow$
high Lorentz boost imparted to secondary beams:
high energy, very collimated and low transverse emittance

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

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$$p + h\nu \longrightarrow \pi^{+} + n$$

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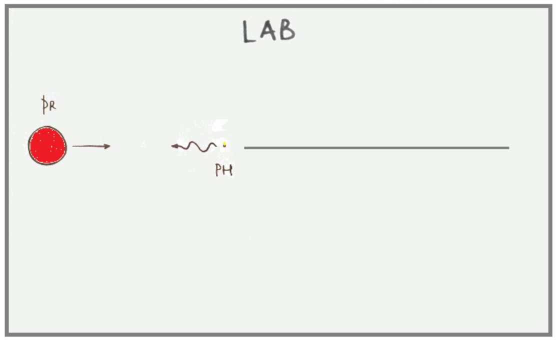
$$p + h\nu \rightarrow \pi^+ + n \text{ AND } \pi^+ \rightarrow \mu^+ + \nu_\mu$$



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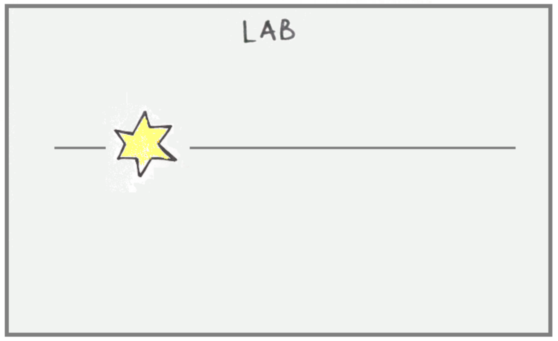

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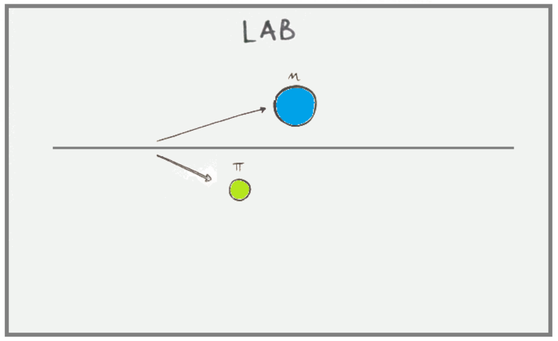

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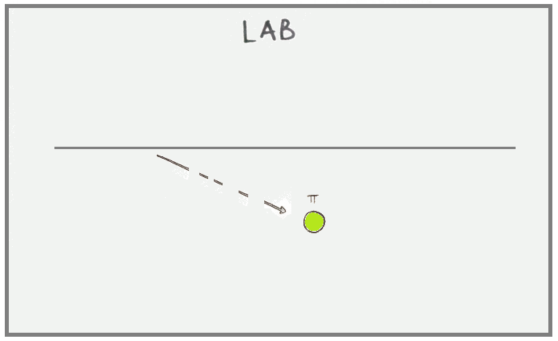

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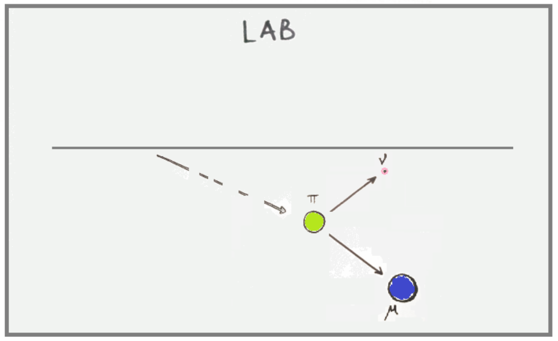

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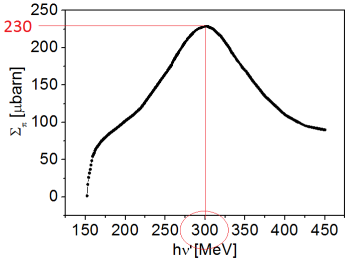
PR source	E_p [TeV]	N_p	σ_0 [μm]	PH source	$h\nu$ [keV]	N_{ph}
LHC	7	$2 \cdot 10^{11}$	7	FEL	20	10^{13}
FCC	50	10^{11}	1.6	FEL	3	10^{14}

hν chosen to maximize Lorentz invariant total cross section of pion photo-production on protons



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

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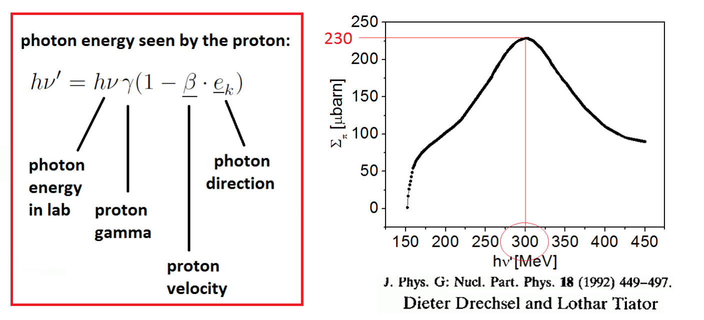

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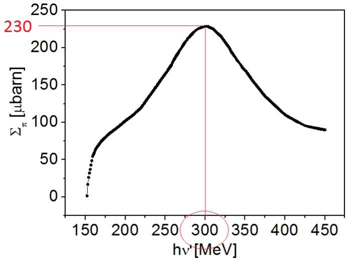
photon energy seen by the proton:

$$h\nu' \simeq 2h\nu\gamma$$

for head-on collision
of ultra-relativistic
proton vs keV photon



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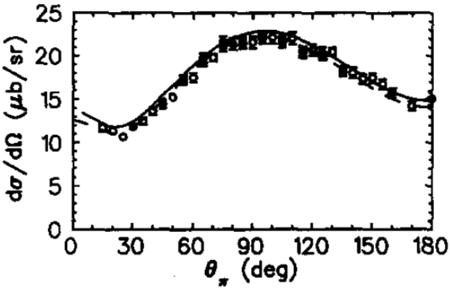
$p + h\nu \to \pi^+ + n$

The probability of the pion to be emitted at a certain angle is proportional to the differential cross section

Ex: $E_p = 7$ TeV, $h\nu = 20$ keV



D. Drechsel *et al.*, *A unitary isobar model for pion photo- and electroproduction on the proton up to 1 GeV*, Nucl. Phys. A 645 (1999) 145-174

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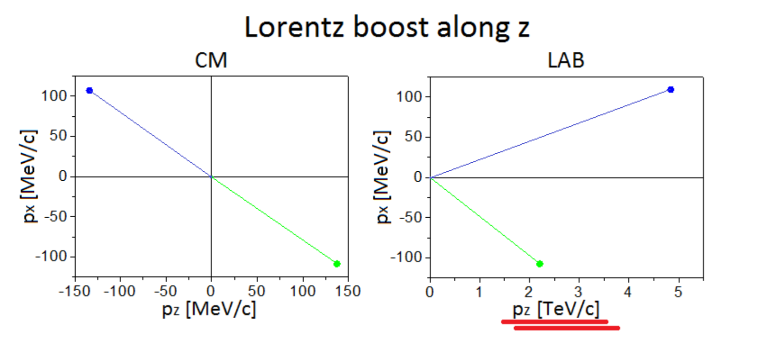
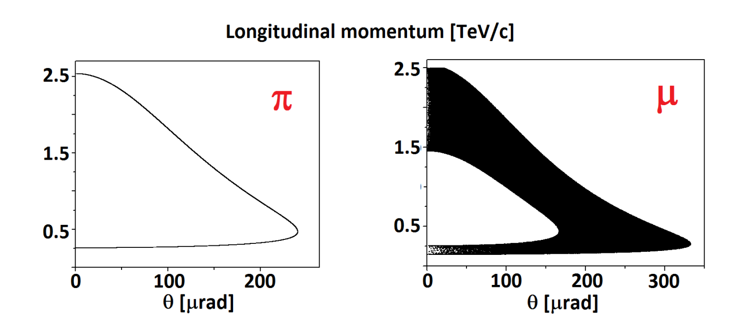


$$\begin{cases} p_{x\pi} = p^*_\pi \sin\theta^* \cos\phi^* \\ p_{y\pi} = p^*_\pi \sin\theta^* \sin\phi^* \\ p_{z\pi} = \gamma_{CM} \left(\sqrt{1 - \frac{1}{\gamma^2_{CM}}} E^*_\pi + p^*_\pi \cos\theta^* \right) \end{cases}$$

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

Event-generator code: results for $E_p = 7$ TeV and $h\nu = 20$ keV, no proton beam emittance.



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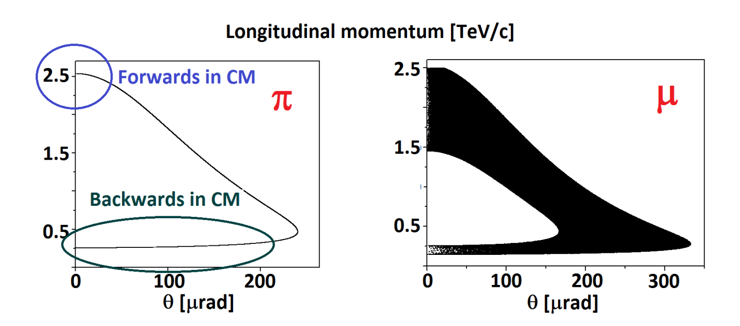

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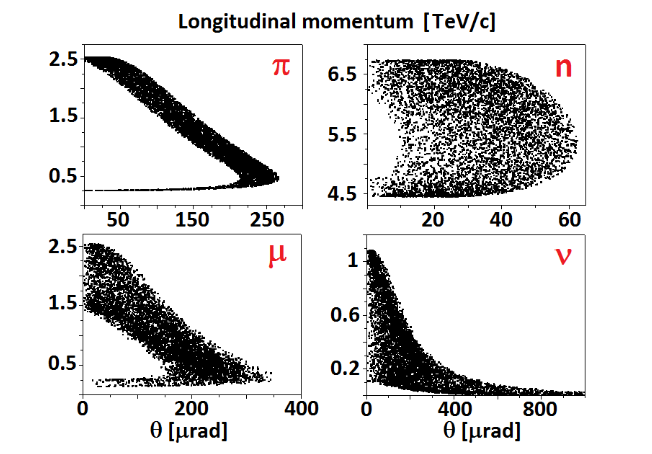
With proton emittance: increase of angular spread and dispersion in momentum for all particles



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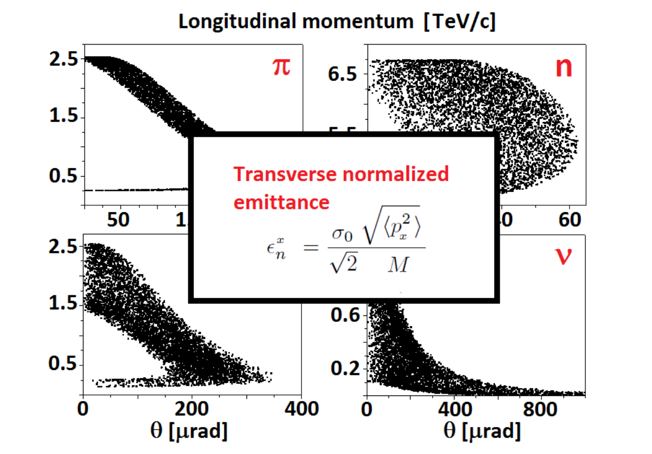

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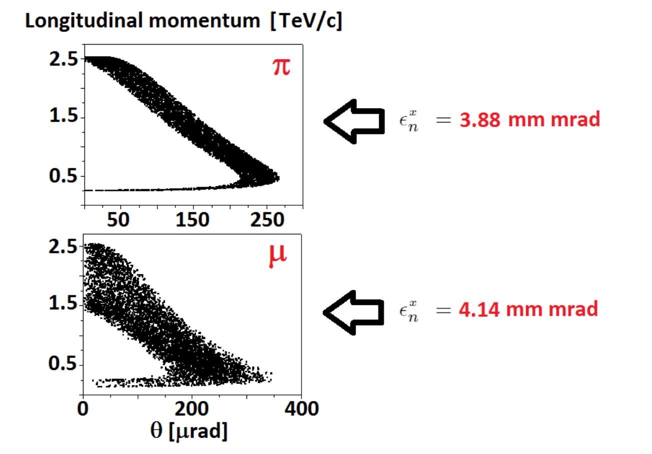

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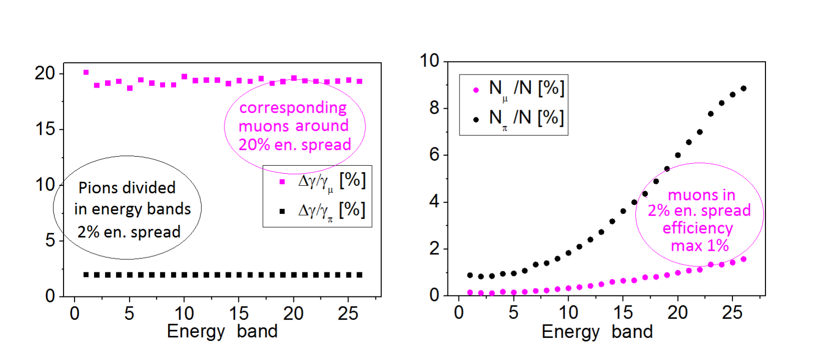
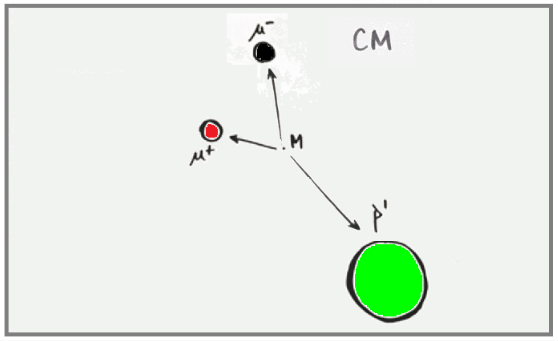
Pions have to run in a storage ring for a time sufficient to their decay into muons and the produced muons have to remain in the ring, i.e. only the muons produced within the energy acceptance of the ring survive.

Ex: $E_p = 50$ TeV, $h\nu = 2.251$ keV and ring 2% en. spread acceptance.



$$p + h\nu \longrightarrow p' + \mu^+\mu^-$$

$p + h\nu \rightarrow p' + \mu^- \mu^+$



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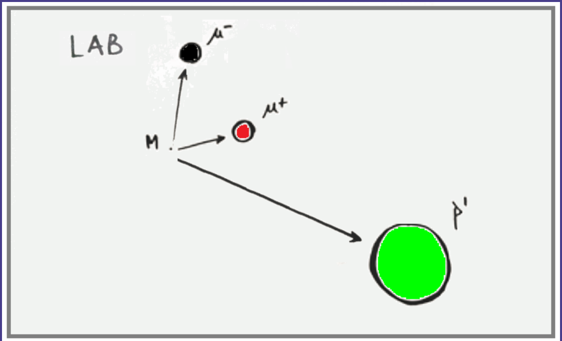

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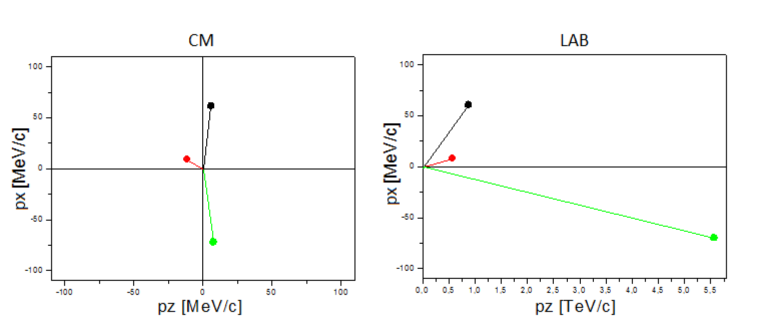
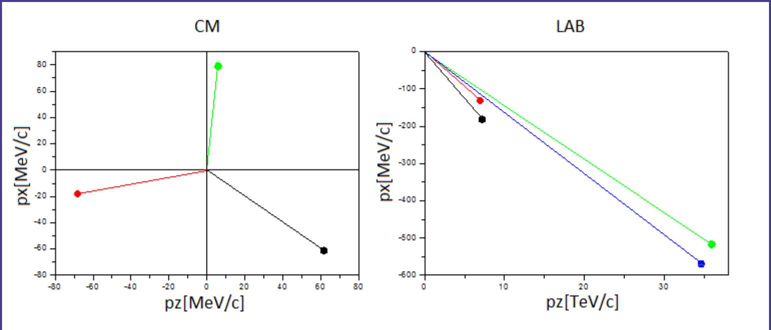
Ex: Lorentz transformation of the momenta of the product particles with boost along the $\vec{\beta}_{CM} = \beta_{CM}\vec{e}_z$.



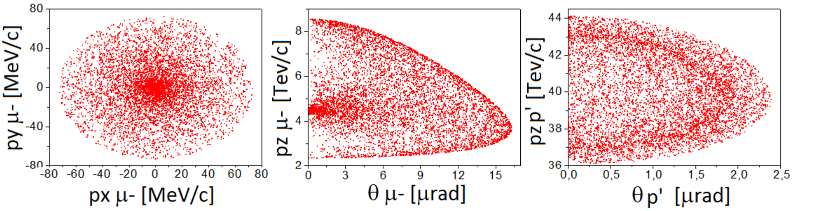
$p + h\nu \rightarrow p' + \mu^- \mu^+$

If the emittance of the incident protons is considered $\Rightarrow$
Lorentz transformation in the generic direction



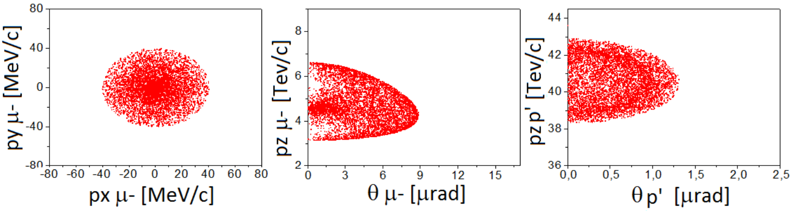
$$p + h\nu \rightarrow p' + \mu^- \mu^+$$

Ep =50 TeV hν=2.5 KeV



$p + h\nu \to p' + \mu^- \mu^+$

Ep =50 TeV   hν=2.3 KeV



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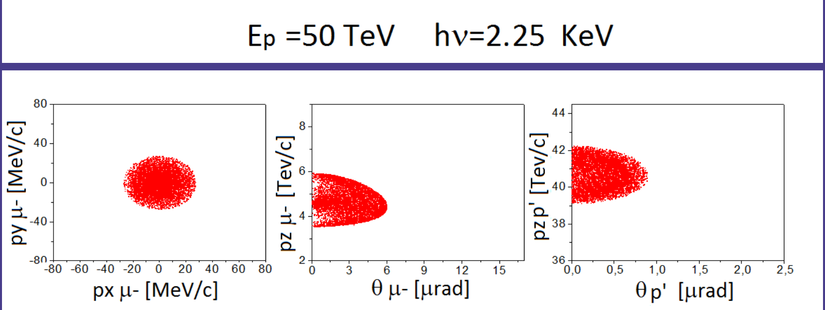

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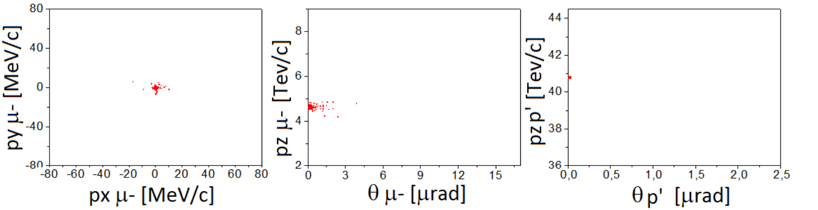

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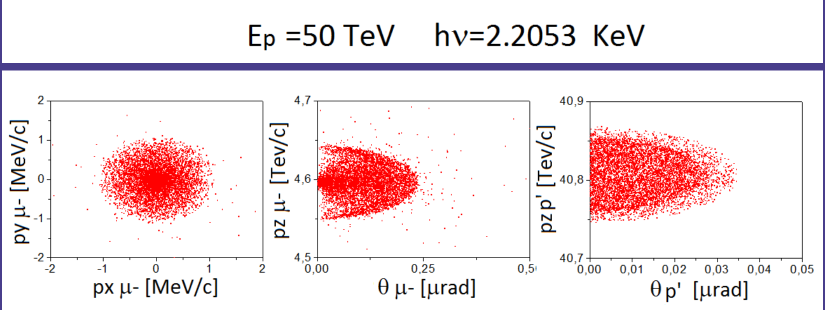


Threshold photon energy in proton rest frame for pair production:

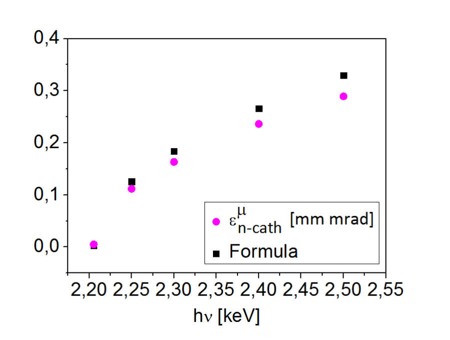
$$h\nu'^{th} = \frac{(2M_\mu + M_p)^2 - M_p^2}{2M_p} = 235\text{MeV}$$

$$\text{Ex: } E_p = 50 \text{ TeV} \Rightarrow h\nu = h\nu'^{th}/(2\gamma) = 2.2053 \text{ keV}$$

$$p + h\nu \rightarrow p' + \mu^- \mu^+$$

$E_p = 50$ TeV, no proton beam emittance, $\Delta_p = 4h\nu\gamma/M_p$

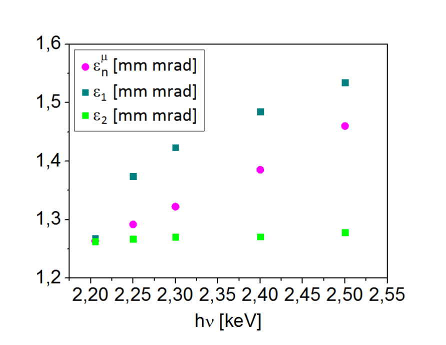
$$\epsilon^{\mu}_{n-cath} \leq \frac{1}{\sqrt{3}} \frac{\sigma_0}{\sqrt{2}} \sqrt{\frac{M_p^2}{4M_\mu^2} \left(\sqrt{1+\Delta_p} - 1\right)^2 - 1}$$



$$p + h\nu \rightarrow p' + \mu^- \mu^+$$

$E_p = 50$ TeV, with incoming proton beam emittance

$$\epsilon_2 = \epsilon^{\mu}_{n-cath} + \epsilon^{p'}_{n} < \epsilon^{\mu}_{n} < \epsilon_1 = \sqrt{(\epsilon^{\mu}_{n-cath})^2 + (\epsilon^{p'}_{n})^2}$$



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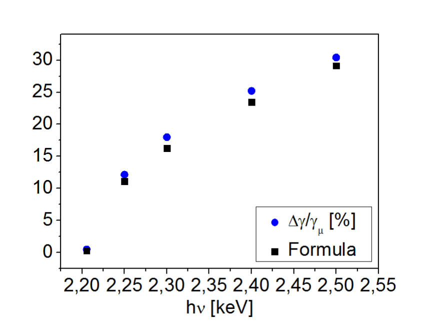
$$\frac{\Delta\gamma}{\gamma}_\mu = \frac{1}{\sqrt{3}}\sqrt{\frac{M_p^2}{4M_\mu^2}\left(\sqrt{1+\Delta_p}-1\right)^2 - 1}$$

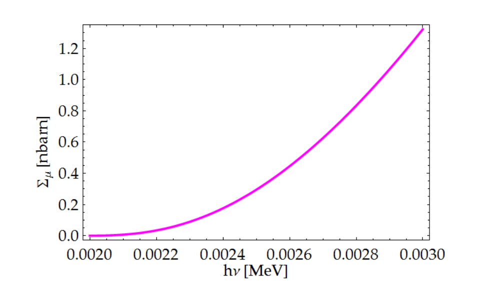


$p + h\nu \to p' + \mu^- \mu^+$

Total cross section close to muon pair threshold: Racah formula

$$\sigma \simeq \alpha Z^2 r_0^2 \frac{2\pi}{3} \left(\frac{k-2}{k}\right)^3 \left(1 + \frac{\epsilon}{2}\right)$$

where $k = h\nu'/M_\mu$, $\epsilon = (k-2)/(k+2)$,
$r_0 = r_e(M_e/M_\mu) = 2.82 \cdot 10^{-15}(0.511/105.65)$ m, $\alpha = 1/137$ and $Z = 1$.



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IDEA: CLOSE TO THRESHOLD TO MINIMIZE ENERGY SPREAD
BUT VERY HARD TO FIND THE CORRECT
DIFFERENTIAL CROSS SECTIONS AT SUCH LOW ENERGIES
UP TO NOW: FLAT DIFFERENTIAL CROSS SECTION

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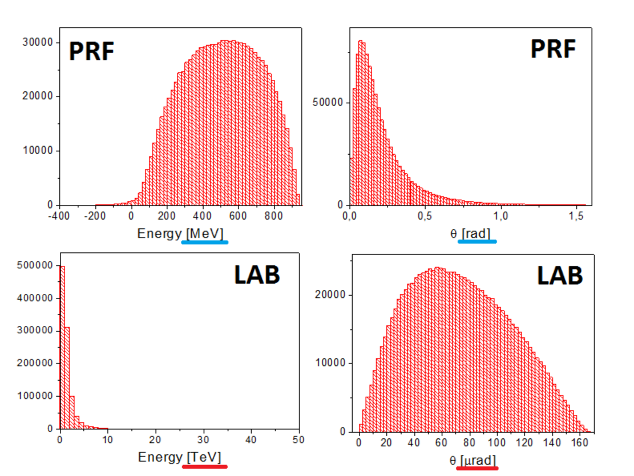
NEXT IDEA: MOVE FROM THRESHOLD SINCE TOTAL
CROSS SECTION HIGHER AND THANKS TO
A NEW CODE BASED ON GEANT4 APPROACH
(CALCULATIONS IN PRF + LORENTZ TRANS TO LAB)
TAKE ADVANTAGE OF THE MUONS' ENERGY DISTRIBUTION

$$p + h\nu \rightarrow p' + \mu^- \mu^+$$

Ex: $E_p = 50$ TeV, $h\nu = 10$ keV $(h\nu' = 1.066$ GeV$)$



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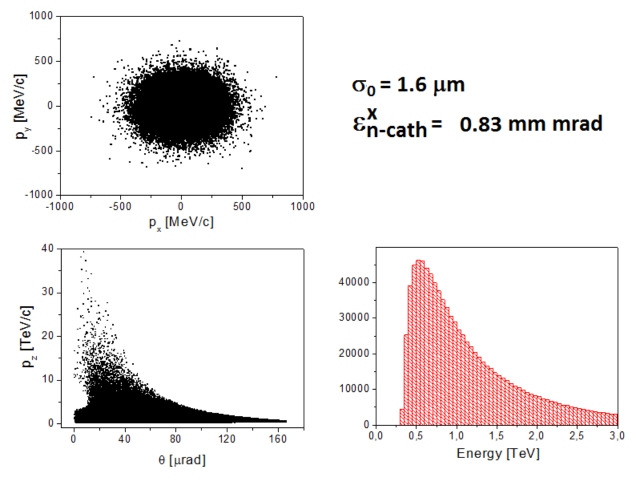

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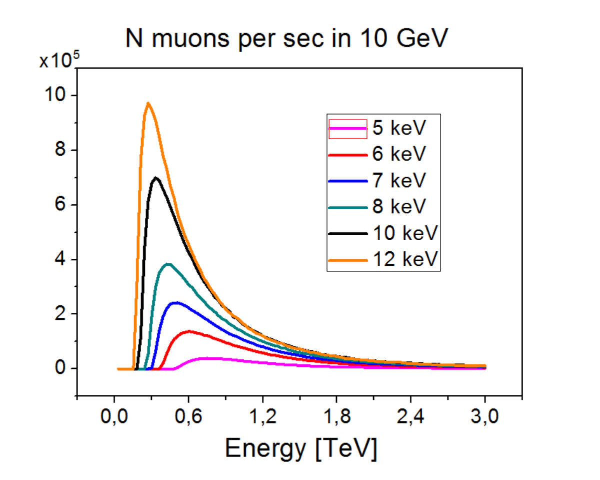
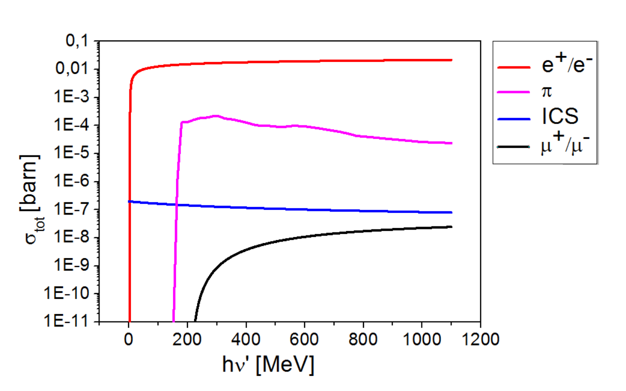
Ex: $E_p = 50$ TeV and various photon energies



$$\mathcal{N} = \mathcal{L} \cdot \sigma_{tot}$$

Total cross section of the relevant reactions



LUMINOSITY AND FLUX

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

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E_p [TeV]	$h\nu$ [keV]	$\mathcal{N}_\pi$ [s^{-1}]	$\mathcal{N}_{\mu^-/\mu^+}$ [s^{-1}]	$\mathcal{N}_{e^-/e^+}$ [s^{-1}]
50	1.43 (π^{th})	$1.86 \cdot 10^{10}$	0	$4.5 \cdot 10^{12}$
50	2.2053 (μ^{th})	$3.72 \cdot 10^{10}$	$1.25 \cdot 10^4$	$5 \cdot 10^{12}$
50	3	$6.5 \cdot 10^{10}$	$4 \cdot 10^5$	$5.4 \cdot 10^{12}$
50	5	$2.48 \cdot 10^{10}$	$1.2 \cdot 10^6$	$5.6 \cdot 10^{12}$
50	10	$8.6 \cdot 10^9$	$4.8 \cdot 10^6$	$6.5 \cdot 10^{12}$
50	12	$6.8 \cdot 10^9$	$5.6 \cdot 10^6$	$6.8 \cdot 10^{12}$

CONCLUSION

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high energy, high collimation, low emittance

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· Important to evaluate the impact on the proton beam of electron/positron pair production and ICS: need to implement a simulation taking into account all the reactions at the same time.

Thank you for your attention!

- L. Serafini, C. Curatolo and V. Petrillo, *Low emittance pion beams generation from bright photons and relativistic protons*, `http://arxiv.org/pdf/1507.06626.pdf` (2015)
- C. Curatolo, *PhD Thesis: High brilliance photon pulses interacting with relativistic electron and proton beams* (2016)
- J. W. Motz, H. A. Olsen and H. W. Koch, *Pair production by photons*, Rev. Mod. Phys. 41 (1969)
- D. Drechsel and L. Tiator, *Threshold pion photoproduction on nucleons*, Nucl. Part. Phys. 18 (1992)
- C. Emma, K. Fang, J. Wu and C. Pellegrini, *High efficiency, multiterawatt x-ray free electron lasers*, Phys. Rev. AB 19 (2016)
- H. Burkhardt, S. R. Kelner and R. P. Kokoulin, *Monte Carlo generator for muon pair production*, Clic-note-511 (2002)