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SNOWMASS REPORT:

IDEAS FOR MUON PRODUCTION FROM POSITRON BEAM INTERACTION ON A PLASMA TARGET

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Abstract

Muon beams are customary obtained via K/p decays produced in proton interaction on target. In this paper we will investigate the possibility to produce low emittance muon beams from electron positron collisions at centre-of-mass energy just above the $\mu^+\mu^-$ production threshold with maximal beam energy asymmetry-i.e. a ~ 45 GeV positron beam interacting on an electron target .

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INTRODUCTION

Muon beams are customary obtained via K/π decays produced in proton interaction on target.
Their use in high energy physics experiments has continous increasing interest for rare decays experiments, precision measurement experiments, for neutrino physics, and for muon colliders feasibility studies. Several dedicated experiments are ongoing to produce high intensity muon beams with low emittance.
In this paper we will investigate the possibility to produce low emittance muon beams from electron positron collisions at centre-of-mass energy just above the $\mu^+\mu^-$ production threshold with maximal beam energy asymmetry-i.e. a ~ 45 GeV positron beam interacting on an electron target. The large boost, γ~200, of the centre-of-mass allows the final state muons to be very collimated, the muons to be produced with high energy with an average laboratory lifetime of about 500 μs, and a minor degradation of the positron beam emittance from bhabha scattering.
The value of the $e^+e^-\rightarrow\mu^+\mu^-$ cross section, about 1 μb just above threshold, requires a target with very high electron density of the order of 10^{20}electrons/cm^{-3} to obtain an reasonable muon production efficiency.
Such and high density can be obtained in a plasma excited via a syncronized electron beam.

1. PROCESSES AT √S AROUND 0.212 GEV

The dominant processes at √s around 0.212 GeV are bhabha scattering, $\mu^+\mu^-$ production, and $\gamma\gamma$ scattering. These processes have been simulated with the
BabaYaga event generator[1] with the exception of collinear radiative bhabha scattering simulated with BBBrem[2]. $\gamma\gamma$ scattering will not be discussed in detail having a cross section that is eventually smaller than that for $\mu^+\mu^-$ production.

1.1 $e^+e^-\rightarrow\mu^+\mu^-$ CHARACTERISTCS

The cross section for continuum muon pair production $e^+e^-\rightarrow\mu^+\mu^-$ just above threshold is the Born cross sec- tion enhanced by the Sommerfeld-Schwinger-Sakharov (SSS) threshold Coulomb resummation factor[3]. The value of cross section for the process $e^+e^-\rightarrow\mu^+\mu^-$ is shown in figure 1 as a function of the centre-of-mass energy. The values obtained from the from the Born level formula and that enhanced by the SSS are shown. It approach its maximum value of ~ 1μb at √s~0.230 GeV

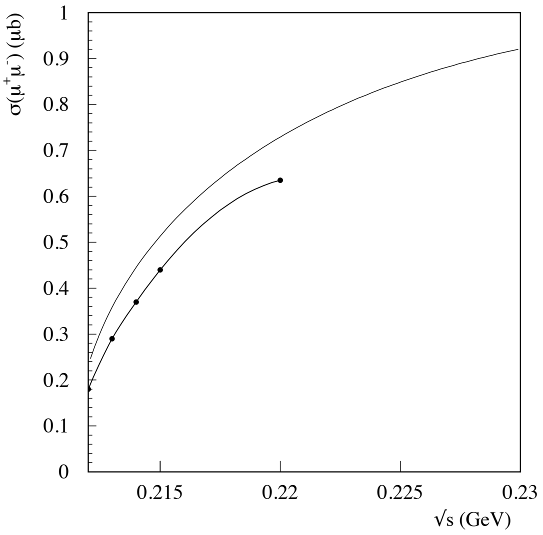


Figure 1: $e^+e^- \rightarrow \mu^+\mu^-$ production cross section around threshold.

In our scheme these values of $\sqrt{s}$ can be obtained from fixed target interacions with a positron beam energy $E_+ \sim s/(2 m_e) \sim 45$ GeV, where m_e is the electron mass with a boost $\gamma \sim E_+/\sqrt{s} \sim \sqrt{s}/(2m_e) \sim 220$.

The scattering angle θ_μ of the outcoming muons has a maximum value for muons emmitted in the rest frame orthogonally to positron beam, its value the depends on the $\sqrt{s}$. In the approximation $\beta_\mu=1$, where β_μ is the muon velocity, one can easily obtain for the maximum scattering angle $\theta_\mu^{max}=4\ m_e\ (s/4-m_\mu)^{1/2}/s$. It's value increases with the $\sqrt{s}$ with approximately the same shape as the $\mu^+\mu^-$ production cross section.

The difference between the maximum and the minimum muon energy ΔE_μ, also depends on $\sqrt{s}$, with the $\beta_\mu=1$ approximation $\Delta E_\mu = \sqrt{s}\ /(2\ m_e)\ (s/4-m_\mu^2)^{1/2}$. These values have to be folded with the muon angular distribution in the rest frame $(1+\cos^2\theta_\mu^*)$.

The value of $\sqrt{s}$ has to be optimized to maximize the $\mu^+\mu^-$ production and to minimize the beam angular divergence and energy spread.

The θ_μ distribution obtained with the BabaYaga generator is shown in figure 2 for different $\sqrt{s}$ values. Muons produced with very small momentum in the rest frame are well contained in a cone of $\sim 5\text{x}10^{-4}$ rad for $\sqrt{s}=0.212$ GeV, the cone size increases to $\sim 1.2\text{x}10^{-4}$ rad at $\sqrt{s}=0.220$ GeV. Similarly, the energy distribution of the muons, shown figure 3, has a rms that increases with $\sqrt{s}$, from about 1 GeV at $\sqrt{s}=0.212$ GeV to ~ 3 GeV at $\sqrt{s}=0.220$ GeV.

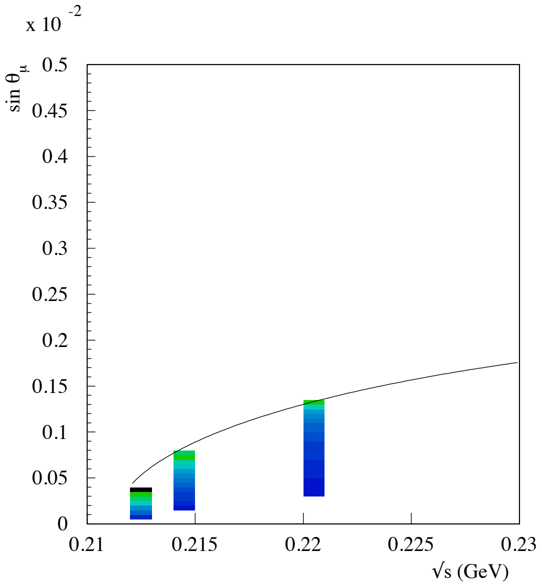


Figure 2: muon scattering angle distribution as a function of √s

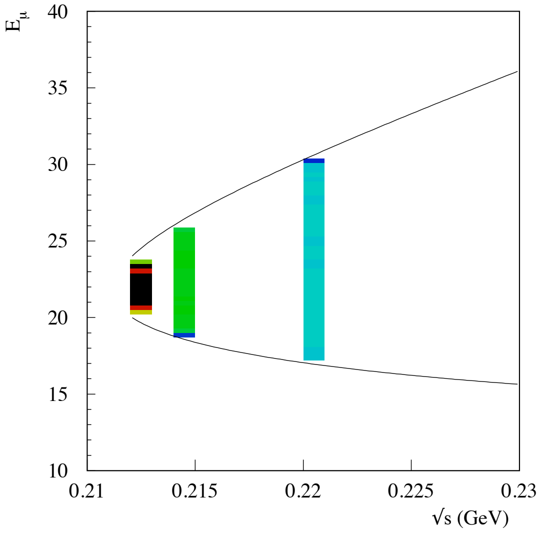


Figure 3: muon energy distribution as a function of √s

It is also possible to produce muonium below the $\mu^+\mu^-$threshold that can be eventually dissociated in the interaction with the plasma. It has been studied in Ref.[3]. The e^+e^- width is proportional to 1/n where n indicates the monium energy level[3]. The cross section of the S^1 state is the narrow width approximation is about 10^{-9} mb E_+/σ_{E+}, where σ_{E+} is the positron beam energy spread. This values makes not realistic the use of this process for copiuous muon production.

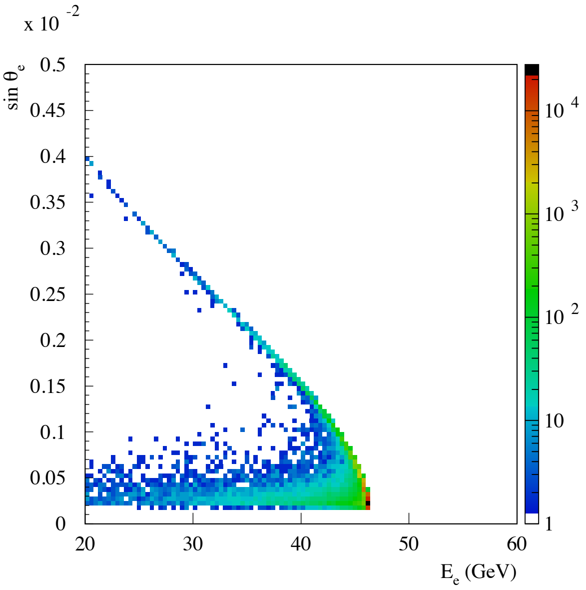
1.2 $e^+e^- \rightarrow e^+e^-\gamma$ CHARACTERISTCS

The bhabha scattering represents the larges source of beam loss in this study setting an upper limit on the "conversion efficiency".

The large angle $e^+e^- \rightarrow e^+e^- \gamma$ process has been simulated in the rest frame using BabaYaga with radiative photon energy, $E\gamma^* < 10$ MeV, and a scattering angle $\theta\gamma > 10°$. The total cross section in the region of $\sqrt{s} = 0.2$ GeV is $\sigma_{bha.} \sim 0.6$ mb.

As expected, the process proceeds via t-channel and most of the generated events are produced at very small positron scattering angle θ_+. Figure [4] shows the distribution of scattering angle as a function of the scattered positron energy for a positron beam energy

$E_+ = 46$ GeV.



The distribution indicates that the beam loss due to this process can be substantially decreased with reasonable acceptances.

Collinear radiative bhabha scattering are simulated with BBBrem[2]. The total cross section is about 150 mb for a $E\gamma > 0.01\ E_+$ and it gets about 60 mb for $E\gamma > 0.1\ E_+$.

This process will actually set a limit to the positron beam effectiveness as it sets limits to the beam lifetime in high luminosity $e^+ e^-$ colliders.

2. WORKING WITH NUMBERS

The number of $\mu^+\mu^-$ pairs produced per interaction is:
$n(\mu^+\mu^-) = n^+\rho^- L\, \sigma(\mu^+\mu^-)$; where n^+ is the number of positrons in the beam), ρ^- is the electron density in the plasma, L is the length of the plasma target, and $\sigma(\mu^+\mu^-)$ is the muon pair production cross section. As described in the previous sections the dominant process at these energies is collinear radiative bhabha scattering with a cross section of about of 150 mb actually setting the value of the positron beam interaction length for a given target density value. Using as reference value for the positron beam degradation 1/e i.e. one beam lifetime, one can determine the maximum achievable value for $(\rho^- L)_{max}=1/\sigma(\text{rad. bhabha}) \approx 10^{25}\ \text{cm}^{-2}$
The ratio of the muon pair production cross section to the radiative bhabha cross section determine the maximum value of the conversion efficiency to muon pairs $\varepsilon(\mu^+\mu^-)$. where $\varepsilon(\mu^+\mu^-)$ is defined as: $n(\mu^+\mu^-)= n^+\, \varepsilon(\mu^+\mu^-)$. Easly one can obtain $n(\mu^+\mu^-)_{max} \approx n^+ 10^{-5}$.

We considered as examples an electron density in the plasma of 10^{20}, 10^{11} positrons in the beam, and a target length of 10 m. Two positron beam energy have been studied to have a $\sqrt{s}$=0.212 GeV and $\sqrt{s}$=0.214 GeV with an energy spread from 0.3%. The number of $\mu^+\mu^-$ pairs produced per interaction is 0.25×10^4 and 0.5×10^4 for 212 MeV and 214 MeV respectively.
The scatter plot distributions of the scattering angle vs the muon beam energy are shown in figure 5 and figure 6 for the $\sqrt{s}$=0.212 GeV and the $\sqrt{s}$=0.214 GeV case respectively.

Present record positron production rate is at the SLAC linac. The SLC collider at SLAC produced high intensity positron bunches at 120 Hz at 46 GeV used to make Z mesons. The positron bunches were accelerated by the s-band linac and had a charge of about 4.5×10^{10} with a length 1 mm (sigma) and a low transverse emittance from the 1.2 GeV damping ring. These positrons were replenished on every pulse using a $4.5\ \times10^{10}$ electron bunch hitting a Tungsten-Rhenium target with an s-band high gradient RF capture cavity.

If the primary goal is to produce more positrons per pulse at the SLAC SLC accelerator, then additional electrons per bunch and more bunches per RF pulse could be accelerated. If some modest loss in transverse emittances is allowed, an increase of about x1.5 electrons per bunch is possible. Furthermore, additional electron bunches (~x2) could be accelerated on each RF pulse by careful beam loading management and by using the full RF pulse length. Thus, a overall gain of x3 is likely.

The production rate of high energy muon pairs from 45 GeV positrons incident on a plasma conversion target can be estimated but should be checked with a experimental test. A low power experimental test of this muon production rate may be possible at the FACET facility at SLAC.

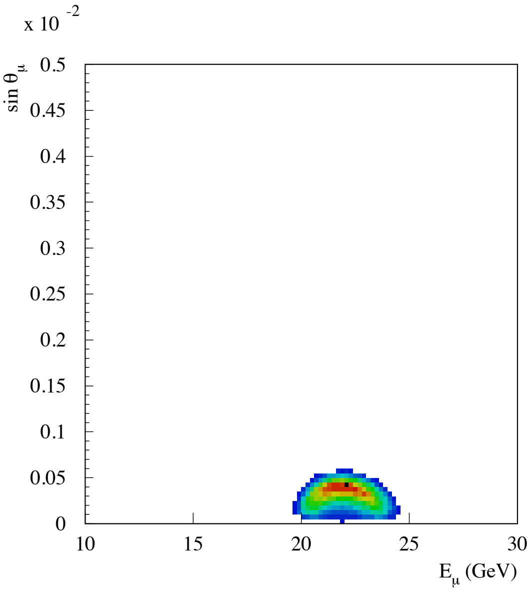


Figure 4: scattering angle vs muon energy distribution for the $\sqrt{s}$=0.212 GeV case.

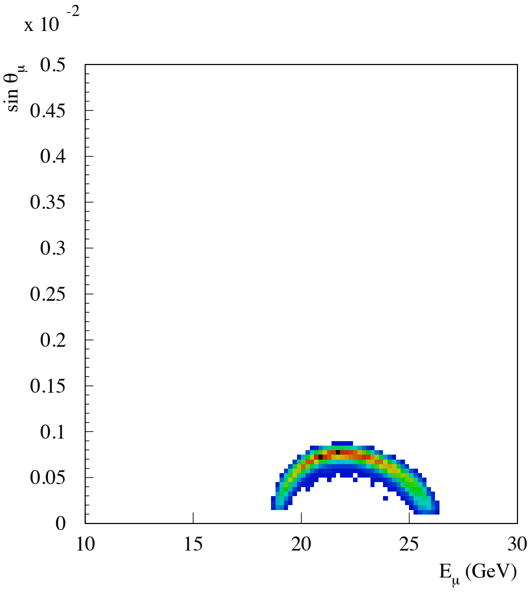


Figure 5: scattering angle vs muon energy distribution for the √s=0.214 GeV case.

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