Physics Case for Project X

Flavor Physics at Fermilab

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A revolution awaits at the Terascale

- First hints appeared over 50 years ago
- Recent discoveries have only increased our expectations

- It’s exciting to finally have the tools we need!
New Tools

- CERN Large Hadron Collider
  - Broad-band initial state, tremendous reach
- Proposed International Linear Collider
  - Clean and controlled initial state, great precision
- LSST, JDEM
  - Large survey telescopes, on Earth and in space
- Underground experiments
  - Innovative approaches to dark matter detection
- Intense proton sources around the world

A new era of discovery!
Project X?
- An ILC-style superconducting intense proton linac

- Over 200 kW of 8 GeV protons out of Recycler
- Over 2 MW of 50-120 GeV protons out of Main Injector
Take Home Messages

● Message One
  ♦ Change the name
    - “What’s in a name? That which we call a rose by any other name would smell as sweet.” NOT!
      ▪ SLAC: Superconducting Linear Accelerator Complex
      ▪ FNAL: Flavor and Neutrino Accelerator (Linear)
      ▪ PPARC: Precision Physics Accelerator Research Center

● Message Two
  ♦ Know the competition
    - Project X is being developed in an era with many exciting (and competing) physics opportunities …
    - As well as new international facilities, especially J-PARC
Take Home Messages

● Message three
  ♦ Frame the opportunity
    – How does Project X advance our understanding of particle physics, consistent with the grand themes outlined by EPP2010?

● Message four
  ♦ Make the physics case
    – Project X needs a strong physics case to go forward
    – Starting with this Workshop, we need to make it …
To my mind, the case for Project X has its roots in the famous question of I.I. Rabi when he learned about the muon:

“Who ordered that?”

Today, we might ask why nature comes in three Xerox copies

We still don’t know …
After 70 years, however, we have learned a lot

- The quark sector is well-characterized
  - CKM matrix has been measured precisely
  - GIM mechanism is well established

- The lepton sector is progressing rapidly
  - New news: Neutrinos have tiny masses
  - PMNS matrix is being measured as we speak

Project X must build on this base

- To add value to the LHC/ILC program
- To answer important new questions in the physics of flavor
In this talk I will sketch the physics case – as I see it today – in three parts:

- Quark Flavor Physics
- Charged Lepton Flavor Physics
- Neutrino Physics

I will ask more questions than I will answer …

- I hope you will support me where I am right …
- I know you will correct me where I am wrong!
  - We have to get this right!
QUARKS
Precision flavor experiments in the quark sector have established:

- Quarks mix: quark flavor number is not conserved
- Protons are very stable: baryon number is conserved
- Flavor-changing neutral currents are suppressed

   - Limits on new FCNC physics are in the range of 1000 TeV, far beyond what is accessible at LHC and ILC
   - Yet we expect a rich new phenomenology at the TeV scale

How does this new physics suppress FCNC?
What does it tell us about the physics of flavor?
In fact, the LHC is not terribly sensitive to the flavor physics of the first and second generations

- It will open the Terascale, but it will not reveal all its salient features
  - That is the primary argument for the ILC
  - It is also a strong argument for the continued pursuit of flavor physics

- Once we cross the threshold, we will need to know all the details
  - To make sense of the discoveries – and the questions that they, in turn, will raise …
Today, before the LHC turns on, there are many models of Terascale physics. They all require some sort of GIM-like mechanism to suppress FCNC

- Minimal Quark Flavor Violation represents a way to think about flavor physics in a consistent low-energy effective field theory. Assumptions:
  - No new light DOF $\Rightarrow$ SU(3) x SU(3) x SU(3) flavor group
  - Flavor symmetry broken only by Yukawa matrices
  - Yukawa matrices act like spurions in effective theory

\[ \lambda_U \sim (\bar{3}, 3, 1) \quad \lambda_D \sim (\bar{3}, 1, 3) \]
Under SU(3) x SU(3) x SU(3), the Yukawa matrices transform as follows

\[ \lambda_U \rightarrow U_U \lambda_U U_Q^\dagger \quad \lambda_D \rightarrow U_D \lambda_D U_Q^\dagger \]

Then the effective Hamiltonian for K → π νν contains

\[ \mathcal{H}_{\text{eff}} = \frac{(\lambda_U^\dagger \lambda_U)^j_i}{\Lambda_{QFV}^2} \bar{q}_j \bar{\sigma}^\mu q^i \bar{\nu} \sigma^\mu \nu \]

where \( \Lambda_{QFV} \) is the scale of quark flavor violation, which we assume is about 1 TeV …
The MQFV formalism describes the low-energy effects of Terascale physics, consistent with the stringent constraints from FCNC

- It provides a baseline – a model-independent framework that we can use to study the reach of future experiments

- It also gives a starting point for discussing the effects of individual models
  - Supersymmetry, extra dimensions, little Higgs, and grand unification …

Cirigliano, Grinstein, Isidori, Wise
Project X is sensitive to the rare decay $K \rightarrow \pi \nu \bar{\nu}$

- Gold plated modes! Clean and calculable …

Other experiments probe other rare processes

- By comparing the results from a suite of different experiments, one can begin to untangle the physics the underlies flavor

We should either confirm MQFV – or refute it

- We learn about Terascale physics, either way!
  - 1 TeV if there is a rich flavor environment at LHC
  - 1000 TeV if the LHC flavor environment is sparse!
LEPTONS
Leptons

- Neutrino experiments have established
  - Leptons mix: lepton flavor number is not conserved
- It is also likely, but not proven, that
  - Lepton number is not conserved

- These facts motivate a rich set of possible experiments at Project X
  - Searching for $\mu \rightarrow e$ conversion
  - Measuring properties of neutrinos
Project X can search for charged lepton flavor violation through $\mu \rightarrow e$ conversion.

Minimal Lepton Flavor Violation provides a plausible framework, since it mimics the physics of the quark sector.

- A risky assumption, given the very different quark and lepton mixings ....

Nevertheless, MLFV provides a consistent and model-independent way to analyze the reach of experiments at Project X.
In the lepton sector, the analysis is a little more complicated than in the quark sector

Assumptions:

- No new light DOF $\Rightarrow$ SU(3) x SU(3) flavor group
  $\Rightarrow$ Neutrinos have a Majorana mass. Can be relaxed ...
- Flavor symmetry broken by Yukawa matrix and by the neutrino Majorana mass matrix
- Yukawa and mass matrices act like spurions in effective theory

\[ \lambda_L \sim (\bar{3},3) \quad g \sim (\bar{6},1) \]
Charged Leptons

- The neutrino mass spurion relates the weak scale $v$ to the scale of lepton number violation, $\Lambda_{LV} \gg v$

\[ m_\nu \sim g \frac{v^2}{\Lambda_{LV}} \quad \Rightarrow \quad g \sim \frac{\Lambda_{LV}}{v^2} \quad m_\nu \sim O(1) \]

- The spurions transform under SU(3) x SU(3)

\[ \lambda_E \rightarrow U_E \lambda_E U_L^\dagger \quad g \rightarrow U_L^* g U_L^\dagger \]

- With two such spurions, the analysis is a bit more complicated than in the quark case
The effective Hamiltonian for $\mu \rightarrow e$ conversion contains

$$\mathcal{H}_{\text{eff}} = \frac{(g^\dagger g)^{j \bar{i}}}{\Lambda_{\text{LFV}}^2} \bar{\ell}_j \sigma^\mu \ell_i \bar{q} \sigma^\mu q$$

where $\Lambda_{\text{LFV}}$ is the scale of lepton flavor violation, which we assume is around 1 TeV …

This rate is potentially accessible with a $\mu \rightarrow e$ conversion experiment at Project X …

- How does it depend on the value of $\sin^2 2\theta_{13}$?
Discovering $\mu \rightarrow e$ conversion would open an important new window on flavor physics

- A key piece of the puzzle
  - Lepton flavor physics $\leftrightarrow$ quark flavor physics

When combined with other experiments, it would either confirm MLFV, or point the way to a deeper understanding

- As with quark flavor, we learn about Terascale physics – either way!
NEUTRINOS
Neutrinos

- Neutrinos have provided much excitement in recent years. They have penetrated popular culture …
- They require new physics, beyond the ordinary Standard Model

◊ What are they telling us?
  - About unification?
    ▪ Masses point to unification scale
    ▪ Mixings, though, are very different from those of the quarks
  - About cosmology?
    ▪ In principle, the neutrino sector contains extra CP violation
To find the answers, we need experiments!
- Are neutrino masses Dirac or Majorana?
- Is the mass ordering normal – or inverted?
- How much CP violation is due to leptons?

Project X has a good chance of answering these questions – provided $\sin^2 2\theta_{13}$ is large enough …
Potential reach:

\[ \sin^2 2\theta_{13} \sim 0.001 \text{ if far detector at DUSEL distance} \]
Neutrinos

Potential reach:
\[ \sin^2 2\theta_{13} \sim 0.001 - 0.0001 \]
if far detector at DUSEL distance
Neutrinos

**Discovery Potential sign$\Delta m^2_{13}$**

- CHOZ Excluded

- Project X with 2 detectors

- Project X with longer baseline detector

**3σ Discovery Potential for $δ≠0$ and $ξ≠r$**

- CHOZ Excluded

- Project X with 2 detectors

- Project X with longer baseline detector
My Conclusions

- Project X offers a potentially rich program of quark and lepton flavor physics in the LHC era
  - Progress, though, will require a variety of approaches
    - B and K systems, $\mu \rightarrow e$ conv, $\mu \rightarrow e \gamma$, muon g-2, EDM …

- A possible Project X physics program could include
  - $K \rightarrow \pi \nu\nu$ and $\mu \rightarrow e$ conversion …
    - As a window on the Terascale – and beyond …
  - Neutrino physics if $\sin^2 2\theta_{13}$ large enough
    - Expect update in 2012-2013 …
  - And who knows what – years down the road …
My Conclusions

- For Project X to be realized, however, many questions have to be answered …
  - What is its role in relation to the LHC?
    - CERN Workshop: *Flavor Physics in the LHC Era*
  - What else is happening – at home and abroad?
    - Can some experiments be done cheaper elsewhere?
  - What are the beam and detector requirements?
    - Do all the experiments need Project X?

- Detailed calculations are needed to convincingly demonstrate the importance of Project X in the worldwide flavor program
My Conclusions

- These are tough times, with lots of competition for funds. Therefore we need to make the physics case for Project X as strong as it can possibly be
  - We should set the bar high – but not impossibly so …
    - Project X is part of a worldwide program in flavor physics
      - It does not need to do everything
      - But it needs to add true value …
  - Clearly, a huge factor is alignment with the ILC …
    - If Project X positions Fermilab as a credible host, it might be well worth the effort. But if Project X gets in the way, it would be a mistake
My Conclusions

- In the years ahead, P5 and HEPAP will evaluate Project X in the context of the overall HEP program
  - A strong physics case can make the choice clear
    - Such a case must place Project X squarely in the context of the most important questions facing our field
  - The case is not there yet … so there is work to do …
- The stakes for are high for us all!