Update on Project X in the Snowmass Process

http://www.snowmass2013.org/

R. Tschirhart
Fermilab

June 5th 2013

U.S. DEPARTMENT OF ENERGY

Fermilab

SNOWMASS WORKING GROUPS

- Energy Frontier
- Intensity Frontier
- Cosmic Frontier
- Frontier Capabilities
- Instrumentation Frontier
- Computing Frontier
- Education and Outreach

Intensity Frontier group charge:

The Intensity Frontier working group is charged with summarizing the current state of knowledge and identifying the most promising future opportunities at the intensity frontier. Topics are described under the working groups.

Conveners: JoAnne Hewett (SLAC), Harry Weerts (Argonne)

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

J. Hewett, IF All Hands Meeting at ANL.

Intensity Frontier Manifesto

All frontiers of high energy physics aim to discover and understand the constituents of matter and their interactions at the highest energies, at the shortest distances, and at the earliest times in the Universe. The Standard Model fails to explain all observed phenomena: new interactions and yet unseen particles must exist. They may manifest themselves either directly, as new particles, or by causing Standard Model reactions to differ from often very precise predictions. The Intensity Frontier explores these fundamental questions by searching for new physics in processes extremely rare or those forbidden in the Standard Model. This requires the greatest possible beam intensities, as well as massive ultra-sensitive detectors. Many of these experiments are sensitive to new physics at higher mass scales, or weaker interaction strengths, than those directly accessible at the LHC or any foreseeable high-energy collider, thus providing opportunities for paradigm-changing new discoveries complementary to Energy and Cosmic Frontier experiments.

The range of experiments encompassing the Intensity Frontier is broad and diverse. Intense beams of neutrinos aimed over long distances at very large detectors will explore the neutrino mass hierarchy, search for CP violation and non-standard interactions, and increase sensitivity to proton decay. Multi-ton-scale detectors will determine whether neutrinos are their own antiparticles. Intense beams of electrons will enable searches for hidden-sector particles that may mediate dark matter interactions. Extremely rare muon and tau decay experiments will search for violation of charged lepton quantum numbers. Measurements of intrinsic lepton properties, such as electric and magnetic dipole moments are another promising thrust. Rare and CP-violating decays of bottom, charm, and strange particles, measured with unprecedented precision, will be important to unravel the new physics underlying discoveries at the LHC. In any new physics scenario, Intensity Frontier experiments with sensitivities to very high mass scales will be a primary tool for exploration.

Frontier Capabilities group charge

Charge: Frontier Facilities will assess the existing and proposed capabilities of two distinct classes of experimental capabilities for high energy physics broadly understood, namely, those provided by accelerator-based facilities and those provided by detector facilities distinct from accelerators. We expect the evaluations to be performed with two principal groups that will operate independently: Accelerator Facilities and Non-accelerator Facilities.

Conveners: William Barletta (MIT), Murdock Gilchriese (LBNL)

Instrumentation frontier charge:

The task of this group is to provide an evaluation of the Detector R&D program being carried out in support of the High Energy Physics science mission, to determine if the existing program meets the science needs of the Energy, Intensity, and Cosmic Frontiers, and to suggest a program to strengthen the field. This group supports the other frontier groups and at the same time identifies and advocates new technologies that have the potential for significant breakthrough in science reach.

Conveners: Marcel Demarteau (ANL),
Howard Nicholson (Mt. Holyoke), Ron Lipton (Fermilab)

Education and Outreach charge:

The Communication, Education and Outreach working group is charged with summarizing the current state of education and outreach programming offered by the particle physics community and identifying promising future opportunities. Audiences include the general public, policy makers and opinion leaders, the science community, and teachers and students in grades 5-16.

Conveners: Marge Bardeen (Fermilab), Dan Cronin-Hennessy (U of M)

How can we build support for and develop understanding of particle physics?

- The questions we want to answer
- Our history and record of accomplishment
- The impact of our research, our tools and our people on society
- The nature of discovery science in general

Notable Project-X events since October 2012

- October 17th-19th: PX MuSR forum.
- October 24th-26th: Muon science forum at the Korean Physical Society meeting.
- November 26th-28th: PX collaboration meeting at Fermilab
- December 12th: PX HEP seminar at the University of Wisconsin.
- January 9th-11th: CPAD Instrumentation Frontier meeting at ANL.
- January 28th: PX HEP seminar at Caltech.
- January 29th-30th: PX Energy Station workshop at Fermilab.
- February 6th-8th: PX at the Fermilab AAC meeting.
- February 13th: PX presentations to the HEPAP facilities subpanel.
- February 13th-15th: Winter Workshop on EDMs
- March 6th-8th: Snowmass neutrino working group meeting at SLAC.
- March 18th-19th PX Machine Advisory Committee meeting.
- March 28th-29th: Near and Far Term Planning for Intensity Frontier Science and Facilities, FRA Visiting comm.
- April 11th-12th: PX outreach meeting at Michigan State University and FRIB
- April 17th-19th: Snowmass Frontier capabilities meeting at BNL.
- April 24th: PX writers meeting at Fermilab.
- April 25th-27th: Snowmass Intensity Frontier All-hands meeting at ANL.
- April 29th-May1st: Kaon 2013, Ann Arbor.
- May 6th-8th: First conference on CLFV workshop, Lecce Italy.
- May 20th: PX colloquium at the University of Washington.
- May 20th-22nd: Opportunities for polarized physics at Fermilab.
- May 25th-27th: ISOUPS: International Symposium on Opportunities for Underground Physics for Snowmass.
- May 29th-31st: Snowmass on the Pacific.
- May 31st: American Particle Physics at CERN and at home article, C. Quigg.
- June 5th: PX presentation to the Fermilab PAC.
- June 13th: PX presentation to the Fermilab Users Meeting.
- June 20th: Submit integrated PX volume to government printing office.
- July 29th-Aug 6th: PX team and bound volumes at Snowmass on the Mississippi.

Genesis and Evolution of the Project X Physics Book

The Book grew from materials developed for, at, and after the Project X Physics Study, June 2012.

Three volumes in a bound set are being developed and rolled out on the Project X website for the Fermilab Users Meeting June 13th:

- **Reference Design Report (150 pages)**
- **Physics Program book (180 pages)**
- **Broader Impacts (90 pages)**

500 bound volumes will be delivered to Snowmass on the Mississippi.

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

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.

The Physics Book:

http://theory.fnal.gov/people/ask/PX-book/

is a comprehensive successor to:

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

Leading
Research Program Developments
since October 2012

Neutrino Physics

- Strong call from the community in the Snowmass process for accelerator driven neutrino experiments.
- Detailed analysis of LBNE neutrino oscillation and Non-Standard-Interaction (NSI) sensitivity for the defined stages of the PX RDR.
- Exploration of neutrino oscillation sensitivity for ‘Stage-4’, beyond the RDR.
- Exploration of integrating the early stages of the Muon Accelerator Program (MAP) with PX and LBNE.

30 Snowmass 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 Snowmass 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:

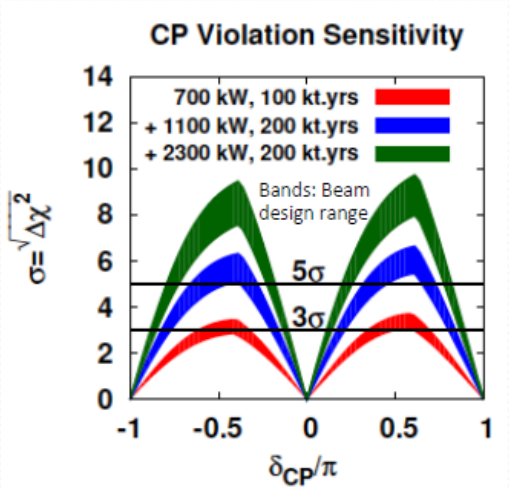
- Concepts based on the 1000kW SNS Hg spallation target.
- Concept based on cyclotrons driving a nuclear beta decay target.
- Concept based on high power cyclotrons driving DAR sources.

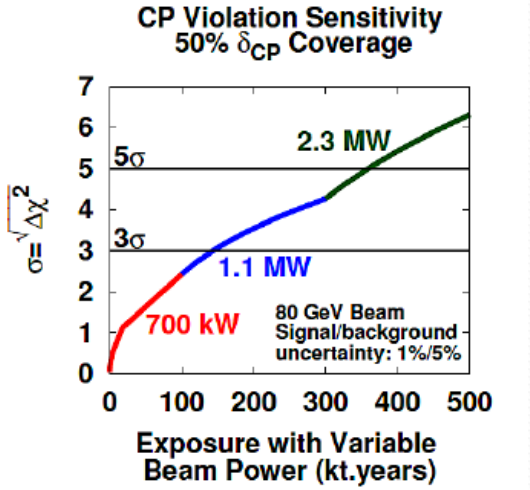
Muon storage rings and Neutrino Factories:

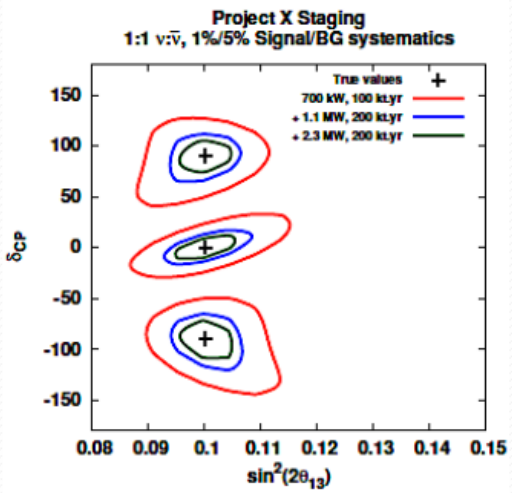
- NuSTORM
- Low energy Neutrino Factory
- Neutrino Factory.

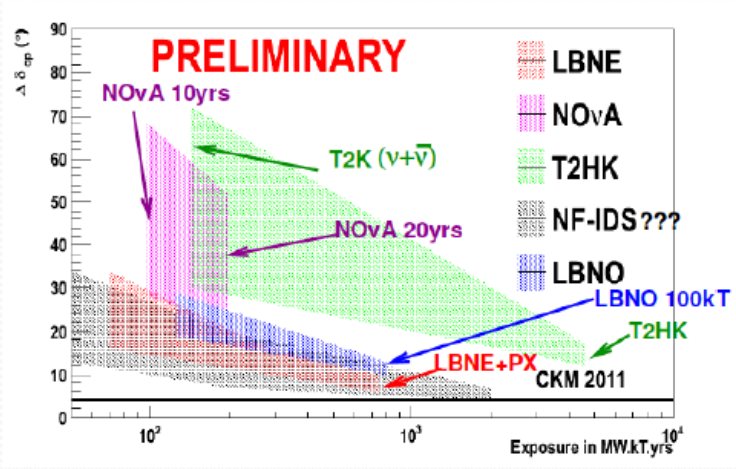
Snowmass neutrino working group meeting SLAC, March 6th-7th 2013

LBNE + Project X is a Full Long-Term Program









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LBNE Leadership team, May 2013

Non Standard Interactions….

Following Ref. [31], NC NSI can be parameterized as new contributions to the MSW matrix in the neutrino-propagation Hamiltonian:

$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\rm MSW} \,, \tag{2.5}$$

with

$$\tilde{V}_{\rm MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix} \tag{2.6}$$

Here, U is the leptonic mixing matrix, and the ϵ-parameters give the magnitude of the NSI relative to standard weak interactions. For new physics scales of few $\times$ 100 GeV, $|\epsilon| \lesssim 0.01$ is expected.

Project X PHYSICS

NC NSI discovery reach (3σ C.L.)

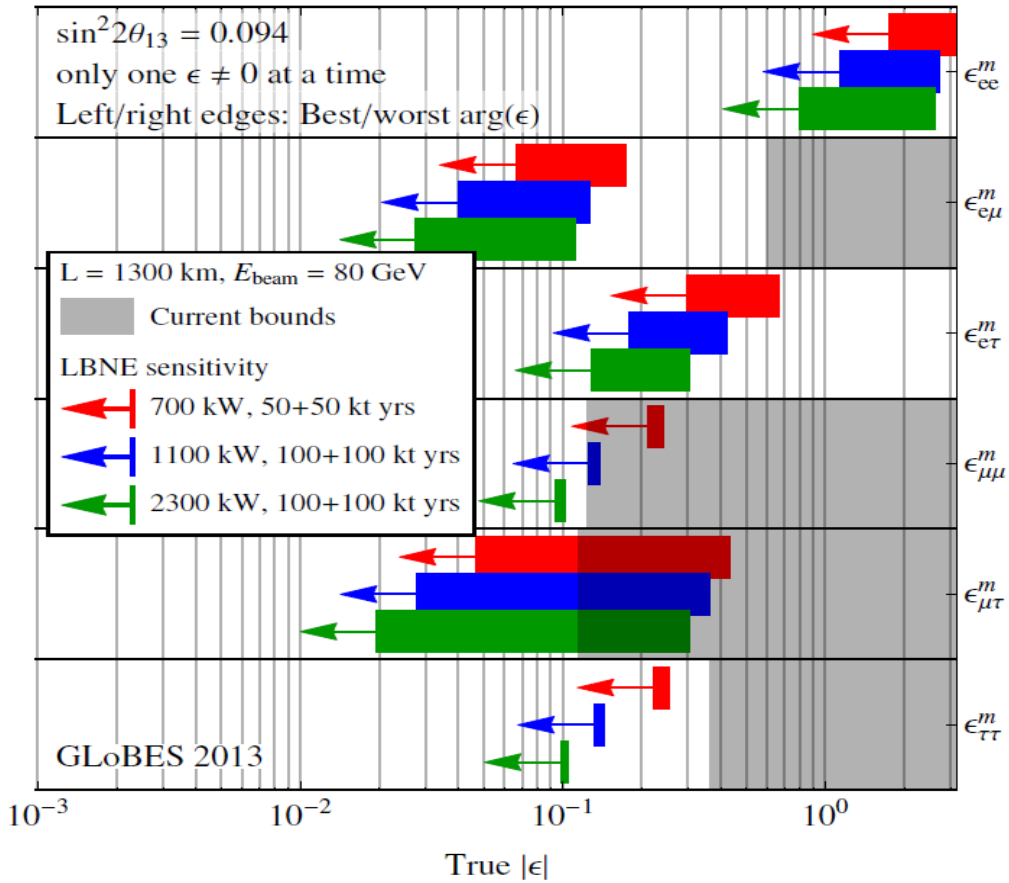


Figure 2.7: Non-standard interaction discovery reach in LBNE at various stages in the evolution of detector mass and beam power. The left and right edges of the error bars correspond to the most favorable and the most unfavorable values for the complex phase of the respective NSI parameters. The gray shaded regions indicate the current model-independent limits on the different parameters at 3 σ [32–34]. For this study the value of $\sin^2 2\theta_{13}$ was assumed to be 0.094. Figure courtesy J. Kopp.

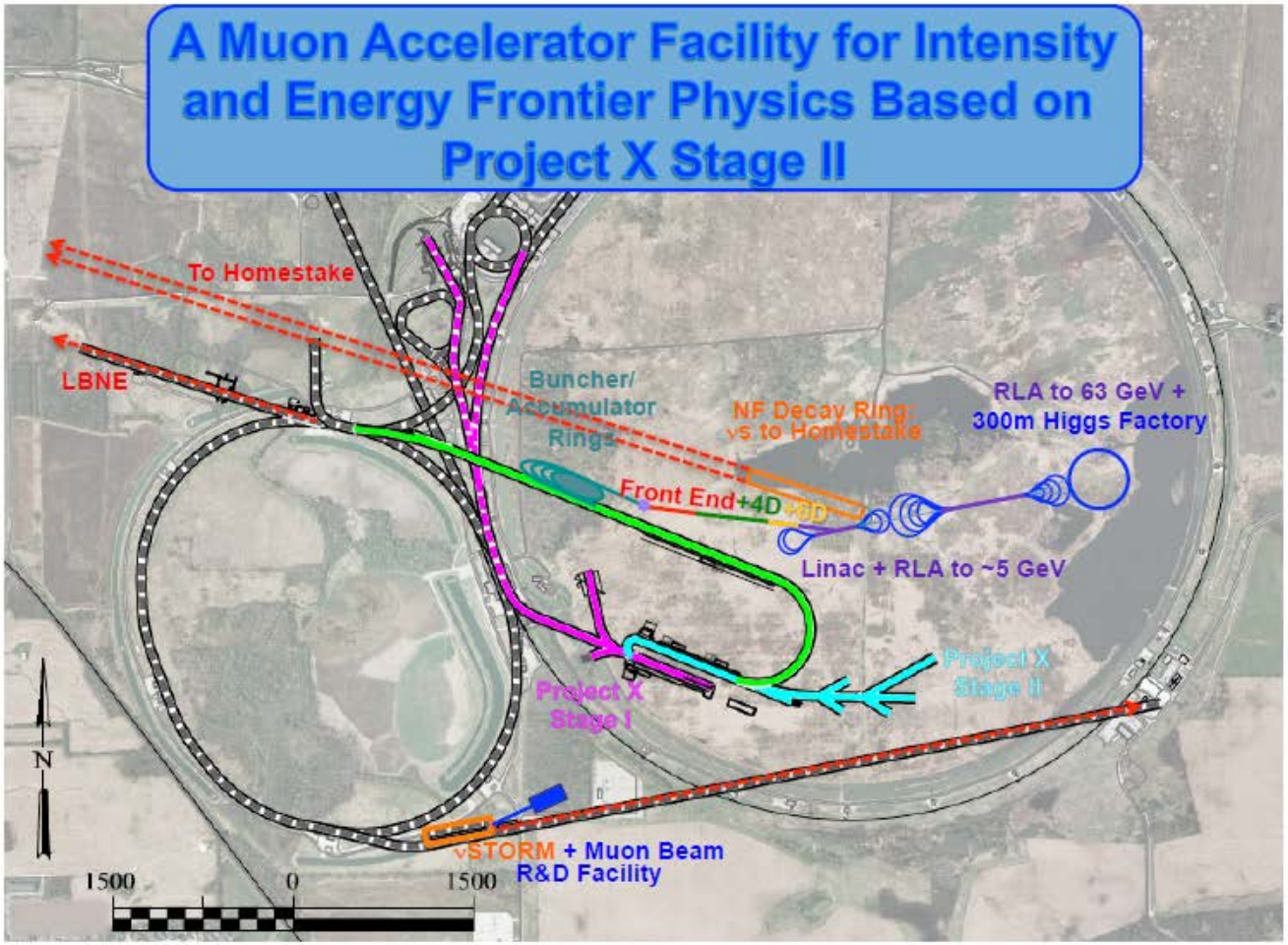


Figure 2.10: Footprint of Neutrino Factory and Muon Collider facilities, including an initial Muon Collider Higgs Factory, on the Fermilab site.

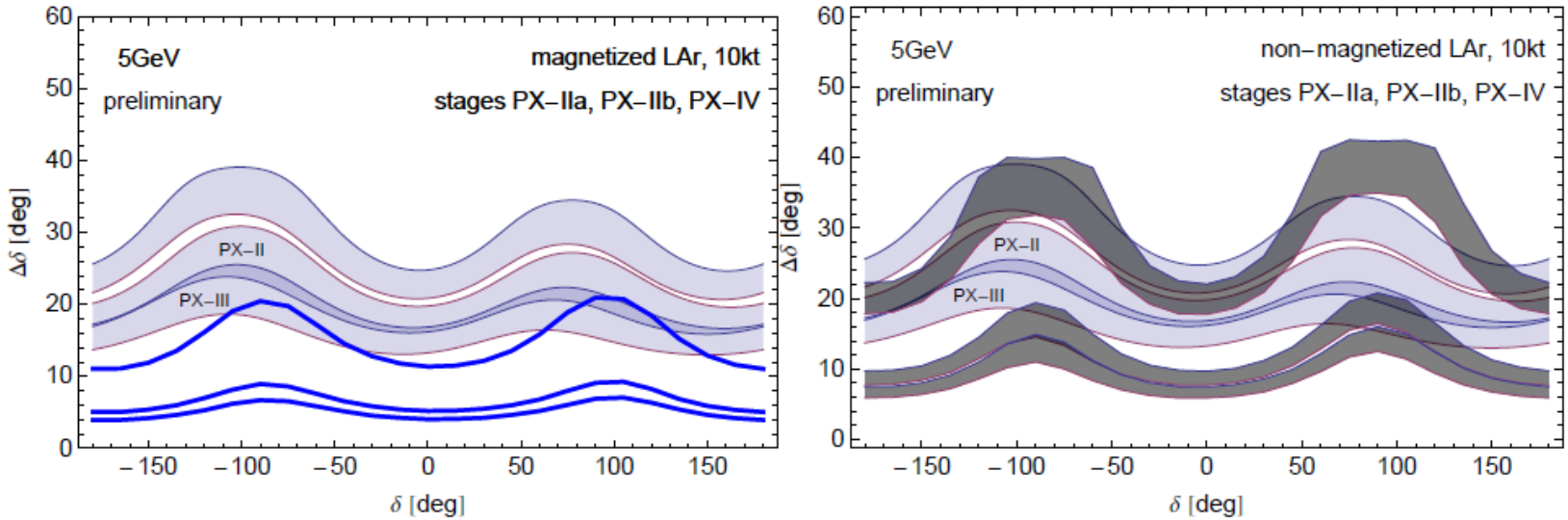


Figure 2.8: his figure shows the accuracy on the CP phase as a function of the true value of the CP phase at 1 sigma confidence level. The light blue bands depict the accuracy as expected from LBNE using the various beams Project X can deliver. In the left hand panel, the thick blue lines represent what a Neutrino Factory beam can do using a magnetized LAr detector. In the right hand panel, the gray bands illustrate the accuracy of a Neutrino Factory using a non-magnetized detector. The Neutrino Factory beam intensities can be found in Tab. 2.1 of this document. This figure is adapted from Ref. [37].

Kaon Physics

The Experimental Quark Flavor Program

Kaons	B-physics	Charm
• KLOE-2	• Belle II	• Belle II
• NA62	• LHCb + Upgrade	• LHCb
• TREK	• ATLAS/CMS	• ATLAS/CMS
• KOTO		• BESIII
• ORKA		• Panda
• Project X experiments		• Future τ/c factories

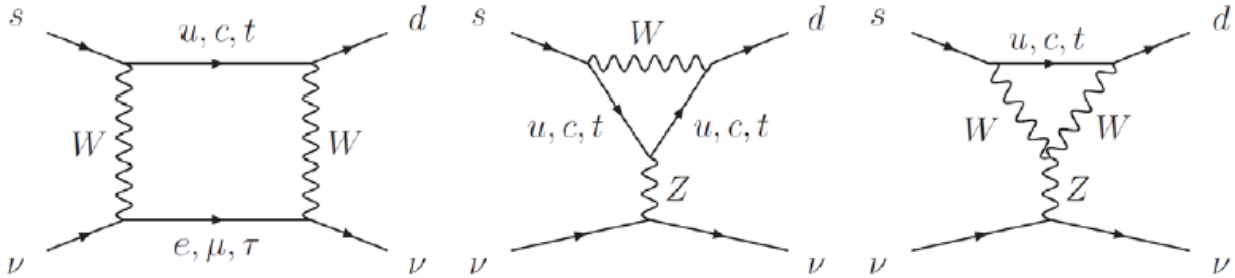
Proposed in U.S.

There is not time to discuss everything in this talk.

April 27, 2013 Argonne IF Workshop 12

J. Ritchie, QFP Summary, IF All Hands Meeting at ANL.

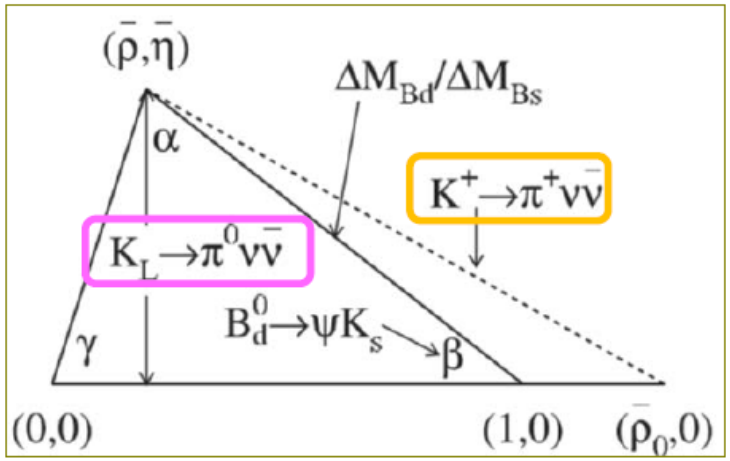
$K \to \pi\nu\bar{\nu}$ in the Standard Model



- A single effective operator

  $(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$

- Dominated by top quark
- Hadronic matrix element shared with $K \to \pi e \nu$
- Standard Model predictions precise



$$B(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (7.8 \pm 0.8) \times 10^{-11}$$

$$B(K_L^0 \to \pi^0 \nu\bar{\nu})_{SM} = (2.4 \pm 0.4) \times 10^{-11}$$

±10% ⇒ ±5%

±16% ⇒ ±11%

Brod, Gorbahn, and Stamou, PR D **83**, 034030(2011)

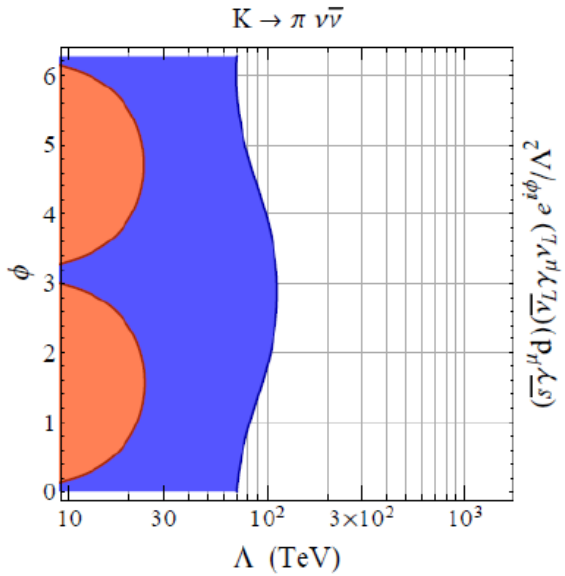
- Largest uncertainty from CKM elements (which will improve)
- Remains clean in New Physics models

April 27, 2013 Argonne IF Workshop 13

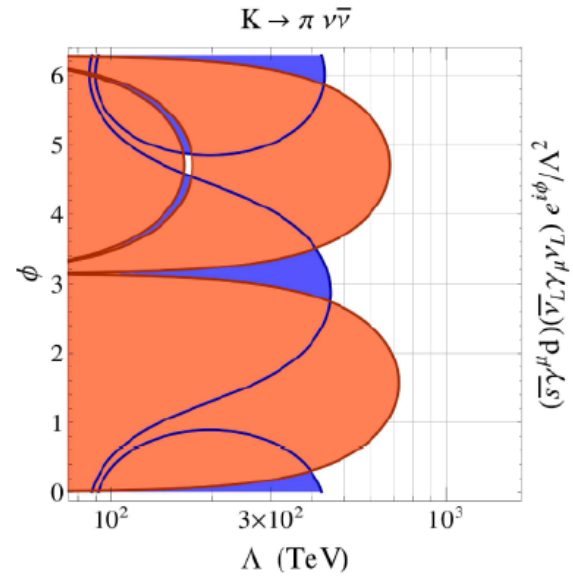
J. Ritchie, QFP Summary, IF All Hands Meeting at ANL.

$$(\bar{s}\gamma^\mu d)(\bar{\nu}_L\gamma_\mu\nu_L)\, e^{i\phi}/\Lambda^2$$

current situation



assuming 5% measurements of both modes



- $K^+ \to \pi^+\nu\bar{\nu}$ already constrains scales of $\sim$ 100 TeV
- $K_L \to \pi^0\nu\bar{\nu}$ bound still above the Grossman-Nir bound
  $\to$ no additional constraint

- $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ give complementary information
- scales of order 700 TeV are probed

Slide from Wolfgang Altmannshofer's talk

April 27, 2013 Argonne IF Workshop 14

J. Ritchie, QFP Summary, IF All Hands Meeting at ANL.

Kaon Projections

a few K observables

Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu})$	7.8×10^{-11}	$1.73^{+1.15}_{-1.05} \times 10^{-10}$	~10% measurement from NA62 ~5% measurement from ORKA ~2% with Project X
$\mathcal{B}(K_L^0 \to \pi^0 \nu\overline{\nu})$	2.43×10^{-11}	$< 2.6 \times 10^{-8}$	1st observation from KOTO ~5% measurement with Project X
$\mathcal{B}(K_L^0 \to \pi^0 e^+ e^-)_{SD}$	1.4×10^{-11}	$< 2.8 \times 10^{-10}$	~10% measurement with Project X
$\mathcal{B}(K_L^0 \to \pi^0 \mu^+ \mu^-)_{SD}$	3.5×10^{-11}	$< 3.8 \times 10^{-10}$	~10% measurement with Project X
$\lvert P_T \rvert$ in $K^+ \to \pi^0 \mu^+ \nu$	$\sim 10^{-7}$	< 0.0050	< 0.0003 from TREK < 0.0001 with Project X
$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$	2.477×10^{-5}	$(2.488 \pm 0.080) \times 10^{-5}$	$\pm 0.054 \times 10^{-5}$ from TREK $\pm 0.025 \times 10^{-5}$ with Project X
$\mathcal{B}(K_L^0 \to \mu^\pm e^\mp)$	$< 10^{-25}$	$< 4.7 \times 10^{-12}$	$< 2 \times 10^{-13}$ with Project X

From the Report of the Heavy Quarks working group, Fundamental Physics at the Intensity Frontier (2012), arXiv:1205.2671

April 27, 2013 Argonne IF Workshop 21

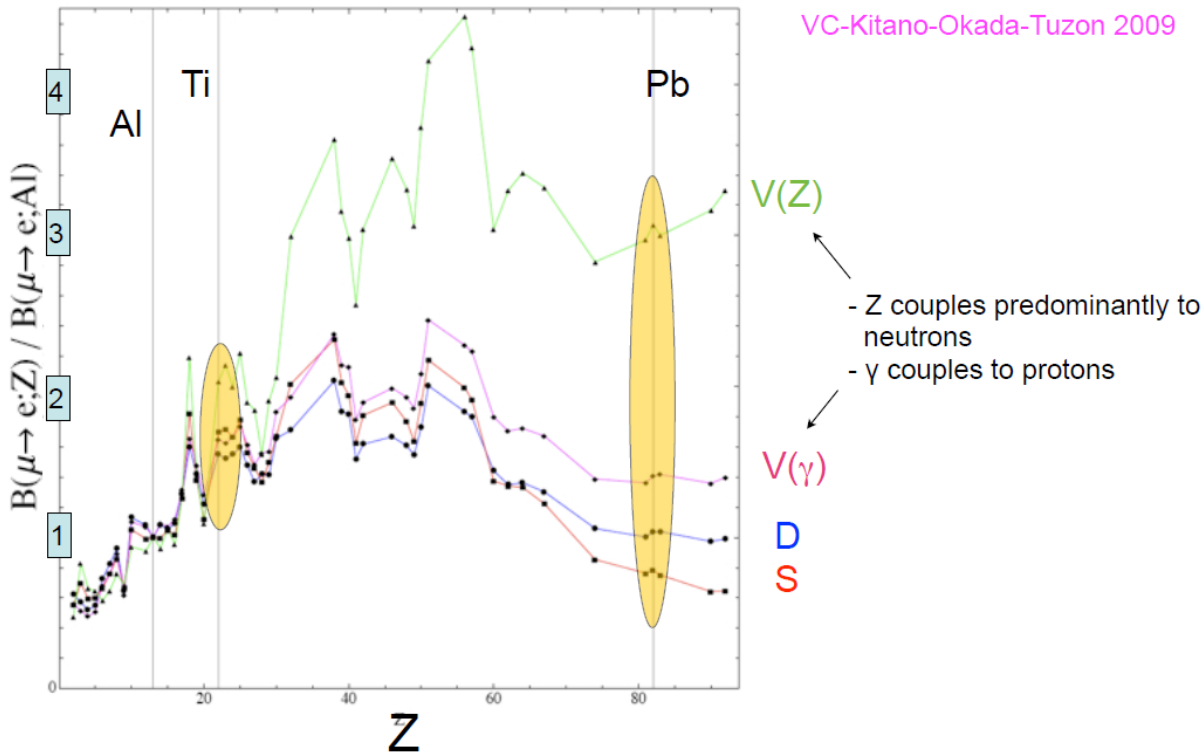
J. Ritchie, QFP Summary, IF All Hands Meeting at ANL.

Muon Physics

- Effort led by Doug Glenzinski to understand how the Mu2e experiment can evolve to higher sensitivity in the Project X era.
- Initial studies indicate that x10 sensitivity increase is plausible with a modest upgrade of the Mu2e experiment.
- In PX Stage-1 operations, beam timing is better, backgrounds are reduced, and radiation damage to critical components scales better.
- Described in PX Physics Book, Whitepaper submitted to Snowmass.

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

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

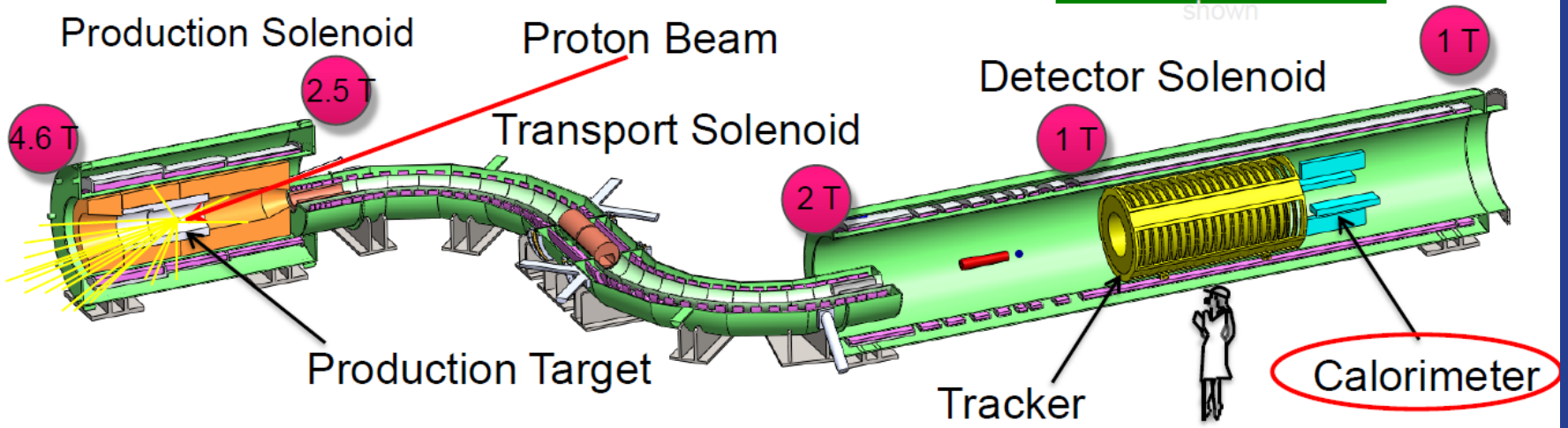
Production Solenoid
- Production target
- Graded field

- 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

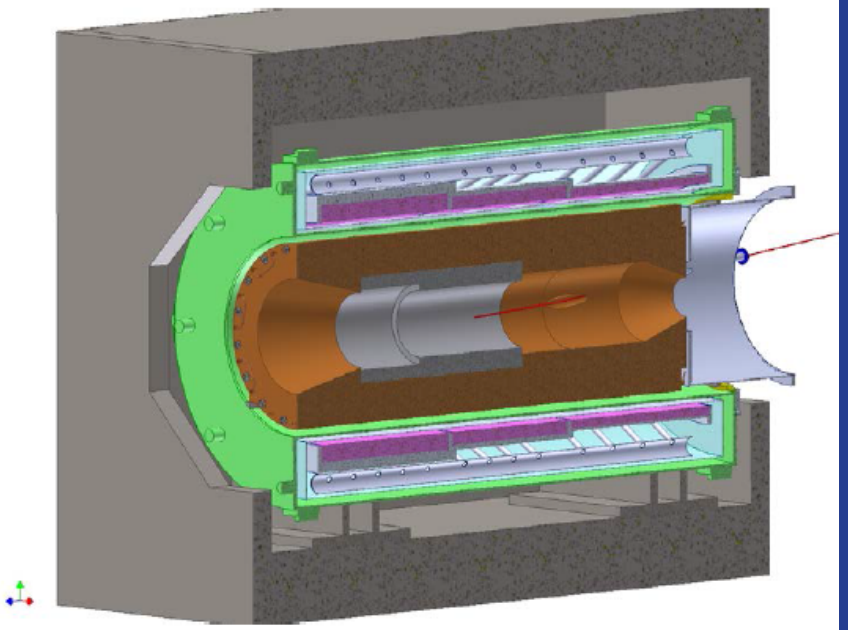
Transport Solenoid
- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator

Cosmic Ray Veto not shown



Requirements to Mu2e Heat and Radiation Shield

- Absorber (heat and radiation shield) is intended to prevent radiation damage to the magnet coil material and ensure quench protection and acceptable heat loads for the lifetime of the experiment



  - Total dynamic heat load on the coils
  - Peak power density in the coils
  - Peak radiation dose to the insulation and epoxy
  - Displacements Per Atom (DPA) to describe how radiation affects the electrical conductivity of metals in the superconducting cable

V. Pronskikh, Radiation damage, NuFact'12, July 23-28, Williamsburg

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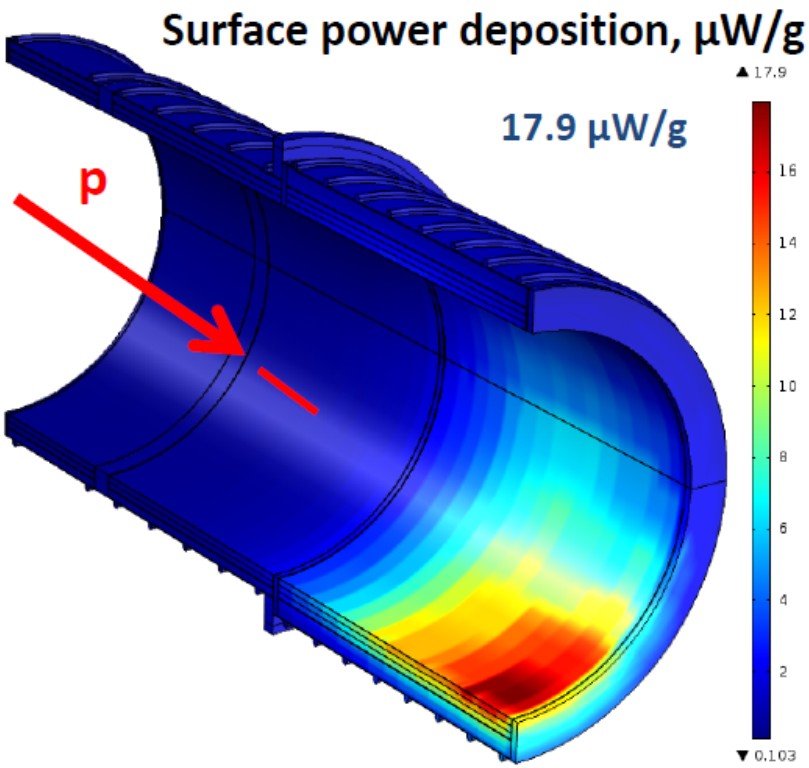
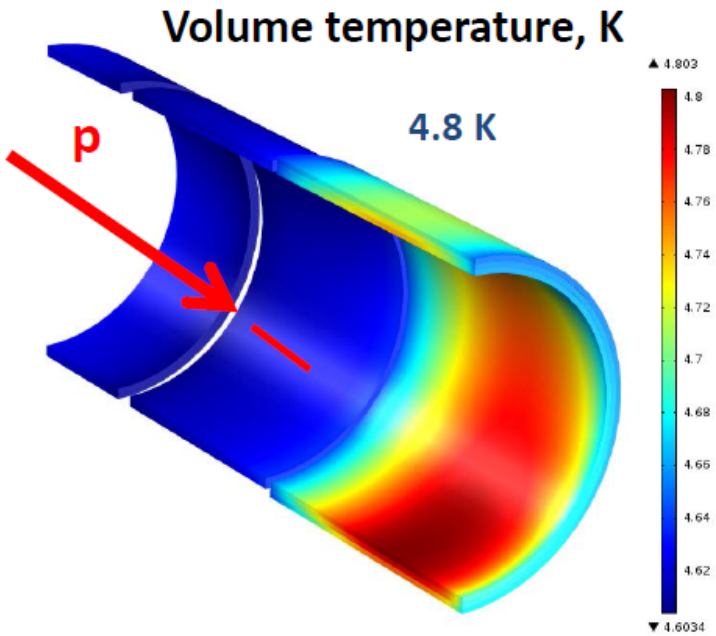
Requirements.
Peak power density





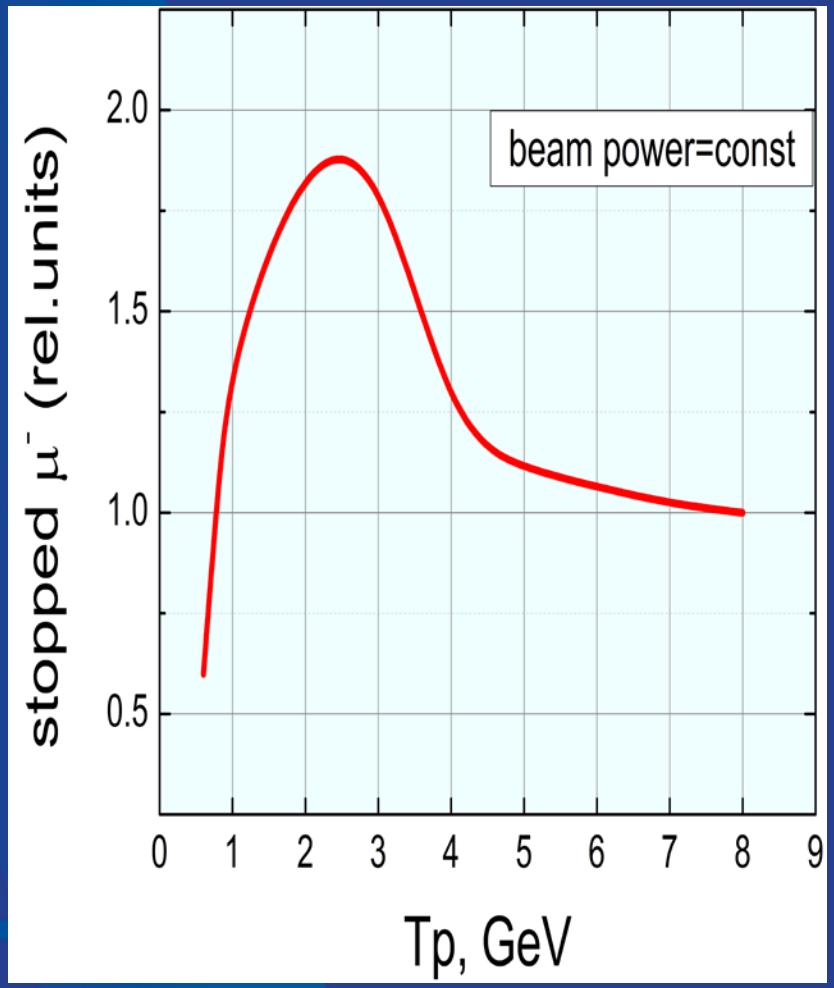
MARS15

T plot for T_0 =4.6K (liquid He temp)
T_c = 6.5K; (supercond+field)
$T_{peak} = T_c$-1.5K = 5.0K.
Peak coil temperature starts to violate allowable value based on 1.5 K thermal margin and 5 T field after 30 µW/g

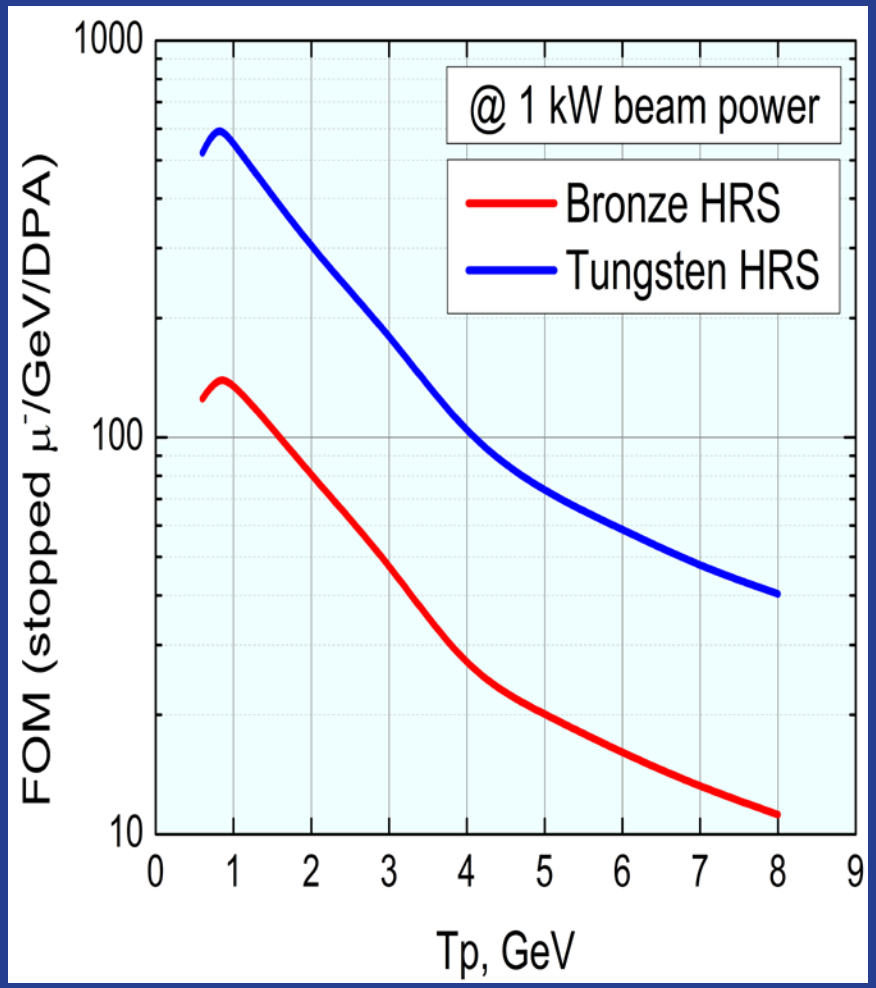
V. Pronskikh, Radiation damage, NuFact'12, July 23-28, Williamsburg

8

Study of optimum proton beam energy



V. Pronskikh et al



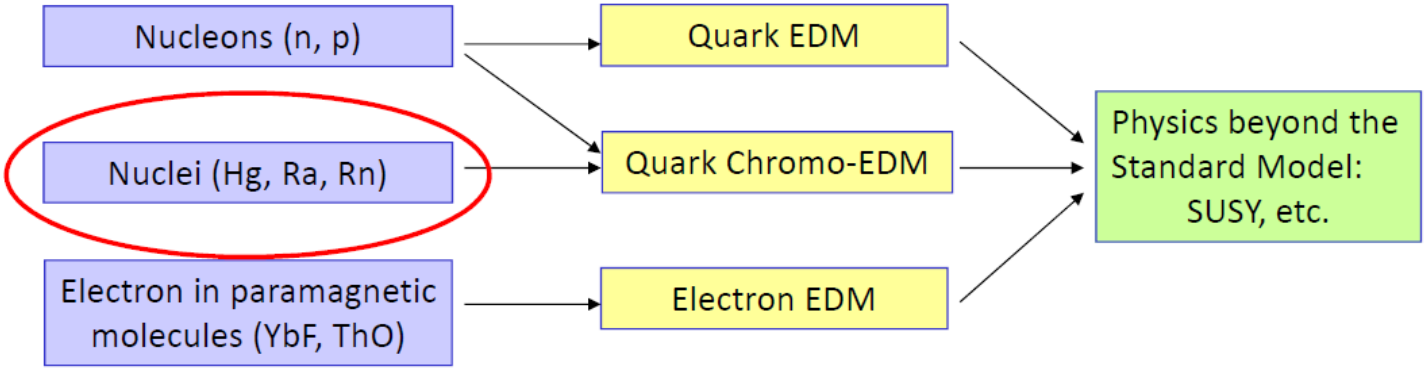
V. Pronskikh et al

EDM experiments

- Fermilab PAC interest and support for developing the proton EDM experiment concept has been appreciated by the broader community.
- Winter workshop on EDMs was well attended and very educational for the ‘HEP’ community.
- Fermilab Accelerator Physics Center (APC) hosted a critical discussion session with proton edm proponents which was constructive and built credibility in the broader HEP accelerator community.

EDM Searches in Three Sectors

Review article: *EDM of Nucleons, Nuclei, and Atoms*
Engel, Ramsey-Musolf, van Kolck, arXiv:1303.2371 (2013)



Sector	Exp Limit (e-cm)	Method	Standard Model
Electron	1×10^{-27}	YbF in a beam	10^{-38}
Neutron	3×10^{-26}	UCN in a bottle	10^{-31}
^{199}Hg	3×10^{-29}	Hg atoms in a cell	10^{-33}

M. Ramsey-Musolf (2009)

Advancing the proton-EDM concept

- Critical technologies: (i) High precision Beam Position Monitors (BPMs), performance at the ILC level. (ii) Spin-tracking simulation suite.
- The Fermilab APC sharp-shooters characterize this experiment as an accelerator physics experiment.
- Staffing to address (i) & (ii). Fermilab support for a Research Associate. Such support can help with the broader log-jam between HEP and NP.

Meanwhile, at the ‘Opportunities for Polarized Physics at Fermilab’ workshop…

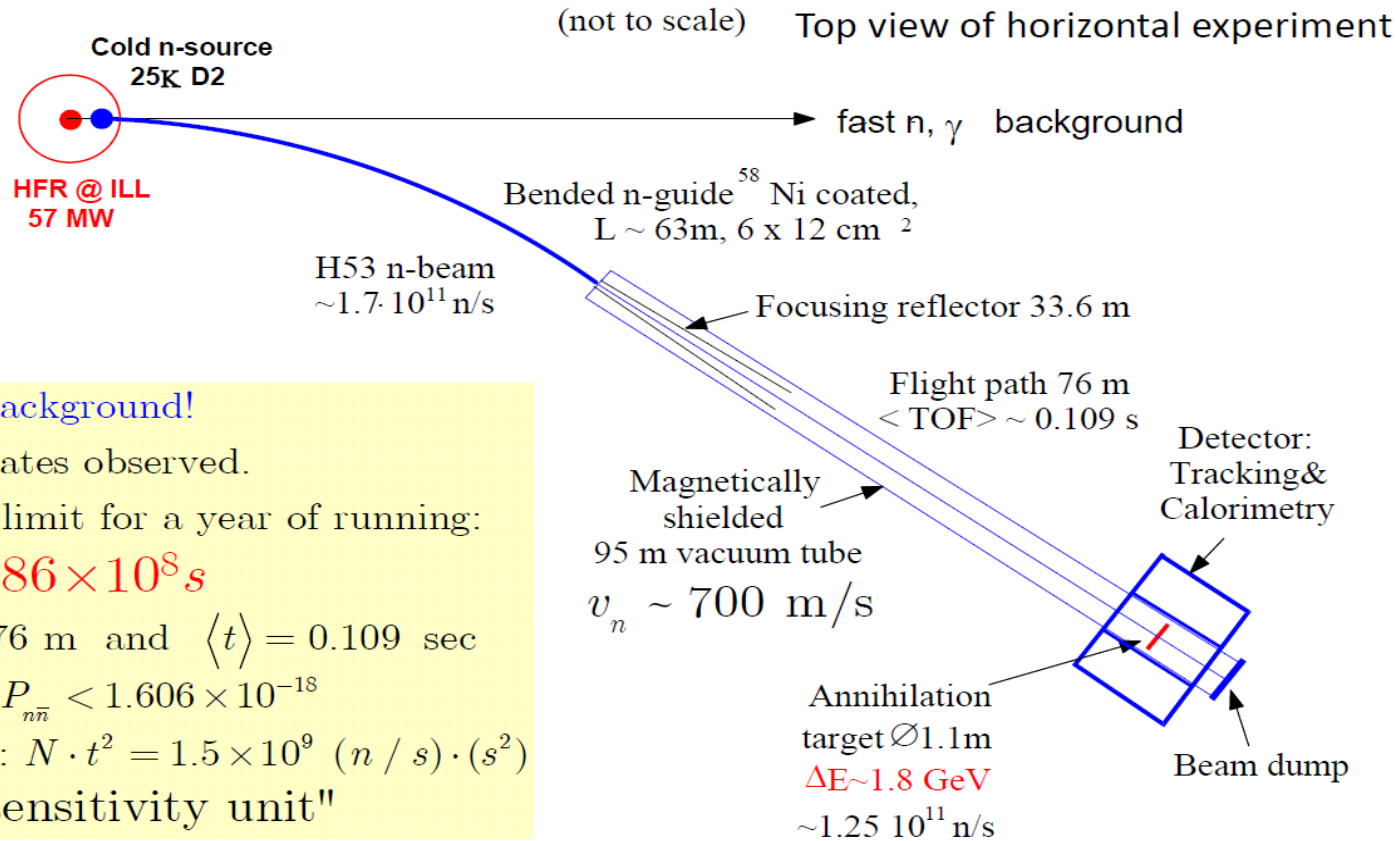
- Bill Morse energized the workshop with the concept of taking a step forward in storage-ring edm research by starting with the electron. The magic electron momentum is 15 MeV/c, requiring a small ring that could demonstrate key concepts and make a competitive physics measurement. Critical issues are polarimetry, machine vacuum.

- Brendan Casey is coordinating a storage-ring forum at the Minneapolis Snowmass meeting to develop four storage-ring white papers: Proton, Electron, Muon, Deuteron/^{3}He.

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 Project X Physics Study

Fermilab

Free neutron antineutron oscillation

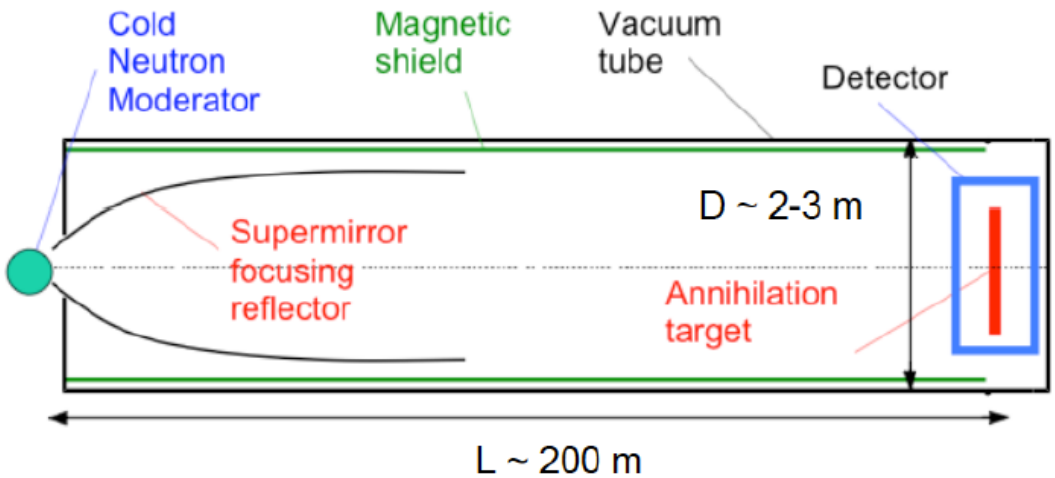
Expression of Interest

Search for Neutron-Antineutron Transformation at Fermilab

The NNbarX Collaboration

need slow neutrons from high flux source, access of neutron focusing reflector to cold source, free flight path of ~200m

Improvement on ILL experiment by factor of ~1000 in transition probability is possible with horizontal experiment at Project X with existing n optics technology, sources, and moderators. Vertical experiment also possible



E. Kearns, Intensity Frontier All Hands Meeting, ANL

NNBarX

- Enthusiastic collaboration!
- Project X and NCSU are jointly supporting a Postdoctoral Research Associate to develop Very-Cold Neutron (VCN) and Ultra-Cold Neutron spallation target designs.
- Growing appreciation in the nucleon decay community and the broader theory community.
- Key Issue: Spallation target design

Communication developments

- Within the Particle Physics community
- Outside of the Particle Physics community

Project-Y: Origins…

Circa 2012

- **The Origin of Mass:**

  How do massless chiral fermions become matter particles?
  (buzzword: "Higgs")

- **The Origin of Matter:**

  Why are there so many different kinds of matter particles with different properties?
  (buzzword: "Flavor")

- **The Origin of the Universe:**

  Where did matter come from in the first place and why didn't it all annihilate with antimatter?
  (buzzwords: "Baryogenesis", "Leptogenesis")

-Joe Lykken

The Project-X Research Program…Redux

Circa 2013

- ***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

The Intensity Frontier Research Program in the Context of the LHC program: Quigg's May 31st Physics Today Article…

"Taken together, and in conversation with studies at the LHC, these experiments can speak to the existence of new forces of nature and new dimensions, including the quantum dimensions that supersymmetry entails, and can test and enrich our understanding of quantum chromodynamics and the electroweak theory. Quantum corrections to standard-model expectations are sensitive to new degrees of freedom at energy scales higher than those directly accessed by the LHC. When the LHC provides evidence for new degrees of freedom, highly sensitive experiments with diverse beams can supply critical insights. "

The Snowmass “Tough Questions” tactic…is it effective?

Intensity Frontier Research Program Summary, Snowmass on the Pacific, May 29th 2013

- **Framework & Texture:** The U.S. Intensity Frontier has a proposed framework and texture to deliver the science: LBNE & Project-X and a texture of experiments. Given the projected funding environment the framework must be strong enough to stand the test of time.

- **Time:** Large projects in Particle Physics will develop and evolve over decades. We know how to do/survive this, and the Tevatron/LHC is the most recent example of a robust framework in our field.

- **Federation:** Improving communication and ties among the texture of Intensity Frontier experiments and the theory community will strengthen the research program. Again, our field has demonstrated this in the evolution of the Energy Frontier program.

- **Resources:** Intensity Frontier researchers must reach out broadly to the funding agencies to communicate how particle physics spans agencies, and where synergies and leverage can be found. DOE/HEP, NP, NSF/NP, NIST, BES, etc.

Summary

- Considerable out-reach effort and development of the Project X resource book has and will continue to communicate the scientific reach of Project X.
- Project X is working closely with the Capabilities as well as the Instrumentation Frontiers in developing materials
- Continued progress will require dedicated resources from Project X R&D for accelerator systems, beams, and targetry.
- Continued progress also requires an allied effort in detector R&D (KA25) and scientific leadership (KA22) from the community and Fermilab staff.

Spares

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!

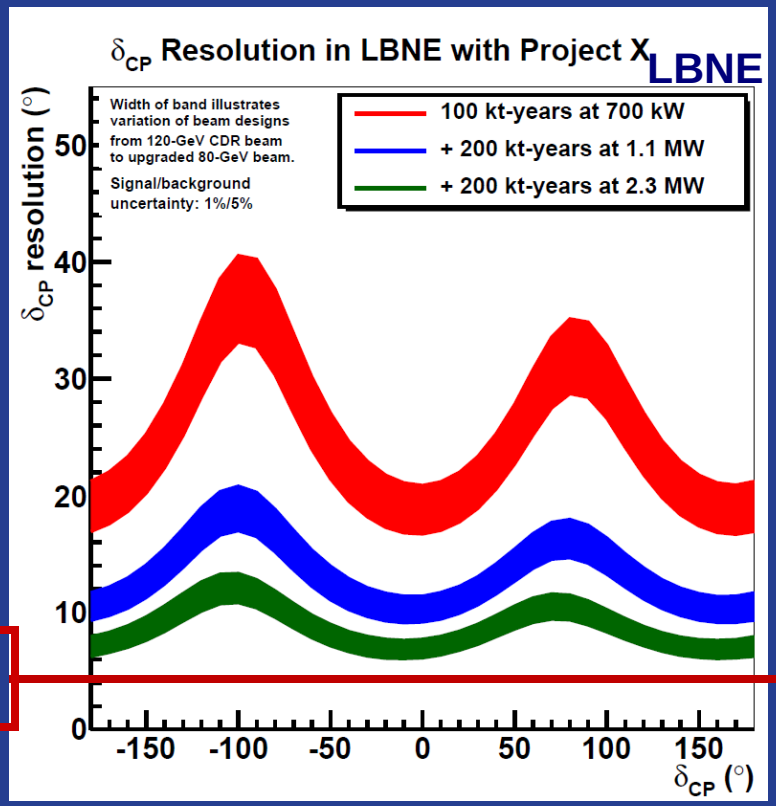
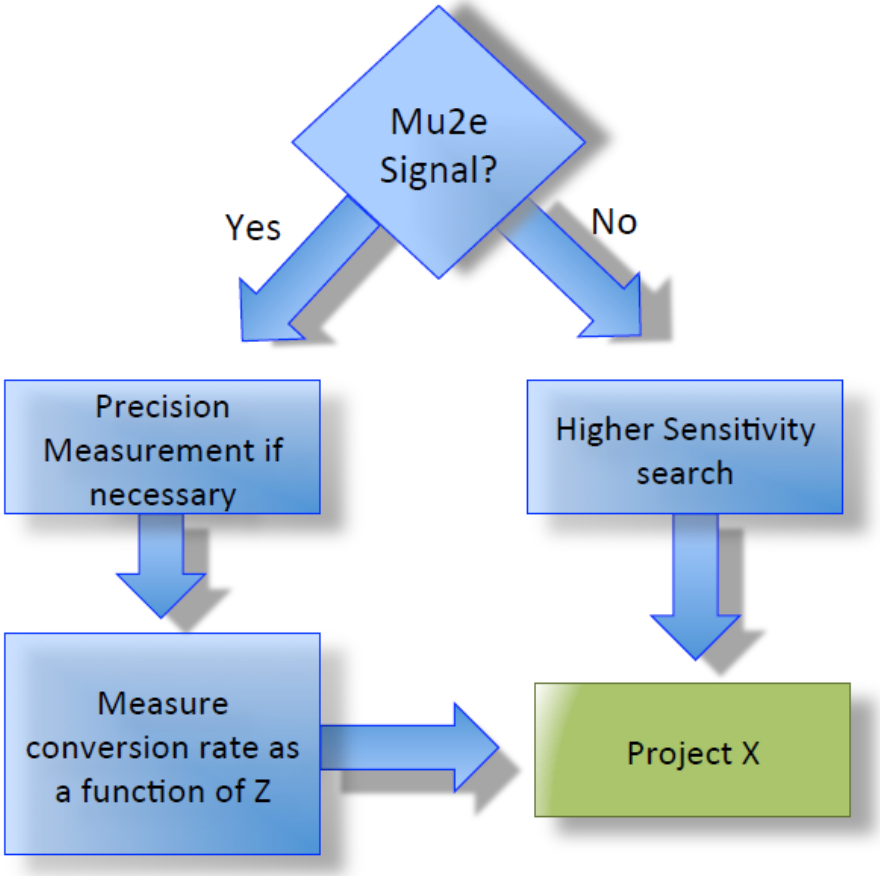


Table 2: SM predictions and current and expected limits on selected examples of EDMs.

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)

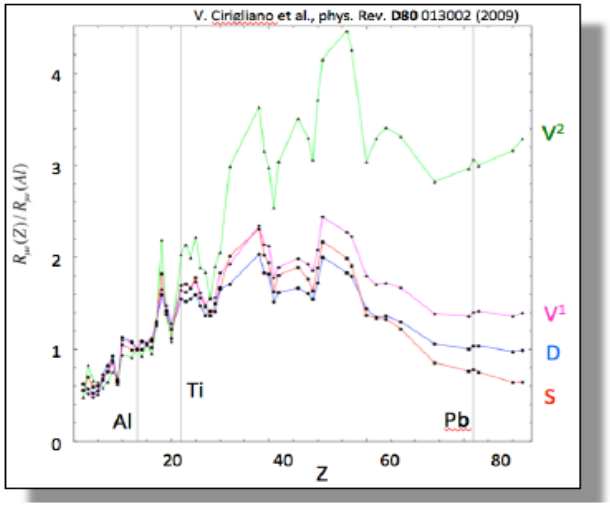
Project-X Stage-1 capability, fnal.projectx.gov

First Phase of Mu2e

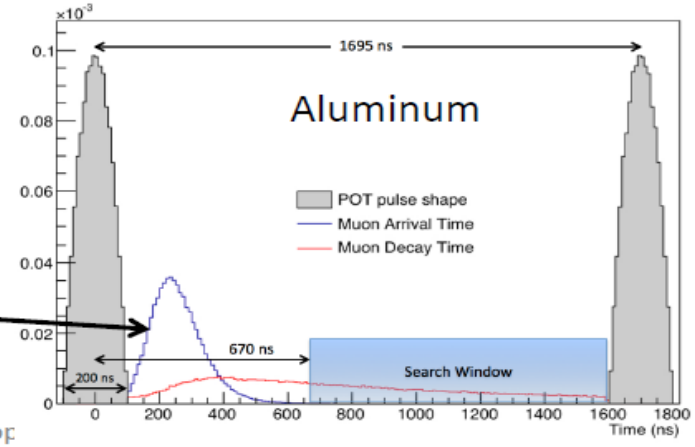


Mu2e Sees a Signal

- If Mu2e sees a signal in its initial run, next step is to map out conversion rate for various target nuclei where model dependent effects vary by a factor of 3.
- However, muon lifetime varies with Z
  - Big impact on execution of measurement



Nucleus (Z)	Muon Lifetime (ns)
Al(13)	864
Ti(22)	329
Au(79)	73

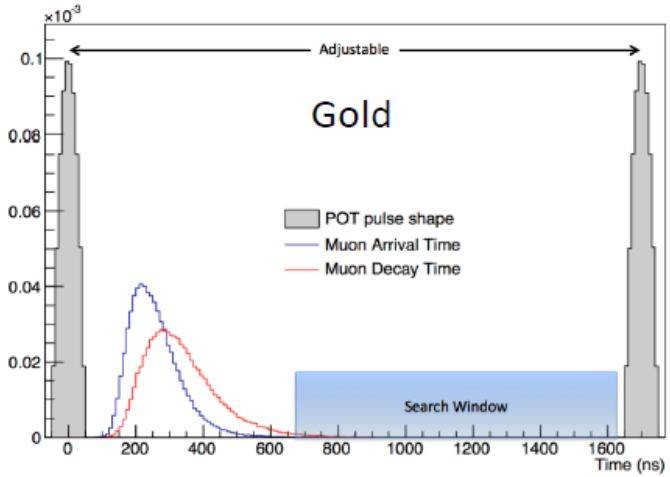


Arrival time of μ/π at stopping target
Increase in muon decays and RPC as one looks earlier in time

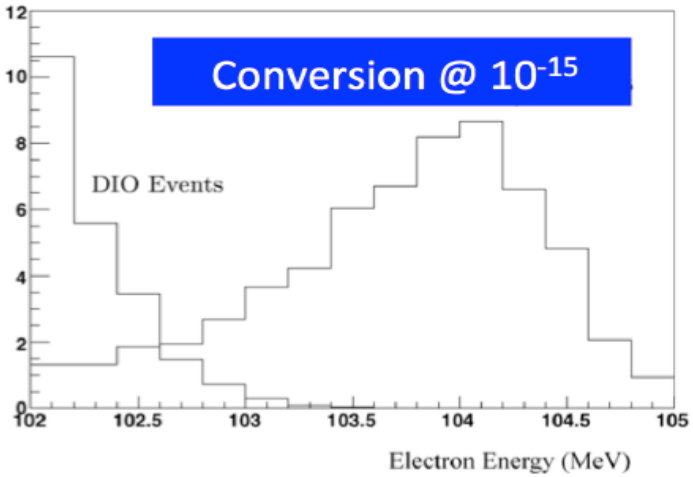
Mu2e Sees a Signal

Stage 1 of Project X makes these measurements possible with the existing solenoid system.

- Narrower proton beam pulse, intrinsic extinction and beam power enables use of stopping targets with shorter muon lifetimes
  - Limit to how early we can search due to muon decay in-flight and RPC background, assuming same background level required.
  - Rely on beam power to wait more muon lifetimes
    - Instantaneous rates decrease with time – reduces backgrounds
  - Flexible time structure allows us to wait longer than 1695 ns if desirable
    - Optimization different for different target nuclei.



Mu2e Does Not See a Signal

Stage I of Project X makes it possible to push the sensitivity another order of magnitude.

- Reductions in background also required. (See Doug Glenzinski's talk)
  - Narrow proton beam pulse and intrinsic extinction provided by Project X reduces prompt backgrounds.
  - No pbar background with 1 GeV protons.
- Improved momentum resolution required to reduce DIO background.