THE "POLARIZED" MODE OF THE TEVATRON MUON BEAM

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Introduction

It is not at all difficult to make a beam of polarized muons. Muons, which are predominantly products of the parity violating weak decay of π and K particles, are naturally polarized. For the decay of a ($\beta \approx 1$) π (K) --> μ + ν, the longitudinal polarization of the μ in the lab is given [1] by

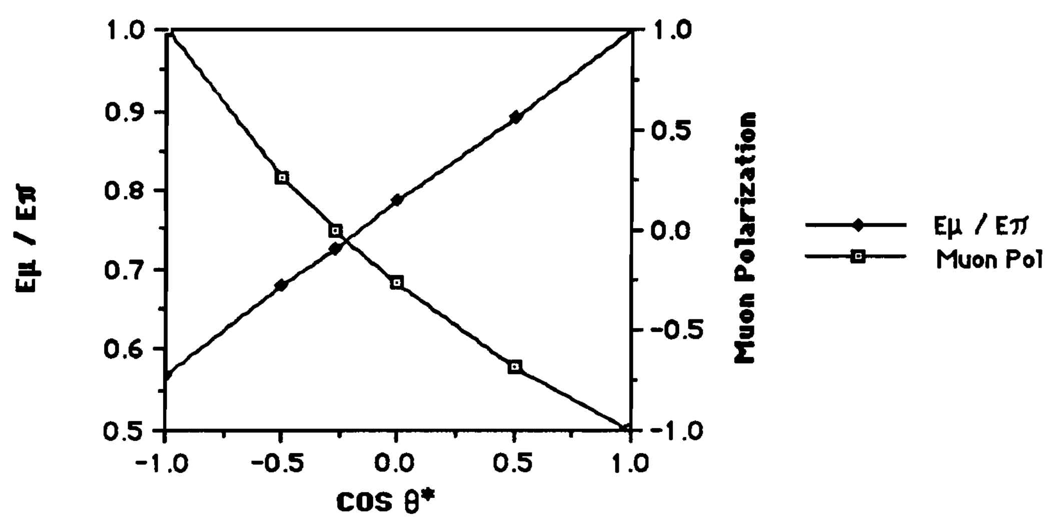
$$\lambda_{\mu} = (E^{*} \cos \theta^{*} + P^{*}) / (E^{*} + P^{*} \cos \theta^{*})$$

while the laboratory energy of the μ is given by

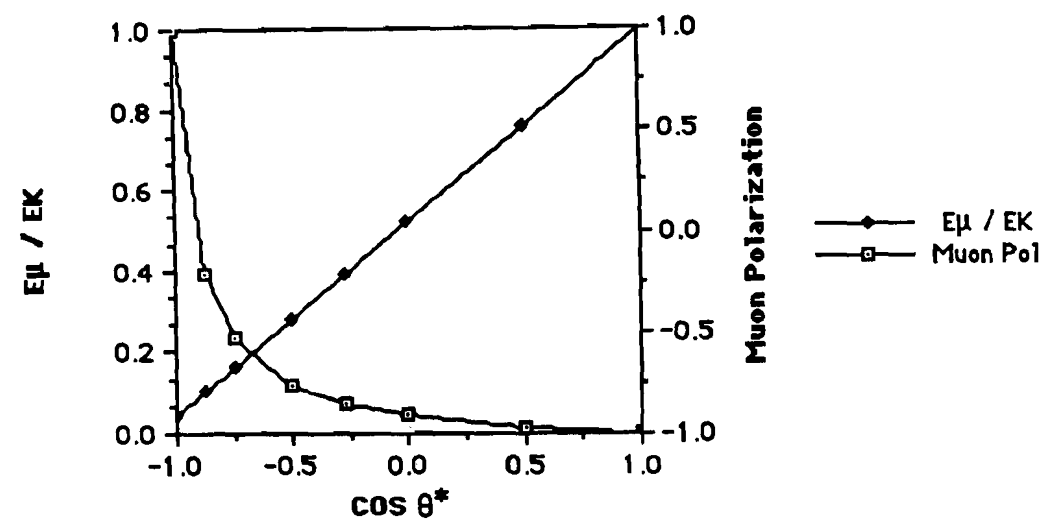
$$E_{\mu} = (E^{*} + P^{*} \cos \theta^{*}) E_{\pi(K)} / M_{\pi(K)}$$

where the * quantities refer to the μ in the cm system.

The longitudinal polarization of the muon is directly related to the laboratory energy of the muon through the cm decay angle θ^{*}. This can be shown graphically for π^{+} decay,

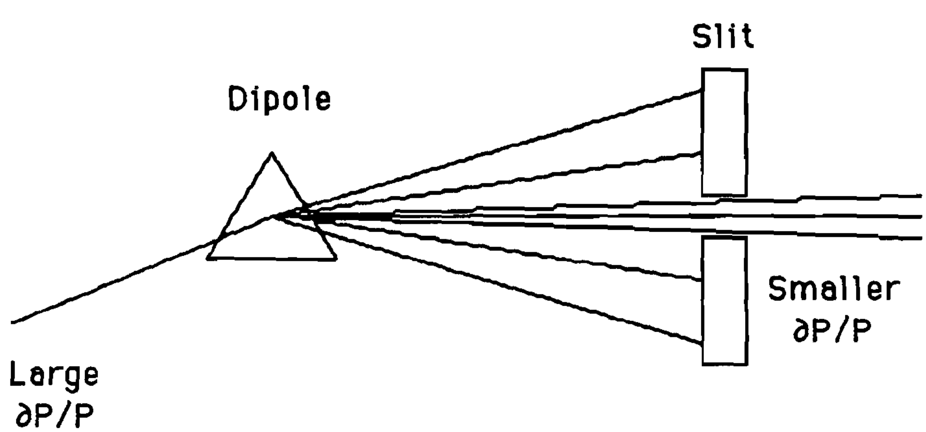


and for K^+ decay



(Note that if $E_\pi = E_K$, then for the same E_μ a μ from K decay has a different value of λ_μ than a μ from π decay.)

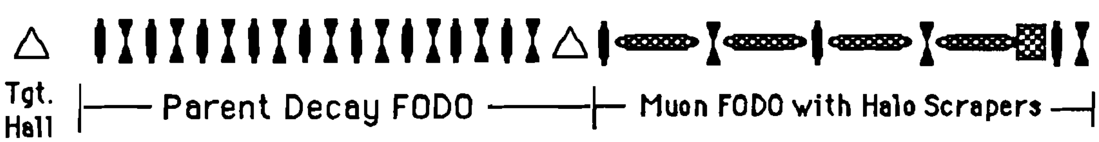
This implies that, for a monochromatic π or K beam, a measure of E_μ would yield λ_μ. The challenge of the beam design is then to produce a beam of muons which has sufficient flux to meet statistical requirements and, simultaneously, minimizes the spread on the the polarization of an *individual muon* which has been determined by measuring its energy. This can be accomplished by the introduction of a dipole field followed by a slit (channel) after a lever arm. By carefully selecting the $\int B.dl$ of the dipole, the length of the lever arm, and the width of the slit, a compromise can be reached which yields the necessary intensity while minimizing $\Delta\lambda_\mu$.



The Tevatron Muon Beam

The muon beam at the Tevatron was designed [2] to be bi-modal. There is a high-energy, high-intensity mode which takes the maximum ∂P/P of the parent particles. This mode was employed in the recently completed fixed-target run where up to 3.5 x 10^7 muons per 23 second spill with $\langle E_\mu \rangle = 500$ GeV were transported to the E665 spectrometer [3]. The second mode, the "polarized" mode, employs a geometry as outlined above to reduce the ∂P/P of the parent particles. A subgroup of the participants of E665 have proposed to use this mode of the beam in a search for right-handed currents [4].

The beam line can be divided into three sections as shown schematically below:



The primary proton beam (800 GeV protons during the recently completed run) is transported to the target hall. A Be target is followed by a bend and a quadrupole doublet which accepts a wide momentum bite around the central momentum. At this point there is an additional bend in the "polarized" mode, followed by a 4 cm wide channel located 60 m downstream to reduce the momentum bite of the parents. For both modes the selected π's and K's are transported through a series of quadrupoles in the decay FODO over a distance of 1.1 Km. At the end of the decay FODO is an absorber consisting of 11m of Be through which only the μ's are transported. Following the absorber is a bend which selects the momentum bite of the muons which then enter the muon FODO. The purpose of the .45 Km muon FODO is to rid the beam of halo (untagged muons) through the use of 50 m of iron toroid of varying radii (18 cm to 3 m). Directly upstream of the experimental hall is a tagging magnet with two upstream and two downstream tagging stations. This system determines the incoming muon momentum to within 0.5%. The central momentum of the decay FODO and the muon FODO can be chosen independently so that by varying the relative tune of the two FODO's either those muons decaying forward or backward in the parent rest frame, roughly corresponding to backward or forward polarized μ^+'s, can be chosen and transported to the experiment.

Sample Tunes of the "Polarized" Mode

Following are three examples which demonstrate the type of μ^+ beams which can be produced using the "polarized" mode of the Tevatron Muon Beam. 800 GeV protons on target are assumed for the tunes and the results can be scaled to a higher incoming proton momentum by multiplying E_μ by the ratio E_p / 800. The quoted intensity and the polarization then is correct for the scaled E_μ.

High Intensity Forward Decay Beam

In this tune, the parent FODO is set to select 400 GeV parents while the decay FODO selects 360 GeV μ's. The characteristics of the beam coming from the two types of parents are;

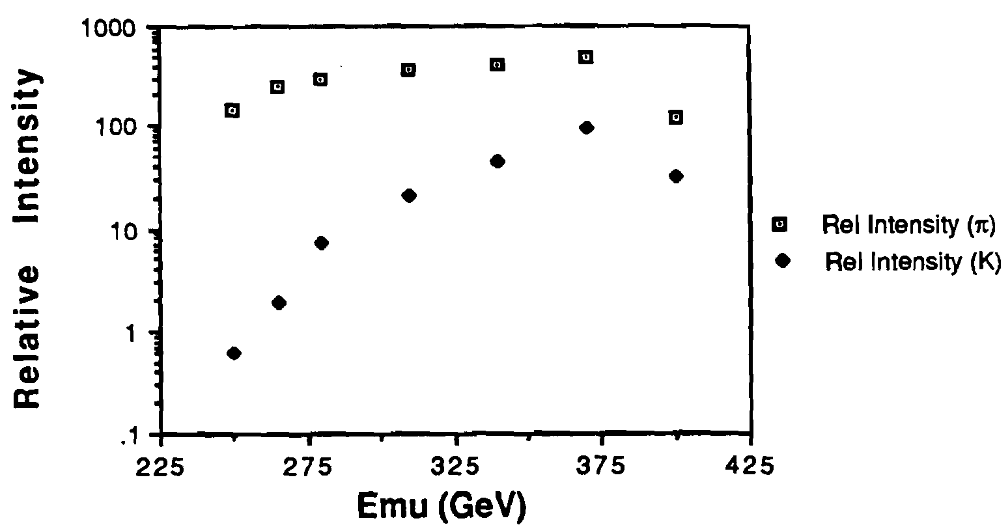
π^+ Decays

Intensity:	$3.1 \times 10^7\ \mu\ /\ 10^{12}$ protons on target
$< E_\mu >$	330 ± 45 GeV

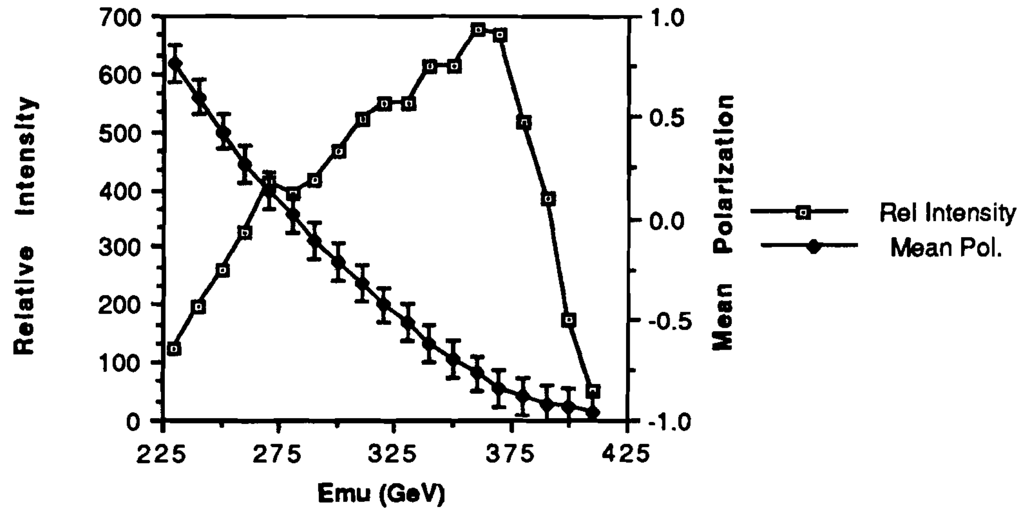
K^+ Decays

Intensity:	$0.4 \times 10^7\ \mu\ /\ 10^{12}$ protons on target
$< E_\mu >$	355 ± 45 GeV

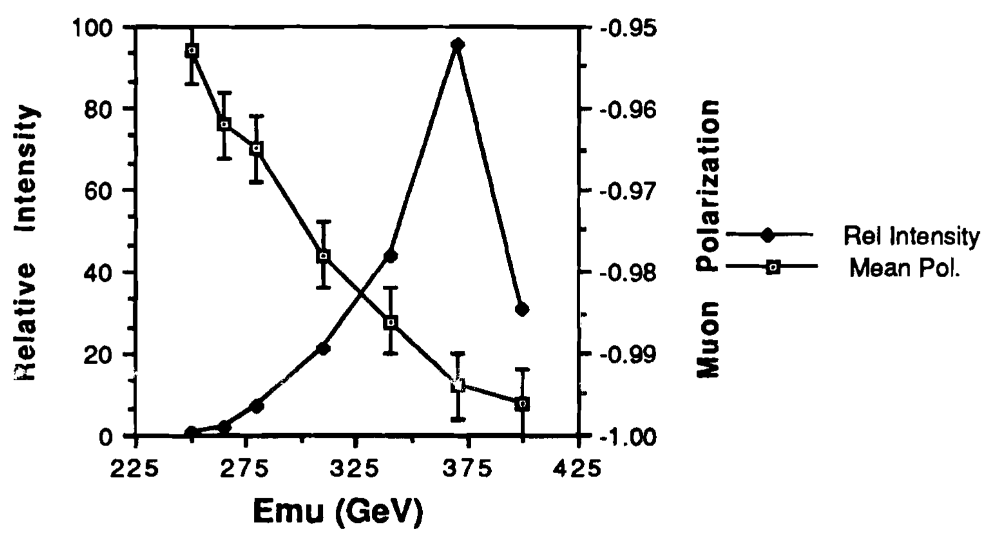
As can be seen, the μ's coming from the K decay are about 10% of the total muons in the beam. The relative yield as a function of E_μ is shown in the following figure.



The relation between E_μ and λ_μ as well as the relative intensity distribution of the muons from π^+ decay is shown below



Note that at the peak of the intensity distribution $\lambda_\mu \approx -0.80$ and the spread on the polarization corresponding to a given E_μ is $\Delta\lambda_\mu \approx 0.10$. The situation with μ's from K^+ decay is quite different, as alluded to earlier.



The peak in the relative intensity occurs at approximately the same value of E, but the corresponding value of λ_μ is -0.995. This implies that, by assuming all μ's come from π decay, approximately 10% of the time the estimated λ_μ from a measurement of E_μ will be incorrect by an amount that is negligible at the highest E_μ but which increases as E_μ decreases.

Backward Decay Beam

In this tune, the parent FODO is set to select 600 GeV parents while the decay FODO selects 360 GeV μ's. The characteristics of the beam coming from the two types of parents are;

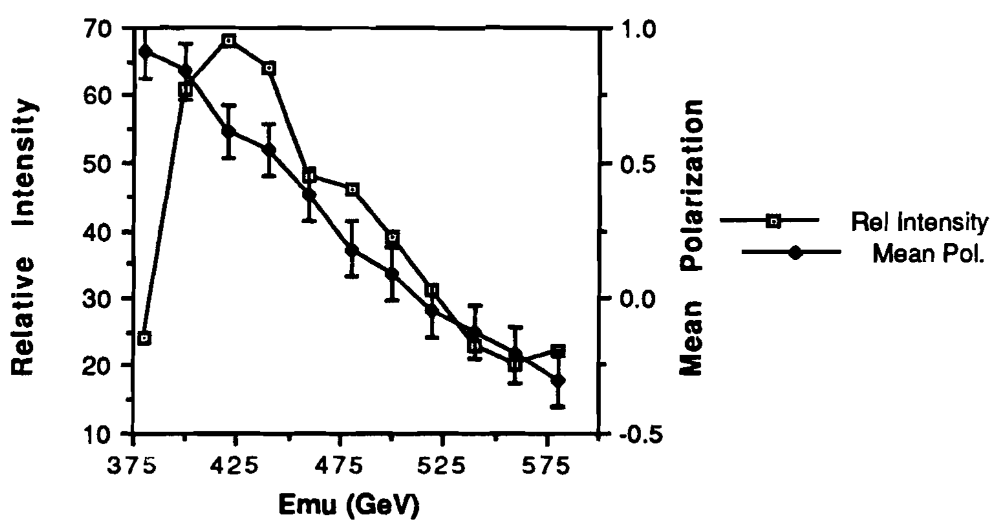
π^+ Decays

Intensity: $1.0 \times 10^6\ \mu\ /\ 10^{12}$ protons on target
$< E_\mu >$ 445 ± 65 GeV

K^+ Decays

Intensity: $0.15 \times 10^6\ \mu\ /\ 10^{12}$ protons on target
$< E_\mu >$ 450 ± 55 GeV

The integrated intensity of this beam is $\approx$ a factor 30 less than the previous high intensity forward decay beam. The relative intensity and mean polarization of μ's from π^+ decay as a function of E_μ is shown in the following figure.



Muons coming from K^+ decay still have values of λ_μ which are close to -1.0 and thus considerably different than the value of λ_μ shown above.

High Energy Forward Decay Beam

In this tune, the parent FODO is set to select 600 GeV parents while the decay FODO selects 550 GeV μ's. The characteristics of the beam coming from the two types of parents are;

π^+ Decays

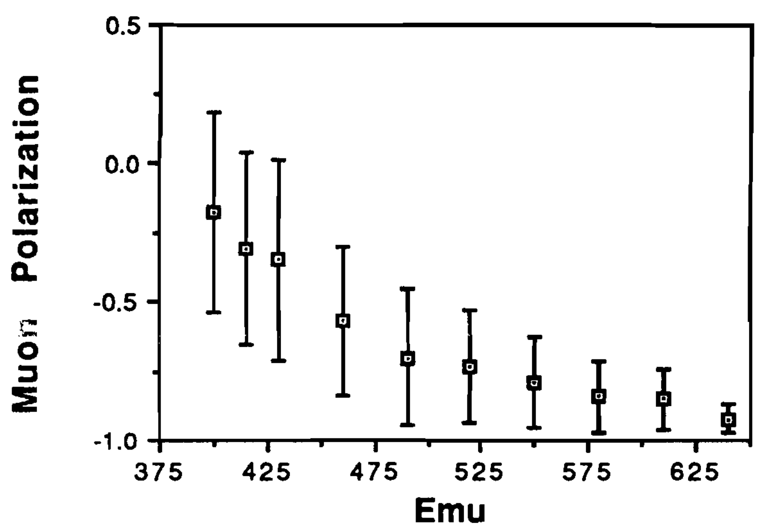
Intensity: $2.0 \times 10^6\ \mu\ /\ 10^{12}$ protons on target
$< E_\mu >$ 530 ± 70 GeV

K^+ Decays

Intensity: $0.3 \times 10^6\ \mu\ /\ 10^{12}$ protons on target
$< E_\mu >$ 555 ± 75 GeV

The shape of the relative intensity and mean polarization as a function of E_μ is similar to the High Intensity Forward Decay Tune with a shift in the E_μ scale to reflect the higher energy tune. The integrated intensity is a factor 15 lower than the High Intensity tune, but the average E_μ is a factor of 1.6 higher. The physics goals of the experiment must decide if the trade-off is worth it.

To conclude this section let me mention that even when using the standard high-intensity mode of the the Tevatron Muon Beam there is a correlation between E_μ and λ_μ. The following is the predicted E_μ vs λ_μ for the beam as used during the recent E665 data run.



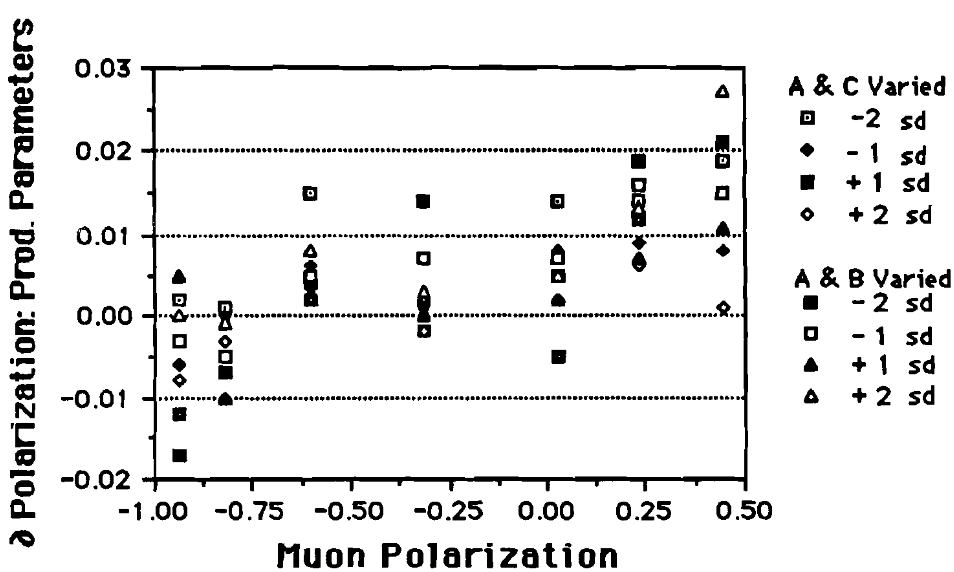
Note that the mean λ_μ ranges only from -0.2 to -0.95 with an average of -0.8 and that the average $\Delta \lambda_\mu$ is a factor of 4 times larger than that which can be achieved with the "polarized" mode of the beam. Recall that the meaning of $\Delta \lambda_\mu$ is the error on the polarization of an <u>individual</u> μ reflecting, mainly, the width of the momentum bite of the parent particles. In a given muon energy bin with a sample of N muons, the error on the mean of λ_μ is decreased by $\sqrt{N}$. This implies that one needs a factor of 16 more events from the high intensity mode to achieve the same $\Delta \lambda_\mu$ obtainable from the "polarized" mode of the beam.

Systematic Errors on the Predicted λ_μ

Aside from the error introduced by the 10% admixture of μ's from K decay, there are several other sources of systematic uncertainties in the determination of λ_μ from a measurement of E_μ. One of the most obvious is the variation of the parameters of the production formula used to generate the parent particles. The production formula used has been determined by A. Malensek [5] and has the form

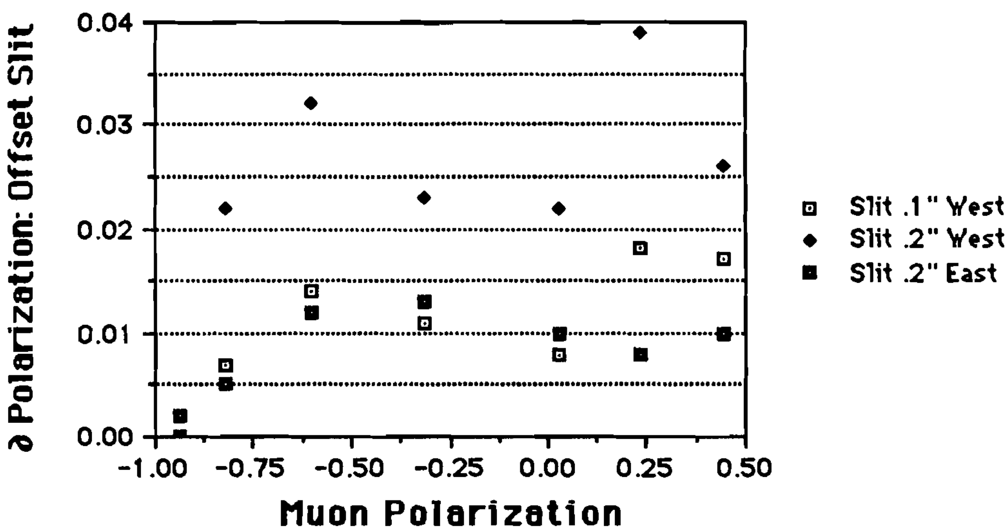
$$N(\pi^+) = B \frac{(1.0 - X_F)^A \, [1.0 + 5.0\, e^{-D X_F}]}{[1.0 + P_T^2 / C]^4}$$

The variables A, B, C, and D were determined in a fit to measured thick target production data (π & K). The four parameters were varied within the two s.d. boundaries to see the effect on the relation between E_μ and λ_μ.



As can be seen the change in λ_μ introduced by varying these parameters by 2 sd is ≈ 0.04 and is a function of λ_μ.

Another possible error which must be considered is the relative placement of the .04 m wide slit with respect to the central ray of the dipole which lies 60 m away. There is no direct line-of-sight between these two beam line components so an offset of 5 mm is not impossible. The sensitivity of λ_μ to such an offset is shown in the following figure,



The error introduced is somewhat smaller but still non-negligible.

Measurement of the Beam Polarization

Due to the possibly large systematic effects as outlined above it would seem prudent to actually measure the dependence of λ_μ on E_μ. There are various ways to do this among them being;

1. Muon Decay A measurement of the spectrum of the decay positron energy yields a measure of the parent muon polarization. This method has been used to measure the polarization [6] of the CERN muon beam.

2. Muon-Electron Scattering There is an asymmetry in μ - electron scattering which is proportional to the polarization of the muon.

Either of these methods can be used to determine the muon polarization to an accuracy which would seem to be demanded by proposed experiments.

References

[1] E. Wigner, Rev. Mod. Physics **29**, 255 (1957).

[2] A. Malensek and J. G. Morfín, The Tevatron Muon Beam: A High Intensity Beam with Well Defined Polarization, Fermilab TM-1193, July, 1983.

[3] Muon Scattering with Hadron Identification at the Tevatron, Proposal of Experiment-665, October, 1980.

[4] Muon Scattering in a Heavy Target Calorimeter, Fermilab Proposal-786.

[5] A. Malensek, Thick Target Production Formulae, Fermilab Physics Note FN-341.

[6] D. Bollini et al., Nuovo Cimento **63A**, 441 (1981).