Fermilab

Physics at an Upgraded Fermilab Proton Driver

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4. Muons
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Steve Geer Colloquium Jan 26th, 2005

Introduction

Following the recommendations of the Fermilab Long Range Planning Committee, the Fermilab Director has requested:

"Preparation of documentation sufficient to establish mission need for the Proton Driver as defined by the Department of Energy CD-0 process."

"Development and documentation of the physics case. I would like this to include both support for a forefront neutrino program at Fermilab in the decade 2010 and beyond, and identification of other opportunities that could potentially be enabled with a Proton driver facility."

Proton Driver Physics Study
Working Groups and Conveners

WG1: Neutrino Oscillations

D. Harris (FNAL), S. Brice (FNAL), W. Winter (Princeton)

WG2: Neutrino Interactions

J. Morfin (FNAL), R. Ransome (Rutgers), R. Tayloe (Indiana)

WG3: Muons

R. Ray (FNAL), R. Roberts (BU)

WG4: Kaons and Pions

H. Nguyen (FNAL), T. Yamanaka (Osaka U.)

WG5: Antiprotons

D. Christian (FNAL), M. Mandelkern (UCI)

WG6: Tevatron Collider

H. Cheung (FNAL), Penny Kasper (FNAL), P. Ratoff (Lancaster U.)

WG7 Neutrons

T. Bowles (LANL), G. Greene (ORNL)

Neutrinos are Everywhere

Neutrinos outnumber ordinary matter particles in the Universe (electrons, protons, neutrons) by a factor of ten billion.

Depending on their masses they may account for a few % of the unknown "dark matter" in the Universe

Neutrinos are important for stellar dynamics: $\sim 7\times 10^{10}\ cm^{-2}s^{-1}$ stream through the Earth from the sun. Neutrinos also govern Supernovae dynamics, and hence heavy element production.

If there is CP Violation in the neutrino sector, then neutrino physics might ultimately be responsible for Baryogenesis.

To understand the nature of the Universe in which we live we must understand the properties of the neutrino.

We Don't Know Everything About Neutrinos

From the US APS Multi-Divisional Study on the Physics of Neutrinos

- *What are the masses of the neutrinos?*
- *What is the pattern of mixing among the different types of neutrinos?*
- *Are neutrinos their own antiparticles?*
- *Do neutrinos violate the symmetry CP?*
- *Are there "sterile" neutrinos?*
- *Do neutrinos have unexpected or exotic properties?*
- *What can neutrinos tell us about the models of new physics beyond the Standard Model?*

Neutrino Oscillations are Exciting

Neutrinos have nonzero masses and mixings !

This is exciting because:

The Standard Model needs modification accommodate neutrino mass terms, which require either the existence of right-handed neutrinos $\rightarrow$ Dirac mass terms, or a violation of lepton number conservation $\rightarrow$ Majorana mass terms. The physics of neutrino masses & mixings is physics beyond the Standard Model

We don't know the neutrino mass spectrum but we do know that neutrino masses & mass splittings are tiny compared to the masses of the other fundamental fermions. This suggests radically new physics, which perhaps originates at the GUT or Planck Scale, or indicates the existence of new spatial dimensions, or …..

Neutrino Measurements Drive Theoretical Ideas

Although we don’t have complete knowledge of the neutrino mixing matrix, we do know it is qualitatively very different from the quark mixing matrix. This necessarily constrains theoretical ideas about the underlying relationship between quarks and leptons.

Over the last few years knowledge of neutrino oscillation parameters has eliminated a previous generation of GUT models, leading to a new set of models designed to accommodate the data.

Further oscillation measurements will necessarily reject the majority of the new models, and hopefully lead to new ideas about physics beyond the Standard Model

Neutrino Oscillation Measurements Drive Theoretical Ideas. This is expected to continue to be the case throughout the Proton Driver era.

Neutrino Mixing

Within the framework of 3-flavor mixing, the 3 known flavor eigenstates (ν_e, ν_μ, ν_τ) are related to 3 neutrino mass eigenstates (ν_1, ν_2, ν_3) :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \big(3\times3\big) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

We know that U_{MNS} is very different from the CKM Matrix

$$U_{MNS}: \begin{pmatrix} \text{large} & \text{large} & \text{small/tiny/0 ?} \\ \text{large} & \text{large} & \text{large} \\ \text{large} & \text{large} & \text{large} \end{pmatrix}$$

$$\text{CKM}: \begin{pmatrix} \sim 1 & \text{small} & \text{tiny} \\ \text{small} & \sim 1 & \text{tiny} \\ \text{tiny} & \text{tiny} & \sim 1 \end{pmatrix}$$

Neutrino Mixing Matrix

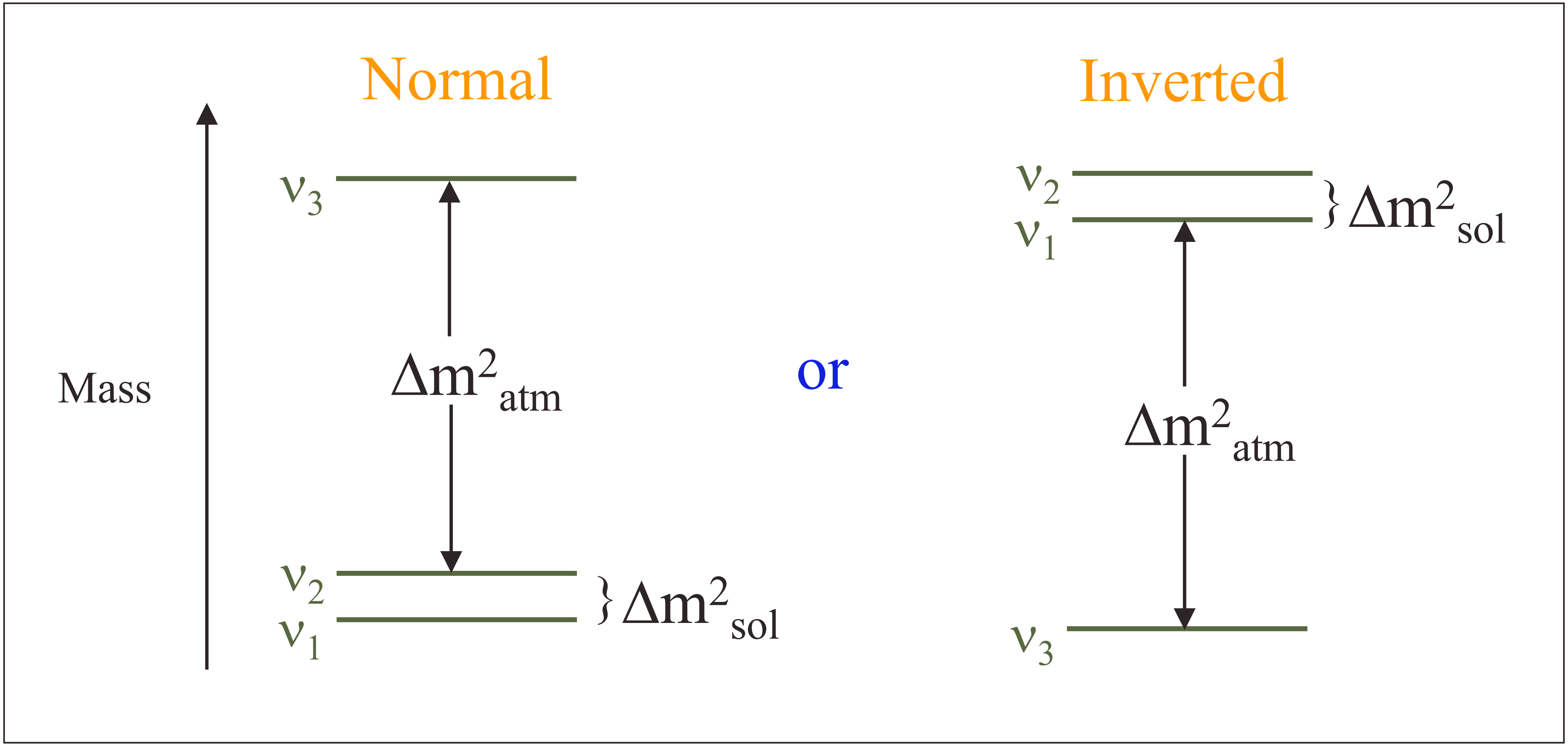
In analogy with the CKM matrix, U_{MNS} can be parameterized using 3 mixing angles (θ_{12} , θ_{23} , θ_{13}) and one complex phase (δ) :

$$\begin{pmatrix} C_{12}C_{23} & S_{12}C_{13} & S_{13}\,e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{23}\,S_{13}\,e^{i\delta} & C_{12}C_{23} - S_{12}C_{23}\,S_{13}\,e^{i\delta} & S_{23}C_{13} \\ S_{12}S_{23} - C_{12}C_{23}\,S_{13}\,e^{i\delta} & -C_{12}S_{23} - S_{12}C_{23}\,S_{13}\,e^{i\delta} & C_{23}C_{13} \end{pmatrix}$$

We do not know the values of θ_{13} or the CP phase δ. If θ_{13} and δ are non-zero, there will be CP Violation in the neutrino sector.

Neutrino Mass Spectrum

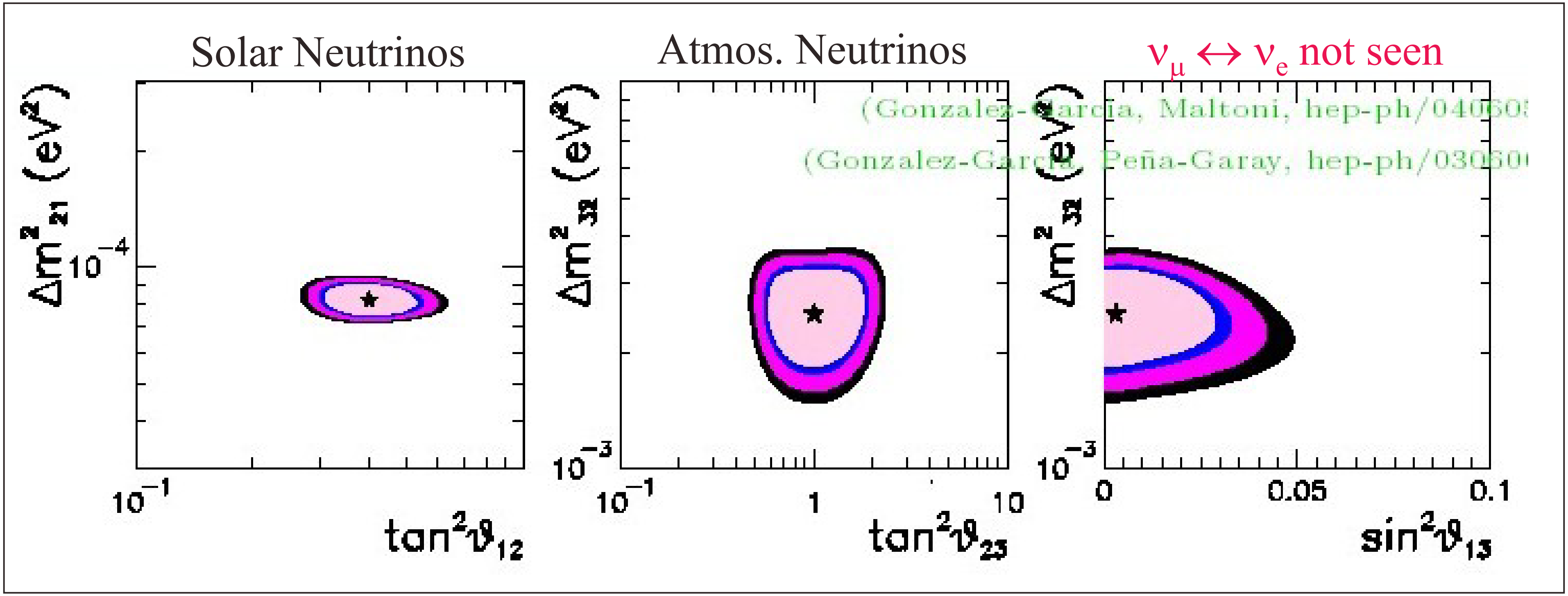
The oscillations are driven by the mass splittings: $\Delta m^2_{ij} \equiv m^2_i - m^2_j$



$\Delta m^2_{sol} \cong 8 \times 10^{-5}\ eV^2, \quad |\Delta m^2_{atm}| \cong 2.5 \times 10^{-3}\ eV^2$

Measured Parameters

For the moment, set aside the LSND result. From the solar-, atmospheric-, and reactor-neutrino data we already know a lot about the mixing matrix and mass splittings:



… but note that we have only an upper limit on θ_{13}, and know nothing about δ. We need to search for $\nu_\mu \leftrightarrow \nu_e$ oscillations !

We want to determine …

θ_{13}, δ, and the mass hierarchy

…. BUT ….

Determining all of the Parameters will be Challenging

In Vacuum:

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m_{ij}^2 \; L / 4E)$$

$$+ 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m_{ij}^2 \; L / 2E)$$

In Matter (For $\nu \to$ anti-ν, $A \to -A$, AND the sign of A depends on the sign of Δm_{32}^2)

$$P(\nu_e \to \nu_\mu) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2}$$

$$\pm \sin \delta_{CP} \; \alpha \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \cos \delta_{CP} \; \alpha \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

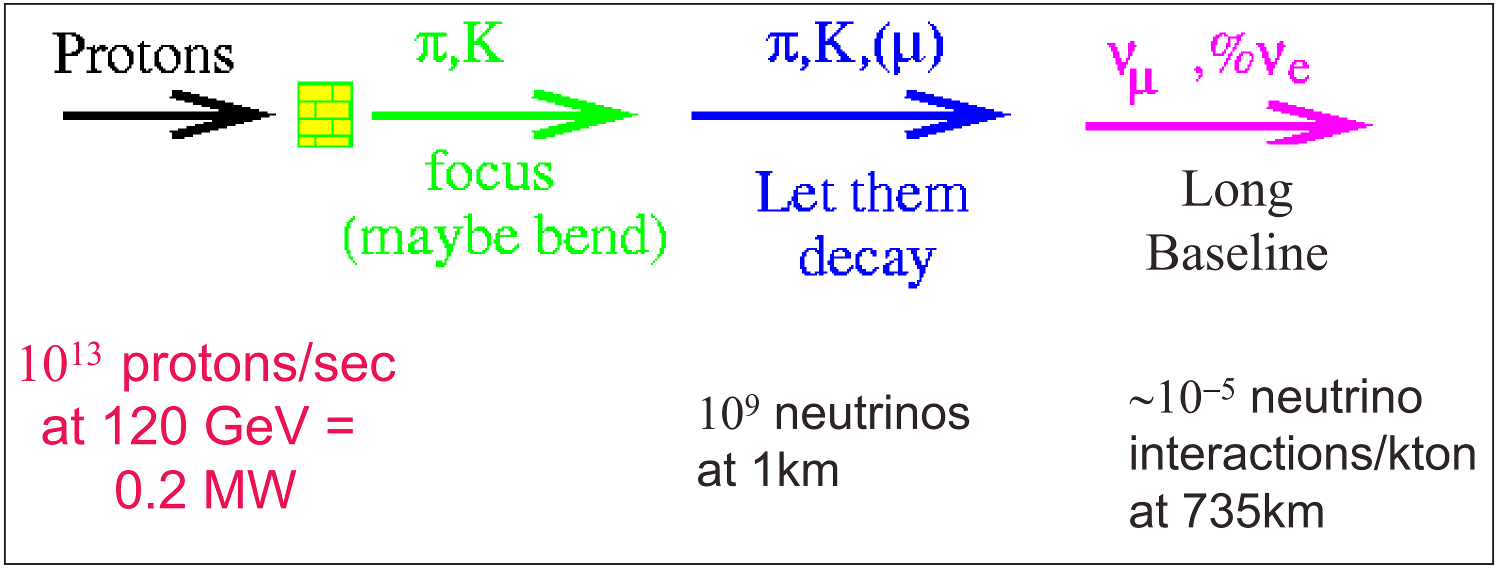
$$+ \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

ν / $\bar{\nu}$ → $\pm$

… but what about LSND & MiniBooNE ?

IF MiniBooNE confirms the neutrino oscillation interpretation of the LSND data life gets much more complicated (and very exciting)

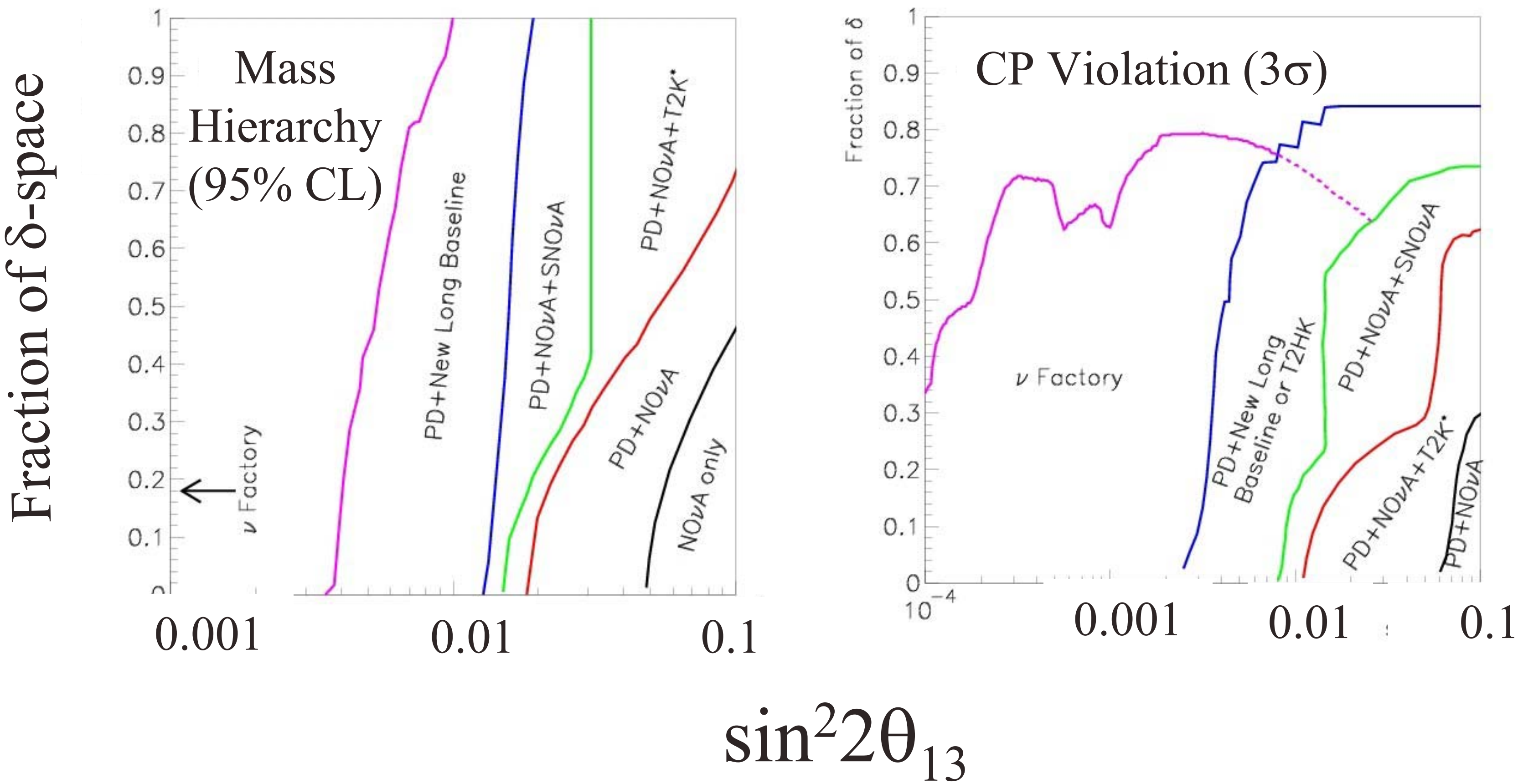
Why Do We Need High Intensity Proton Beams



We want to study rare processes. The upper limit on the all important $\nu_\mu \rightarrow \nu_e$ oscillation amplitude is ~5% !

NEED MW-CLASS MULTI-GeV PROTON SOURCES

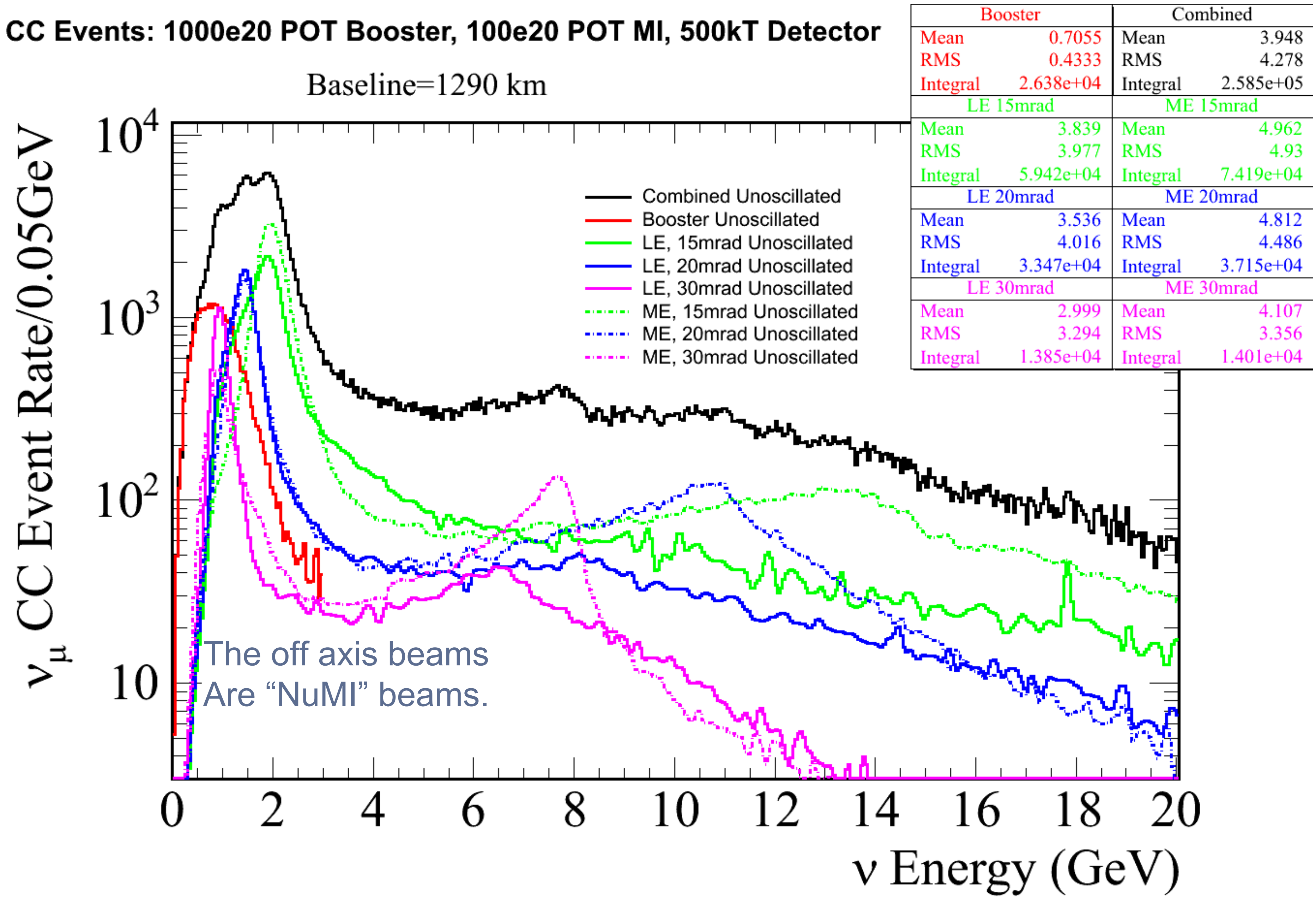
A Long-Baseline Fermilab Proton Driver Program would make Critical Contributions to the Global Program



In all scenarios it appears the Proton Driver has a critical role to play.

The 8 GeV Beam offers an interesting (unique) possibility

Doug Michael, Chris Smith Mark Messier



Neutrino Scattering Motivation

High precision neutrino and antineutrino measurements with nuclear & nucleon targets are needed for the oscillation physics program to reduce systematics from cross-section uncertainties.

Neutrino scattering measurements are of interest in their own right:

CC QE Scattering → Nucleon structure & binding of the nucleons within the nucleus
NC Elastic Scattering → Spin structure of the nucleon & the strange quark contribution
Resonant & coherent production of pions → Resonant structure of the nucleon & non-perturbative QCD tests
Strange Particle Production → Understand backgrounds for proton decay searches
Neutrino-Electron Elastic Scattering → Neutrino magnetic moment

Neutrino Scattering: Need for Higher Intensity

In the pre-Proton Driver era we expect high precision neutrino measurements of CC & NC (quasi)elastic scattering, and CC & NC producion of pions and strange particles off nuclear targets.

However: (i) The antineutrino event rate is down by a factor of 3-5 (depending on energy) compared to the neutrino rate … due to the cross-sections and the π+/ π - production ratio, and (ii) The H_2 & D_2 target rates are down by an order of magnitude compared to nuclear target rates.

We will need the Proton Driver to make high-precision measurements with antineutrino beams on nuclear targets, and with both neutrino and antineutrino beams on nucleon targets (H_2,D_2).

Interest of Nuclear Physicists

Neutrino scattering experiments at a Proton Driver would enable progress in:

Weak Form Factors
PDFs (d/u at high x)
Generalized PDFs
Strange quark content
Quark-Hadron Duality tests (structure functions in the resonant region)

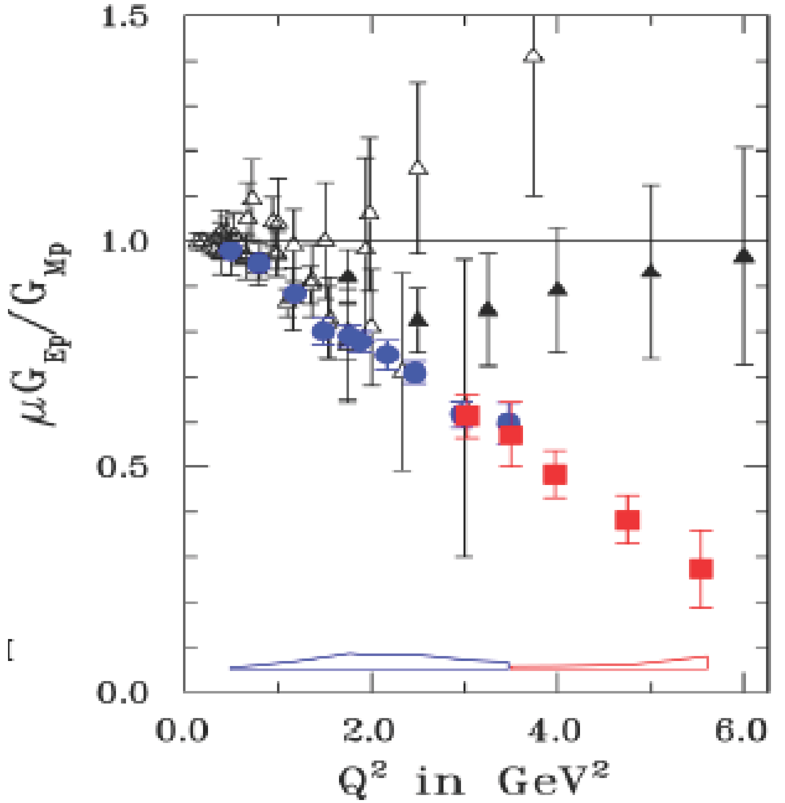
Hence there is a program of nuclear physics measurements which complements the electron scattering program at JLab and provides important input for astrophysics & nuclear physics calculations.

Interface between Particle & Nuclear Physics: One Example – The Weak Form Factor

For many years it was assumed that charge & magnetic distributions within the nucleon are exponential. However JLab measurements → charge distribution is broader than the magnetic one.

In the language of particle physics, the Perturbative QCD prediction is that Q^2F_1/F_2 is constant. Instead it appears that QF_1/F_2 approaches constant. The underlying reason is not understood, but appears to be something to do with angular momentum between the quarks.

To make further progress we would like to know the Weak Form Factor … which can be determined from neutrino-nucleon elastic (or QE) scattering at a Proton Driver.



Old data (triangles) wrong because of large radiative corrections

8 GeV Neutrino Scattering Program

The 8 GeV beam would play a critical role, enabling low energy (~1GeV) neutrino interactions to be measured with a narrow band beam, no high-energy (background generating) tail, and a 64-fold increase in intensity (wrt MiniBooNE).

Important measurements to reduce systematic uncertainties on neutrino oscillation results.

First precision measurements of low energy antineutrino scattering on nuclear targets, and neutrino & antineutrino scattering on nucleon targets.

Neutrino-electron scattering measurements provide way to improve sensitivity to neutrino magnetic moment →sensitive to new physics.

Statistics will still limit the precision of many measurements, motivating the full 2MW beam power at 8 GeV.

MI Neutrino Scattering Program

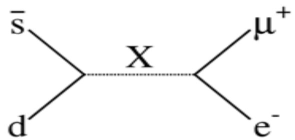
The 120 GeV beam would enable lower cross-section processes to be explored, and precision measurements of the DIS regime.

The primary interest will be in high-precision measurements with antineutrino beams on nuclear targets, and with both neutrino and antineutrino beams on nucleon targets (H_2,D_2).

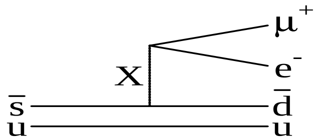
The antineutrino beam needs to be a sign-selected beam to reduce neutrino contamination.

Low Energy Probes of High Mass Scales

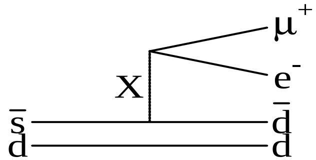
Mass Limit



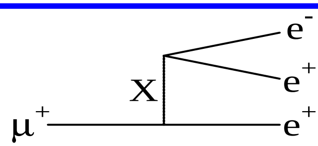
$B(K_L \to \mu e) < 4.7 \times 10^{-12}$ — 150 TeV/c^2



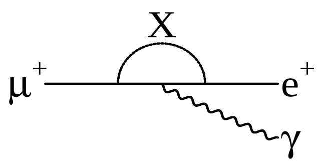
$B(K^+ \to \pi^+\mu^+e^-) < 4 \times 10^{-11}$ — 31 TeV/c^2



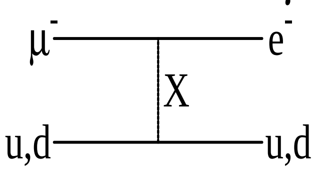
$B(K_L \to \pi^\circ\mu^+e^-) < 3.2 \times 10^{-10}$ — 37 TeV/c^2



$B(\mu^+ \to eee) < 1 \times 10^{-12}$ — 86 TeV/c^2



$B(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11}$ — 21 TeV/c^2



Normalized Rate $< 6.1 \times 10^{-13}$ — 365 TeV/c^2

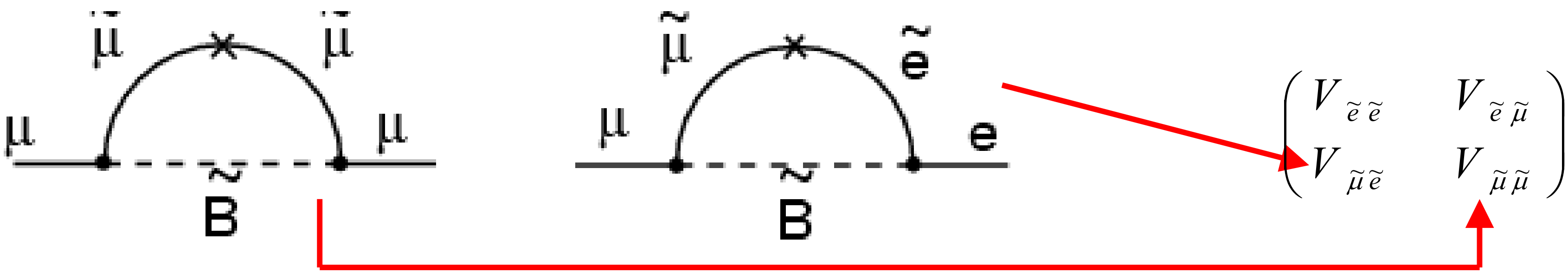
Many of these experiments are rate limited. Progress requires new beams and progress with detectors and/or readout

Muon Physics

Lepton Flavor Violation (LFV) has been established in the neutrino sector, suggesting new LFV processes at high mass scales. This physics might result in observable effects in the muon sector (?)

In addition, precision muon experiments are sensitive to new physics at the TeV scale … complementary to the LHC experiments. Examples: muon (g-2), Electric Dipole Moment, and LFV muon decays.

Within the framework of Supersymmetry:



Muon (g-2)
and EDM

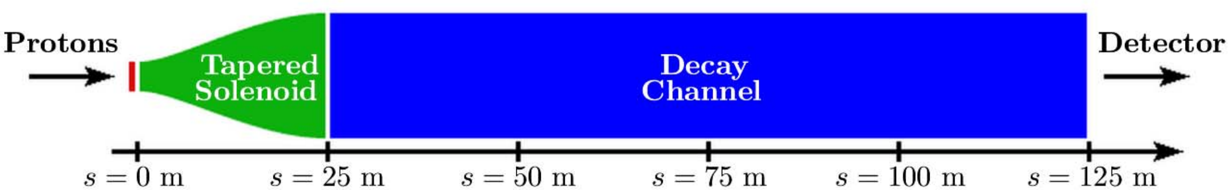
LFV
Decays

Muon Physics – An Ideal Source

Low energy precision muon experiments require high intensity beams & an appropriate bunch structure. Different experiments require different bunch structures, hence flexibility is desirable.

A 0.5-2 MW Proton Source at 8 GeV together with a rebuncher (the Recycler ?) could provide an ideal (& unique) front end for a cutting edge World class long-term muon program.

Recycler ring would be loaded with one Linac pulse (1.5×10^{14} protons) every 100 ms, and the protons chopped into 588 bunches, 3ns bunch width



MARS simulations yield 0.2 muons/p …momenta O(100 MeV/c), occupying large transverse phase space

→ 3×10^{21} muons per year (10^7 secs)

Kevin Paul et al

Muon Physics - Sensitivity

The estimated number of low energy muons that could be provided with a new Proton Driver (3×10^{21} per year) is very large … but its utilization will probably be very inefficient (large phase space).

Muon Source Requirements to Needed Make Progress

Experiment	q_μ	$\int I_\mu dt$	I_0/I_m	δT [ns]	ΔT [μs]	E_μ [MeV]	$\Delta p_\mu/p_\mu$ [%]
$\mu^- N \to e^- N^\dagger$	$-$	10^{21}	$< 10^{-10}$	≤ 100	≥ 1	< 20	< 10
$\mu^- N \to e^- N^\ddagger$	$-$	10^{20}	n/a	n/a	n/a	< 20	< 10
$\mu \to e\gamma$	$+$	10^{17}	n/a	n/a	n/a	1…4	< 10
$\mu \to eee$	$+$	10^{17}	n/a	n/a	n/a	1…4	< 10
$\mu^+ e^- \to \mu^- e^+$	$+$	10^{16}	$< 10^{-4}$	< 1000	≥ 20	1…4	1…2
τ_μ	$+$	10^{14}	$< 10^{-4}$	< 100	≥ 20	4	1…10
transvers. polariz.	$+$	10^{16}	$< 10^{-4}$	< 0.5	> 0.02	30-40	1…3
$g_\mu - 2$	$\pm$	10^{15}	$< 10^{-7}$	≤ 50	$\geq 10^3$	3100	10^{-2}
edm_μ	$\pm$	10^{16}	$< 10^{-6}$	≤ 50	$\geq 10^3$	$\leq$1000	$\leq 10^{-3}$
M_{HFS}	$+$	10^{15}	$< 10^{-4}$	≤ 1000	≥ 20	4	1…3
M_{1s2s}	$+$	10^{14}	$< 10^{-3}$	≤ 500	$\geq 10^3$	1…4	1…2
μ^- atoms	$-$	10^{14}	$< 10^{-3}$	≤ 500	≥ 20	1…4	1…5
condensed matter (incl. bio sciences)	$\pm$	10^{14}	$< 10^{-3}$	< 50	≥ 20	1…4	1…5

Most experiments require p < 29 MeV/c, good extinction factors, small Δp/p.

To make progress we need to try to design a cost-effective muon source, the matching to the candidate exper-iments → evaluate cost & performance.

Cost may be the make or break issue.

Muon Physics: $a_\mu = (g-2)/2$

Sensitive to muon substructure, anomalous gauge couplings, leptoquarks, supersymmetry, …).

The present BNL g-2 result shows a 2.7σ effect ???

Minimal SUSY models predict, for some regions of parameter space, large contributions to a_μ – arising from loops with a chargino and muon sneutrino and loops with a neutralino and smuon.

If SUSY is discovered at the Tevatron or LHC and sparticle masses measured, a new round of muon g-2 measurements would yield information about tan β and SUSY mixing.

If new physics is not seen at the LHC, new g-2 measurements would provide one of the few practical ways of probing higher mass scales.

Muon Physics: EDM

Electric Dipole Moments violate P & T invariance & hence CP (if CPT conserved). Non-zero EDMs would indicate a new source of CP violation beyond the Standard Model.

There are regions of SUSY parameter space that predict large EDMs. If SUSY is discovered at the Tevatron or LHC, measurements of the muon EDM, together with a_μ, will provide information about the new CP-violating phases difficult to obtain any other way.

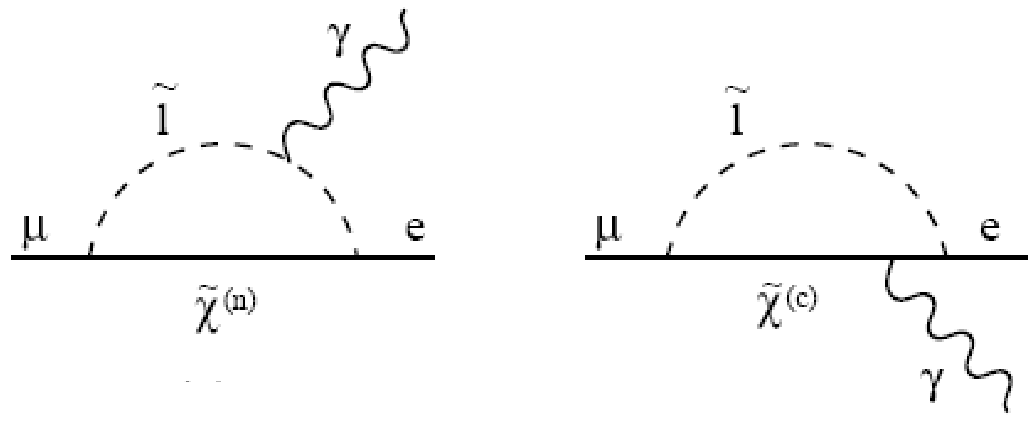
Present EDM limits ($d_\mu < 3.7 \times 10^{-19}$ e-cm). An experiment has been proposed at JPARC to obtain a sensitivity of 10^{-24} e-cm. To go further will need better beam structure with many short pulses, each separated by >500μs. Depending on the fate of the JPARC proposal a Fermilab Proton Driver experiment might be designed to have a sensitivity anywhere in the range 10^{-24} - 10^{-26} e-cm

Muon Physics – LFV Decays

$\mu \to e\gamma$, $\mu \to e$ conversion, $\mu \to eee$, …

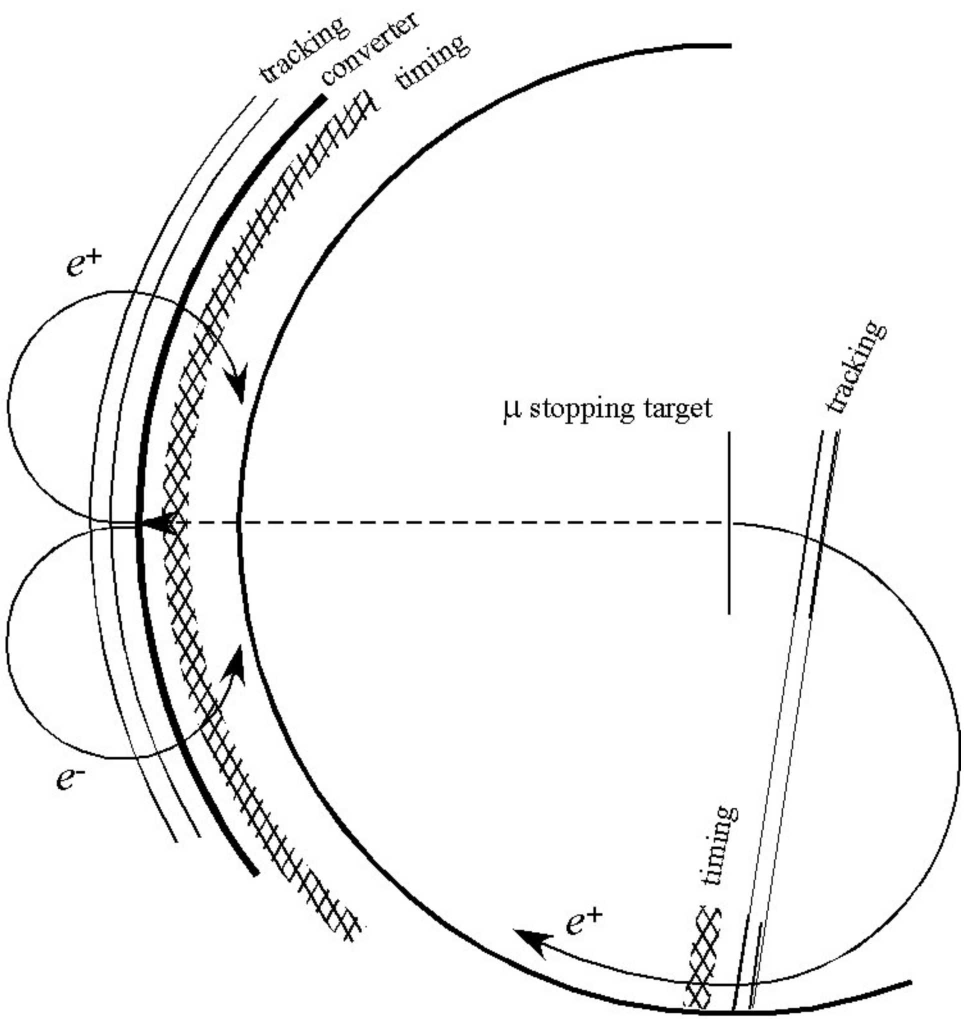
In SUSY Seesaw models LFV depends on SUSY breaking, & can be sizable. If SUSY observed at the LHC, LFV searches/measurements → information about SUSY breaking.

Example: $\mu \to e\gamma$



Present limit: BR < 1.2×10^{-11}. The MEG experiment at PSI expected to improve sensitivity to ~ 10^{-14} by end of decade … the MEG sensitivity will complement LHC measurements. Further progress depends requires an improved muon source & better detector technology giving better background rejection (i.e. resolutions) & enabling higher rates.

Example: $\mu \rightarrow e\gamma$ (Fritz DeJongh).



Use BTeV silicon pixel detectors for tracking → sensitivity comparable to MEG, limited by scattering in relatively thick pixels.

Imagine pixel thickness reduced by ×10. With idealized detector geometry it has been shown that BR sensitivities $O(10^{-15} – 10^{-16})$ are plausible.

Pions

Use 8 GeV proton beam + Recycler (?) as a stretcher.

Interface between particle & nuclear physics: Meson & baryon spectroscopy & Lattice Gauge Theory tests. Would complement the JLab program. Baryon spectroscopy requires a 2.5 GeV/c π/K tagged secondary beam.

$\pi e2$ & $\pi\mu 2$ decays → precise probe of e-μ universality in the weak interaction. Theoretical predictions 40 × more precise than experiment.

$\pi^+ \rightarrow e + \nu\pi^0$ potentially offers improved V_{ud} measurement.

Kaons

Mode	Sample	Physics	Number of Protons on Target
$K^+ \rightarrow \pi^+ \nu\nu$	1000	3% $(V_{ts}{}^*V_{td})$	1.5×10^{20}
$K_L \rightarrow \pi^0 \nu\nu$	1000	1.5% $Im(V_{ts}{}^*V_{td})$	1.6×10^{21}
$K_L \rightarrow \pi^0 ee$	2×10^4	10% $Im(V_{ts}{}^*V_{td})$	2.5×10^{20}
$K_S\text{-}K_L \rightarrow \pi^0 ee$	TBD	10% $Im(V_{ts}{}^*V_{td})$	TBD

Present generation of rare kaon decay experiments are already rate limited. Future experiments at the Proton Driver would need to benefit from a DC beam with a large duty cycle (refit Tevatron Ring with permanent magnet dipoles ?) & the improvements in instrumentation expected in the next few years. If this can be accomplished the Proton Driver would offer the possibility of advances in kaon decay sensitivity.

Neutrons

Proton Driver would be comparable in its neutron capabilities with an upgraded SNS. There are some physics topics that will not be covered by the SNS program, and could be unique to the Proton Driver: (i) Production of ultra-cold neutrons → neutron EDM and lifetime, (ii) neutron induced "upsets" in semiconductors, (iii) n-nbar oscillations (improve sensitivity by ×100)

Antiprotons

The antiproton source could be used with the Proton Driver for a continuation of the low energy antiproton program: (i) Bottom-onium formation (?), (ii) CP Violation in hyperon decays – order of magnitude improvement in sensitivity over HyperCP, (iii) Light hadron spectroscopy (?)

SUMMARY: The Neutrino Physics Case for a Fermilab Proton Driver seems to be Strong

Neutrino Oscillation physics is exciting $\rightarrow$ World Class multi-phase program with the potential for big discoveries

The Proton Driver program would make critical contributions to the Global program in all θ_{13} scenarios, & (within reason) independent of exactly what else is built and when.

Neutrino scattering physics broadens the program $\rightarrow$ many thesis topics

Fermilab can build upon its existing significant investment in hosting the US accelerator based neutrino program.

SUMMARY: The Proton Driver could support a diverse physics program

Physics of LFV $\leftrightarrow$ Probing the GUT scale:
Neutrino Oscillations, precision muon experiments.

Physics at the TeV-scale (complementary to the LHC program):
Precision muon and kaon experiments, neutron experiments (?)

Interface between particle and nuclear physics (complementary to Jlab program):
Neutrino scattering, hadron spectroscopy ….

Other possibilities:
Neutrons, antiprotons, …

Invitation

To learn more:

Weekly General Proton Driver Meetings:
Wednesdays at 2pm in 1 West

http://protondriver.fnal.gov/

Much has been done, but there is much more to do.