Physics Case for Project X

Flavor Physics at Fermilab

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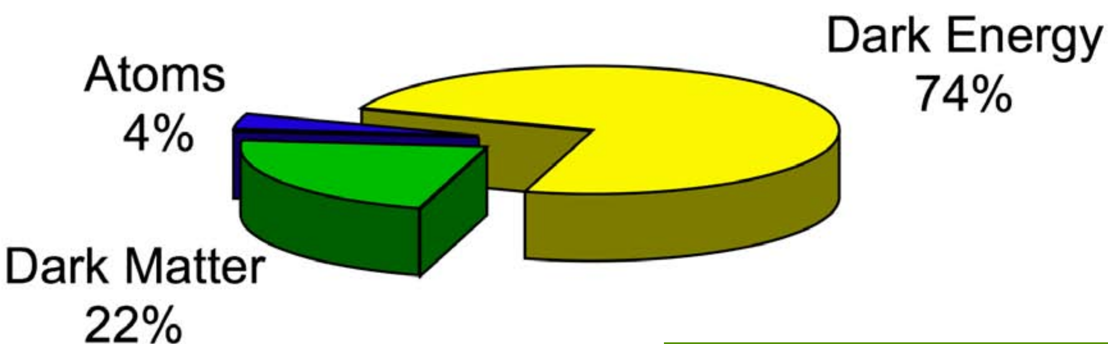
11/16/07

Context

- A revolution awaits at the Terascale
  - First hints appeared over 50 years ago
  - Recent discoveries have only increased our expectations



Composition of Universe

- It's exciting to finally have the tools we need!

New Tools

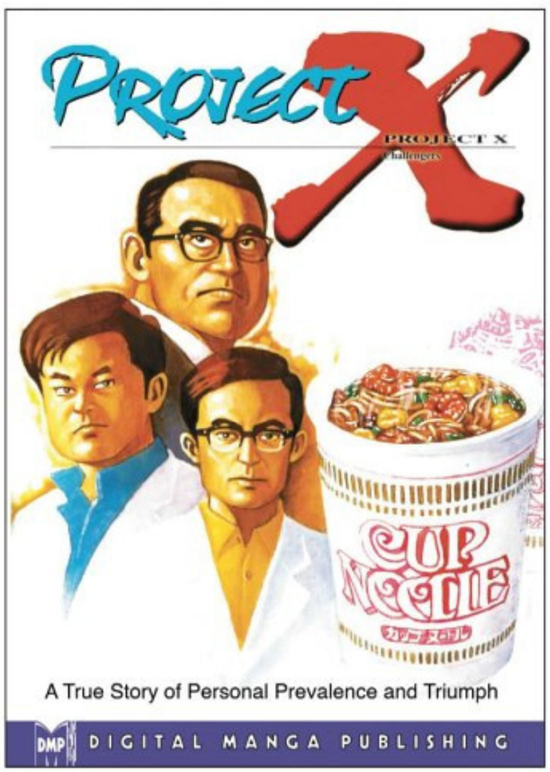
- CERN Large Hadron Collider
  - Broad-band initial state, tremendous reach
- Proposed International Linear Collider
  - Clean and controlled initial state, great precision
- LSST, JDEM
  - Large survey telescopes, on Earth and in space
- Underground experiments
  - Innovative approaches to dark matter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

A new era of discovery!

Project X?


Project X™
Project management for the rest of us.
Manage your success


Project X
Jim Shepard
a novel


PROJECT X
PROJECT X
Challengers
CUP NOODLE
A True Story of Personal Prevalence and Triumph
DMP
DIGITAL MANGA PUBLISHING


project-x
CLOSING DOWN THE SYSTEMS

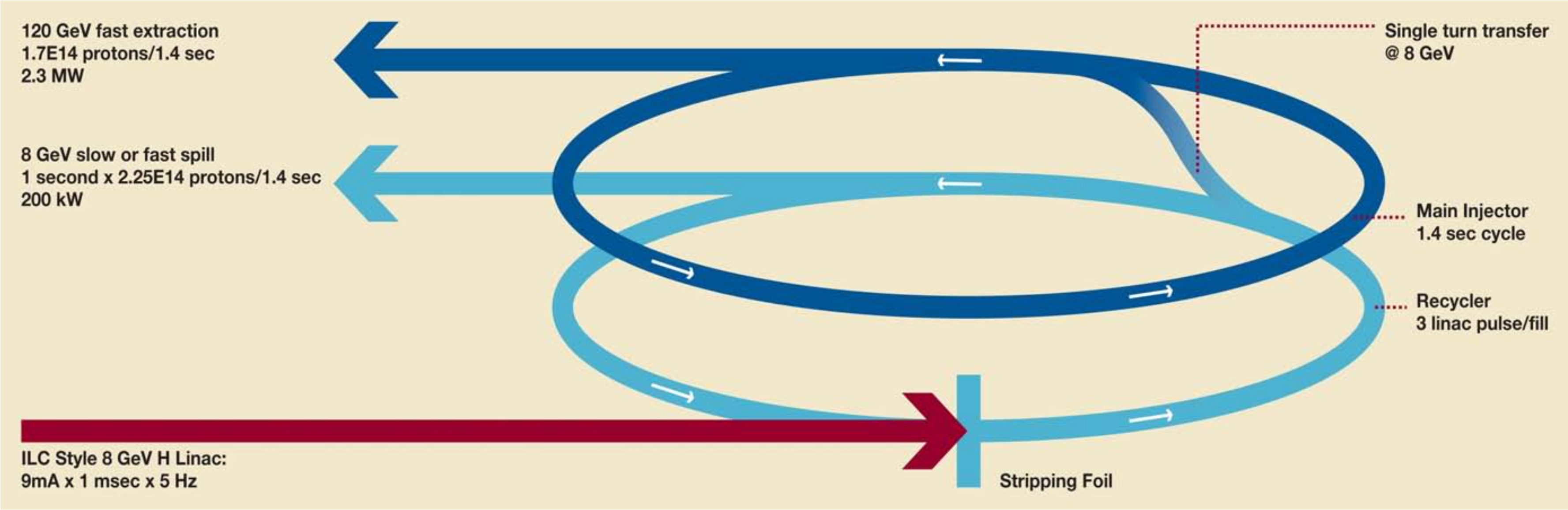

PROJECT-X
CLASSIC
TEAM17
ONE MEG AMIGA


IT HAPPENED IN THIS UNIVERSE A LONG TIME AHEAD, THE YEAR 2118...
PARAMOUNT PICTURES presents
A WILLIAM CASTLE PRODUCTION
PROJECT X
CHRISTOPHER GEORGE · GRETA BALDWIN


PROJECT X
JAMES HORNER

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

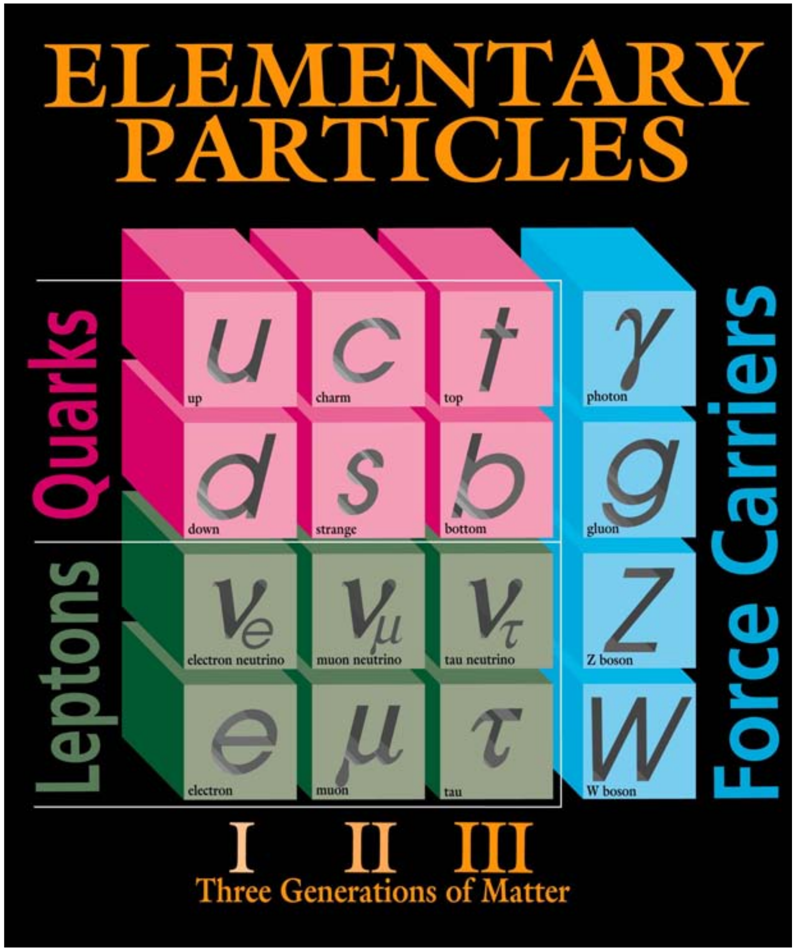
Take Home Messages

- 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
    - <u>Starting with this Workshop, we need to make it</u> …

The Physics Case

X

- 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 …



The Physics Case

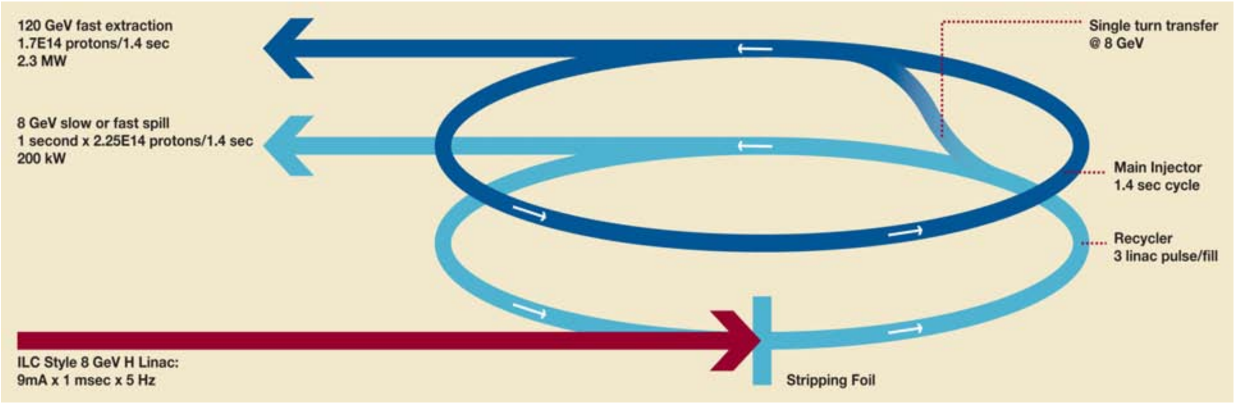
- After 70 years, however, we have learned a lot
  - The quark sector is well-characterized
    - CKM matrix has been measured precisely
    - GIM mechanism is well established
  - The lepton sector is progressing rapidly
    - New news: Neutrinos have tiny masses
    - PMNS matrix is being measured 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

This Talk

- 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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Single turn transfer
@ 8 GeV
Main Injector
1.4 sec cycle
Recycler
3 linac pulse/fill
ILC Style 8 GeV H Linac:
9mA x 1 msec x 5 Hz
Stripping Foil

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?

Quarks

- 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 …

Quarks

- 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

$$\lambda_U \sim (\bar{3},3,1) \qquad \lambda_D \sim (\bar{3},1,3)$$

Quarks

- Under SU(3) x SU(3) x SU(3), the Yukawa matrices transform as follows

$$\lambda_U \;\rightarrow\; U_U\,\lambda_U\,U_Q^\dagger \qquad\qquad \lambda_D \;\rightarrow\; U_D\,\lambda_D\,U_Q^\dagger$$

- Then the effective Hamiltonian for K → π νν contains

$$\mathcal{H}_{\rm eff} \;=\; \frac{(\lambda_U^\dagger\,\lambda_U)^j{}_i}{\Lambda_{\rm QFV}^2}\;\bar{q}_j\bar{\sigma}^\mu q^i\;\bar{\nu}\bar{\sigma}^\mu\nu$$

where Λ_{QFV} is the scale of quark flavor violation, which we assume is about 1 TeV …

Quarks

X

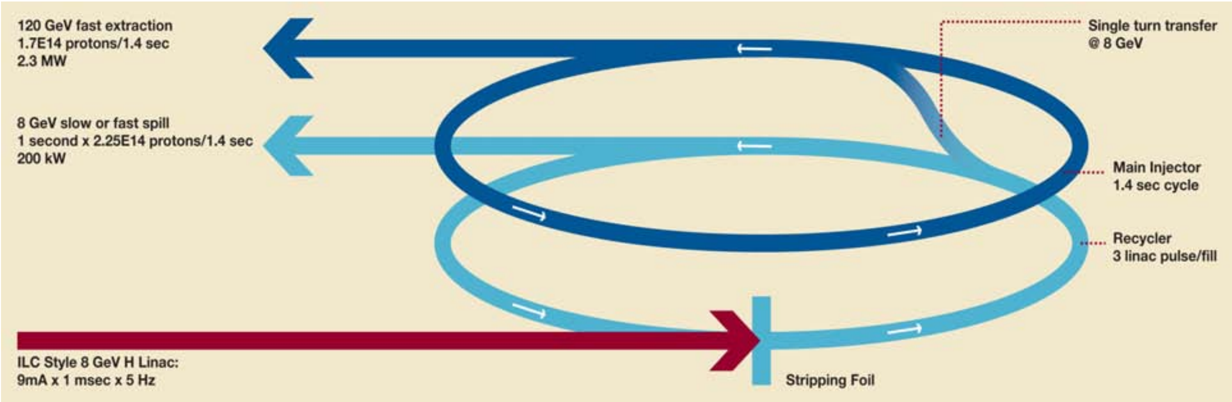
- The MQFV formalism describes the low-energy effects of Terascale physics, consistent with the stringent constraints from FCNC
  - It provides a baseline – a model-independent framework that we can use to study the reach of future experiments
- It also gives a starting point for discussing the effects of individual models
  - Supersymmetry, extra dimensions, little Higgs, and grand unification …

Cirigliano, Grinstein, Isidori, Wise

Quarks

- Project X is sensitive to the rare decay K $\rightarrow$ π $\nu\nu$
  - 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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Leptons

X

- 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 experi-ments at Project X
  - Searching for $\mu \rightarrow e$ conversion
  - Measuring properties of neutrinos

Charged Leptons

- 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

Charged Leptons

- 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

$$\lambda_L \sim (\bar{3},3) \qquad g \sim (\bar{6},1)$$

Charged Leptons

X

- The neutrino mass spurion relates the weak scale v to the scale of lepton number violation, Λ_{LV} >> v

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

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

$$\lambda_E \;\rightarrow\; U_E \, \lambda_E \, U_L^\dagger \qquad\qquad g \;\rightarrow\; U_L^* \, g \, U_L^\dagger$$

- With two such spurions, the analysis is a bit more complicated than in the quark case

Charged Leptons

X

- The effective Hamiltonian for $\mu \to e$ conversion contains

$$\mathcal{H}_{\rm eff} = \frac{(g^\dagger g)^j{}_i}{\Lambda^2_{\rm LFV}}\, \bar{\ell}_j \bar{\sigma}^\mu \ell^i \, \bar{q} \bar{\sigma}^\mu q$$

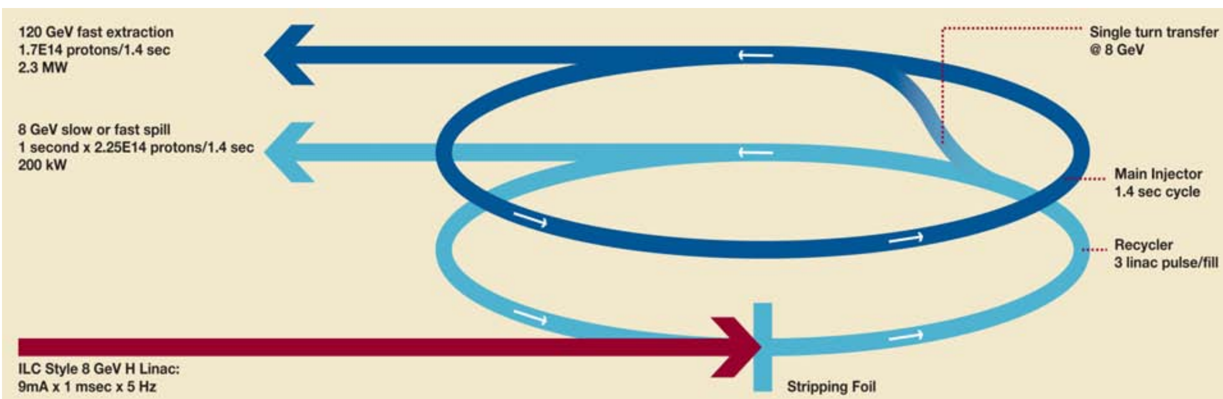
  where $\Lambda_{\rm LFV}$ is the scale of lepton flavor violation, which we assume is around 1 TeV …

- This rate is potentially accessible with a $\mu \to e$ conversion experiment at Project X …
  - How does it depend on the value of $\sin^2 2\theta_{13}$?

Charged Leptons

- Discovering $\mu \rightarrow e$ conversion would open an important new window on flavor physics
  - A key piece of the puzzle
    - Lepton flavor physics ⇔ 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



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Neutrinos

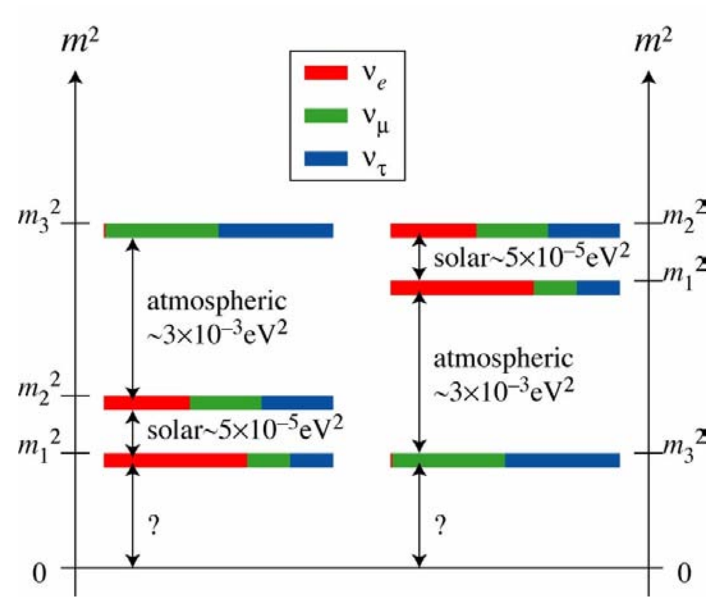
X

- 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

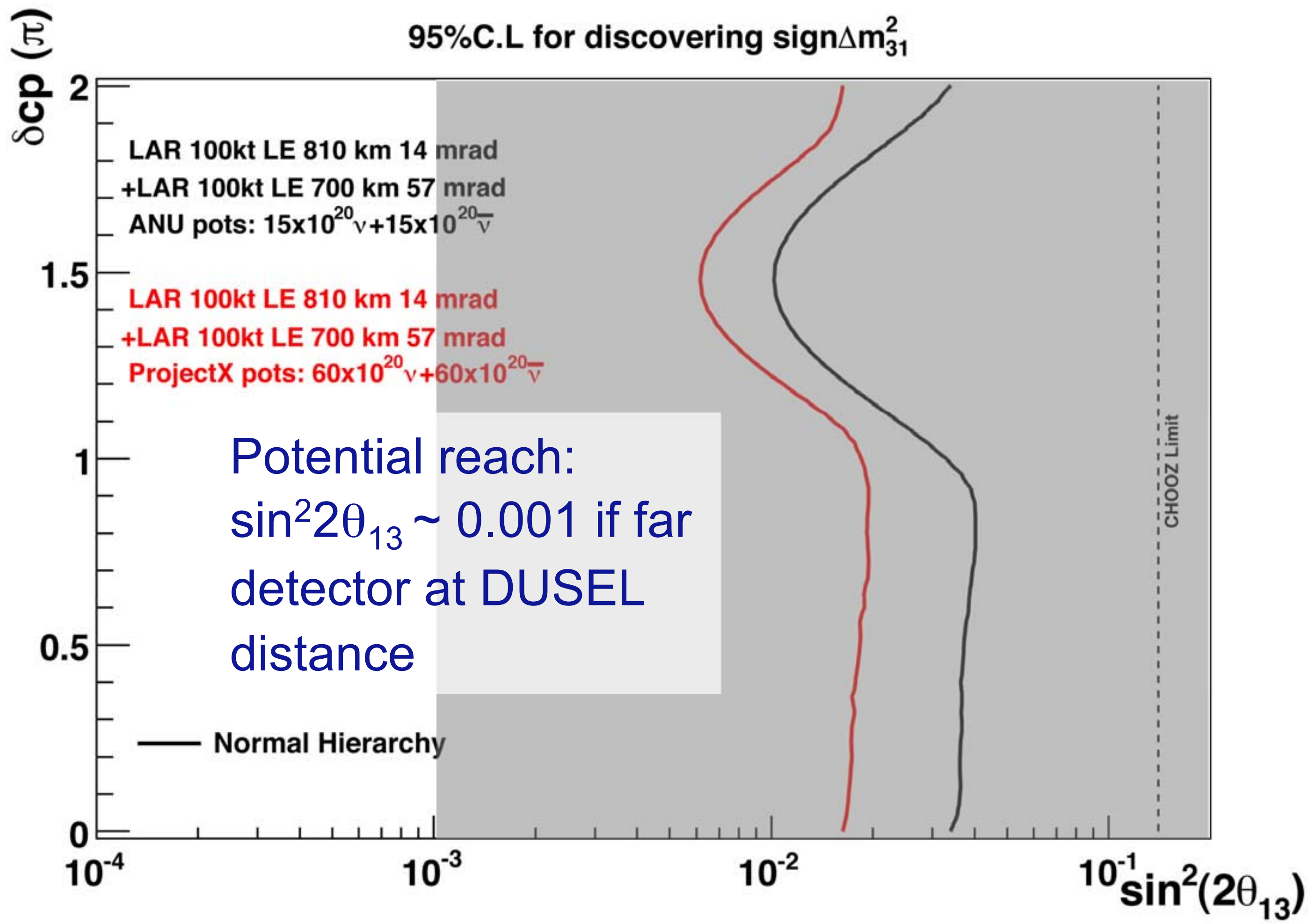
Neutrinos

- 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 …



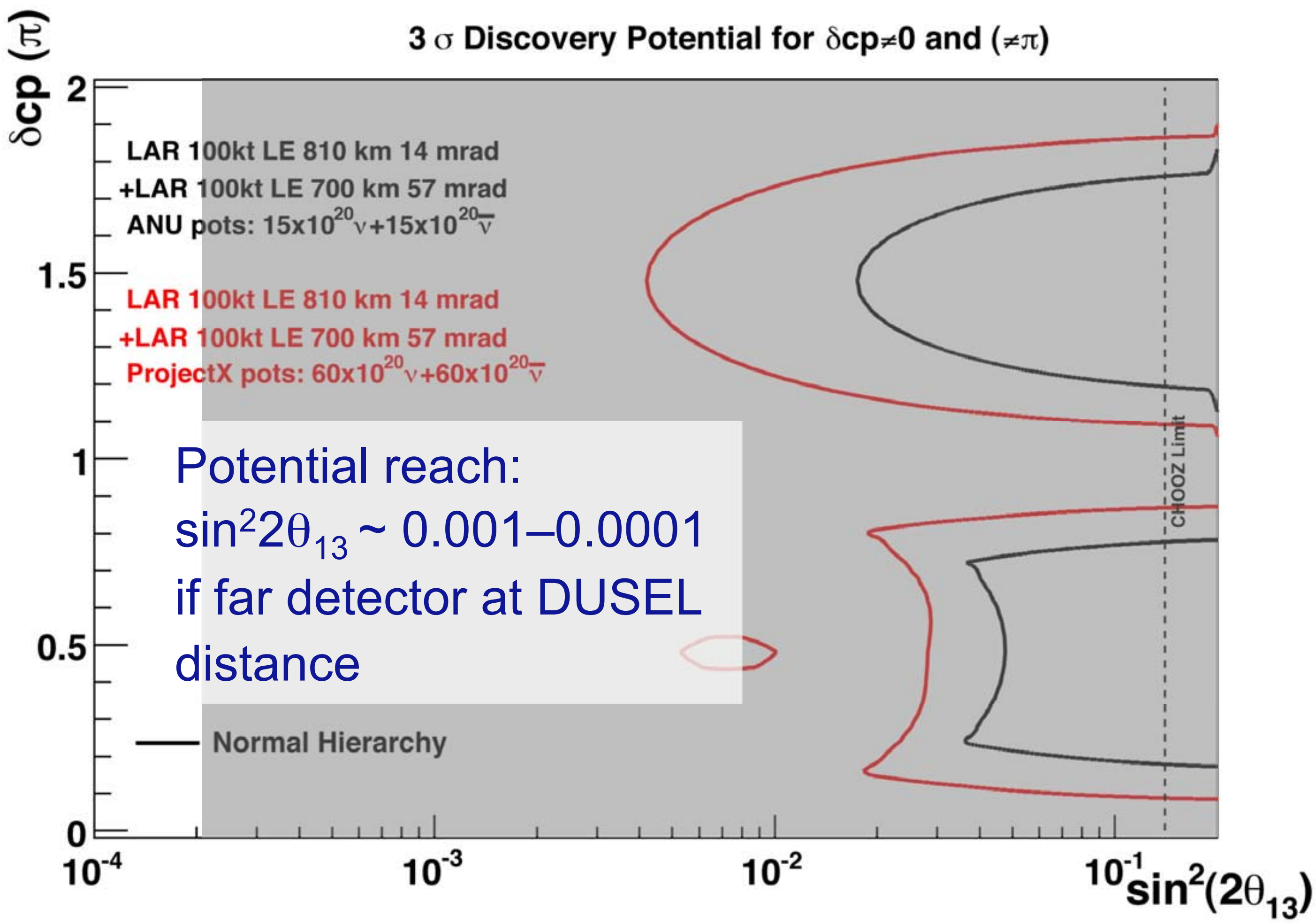
Neutrinos



Potential reach: $\sin^2 2\theta_{13} \sim 0.001$ if far detector at DUSEL distance

Saoulidou

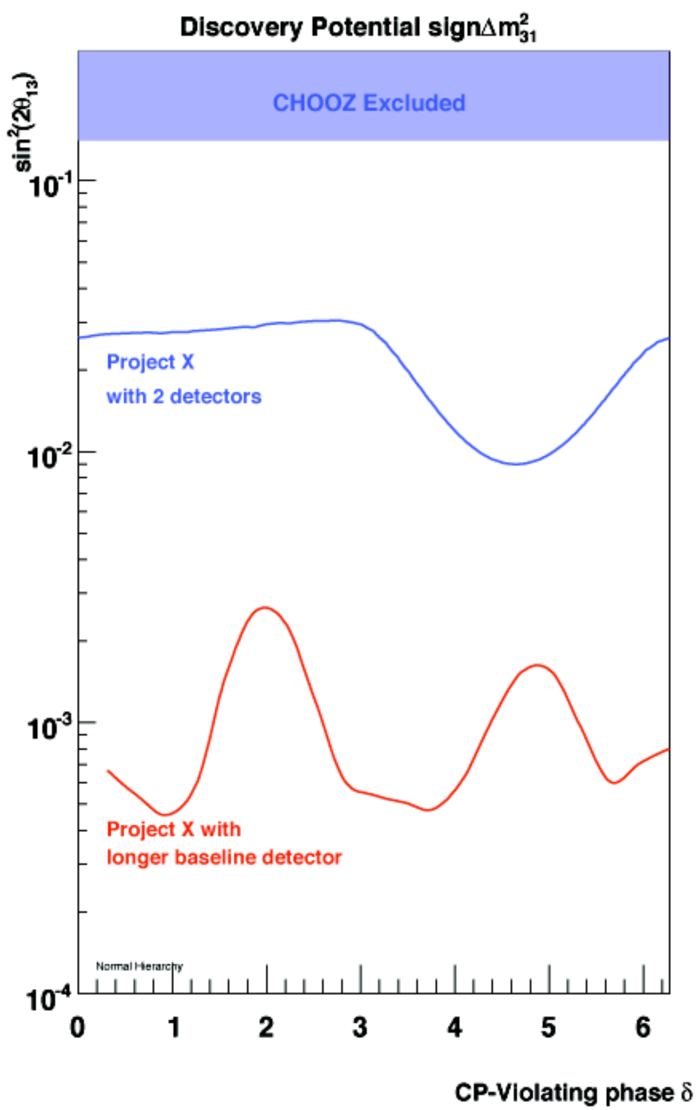
Neutrinos

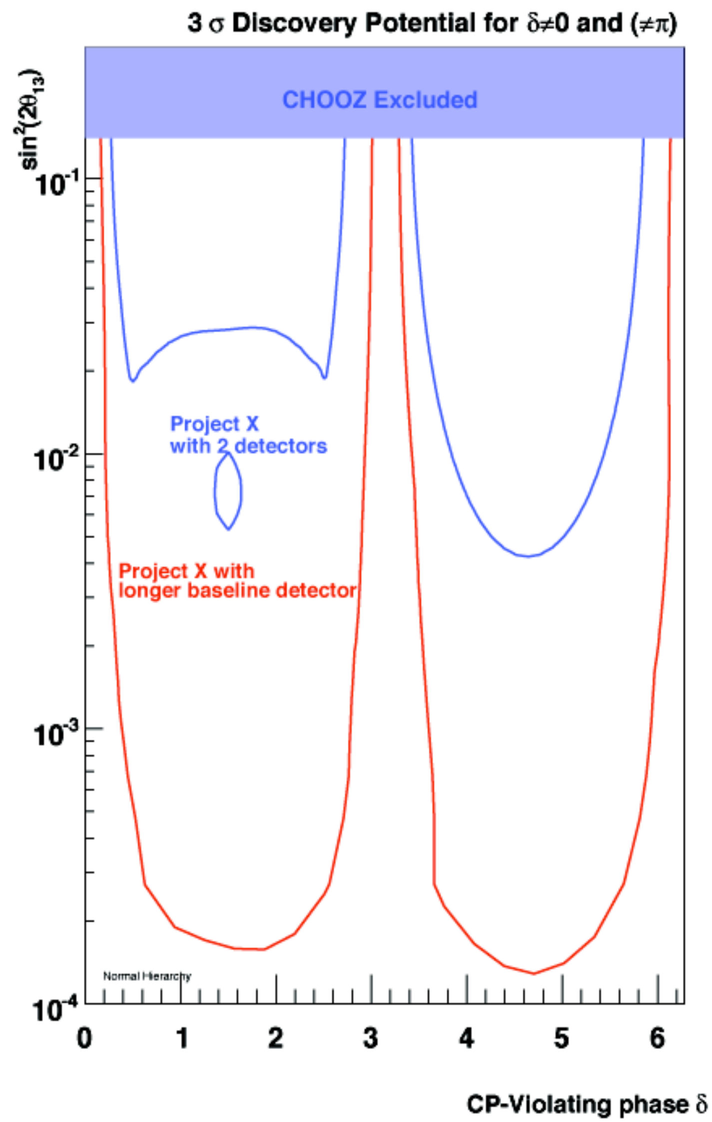


Potential reach:
$\sin^2 2\theta_{13} \sim 0.001–0.0001$
if far detector at DUSEL
distance

Saoulidou

Neutrinos





Saoulidou

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, $\mu \to$ e conv, $\mu \to$ e γ, muon g-2, EDM …
- A possible Project X physics program could include
  - K $\to \pi\ \nu\nu$ and $\mu \to$ 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 it not there yet … so there is work to do …
  - The stakes for are high for us all!