Near and Far Term Planning for Intensity Frontier Science and Facilities

R. Tschirhart

FRA Visiting Committee Meeting

March 28-29, 2013

U.S. DEPARTMENT OF ENERGY

Fermilab

Intensity Frontier Science

SLAC

The Intensity Frontier addresses fundamental questions:

Are there new sources of CPV?

Is there CPV in the leptonic sector?

Are ν's Majorana or Dirac?

Do the forces unify?

Is there a weakly coupled Hidden Sector linked to Dark Matter?

Are apparent symmetries (B,L) violated at high scales?

What is the flavor sector of new physics?

Can we expand the new physics reach of the energy frontier?

JoAnne Hewett, March 2013

In the absence of new facilities enabling new experiments…

From Hitoshi Murayama , ICFA October 2011

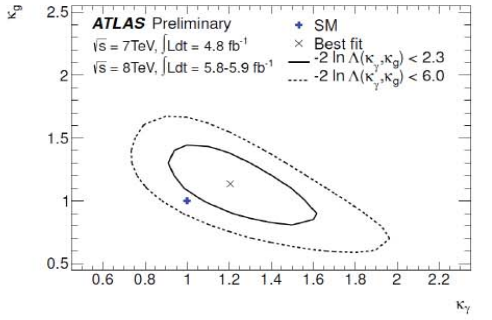
Intensity Frontier Killer App? Not a *single* experiment! The *science* requires multiple probes.

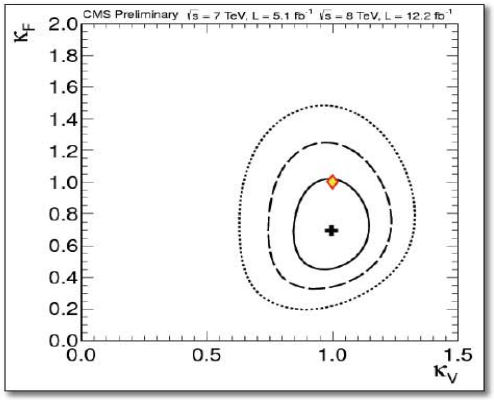
Apologies to Jurassic Park and Hitoshi Murayama, ICFA October 2011

What sub-detector in CMS or ATLAS is the Killer App?

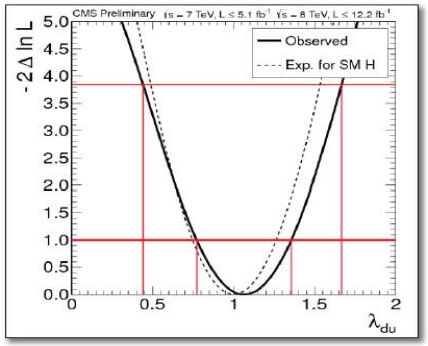
For Discovery of the Standard Model Scalar??

Couplings

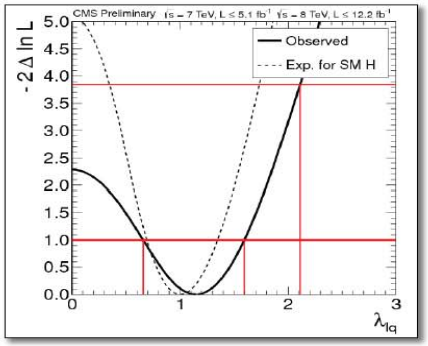




λ_{du}: ratio of couplings between down- and up-fermions



λ_{lq}: ratio of couplings between leptons and quarks



Both ratios consistent with 1

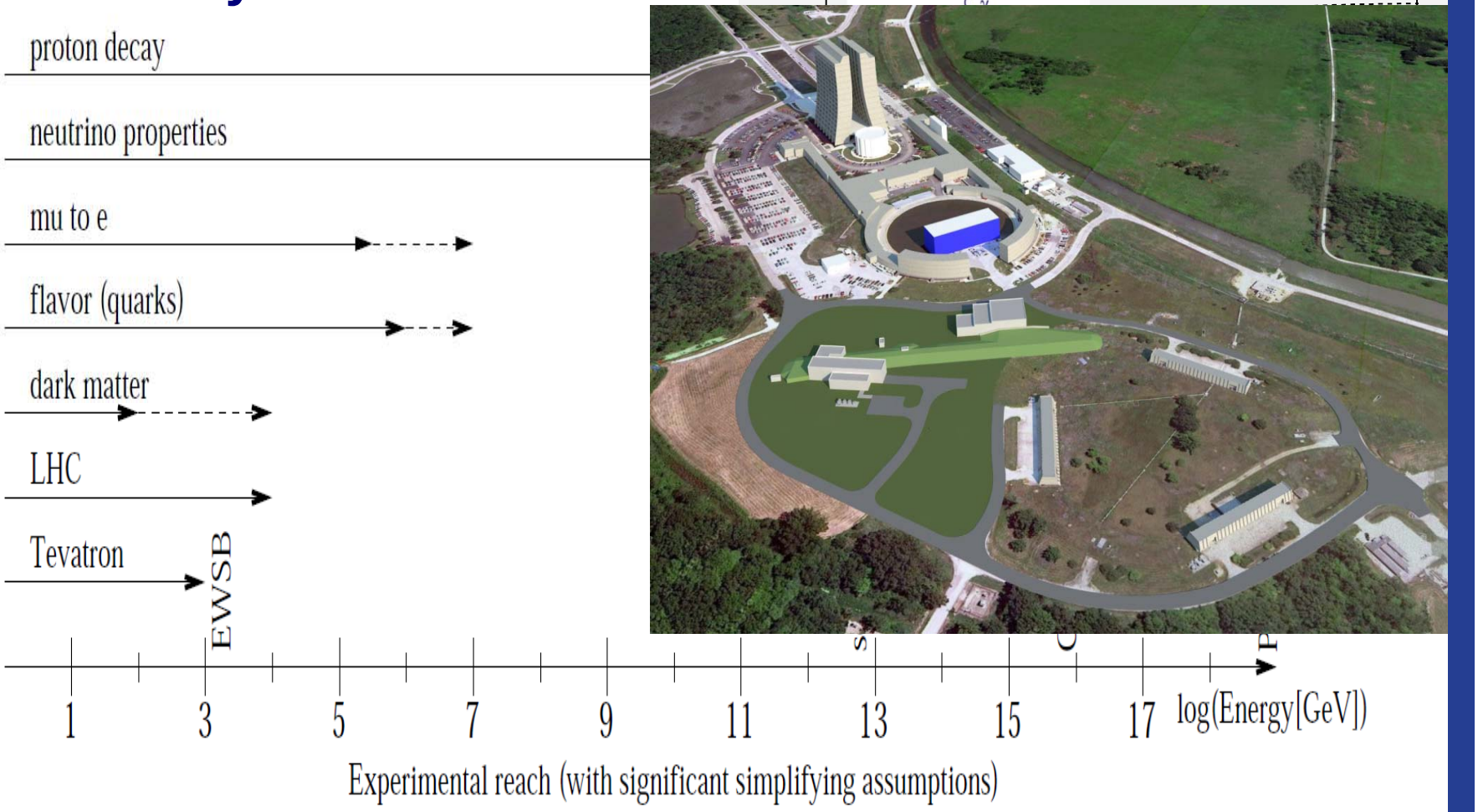
P. Sphicas
Experimental highlights

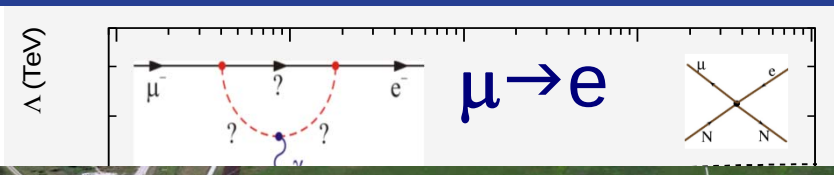
Rencontres de Moriond, EWK session
Mar 09, 2013

69

Searches for BSM physics

Indirect Pursuit of BSM from the Intensity Frontier…

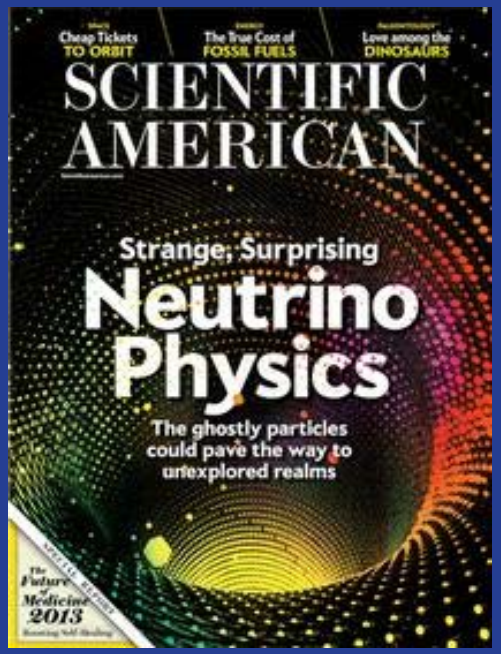


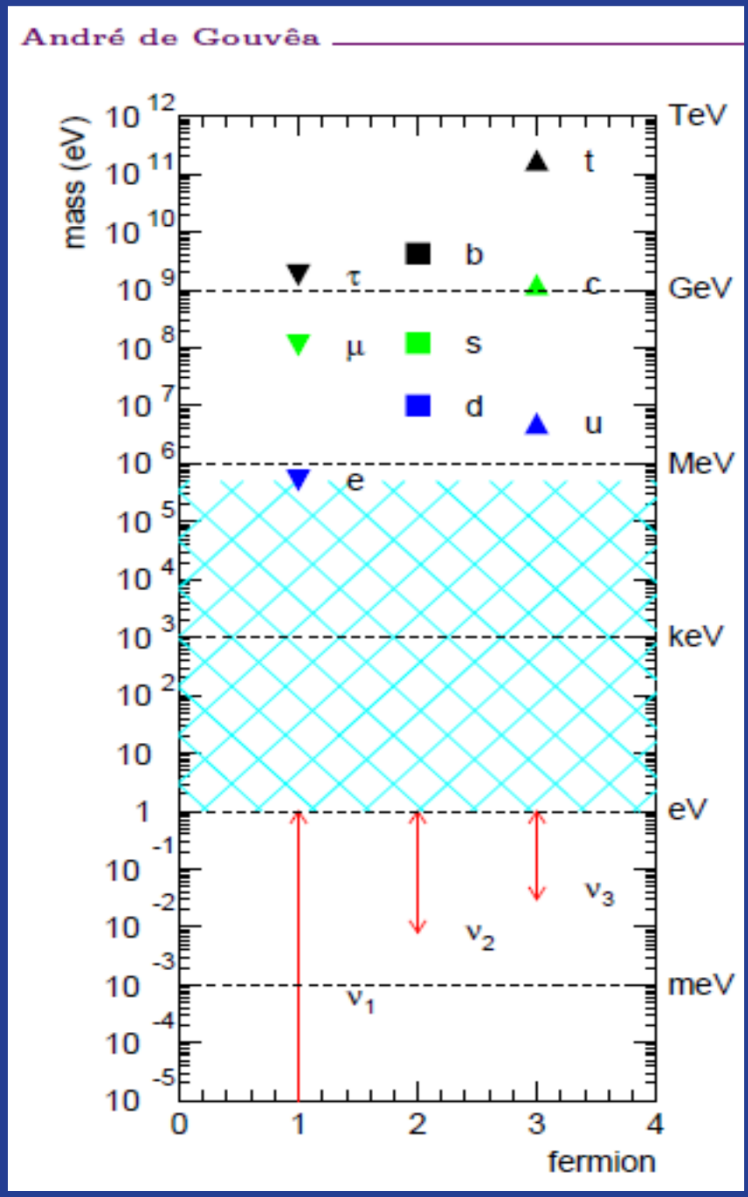


Y. Grossman, Z. Ligeti, Project X Physics Study (PXPS)

Physics Beyond the Standard Model has been discovered….

What does it mean?





On Electroweak Symmetry Breaking

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC and charged-lepton flavor violation may provide more information.

Searches for nucleon decay provide the only handle on a new energy scale (3) if that new scale happens to be very small. Unique capability!

Snowmass neutrino working group meeting, SLAC, March 6th-7th

A Really Reasonable, Simple Paradigm:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Definition of neutrino mass eigenstates (who are ν_1, ν_2, ν_3?):

- $m_1^2 < m_2^2$ $\qquad \Delta m^2_{13} < 0$ – Inverted Mass Hierarchy
- $m_2^2 - m_1^2 \ll |m_3^2 - m^2_{1,2}|$ $\qquad \Delta m^2_{13} > 0$ – Normal Mass Hierarchy

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \qquad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \qquad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

[For a detailed discussion see e.g. AdG, Jenkins, PRD78, 053003 (2008)]

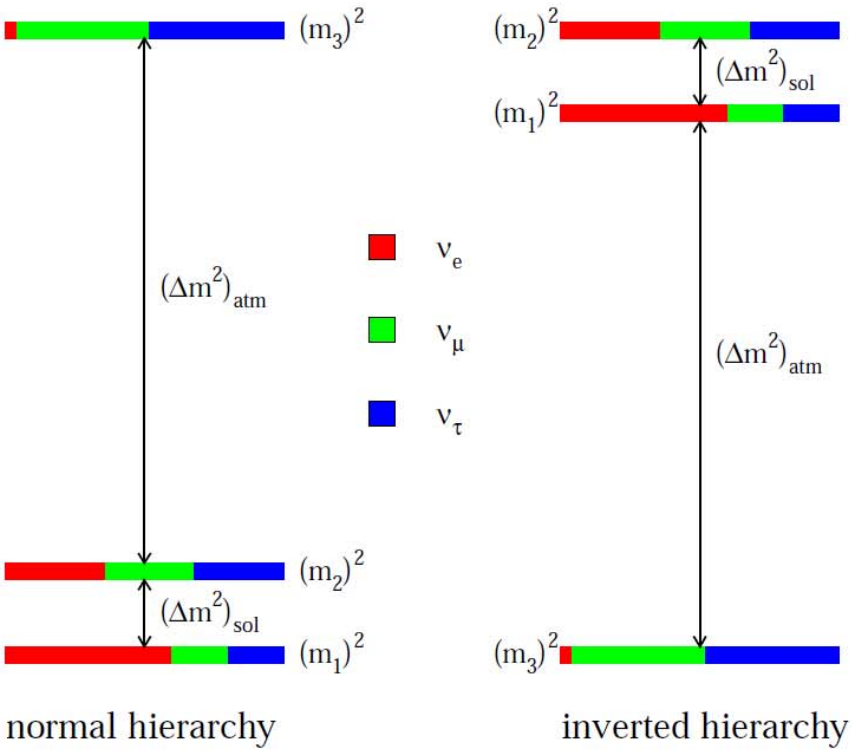
Three-Flavor Paradigm Fits All* Data Really Well (arXiv:1209.3023):

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \to 0.34$	0.31 ± 0.013	$0.27 \to 0.35$
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \to 36$	33.9 ± 0.8	$31 \to 36$
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$	$0.41^{+0.030}_{-0.029} \oplus 0.60^{+0.020}_{-0.026}$	$0.34 \to 0.67$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$	$40.1^{+2.1}_{-1.7} \oplus 50.7^{+1.1}_{-1.5}$	$36 \to 55$
$\sin^2\theta_{13}$	0.023 ± 0.0023	$0.016 \to 0.030$	0.025 ± 0.0023	$0.018 \to 0.033$
$\theta_{13}/^\circ$	$8.6^{+0.44}_{-0.46}$	$7.2 \to 9.5$	$9.2^{+0.42}_{-0.45}$	$7.7 \to 10.$
$\delta_{CP}/^\circ$	240^{+102}_{-74}	$0 \to 360$	238^{+95}_{-51}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	7.50 ± 0.185	$7.00 \to 8.09$	$7.50^{+0.205}_{-0.160}$	$7.04 \to 8.12$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$	$2.49^{+0.055}_{-0.051}$	$2.29 \to 2.71$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.43^{+0.042}_{-0.065}$	$-2.65 \to -2.24$	$-2.47^{+0.073}_{-0.064}$	$-2.68 \to -2.25$

Table 1: Three-flavour oscillation parameters from our fit to global data after the Neutrino 2012 conference. For "Free Fluxes + RSBL" reactor fluxes have been left free in the fit and short baseline reactor data (RSBL) with $L \lesssim 100$ m are included; for "Huber Fluxes, no RSBL" the flux prediction from [42] are adopted and RSBL data are not used in the fit.

* Modulo Short-Baseline Anomalies

What We Know We Don't Know: "Missing" Oscillation Parameters



- ~~What is the ν_e component of ν_3?~~ ($\theta_{13} \neq 0$!)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

$\Rightarrow$ All of the above can "only" be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)

Understanding Fermion Mixing – Precision

The other puzzling phenomenon uncovered by the neutrino data is the fact that Neutrino Mixing is Strange. What does this mean?

It means that lepton mixing is very different from quark mixing:

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

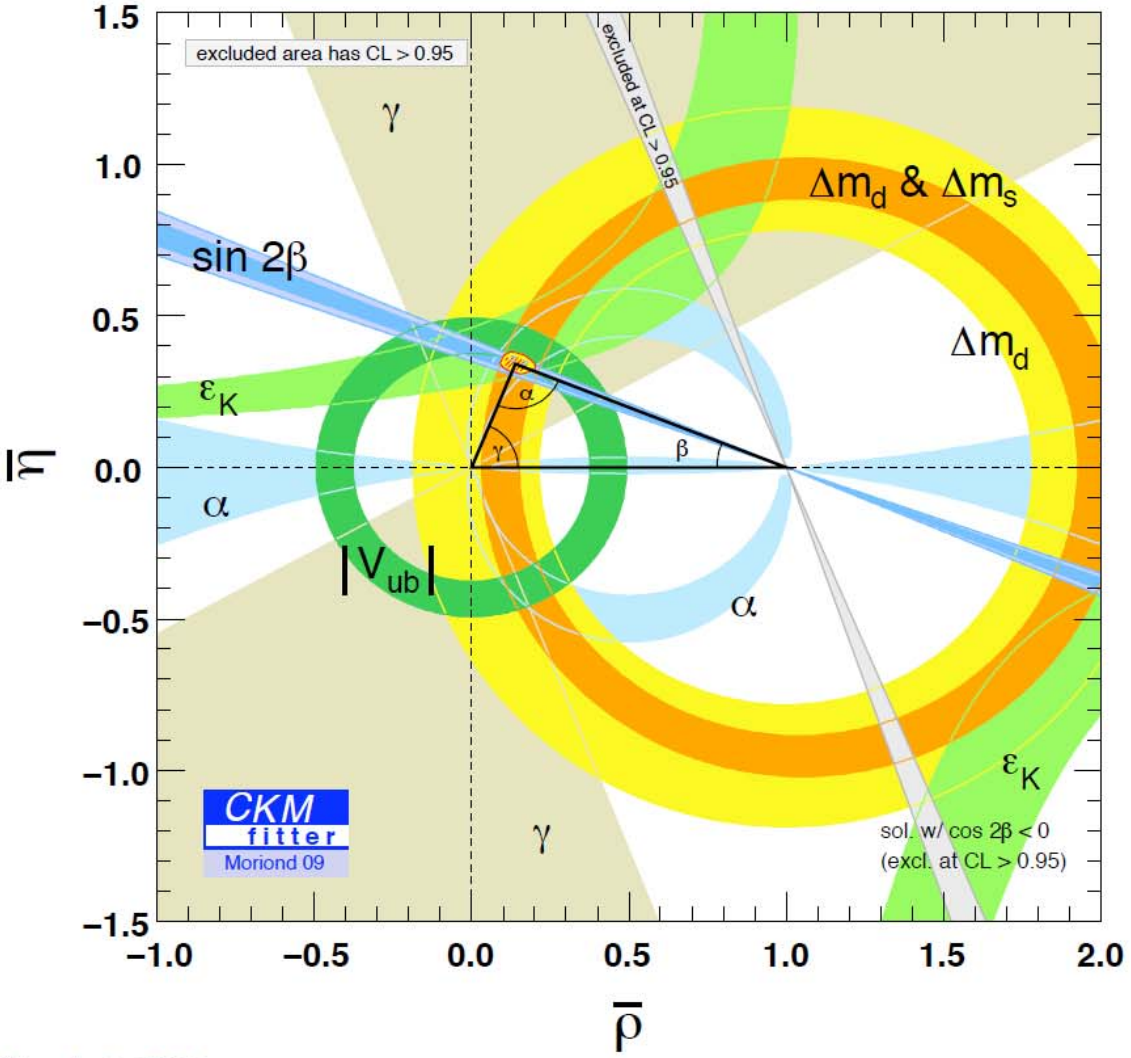
$[|(V_{MNS})_{e3}| < 0.2]$

WHY?

They certainly look VERY different, but which one would you label as "strange"?

Snowmass neutrino working group meeting, SLAC, March 6th-7th

What we ultimately want to achieve:



We need to do this in the lepton sector!

Snowmass neutrino working group meeting, SLAC, March 6th-7th

Project X era CP violation research opportunities

Neutrinos: > x3 increase in LBNE neutrino statistics.

Electric **D**ipole **M**oments:

- Proton-EDM, x10^6 reach, *new capability*
- Muon-EDM, x10^4 reach, *new capability*
- Neutron EDM, x10^2-10^3 reach
- Atomic EDMs. x10^3-10^4 reach, goal of surpassing Hg!

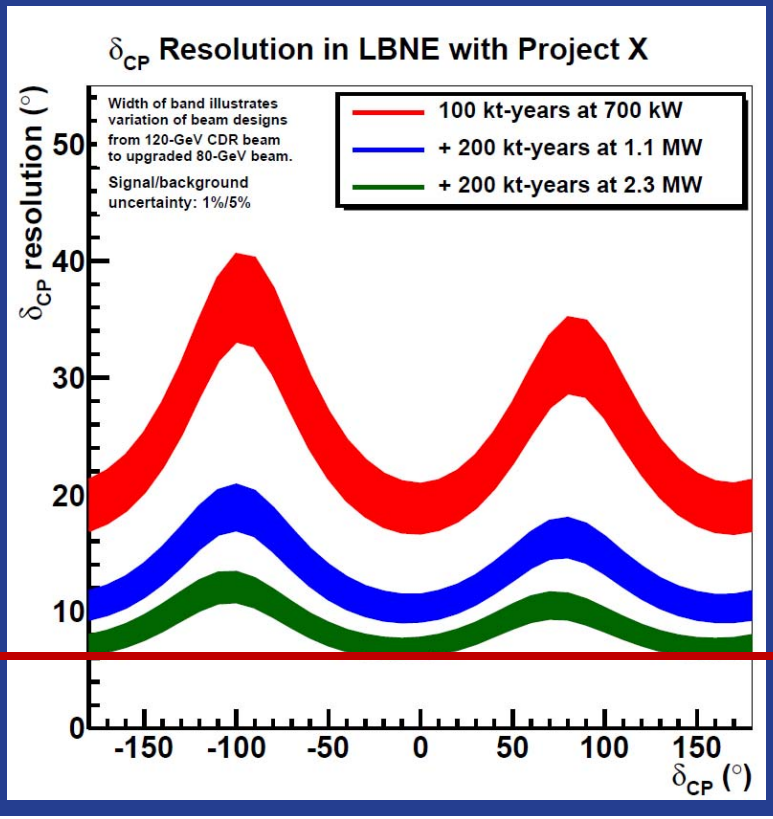


Table 2: SM predictions and current and expected limits on selected examples of EDMs.

EDMs	SM	current limit	Project X
electron	$\sim 10^{-38}$ e cm	1.0×10^{-27} e cm	$\sim 10^{-30}$ e cm
muon	$\sim 10^{-35}$ e cm	1.1×10^{-19} e cm	$\sim 10^{-23}$ e cm
neutron	$\sim 10^{-31}$ e cm	2.9×10^{-26} e cm	$\sim 10^{-29}$ e cm
proton	$\sim 10^{-31}$ e cm	6.5×10^{-23} e cm	$\sim 10^{-29}$ e cm
nuclei	$\sim 10^{-33}$ e cm (^{199}Hg)	3.1×10^{-29} e cm (^{199}Hg)	$\sim 10^{-29}$ e cm (^{225}Ra)

2008 P5 – Intensity Frontier - 1

Neutrino program w/ Project X

The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL and a high-intensity neutrino source at Fermilab.

The panel recommends an R&D program in the immediate future to design a multi-megawatt proton source at Fermilab and a neutrino beamline to DUSEL and recommends carrying out R&D on the technologies for a large multi-purpose neutrino and proton decay detector.

DUSEL

The panel endorses the importance of a deep underground laboratory to particle physics and urges NSF to make this facility a reality as rapidly as possible. Furthermore the panel recommends that DOE and NSF work together to realize the experimental particle physics program at DUSEL.

Other neutrino recommendations:

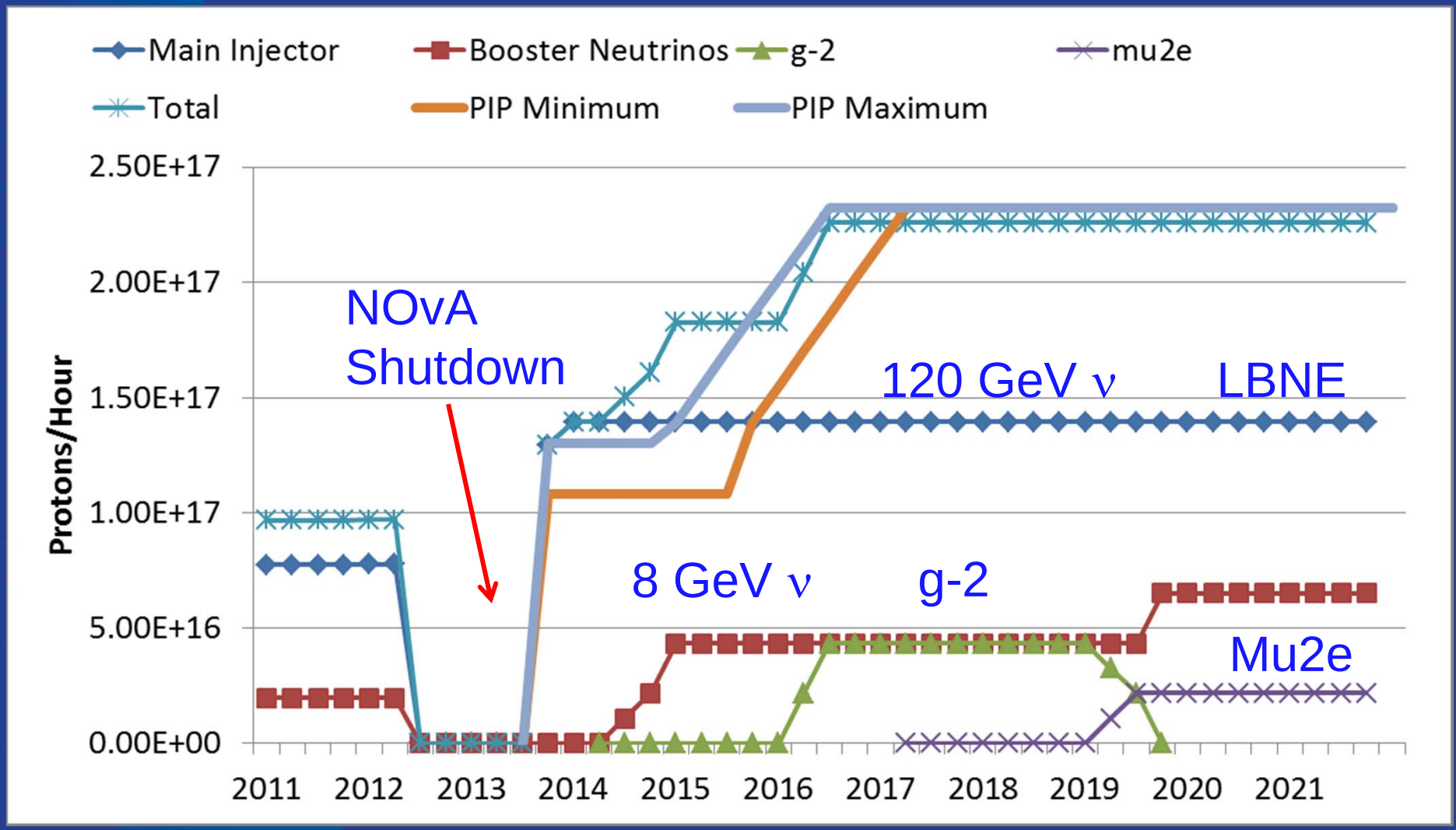
- **700 kW proton beam**
- **NOvA in all but bad budget scenario**
- **Daya Bay & DoubleCHOOZ**
- **Neutrinoless double beta decay**

Note:
Possible LBNE + Project X start within 10 yrs

Lankford, HEPAP Subpanel Report, March 11, 2013 16

Proton Improvement Plan…

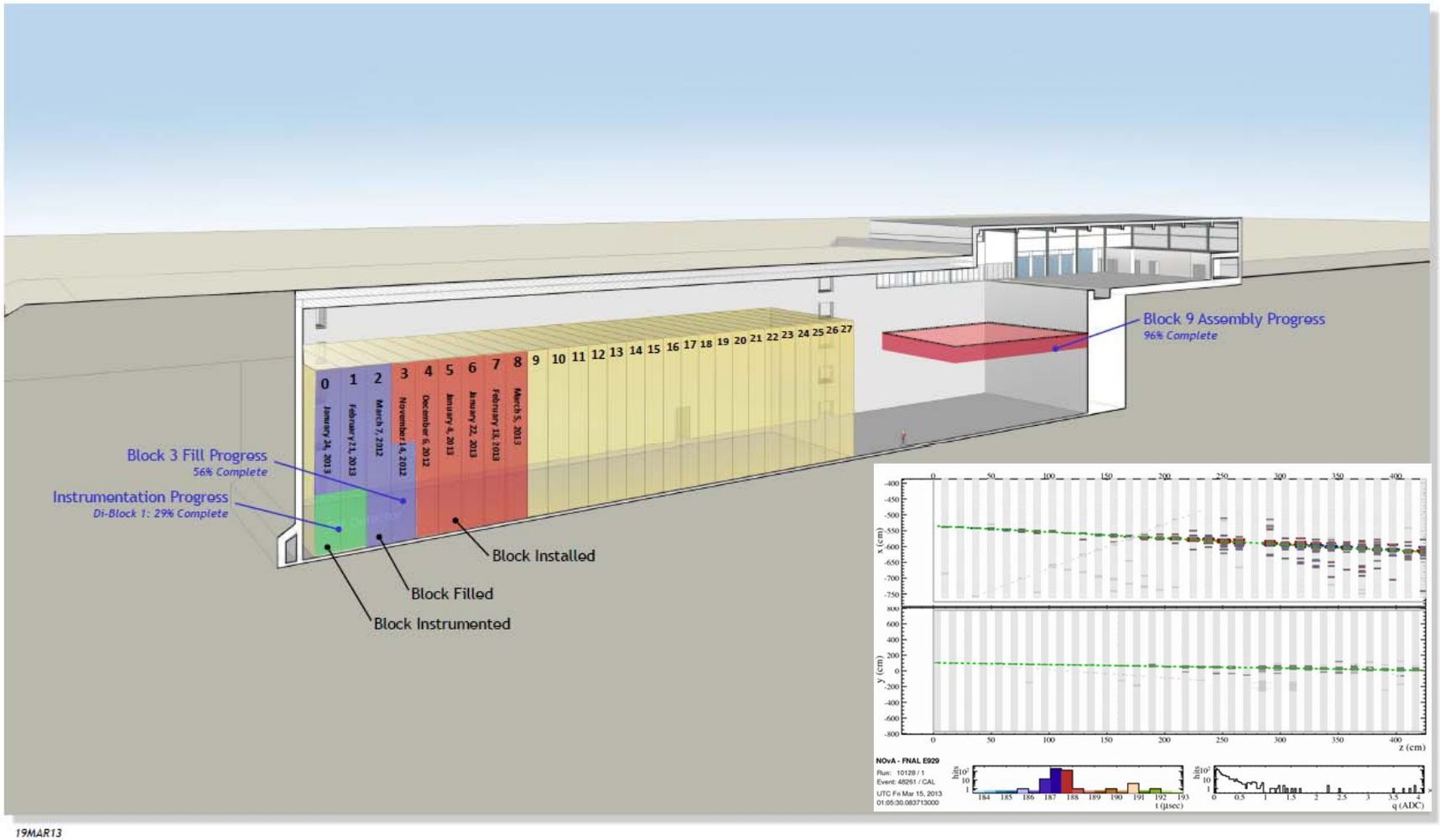
"The *sine qua non* of the Fermilab program is protons" [FRAVC 2012]



Fermilab

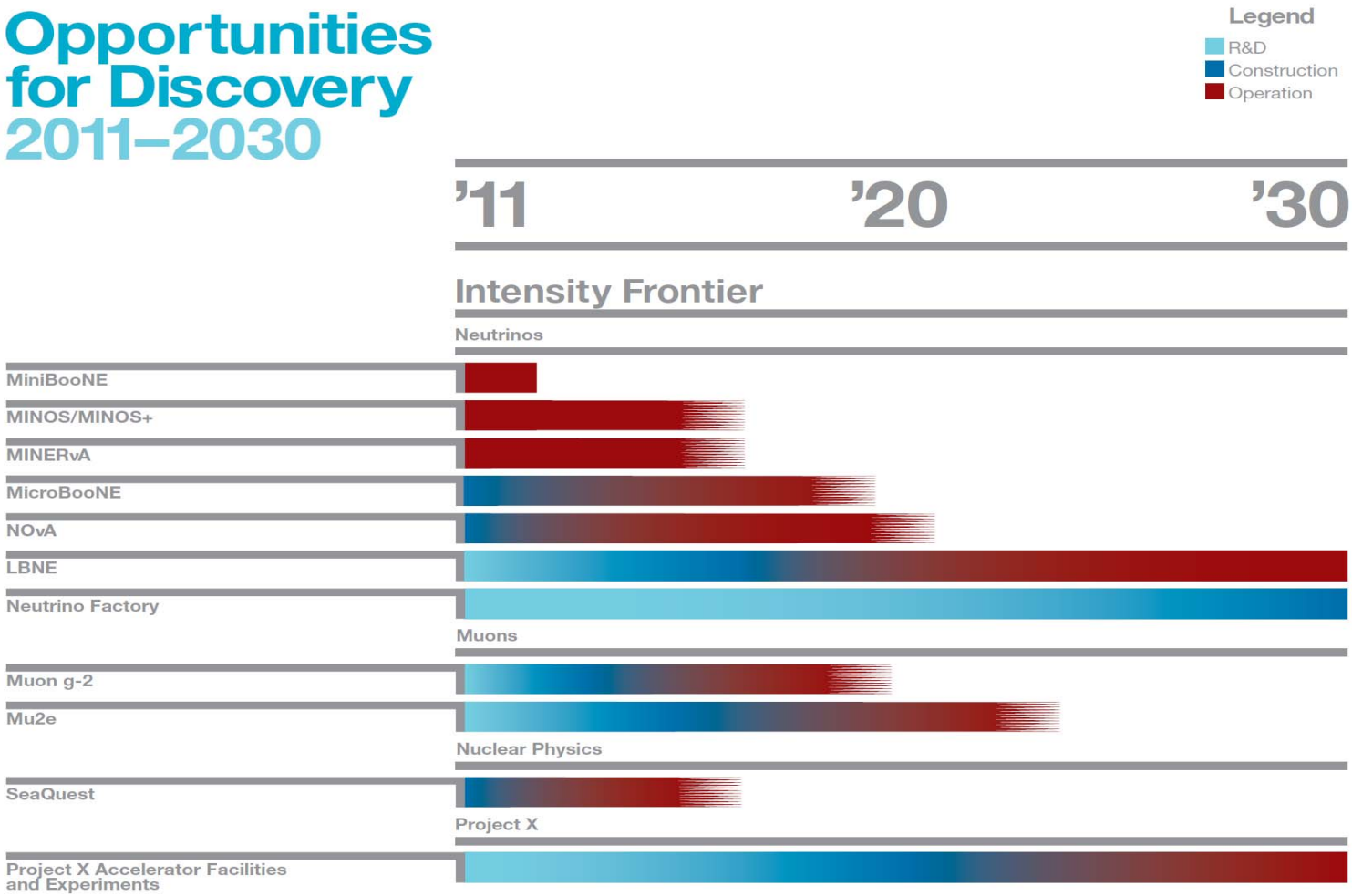
NOvA Facility in Soldier Field

NOvA Far Detector Assembly Progress



The Plan Today…

Plan for discovery…



30 White Papers submitted that need accelerators as neutrino drivers

Super beams:

- Opportunities for Precision Tests of Three-Neutrino Mixing and Beyond with LBNE
- Precision Studies of Nucleon Structure and Medium Modifications with Neutrino Beams
- Hyper-Kamiokande Physics Opportunities
- Getting the Most Out of the On-Axis NuMI Beam
- Performance of a Low-Luminosity Low Energy Neutrino Factory
- Liquid Argon Near Detector for the BNB – Neutrino Intensity Frontier White Paper
- LAr1: Addressing the short-baseline anomalies
- Opportunities for Precision Neutrino Physics and Constraining Oscillation Systematics with an LBNE Near Detector
- NUMI Running with the LANL LDRD Liquid Argon TPC
- MiniBooNE+: A new investigation of oscillations with improved sensitivity in an enhanced MiniBooNE experiment
- Extending the NOvA Physics Program
- The MiniBooNE-II Proposal: A 5-sigma Test of MiniBooNE's Neutrino Mode Excess
- MINOS+: Using the NuMI Beam as a Precision Tool for Neutrino Physics
- A Second Detector at an Off-axis Location to Enhance the Mass Hierarchy Discovery Potential in LBNE
- Nonstandard Interaction in tau-neutrino nucleon scattering
- SciNOvA: A Measurement of Neutrino-Nucleus Scattering in a Narrow-Band Beam.
- CHerenkov detectors In mine PitS (CHIPS)A White Paper
- Proposal for a neutrino Super Beam using the ESS 5 MW, 2.5 GeV linac as proton driver
- Precision Neutrino Oscillation Measurements using Simultaneous High-Power, Low-Energy Project-X Beams

Decay-at-Rest (DAR) sources:

Whitepaper on Cyclotrons as Drivers for Precision Neutrino Experiments

Whitepaper on the DAEδALUS Experiment

Whitepaper on the IsoDAR experiment

Measuring Neutrino Cross Sections on Argon for Supernova Neutrino Detection

OscSNS: A Precision Neutrino Oscillation Experiment at the SNS

Searches for CENNS at the Spallation Neutron Source

Opportunities for Neutrino Measurements at the Spallation Neutron Source

Measuring CENNS in the Low Energy Neutrino Source at Fermilab

Muon storage rings and Neutrino Factories:

The Neutrino Factory

Nu-STORM: Neutrinos from STORed Muons

Cross section measurements at nu-STORM

Snowmass neutrino working group meeting SLAC, March 6th-7th 2013

30 White Papers submitted that need accelerators as neutrino drivers

Super beams:

- Concepts based on the 700kW 120 GeV Fermilab NuMI beam
- Concepts based on the 15kW+ 8 GeV Fermilab Booster Neutrino Beam
- Concepts based on the 700kW 120GeV Fermilab LBNE beam
- Concept based on the megawatt+ 30 GeV JPARC T2X beam.
- Concepts based on the 2300kW 60-120GeV Fermilab LBNE beam.
- Concept based on multi-Megawatt ESS beams.
- Concept based on dual multi-Megawatt Project-X beams illuminating LBNE.

Decay-at-Rest (DAR) sources:

- Concepts based on the 1000kW SNS Hg spallation target.
- Concept based on cyclotrons driving a nuclear beta decay target.
- Concept based on high power cyclotrons driving DAR sources.

Muon storage rings and Neutrino Factories:

- NuSTORM
- Low energy Neutrino Factory
- Neutrino Factory.

Snowmass neutrino working group meeting SLAC, March 6th-7th 2013

Relationship to Community Planning & P5 Process

- See recent letter from Fleming Crim (NSF) & Jim Siegrist (DOE).

- A multistep process
  - Each step will inform and prepare for the next.

- Facilities subpanel is 1st step.
  - Note well-defined scope: >100M$ & 10 years
  - No rank ordering by HEP
  - NOT intended to preclude add'l. ideas that emerge in subsequent steps

- DPF-led community planning ("*Snowmass*") process is 2nd step.
  - Capable of more detailed studies
  - Culminates in July 20 – August 10 workshop
  - Wider portfolio of activities
  - ~20 year time horizon

- Project prioritization subpanel is 3rd step.
  - Expected after Snowmass process complete
  - Work with input from Snowmass + budgetary input from DOE/NSF
  - Form strategic plan in various scenarios
  - HEPAP/P5 is one of few official paths for agencies to gather community input.

Lankford, HEPAP Subpanel Report, March 11, 2013 4

Intensity Frontier - Facilities

Neutrino physics:

- Long baseline:
  - NOvA – coming on line this year; MINOS+ this year
  - LBNE – CD-1 approval for Stage 1, with possible further enhancements from international collaboration; further stage(s) in future
- Short baseline:
  - MINERvA, MicroBooNE
  - nuSTORM – conceptual stage

Flavor physics in the quark sector:

- PEP-II/BABAR & CESR/CLEO - closed 2008
- LHCb – small but important US participation
- Super-KEKB/BELLE-II

Muon physics:

- g-2 – in preparation
- Mu2e – CD-1 approved;

Project X:

- Project X accelerator: technically ready for construction
- Project X experimental program:
  - Significantly enhances LBNE & Mu2e (the CD-1 approved experiments)
  - Rich scientific program – in conceptual development

Lankford, HEPAP Subpanel Report, March 11, 2013

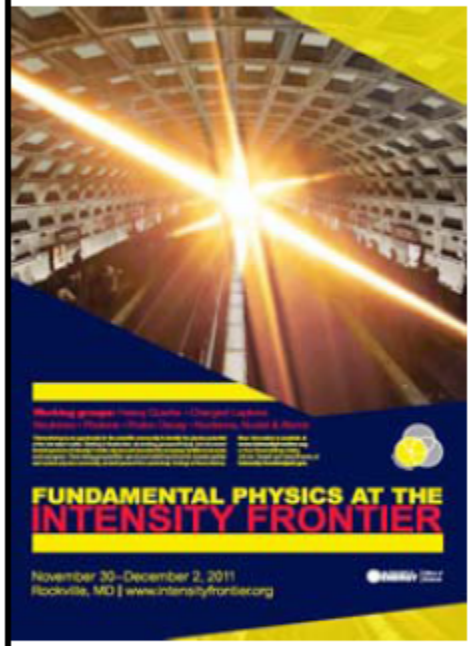
Facility subpanel recommendations, accepted by HEPAP:

- LBNE: Stage 1 begins a world leading program in neutrino physics +… . Science reach of Stage 1 is *important* and it lays the groundwork for an *absolutely central* facility. *Ready for construction,* planned start in 2016 and completed in 2023.
- MU2E: Will search for muon to electron conversion in the field of a nucleus with unparalleled sensitivity. It is *absolutely central. Ready for construction* starting in 2014, completed in 2018.
- PROJECT X: Unique world leading facility at Fermilab for intensity frontier physics. It is *absolutely central* and although it is pre CD0 it is *ready for construction*.
- nuSTORM: Muon storage ring that would provide neutrino beams with well defined flavor composition and spectrum. While the committee is not aware of major technical challenges in realizing nuSTORM, its performance *requirements are not yet fully defined*. While nuSTORM has great potential we *don't know enough* yet to assess nuSTORM's role in US world-leading science.

Mark Wise, HEPAP March 11th 2013

Intensity Frontier Workshop

SLAC



Fundamental Physics at the Intensity Frontier **: Rockville, MD Nov 30-Dec 2, 2011**

Jointly Sponsored by DOE office of HEP and Nuclear Physics

~500 participants

3 days of vibrant talks and discussion

Charge:

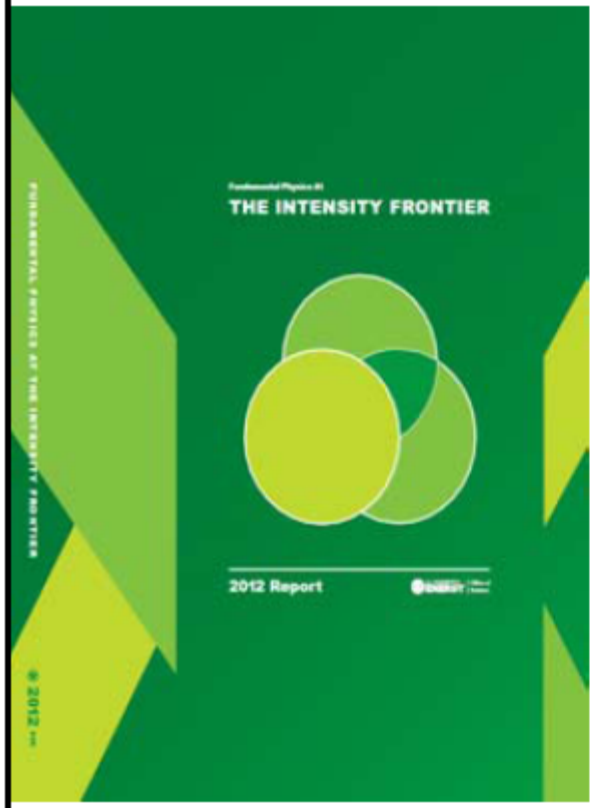
Document the science opportunities at the Intensity Frontier

Identify experiments and facilities needed for components of program

JoAnne Hewett, March 2013

Workshop Report

SLAC



arXiv:1205.2671

Everyone who contributed is an author

- ~ 440 authors
- ~ 220 pages

Contents:

- Exec Summary
- Chapter for each working group
- Technical Summary

JoAnne Hewett, March 2013

Intensity Frontier Plan for "Snowmass"

SLAC

- Follow same working group structure
- Incorporate recent results/plans in neutrino sector
- Continue to develop science case for next 2 decades
- Educate community on Intensity Frontier discovery potential so that community can communicate science to others
- Engage the full HEP community
- Further explore connections with other frontiers

Develop crisp message that captures the essence of Intensity Frontier science

JoAnne Hewett, March 2013

CSS13 Working Groups

SLAC

Quark Flavor Physics: Joel Butler, Zoltan Ligeti, Jack Ritchie	K, D & B Meson decays/properties
Charged Lepton Processes Brendan Casey, Yuval Grossman, David Hitlin	Precision measurements with muons, taus
Neutrinos Andre deGouvea, Kevin Pitts, Kate Scholberg, Sam Zeller	All experiments for properties of neutrinos. Accelerator & non-accel.
Baryon Number Violation Kaladi Babu, Ed Kearns	Proton decay, Neutron Oscillation
New Light, Weakly Coupled Particles Rouven Essig, John Jaros, William Wester	"Dark" photons, paraphotons, axions, WISPs
Nucleons, Nuclei & Atoms Krishna Kumar, Z.-T. Lu, Michael Ramsey-Musolf	Properties of nucleons, nuclei or atoms (EDM), as related to HEP

JoAnne Hewett, March 2013

All Hands Intensity Frontier Meeting

SLAC

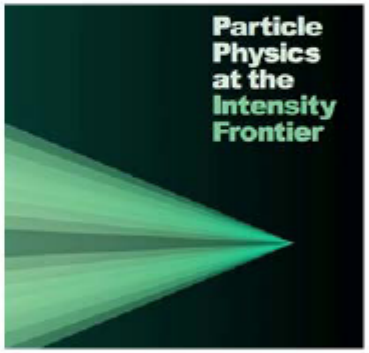
Intensity Frontier Workshop

25-27 April 2013 *Argonne National Laboratory*
US/Central timezone

Overview
Intensity Frontier Page
Agenda
Step 1: Register
Registration Form
Step 2: Payment
List of registrants
Accommodations
Where to Eat
Transportation
GreenLab Shuttle
Child Care Options

Support

Registration is now open!



Please Register!!

As part of the ongoing 2013 Community Summer Study ("Snowmass") the Intensity Frontier working group will host an all-hands workshop on April 25-27, 2013 at Argonne National Laboratory. This workshop will directly follow a writers meeting of the Project X Physics Study which will be held at Fermilab on April 24, 2013.

Charge for the April 2013 Intensity Frontier Workshop

Develop a coherent and interconnected view of the Intensity Frontier that will be presented at Snowmass. Describe future facilities and experiments at the Intensity Frontier and their capabilities. Document the contributions of the Intensity Frontier towards addressing the major questions in particle physics and explain how and why it is complementary to the other frontiers, which together constitute experimental particle physics. Leave the workshop with a clear understanding of what the approach will be at Snowmass 2013.

JoAnne Hewett, March 2013

Project-X:

- Evolution of the existing Fermilab accelerator complex with the revolution in Super-Conducting RF Technology.

The Project-X Research Program

- ***Neutrino experiments***

A high-power proton source with proton energies between 1 and 120 GeV would produce intense neutrino sources and beams illuminating near detectors on the Fermilab site and massive detectors at distant underground laboratories.

- ***Kaon, muon, nuclei & nucleon precision experiments***

These could include world leading experiments searching for lepton flavor violation in muons, atomic, muon, nuclear and nucleon electron dipole moments (edms), precision measurement of neutron properties (e.g. n,nbar oscillations) and world-leading precision measurements of ultra-rare kaon decays.

- ***Platform for evolution to a Neutrino Factory and Muon Collider***

Neutrino Factory and Muon-Collider concepts depend critically on developing high intensity proton source technologies.

- ***Material Science and Nuclear Energy Applications***

Accelerator, spallation, target and transmutation technology demonstrations which could investigate and develop accelerator technologies important to the design of future nuclear waste transmutation systems and future thorium fuel-cycle power systems. Possible applications of muon Spin Resonance techniques (muSR). as a sensitive probes of the magnetic structure of materials .

Detailed discussion on Project X website

The Project-X Research Program…Redux

- ***New Forces***

  Lepton Flavor Violation (e.g. $\mu \rightarrow e$)

  Baryon Number Violation ($n \rightarrow \bar{n}$ oscillations)

  Non-standard flavor changing neutral currents

- ***New properties of matter***

  CP violation in neutrinos, charged leptons, quarks

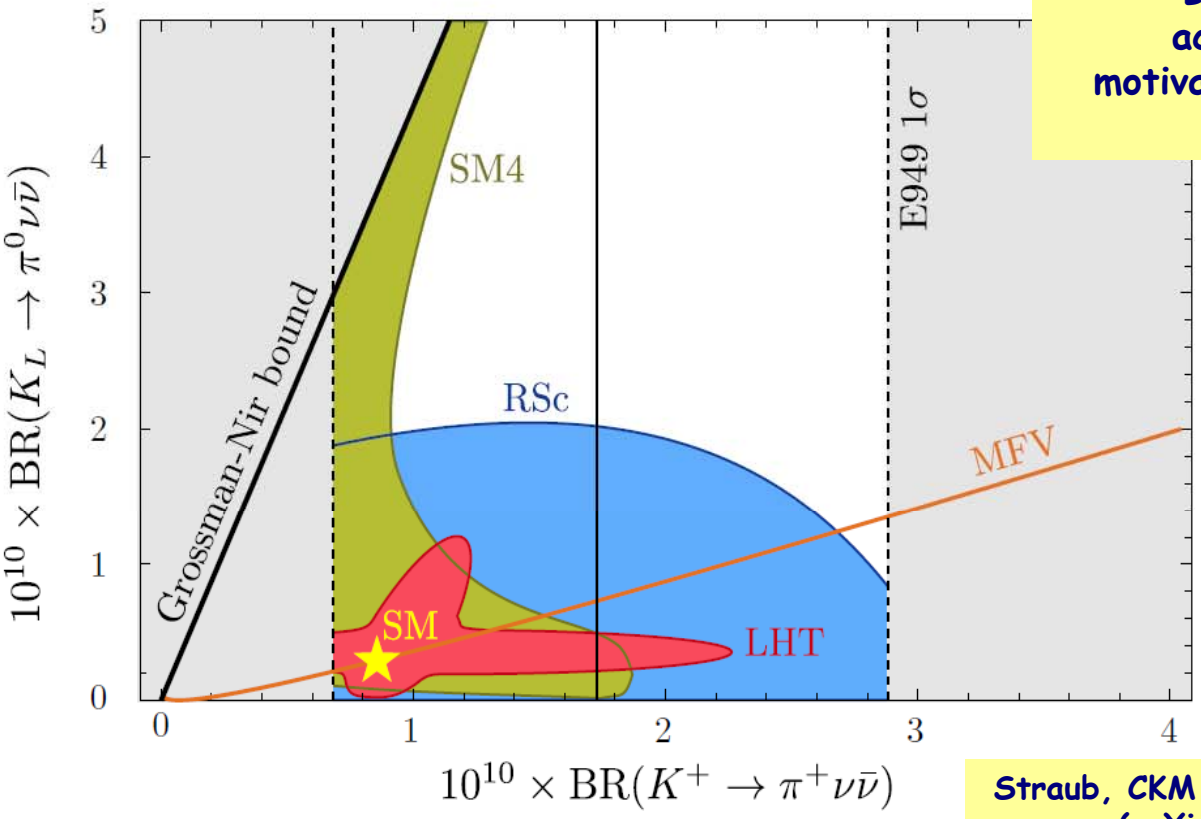
- ***New dimensions***

  e.g. super-symmetric amplitudes via EDMs

  Warped dimensions via kaon decays

Rare processes can dissect new physics…
e.g. Warped Extra Dimensions as a Theory of Flavor??

Buras et al. SM accuracy of <5%, motivates 1000-event experiments



Straub, CKM 2010 workshop (arXiv:1012.3893v2)

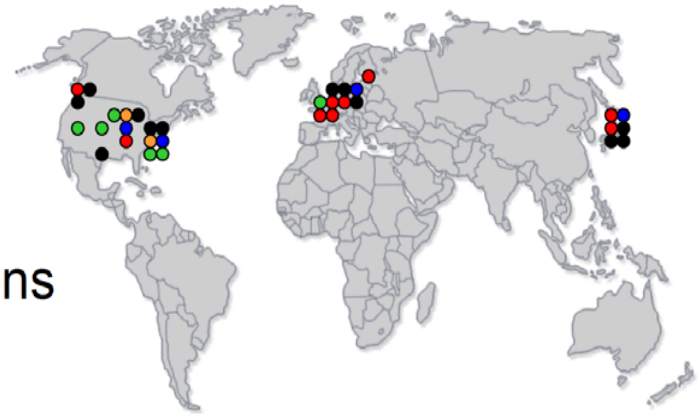
Figure 1: Correlation between the branching ratios of $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ in MFV and three concrete NP models. The gray area is ruled out experimentally or model-independently by the GN bound. The SM point is marked by a star.

Electric Dipole Moment Research Worldwide…

- Neutrons ~200
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC
- Molecules ~50
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

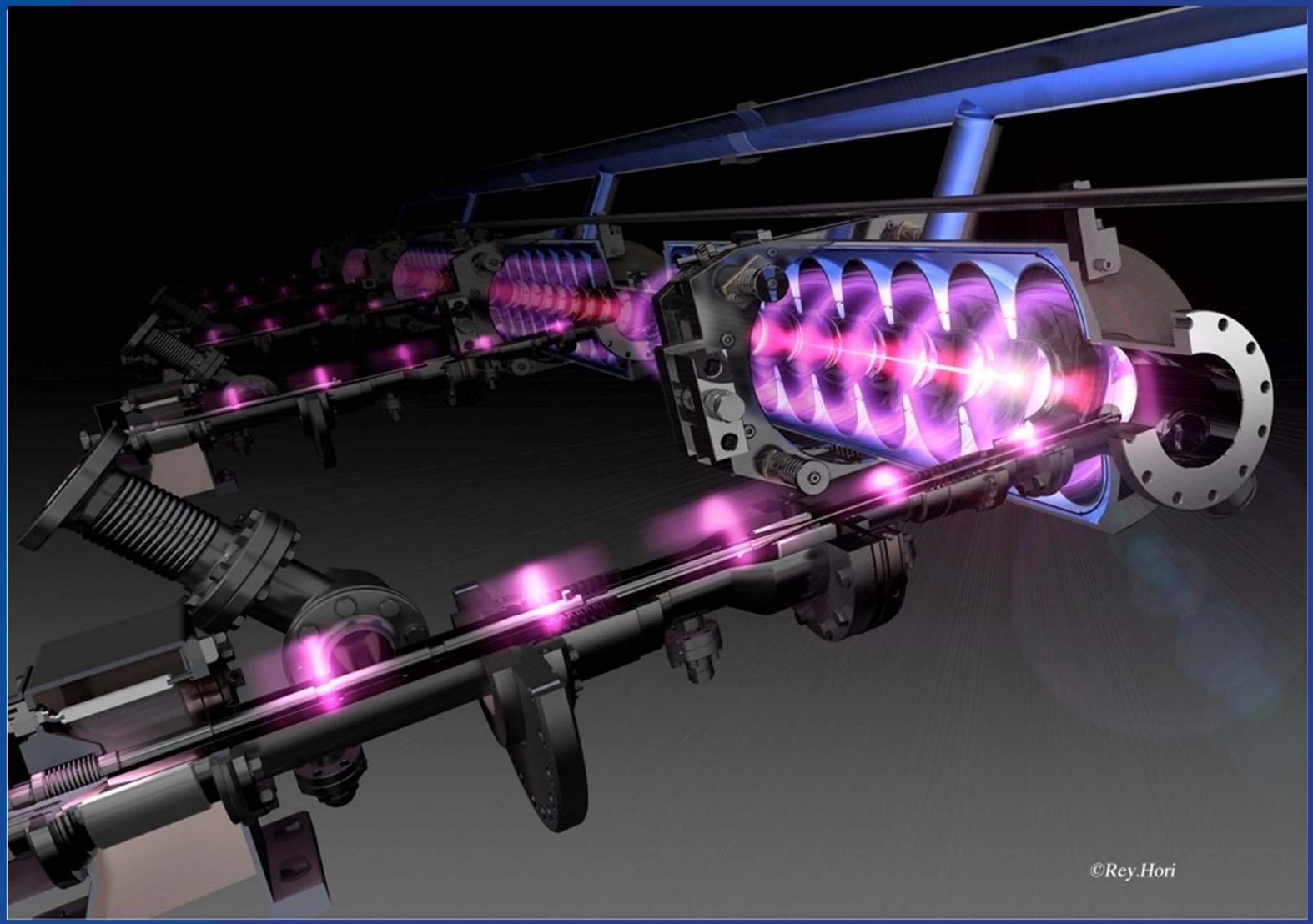
- Atoms ~100
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto



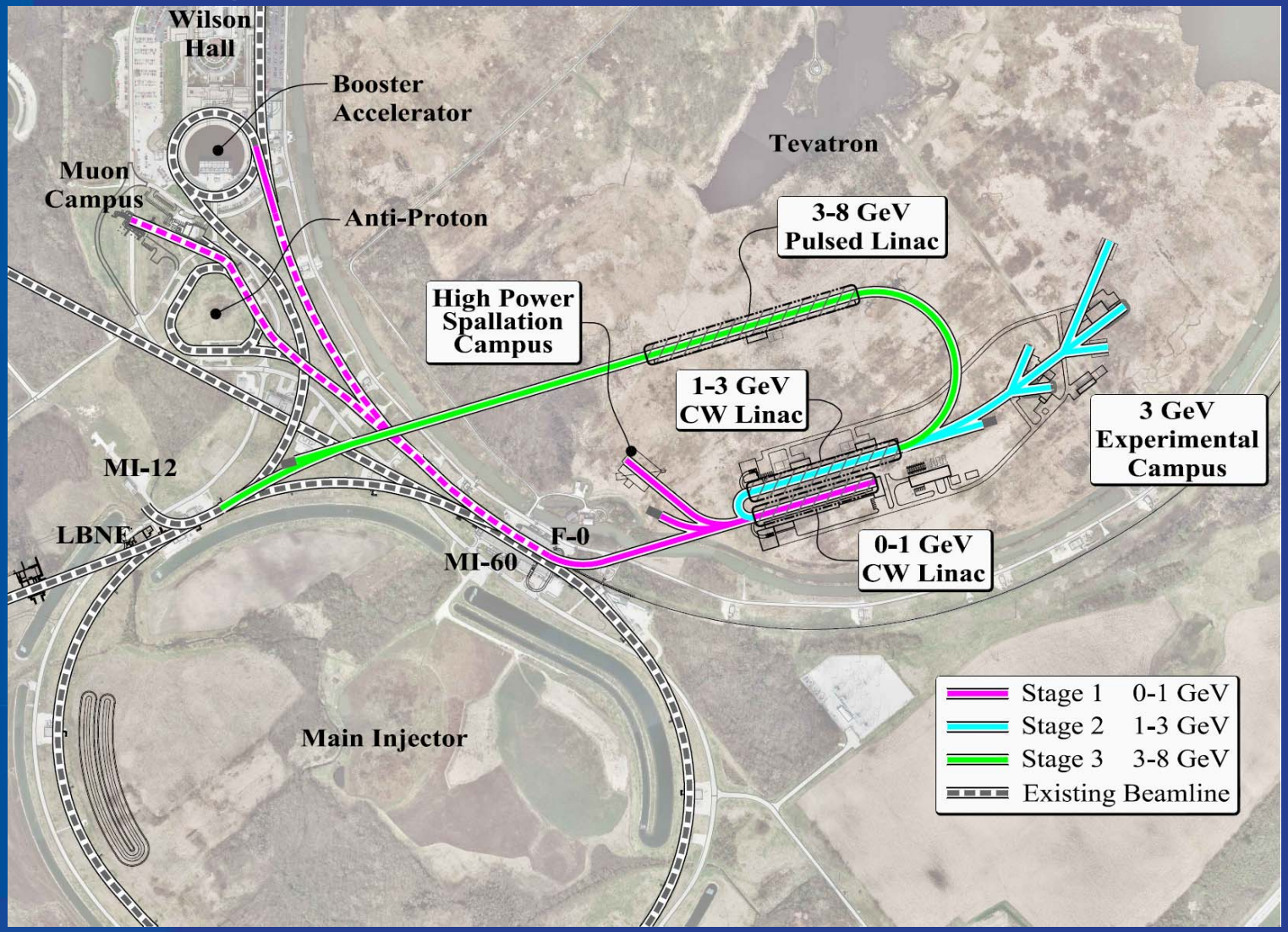
- Ions-Muons ~200
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC
- Solids ~10
  - GGG@Indiana
  - ferroelectrics@Yale

Courtesy Klaus Kirch CIPANP 2012

Beam Power is the Gateway to the Intensity Frontier…



Evolution from the Energy Frontier to the Intensity Frontier at Fermilab…



Summary of the Project X Physics Study June 14th-22nd 2012

- 220 participants
- Detailed investigation of experimental concepts and required detector R&D.
- Serving as the basis for research program "Golden Book" now under development for Snowmass

PX Physics Study Conveners for Experimental Concepts and Sensitivities

Neutrinos:

Andre de Gouvea (Northwestern University), Patrick Huber (Virginia Tech) , Geoff Mills (LANL)
Ko Nishikawa (University of Chicago/FNAL), Steve Geer (FNAL)

Muon Experiments:

Bob Bernstein (Fermilab), Graham Kribs, (University of Oregon)

Kaon Experiments:

Kevin Pitts (University of Illinois UC), Vincenzo Cirigliano (LANL)

EDMs:

Tim Chupp (University of Michigan) , Susan Gardner (University of Kentucky), Zheng-Tian Lu (ANL)

n-nbar oscillations:

Chris Quigg (FNAL), Albert Young (North Carolina State University)

Hadron physics:

Stephen Godfrey (Carleton University), Paul Reimer (ANL)

Hidden Sector physics:

William Wester (FNAL)

PX Physics Study Conveners for Enabling Technologies and Techniques

High rate Precision Photon Calorimetry:

David Hitlin (Caltech), Milind Diwan (BNL)

Very Low-Mass High-Rate Charged Particle Tracking:

Ron Lipton (FNAL), Jack Ritchie (University of Texas, Austin)

Time-of-Flight System Performance below 10 psec:

Mike Albrow (FNAL), Bob Wagner (ANL)

High Precision Measurement of Neutrino Interactions:

Kevin McFarland (Rochester University), Jonghee Yoo (FNAL), Rex Tayloe (University of Indiana)

Large Area Cost Effective (LACE) Detector Technologies:

Mayly Sanchez (Iowa State University), Yury Kamyshkov (University of Tennessee)

Lattice QCD:

Ruth Van de Water (BNL), Tom Blum (University of Connecticut)

Example Research Program, definitive space of accelerator parameters on PXPS Indico site

Project X Campaign

Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW +0-50kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.

** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.

Stage-1 Accelerator Resources:

- Promotes the Main Injector (MI) to a Mega-Watt class machine for neutrinos, and increases the potential beam power for other medium power MI experiments (e.g. ORKA, nu-STORM).
- Unshackles the $\mu \rightarrow e$ (Mu2e) experiment from the Booster complex: Potentially increases sensitivity of Mu2e by x10 - x100 with 1-GeV CW drive beam.
- High power spallation target optimized for ultra-cold neutron and atomic-edm particle physics experiments and neutron$\Leftrightarrow$anti-neutron oscillation experiments.
- Capability to drive polarized protons to a proton-edm experiment.
- Increases the available integrated 8 GeV power for other experiments (e.g. short-baseline neutrinos) from the Booster complex by liberating Mu2e.

Since PXPS, Development of Stage-1 Research Program

Physics Opportunities with Stage 1 of Project X

Wolfgang Altmannshofer, Marcela Carena, Patrick Fox, Stuart Henderson, Stephen Holmes, Young-Kee Kim, Joachim Kopp, Andreas Kronfeld, Joseph Lykken, Chris Quigg, and Robert Tschirhart

August 2012

Rare Processes Research
Probing far Beyond the TeV scale with Stage-1

- x10 improvement in mu2e sensitivity. Platform for next generation rare muon decay experiments such as $\mu \rightarrow 3e$.

- x100 improvement in $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ sensitivity, many other rare K^+ modes.

Process	Current	ORKA	Comment
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$	7 events	1000 events	
$K^+ \rightarrow \pi^+ X^0$	$< 0.73 \times 10^{-10}$ at 90% CL	$< 2 \times 10^{-12}$	$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is a background
$K^+ \rightarrow \pi^+ \pi^0 \nu\nu$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \rightarrow \pi^+ \pi^0 X^0$	$\lesssim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \rightarrow \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$	
$K^+ \rightarrow \mu^+ \nu_{heavy}$	$< 2\text{–}10 \times 10^{-8}$	$< 1 \times 10^{-10}$	150 MeV $< m_\nu <$ 270 MeV
$K^+ \rightarrow \mu^+ \nu_\mu \nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$	
$K^+ \rightarrow \pi^+ \gamma\gamma$	293 events	200,000 events	
$\Gamma(Ke2)/\Gamma(K\mu 2)$	$\pm 0.5\%$	$\pm 0.1\%$	
$\pi^0 \rightarrow \nu\bar{\nu}$	$< 2.7 \times 10^{-7}$	$< 4\text{–}50 \times 10^{-9}$	depending on technique
$\pi^0 \rightarrow \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$	

PAC Feedback Regarding the Proton EDM Expression of Interest.

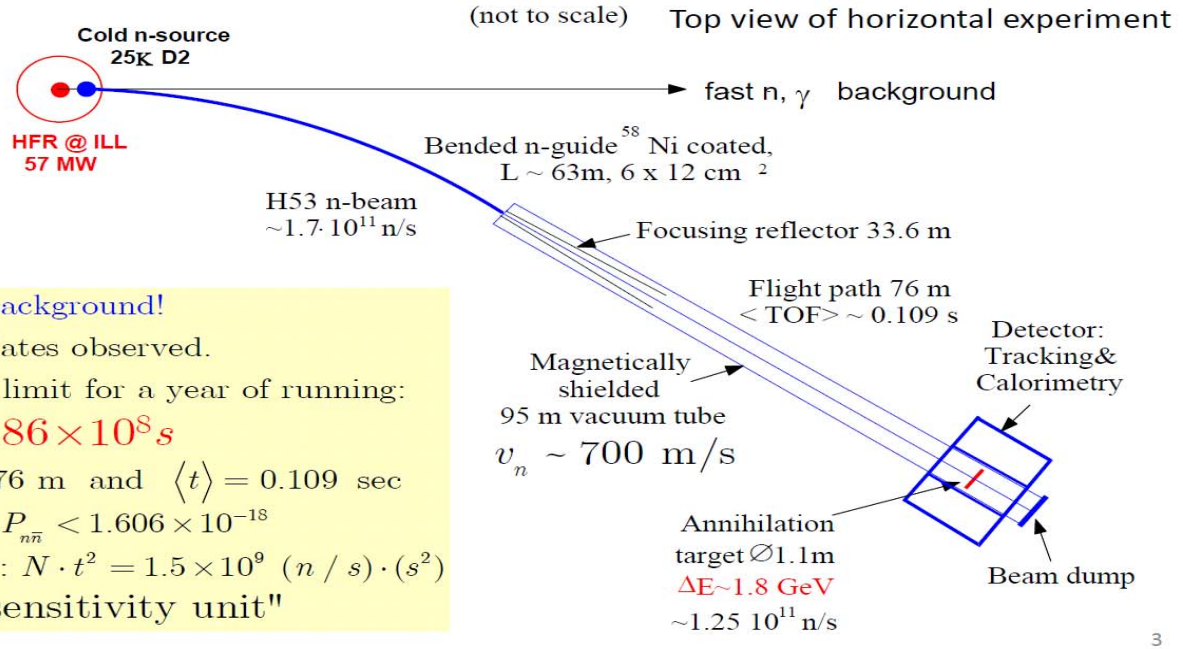
- "…This experiment represents an exciting opportunity for Fermilab."
- "…The PAC recommends that Fermilab and Brookhaven management work together, and with potential international partners, to find a way for critical R&D for this promising experiment to proceed."
- This experiment requires 236 MeV/c polarized protons of modest intensity, injection every 20-60 minutes.

Stage-1 presents an opportunity to increase n-nbar search sensitivity by > x20

Previous n-nbar search experiment with free neutrons

At ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

Z. Phys., C63 (1994) 409



No GeV background!

No candidates observed.

Measured limit for a year of running:

$\tau_{n\bar{n}} > 0.86 \times 10^8 s$

with L ~ 76 m and $\langle t \rangle = 0.109$ sec

measured $P_{n\bar{n}} < 1.606 \times 10^{-18}$

sensitivity: $N \cdot t^2 = 1.5 \times 10^9 \ (n/s) \cdot (s^2)$

$\doteq$ "ILL sensitivity unit"

3

Dubbers, Kamyshkov PXPS

PAC Feedback Regarding the n↔$\bar{n}$ Expression of Interest.

- "…The observation of n↔nbar oscillation would be a major breakthrough in particle physics, providing evidence for baryon number violation, which is needed to explain the observed baryon asymmetry of the Universe."

- "…The PAC recommends that R&D be supported, when possible, for the design of the spallation target, and for the overall optimization of the experiment, to bring it to the level required for a proposal to be prepared. The NNbarX experiment would be an interesting addition to the wider physics program involving neutrons at the first stage of Project-X."

Example Research Program, definitive space of accelerator parameters on PXPS Indico site

Project X Campaign

Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW +0-50kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.

** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.

Science Enabled with Stage-2

- World leading kaon physics program: Megawatt power (x10 over competing facilities) can drive multiple experiments.
- World class muon physics program: Mu2e descendant migrates to a higher power campus. Megawatt power for conversion experiments (x10 over competing $\mu \rightarrow e$ facilities), opportunities for major next steps in other channels (e.g. $\mu \rightarrow 3e$, others).
- Maintains Main Injector beam power at lower energies (e.g. 60 GeV) enhancing the neutrino spectrum for long baseline experiments.

Mu2e Search for $\mu^- \rightarrow e^-$ conversion at 10^{-16}

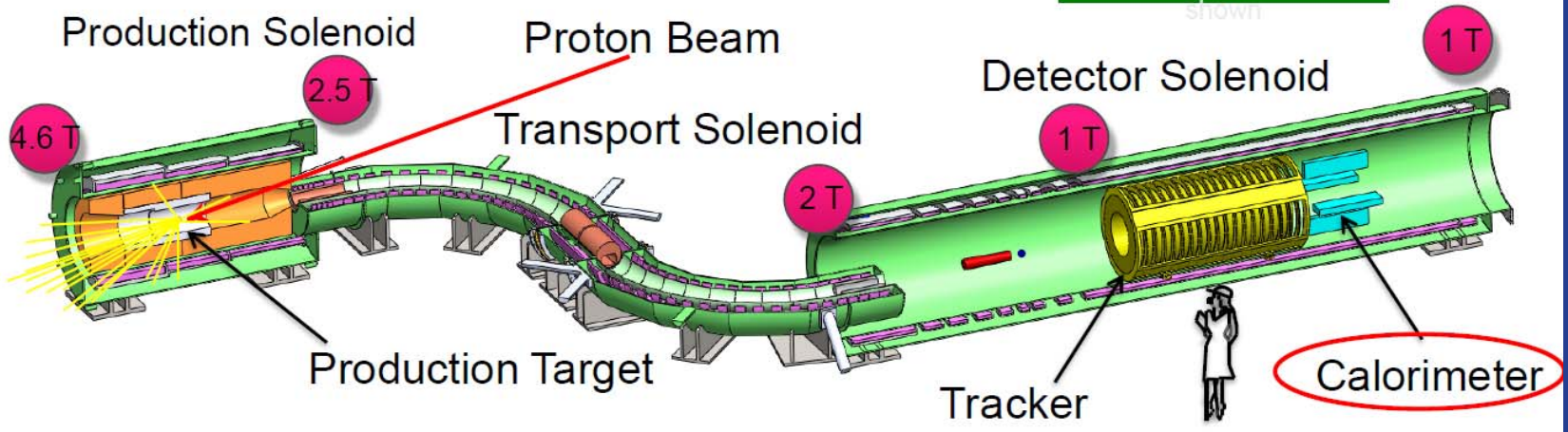
Production Solenoid
- Production target
- Graded field

- Delivers ~ 0.0016 stopped μ^- per incident proton
- 10^{10} Hz of stopped muons

Detector Solenoid
- Muon stopping target
- Tracker
- Calorimeter
- Warm bore evacuated to 10^{-4} Torr

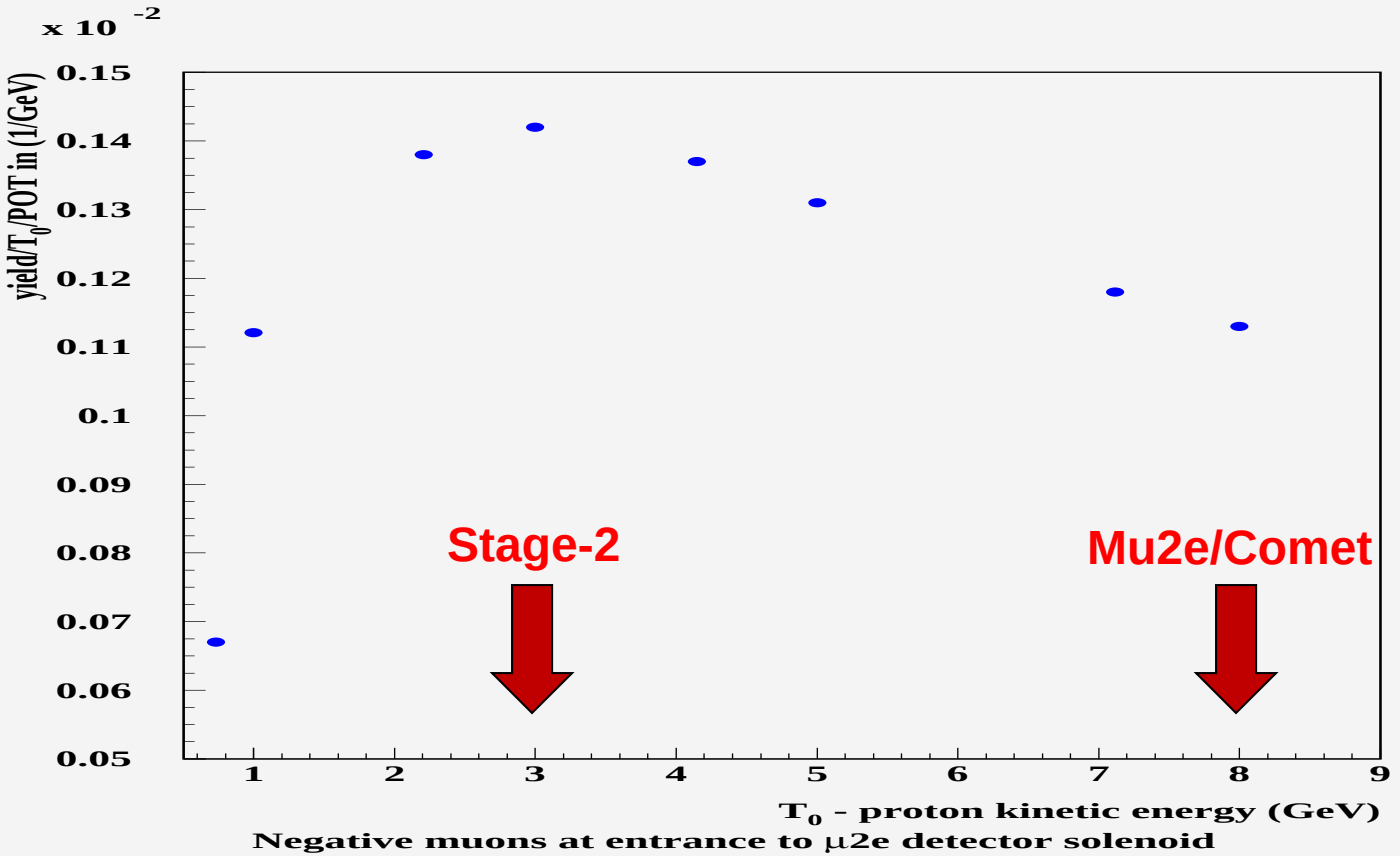
Transport Solenoid
- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator

Cosmic Ray Veto not shown



What is the optimum proton beam energy to drive a MELC/MECO/Comet-Mu2E experiment?

Yield / Watt

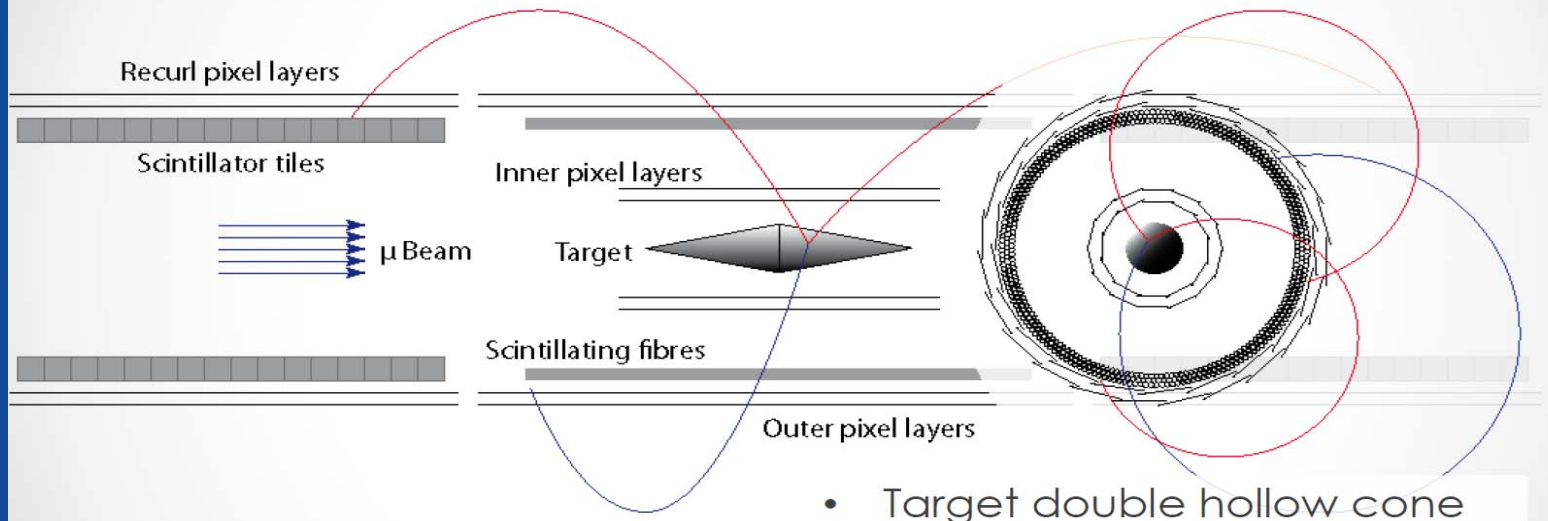


S. Striganov et al PXPS, work in progress

0.1% X_0 per layer, 100 psec track timing…

$\mu \rightarrow 3e$, $\mu \rightarrow e\gamma^*$

The Mu3e Experiment



- Muon beam O(10^9/s)
- Helium atmosphere
- 1 T B-field

- Target double hollow cone
- Silicon pixel tracker
- Scintillating fiber tracker
- Tile hodoscope

Dirk Wiedner, Mu3e collaboration 7/17/2012 21

Dirk Wiedner, Mu3e Initiative at PSI

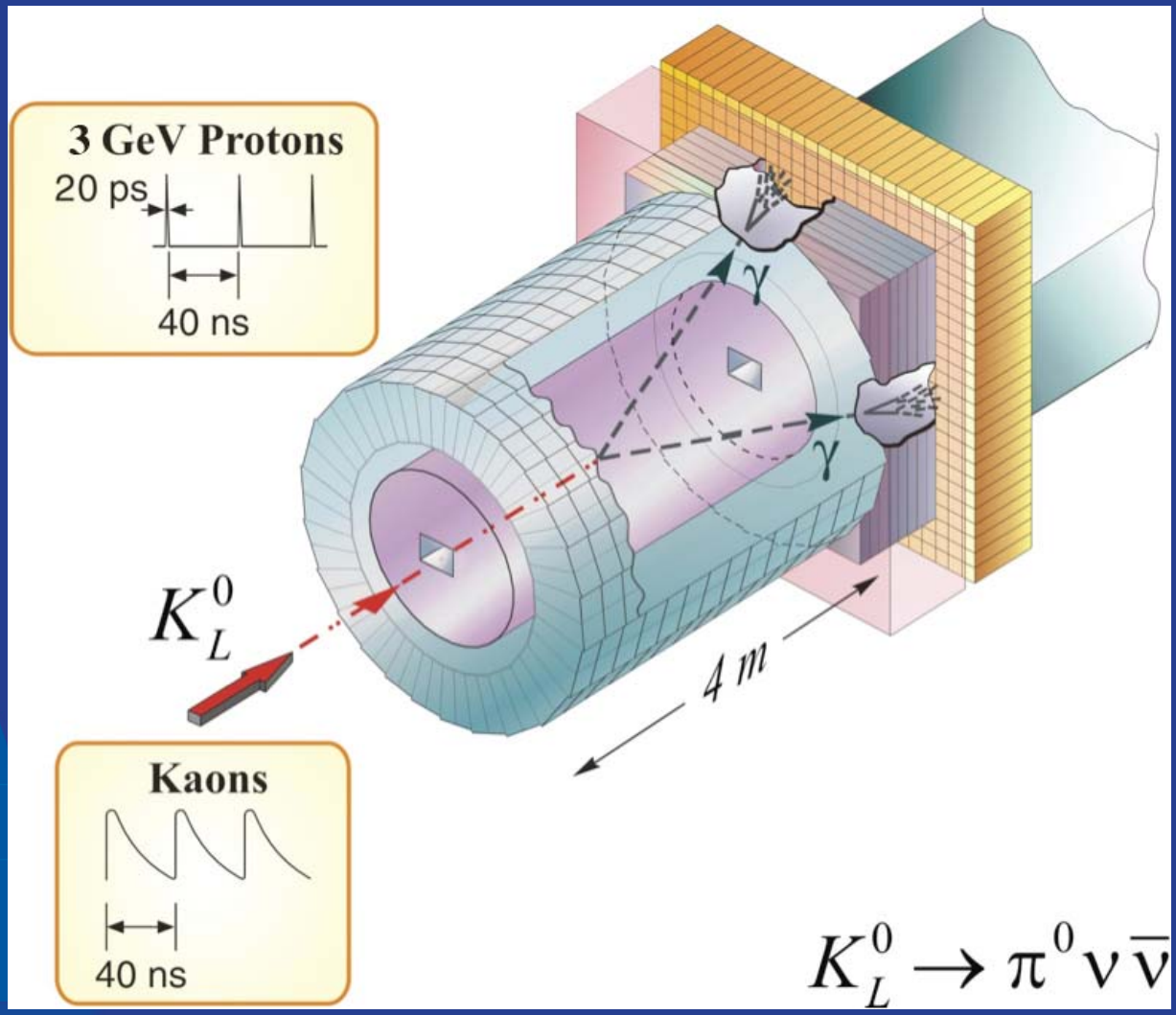
Kaons at Project X

- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$
  - but hopefully it's already done to a few %.
- $K_L \rightarrow \pi^0 \nu\bar{\nu}$
  - "This experiment was made for Project X" –L. Littenberg
- Many other modes of interest
  - T violation in $K^+ \rightarrow \pi^0 \mu\nu$ (TREK)
  - Universality $\Gamma(K^+ \rightarrow e^+\nu)/\Gamma(K^+ \rightarrow \mu^+\nu)$
  - $K_L \rightarrow \pi^0\mu\mu$ and π^0ee (look at K_S/K_L interference?)
  - K^+, K_L lepton flavor violation e.g. $K_L \rightarrow \mu e$
  - $K_L \rightarrow \gamma\gamma$
  - …

Kevin Pitts, PXPS

21-Jun-12 Kaon Experimental Summary Kevin Pitts (kpitts@illinois.edu) 19

“Nothing in, nothing out…” Next generation photon measurements crucial.



Example Research Program, definitive space of accelerator parameters on PXPS Indico site

Project X Campaign

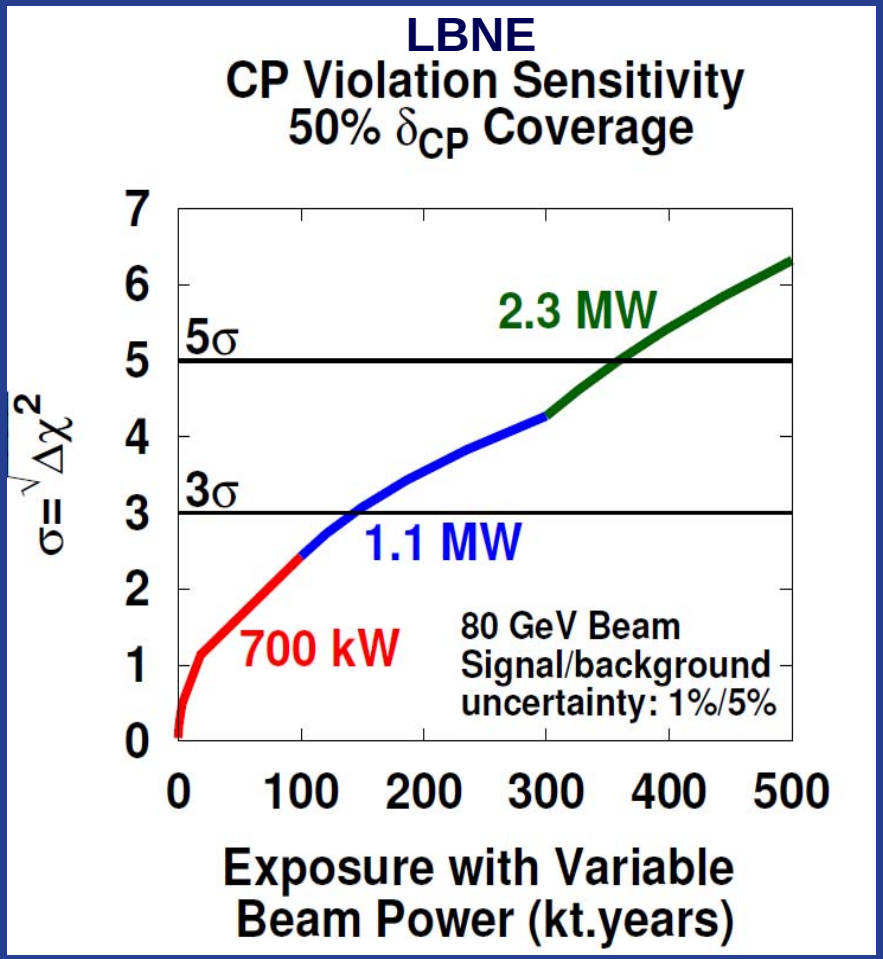
Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 3 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW +0-50kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.

** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.

Science Enabled with Stage-3 (RDR)

- Main Injector power upgrade to >2 Mega Watts for 60-120 GeV beam, doubling power to the long baseline Main Injector Neutrinos (LBNE) and Main Injector near-detector neutrino physics.
- 8 GeV beam power for experiments is doubled to now x10 the MiniBooNE era, which will support a new generation of short-baseline neutrino physics.



Example Research Program, definitive space of accelerator parameters on PXPS Indico site

Project X Campaign

Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW +0-50kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.

** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.

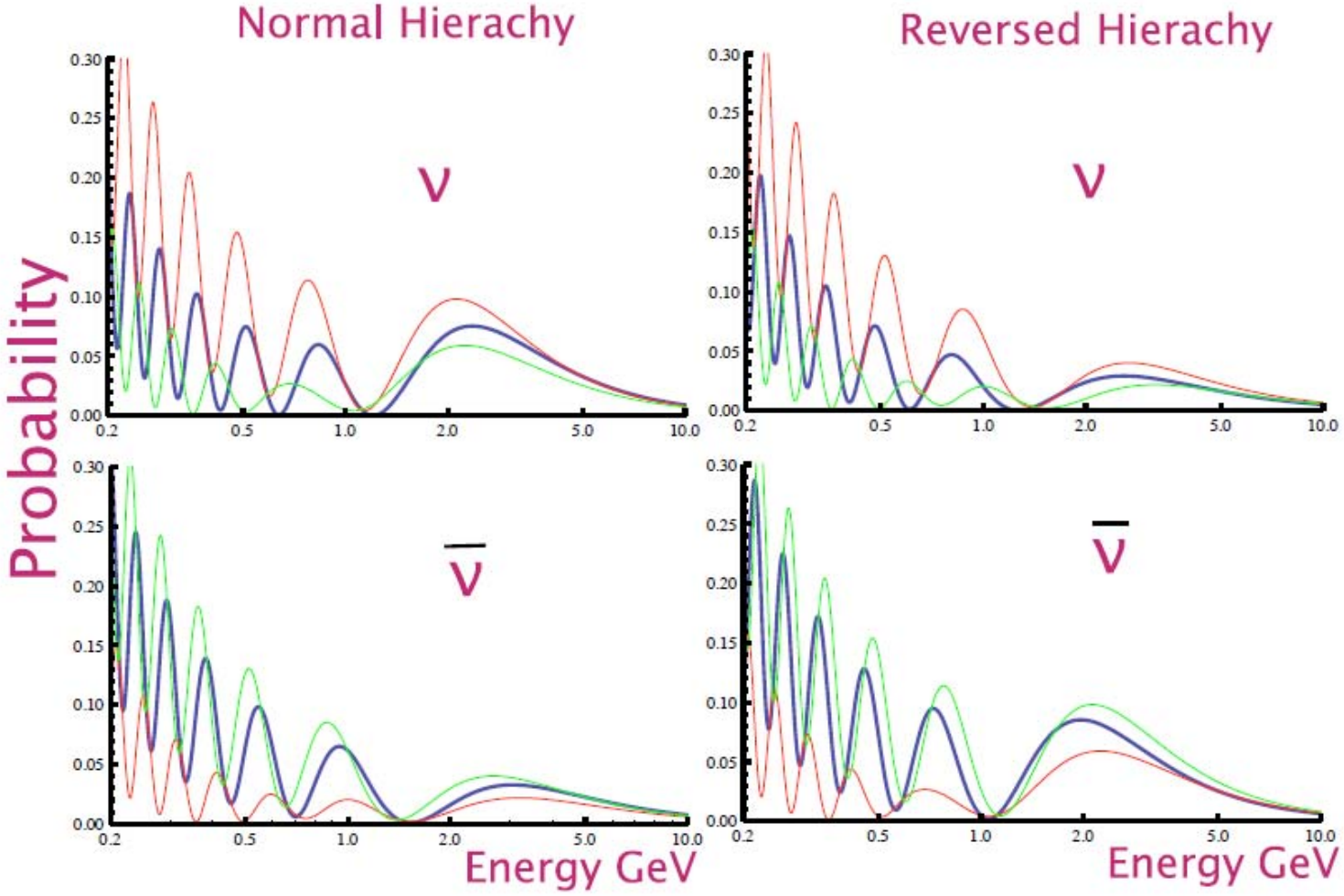


FIG. 3: Appearance probability for $\nu_\mu \rightarrow \nu_e$ as a function of energy at a distance of 1300 km. The top plots are for neutrinos and bottom plots are for anti-neutrinos. The left side plots are for normal mass ordering and right hand side are for reversed mass ordering. The parameters used for these plots are $\Delta m^2_{32} = 0.0025eV^2$, $\Delta m^2_{12} = 7.6 \times 10^-5eV^2$, $\theta_{23} = \pi/4$, $\theta_{12} = 34^o$, $\theta_{13} = 9.2^o$. The blue curve in all cases is for $\delta_{CP} = 0$ and the red and green curves are for $\delta_{CP} = \pi/2$ and $-\pi/2$, respectively.

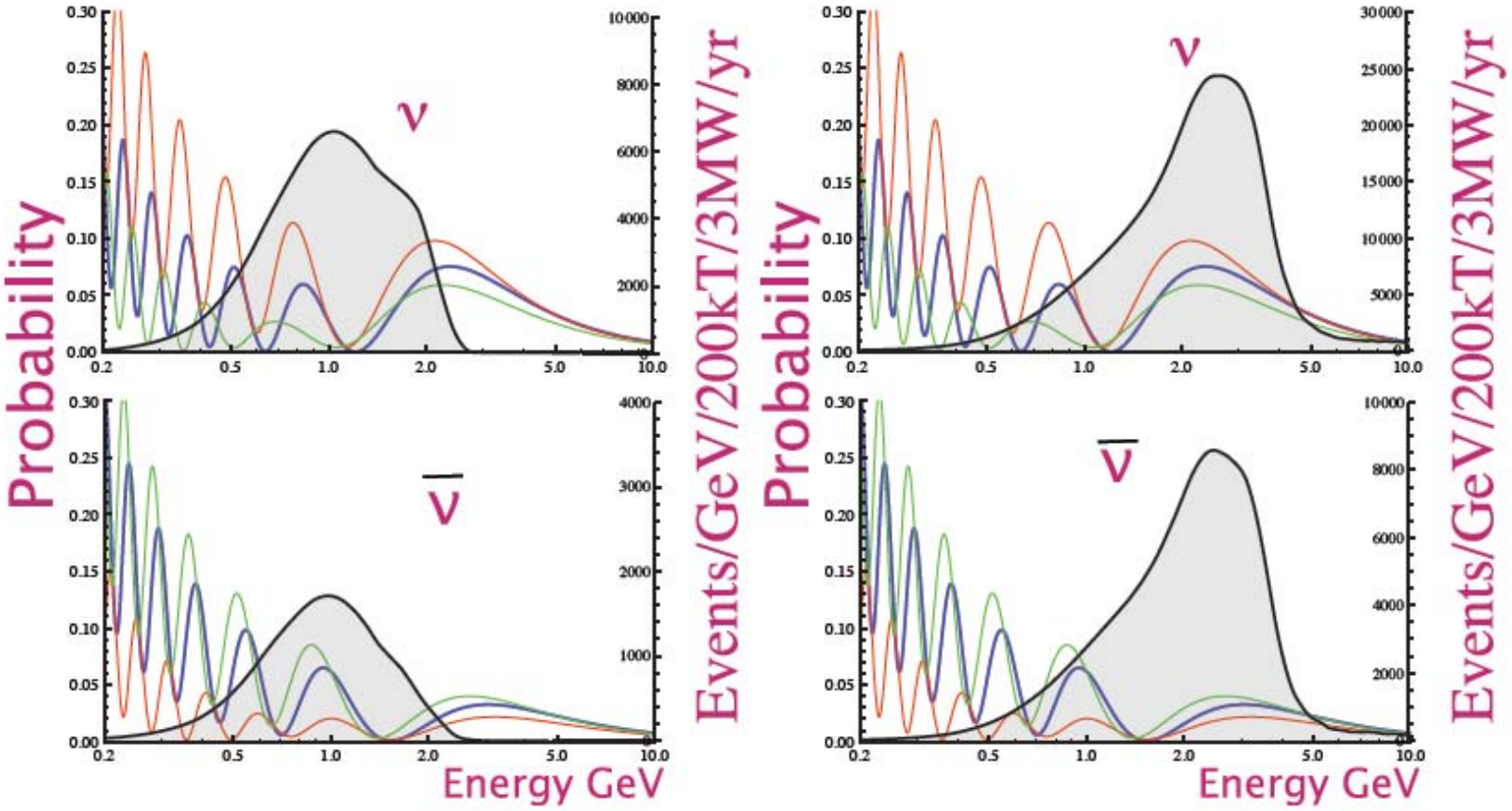


FIG. 5: Spectra of event rates as a function of energy for 8 GeV (left) and 60 GeV (right) proton beams from Fermilab. The spectra are superimposed on the expected oscillation probability for normal hierarchy. Spectra are for the total charged current cross-section for muon neutrino (top) and antineutrinos (bottom). The beam is from Fermilab to Homestake over a distance of 1300 km; the intensity for the 8 GeV beam is assumed to be 3 MW and for 60 GeV it is 2 MW. The detector size is 200 kTon fiducial mass.

Science Enabled with Stage-4 (Beyond RDR)

- 4000kW @ 8 GeV and 4000kW at 60 GeV for the ultimate super beams.
- Double super-beam technique can tune illumination of the first and second maxima of long-baseline experiments of very massive next generation long-baseline detectors.
- Driver for an extremely powerful muon storage ring neutrino source, ultimately leading to a neutrino factory as motivated by the physics.

Summary

Particle Physics is exciting

Recent discoveries and innovation have positioned us to ask and answer deep fundamental questions

The main challenge world-wide now is budgetary

Fermilab is executing and developing a plan in a global context to advance particle physics with Intensity Frontier tools