

# Deep Inelastic Scattering at a Muon Collider - Neutrino Physics

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## I INTRODUCTION

Colliding muon beams are not the only source of interesting interactions at a muon-collider complex. A muon-proton collider is a distinct possibility and the muon beams themselves will produce high flux beams of muon and electron neutrinos wherever there is a long straight section. Muon-proton physics would require an additional proton machine joined to the muon collider complex but first rate neutrino physics requires only that a detector be located in the path of the neutrinos coming from the muon-collider complex. The DIS group considered both of these options, our conclusion is that a muon-proton collider is feasible, although not easy or cheap. Neutrino physics at a muon collider appears to be easy, inexpensive and would extend present measurements by several orders of magnitude.

The deep-inelastic-scattering (DIS) group considered two scenarios, a 200 GeV  $\mu \times 1000$  GeV p collider [1] and neutrino beams generated by the decay of 250 GeV muons. [10] Use of the muon beam in fixed target mode was not considered as most existing experiments are already systematics limited.

## II MUON-PROTON COLLIDER

The 200 GeV  $\mu \times 1000$  GeV p collider option is described in detail in a paper by V. Shiltzev [1] and a contribution by S. Ritz [3] to these proceedings. Such a collider would reach 3 times the center of mass energy of the current HERA  $e-p$  collider with much higher luminosity.

## A Detector Design

A one TeV proton beam can be considered to consist of quark and gluon beams with typical energies between 0 and 3-400 GeV. As a result, the CM frame for valence quarks colliding with 200 GeV muons would be almost at rest in the lab frame. These kinematics are similar to those at D0 and CDF. This suggests a detector design similar to those at present colliders, with emphasis on the detection (and rejection) of muons in the final state. Due to background from muon halo around the beamline, scattering angles below 10 degrees would be very hard to measure. This essentially rules out measurements at very low quark momentum fraction  $x$ .

## B Physics Possibilities

Physics possibilities at a  $\mu-p$  collider were suggested by M. Klasen, S. Magill, A. Caldwell, D. Krakauer, F. Olness and S. Ritz.

An integrated luminosity of  $10 \text{ fb}^{-1}/\text{year}$  was suggested in the preliminary  $\mu-p$  collider study by V. Shiltzev. With  $10 \text{ fb}^{-1}$ , 1 M events/year would be detected with momentum transfer  $Q^2$  greater than 5000,  $\text{GeV}^2$ . The present Zeus sample from  $34 \text{ nb}^{-1}$  is 326 events above 5000  $\text{GeV}^2$ .

These large data samples, even in the absence of low  $x$  acceptance, will allow very accurate measurements of the proton (and photon, see the contribution of M. Klasen) structure functions and their evolution over a  $Q^2$  range where perturbative QCD calculations are reliable. At these  $Q^2$ , charged current interactions via  $W$  boson exchange also become a significant fraction of the total scattering cross section. This allows measurements of the quark content of the proton and of the electro-weak couplings similar to those presently done in neutrino experiments at  $Q^2 \ll 500 \text{ GeV}^2$ .

With the same 1 year run, limits on lepto-quarks with standard couplings could be extended up to 800 GeV with coupling limits of  $2 \times 10^{-3}$  at 200 GeV. Limit can also be placed on some Higgs production models for masses less than 120 GeV.

## C The bad news

Unfortunately, muon backgrounds due to beam losses elsewhere in the machine are believed to be very large with rates of up to 1 muon/cm<sup>2</sup>/crossing. Most  $\mu-p$  physics depends critically on the detection (or definite non-detection in the case of charged current interactions) of a single muon in the final state. Where  $\mu\mu \rightarrow H \rightarrow bb$  may still be detectable in this environment, studying  $\mu p \rightarrow \mu X$  will be much more difficult. Our conclusion is that designing a detector able to withstand these background rates would be even more difficult than detectors for the muon-collider itself.

### III NEUTRINO BEAMS

The muon-collider complex will produce very intense neutrino beams; so intense that the original calculations of neutrino fluxes at the muon collider were in the context of radiation safety.

The neutrino flux, both  $\nu_\mu$  and  $\bar{\nu}_e$ , results from decays in flight of muons within the FMC. Intense collimated neutrino beams will be produced from any straight section in the muon-collider complex. As we were interested in high energy neutrino beams, we considered the beams coming from the last phase of the recirculating linacs (RLA3) and from a 10 m straight section in the muon-collider (FMC) itself. In both cases we considered the fluxes available to a parasitic neutrino experiment, one where no modification to the lattice or the number of turns at a given energy is made. Increases of factors of 10 in neutrino fluxes could be achieved by simply lengthening the straight sections or letting the beam coast for a small fraction of a lifetime once it reaches full energy in the RLA3. For more details on the beam flux calculations see the contributions by D. Harris and K.C. McFarland [10] to these proceedings.

The beam line parameters we assumed were:

Source	RLA3	250 GeV Muon Collider (FMC)
$E_\mu$	150 – 250 GeV	250 GeV
turns/pulse	12	1560
decay length	533 m	10 m
$\langle E_{\nu_\mu} \rangle$	135 GeV	178 GeV
beam size 600 m	50% < 25 cm	50% < 15 cm
Event Rate per 40 tons/year	$5 \times 10^9$	$5 \times 10^9$

TABLE 1. Neutrino fluxes and event rates for two parasitic neutrino beams, numbers are for muon neutrinos only. The RLA3 rates assume that the machine is ramping through 12 turns.

Table 1 shows the parameters of the RLA3 and muon-collider interaction regions relevant to neutrino physics. Both will produce energetic neutrino beams, the RLA3 option has lower energy because the muons are at full energy only during the final turn. In both cases, a 40-ton neutrino detector located 600 m away would see 500 neutrino interactions per second of which 50% would be within 15-25 cm of the detector center.

Figure 1 shows the muon neutrino interaction rates as a function of energy expected from the RLA3 and collider straight sections for a 250 GeV muon collider.

In contrast, existing experiments see rates of order one neutrino interaction/second in fiducial volumes ten times larger. This increase of three orders of magnitude in neutrino flux calls for completely new thinking about detector design.

### A Neutrino beam characteristics at a muon collider

Neutrino beams from muon decay would be substantially cleaner than those produced by the decay of pions and kaons in present beamlines. Such beamlines use protons and very complex targeting systems to produce pions and kaons with momentum spreads of  $\approx 10\%$ . The exact momentum distributions of the decaying mesons are difficult to measure in situ. In addition, other processes involving neutral kaons and charm produced in the target or

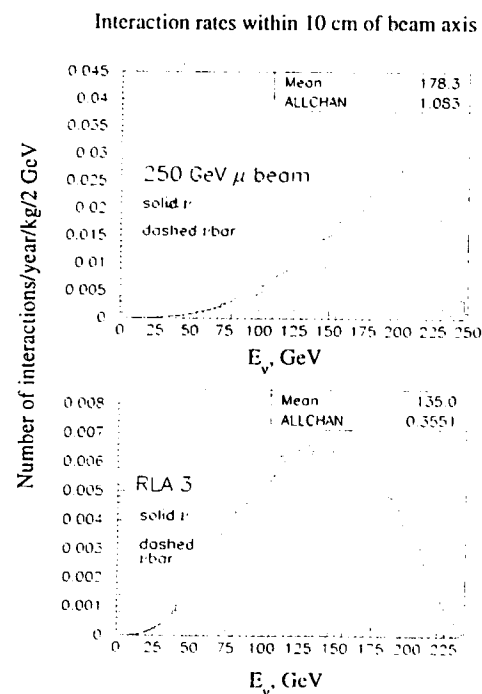


FIGURE 1. Neutrino interaction rates as a function of neutrino energy for  $\nu_\mu$  and  $\bar{\nu}_e$  beams from a 250 GeV muon-collider complex

dump can produce background neutrinos. Accurate knowledge of the neutrino flux requires careful simulation of the beamline and many underlying physical processes. As a result, the total neutrino-scattering cross section is still not well understood and was last measured in the late 1980's. [5]

In contrast, at the muon collider, the muon beam will be essentially monochromatic and there will be no dumps to produce stray neutrinos. The neutrino flux, for both muons and electrons, will depend only on the beam energy, beam intensity and the muon polarization. Although we did not do detailed studies for this workshop, we believe that the well defined beam spectra at a muon collider will substantially lower the systematic uncertainties in most measurements.

Note: For many neutrino physics topics, comparison of neutrino and anti-neutrino rates *in the same detector* are needed. Polarity reversal in the beamlines is absolutely necessary for neutrino physics.

## B Backgrounds from neutrino-reinteractions

Any neutrino detector must be located far enough away from the accelerator for primary muons to range out. For 250 GeV muons going through concrete this distance is around 600 meters. However, the neutrinos can reinteract in any shielding material and, in the case of a very intense beam, the reinteraction products from the shielding could be significant even at large distances from the accelerator. For example, the studies by Harris and McFarland [10] showed that a 40 ton detector with multiple tons of concrete directly preceding it will be overwhelmed by muons produced in neutrino interactions upstream in the shielding. In present experiments, such upstream interactions already result in 5-10% deadtime. In the high flux environment of the muon-collider complex, vetoing such interactions would be futile. In the RLA3 scenario, this upstream muon rate would be 4/event!

A possible solution is 300 meters of magnetized iron followed by 300 meters of air which would allow muons produced in the iron to sweep away from the detector. A simple calculation indicates that such a system reduces the muon flux from the shielding by more than an order of magnitude. A clean neutrino experiment does appear to be possible in the muon-collider environment.

## C Limitations of present Neutrino Experiments

To date, two paths have been taken in studying high energy neutrino interactions. In one, maximum statistical power is gained by the use of massive targets weighing hundreds of tons. This is the path followed by CCFR, CDHSW and CHARM [6] and used in high statistics measurements of structure functions and weak interaction couplings. Such targets provide high statistics with the following compromises:

- High A targets - results from muon and electron scattering [7] indicate that the total cross section can vary by up to 30% as A increases, with diffractive production becoming much more important at high A and low  $Q^2$ .
- Coarse grained measurement - the target material itself causes substantial multiple scattering. Typical angular resolutions are 10 mr and momentum resolutions are worse than 10%. The accessible kinematic region is highly restricted and unsmearing the data is very difficult. These measurement difficulties have limited the kinematic regions accessible to high statistics experiment to momentum fraction  $x > 0.01$ .

The alternatives, fine-grained low mass experiments, (E872, CHORUS, FOCUS, BEBC, LAB C) suffer from low statistics.

Despite these substantial experimental limitations, neutrino experiments are still our only direct source of information on the anti-quark content in the proton and provide competitive measurements of some Kobayashi-Maskawa matrix elements, the strong coupling constant, and the Weinberg Angle.

The factor of a thousand in flux available parasitically at the muon-collider complex changes this picture entirely. For the purposes of this workshop, we followed a suggestion by Bruce King [9] (see his writeup in these proceedings) and considered a radically different experimental design, similar in many ways to the spectrometers used in muon scattering experiments such as SMC and E665. The change in perspective is illustrated in table II where we redefine the figure of merit for a neutrino experiment from interactions/kilo-ton of steel/year to interactions/meter of liquid hydrogen/year.

Table 2 shows the rates expected in a 10 cm diameter  $\times$  100 cm long hydrogen target in one year of running. Rates for a larger detector are also shown.

Target radius	RLA3	250 GeV Muon Collider	CCFR
10 cm	750,000	2,400,000	
200 cm	6,500,000	9,400,000	2,000,000

TABLE 2. Muon neutrino interaction rates/year expected in a one meter long liquid hydrogen target located 600 m from the muon-collider complex. The CCFR detector rates, with 680 tons of fiducial volume, are shown for contrast.

A small hydrogen target would see interaction rates/year of 1-2 M, directly comparable to the present NuTeV experiment which uses a 680 ton iron target. The gain in statistical power comes from two factors, first the flux of neutrinos is several thousand times higher, and second, the beam is more collimated, allowing a much smaller and hence less massive target.

Bruce King proposes an experiment with a hydrogen target followed by silicon strip detectors, a TPC, Cerenkov counters for particle ID and electro-

magnetic and hadronic calorimetry. This detector is quite similar to existing Fermilab and CERN fixed-target spectrometers and would provide very accurate measurements of neutrino events.

## IV PHYSICS WITH A LIGHT NEUTRINO DETECTOR

### A Weinberg Angle measurements

The ratio of neutral current to charged current interactions observed in muon neutrino interactions provide an interesting measurement of the Weinberg angle  $\sin^2 \theta_W$  which is complimentary to direct measurements of the  $W$  mass and to indirect measurements made at  $e^+e^-$  colliders. The current NuTeV experiment should measure  $M_W$  with a precision of 125 MeV using around 1M events. The muon collider neutrino beams would provide both more statistics and eliminate the most important systematic uncertainties in present measurements. This topic is treated in more detail in the contribution

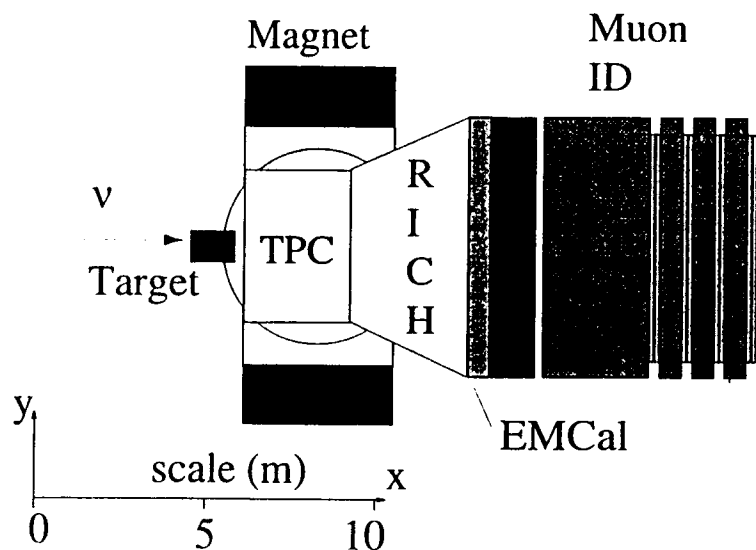


FIGURE 2. A typical fixed target experiment in a neutrino beam. The target is 1m of liquid deuterium followed by a TPC for tracking, a ring imaging Cerenkov chamber for particle ID, electromagnetic and hadronic calorimetry and a muon tagging system.

to these proceedings by J. Yu and A.V. Kotwal [8]. A deuterium target 1 meter in diameter and 1 meter long could detect 20 M  $\nu_\mu$  and 20 M  $\bar{\nu}_e$  interactions per year. This would yield a statistical error of 0.0004 on the Weinberg angle, an improvement of a factor of 5 from the current NuTeV measurements. At present, the major sources of systematic errors in this measurement are:

- The kinematic suppression of  $s \rightarrow c + W^-$  vs  $s \rightarrow s + Z^0$  which depends on the dynamics of charm production. This suppression artificially raises the ratio of cross sections and introduces an energy dependence which is presently one of the largest errors in neutrino measurements of  $\sin^2 \theta_W$ .  
Solution - measure charm production directly via a silicon vertex detector.
- $\bar{\nu}_e$  contamination in the beam. In coarse-grained detectors,  $\bar{\nu}_e \rightarrow eW^+$  looks like  $\nu_\mu \rightarrow \nu_\mu Z^0$  as final-state electrons are merged with the hadronic shower.

Solution - a low density detector will allow detection and identification of the final state electron. The anti-neutrino background becomes an advantage, one can use the electron neutrinos from the beam to double the statistical power of the measurement.

A quick estimate for the first year of running a parasitic small experiment is  $\Delta \sin^2 \theta_W \leq 0.00010$  which translates into an error on the mass of the  $W$  of 30-50 MeV.

### B Charm production

Around 5% of charged current neutrino interactions involve charm production. One could expect 100 - 500 K reconstructed charm events per year from a small active silicon target. While these rates are low compared to present Fermilab fixed target experiments and  $e^+e^-$  colliders, a charm measurement in a 180 GeV neutrino beam combines the decay length resolution of fixed target experiments with the low backgrounds seen at lepton colliders. In addition, the sign of the charmed quark is tagged by the muon or electron charge, allowing studies of Cabibbo suppressed modes and CP violation in the charm system which are competitive with much higher statistics samples from lepton colliders.

See the contributions by Panagiotis Spentzouris [12] in these proceedings for more detail on charm production.

#### 1 Bubble Chambers?

A 1 meter diameter liquid hydrogen bubble chamber would trigger at 1 Hz, an event rate which has been feasible in such experiments since the 1970's.

With high resolution CCD readout and 2010 pattern recognition algorithms, bubble chamber measurements of short-lived particles similar to those done at SLAC and in the Tohoku bubble chamber at Fermilab may again be feasible.

### C Quark content of the proton

Charged-current neutrino scattering is uniquely sensitive to the quark content of the proton as neutrinos are very selective about the helicity and charge of quarks they will scatter from.

- Neutrino scattering from protons is sensitive to  $d$ ,  $s$  and  $\bar{u}$  quarks,
- Anti-neutrino scattering is sensitive to  $\bar{d}$ ,  $\bar{s}$  and  $u$  quarks.
- The relative contributions  $d$  and  $s$  quarks can be untangled via charm production.
- Data from deuterium targets provides a different mix of  $u$  and  $d$  quarks in the target and thus allows one to distinguish  $u$  from  $d$  and  $\bar{u}$  from  $\bar{d}$ .

High statistics neutrino experiments with good charm tagging will be able to give accurate parton distributions for each flavor. Such measurements will be of considerable use to the LHC experiments.

### D Spin physics

Neutrino beams, as they are guaranteed to be 100% polarized, are also ideal for spin physics measurements. Neutrinos only scatter from left-handed quarks or right-handed anti-quarks, while anti-neutrinos have the opposite taste. A polarized target allows measurements of the spin asymmetries in parton densities where  $\Delta q$  is defined as the difference between the quark contents parallel and anti-parallel to the proton spin. A large (200 kG) polarized target could see up to 1M events/year from polarized nuclei with charm in the final state. This would yield a 3% measurement of the spin asymmetry in the strange sea. [11]

### E B- physics?

Bruce King, Donna Naples and Alex Romosan pointed out that an active silicon target could be used to search for the process  $u \rightarrow b$ . As there is little contribution from  $c \rightarrow b$  due to the suppression of charm quarks in the proton, this process would provide a very clean measurement of  $V_{ub}$ . A small parasitic experiment such as those considered above, would yield 20 such events/year, a bigger target, longer running or longer straight sections could make this a high precision measurement.

### F Higher energies

As the neutrino interaction cross section scales with beam energy for center-of-mass energies  $\ll M_W$ , the event rates shown here will rise linearly with machine energy. Charm and B production rates should rise even faster as they are currently limited by kinematic constraints. Shielding design will become more crucial as the backgrounds, which come from neutrinos, will scale with the event rate.

### V CONCLUSIONS

A  $\mu$ -p collider is very attractive, with very high luminosity and three times the center-of-mass energy currently available at HERA. Unfortunately, backgrounds from muon halo make measuring the final state muon very difficult. A muon collider would be confined to high- $x$  high- $Q^2$  kinematics.

However, the muon-collider complex, even during intermediate phases of construction, will provide neutrino beams of unprecedented cleanliness and intensity. Measurements which have been done poorly (total cross section) or not at all ( $u \rightarrow b$ ) can be done with high precision. Detector designs previously used in fixed target hadron and muon experiments could be directly adapted to neutrino physics. We were unable to find any technical problems which would prevent the muon-collider complex from producing a revolution in neutrino physics at an energy of 250 GeV. Prospects improve even further if the machine energy is raised.

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## Higgs Boson and Z Physics at the First Muon Collider

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**Abstract.** The potential for the Higgs boson and Z-pole physics at the first muon collider is summarized, based on the discussions at the "Workshop on the Physics at the First Muon Collider and at the Front End of a Muon Collider".

### INTRODUCTION

Muon colliders offer a wide range of opportunities for exploring the physics within and beyond the Standard Model (SM). Because the muon mass is about 200 times larger than the electron mass,  $s$ -channel production of the Higgs boson, and its associated advantages with regard to measurements of Higgs boson properties, is one of the unique features of a muon collider. Since the muons are produced in a decay channel by moving pions, the muons naturally carry a longitudinal polarization of about 20%. A collider allowing for adroit manipulation of the polarization and center of mass energy, combined with the prospect of luminosities in the range of  $10^{32} < \mathcal{L} < 10^{33} \text{cm}^{-2}\text{s}^{-1}$  would make for a very powerful probe of the structure of the fundamental forces with unparalleled potential. In this report a summary of the Higgs and Z-pole physics, as well as some other aspects of the electroweak boson physics, as discussed at the workshop on the physics at the First Muon Collider (FMC), is presented [1].

### EXPERIMENTAL CONSIDERATIONS

The experiments at the  $e^+e^-$ -colliders LEP and SLC have shown that the calibration of the luminosity, beam energy and beam polarization is crucial for the physics results obtained. At LEP the luminosity is measured with small angle silicon based calorimeters, counting Bhabha events to a precision of  $\frac{\delta\mathcal{L}}{\mathcal{L}} = 10^{-3}$ . The Bhabha cross section has been measured down to angles of about 30 mrad with respect to the beam direction. At the FMC, however, it is not clear if the muon Bhabha cross