Figure 1: Energy weighted fluxes for NuTeV (left) and DONuT (right)

A Fixed Target Program Using 1 TeV Protons On Target

Names

Abstract: This document describes the physics potential of a Fixed Target program based on a 1 TeV proton source. Two sources may be: the existing Tevatron at Fermilab and a possible upgrade to the SPS at CERN, called SPS+. The possible Fixed Target beams which can be provided are described. The goals and tentative layout of some experiments which could run in such a program are considered. The physics which is highlighted are examples which are either unique to the program, or difficult to accomplish at other venues. From this one can see that these experiments represent opportunities complementary to the ongoing program

1 Introduction

This paper describes a fixed target program which can be run at a 800 GeV to 1 TeV fixed target facility. The physics described here is unique to such a facility and complements the ongoing physics program envisioned by the community for the late 2010's. The goal is to illustrate the strength and richness of the program. We concentrate on three example experiments in detail: ν-e scattering, ν_τ studies and searches for rare processes in the D-sector. We also offer examples of smaller experiments which could run along with the larger examples.

There are two possible sources of ~ 1 TeV protons which may be available. The first is the Tevatron at Fermilab, which can be modified for fixed target running. The second is the SPS+ which is planned at CERN as part of the LHC upgrade program. The fixed target program described here can run when the SPS+ is not used for LHC. More details about running both machines are provided in Appendix A.

Along with a wide option of slow-spill beams, an ~ 1 TeV machine can create a unique ultra-high-energy neutrino facility. The facility would impinge protons on a target and a dump. This produces two beams which can run simultaneously. A very pure sign-selected ("SSQT") high energy ν_μ beam can be created. At the Tevatron a beam with 20 times the ptoyon delivery of the previous NuTeV experiment can be produced. At SPS+ the rate will be **xxx** times the rate supplied to NuTeV. At the same time, using the beam dump, a flux enriched in ν_τs which are above charged current (CC) threshold can be produced. This is the only practical source of ν_τs above threshold, since long-baseline experiments, which produce ν_τs through oscillations, must run at low energies. We will assume that the relative ν_μ to ν_τ rate will be the same as was achieved by DONuT. The flux in one year of running will be greater than 150 times that of the previous DONuT Experiment, depending on the source. The flux distributions of DONuT and NuTeV are shown in Fig. 1, illustrating the unique energy and flavor distributions.

2 Neutrino-electron Scattering

Neutrino-electron scattering ($\nu_\mu + e \to \nu_\mu + e$) is an ideal process to search for beyond the Standard Model at Terascale energies through precision electroweak measurements. The low cross section for this process demands a very high intensity beam. In order to reduce systematics and reach precision better than 1% on this cross section, this process can be normalized to it's charged-current sister process, "inverse muon decay" ($\nu_\mu + e \rightarrow \nu_e + \mu$). The threshold for ths process is 11 GeV. Thus the experiment requires a high energy neutrino flux, as can only be provided by a ~ 1 TeV proton primary beam. Once a high-energy, high-intensity neutrino flux is established, a detector optimized for $\nu - e$ scattering can also be used for precision structure function and QCD measurements and direct searches.

The physics reach of NuSOnG for Beyond Standard Model Physics is in the 1 to 7 TeV range, depending on the model. The sensitivity to new physics complements the LHC and bring unique new opportunities to the program. The full physics program is discussed in detail elsewhere [**?**, **?**], and in this paper we provide an overview which illustrates the value of this experiment.

2.1 The Beam

For this discussion, we will assume a NuSOnG beam design which is the sam as that used by the NuTeV experiment, which ran from 1993-1996 at Fermilab [**?**]. We will assume 2×10^{20} high energy (800 GeV to 1 TeV) protons impinge on a beryllium oxide target. The resulting measons traverse a quadrupole-focused, sign-selected magnetic beamline, hence the dsign is called a "sign-selected quad triplet" or SSQT. NuSOnG will run with $1.5{\times}10^{20}$ p.o.t. in neutrino mode, and 0.5×10^{20} p.o.t. in antineutrino mode. The result is a beam of very "right sign" purity ($> 98\%$) and very low ν_e contamination (2%). The ν_e in the beam is due mainly to K^+ decays which can be well-constrained by the $K^+ \rightarrow \nu_\mu$ flux which populates the high energy range of the neutrino flux. The magnetic bend substantially reduces ν_e from K_L decay which tend to go forward and thus not be directed at the detector.

2.2 The Detector

The baseline design for the NuSOnG detector is a 3.5 kton glass-target design inspired by the design of the Charm II experiment. The detector is broken into four identical subdetectors, each consisting of a 5m $\times$ 5m $\times$ xxxm target followed by an **xx** m long muon spectrometer. Breaking the design into four sctions assures high acceptance for muons produced in the target calorimeter to reach the toroid. A gap of **xxx** m extends between each detector to allow for a calibration beam to impinge on the taget. The total length of the detector is, therefore, 200 m.

The total target is composed of 2500 sheets of glass which are 2.5 cm (0.25 λ_0) thick. This provides an isoscalar target for neutrino-quark interaction studies. Interspresed between the galss sheets are proportional tubes or scintillator planes. Ths gives a target which is made of isosclar material with ne 1/4 radiation length sampling. The total target material is six times greater than NuTeV.

2.3 Rates

When the 3.5 kton detector is combined with the high intensity, high energy beam, this yields remarkable rates. One expects > 600M ν_μ cc events and > 65M ν_e CC events. This can be compared to past samples of < 20M [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**] and $\sim$ 500k [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**], respectively. With such large data samples, NuSOnG can explore for processes which are within the Standard Model, but rare, or Beyond the Standard Model which have not been studied before.

The expected rates for specific event types are given in table . In particular, one should note that the neutrino electron scattering sample is 40 times that of previous experiments.

600M	ν_μ CC Deep Inelastic Scattering
190M	ν_μ NC Deep Inelastic Scattering
75k	ν_μ electron NC elastic scatters (ES)
700k	ν_μ electron CC quasi-elastic scatters (IMD)
33M	$\bar{\nu}_\mu$ CC Deep Inelastic Scattering
12M	$\bar{\nu}_\mu$ NC Deep Inelastic Scattering
7k	$\bar{\nu}_\mu$ electron NC elastic scatters (ES)
0k	$\bar{\nu}_\mu$ electron CC quasi-elastic scatters (WSIMD)

Table 1: Rates for NuSOnG assuming 2×10^{20} protons on target. NC indicates "neutral current" and CC indicates "charged current."

2.4 Neutral Current Neutrino Scattering Measurements

Neutrino neutral current scattering provides an ideal opportunity to probe for new physics through the weak mixing angle, $\sin^2\theta_W$ and the ratio of neutral to charged current couplings, ρ. There is a long history of experiments which have exploited precision neutral current quark scattering for this purpose. A surprising result from NuTeV, which the most recent and highest precision showed a 3σ discrepancy with the Standard Model. This could indicate new physics, however a case has been made for standard model effects such as isospin violation in the nucleon. This hypothesis can be addressed by future precise structure function measurements, including those from NuSOnG. However, it serves to illustrate the point that Beyond Standard Model searches which rely upon QCScan face substantial model uncertainties.

A unique feature of NuSOnG is it ability to test the NC couplings by studying scattering of neutrinos from both electrons and quarks. NuSOnG makes four measurements, two using electron targets: **xxx equations here** and two using quark targets: **xxx equations here**. The first and third measurements have the very high precision. A deviation from the Standard Model predictions in both the electron and quark measurements would present a compelling case for new physics... **xxx how well we do...**

2.5 Beyond Standard Model Reach

put text here!

2.6 Complementarity with the Program

and more text here...

3 ν_τ Experiments

The main focus of a ν_τ beam-dump experiment would be precision measurement of the relative weak charged-current cross section to test Standard Model lepton universality probing potential new physics. Such an experiment requires a detector with large mass and high resolution for track and shower identification capable of operating effectively in the unprecidented neutrino flux described in the previous section. DONuT acheived these requirements with an emulsion detector, but that technology is not preferable with orders of magnitude higher neutrino flux than was seen during their operation. A liquid argon time projection chamber (LAr TPC) of 0.5 - 1.0 kT mass will meet these requirements, including the ability to operate efficiently in the intense flux of this facility.

A 1 kT detector combined with a proton flux 150 times higher than that used for DONuT will yield a naive expectation of 300,000 times more neutrino interactions than DONuT per 6 month period, or order 6 million ν_τ interactions per year.

A LAr TPC will likely not have sufficient resolution to identify charged tau lepton tracks directly, however this is not necessary for tau event identification as evinced by a long history of tau physics at electron-positron and hadron colliders. After track and electromagnetic shower reconstruction, a charged tau event may be identified primarily by a combination of missing transverse momentum and invariant mass reconstruction of tau-daughter candidates. A magnetic field would enhance charged tau event identification as well as provide a means to distinguish neutrino and anti-neutrino events for separate rate measurements.

A large neutrino detector with fast triggering, high resolution track and shower reconstruction, and particle identification by specific ionization energy loss promotes a rich program of physics beyond simply ν_τ weak charged-current cross section measurement.

- relative $\nu_\tau/\nu_\mu/\nu_e$/NC cross-sections
- charged τ physics
- kinematic charged τ mass measurement
- precision absolute measurement of ν_τ, ν_μ, ν_e CC & NC cross-sections on LAr
- low background exclusive ν cross-sections (NC coherent $\pi^0/\pi^\pm$, ...)
- search for ν_τ, ν_μ, ν_e magnetic moment
- cosmic ray studies (rates, flavor,...)
- atmospheric ν studies (rates, flavor, oscillation,...)
- solar ν: $\nu\ e \ \rightarrow\ \nu\ e$ (1evt/ton/yr) vs. $\nu_e\ Ar\ \rightarrow\ K^*\ e$ (4evt/ton/yr) sensitive to ν_e oscillation probability
- direct/endpoint kinematic ν mass measurement
- millicharged/fractional-charged particle search (beam/cosmic)
- magnetic monopole search
- supernova neutrinos
- proton decay of O(10^{32}yr) for certain exclusive multi-prong channels

4 Charm Studies

5 Complementary Smaller Experiments

5.1 A Low Mass Detector for charm and oscillation studies

5.2 Searches for Exotic Neutrinos

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Singlet (sterile) neutrino states arise in models which try to implement massive (light) neutrinos in extensions of the Standard Model. In principle 3 singlet states N1, N2 and N3 are associated with the

3 active neutrinos. In the original see-saw mechanism, these new states have very large masses, but variations like the nMSM model (1) give them masses which are within reach of experimental searches. Limits exist from laboratory experiments, but they extend to masses up to 450 MeV, and apply to couplings with the e or m. An upgraded Tevatron machine could enlarge the domain of exploration in masses and couplings with the study of neutrinos coming from D and B decays. For the first time, mixings to the nt could be efficiently investigated.

5.2.1 Production of sterile neutrinos

If heavy neutrinos exist, they mix with active neutrinos through a unitary transformation. Any neutrino beam will contain a fraction of heavy neutrinos at the level UNl2 where U denotes the mixing matrix element between the heavy state N and the charged lepton l, l being either e or m or t. At low energy accelerators, neutrinos are emitted in pion and kaon decays. At higher energies, charm, and beauty contribute. Kinematically the mass range allowed for the production of a heavy N depends on the emission process. In pm decays, sterile neutrinos can reach a mass of 30 MeV. In pe, the range increases to 130 MeV. Kaons allow larger masses, up to 450 MeV. D decays extend the range to 1.4 GeV and B decays to 4.5 GeV. The flux of N accompanies the flux of known neutrinos at the level of UNl2. Corrections to this straightforward result come from helicity conservation which applies differently here. For example, for massless neutrinos, it suppresses pe decays relative to pm decays. This is not true anymore for p eN. Phase space considerations have also to be taken into account. Thus, precise calculations have to be done in all the possible cases to be considered.

5.2.2 Decays of sterile neutrinos

N's are not stable. They will decay through purely weak interactions. The lifetime critically depends on the mass, it varies as m-5 power. Decay modes depend on the N mass. As soon as the mass is greater than 1 MeV, the first channel to open is N een. With increasing masses, new modes open, and one can obtain emn, pe, mmn, pm. For higher mass states potentially produced in B decays, new modes become relevant. For example, for masses above 2 GeV, one can envisage the channels De, Dm or even Dt. Exact branching fractions require precise calculations. The lifetime is given by the formula applying to weak decays, apart from a general suppression factor coming again from the mixing UNl2. Other factors coming from helicity and phase space considerations have to be included.

5.2.3 Previous results

With low energy neutrino beams, the search consists in looking for a decay signature, typically two charged tracks, one of them being a lepton, reconstructing a vertex in an empty volume. This has been attempted at CERN by the low energy experiment PS191 (2) with 5 1018 protons of 19 GeV on target, or about 1015 neutrinos crossing the detector volume. Neutrinos were produced in p and K decays. Thus the limits apply to couplings to e and m. Kinematically, the t is not accessible neither in production nor in decay. The explored mass range is limited to at most 450 MeV. The limits on the UNl2 couplings reach the level of 10-8 in a large range of accessible masses and for all combinations of mixings to e or m. Soon-to-run experiments could improve these results by an order of magnitude. In order to increase further the domain of exploration, it is necessary to consider higher energy beams producing neutrinos via D and B decays. B's decay into the 3 leptonic channels, Xene, Xmnm, Xtnt, with branching fractions respectively 10%, 10% and 5%. This allows the search of N states with masses up to 4.5 GeV. Since the limits vary as the square root of the accumulated neutrino flux, the number of pot's has to be maximal.

5.2.4 Detector considerations

The experiment consists in detecting a decay vertex arising in an empty volume and characterized by, in most cases, two charged tracks. The detector, installed in a high intensity neutrino beam, requires a decay volume followed by a calorimeter. The search directly depends on the length of the decay volume. It is better done at the minimum energy compatible with the production of the searched-for states. The advantage of an upgraded machine directly comes from the much increased luminosity. But, as a consequence, the background which comes from neutrino interactions is also substantially increased. The number of interactions in 12 m of air is not negligible. It can amount to several 10000. Charged currents will give a muon in the final state in 99% of the cases. It becomes essential to have an evacuated volume and the calorimeter must be able to efficiently identify electrons and muons. Studies have been made for the decay volume. The figure shows a 12 m long pipe where the vacuum can be pushed down to 10-3 atm. The background becomes manageable. A higher vacuum would require much more sophisticated techniques. The vacuum volume has to be followed by a tracker and a calorimeter. The best limits on couplings come from exclusive channels: pe and pm for low masses, Ke and Km for intermediate masses, De and Dm for higher masses. If the decay channel can be totally reconstructed, two essential constraints arise: 1) the reconstructed direction of arrival must point to the neutrino production target 2) the invariant mass of the detected particles must reconstruct a fixed mass. For example, one can search for a final state D(Kpp)e. This means that the calorimeter must have good capabilities for track reconstruction and identification. It must be fine grain, preferably with a magnetic field. An extra-tracker in front of the calorimeter helps to reconstruct the decay vertex.

5.2.5 Conclusion

Heavy neutral leptons arise in models which try to accommodate massive active neutrinos. Searches have been done in low energy neutrino beams. The advantage of an upgraded high energy machine is two-fold: the high energy allows to explore a larger domain of masses, up to the B mass, furthermore, the high luminosity pushes down the limits. In particular, it can set meaningful limits on the practically unexplored coupling to the t. The fascinating possibility of finding sterile neutrinos could be tested in future experiments.

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5.3 Rare Event Searches Using Hyperon Beams

6 Conclusions

APPENDIX: Specifics of Running 1 TeV Beams

A The Tevatron

Previous 800 GeV fixed target operation of the Tevatron ran with a maximum throughput of roughly 25-28 $\times 10^{12}$ protons (25-28 Tp) per pulse every 60 sec with a duty cycle of roughly 33-40%. The beam was shared, over a 20-23 sec flat-top period, between slow spill experiments and neutrino experiments which required fast extracted beams. To meet the demands of NuSOnG, the facility needs to be able to deliver approximately 2×10^{20} protons on target over five years of running at 66% overall operation efficiency per year. This translates to an average particle delivery rate during running of about 1.8 Tp/sec. Assuming that only a 40 second ramp will be required for NuSOnG, then each ramping of the Tevatron would need to deliver about 75 Tp, more than 2.5 times the previous record intensity. The subsections below address some of the major issues regarding re-institution of a Tevatron fixed target program, and issues associated with meeting the above intensity demand.

A.1 Magnet Ramping

The original Tevatron fixed target program ran at 800 GeV, and stress and strain on the superconducting magnets was a major issue early in the program. Issues with lead restraints within the cryostat were eventually identified and all dipole magnets were repaired in the tunnel in the late 1980's. Since that time, the Tevatron has been able to average over 250,000 cycles between failures of dipole magnets [?]. This "rate" includes failures of Collider-specific magnets, such as low-beta quadrupoles. Note that a neutrino program which demands 2×10^{20} POT, using a synchrotron that delivers 75 Tp every cycle, requires about 2.7 million cycles – thus, on the order of 10 failures could be expected during the course of the experiment.

Once the fixed target operation was halted, and only Collider operation was foreseen, the capability to repair and rebuild Tevatron magnets was greatly reduced at the laboratory. However, assuming no need for building new magnets from scratch, capabilities still exist to perform repairs and, along with the given inventory of spare Tevatron magnets and corrector packages, a multi-year fixed target operation consistent with the above is sustainable from this aspect [?].

Ramp rate studies of Tevatron dipole magnets have been performed, and rates of 200-300 A/sec can be maintained at 4.6° K without quenching [?]. The current power supply system can still perform at this level. To increase reliability, however, some PS system components may need to be upgraded. Additionally, the Tevatron RF system is still capable of running in the fixed target state, though beam loading effects and appropriate compensation will need to be investigated for the anticipated higher intensity operation. Two Main Injector pulses would be used to fill the Tevatron. At 3 sec per 150 GeV MI cycle, this constitutes a 15% impact on other MI demands.

A.2 Comments on High intensity

The record intensity extracted from the Tevatron in a cycle at 800 GeV was almost 30 Tp, in 1997, though 20-25 Tp was far more typical. At that time, the bunch length during acceleration would shrink to the point where a longitudinal instability at higher energies (∼600 GeV), resulting in aborts and sometimes quenches. This was compensated as well as possible with "bunch spreading" techniques (blowing up the emittance via RF noise sources). Today, the Main Injector is capable of providing greater than 40 Tp per pulse, which could, in principle, fill the Tevatron to 80 Tp. Many improvements to the Tevatron beam impedance have been made during Run II, including, for example, reduction of the Lambertson magnet transverse impedances which were identified as major sources. Additionally, advances in RF techniques/technology and damper systems, *etc.*, may allow, with enough studies and money, much better compensation of these effects, if required. This is a primary R&D point, if intensities near 75 Tp are to be realized in the Tevatron.

A.3 Re-commissioning of Extraction System

Returning the Tevatron to fixed target operation would require the re-installation of the extraction channel in the A0 straight section from which beam would be transported to the existing Switchyard area and on to the experimental target station. The electrostatic septa were located at the D0 straight section and could straightforwardly be reinstalled in the original configuration. All of this equipment is currently in storage and available for use. The B0 straight section, currently housing the CDF detector, would be replaced with standard long straight section optical components. Thus, the higher heat leak elements presently installed in the B0 and D0 regions would be absent, requiring less demands from the cryogenics system.

The other necessary piece of hardware is the slow-spill feedback system, referred to as "QXR" which employs fast air-core quadrupoles installed at warm straight sections in the Tevatron for fast feedback tune adjustment during the resonant extraction process. Again, this equipment mostly still exists, though it may be desirable to perform a low-cost upgrade to modernize some electronic components.

The neutrino experiment being discussed has requested "pinged" beam, short bursts of particles brought about by the QXR system. NuSOnG will likely require tens of *pings* per cycle, during an assumed 1 sec flat-top. Resonant extraction is an inherently lossy process, on the scale of 1-2%, determined by the particle step size across the thin electrostatic septum wires. Historically, loss rates were tolerable with between 20-30 Tp extracted over 20 seconds. Extracting 2.5 times this amount in 1/20-*th* the amount of time without quenching the Tevatron will need further study, though should be feasible. Alternative methods for fast extraction could be contemplated, though perhaps at a price. For instance, if an appropriate RF bunching scheme (using a 2.5 MHz RF system, for example) can be employed to prepare bunches spaced by 400 ns, then a fast kicker magnet system might be able to extract 50 such bunches one-by-one to the switchyard, a much cleaner extraction process. Spreading the beam across fewer, longer bunches may also help to mitigate coherent instability issues. This opens up another possible R&D point to pursue. To set the scale, the highest intensity extracted in a single pulse (*i.e.*, not during a slow spill) without quenching the Tevatron was about 10 Tp[**?**]. (Also, this was a test, not a normal operational procedure.)

The exact method used for 800 GeV operation would be a point closely negotiated between the laboratory and the experiment(s) using the beam. Both resonant extraction and kicker methods should be feasible within reasonable constraints.

A.4 Tevatron abort system

The abort system used during high intensity fixed target operation was located at C0 and was capable of absorbing 1 TeV proton beams at 30 Tp, repeatedly every "several" seconds, to the abort dump. While not used in Collider operation, this beam dump and beam delivery equipment near the C0 straight section is still available and still accessible, and requires re-installation of extraction devices and their power supplies. The ultimate parameters of the neutrino experiment being discussed pushes the beam stored energy from about 3.5 MJ (27 Tp at 800 GeV) toward 10 MJ. The design limits of this system would need to be re-examined, and the implications and environmental impact of re-establishing this area as the primary abort must be looked at carefully.

A.5 The SPS+ Option

References