Gamma Factory High Intensity Muon Source - Exploratory Studies

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Outline

- Introduction
- Gamma Factory concept
- Production of muons by photons
- Gamma Factory photon beam
- Target optimization
- Gamma Factory muon source characteristics (Pions, Muons)
- Summary

Introduction

- Muon collider is the only viable project for the multi TeV lepton collisions.
- Being about 200 times more massive than electrons, muons suffer significantly less from synchrotron-radiation losses and therefore can be accelerated efficiently in a circular machine.
- But reaching high luminosities is extremely tough owing to short muon lifetime at rest (2.2 μs) and the difficulty of producing large numbers of muons in suitably shaped bunches.
- Muon beams are obtained via **K** or π decays produced in proton interaction to a target.

We propose and present our initial exploratory studies of a new scheme for the high-intensity muon source. This scheme is capable to produce more than **10^{13} of both μ^- and μ^+ per second**. In the proposed scheme, the combined muon source is driven by the photon beam.

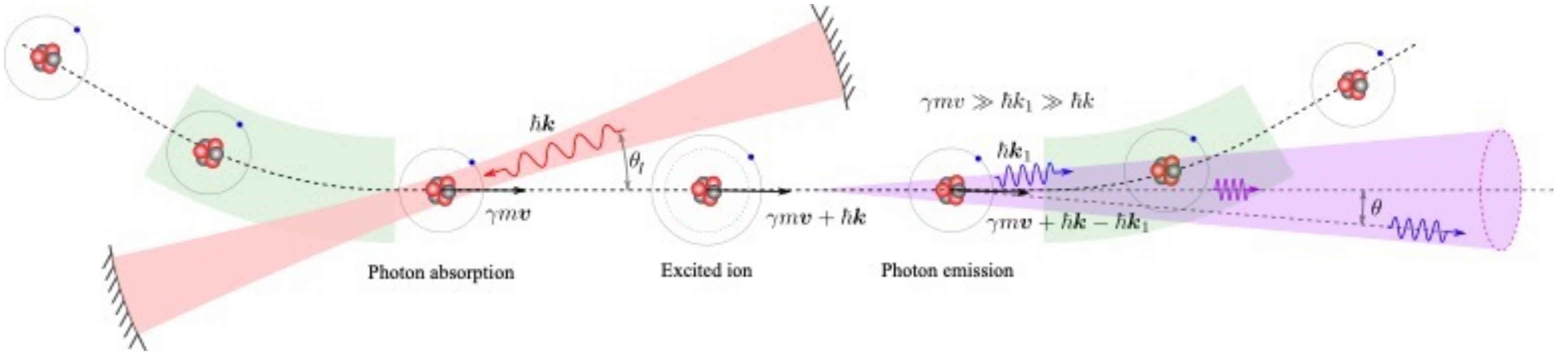
Photon beam-driven muon sources have never been studied before because no technology has been proposed to create photon beams of sufficiently high energy and power to be competitive with the proton-beam-driven sources.

Gamma Factory Project

- The Gamma Factory (GF) project is explored within the CERN Physics Beyond Collider program.
- The proposed light source could be realized at CERN by using the infrastructure of the existing accelerator facilities.
- The underlying idea of the Gamma Factory is to generate the photon beams by resonant backscattering of laser photons off atomic beams of partially stripped ions (PSI) circulating in the LHC storage rings.

It could push the intensity limits of the presently operating light-sources by at least 7 orders of magnitude, reaching the flux of the order of 10^{17} photons/s, in the particularly interesting gamma energy domain of $1 \leq E \leq 400$ MeV.

The maximal achieved photon beam energy is 400MeV for the present magnetic field limit of the LHC dipoles. It can be extended to 1.6 GeV if the HE-LHC upgrade is realized in the future.



GF project in detail:
Gamma-Factory @CERN –Status and Perspectives
Mieczyslaw Witold Krasny
Apr 05, 2023, 11:40 am

M. W. Krasny, The Gamma Factory proposal for CERN (2015), arXiv:1511.07794 [hep-ex].

Photon Conversion

1. Photons conversion into $\mu^-\mu^+$ pair in the EM field of the target nuclei.

Photon energy is close to muon pair production threshold $2m_\mu$ = 211 meV

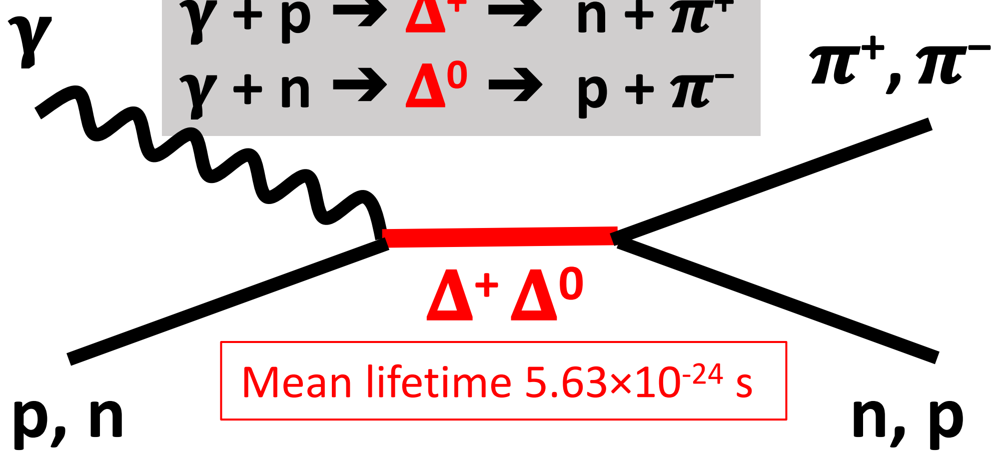
Small cross section for GF energy range ~300 MeV (contribution is below ~0.05%).

2. Photo production of pions followed by pion decay into muon. Pions are produced predominantly from the γ-proton and γ-neutron processes. Δ baryons with mass near 1232 MeV decay via weak force into a nucleon and pion.

Pion photoproduction

$\gamma + p \rightarrow \Delta^+ \rightarrow n + \pi^+$

$\gamma + n \rightarrow \Delta^0 \rightarrow p + \pi^-$

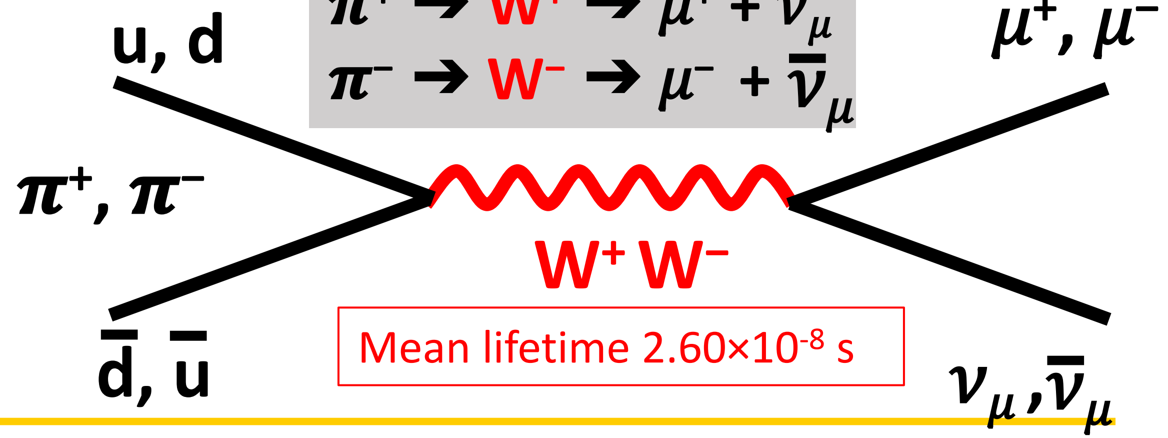


Charged Pion Decay

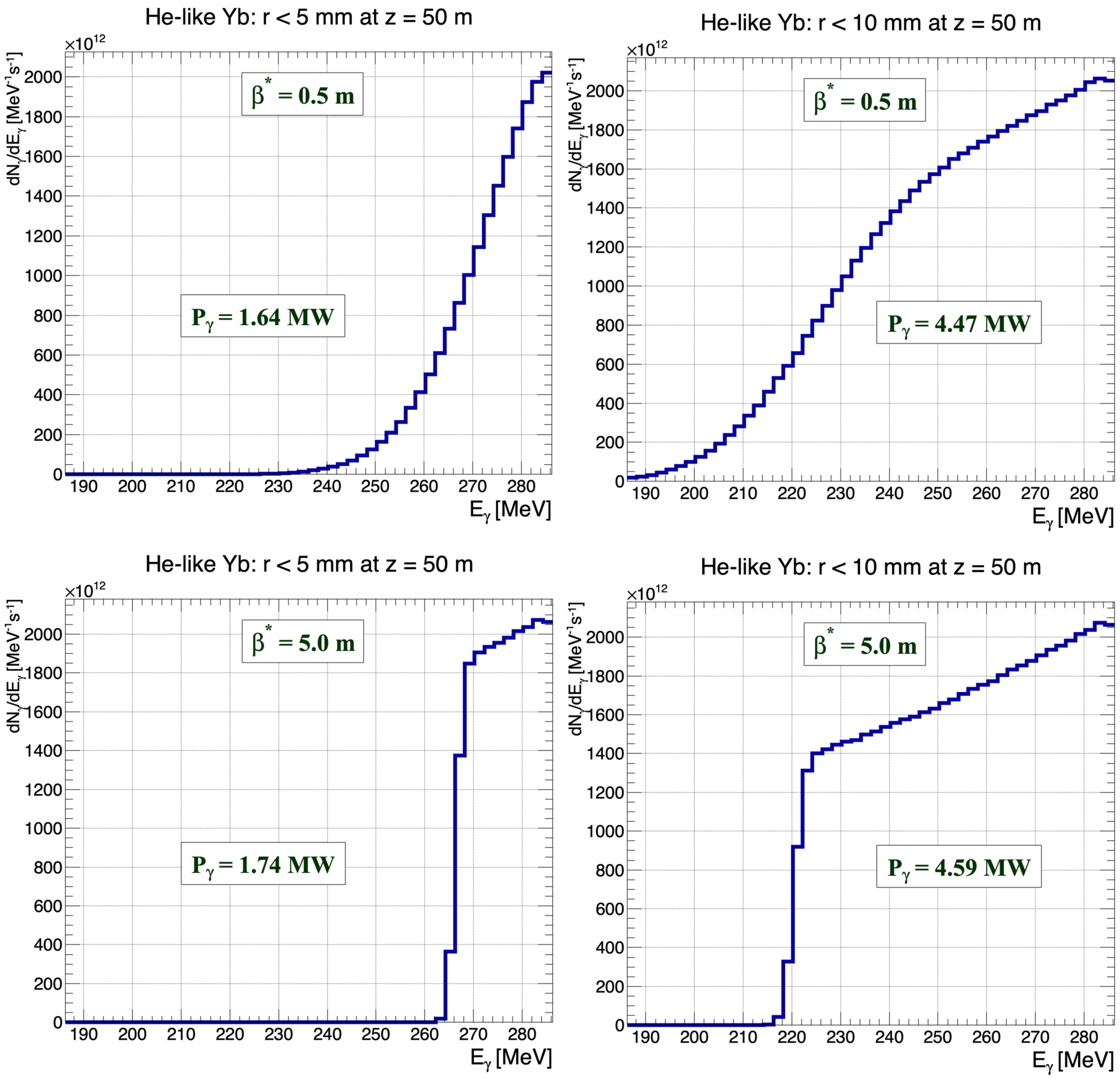
weak interaction

$\pi^+ \rightarrow W^+ \rightarrow \mu^+ + \nu_\mu$

$\pi^- \rightarrow W^- \rightarrow \mu^- + \bar{\nu}_\mu$



Gamma Factory Photon Beam



PSI beam	$^{174}_{70}\mathrm{Yb}^{68+}$
m – ion mass	161.088 GeV/c^2
E – mean energy	440 TeV
$\gamma_L = E/mc^2$ – mean Lorentz relativistic factor	2731.3
N – number ions per bunch	10^9
σ_E/E – RMS relative energy spread	2×10^{-4}
$\beta_x = \beta_y$ – β-function at IP	0.5 m
$\sigma_x = \sigma_y$ – RMS transverse size	16 μm
σ_z – RMS bunch length	15 cm
Bunch repetition rate	20 MHz
Laser	Yb:YAG
λ – photon wavelength	129.25 nm
$\hbar\omega$ – photon energy	9.5926 eV
σ_λ/λ – RMS relative band spread	2×10^{-4}
U – single pulse energy at IP	5 mJ
$\sigma_x = \sigma_y$ – RMS transverse intensity distribution at IP	20 μm
σ_z – RMS pulse length	15 cm
θ_l – collision angle	0 deg
Atomic transition of $^{174}_{70}\mathrm{Yb}^{68+}$	$1s^2\,{}^1S_0 \rightarrow 1s2p\,{}^1P_1$
$\hbar\omega'_r$ – resonance energy	52.4 keV
τ' – mean lifetime of spontaneous emission	1.01×10^{-16} s
g_1, g_2 – degeneracy factors of the ground and excited states	1, 3
$\hbar\omega_1^{max}$ – maximum emitted photon energy	286.2 MeV

GF-CAIN (Wiesław Płaczek) is a customized and dedicated for the GF version of the MC program **CAIN (Kaoru Yokoya)** developed at KEK-Tsukuba, Japan, for the ILC project.

Interactions of PSI bunch with the laser pulse including processes of atomic photon absorption, spontaneous and stimulated photon emissions have been simulated using the MC generator GF-CAIN for the helium-like ytterbium-ion beam with the parameters given in table.

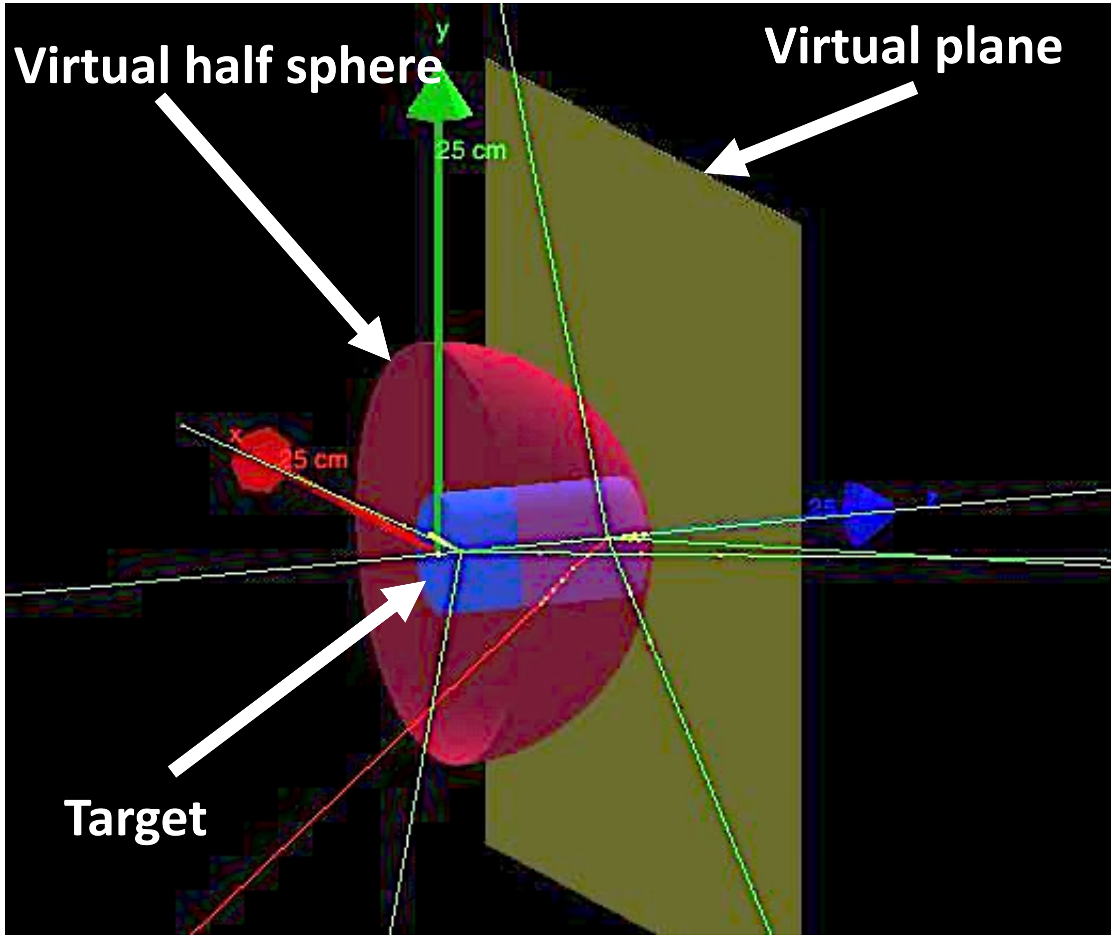
The maximal photon beam energy to be reached in this scheme is 286.2 MeV. The GF photon beam of the power up to 4 MW can be generated in this scheme with the presently operating LHC cavities and 1000 bunches of 109 ions per bunch.

GEANT4 Simulation Layout

In the first step Monte-Carlo simulations were done for the monochromatic, point-like, zero-divergence, 1MW (N_γ = $2x10^{16}$ photons/s) beam of photons with the energy of 300 MeV.

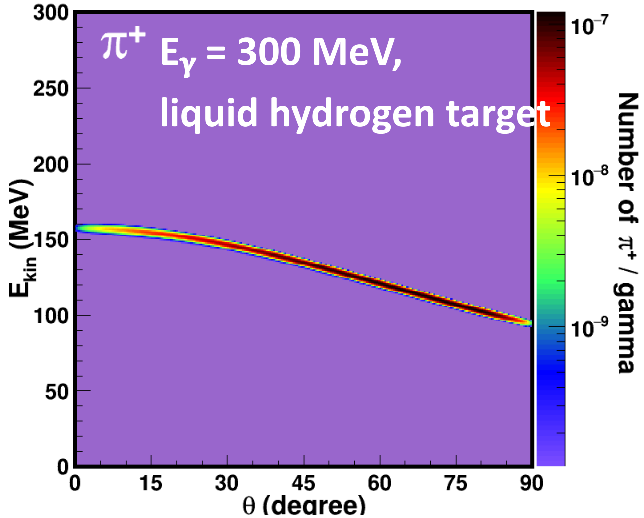
Different materials were investigated as a target candidates - graphite, beryllium, copper, tungsten etc.

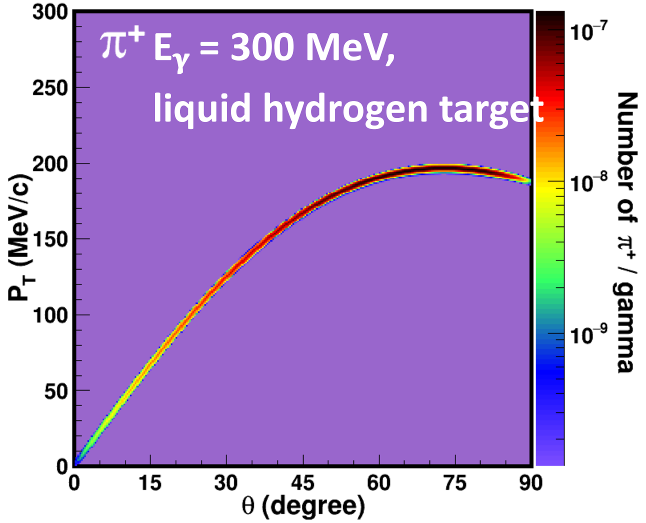
For graphite target we have nearly the same number of π^+ and π^-.



Target Optimization: Material

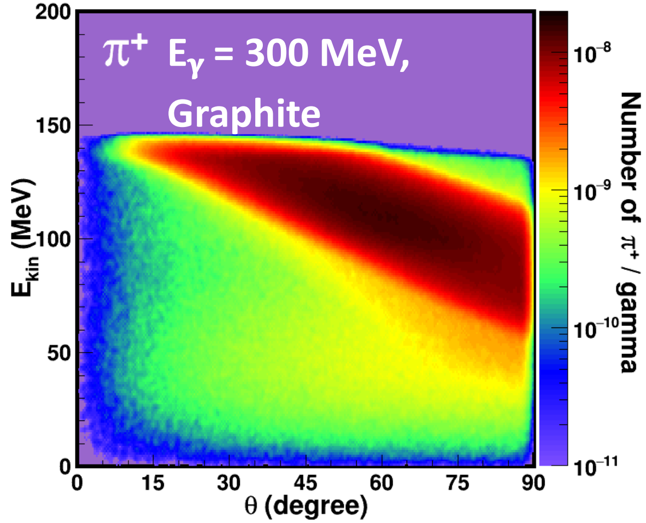
Correlations of the kinetic energy and the transverse momenta of the produced pions with their polar emission angles are shown for the 300MeV photon-beam colliding with the hydrogen and graphite targets.

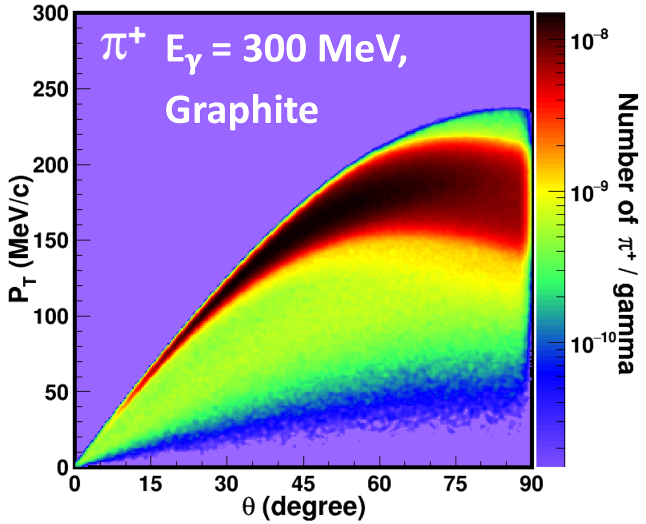


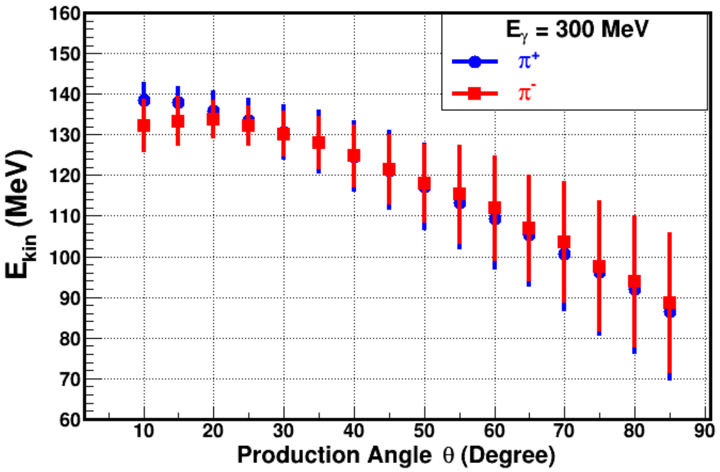


- ***Pion energy and transverse momentum no longer random***
- ***Fully specified by: pion emission angle, θ***

Symmetry of π^+ and π^- production for isoscalar target (e.g. graphite) ***(the cost: Fermi smearing - error bars)***

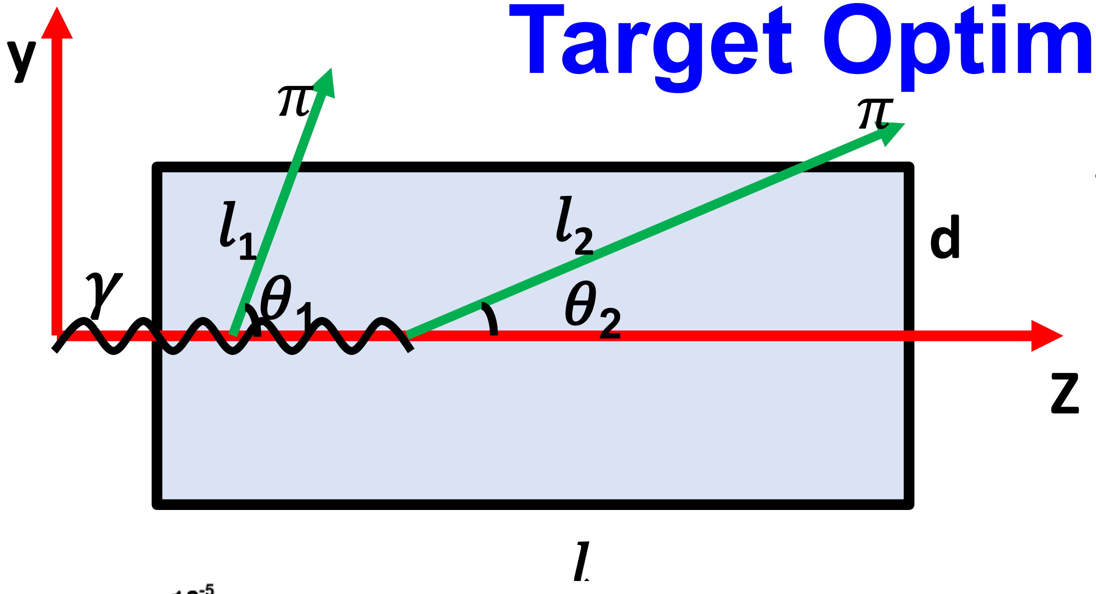






The error bars are the standard deviation σ_{FM} of kinetic energy distribution. The FM smearing of the pion kinetic energy varies 10MeV - 30 MeV.

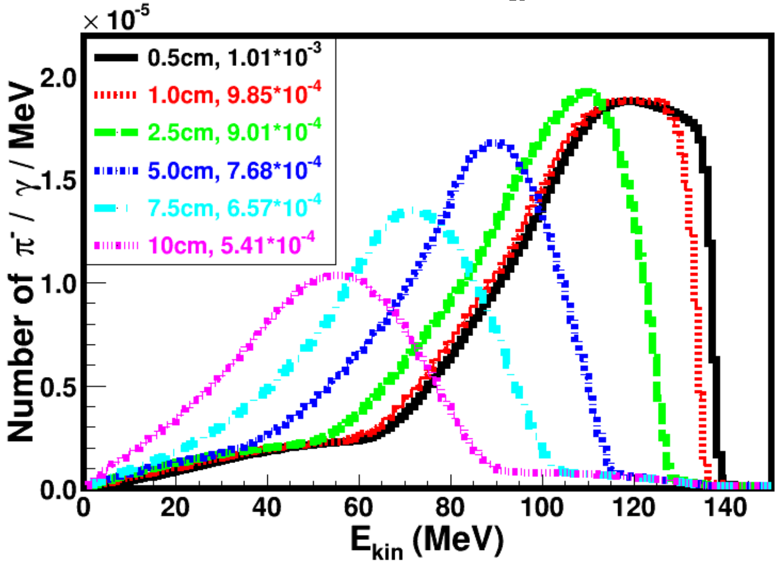
Target Optimization: Radius



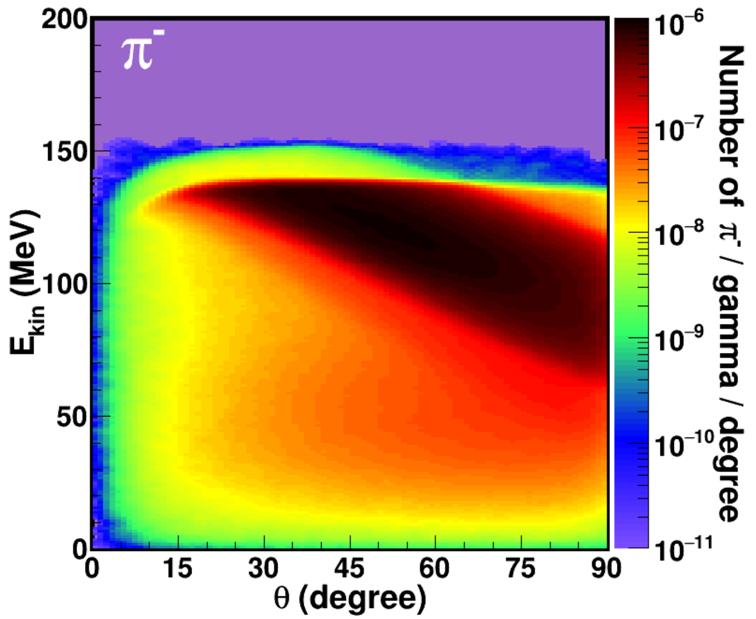
$$\frac{dE}{dx} = \ \varepsilon \sim 5 \text{ MeV / cm - Energy loss}$$

l = d / sinθ - Distance traveling in target

Correlations of the kinetic energy and the production angle for π^-. Graphite target: length of 40 cm and the radius of 0.5 cm.



Radius (cm)	E_{kin}^{mean} MeV	$\sigma_{E_{kin}}$ MeV
0.5	116.43	23.92
1.0	114.55	23.70
2.5	**102.50**	**16.13**
5.0	85.67	16.65
7.5	69.52	18.60
10	52.38	20.86

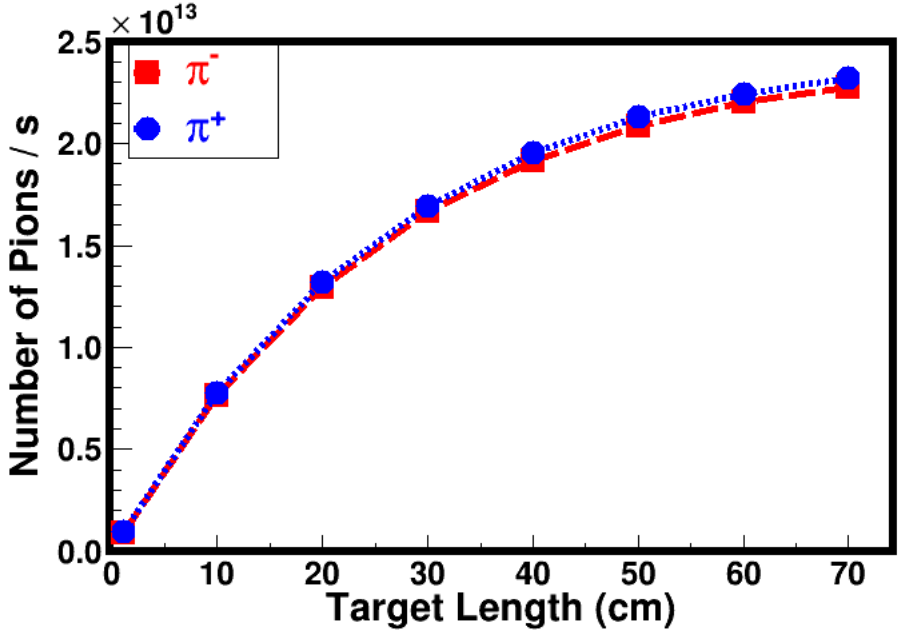


Further "monochromatisation" of the pion kinetic energy by a suitable choice of the target radius

Target Optimization: Length

The number of pions with the production angle $\theta_{prod} < 90^o$ in the laboratory frame as a function of the graphite target length with the target radius of 2.5 cm.

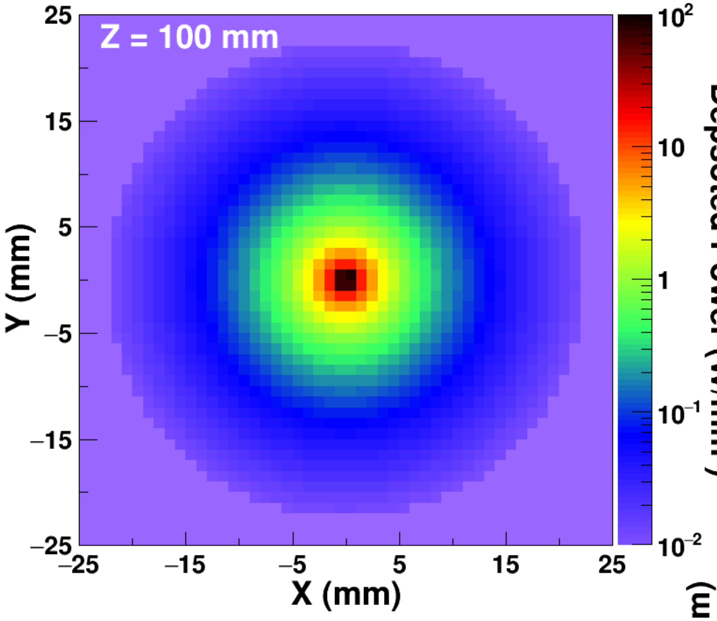
Length (cm)	N_{π^+} x10^{11}	N_{π^-} x10^{11}
1.0	9.28	9.14
10.0	77.64	76.32
20.0	131.78	129.49
30.0	169.42	166.43
40.0	195.32	191.87
50.0	212.91	208.98
60.0	224.42	227.76

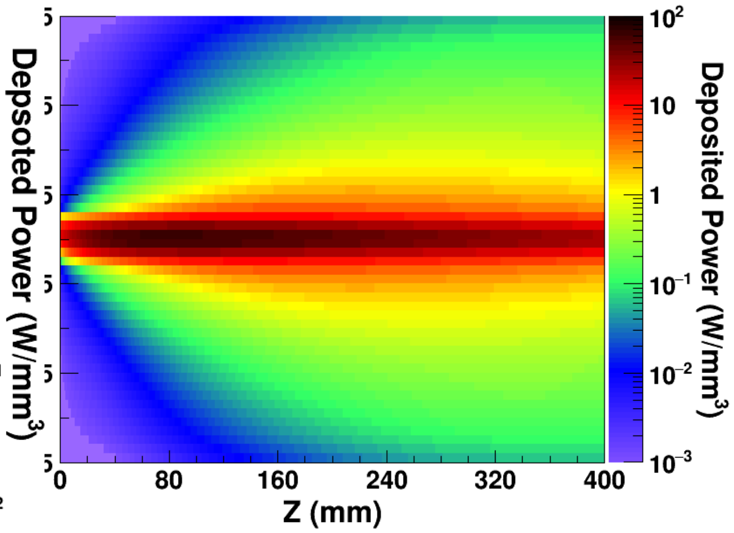


Dominant process is conversion of photons into e^+e^- pairs in EM field of target atoms. For the target length above 1X0 (19.3 cm for the graphite), the increase of the pion production rate slows down. The EM cascade contributes to the target heating but hardly increases the number of the produced pions.

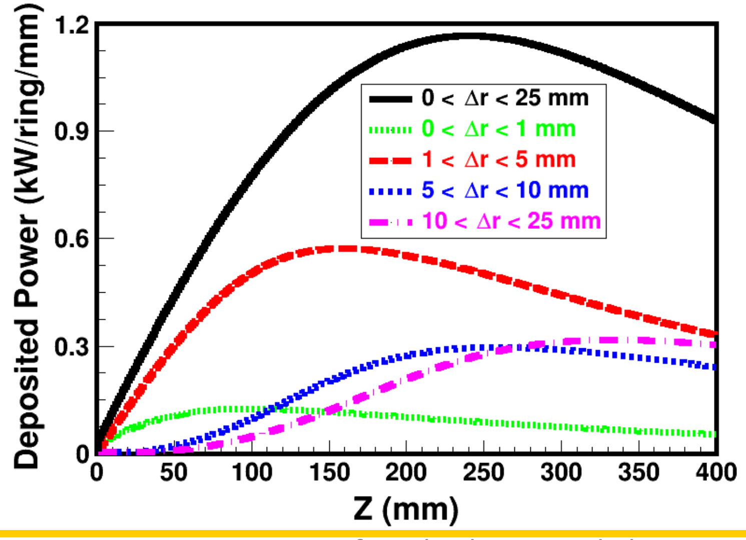
Target Optimization: Heat Load

Longitudinal and transverse profiles of the deposited power





Length (cm)	E_{dep} (kW)	$\sigma_{x/y}$ (mm)
10.0	42.7	2.1
20.0	142.0	3.0
40.0	360.4	4.1



Target: graphite, radius 2.5 cm, length 40 cm, high melting temperature and carbon nuclei are isoscalar.

Photon beam: point like, E_γ = 300 MeV, power 1MW

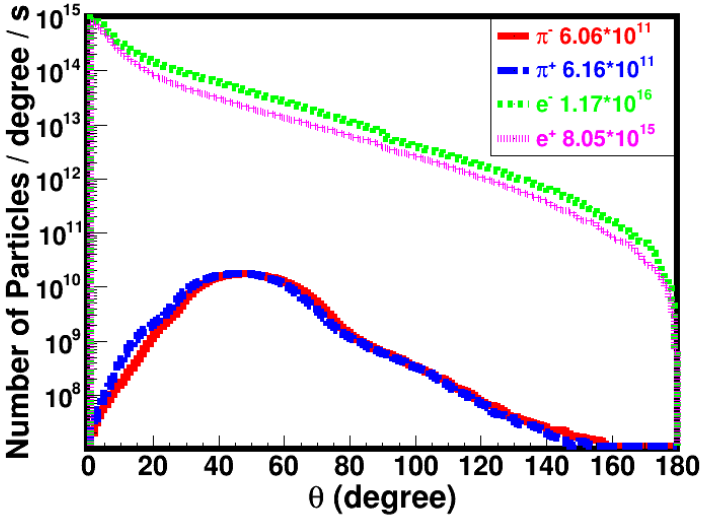
The target volume average power dissipation in the 20 cm long targets with the radius of 2.5 cm is 361.6 W/cm^3.

The forced water cooling of solid targets, the maximum surface heat flux that can be removed is ~200W/cm^3.

Possible solution: increase target radius and rotating target.

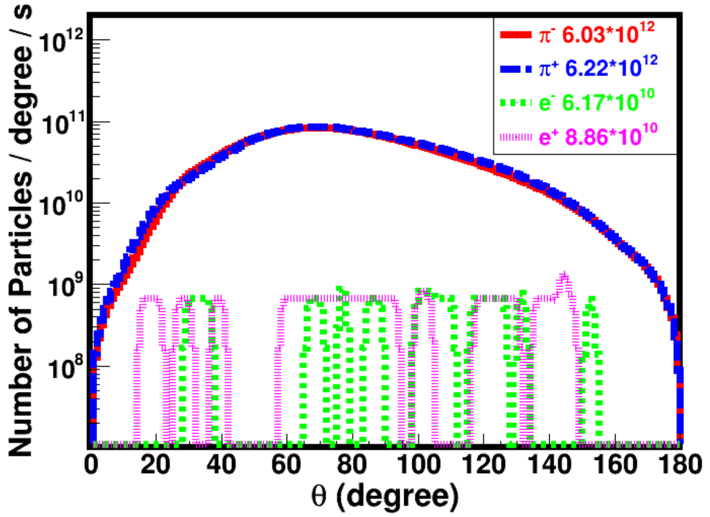
Estimated temperature rise in the graphite target due to the impact of the GF 1MW photon beam is (if the heat is not evacuated) **ΔT ≈ 230^{o}C/s**.

Particle Selection
1. Difference in velocities of pions and electrons



Distributions for particles reaching the propagation distance of 10m within the time slot of 20 - 40 ns following the time of the impact of the photon beam on the target.

Clear separation of the pions and the electrons/positrons for the photon beam.

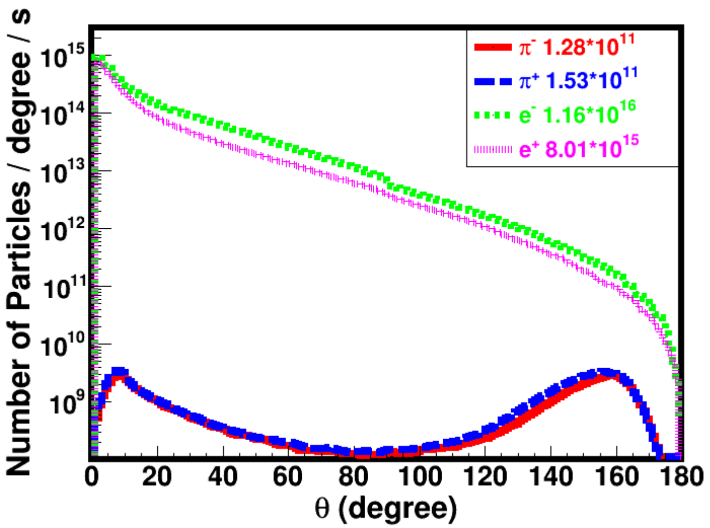


Distributions for particles reaching the propagation distance of 40 - 60 ns time interval.

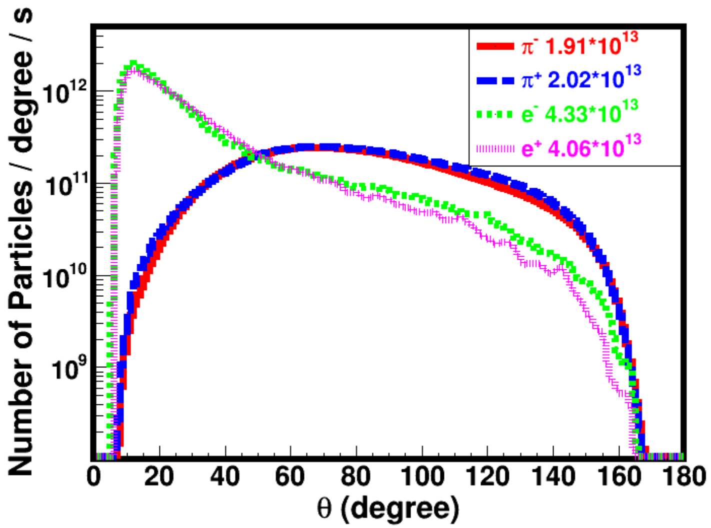
Clear separation of the pions and the electrons/positrons for the photon beam.

Particle Selection
2. Difference in their production mechanism

Distribution of particles which are produced with transverse momenta $P_T < 30$ MeV/c



Distribution of particles which are produced with transverse momenta $P_T > 30$ MeV/c



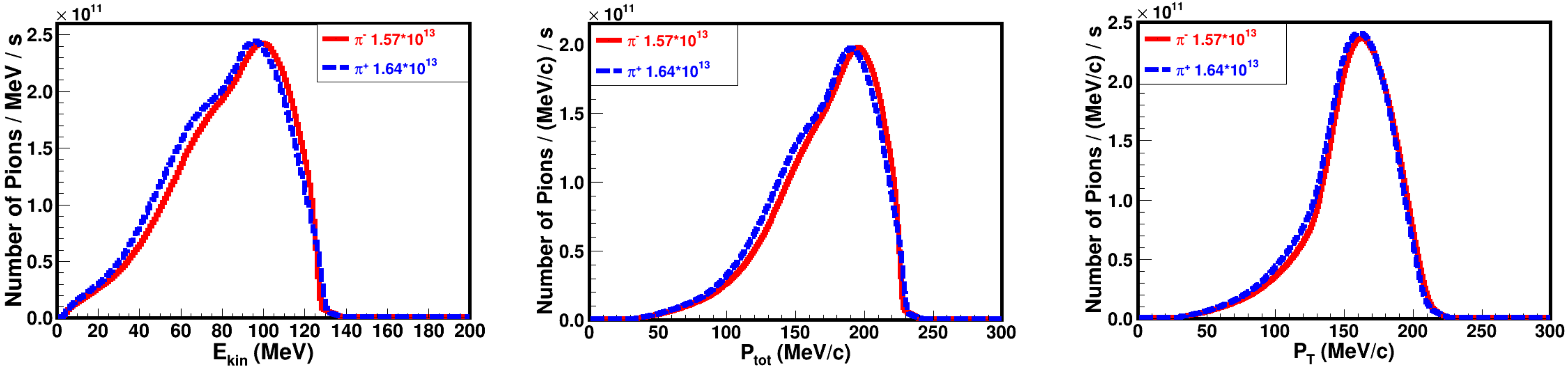
Particles having $P_T > 30$ MeV/c and collected in the angular region of $\theta \geq 40^o$ are predominantly the pions.

The transverse momentum cut separation can be achieved by introducing a solenoidal magnetic field in the target zone.

The electron and positron transverse momenta are determined by the atomic form-factors. They are thus produced at small transverse momenta.

On the contrary, the pion transverse momenta are determined by the nuclear/nucleon form-factors. Thus, pions are produced at significantly higher transverse momenta.

Pions Spectral Density

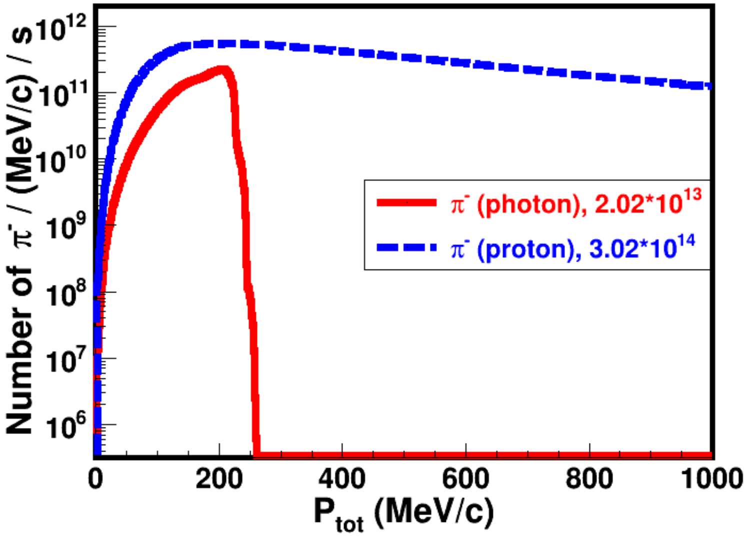


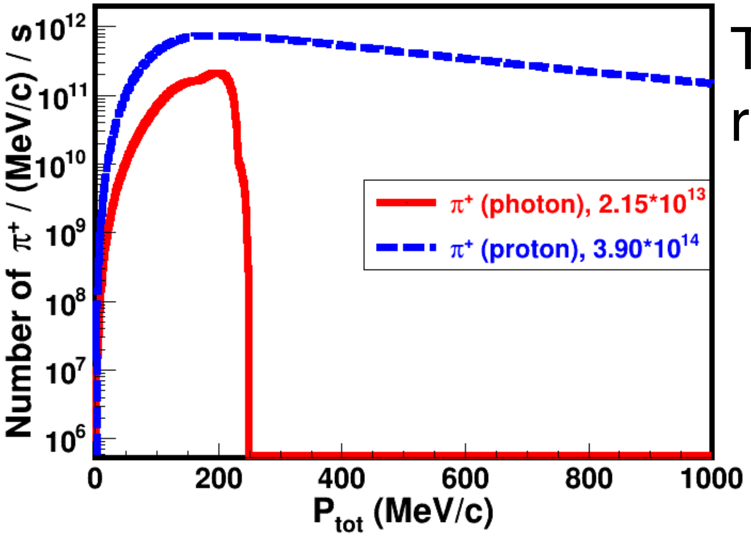
Pions are selected by imposing: (1) the transverse-momentum cut $P_T \geq 30$ MeV/c and (2) the angular cut $40^o \leq \theta \leq 120^o$. For the 1MW and 300MeV monochromatic photon beam, the number of the produced π^+ and π^- is 1.64×10^{13} s^{-1} and 1.57×10^{13} s^{-1}.

The asymmetry in pion number reflects the charge-dependent final state interactions of pions propagating through the nuclei.

1. For 1MW and 300MeV photon beam one can achieve the pion fluxes higher than **10^{13} s^{-1}**.
2. The pions are produced over a narrow range of the momentum and transverse momentum distributions. The widths of the total momentum and transverse-momentum distributions are : **$\sigma_{P_{tot}} = 24$ MeV/c and $\sigma_{P_T} = 22$ MeV/c**.

Comparison of the Proton and Photon Beam Driven Schemes





Target: graphite, length 20 cm, radius 2.5 cm.

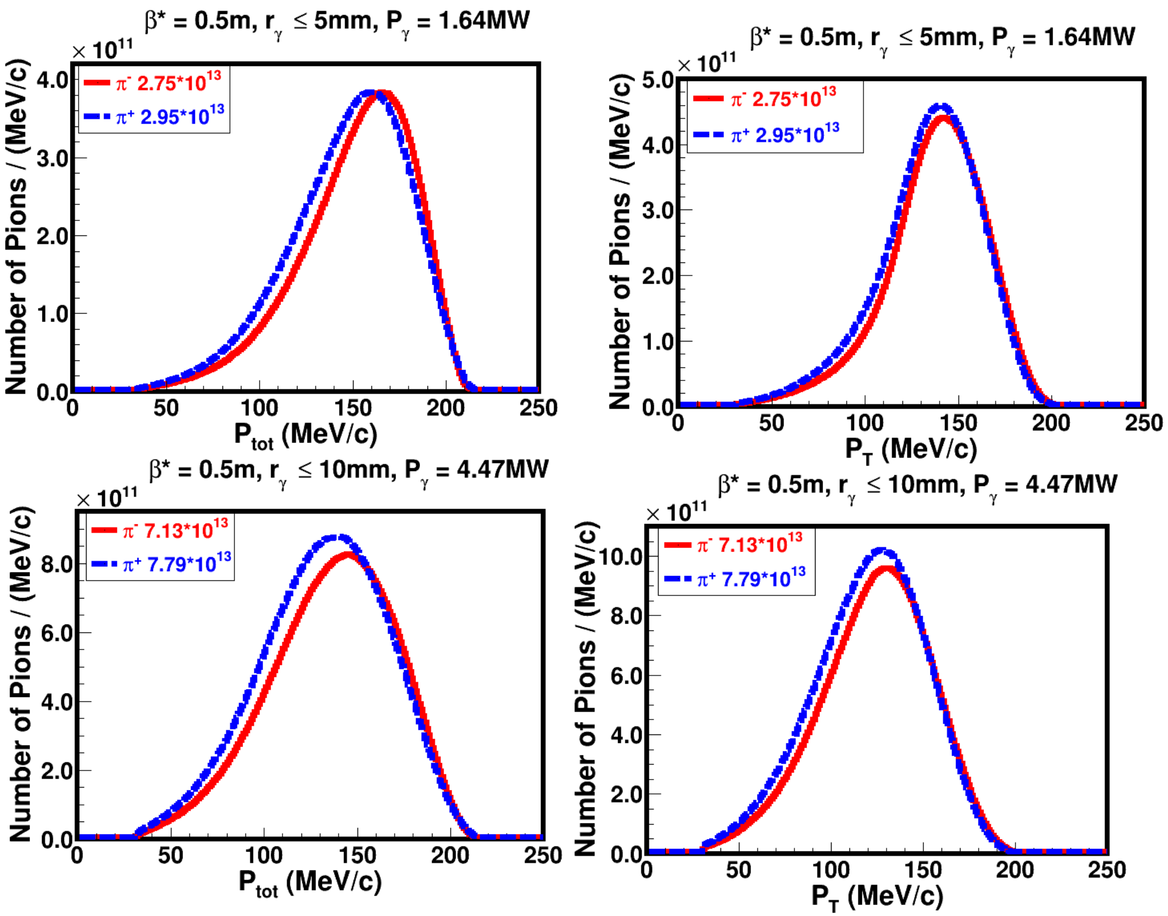
Consider the 1MW beam of photons at 300MeV and the 1MW a beam of protons at 8 GeV.

For example, if the pion collection is restricted to the momentum interval of 100 MeV/c < P_{tot} < 200 MeV/c and the transverse momentum interval of 140 MeV/c < P_T < 180 MeV/c (to reduce the spectral width and thus the initial emittance of the pion beam), then the proton beam produces only a factor of 1.8 more π^- and a factor 2.4 more π^+ than the photon beam of the equivalent power.

For the above pion selection criteria, both beams can thus be considered as almost equivalent.

Monte-Carlo Simulation Results with GF Photon Beam

Momentum distribution of π^+ and π^-



The plots are made for the photon beam collimated at the distance of 50m from its production point by the radial collimator slit of $r_\gamma \leq 5$mm and $r_\gamma \leq 10$mm.
Target: graphite, radius 2.5 cm, length 20 cm.

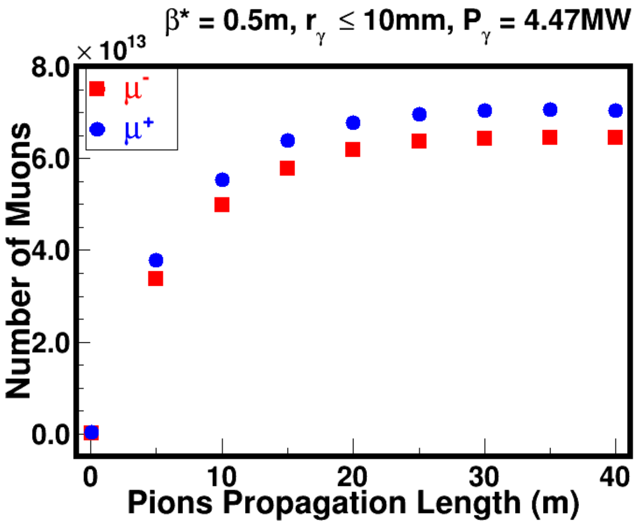
Opening the radial collimator slit to the latter value increases the number of the selected π^- from 2.75×10^{13} s^{-1} to 7.13×10^{13} s^{-1} and the number of the selected π^+ from 2.95×10^{13} s^{-1} to 7.79×10^{13} s^{-1}.
Increase of the pion yields is associated with a deterioration of the RMS of the momentum distribution from 31 MeV/c to 37 MeV/c and the RMS of the transverse momentum distribution from 25 MeV/c to 31 MeV/c. The values are by a factor of 1.5 larger than those for the monochromatic point-like beam discussed before.

Pions collection criteria

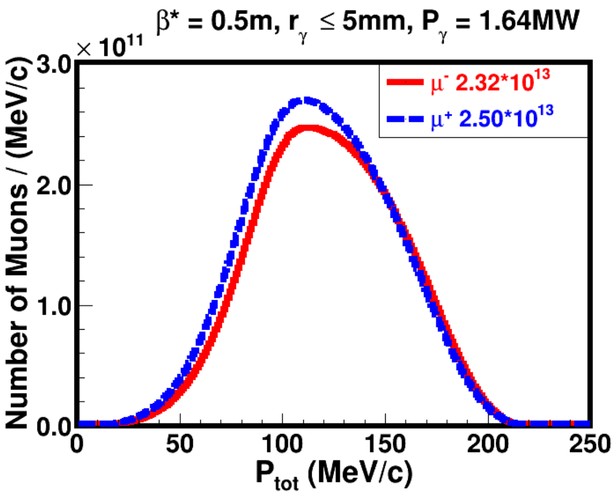
- angular range of $40^o - 120^o$.
- transverse momentum satisfies the condition: $P_T > 30$ MeV/c.

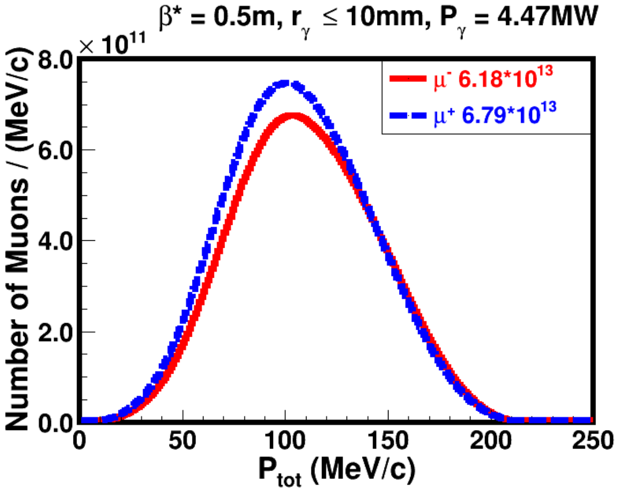
Number of produced μ^+ and μ^-

Pion production is an intermediate step of the production of the muon beam.



The GF photon beam produces pions that are non-relativistic. Most of them decay into muons and neutrinos over their propagation path of the 20 m length. Pions mean lifetime - 26 nsec.





These plots are made assuming that all the pions satisfying the pion selection criteria

- **angular range of 40º – 120º.**
- **transverse momentum satisfies the condition: P_T > 30 MeV/c.**

The numbers of the produced muons for the two beam collimation scenarios are:

Muons	$r_\gamma \leq 5$mm	$r_\gamma \leq 10$mm
μ^-	$2.32\times10^{13}\ s^{-1}$	$6.18\times10^{13}\ s^{-1}$
μ^+	$2.50\times10^{13}\ s^{-1}$	$6.79\times10^{13}\ s^{-1}$

Next Steps

The presented studies can be considered as the initial, exploratory step towards muon, positron and neutrino sources by Gamma Factory project.

- Conceptual and technical designs of the pion, muon, and positrons collection scheme would have to be developed to find out which fraction of produced and selected particles would finally be transformed into bunches of muon and positron beams. Such studies have been performed over the last 30 years for the proton-beam-driven muon sources. They need to be initiated for the photon-beam-driven sources.
- The efficient collection of pions, and subsequently muons, over the distance of ≈20m is highly non-trivial. The initial idea is to profit from the small RMS values of the longitudinal and transverse momentum distributions and design the pion collection zone with the toroidal magnetic field and the accelerating gradient electric field to collect the majority of the positive (negative) pions produced over a large angular acceptance region
- The pion beam forming stage must be quick enough to collect most of muons produced by the pion beam moving already parallel to the photon beam axis.
- Detailed studies of the target heat load with realistic photon beam with 1.64MW and 4.47MX power.
- In the toroid scheme of the pion collection step, two independent GF photon beams would have to be created to collect separately the positive and negative pions and muons.

Conclusions

- The initial exploratory studies of the photon-beam-driven muon and positron sources were done.
- The photon-beam-driven source, based on the exclusive single-pion production is expected to be charge symmetric for the beam energy tuned below the two-pion production threshold and using isoscalar tagets.
- MC simulations were done for production of muon beam using GF scenarios based on the helium-like ytterbium beams stored in the LHC.
- Dedicated MC simulations were done for each process separately to obtain optimal target parameters.
- We have optimized the beam and target parameters and compared the photon-beam-driven scheme with the canonical proton-beam-driven one.
- We have demonstrated that the GF scheme has a potential of increasing the intensity of the presently operating muon sources by up to 4 orders of magnitude, generating the fluxes larger than **10^{13}** muons per second.
- GF lepton source scheme could appear to be the most efficient, low-cost solution to provide the requisite, high-intensity and polarized lepton beams for the future accelerators.

Thank you for your attention