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

A Fixed Target Program Using 800 GeV to 1 TeV Protons On Target

Names

Abstract: This document describes the physics potential of a Fixed Target program based on an ∼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 $\sim$ 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 $\sim$ 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 proton 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" ($\nu_\mu + e \to \nu_e + \mu$). The threshold for this 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 brings 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 same 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 mesons traverse a quadrupole-focused, sign-selected magnetic beamline, hence the design 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 low ν_e contamination (2%). The ν_e in the beam is due mainly to K^+ decays which can be well-constrained by the $K^+ \to \nu_\mu$ 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 $5\text{m} \times 5\text{m} \times xxx\text{m}$ target followed by an **xx** m long muon spectrometer. Breaking the design into four sections 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 target. 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. Interspersed between the glass sheets are proportional tubes or scintillator planes. The total target mass 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 ~ 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.

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

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."

long history of experiments which have exploited precision neutral current quark scattering for this purpose. A surprising result from NuTeV, which has 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 QCD face substantial model uncertainties.

A unique feature of NuSOnG is its 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

Elastic neutrino electron scattering is a purely leptonic electroweak process. It can be computed within the standard model, with high precision [1] and hence and hence provides a very clean probe of physics beyond the standard model. The effect of new, heavy ($M_{\rm new} \gg \sqrt{s}$) degrees of freedom to $\nu_\mu e^- \to \nu_\alpha e^-$, where $\alpha = e, \mu, \tau$ can be parameterized by the effective Lagrangian

$$\mathcal{L}^e_{\rm NSI} = +\frac{\sqrt{2}}{\Lambda^2}\Big[\,\bar{\nu}_\alpha\gamma_\sigma P_L \nu_\mu\Big]\Big[\cos\theta\,\bar{e}\gamma^\sigma P_L e + \sin\theta\,\bar{e}\gamma^\sigma P_R e\Big]\,. \quad (1)$$

New Physics, regardless of its origin,[1] manifests itself through two coefficients: Λ and θ. Λ is the mass scale associated to the new physics, while $\theta \in [0, 2\pi]$ governs whether the new physics interacts mostly with right-chiral or left-chiral electrons, and also governs whether the new physics contribution interferes constructively or destructively with the standard model process (Z-boson t-channel exchange) in the case $\alpha = \mu$.

Fig. 2 depicts NuSOnG's ability to exclude Λ as a function of θ for $\alpha = \mu$ or $\alpha \neq \mu$ assuming its $\nu + e$ elastic scattering data sample is consistent with standard model expectations. It also depicts NuSOnG's ability to measure Λ and θ in case a significant discrepancy is observed. For more details see [2]. In the case $\alpha = \mu$, where new physics effects interfere with the standard model contribution, NuSOnG is sensitive to $\Lambda \lesssim 4$ TeV while in the $\alpha \neq \mu$ case the NuSOnG is sensitive to $\Lambda \lesssim 1.2$ TeV.

[1] We are neglecting neutrino currents involving right-handed neutrinos or lepton-number violation. These are expected to be severely suppressed as they are intimately connects to neutrino masses (and, to a lesser extent, charged-lepton masses). Once constraints related to neutrino masses are taken into account, these contributions are well outside the reach of TeV-sensitive new physics searches.

The new physics reach of NuSOnG is competitive and also complementary to that of the LHC, where new physics in the neutrino sector is hard to access. The new physics reach of NuSOnG is competive with other leptonic probes (which involve only charged leptons), including LEP2 **ref**, and precision measurements of Møller scattering **ref**.

Figure 2: (DARK LINES) 95% confidence level sensitivity of NuSOnG to new heavy physics described by Eq. (1) when $\nu_\alpha = \nu_\mu$ (higher curve) and $\nu_\alpha \neq \nu_\mu$ (lower curve). (CLOSED CONTOURS) NuSOnG measurement of Λ and θ, at the 95% level, assuming $\nu_\alpha = \nu_\mu$, $\Lambda = 3.5$ TeV and $\theta = 2\pi/3$ (higher, solid contour) and $\nu_\alpha \neq \nu_\mu$, $\Lambda = 1$ TeV and $\theta = 4\pi/3$ (lower, dashed contour). Note that in the pseudoelastic scattering case ($\nu_\alpha \neq \nu_\mu$) θ and $\pi + \theta$ are physically indistinguishable. From [2].

Figure 3: Some examples of NuSOnG's 2σ sensitivity to new high-mass particles commonly considered in the literature. For explanation of these ranges, and further examples, see [2].

Several specific new physics scenarios can be probed by a high statistics, high precision measurement of neutrino–matter interactions. NuSOnG's reach to several heavy new physics scenarios is summarized in Fig. 3. There, we consider not only information obtained from neutrino–electron elastic scattering and inverse muon decay but also from neutrino–quark scattering (both neutral current and charge current data). If the new physics scale is below a few TeV new physics we expect NuSOnG data to significantly deviate from Standard Model expectations.

A more detailed comparison of NuSOnGs capabilities is summarized in Table 2.

Table 2: Summary of NuSOnG's contribution in the case of specific models. See [2] for details.

Model	Contribution of NuSOnG Measurement
Typical Z' Choices: $(B - xL)$,$(q - xu)$,$(d + xu)$	At the level of, and complementary to, LEP II bounds.
Extended Higgs Sector	At the level of, and complementary to τ decay bounds.
R-parity Violating SUSY	Sensitivity to masses ~ 2 TeV at 95% CL. Improves bounds on slepton couplings by $\sim 30\%$ and on some squark couplings by factors of 3-5.
Intergenerational Leptoquarks (non-degenerate masses)	Accesses unique combinations of couplings. Also accesses coupling combinations explored by π decay bounds, at a similar level.

Finally, NuSOnG is also sensitive to the existence of new *light* degrees of freedom, including neutral heavy leptons. A particularly interesting signal to look for is wrong-sign inverse muon decay ($\bar{\nu}_\mu + e^- \to \bar{\nu}_\alpha + \mu^-$), which, given our current understanding of neutrino masses and lepton mixing, only occurs at a negligible level. Wrong-sign inverse muon decay would point to short oscillation length neutrino oscillations (mediated by sterile neutrinos), a non-unitary lepton mixing matrix, non-standard neutrino interactions, etc.

2.6 Complementarity with the Program

and more text here...

3 ν_τ Experiments

Since the discovery of the charged τ lepton [3], physicists have assumed the existence of a weak partner particle, ν_τ, analagous to the neutrino partners of the e and μ leptons. Indeed, the wealth of studies of charged τ lepton properties require an accompanying tau-neutrino (ν_τ) for a consistent description of the observed dynamics. Little is directly known about the so-called ν_τ itself. [2] To date, only nine ν_τ charged-current events have ever been detected [4, 5] and all other information we have on this neutrino weak eigenstate is indirect. [3] An experiment sensitive to τ leptons placed along the path of an intense, ν_τ-rich neutrino beam would add significantly to our understanding of electroweak interactions and would be sensitive to certain hard-to-get manifestations of new physics.

Advances in the development of liquid argon time-projection-chambers (LAr TPCs), notably for the ArgoNeuT [] and MicroBooNE [] Fermilab projects and ICARUS [] at CERN, suggests it would be a good choice of base detector technology. A 500 ton LAr TPC would fulfill the physics requirements to discriminate high energy ν_τ charged current interactions while also providing a useful step in the development of the LAr TPC technology. Experience with progressively larger LAr TPC devices will enable easier deployment for future projects with requirements for fiducial masses of 5 kiloton or more, as has been suggested for future long-baseline neutrino-oscillation experiments at the Deep Underground Science and Engineering Laboratory (DUSEL) [] and other facilities.

3.1 The Neutrino Source

For discussion of this ν_τ experiment, we assume a similar neutrino production facility as was used for DONuT [4], but at the higher intensity described elsewhere in this document. Neutrinos delivered to the detector are the result of the decay of particles in hadronic showers produced by primary proton interactions. Tau-neutrinos are produced primarily by the decay of D_s mesons, with a branching fraction $\mathcal{B}(D_s^- \to \tau^- \bar{\nu}_\tau) = (6.6 \pm 0.6)\%$ [9]. The 800 GeV protons from the Tevatron are stopped in a beam dump in the form of a tungsten alloy block; DONuT used a 10 cm $\times$ 10 cm $\times$ 1m block, however the increased intensity of today's Tevatron facility may require optimization in this choice. Following the beam dump are dipole magnets sufficient to absorb interaction products and deflect away high energy muons from the beam center. After the magnets, a passive absorber is required to further reduce the flux of muons and other interaction products from the beam center. DONuT used 18 m of steel not more than 2 m from the beam center for this purpose. Emerging from this absorber are a reduced flux of muons and a flux of neutrinos of which 3% will be $\nu_\tau + \bar{\nu}_\tau$. The increased intensity of the present Tevatron will result in an integrated neutrino flux over a year approximately 150 times that delivered to DONuT.

3.2 The Detector

The requirements for an optimal neutrino detector include (a) large mass, (b) low unit cost, (c) long-term reliable operation, (d) low energy threshold, (e) high spatial resolution, (f) good energy resolution, (g) homogeneous media allowing consistent detection capability throughout, and (h) density and radiation length balanced between containment and spatial resolution of electromagnetic showers. The DONuT experiment used a primary detector composed of 260 kg of nuclear emulsion modules stacked along the beam line, with each module exposed only for a limited time to avoid track density higher than 10^5 per cm^2. With the increased intensity of the Tevatron and significantly larger event sample required for a precision ν_τ appearance measurement, an emulsion detector is not pragmatic. Current technologies that may satisfy the above requirements are water Cherenkov tanks, as employed by (i.e.) T2K [], or LAr TPC used by current and developing experiments ArgoNeuT [] and MicroBooNE []. Spatial resolution, energy resolution and low energy threshold are characteristics expected

[2] We will henceforth mean by "ν_τ," the neutrino initially prepared in the weak eigenstate with τ lepton number ± 1, as the mass and weak eigenstates of the Standard Model neutrinos have demonstrably been shown to be distinct with the observation of neutrino oscillation.

[3] Solar and atmospheric neutrino experiments have data which is best interpreted as evidence for ν_τ neutral current interactions. The SuperKamiokande atmospheric neutrino data also statistically favors the presence of both neutral current and charged current ν_τ initiated events [7, 8].

of LAr TPC detectors which will allow the full reconstruction of ν_τ charged-current interactions and the identification of the resulting charged τ. The use of a LAr TPC as primary detector technology facilitates the identification of typical charged τ decay products with excellent vertex and energy reconstruction sufficient to kinematically reconstruct the intermediate τ, with the possibility to reconstruct the short τ track in the highest energy interactions (i.e. a 200 GeV τ travels a mean distance of 9.7 mm which is likely to be much larger than the position resolution along the beam direction). With this technology, the energy resolution of hits and reconstructed objects within the detector will allow efficient identification of charged particles (electrons, muons, pions, kaons) as well as π^0, all necessary for kinematic reconstruction of charged τs. Kinematic separation of ν_τ charged current interactions with $\tau \to \ell\nu\bar{\nu}$ decays from ν_μ and ν_e charged current interactions is possible by analysis of missing transverse momentum, which is likely to be non-zero for ν_τ charged current interactions and close to zero otherwise. If a magnetic field is employed with the TPC, charge-sign identification is possible, which will reduce the combinatorial background in kinematically reconstructing ν_τ charged current interactions, allow separate ν_τ and $\bar{\nu}_\tau$ measurement, and provide a second method of track momentum/energy determination especially useful for events with exiting tracks.

The DONuT experiment had a mass of 0.5 ton. The data accumulated in a neutrino detector is proportional to the mass. A mass for the proposed LAr TPC suitable to accomplish the precision physics goals as well as act as a natural intermediate step between present and proposed future LAr detectors is 1000 ton. This is a three order of magnitude increase in mass over DONuT. Combined with the assumed increase in neutrino flux, this experiment should accumulate a data sample 6×10^5 larger than that observed by DONuT, equivalently $\mathcal{O}$(6 million) ν_τ charged current interactions with one year of data.

3.3 Standard Model and Beyond

Here we highlight the prospects for measuring charged and neutral current ν_τ–matter scattering, observing ν_τ–electron scattering and probing electromagnetic properties of the tau neutrino. In the standard model, ν_τ charged current interactions are mediated by W-boson exchange. There is only one measurement (with error bars around 50%) of the charged-current scattering cross-section with initial-state tau neutrinos [4], and it agrees with standard model expectations. The expectations are, however, that the $\nu_\tau \to \tau$ transitions are well-described by the standard model thanks to abundant data on τ lepton processes, including $\tau \to \nu_\tau \ell \nu_\ell$ ($\ell = e, \mu$), $\tau \to \nu_\tau$+hadrons, $D_{(s)} \to \tau\nu_\tau$, etc. The precision of measurement of ν_τ charged-current events is of the utmost importance as it provides a normalization for neutral-current measurements, which are only very poorly constrained. Furthermore, a τ-lepton sensitive neutrino detector may also place bounds on flavor-violating processes such as $\nu_{e,\mu} + X \to \tau + Y$. These are already strongly constrained by the NOMAD experiment [10] and it is not clear that systematic uncertainties associated with a ν_τ-rich beam can significantly improve on current bounds.

In the standard model, neutral current interactions are mediated by Z boson exchange. Unlike charged-current processes, neutral current processes involving ν_τ are only very poorly constrained, especially for interactions with final state ν_τ and ν_e [11]. In more detail, if we add to the standard model effective operators of the type (see Eq. (1))

$$\mathcal{L}_{\rm NSI}^{\nu_\tau} = \sum_{f=e,u,d} \frac{\sqrt{2}}{\Lambda^2} \Big[\bar{\nu}_\alpha \gamma_\sigma P_L \nu_\tau \Big] \Big[\cos\theta_f \, \bar{f}\gamma^\sigma P_L f + \sin\theta_f \, \bar{f}\gamma^\sigma P_R f \Big] \,, \tag{2}$$

current data constrain $\Lambda \lesssim 100$ GeV for all f and θ_f for $\alpha = e, \tau$. Such weak-scale new physics processes are not only allowed but, if present, known to significantly impact the interpretation of neutrino oscillation experiments (see, for example, Ref. [12] for a detailed discussion). A high statistics

ν-tau rich experiment should be able to significantly improve on current bounds or, perhaps, reveal new physics in the neutrino sector.

Finally, a high statistics experiment should also be sensitive to $\nu_\alpha + e$-scattering events. These can used (see section on NuSOnG) to look for different manifestations of physics beyond the standard model. With a ν_τ-rich beam, one can place bounds on what is naively referred to as the magnetic moment of the tau-neutrino. In more detail, one is sensitive to interactions of the type

$$\mathcal{L}_{\rm mag.mom.} = \frac{\lambda^{\alpha\beta}}{\Lambda}\left[\bar{\nu}_\alpha \sigma^{\rho\sigma}\nu_\beta\right]F_{\rho\sigma}, \tag{3}$$

where $\alpha, \beta = e, \mu, \tau$ and $F_{\rho\sigma}$ is the electromagnetic field-strength. The nature of the dimensionless coefficients λ depends on the nature of the neutrino fields (Majorana versus Dirac) and their magnitude is expected to be negligibly small in the absence of new physics beyond the standard model, which here is characterized by the new physics scale Λ. What is referred to as the magnetic moment of a particular neutrino flavor is process dependent and involves different functions of the λ coefficients. While bounds on the "electron-neutrino" and "muon-neutrino" magnetic moments are much better than one can hope to achieve with a next generation ν_τ experiment, it is clear that the information one can acquire with the ν_τ experiment is independent from that obtained with ν_e and ν_μ scattering (even if the neutrino are Majorana fermions and the appropriate matrix of λ-coefficients is anti-symmetric). Astrophysics also provides some stringent flavor independent bounds, but these are often model dependent and need to be "confirmed" by terrestrial experiments. Finally, we note that other electromagnetic properties of the tau-neutrino can be probed by neutrino electron scattering (see, for example, Ref. [13]).

Additionally, an intense ν_τ-rich neutrino beam offers a potentially large sample of highly polarized single charged τ leptons which may be uniquely exploited to measure the charged τ magnetic moment. This sample of neutrino-produced single τs may also provide an independent measurement of other *tau* properties in an environment with very different systematic uncertainties than those of the electron-positron collider experiments where the vast majority of τ physics has been studied in the last three decades.

3.4 Primary Measurements

The fast triggering, high spacial and energy resolution, and particle identification by specific ionization energy loss promotes a rich program of physics. The primary measurement of this experiment will be the high precision relative cross section measurement, $\sigma_\tau/\sigma_{(\mu,e)}$, for charged current interactions of ν_e, ν_μ, and ν_τ neutrinos, which provides a sensitive test of the Standard Model as outlined in the previous section. When combined with measurements/limits from NuSOnG or current limits on the magnetic moment of ν_μ and ν_e, similar searches for events consistent with neutrino magnetic moment interactions in a ν_τ-rich beam can provide sensitivity up to five orders of magnitude more stringent than those of DONuT on the ν_τ magnetic moment, the only previous search for direct observation of a ν_τ magnetic moment.

Utilizing the sample of $\mathcal{O}(10^6)$ charged τ leptons resulting from ν_τ charged current interactions with one year of exposure, several measurements of charged τ properties are also possible. In particular, due to the significant and predictable polarization of the single charged τs produced by ν_τ charged current interactions, this experiment will be much more sensitive to the magnetic moment of the τ than previous experiments. Despite the much smaller sample of τs than accumulated by present B-factories ($\mathcal{O}(10^9)$ τs), the unique environment of this detector and production mechanism provides a very different set of systematic uncertainties which allows an interesting laboratory for the verification of virtually all τ properties, including branching fraction measurements as small as $\mathcal{O}(10^{-5})$.

Further neutrino physics which may be measurable in this detector includes exclusive cross section measurements, such as coherent-pion production in neutral current and charged current interactions as well as $\nu_\tau e$ charged and neutral current interactions. The significant size and low energy threshold of the LAr TPC also allows measurement of solar neutrino rates as well as supernova neutrino sensitivity out of time with the beam spill. The proximity of the detector to the surface, expected pointing resolution of reconstructed tracks, and the size of the detector will yield a significant rate of cosmic-ray induced muons offering a wealth of interesting opportunities ranging from the observation of climactic changes in the atmosphere to searching for point sources of cosmic rays and sensitivity to the solar magnetic field.

3.5 ν_τ Summary

4 Charm Studies

Introduction

Fixed-target charm at the Fermilab Tevatron? Didnt we do that for over twenty years ending a decade ago? Why revisit that strategy?

Yes, we did have a very successful fixed-target charm program at Fermilab. Not only did it provide high precision measurements (some of which remain the most precise even today), but it also advanced flavor physics thinking in a way that still underlies many current analyses. It also demonstrated the utility of precision vertexing for heavy flavor physics, paving the way for the incorporation of silicon tracking systems in all the latest experiments. The fixed-target charm program ended when the technologies used were more-or-less played out, and attention turned to the opportunities at colliders, both at e+e- and hadron machines. The reason to bring a fixed-target charm experiment up now is a combination of the availability of technology well beyond what was available at the end of the previous program, and because it may be the most cost-effective way forward in this area. We will address these new opportunities below.

In the recent Roadmap for US High-Energy Physics written by the P5 committee, future operation of the Tevatron was not considered. However, there exists a plan to keep the Tevatron cold after completion of the Collider program such that it could easily be operated again should sufficiently comp elling physics opportunities arise. We believe one such opportunity is in charm physics, where mixing has recently been observed but current sensitivity to CP violation (CPV) is limited. A fixed-target charm experiment at the Tevatron has the potential to greatly improve upon the sensitivity to mixing and CPV achieved by the B factories. If a Super B-factory is not realized in the future, such an experiment could be the only way forward. A fixed-target charm experiment at the Tevatron could also be cost effective, as the Tevatron would not need to be run in collider mode, and also the beam energy could be reduced and still remain far above threshold. The goal of this chapter is to present the physics case for such a charm experiment. We mention, where relevant, those measurements that would not be competitive with those of a Super-B factory. We note that the most sensitive measurements of mixing and CPV rely on measuring decay-time distributions; for this type of measurement, a fixed target experiment has an advantage over an e+e- B factory experiment due to the fact that the mean decay length is notably larger than the vertex resolution.

Brief overview of technologies leading to new opportunities:

- Silicon pixels/vertexing
- Triggering on decay vertices, impact parameters
- RICH detectors, pi/K separation
- Micro gas tracking detectors, e.g., GEM

Physics topics:

- CP violation in D mixing
- Lifetimes and lifetime differences
- Direct CPV searches
- Rare and forbidden charm decays
- Spectroscopy via Dalitz-plot analyses
- Spectroscopy via production (e.g., double charm baryons)

Comparisons with other experiments:

- LHC
- Super B-Factories

Summary

In brief, we write this chapter to keep the possibility of a fixed-target charm experiment at the Tevatron a viable option for Fermilab (and the US HEP program), to be decided upon once there is a clearer picture of available funding, manpower, and feasibility of the current roadmap.

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.

References

1. T.Asaka and M. Shaposhnikov, Phys.Letters B620 (2005) 17, M. Shaposhnikov, Nucl.Physics B 763 (2007)49 M. Shaposhnikov, astro-ph/0703673, A.D.Dolgov et al., astro-ph/0008138, M.Viel et al., astro-ph/0501562 2. G.Bernardi et al, Phys.Letters 166B (1986) 479 G.Bernardi et al, Phys.Letters B203 (1988) 332 P.Astier et al., Phys.Letters B506 (2001) 27

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

[1] G. 't Hooft, Phys. Lett. B **37**, 195 (1971).

[2] T. Adams *et al.* [NuSOnG Collaboration], arXiv:0803.0354 [hep-ph].

[3] M. L. Perl *et al.*, Phys. Rev. Lett. **35**, 1489 (1975).

[4] K. Kodama *et al.*, Phys. Rev. D **78**, 052002 (2008).

[5] K. Kodama *et al.* [DONUT Collaboration], Phys. Lett. B **504**, 218 (2001) [arXiv:hep-ex/0012035].

[6] R. Schwienhorst *et al.* [DONUT Collaboration], Phys. Lett. B **513**, 23 (2001) [arXiv:hep-ex/0102026].

[7] K. Abe *et al.* [Super-Kamiokande Collaboration], Phys. Rev. Lett. **97**, 171801 (2006) [arXiv:hep-ex/0607059].

[8] S. Fukuda *et al.* [Super-Kamiokande Collaboration], Phys. Rev. Lett. **85**, 3999 (2000) [arXiv:hep-ex/0009001].

[9] C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667**, 1 (2008).

[10] P. Astier *et al.* [NOMAD Collaboration], Nucl. Phys. B **611**, 3 (2001) [arXiv:hep-ex/0106102].

[11] S. Davidson, C. Pena-Garay, N. Rius and A. Santamaria, JHEP **0303**, 011 (2003) [arXiv:hep-ph/0302093].

[12] A. Friedland and C. Lunardini, Phys. Rev. D **72**, 053009 (2005) [arXiv:hep-ph/0506143].

[13] M. Hirsch, E. Nardi and D. Restrepo, Phys. Rev. D **67**, 033005 (2003) [arXiv:hep-ph/0210137].