The High Intensity Horizon at Fermilab

R. Tschirhart
Asilomar, California
May 27th, 2013

U.S. DEPARTMENT OF ENERGY

Fermilab

Ten-Year Goals for Fermilab

1. Fermilab is the world leader on the Intensity Frontier

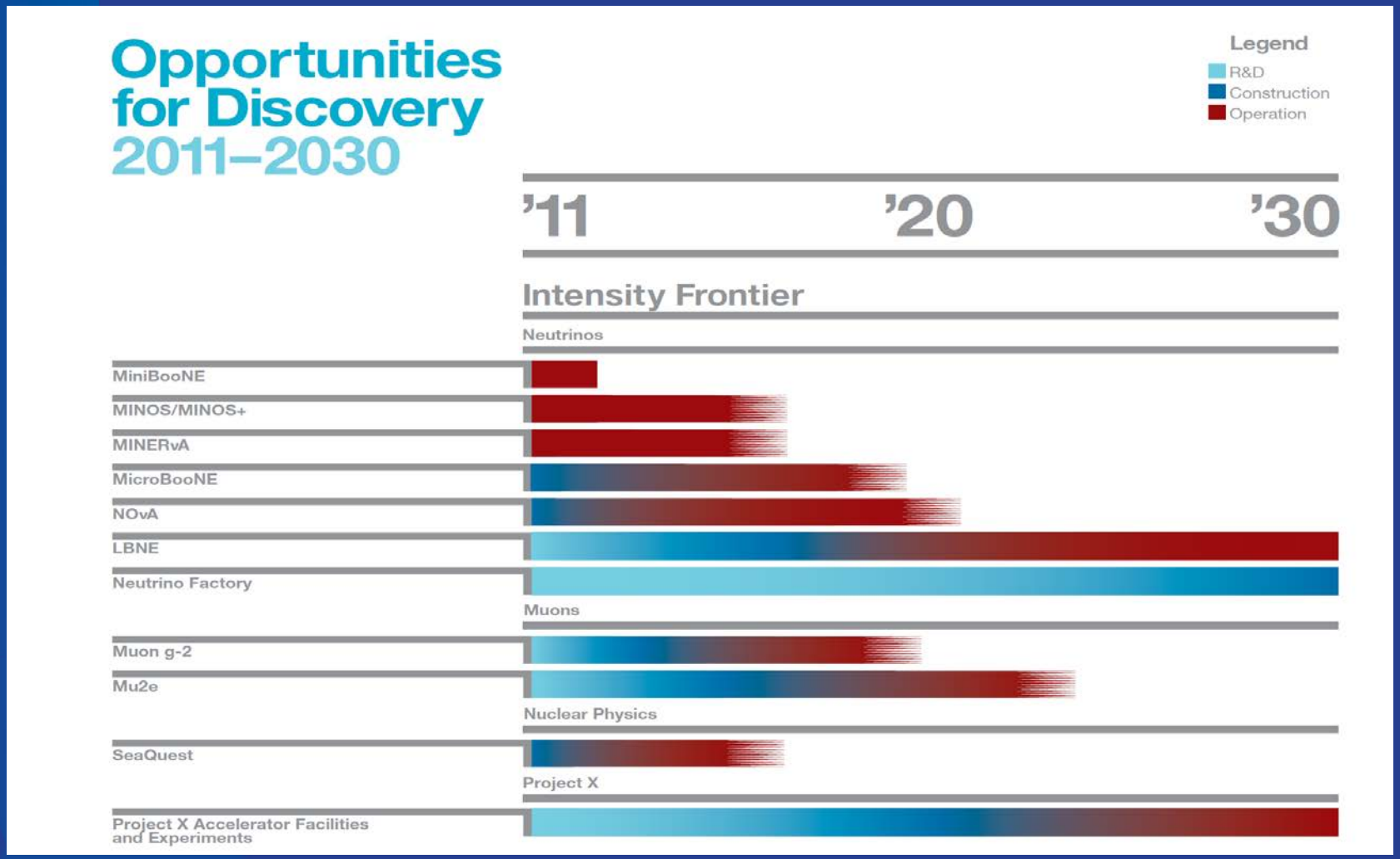
2. Fermilab is a world leader on the Energy Frontier and the Cosmic Frontier

3. Fermilab plays a leadership role in developing the technology for next generation accelerator facilities and in advancing basic understanding

4. Fermilab plays a leadership role in developing the technology for next generation detectors and computing facilities

5. Fermilab plays a leading role in applying technologies to society's problems

Plan for Intensity Frontier Discovery…



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…

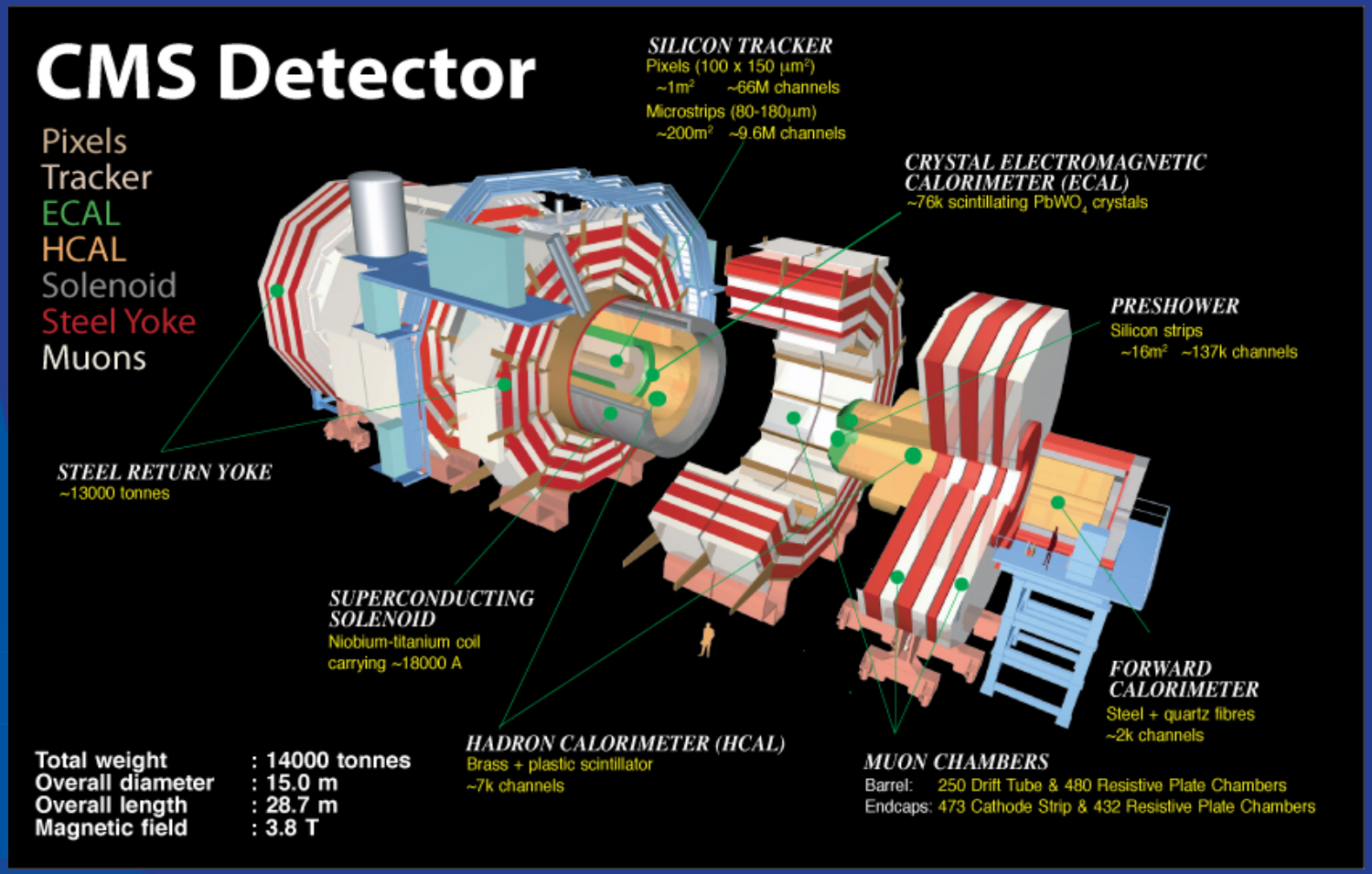
From Hitoshi Murayama , ICFA October 2011

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?

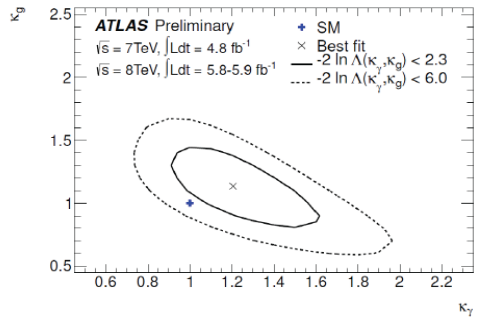
For Discovery of the Standard Model Scalar??

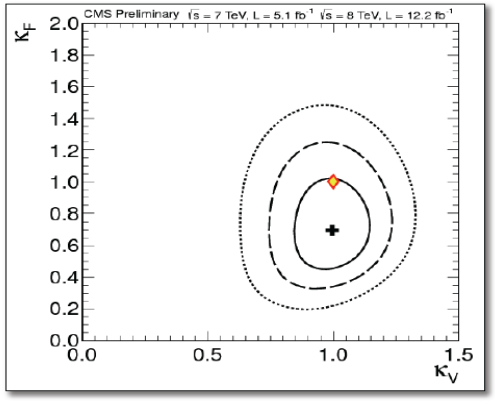


What sub-detector in CMS or ATLAS is the Killer App?

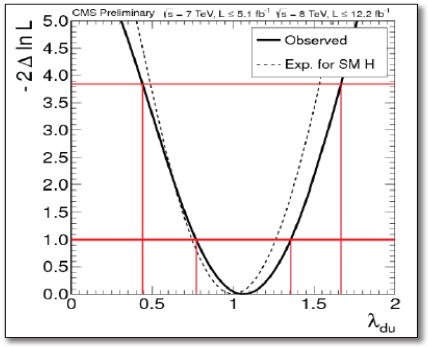
For Discovery of the Standard Model Scalar??

Couplings

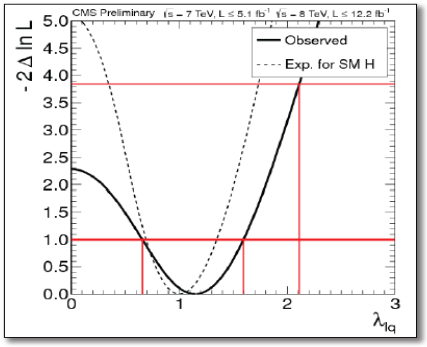




λ_{du}: ratio of couplings between down- and up-fermions



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



Both ratios consistent with 1

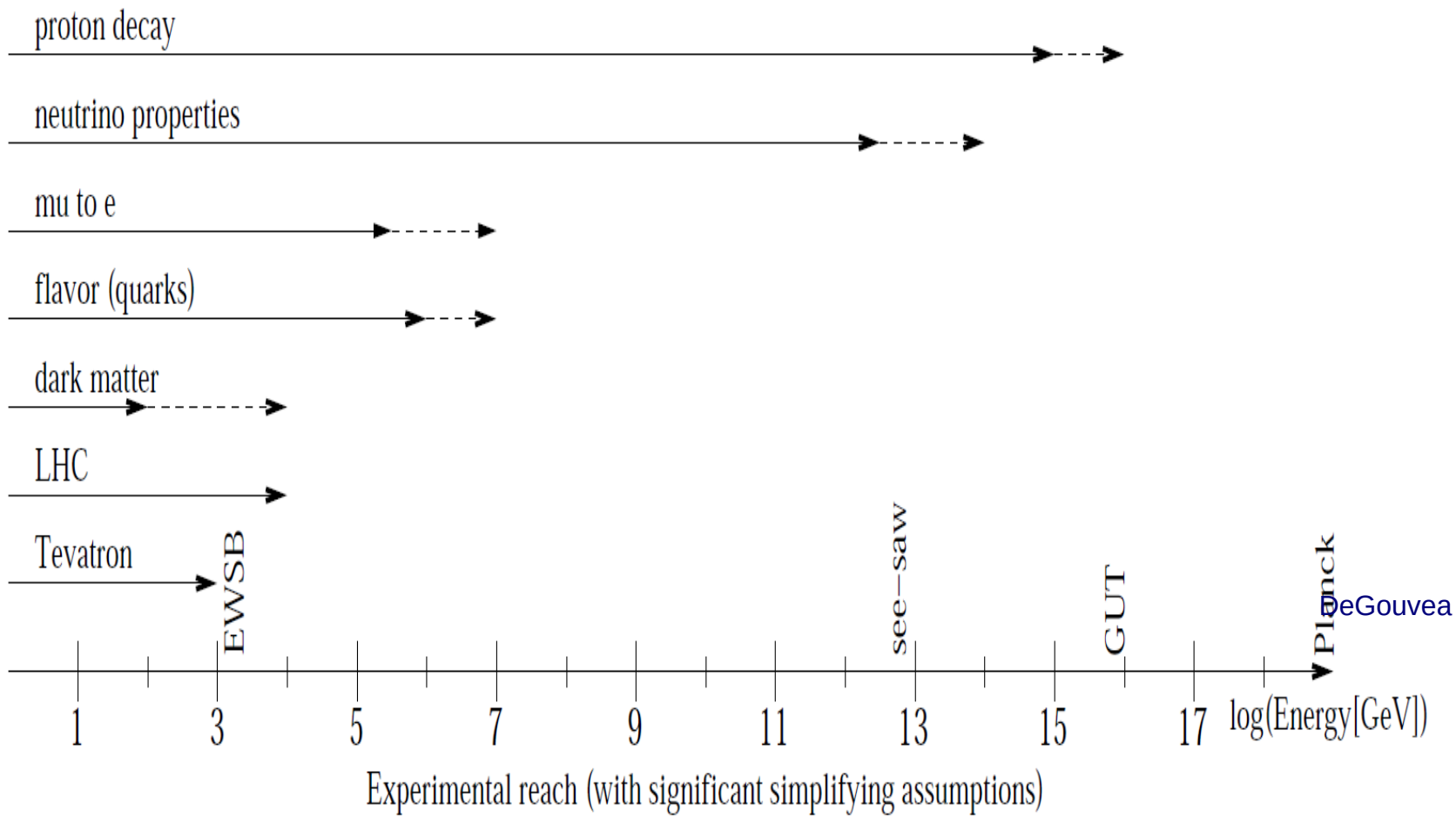
P. Sphicas
Experimental highlights

Rencontres de Moriond, EWK session
Mar 09, 2013

69

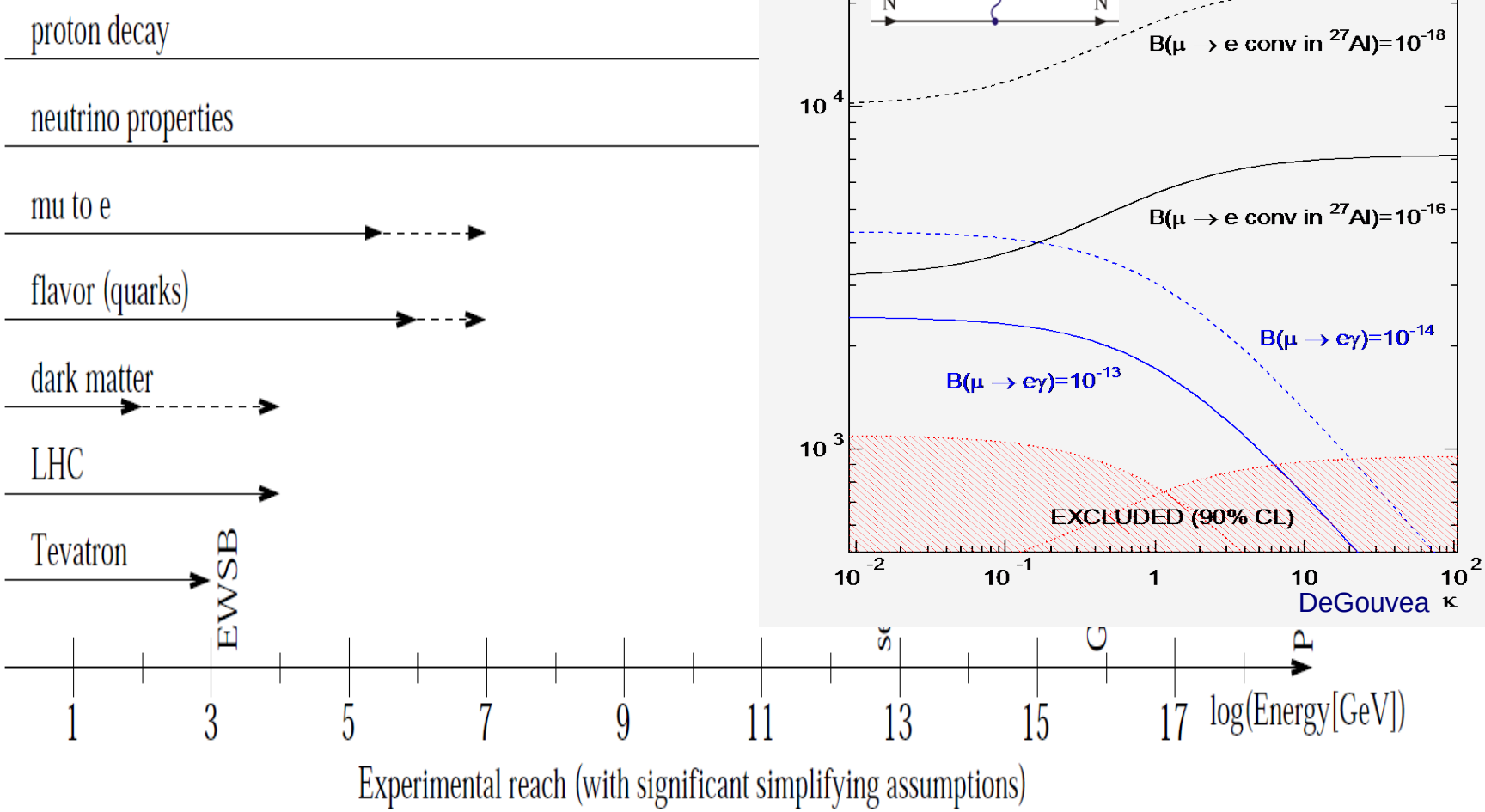
Searches for BSM physics

Indirect Pursuit of BSM from the Intensity Frontier…



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

Indirect Pursuit of BSM from the Intensity Frontier…



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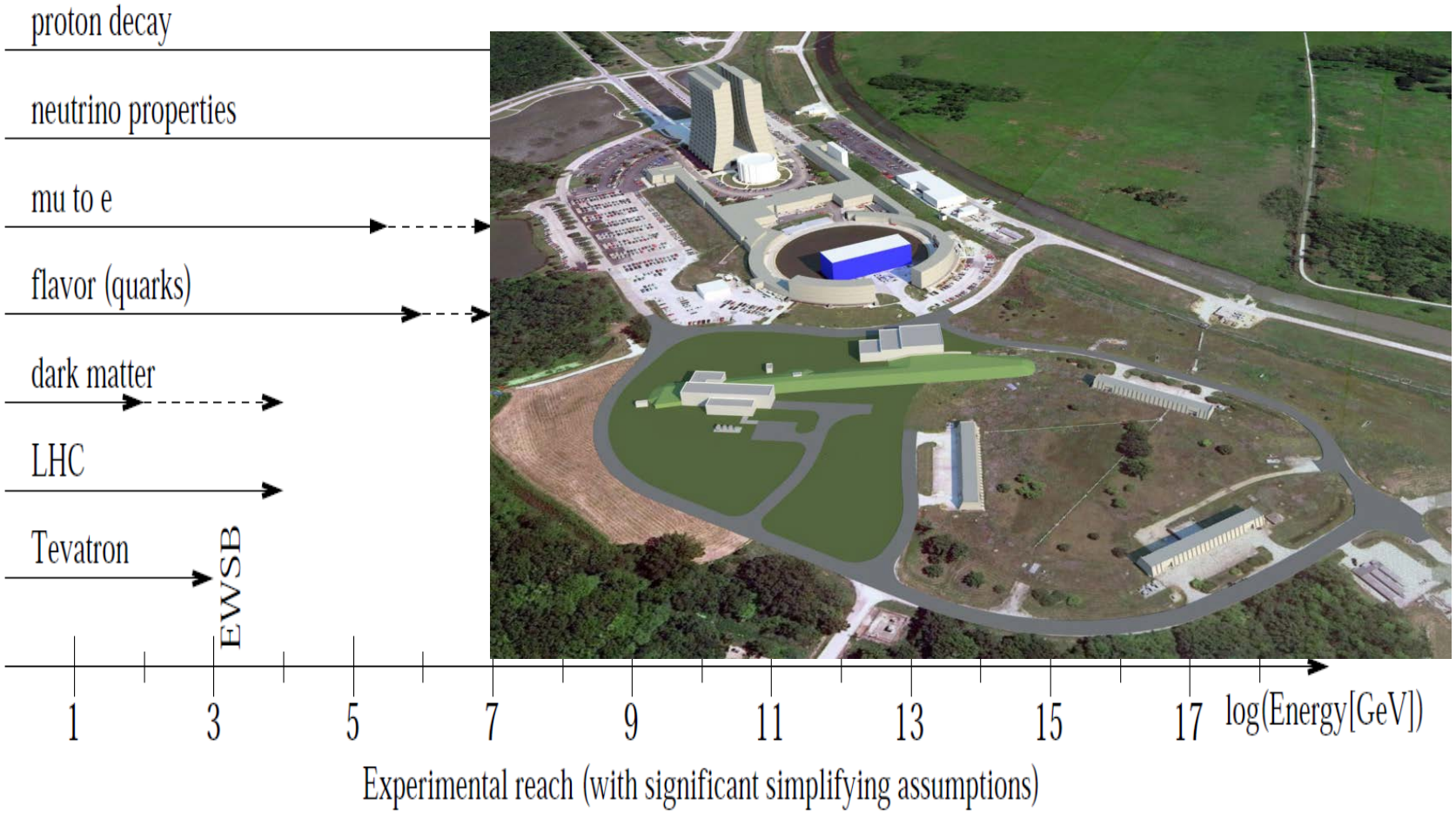
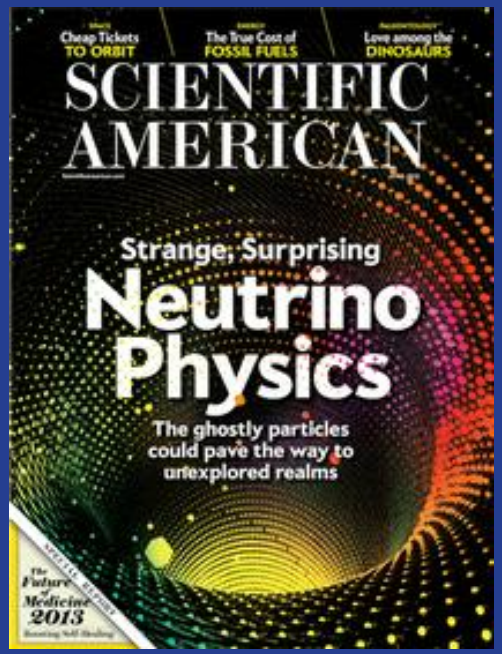
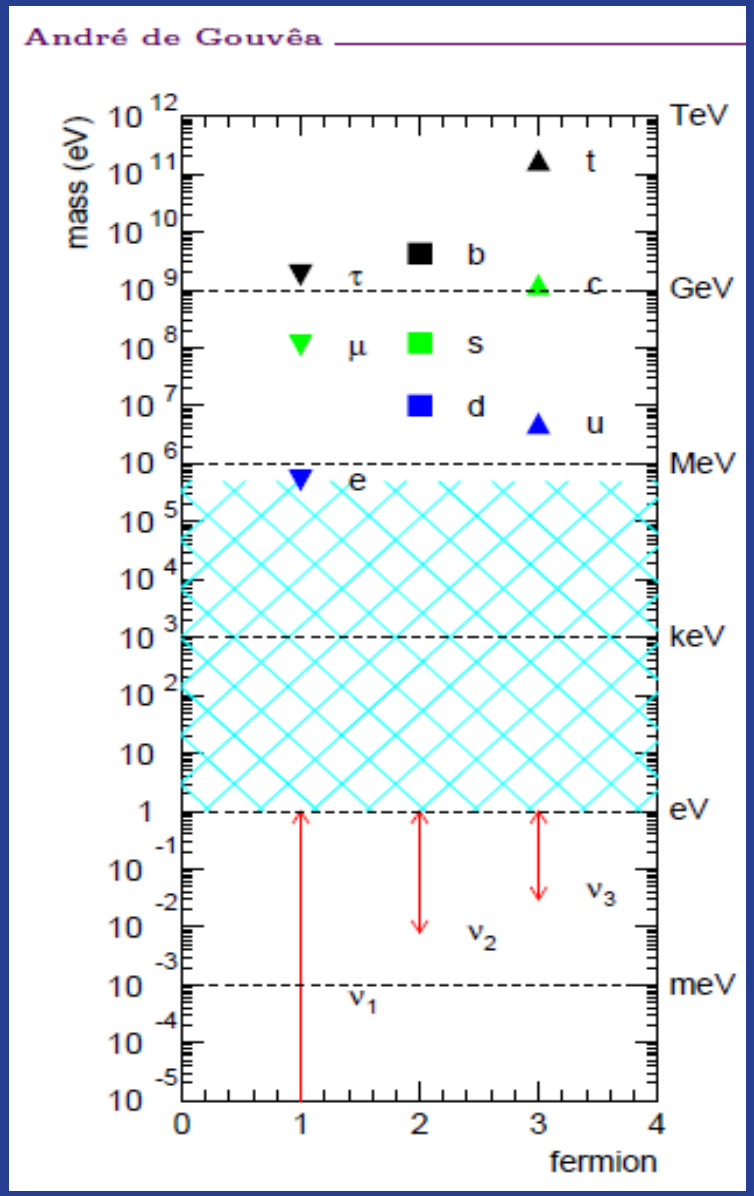


Y. Grossman, Z. Ligeti, Project X Physics Study (PXPS)

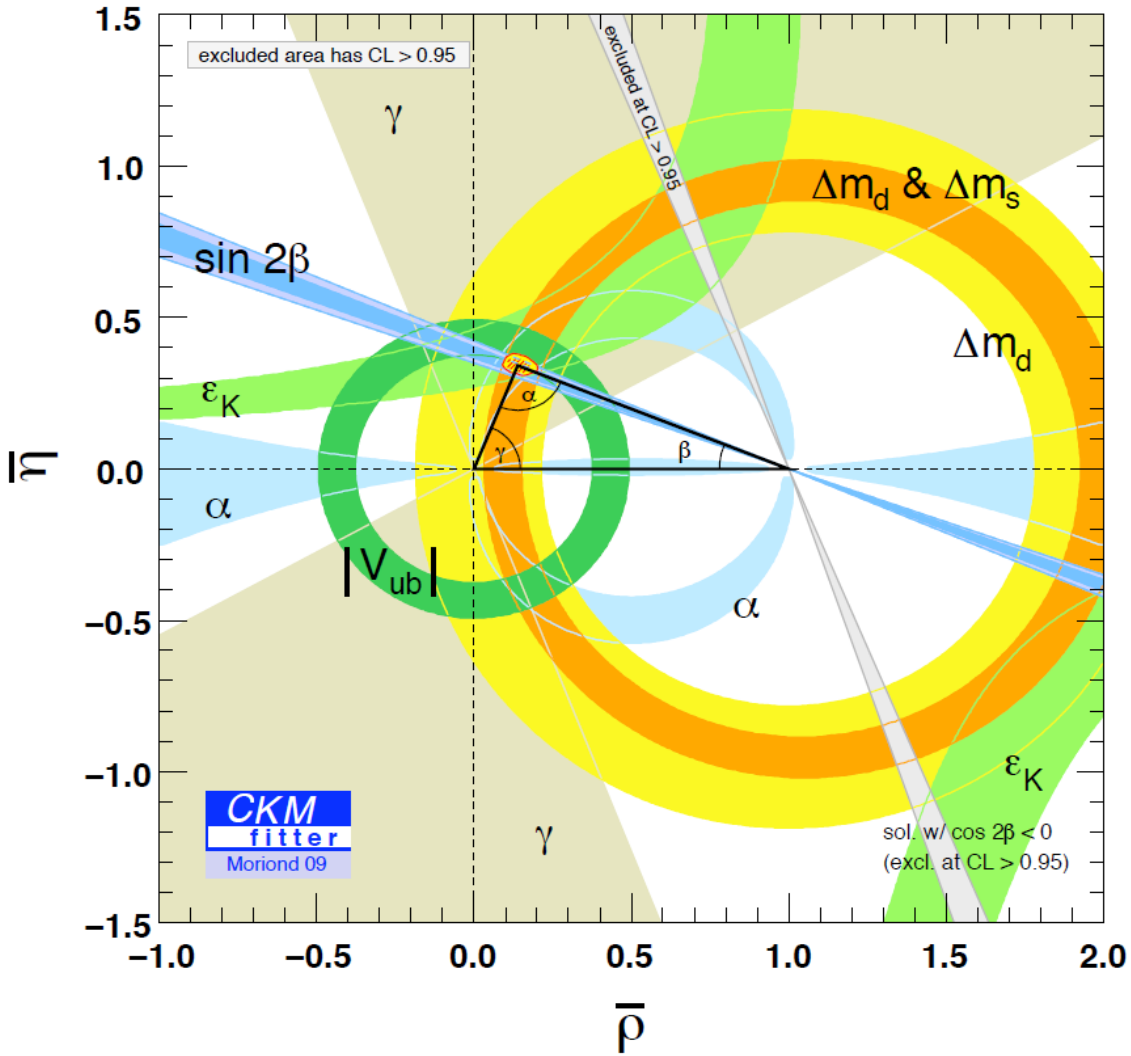
Physics Beyond the Standard Model has been discovered….

What does it mean?





What we ultimately want to achieve:



We need to do this in the lepton sector!

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!

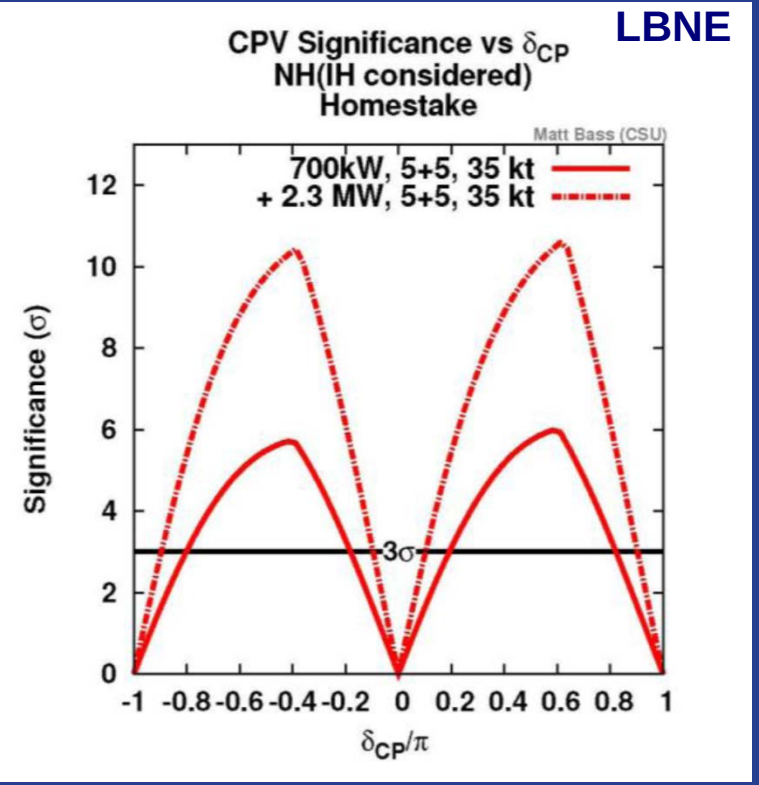


Table 2: SM predictions and current and expected limits on selected examples of EDMs.

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

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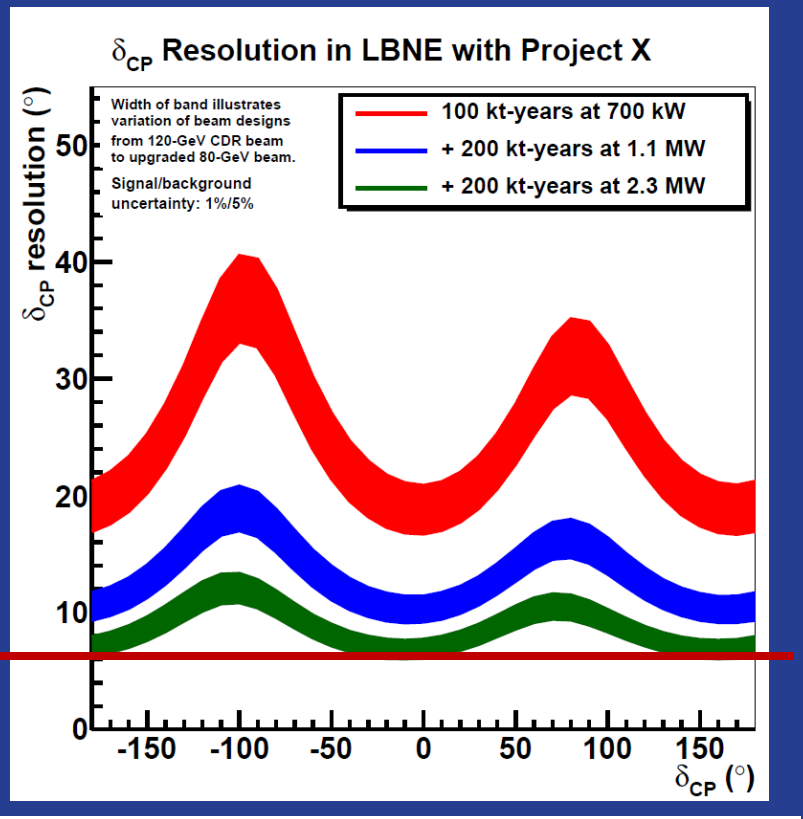

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30 White Papers submitted that need accelerators as neutrino drivers

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

Facility subpanel recommendations,

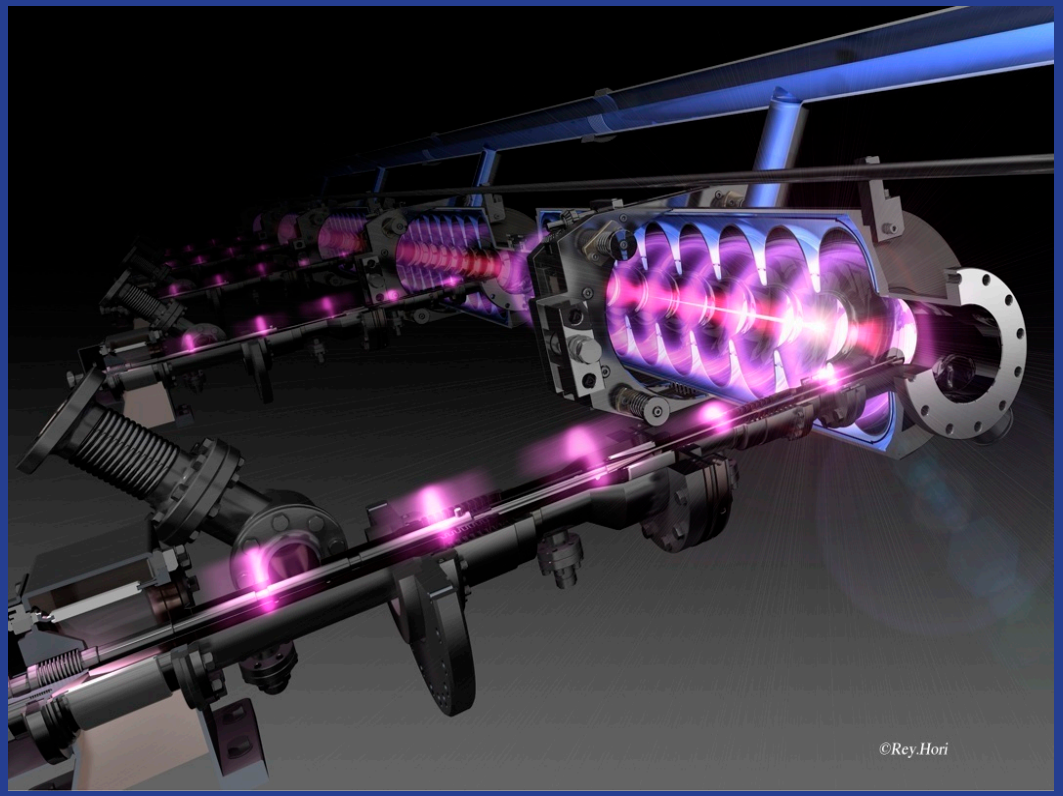
accepted by the High Energy Physics Advisory Panel: HEPAP:

- 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

Project-X:

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



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

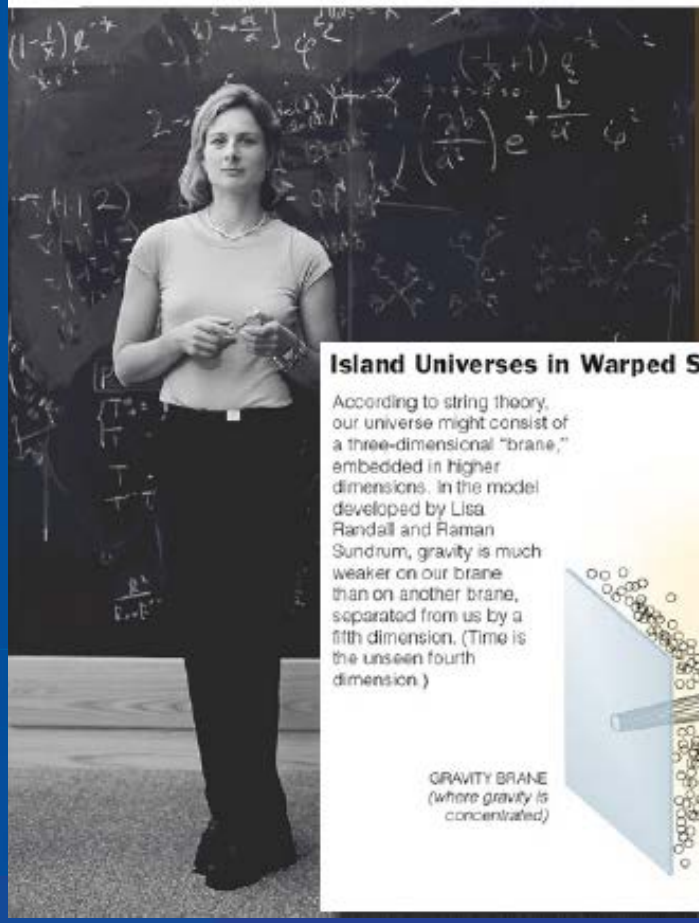
- ***New dimensions***

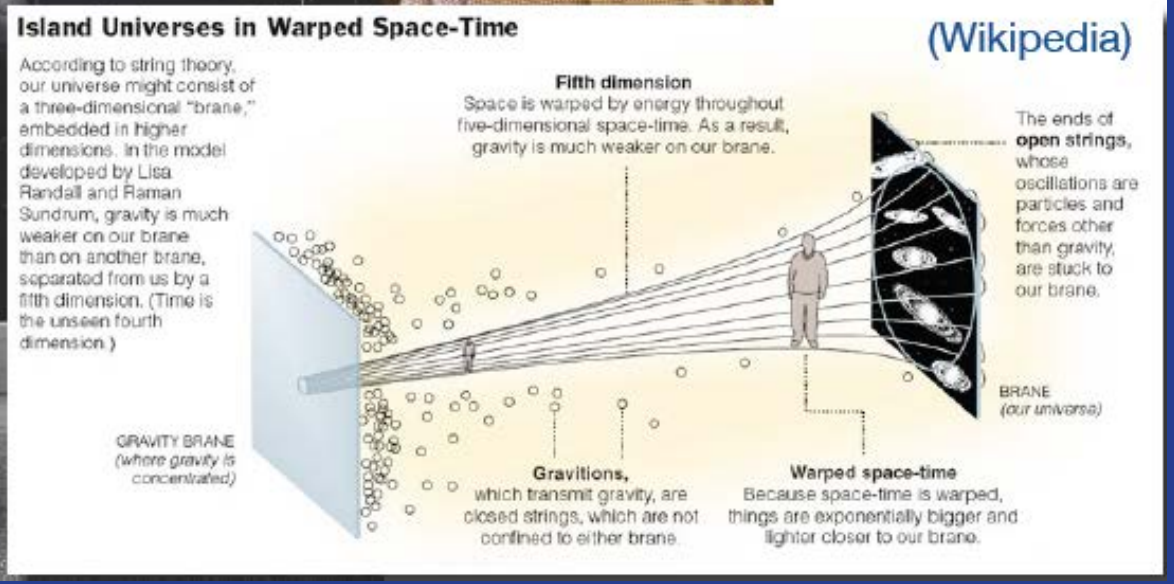
  e.g. super-symmetric amplitudes via EDMs

  Warped dimensions via kaon decays

Rare processes have Model Discrimination Power… e.g. Warped Extra Dimensions as a Theory of Flavor??

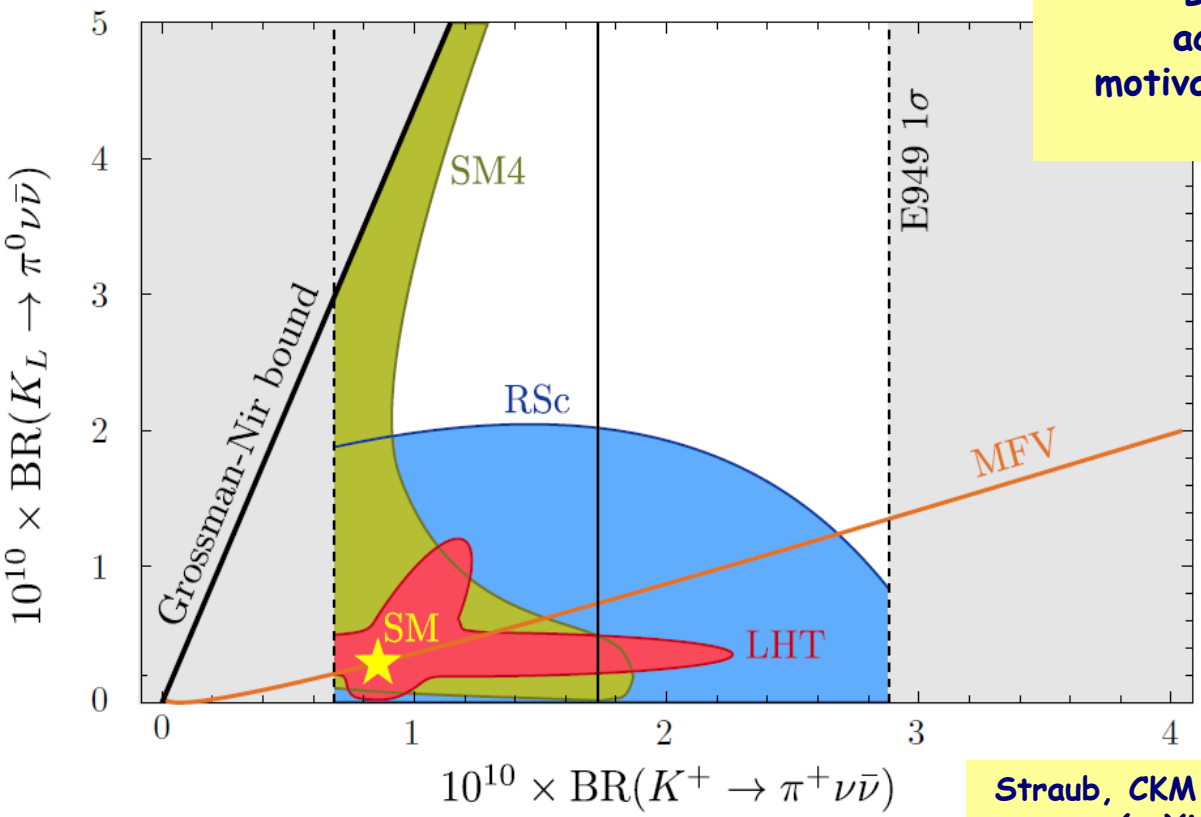
The Randall-Sundrum (RS) idea





Rare processes have Model Discrimination Power… e.g. Warped Extra Dimensions as a Theory of Flavor??

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

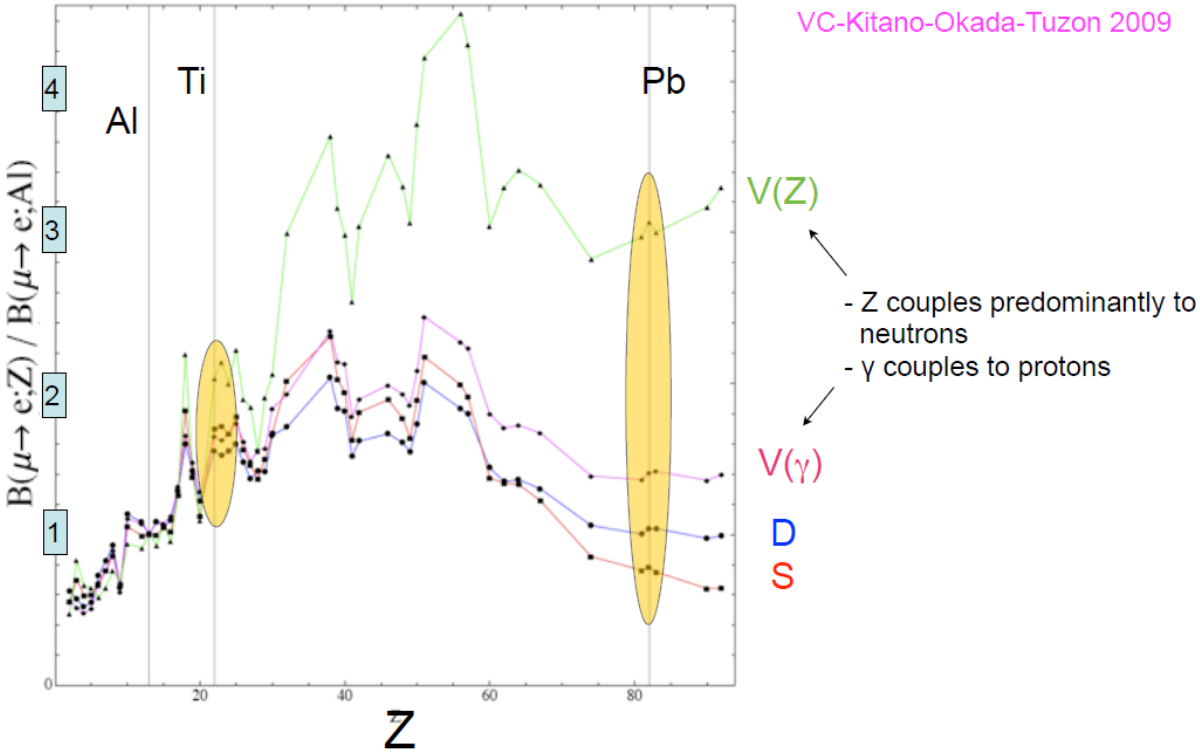


Straub, CKM 2010 workshop (arXiv:1012.3893v2)

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.

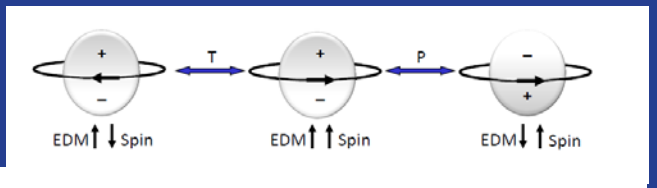
Model Discrimination Power in the Mu2e Program

- Test any single-operator model via target-dependence of μ→e rate



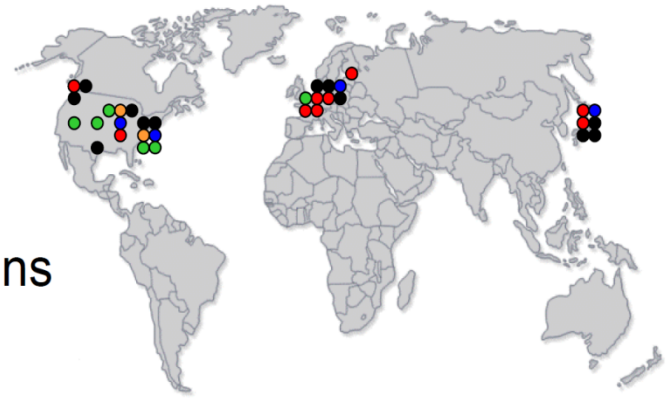
- Essentially free of theory uncertainty (largely cancels in ratios)
- Discrimination: need ~5% measure of Ti/Al or ~20% measure of Pb/Al
- Ideal world: use Al and a large Z-target (D,V,S have largest separation): challenge for experiments

EDM Research Worldwide…



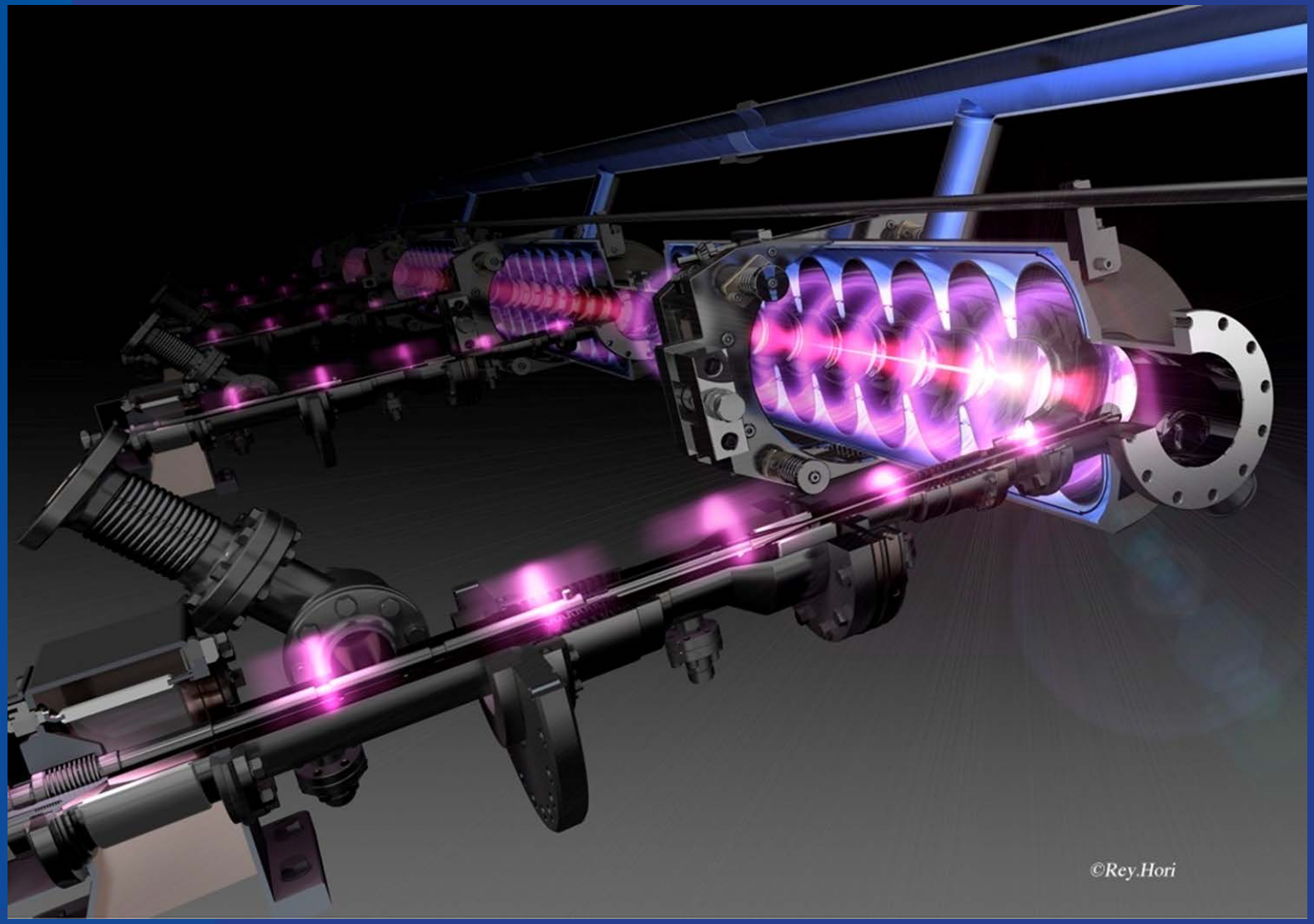
Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- 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
- 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

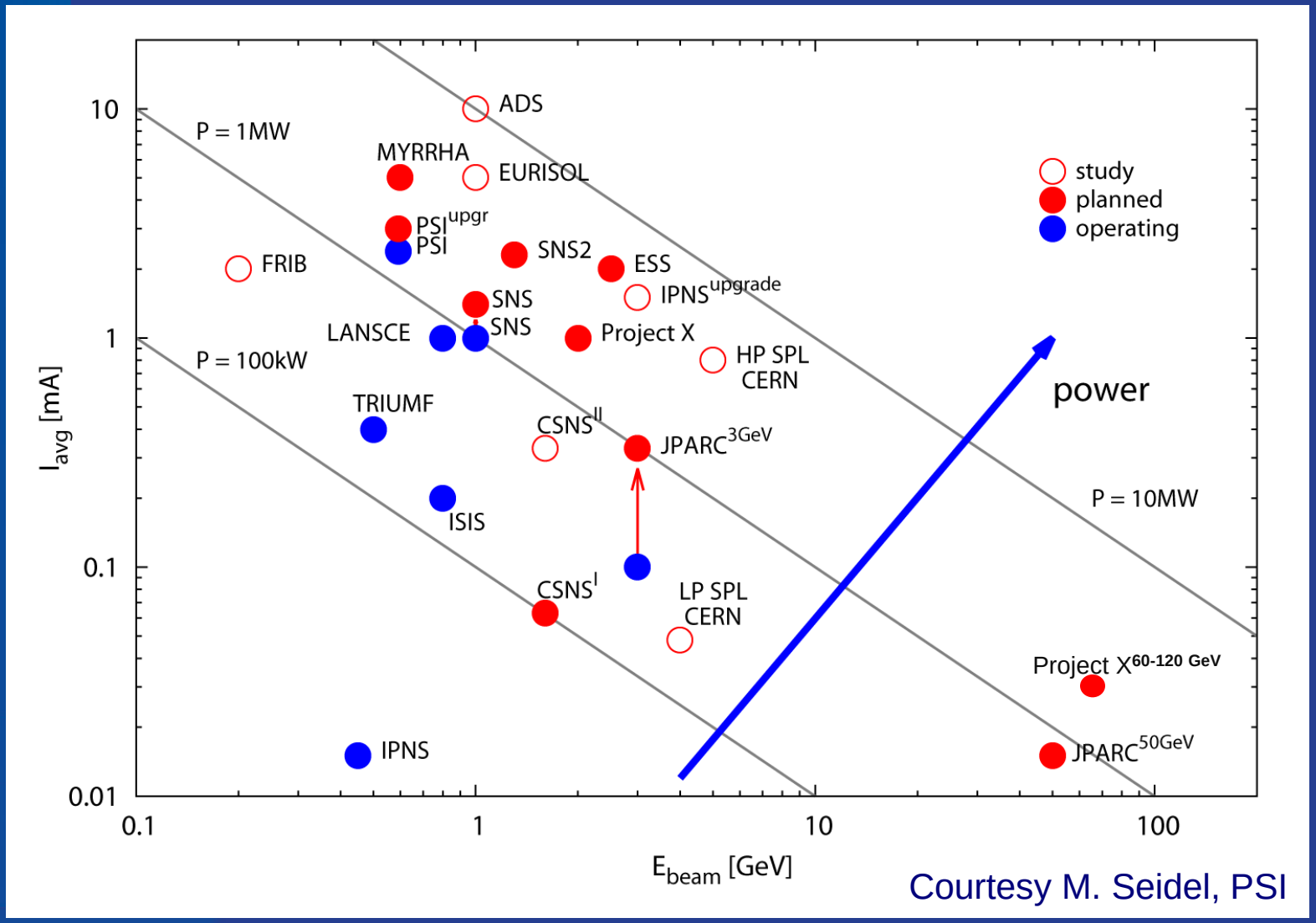


Courtesy Klaus Kirch CIPANP 2012

Beam Power is the Gateway to the Intensity Frontier…



Beam Power is the Gateway to the Intensity Frontier…



Courtesy M. Seidel, PSI

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

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

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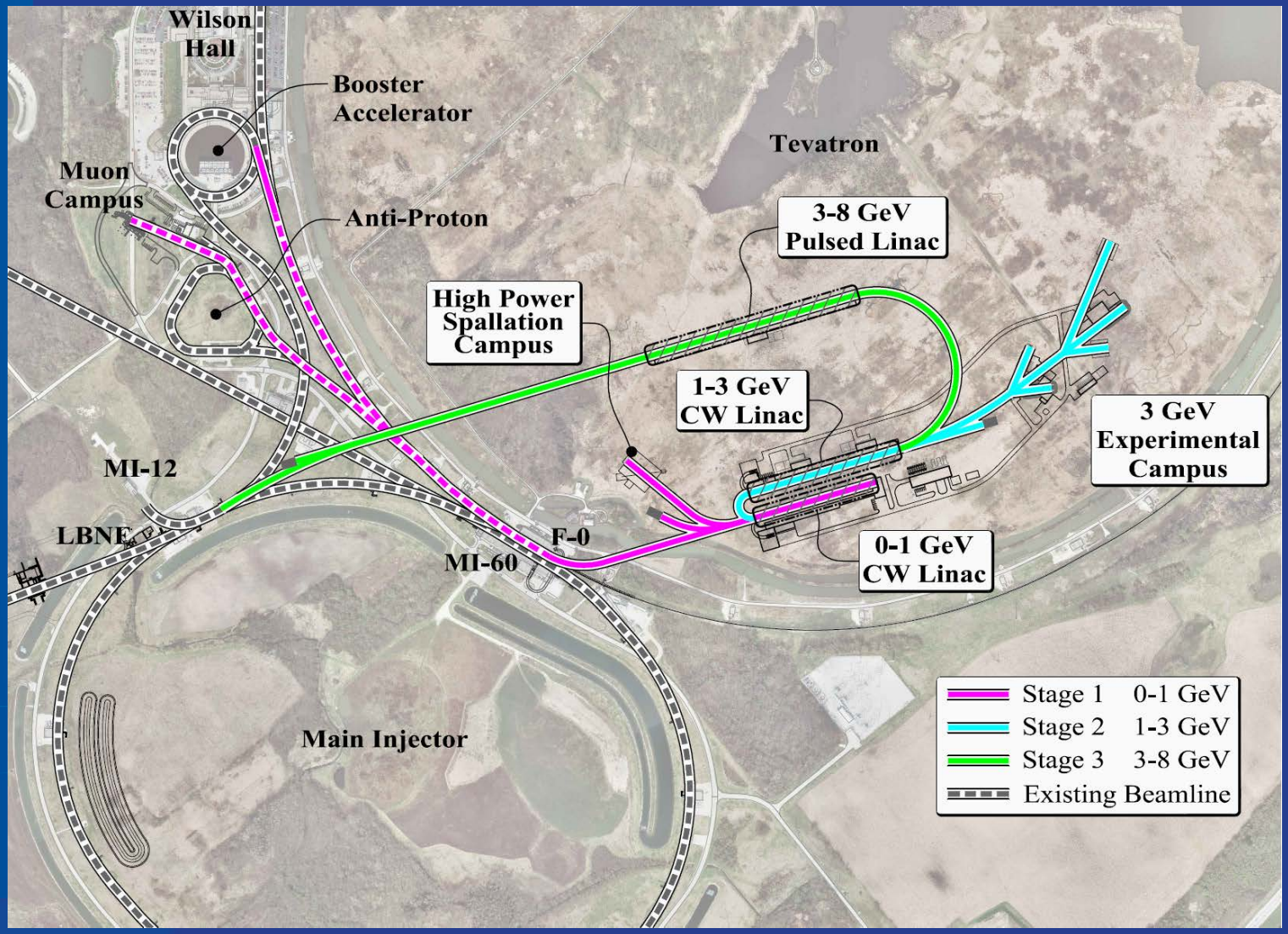
Evolution from the Energy Frontier to the Intensity Frontier at Fermilab…



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:

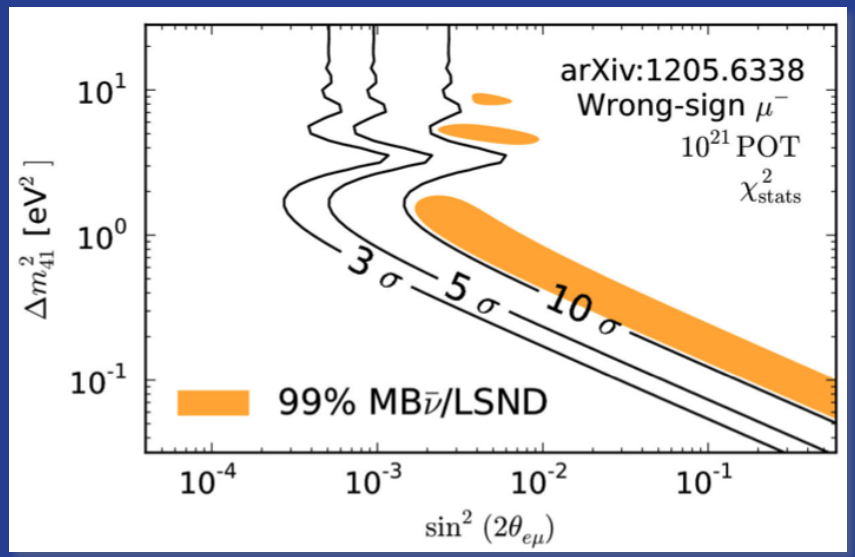
- Promotes the Main Injector (MI) to a Mega-Watt class machine for neutrinos, and increases the potential beam power for other medium power MI experiments (e.g. ORKA, nu-STORM).
- Unshackles the $\mu \rightarrow e$ (Mu2e) experiment from the Booster complex: Potentially increases sensitivity of Mu2e 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.

νSTORM

- ν's from a few-GeV muon storage ring aimed at near & far magnetized iron detectors

- $\nu_e \rightarrow \nu_\mu$ appearance
  (CPT conjugate to MiniBooNE)

- testbed for future μ storage rings



(C. Tunnell, Oxford)

(110 collaborators, 37 institutions)

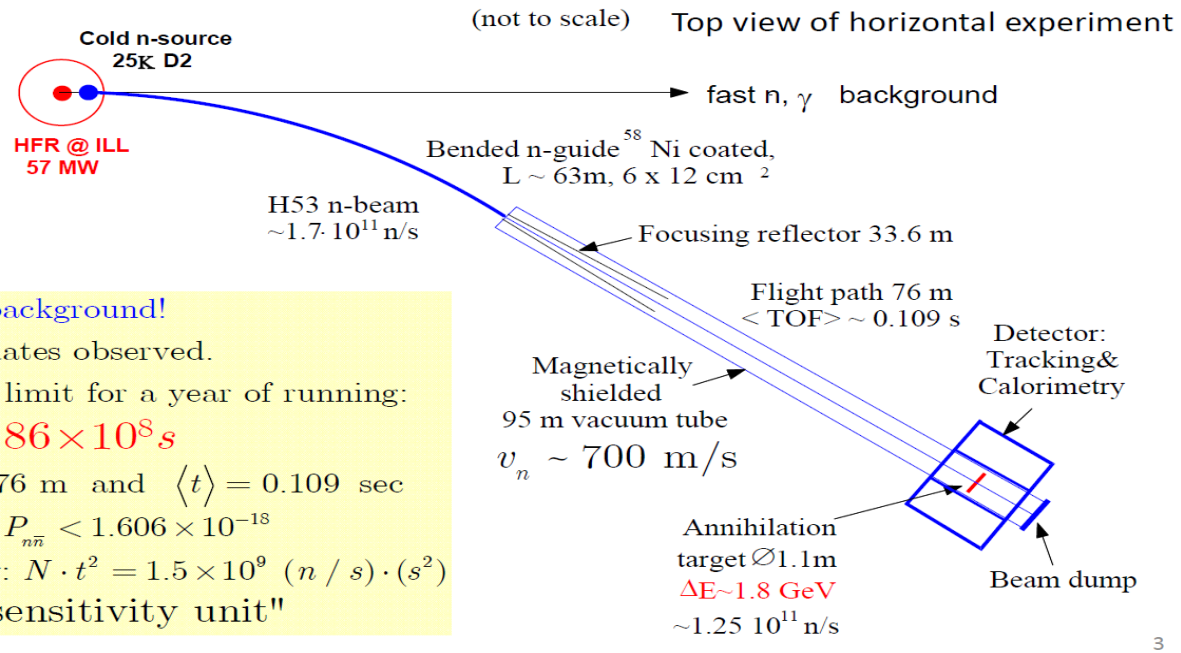
https://indico.fnal.gov/conferenceDisplay.py?confId=6794

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 $n \leftrightarrow \bar{n}$ 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

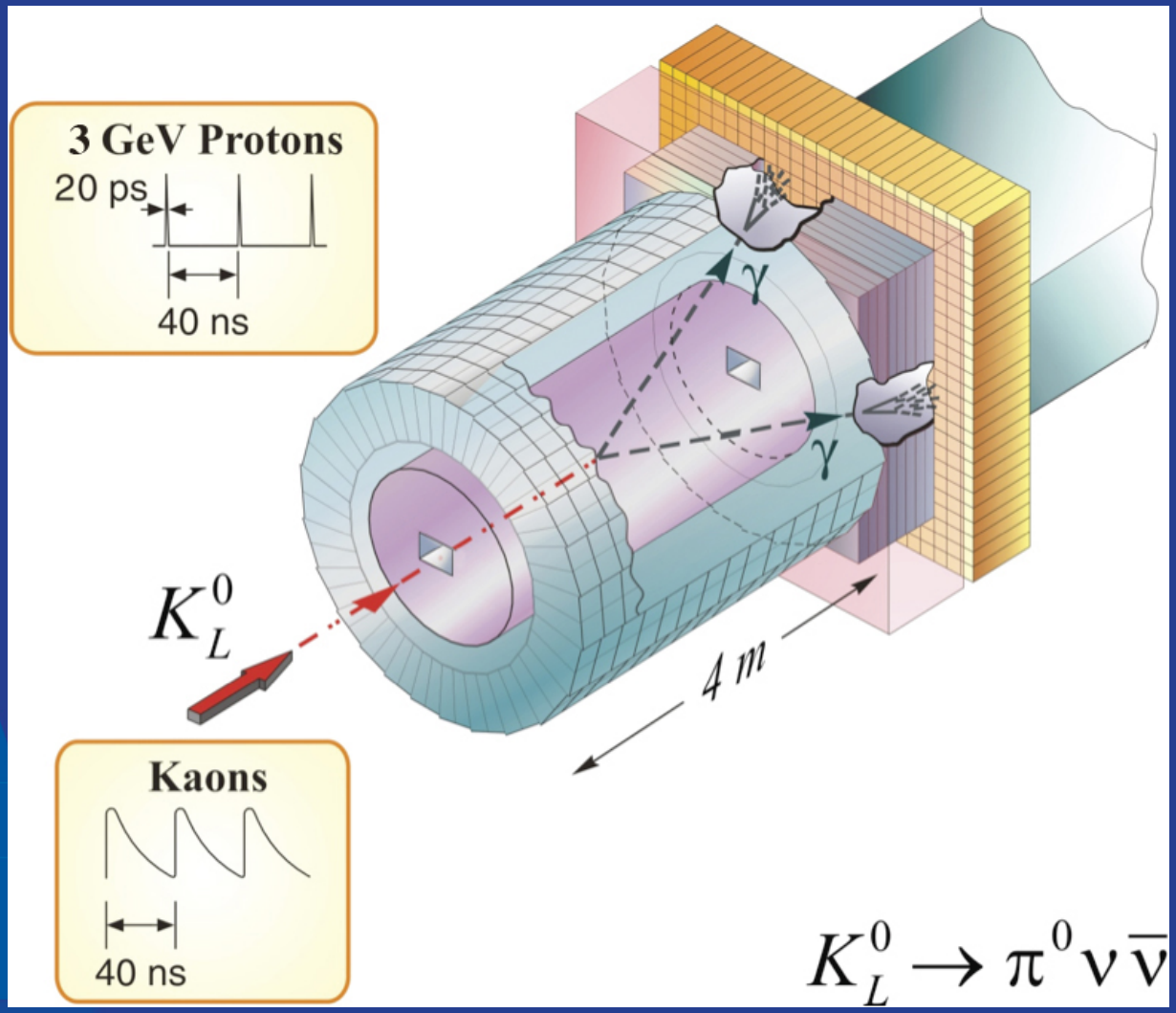
* Operating point in range depends on MI energy for neutrinos.

** 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.

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



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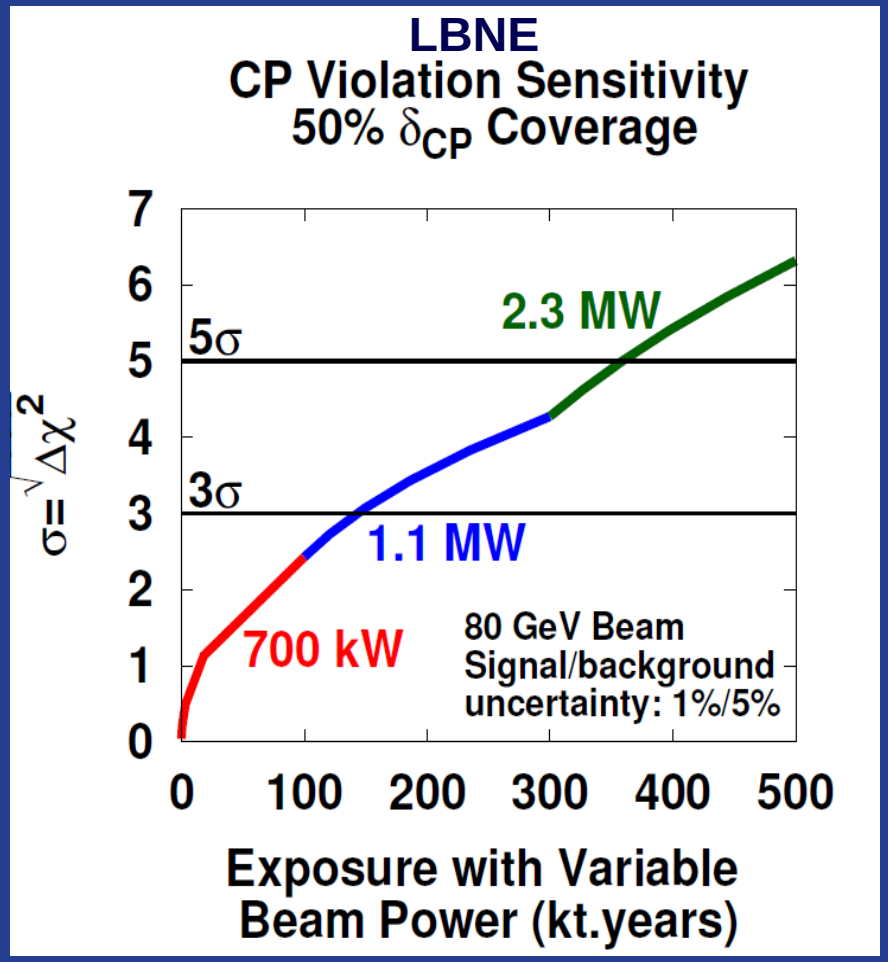
Science Enabled with Stage-3 (RDR)

- 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.



The High Intensity Horizon

- Project-X is a staged evolution of the best assets of the Fermilab accelerator complex with the revolution in super-conducting RF technology.

- Each Stage of Project-X will raise many boats of the Intensity Frontier in particle physics, with a program scope of more than 20 world-leading particle physics experiments and an associated robust user community.

- Stage-1 of Project X can host a program of world class experiments, with “Day-1” experiments inherited from the investments being made now in advance of Project-X operations which could commence at the close of this decade.

Spares

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).

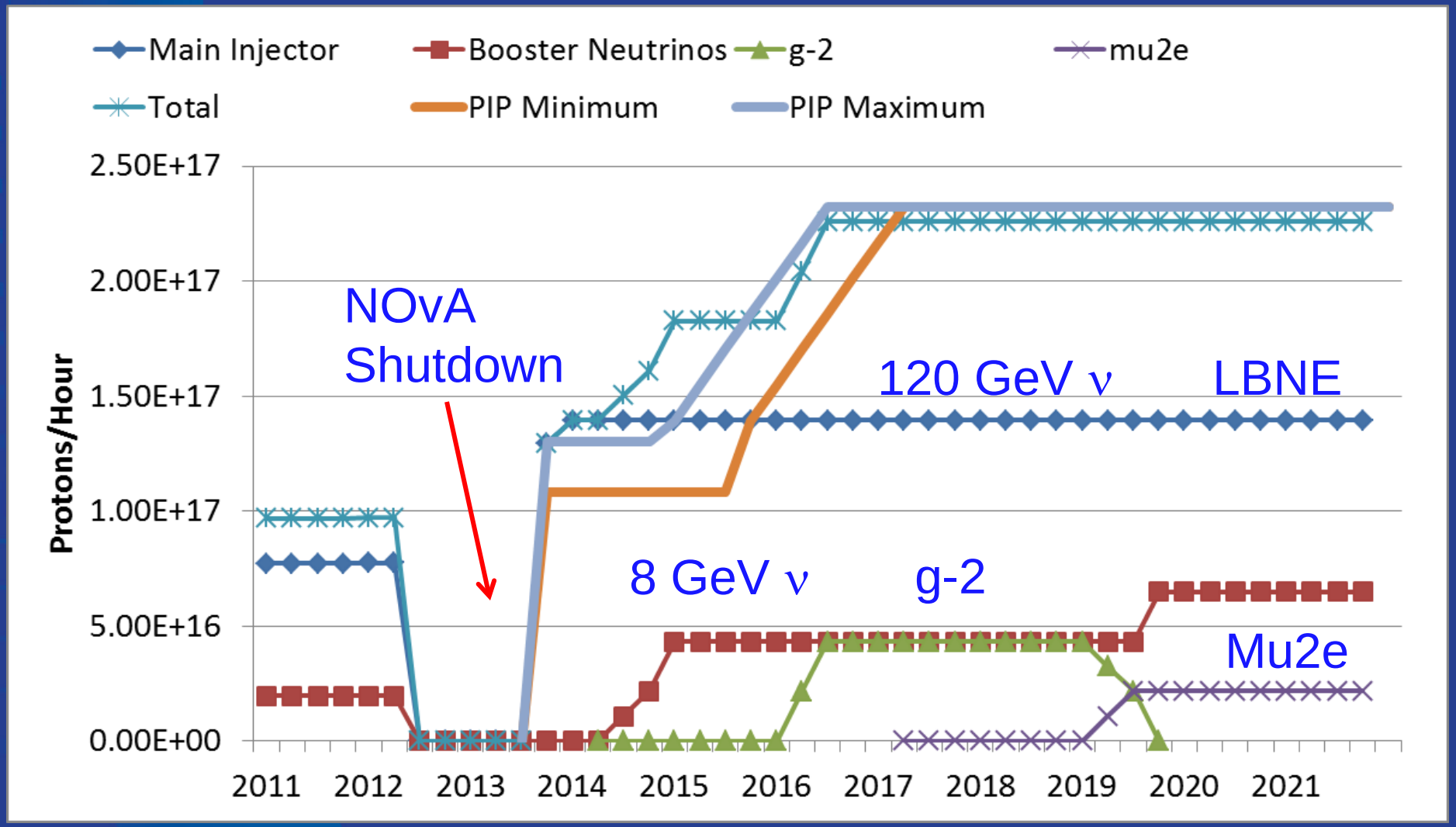
Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC and charged-lepton flavor violation may provide more information.

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

Proton Improvement Plan…

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



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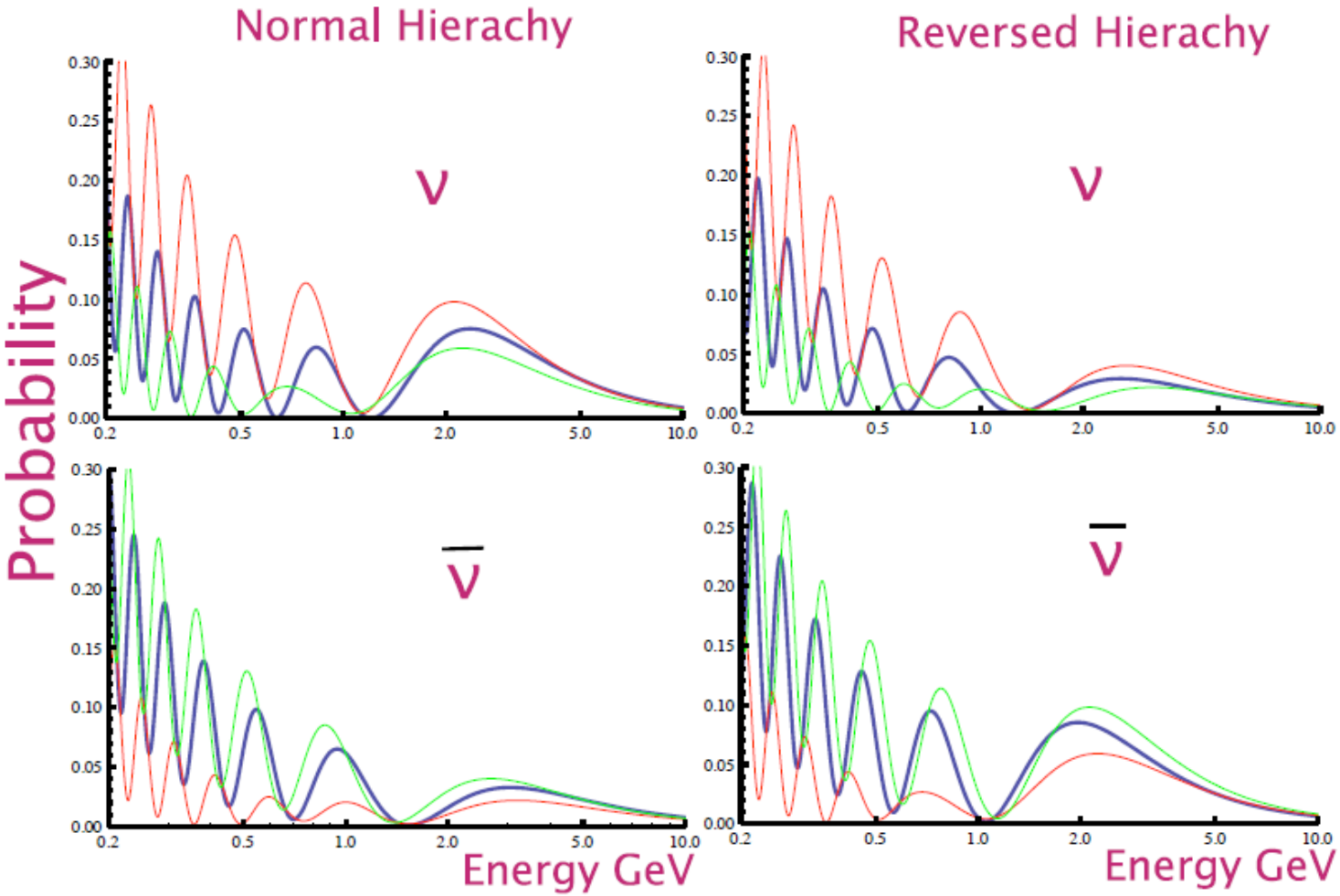


FIG. 3: Appearance probability for $\nu_\mu \to \nu_e$ as a function of energy at a distance of 1300 km. The top plots are for neutrinos and bottom plots are for anti-neutrinos. The left side plots are for normal mass ordering and right hand side are for reversed mass ordering. The parameters used for 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.

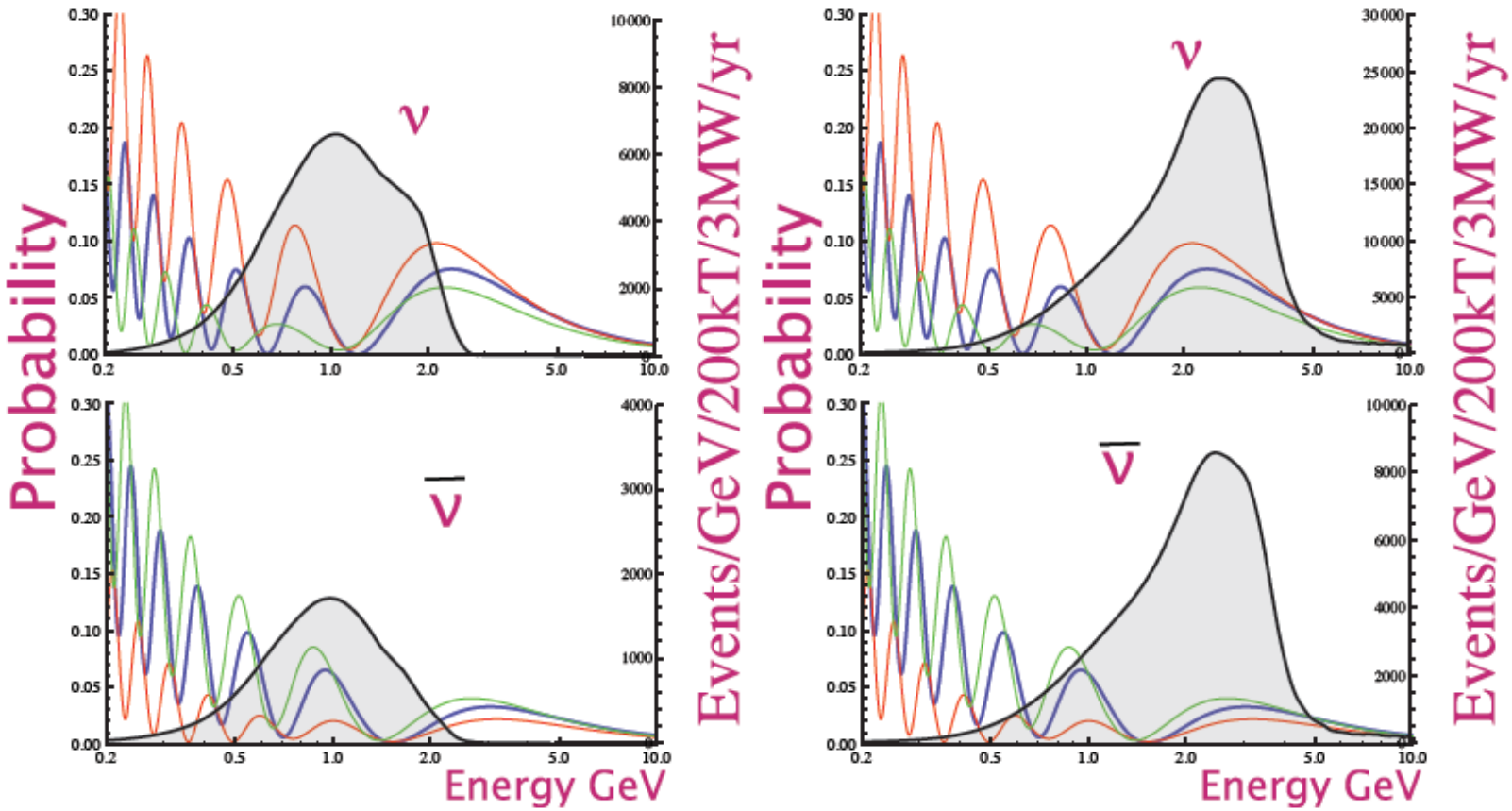
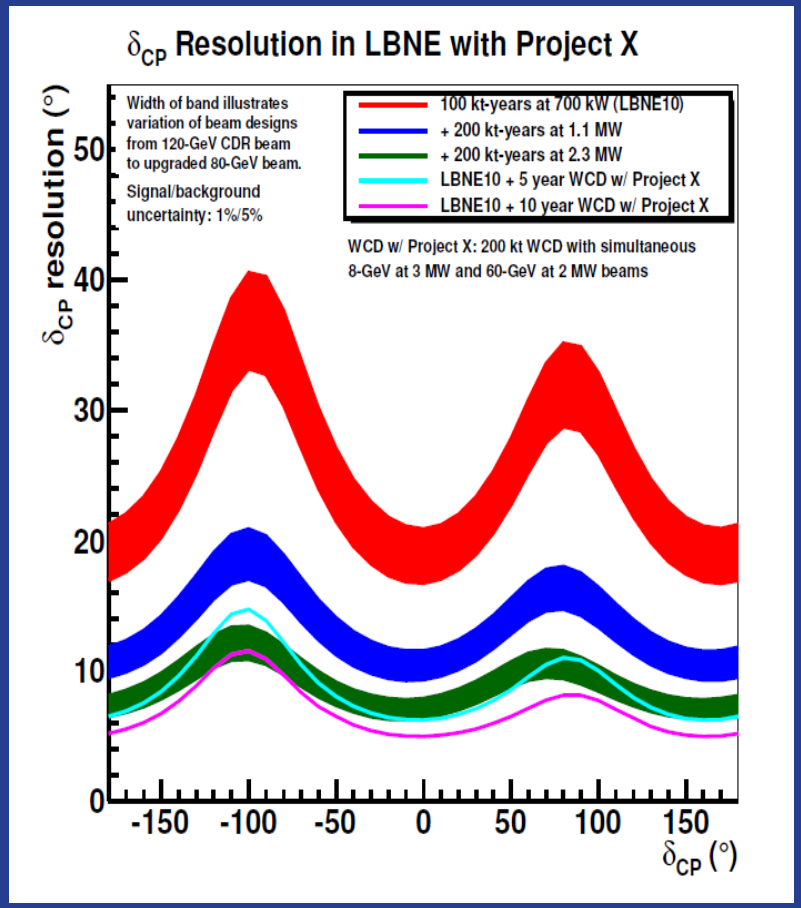


FIG. 5: Spectra of event rates as a function of energy for 8 GeV (left) and 60 GeV (right) proton beams from Fermilab. The spectra are superimposed on the expected oscillation probability for normal hierarchy. Spectra are for the total charged current cross-section for muon neutrino (top) and antineutrinos (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.