Project-X

RESMM12 Feb 14th 2012

R.Tschirhart
Fermilab

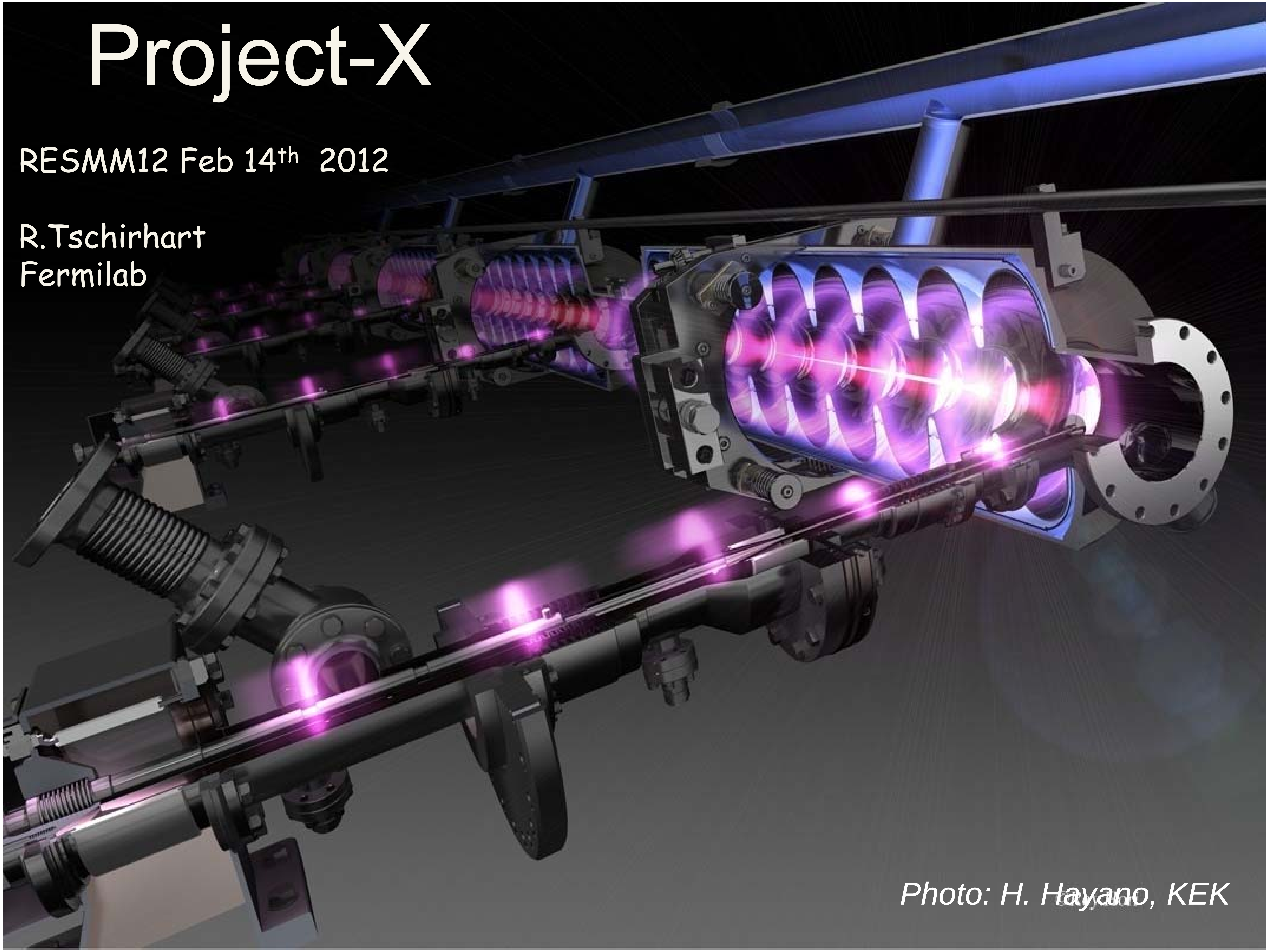


Photo: H. Hayano, KEK

The Project-X Research Program

- ***Neutrino oscillation experiments***
- A high-power proton source with proton energies between 8 (3) and 120 GeV would produce intense neutrino beams directed toward near detectors on the Fermilab site and massive detectors at distant underground laboratories.

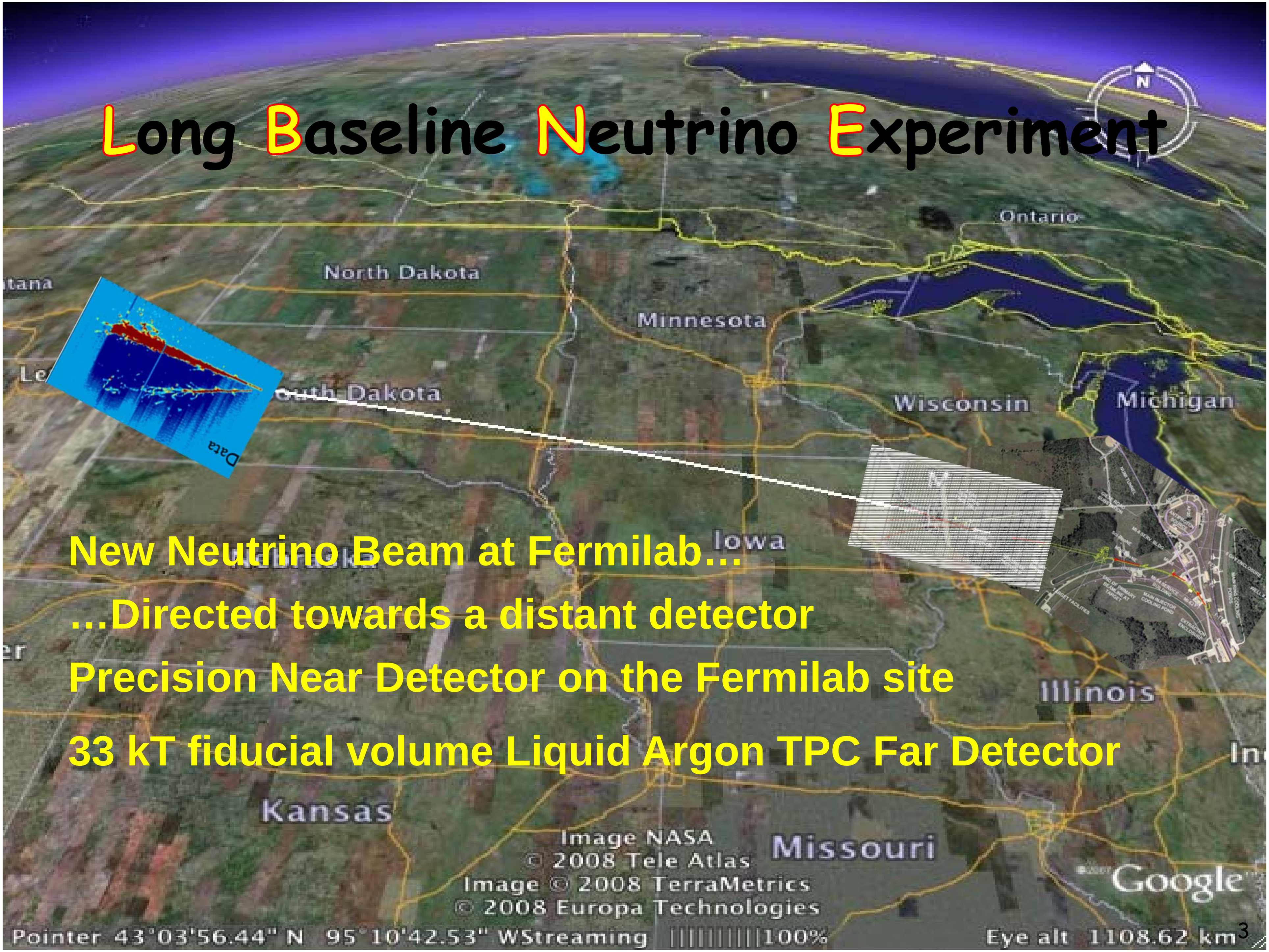
- ***Kaon, muon, nuclei & neutron precision experiments***
- These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (edms), precision measurement of neutron properties and world-leading precision measurements of ultra-rare 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.

- ***Nuclear Energy Applications***
- Accelerator, spallation, target and transmutation technology demonstration which could investigate and develop accelerator technologies important to the design of future nuclear waste transmutation systems and future thorium fuel-cycle power systems.

Detailed Discussion: Project X website

Long Baseline Neutrino Experiment



New Neutrino Beam at Fermilab…

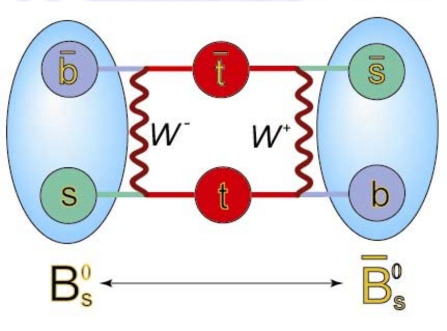
…Directed towards a distant detector

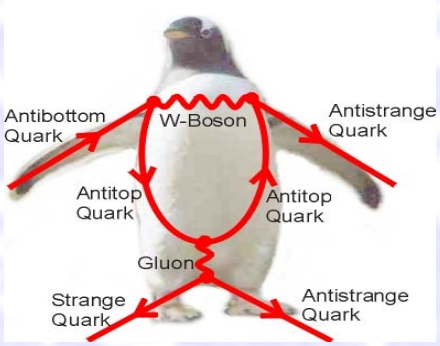
Precision Near Detector on the Fermilab site

33 kT fiducial volume Liquid Argon TPC Far Detector

Kaon, Muon and EDM Experiments Deeply Attack the Flavor Problem

Why don't we see the *Terascale Physics we expect* affecting the flavor physics we study today??





-Measures of the "Flavor" problem-

Generic couplings in new physics push the mass scale very high…. TeV scale new physics corresponds to highly constrained and tuned couplings of new physics

Operator	Bounds on Λ [TeV] ($C=1$)		Bounds on C ($\Lambda = 1\,\text{TeV}$)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p \rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p \rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2	2.2×10^2	7.6×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2	7.4×10^2	1.3×10^{-5}	3.0×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

Table 1-1. *Bounds on $\Delta F = 2$ operators of the form $(C/\Lambda^2)\,\mathcal{O}$, with $\mathcal{O}$ given in the first column. The bounds on Λ assume $C = 1$, and the bounds on C assume $\Lambda = 1$ TeV. (From Ref. [8].)*

From the heavy quark working group writeup summarizing the Intensity Frontier Workshop (http://www.intensityfrontier.org/)

In the absence of new facilities enabling new experiments…

From Hitoshi Murayama , ICFA October 2011

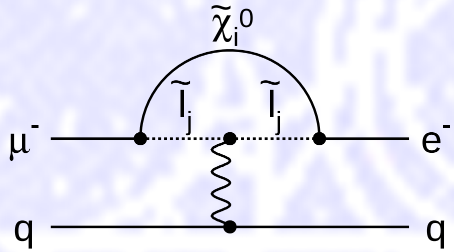
New facilities drive the Synergy between Experimental Frontiers to directly confront theory…

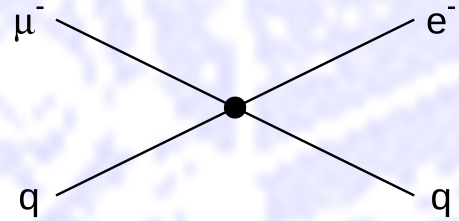
Modified from Hitoshi Murayama , ICFA October 2011

Deepest Probe of the Flavor Problem: muon-to-electron Conversion Expt at Project-X

Supersymmetry

Predictions at 10^{-15}



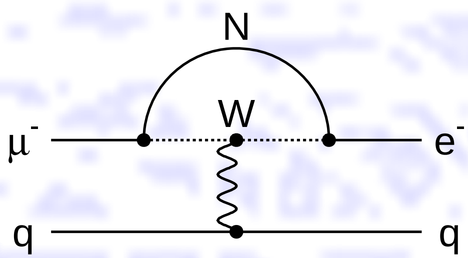


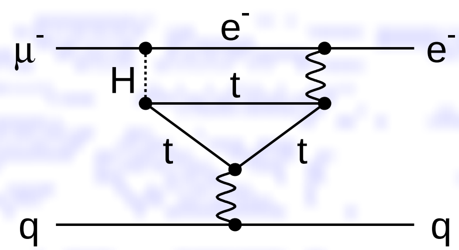
Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

$|U_{\mu N}^* U_{eN}|^2 = 8 \times 10^{-13}$





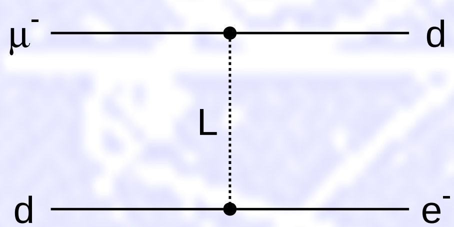
Second Higgs doublet

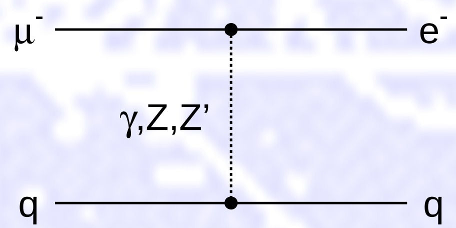
$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Leptoquarks

$M_L =$

$3000\sqrt{\lambda_{\mu d}\lambda_{ed}}$ TeV/c^2





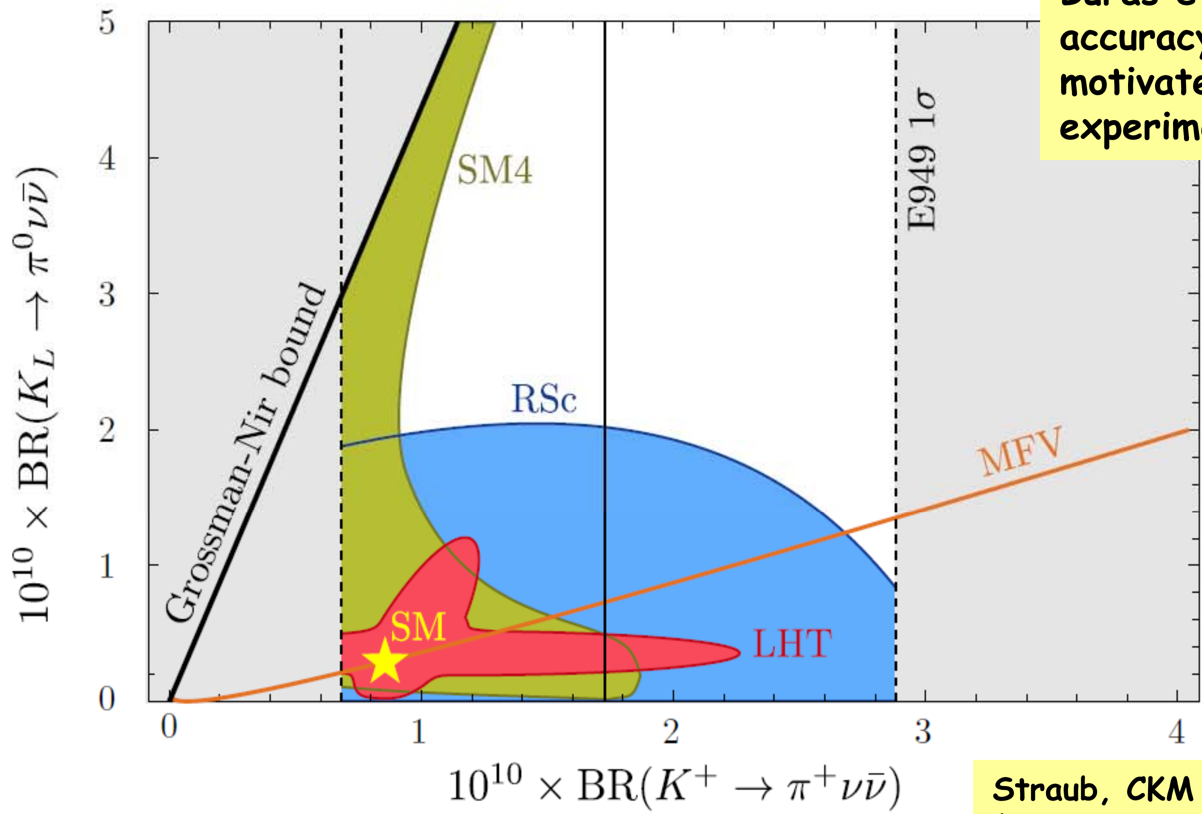
Heavy Z', Anomalous Z coupling

$M_{Z'} = 3000$ TeV/c^2

$B(Z \to \mu e) < 10^{-17}$

After W. Marciano

Rare processes sensitive to new physics… Warped Extra Dimensions as a Theory of Flavor??



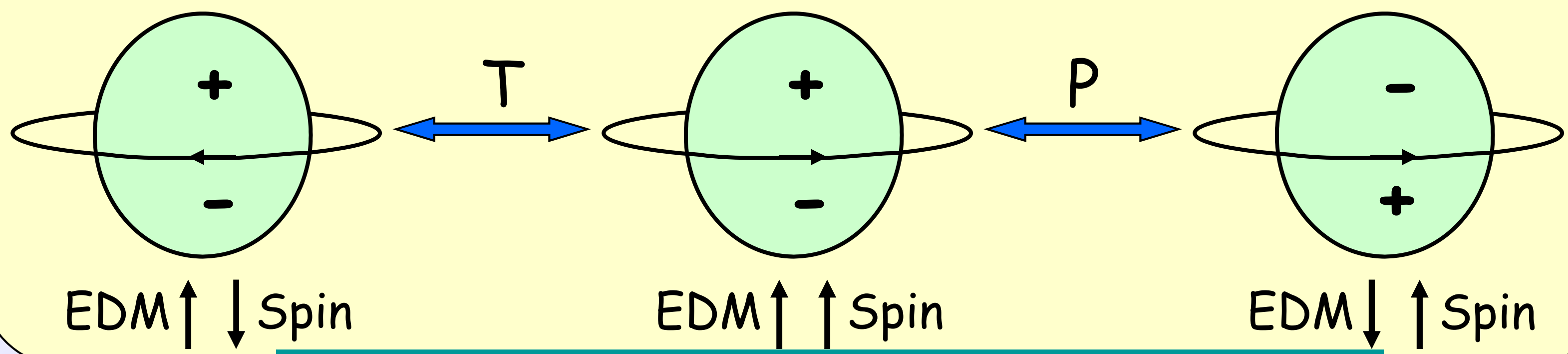
Buras et al. SM accuracy of <5%, motivates 1000-event experiments

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.

The Quest for Electric Dipole Moments

A permanent EDM violates both time-reversal symmetry and parity



To understand the origin of the symmetry violations, you need many experiments!

Neutron → Quark EDM, Quark Chromo-EDM

Diamagnetic Atoms (Hg, Xe, Ra, Rn) → Quark Chromo-EDM

Paramagnetic Atoms (Tl, Fr) Molecules (PbO) → Electron EDM

Quark EDM, Quark Chromo-EDM, Electron EDM → Physics beyond the Standard Model: SUSY, Strings …

Guy Savard, ANL

This Science has attracted Competition: The Proton Source Landscape This Decade...

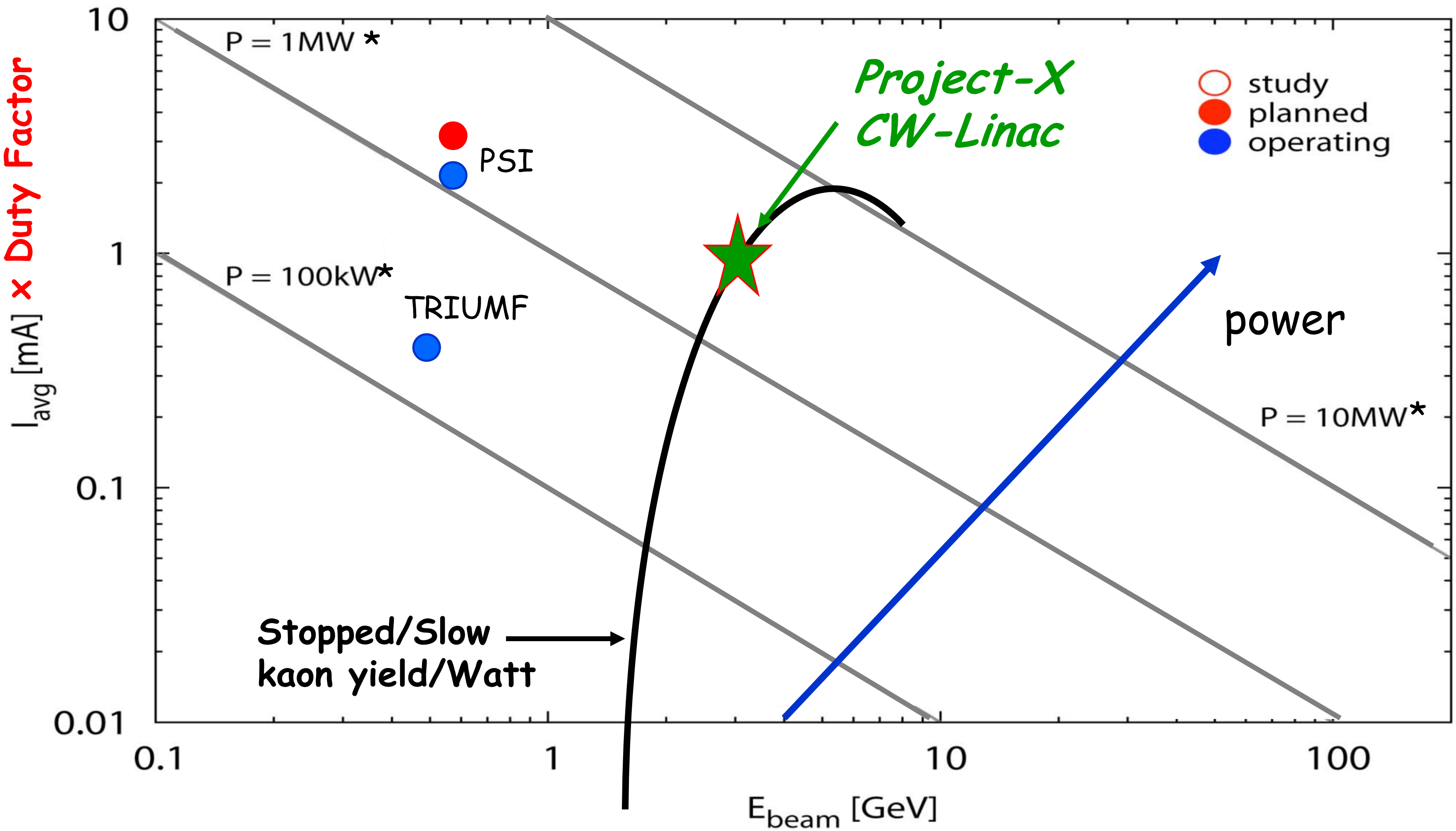
- Pulsed machines driving neutrino horns:
  SPS (0.5 MW), Main Injector (0.3 MW now, 0.7 MW for Nova), JPARC (plan for 1.7 MW)

- Cyclotrons and synchrotrons driving muon programs
  PSI (1.3 MW, 600 MeV), JPARC RCS (0.1-0.3 MW)

- Synchrotrons driving kaon physics programs.
  SPS (0.015 MW), JPARC (goal of >0.1 MW), Tevatron (0.1 MW)

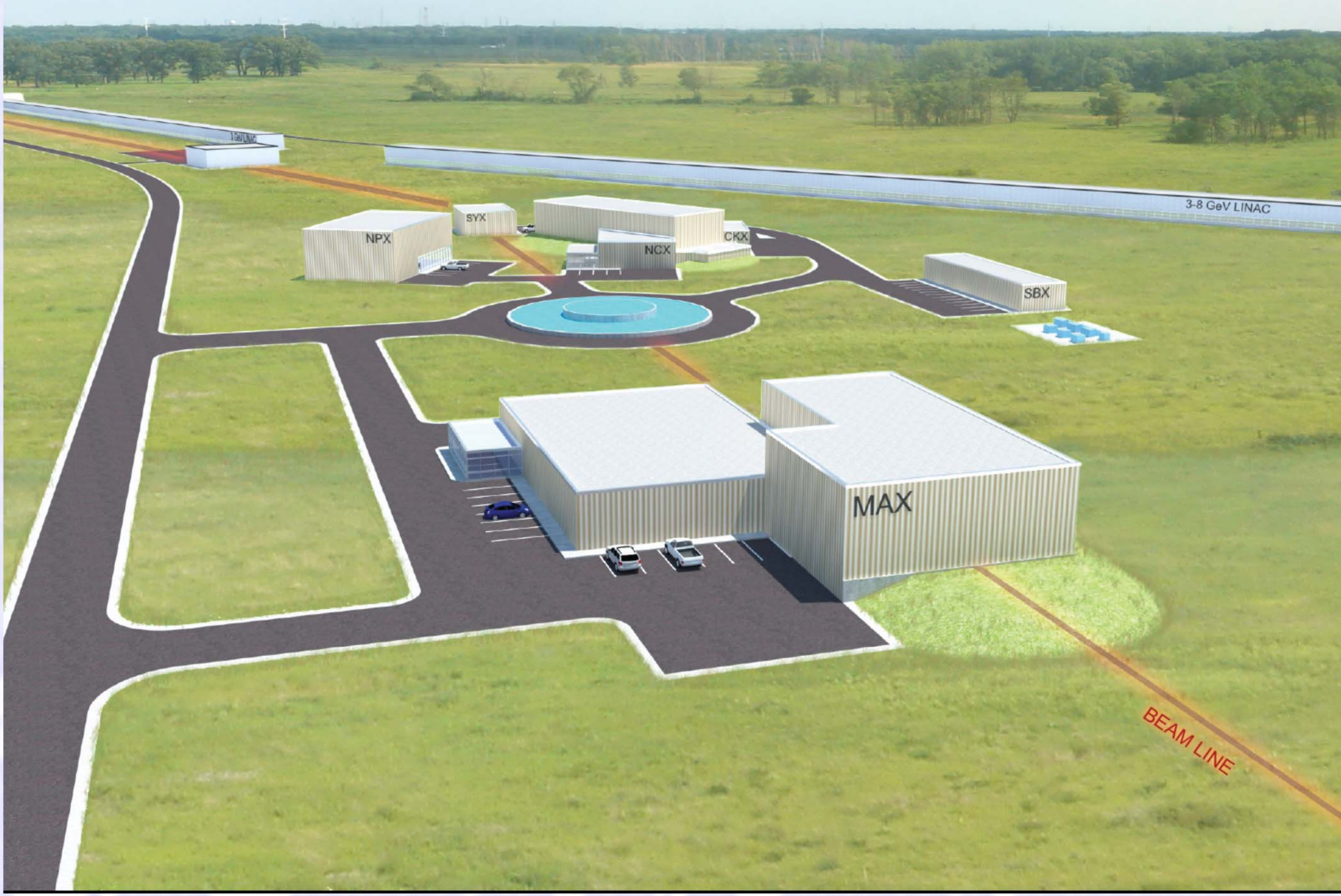
- Linear machines driving nuclear and neutron programs:
  SNS, LANL, FRIB....not providing CW light-nuclei beams.

The High Duty Factor Proton Source Landscape This Decade...



* Beam power x **Duty Factor**

Project-X Rare Processes Research Campus

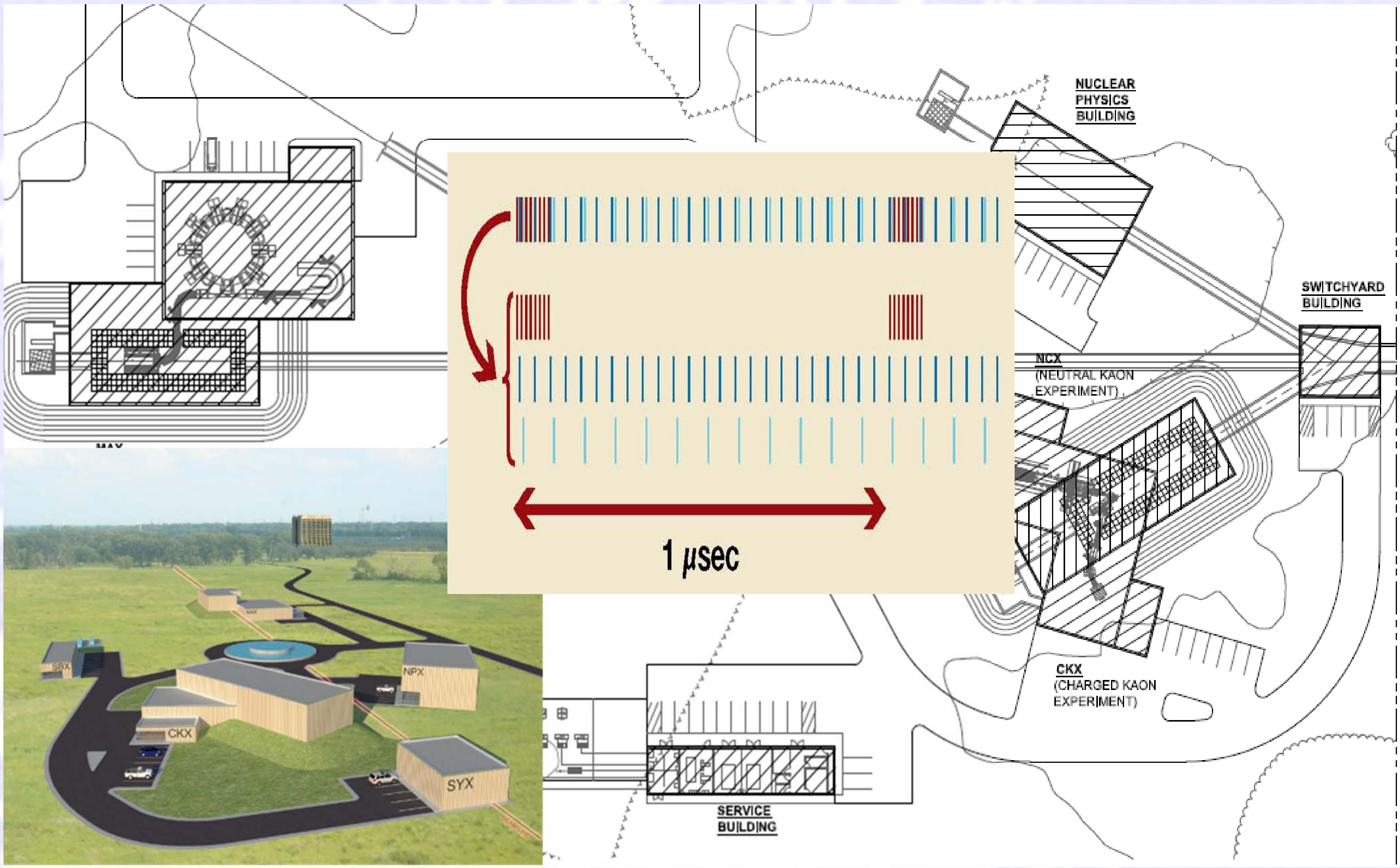


Project-X Accelerator Functional Requirements

CW Linac		
Particle Type	H^-	
Beam Kinetic Energy	3.0	GeV
Average Beam Current	1	mA
Linac pulse rate	CW	
Beam Power	3000	kW
Beam Power to 3 GeV program	2870	kW
RCS/Pulsed Linac		
Particle Type	protons/H^-	
Beam Kinetic Energy	8.0	GeV
Pulse rate	10	Hz
Pulse Width	0.002/4.3	msec
Cycles to MI	6	
Particles per cycle to Recycler	2.6×10^{13}	
Beam Power to 8 GeV program	190	kW
Main Injector/Recycler		
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.3	sec
Particles per cycle	1.6×10^{14}	
Beam Power at 120 GeV	2200	kW

simultaneous

Near Term R&D: Demonstrate Wide Band Chopper Capability



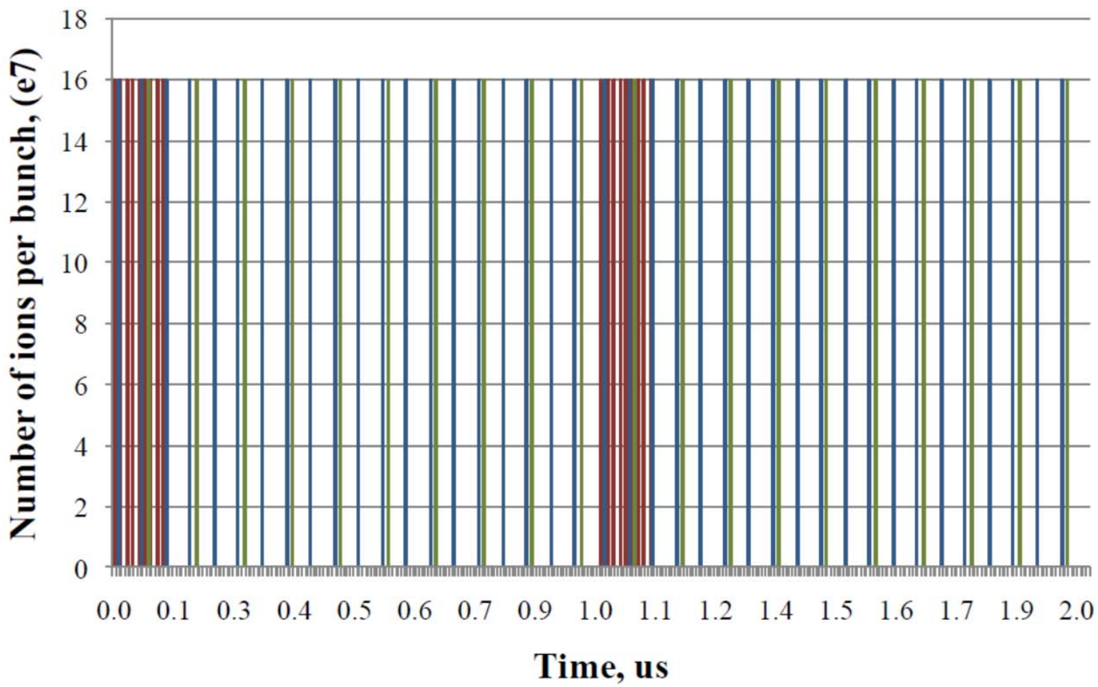
Project X

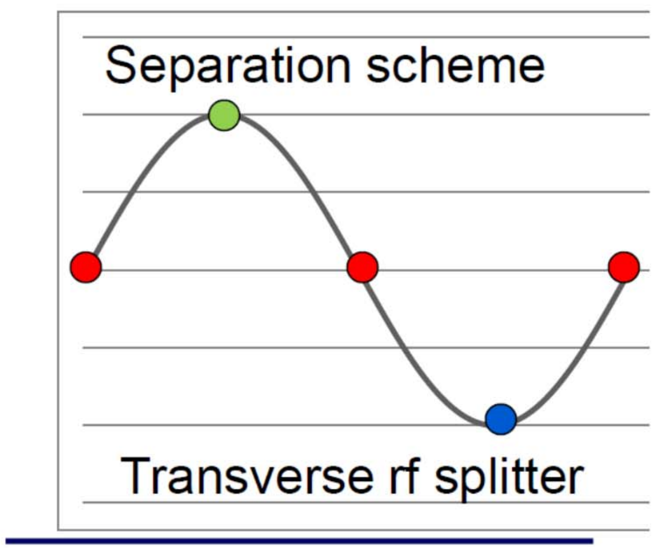
Chopping and splitting for 3-GeV experiments

1 μsec period at 3 GeV

Muon pulses (16e7) 81.25 MHz, 100 nsec at 1 MHz	700 kW
Kaon pulses (16e7) 20.3 MHz	1540 kW
Nuclear pulses (16e7) 10.15 MHz	770 kW

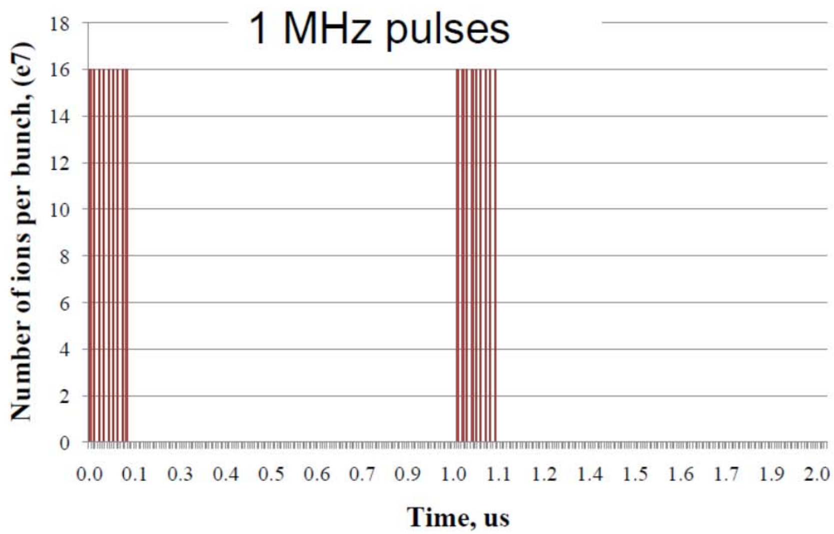
Ion source and RFQ operate at 4.2 mA
75% of bunches are chopped at 2.5 MeV after RFQ

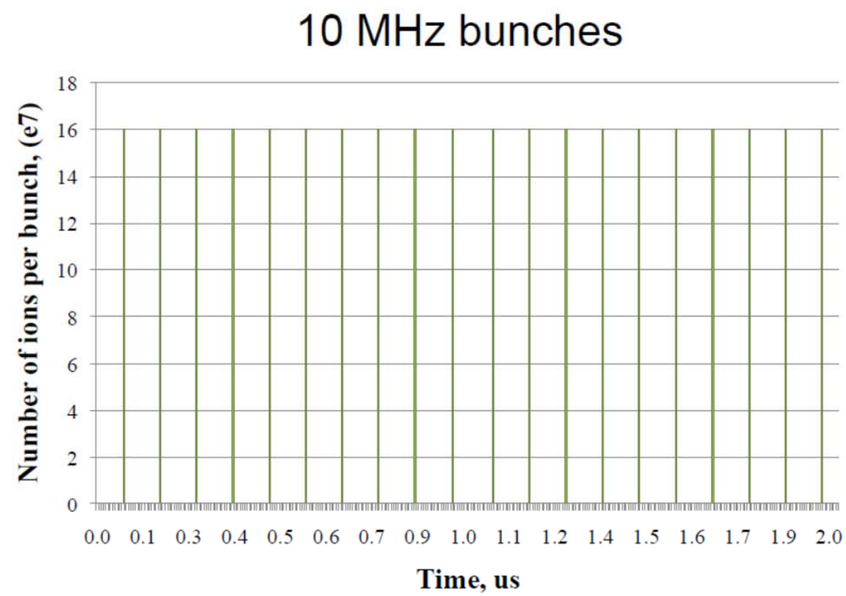


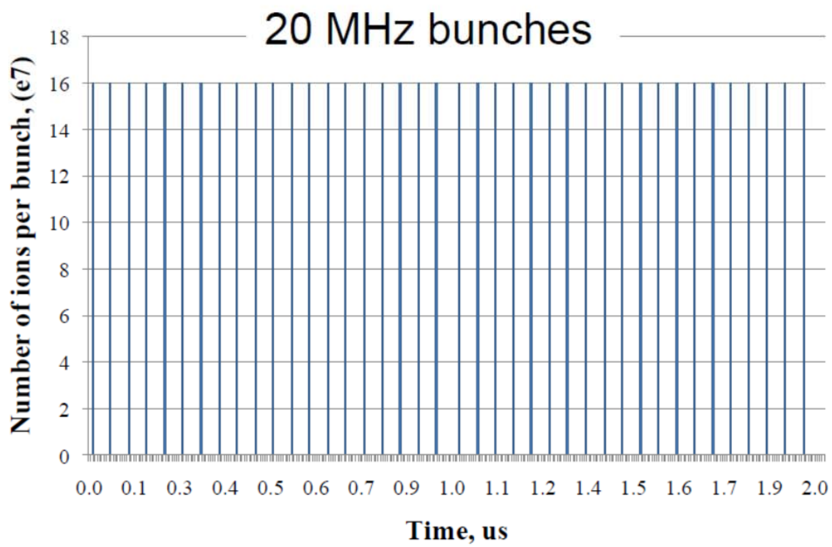


Courtesy of Nagaitsev

Beam after splitter







The "PXIE" R&D project develops the LEBT & MEBT technology to validate this opportunity.

Courtesy of Nagaitsev

An Incomplete Menu of World Class Research Targets Enabled by Project-X

Neutrino Physics:

- **Mass Hierarchy**
- **CP violation**
- **Precision measurement of the θ_{23} (atmospheric mixing). Maximal??**
- Anomalous interactions, e.g. $\nu_\mu \rightarrow \nu_\tau$ probed with target emulsions (Madrid Neutrino NSI Workshop, Dec 2009)
- Search for sterile neutrinos, CP & CPT violating effects in next generation $\nu_e, \bar{\nu}_e \rightarrow X$ experiments….x3 beam power @ 120 GeV, **x10-x20 power @ 8 GeV**.
- Next generation precision cross section measurements.

Day-1 Experiments

An Incomplete Menu of World Class Research Targets Enabled by Project-X

Muon Physics:

Day-1 Experiment

- **Next generation muon-to-electron conversion experiment, new techniques for higher sensitivity and/or other nuclei.**
- Next generation $(g\text{-}2)_\mu$ if motivated by next round, theory, LHC. New techniques proposed to JPARC that are beam-power hungry…
- μ edm
- $\mu \rightarrow 3e$
- $\mu^+ e^- \rightarrow \mu^- e^+$
- $\mu^- A \rightarrow \mu^+ A'$; $\mu^- A \rightarrow e^+ A'$; $\mu^- e^- (A) \rightarrow e^- e^- (A)$
- Systematic study of radiative muon capture on nuclei.

An Incomplete Menu of World Class Research Targets Enabled by Project-X

Kaon Physics:

Possible Day-1 Experiments

- $K^+ \rightarrow \pi^+\nu\bar{\nu}$: >1000 events, Precision rate and form factor.
- $K_L \rightarrow \pi^0\nu\bar{\nu}$: 1000 events, enabled by high flux & precision TOF.
- $K^+ \rightarrow \pi^0\mu^+\nu$: Measurement of T-violating muon polarization.
- $K^+ \rightarrow (\pi,\mu)^+\nu_X$: Search for anomalous heavy neutrinos.
- $K^0 \rightarrow \pi^0 e^+e^-$: <10% measurement of CP violating amplitude.
- $K^0 \rightarrow \pi^0\mu^+\mu^-$: <10% measurement of CP violating amplitude.
- $K^0 \rightarrow X$: Precision study of a pure K^0 interferometer: Reaching out to the Plank scale ($\Delta m_K/m_K \sim 1/m_P$)
- $K^0, K^+ \rightarrow$ LFV: Next generation Lepton Flavor Violation experiments

…and more

An Incomplete Menu of World Class Research Targets Enabled by Project-X

Possible Day-1 Experiment

Nuclear Enabled Particle Physics:

- Production of Ra, Rd, Fr isotopes for nuclear edm experiments that are uniquely sensitive to Quark-Chromo and electron EDM's. Production of Very-cold and Ultra-cold neutrons for EDM and n-nbar.

Baryon Physics:

- pp $\rightarrow \overline{\Sigma}^{+} K^{0} p^{+}$; $\Sigma^{+} \rightarrow p^{+} \mu^{+} \mu^{-}$ (HyperCP anomaly, and other rare Σ^{+} decays)
- pp $\rightarrow K^{+} \Lambda^{0} p^{+}$; Λ^{0} ultra rare decays
- neutron – antineutron oscillations
- $\Lambda^{0} \leftrightarrow \overline{\Lambda}^{0}$ oscillations (Project-X operates below anti-baryon threshold)
- neutron EDMs

Example Power Staging for the Research Program

Program:	Stage-0: Proton Improvement Plan	Stage-1: 1 GeV CW Linac driving Booster & Muon, EDM programs	Stage-2: Upgrade to 3 GeV CW Linac (MI>70 GeV)	Stage-3: Project X RDR (MI>60GeV)	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2300 kW	2300-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-40 kW* + 0-90 kW**	0-40 kW*	85 kW	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	85 kW	1000 kW
1-3 GeV Muon program	-----	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	1100 kW	1100 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
# Programs:	4	8	8	8	8
Total* power (mean):	660 kW	1950 kW	4230 kW	5490 kW	11300kW

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

Main Injector Primary Proton Beam Power (R. Zwaska)

BROOKHAVEN NATIONAL LABORATORY

Impact of Project X on LBNE

Mary Bishai (LBNE collaboration) Brookhaven National Laboratory

Intro

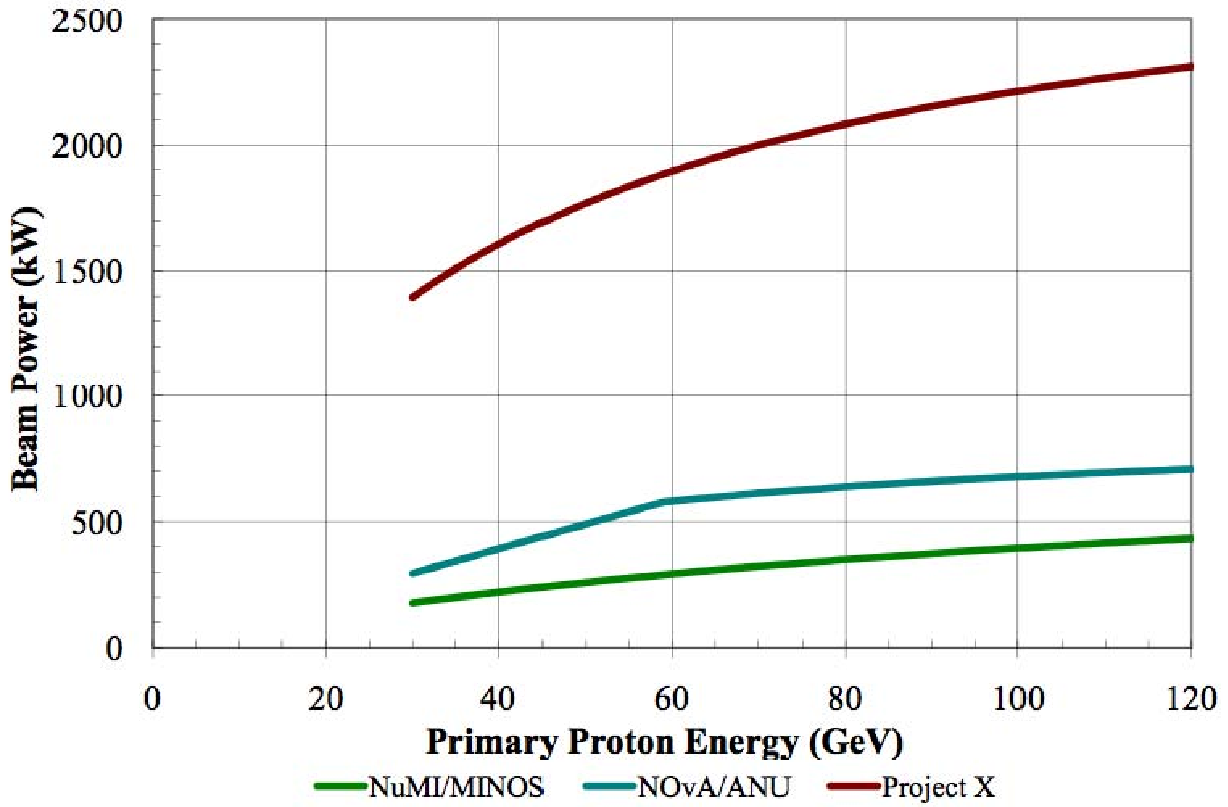
LBNE Beams

LBNE Detectors

Beam Physics with Project X

Summary

With Project X:



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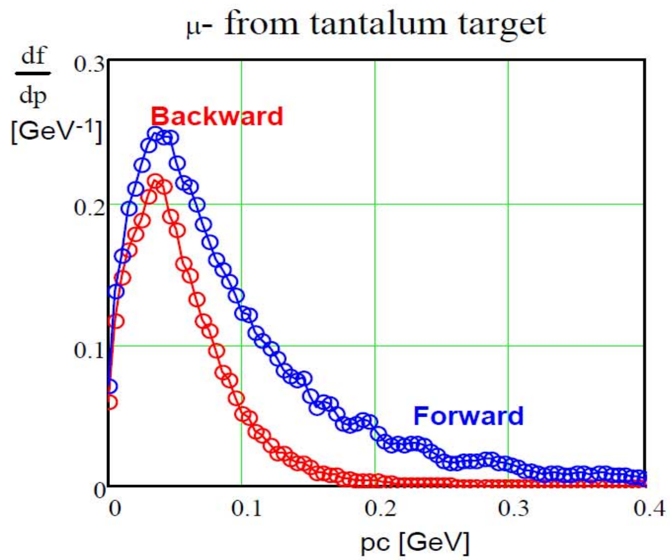
Muon Yields with High Power Compact Targets…

Muon Yield from Cylindrical Target

V. Lebedev, AAC meeting, Dec 2011



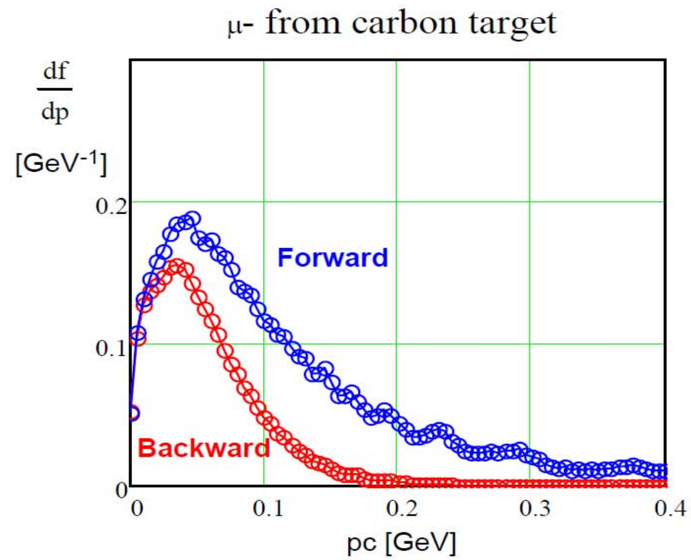
Tantalum hollow cylinder

R_{out}=20 cm, ΔR=5 mm, L=16 cm, θ=300 mrad

Total muon yield at ±10 m

Forward – 1.4% per proton GeV

Backward – 0.73% per proton GeV



Carbon hollow cylinder

R_{out}=20 cm, ΔR=5 mm, L=40 cm, θ=200 mrad

Total muon yield at ±10 m

Forward – 1.3% per proton GeV

Backward – 0.59% per proton GeV

Yield per 1 GeV of proton energy: pc=3 GeV/ (E_{kin}=2.2 GeV),

$\sigma_x = \sigma_y$ = 1 mm – parallel beam, proton multiple scattering unaccounted

- Small difference between forward and backward muons for Pc<50 MeV
- For pc<120 MeV a weak dependence on E_{kin_prot} for $E_{kin\_prot} \in [1, 8]$ GeV/c

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The Mega-Watt Jungle…

Apologies to Jurassic Park and Hitoshi Murayama , ICFA October 2011

A Few High Power Target Issues…

- Modelling of beam energy deposition
- Modelling of secondary particle production
- Modelling of target material response using FEA codes
- Target cooling or replacement
- Activation and radiation damage everywhere
- Thermal shock
- Target lifetime
- Particle capture, moderation and delivery
- Beam windows
- Target station design, inc. shielding, RH, licensing, etc
- Diagnostics in high radiation environments
- Demanding environmental and safety requirements

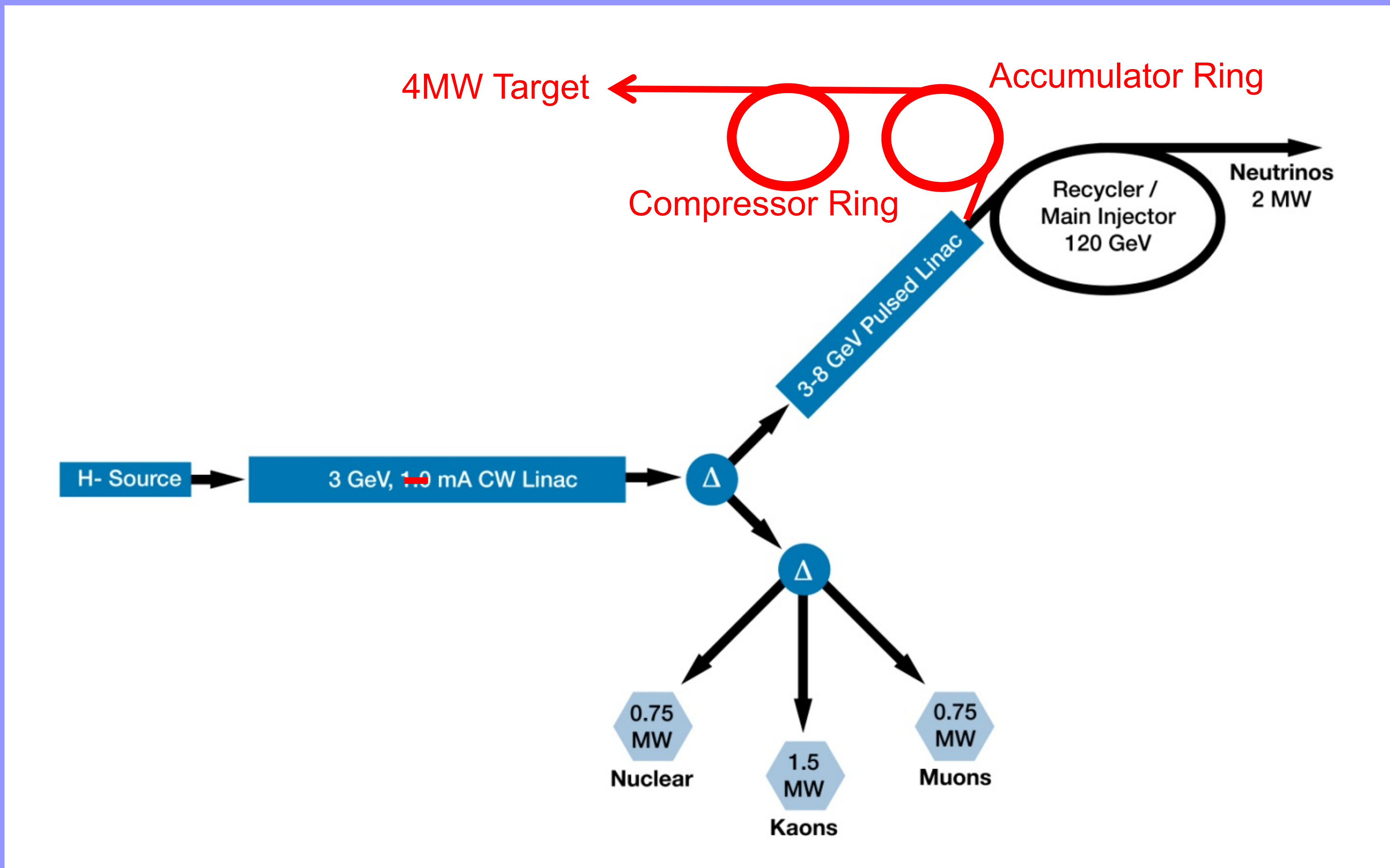
Courtesy Patrick Hurh and the UKHPT/STFC

Summary

- Project X is the driving force of the Intensity Frontier roadmap at Fermilab and a platform from which to reach toward the Muon Collider.
- The Project X research program deeply attacks the central question in particle physics today, the question of "naturalness" and physics at the TeV scale and beyond.
- We need you. The success of the Fermilab roadmap depends critically on R&D toward next generation high power targetry and beamlines…these are the foundation of experiments in the US and world-wide program for decades to come.

Spare Slides

MAP Layout based upon Project X



Project X Upgrade Proton Driver - 3

Pulsed Linac

1.3GHz SRF

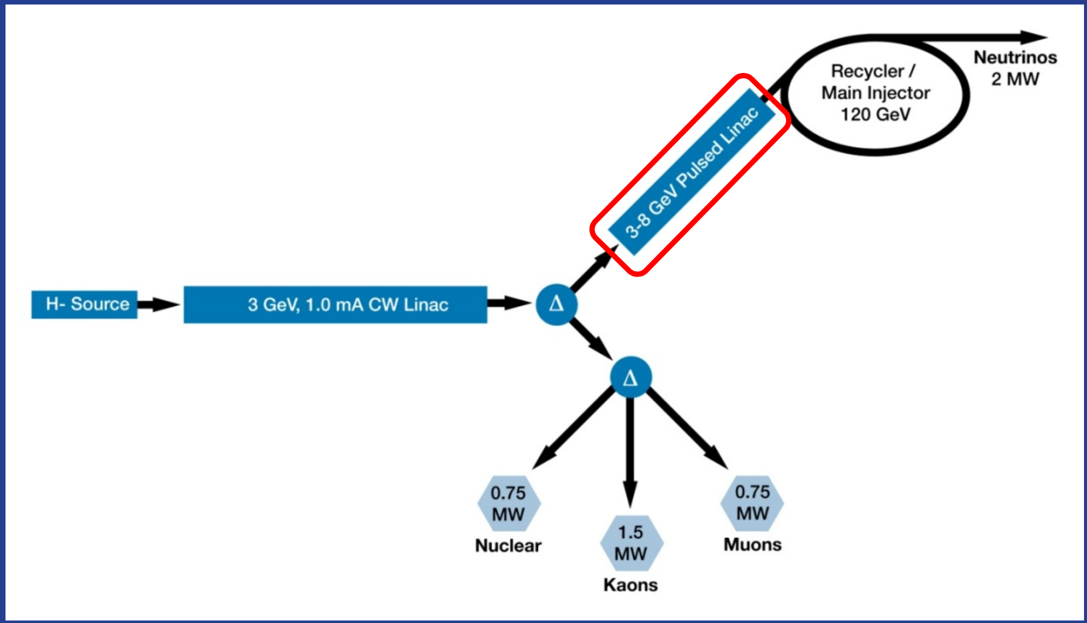
3-8 GeV

10% ~~5%~~ duty factor at ~~10Hz~~ 15Hz

More RF power

Upgrade of couplers

More cryo capicity



Pursuing next-generation neutrino parameters is beam-power hungry: **Project-X *Triples* LBNE (Power x Mass) Reach**

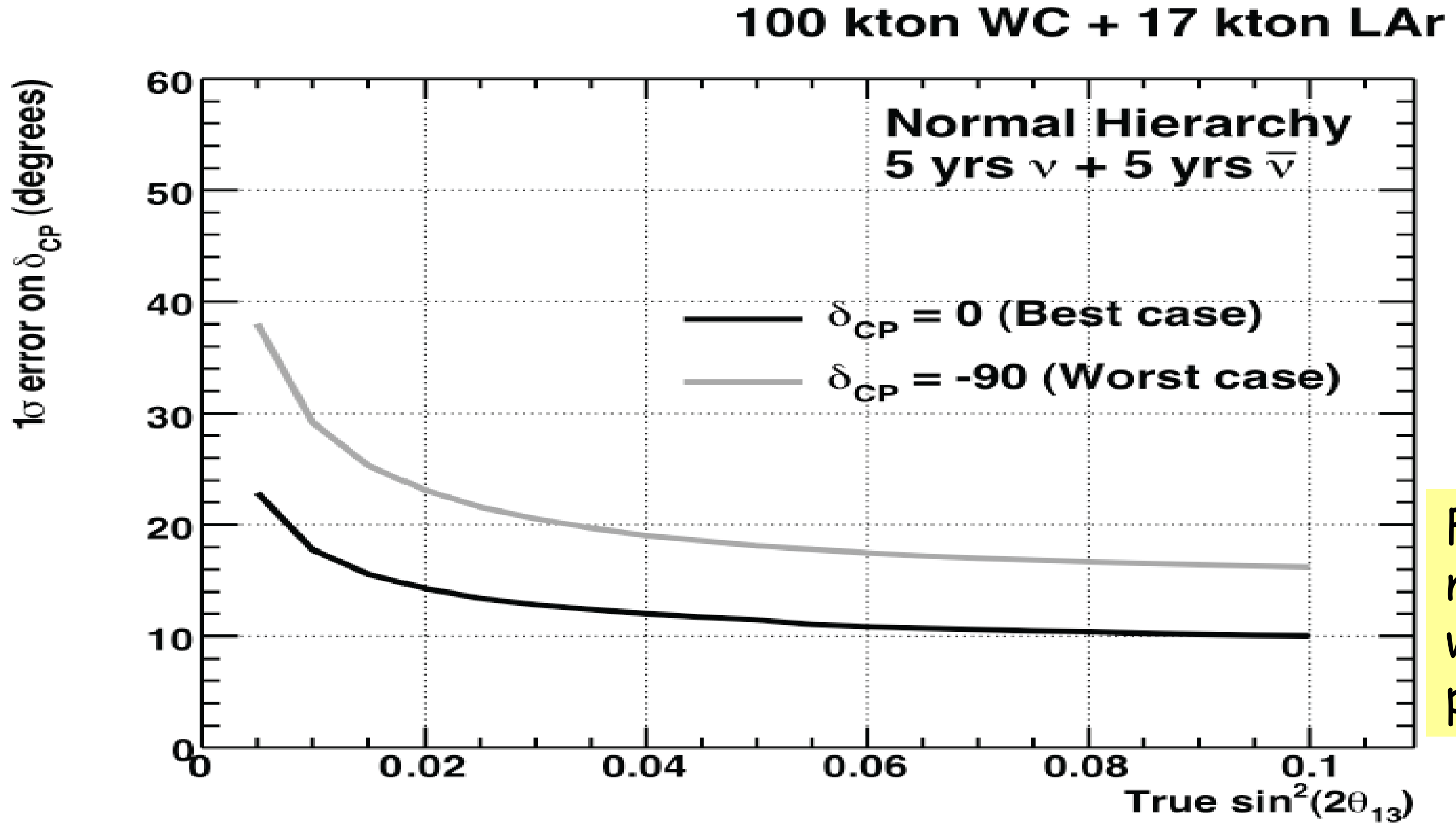
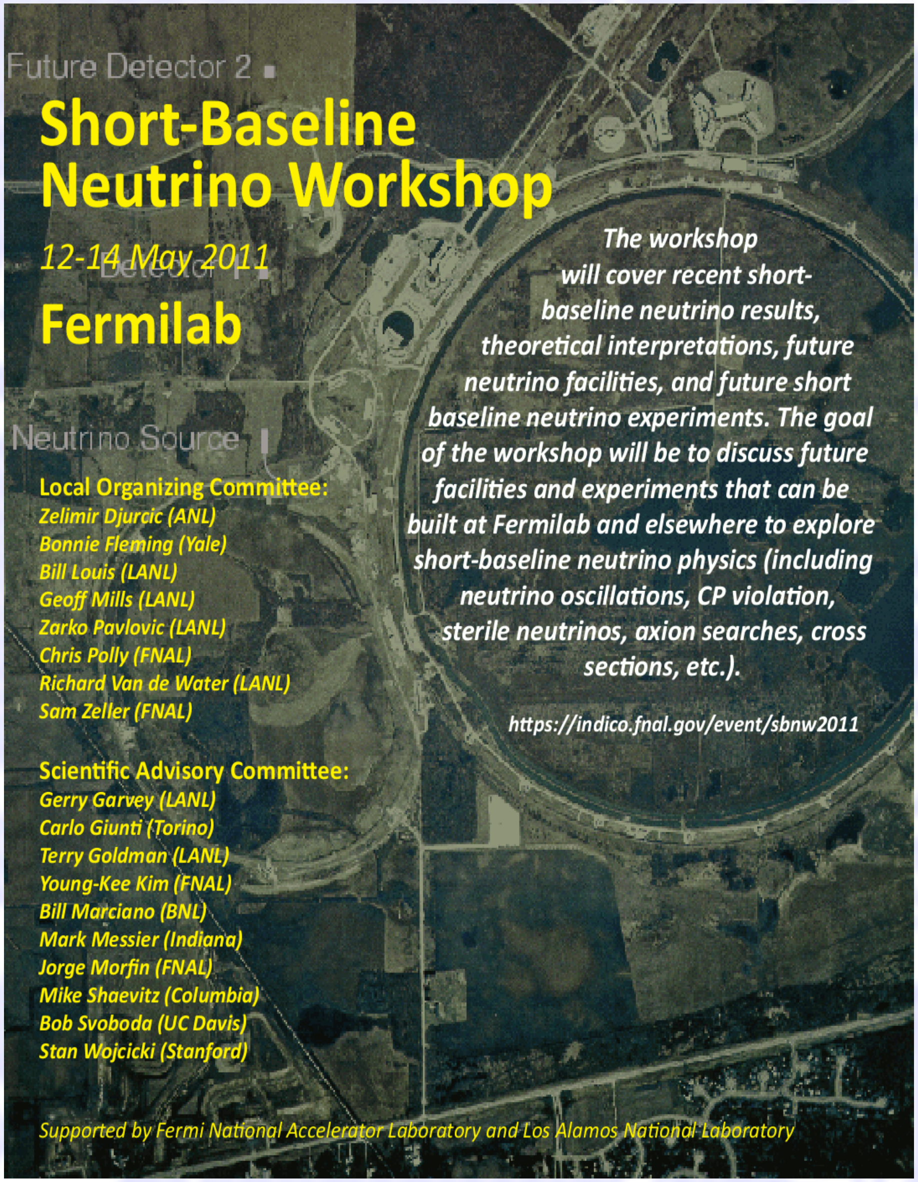


Figure 3: Plot showing 1 sigma error (in degrees) on δ_{CP} at an LBNE far detector complex composed of a 100-kT water Cherenkov detector and a 17-kT liquid argon detector. The exposure assumes a 700-kW proton beam. [Plot courtesy of Lisa Whitehead, Brookhaven National Laboratory]

From the neutrino white paper



Project-X Opportunities

- Follow leads on 3+N sterile neutrinos:

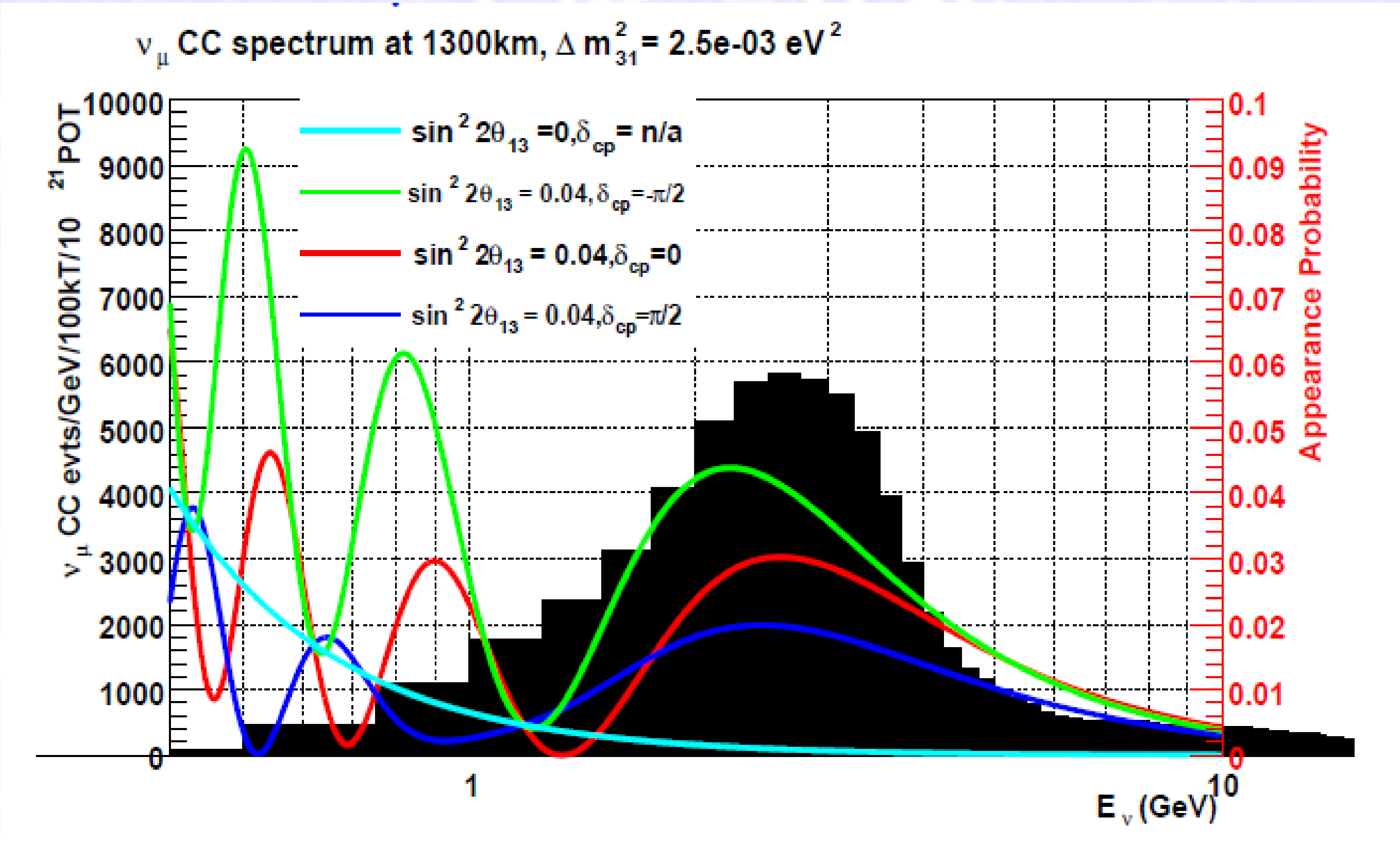
190 kW 8-GeV beam power
1000 kW class 3-GeV DIF driver

Higher 8-GeV beam power??

- Beam dump exotics search
- Precision neutrino cross sections
- Flux measurements with H/D_2

SBNW11 Summary : R. Van de Water (LANL)

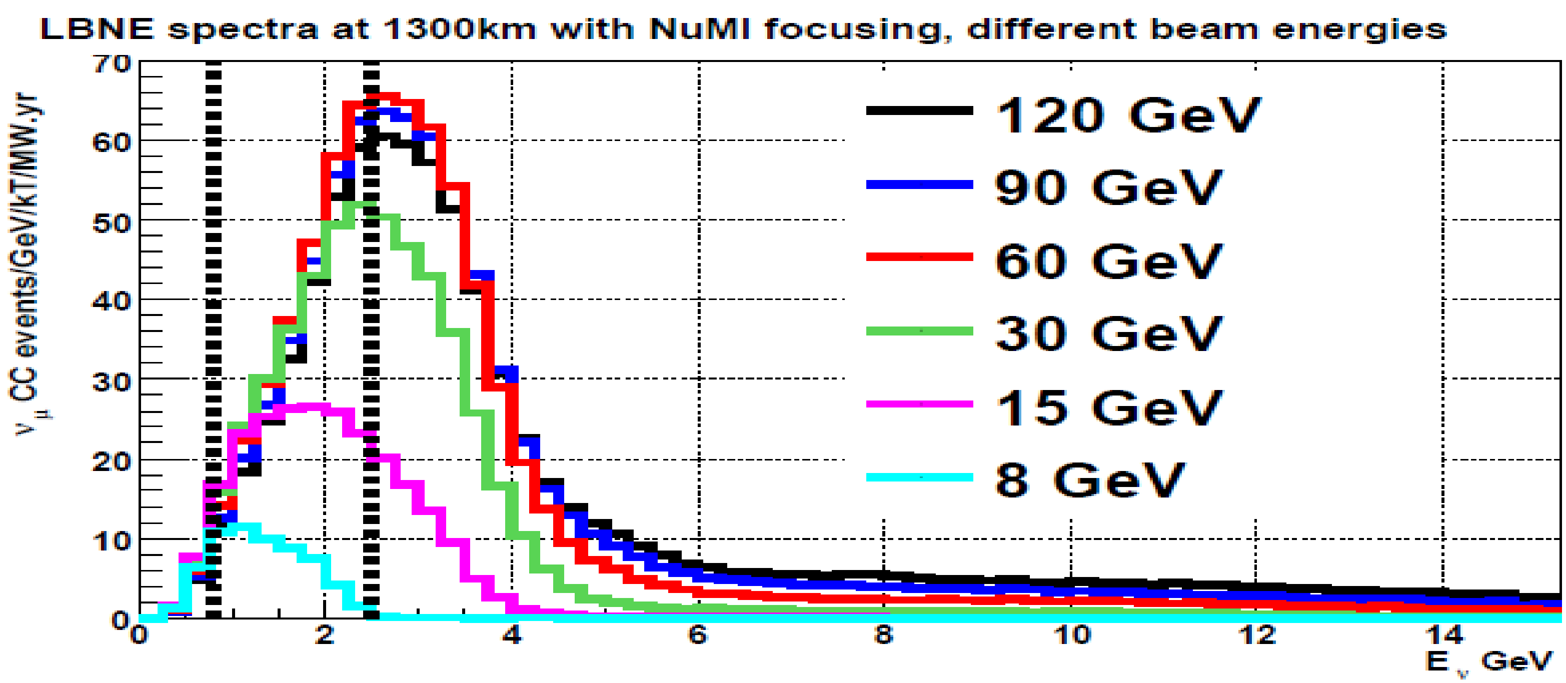
Tuning the LBNE spectrum



Mary Bishai, Neutrino Working Group meeting October 24th, 2011

- A task force (K. Gollwitzer) to develop a path from Project-X to a Neutrino-Factory/Muon-Collider has recently reported a concept to raise available 8 GeV beam power from 190kW to 4000kW! This path re-uses 75% of the Project-X facility.

- The joint reach of simultaneous 2MW@60 GeV and 4MW@8 GeV is very interesting. This idea has been long been considered (D Michael) and more recently by Mary Bishai and Jeff Nelson.



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Impact of Project X on LBNE

Mary Bishai (LBNE collaboration) Brookhaven National Laboratory

Intro

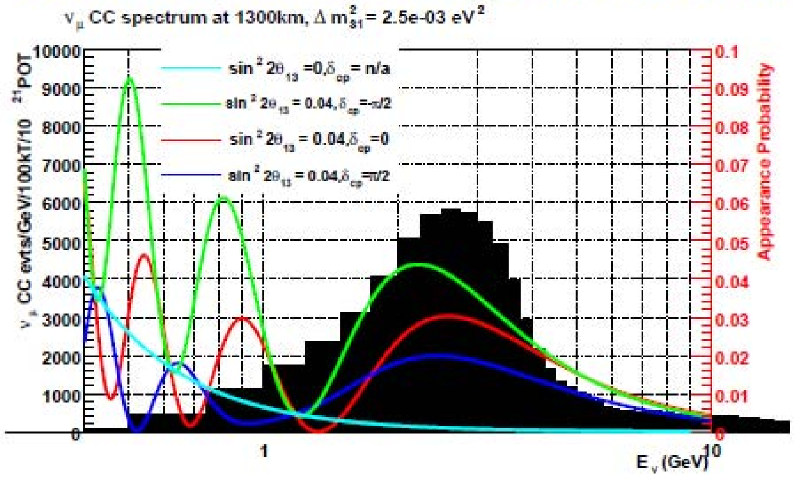
LBNE Beams

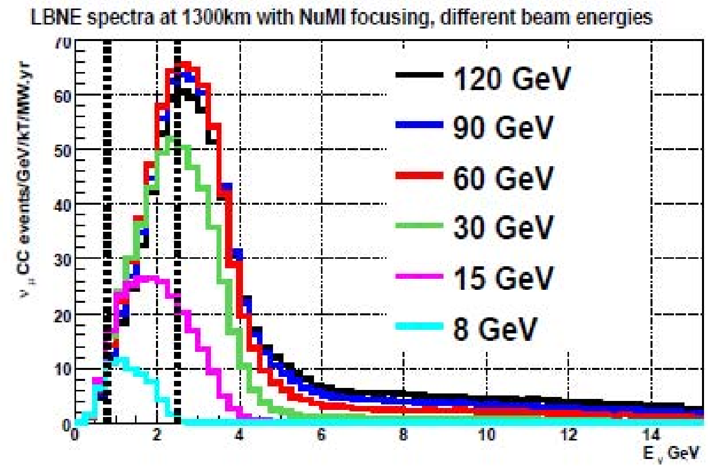
LBNE Detectors

Beam Physics with Project X

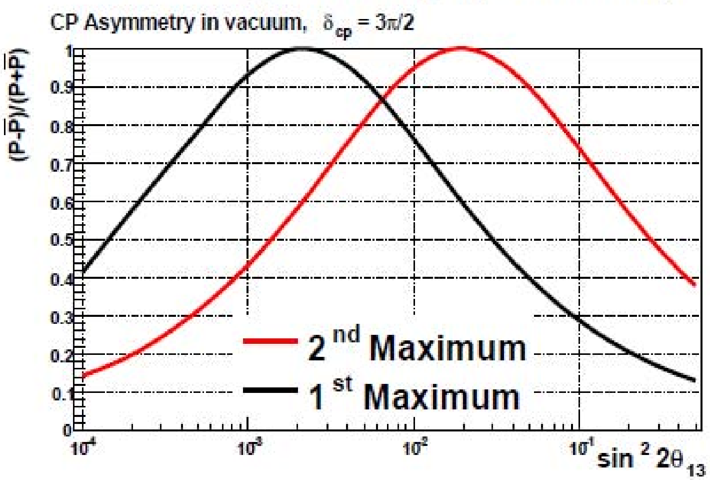
Summary

Wide-band beam to cover BOTH oscillation maxima for best CP Violation/Mass Hierarchy sensitivity

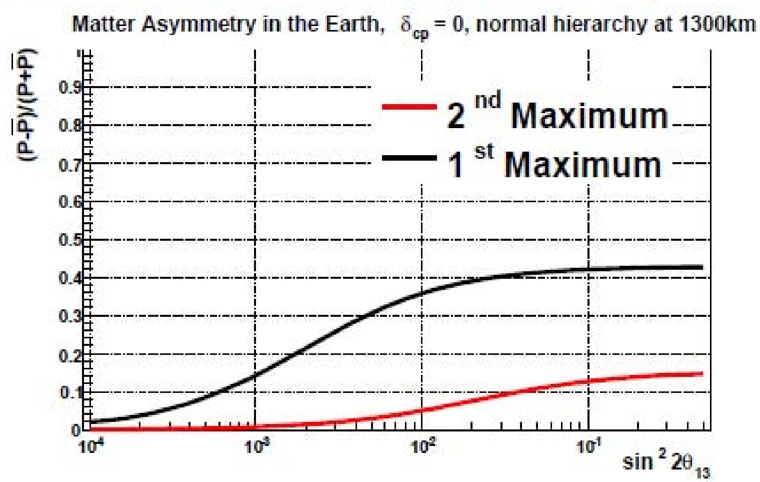




CP Asymmetry (vacuum)

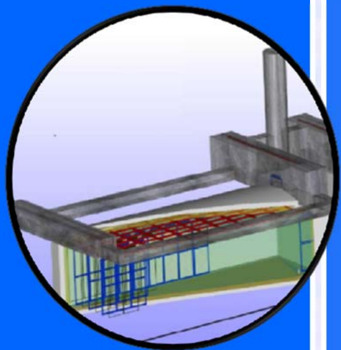


Matter Asymmetry (no CPV)



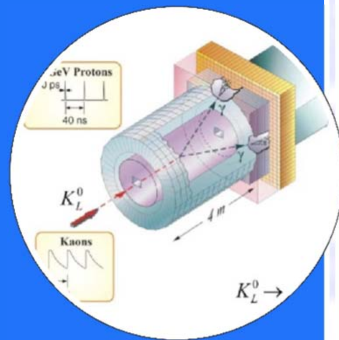
Mary Bishai, Neutrino Working Group meeting October 24th, 2011

Project X: new experiments



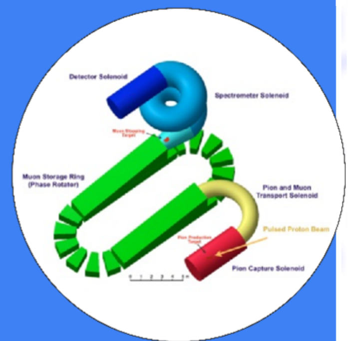
Neutrinos

- Matter-antimatter asymmetry
- Neutrino mass spectrum
- Neutrino-antineutrino differences
- Anomalous interactions
- Proton decay
- SuperNova bursts



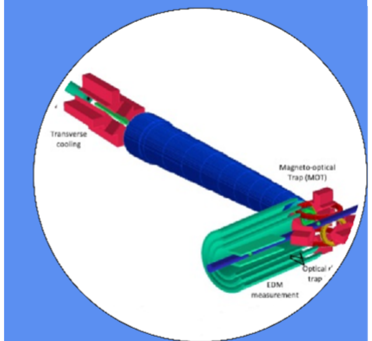
Kaons

- Physics beyond the Standard Model
- Elucidation of LHC discoveries
- Two to three orders of magnitude increase in sensitivity



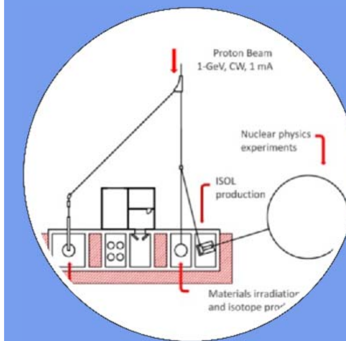
Muons

- Oscillation in charged leptons
- Physics beyond the Standard Model
- Elucidation of LHC physics
- Sensitive to energy/mass scales three orders of magnitude beyond LHC



Nuclei

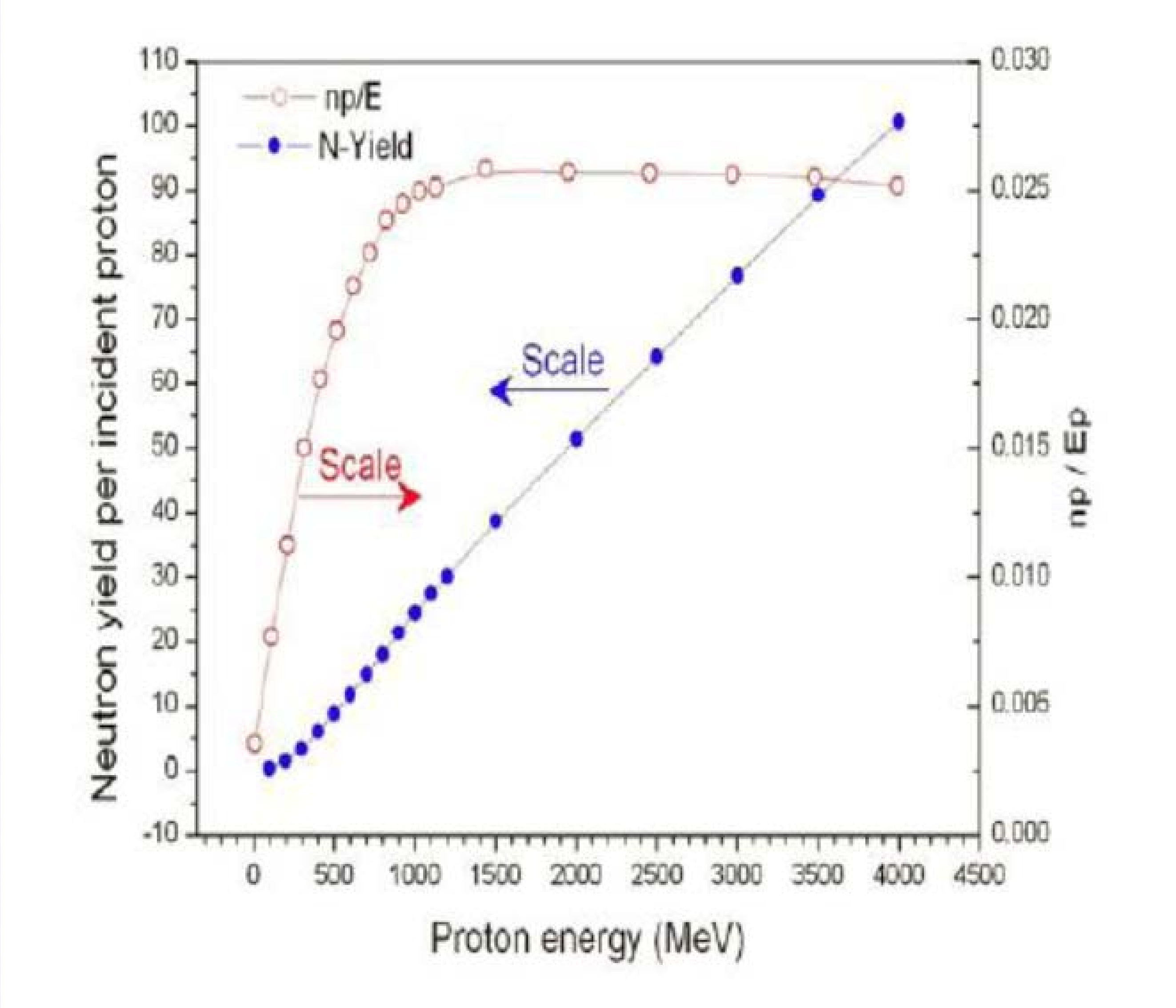
- New generation of symmetry-test experiments
- Electric Dipole Moments
- Three or more orders of magnitude increase in Francium, Radium, Actinium isotopes



Energy Applications

- Transmutation experiments with nuclear waste
- Spallation target configurations
- Materials test under high irradiation
- Neutron fluxes relevant to ADS

Optimum Energy for ADS R&D



High Duty-Factor Proton Beams
Why is this important to Rare Processes?

- Experiments that reconstruct an "event" to a particular time from sub-detector elements are intrinsically vulnerable to making mistakes at high instantaneous intensity (I). The probability of making a mistake is proportional to $I^2 \times \delta t$, where δt is the event resolving time.
- Searching for rare processes requires high intensity.
- Controlling backgrounds means minimizing the instantaneous rate and maximizing the time resolution performance of the experiment.
- This is a common problem for Run-II, LHC, Mu2e, High-School class reunions, etc.

Kaon Yields at Constant Beam Power

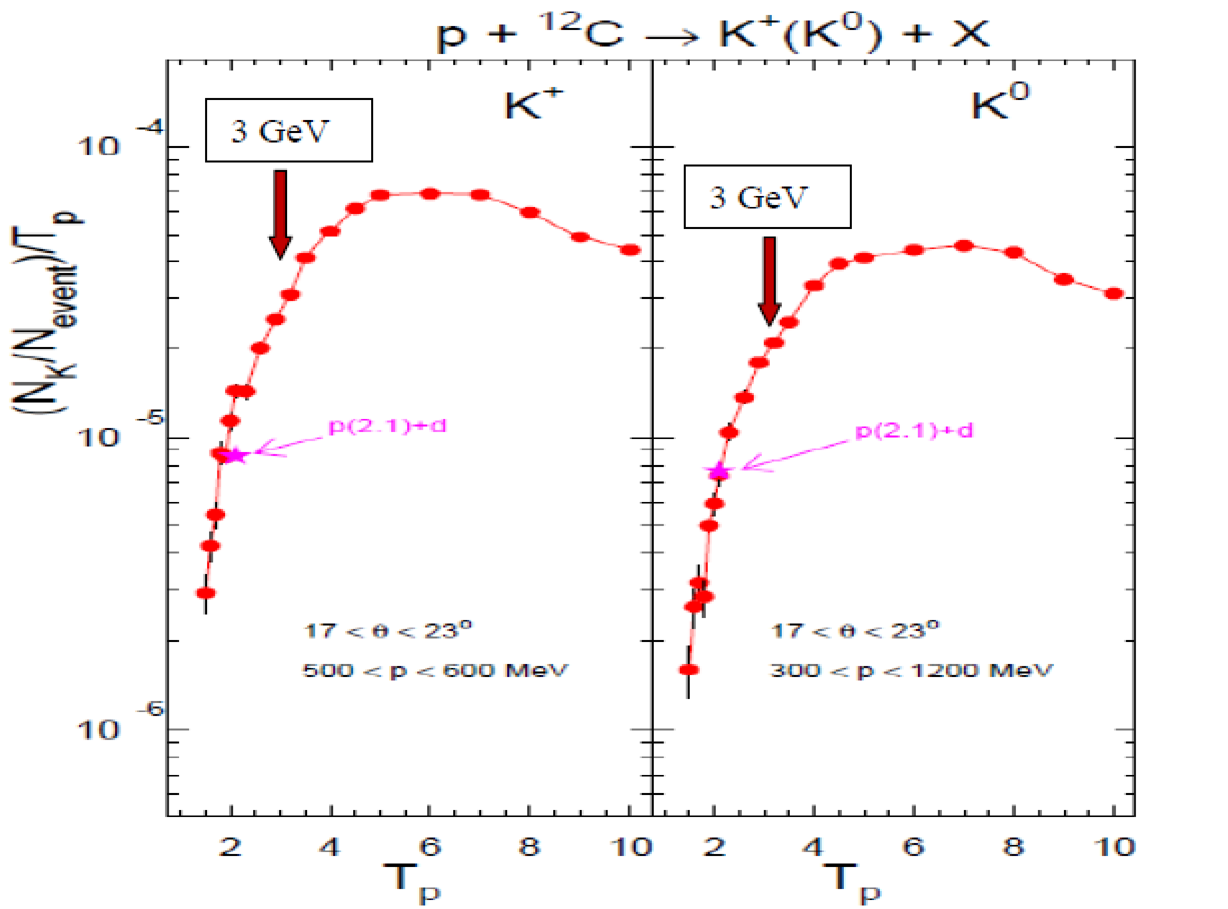
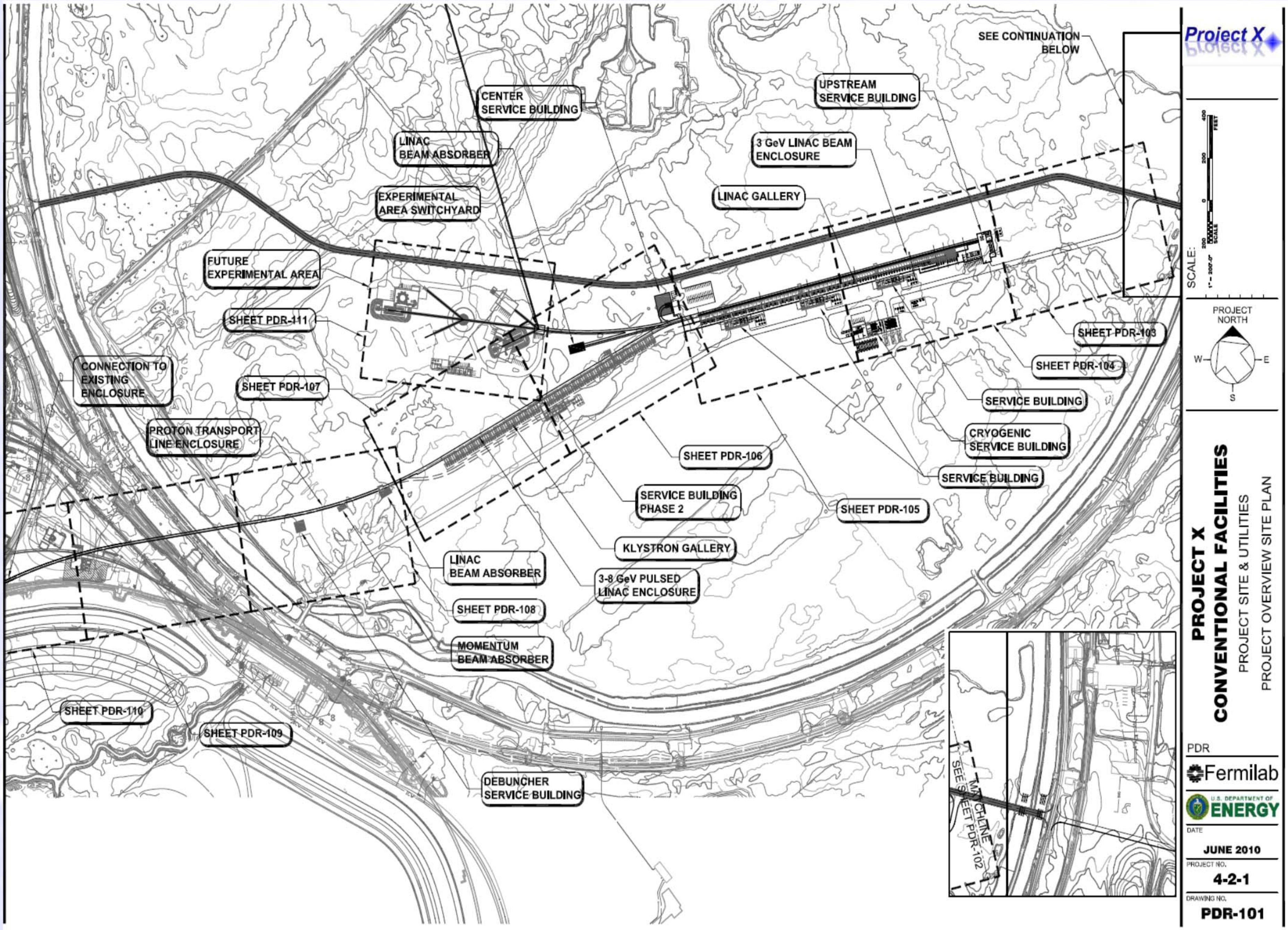


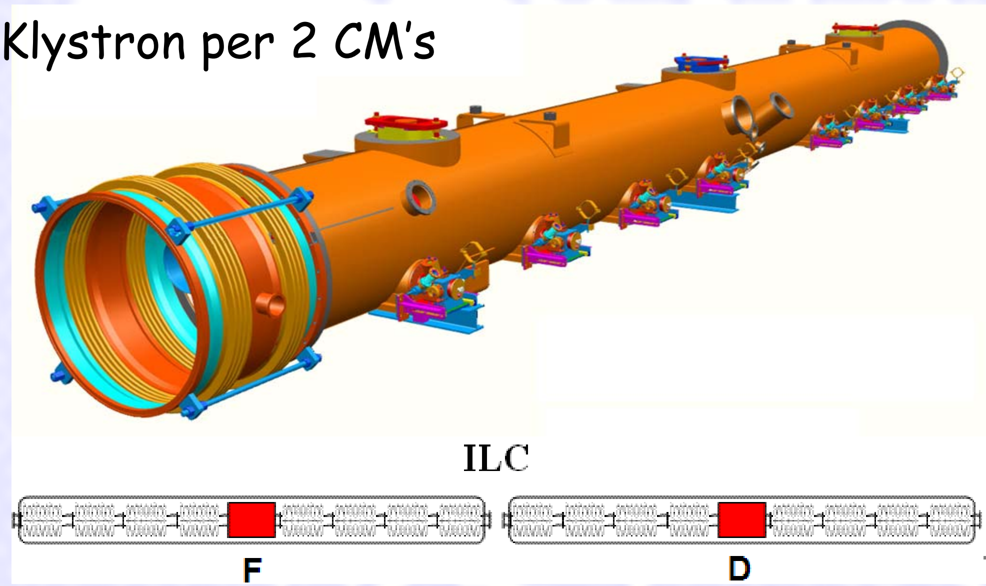
Figure 2: The estimated (LAQGSM/MARS15) kaon yield at constant beam power (yield/T_p) for experimentally optimal angular and energy regions as a function of T_p (GeV).



SEE CONTINUATION BELOW
UPSTREAM SERVICE BUILDING
CENTER SERVICE BUILDING
LINAC BEAM ABSORBER
3 GeV LINAC BEAM ENCLOSURE
LINAC GALLERY
EXPERIMENTAL AREA SWITCHYARD
FUTURE EXPERIMENTAL AREA
SHEET PDR-111
SHEET PDR-103
SHEET PDR-104
CONNECTION TO EXISTING ENCLOSURE
SHEET PDR-107
SERVICE BUILDING
PROTON TRANSPORT LINE ENCLOSURE
CRYOGENIC SERVICE BUILDING
SHEET PDR-106
SERVICE BUILDING
SERVICE BUILDING PHASE 2
SHEET PDR-105
KLYSTRON GALLERY
LINAC BEAM ABSORBER
3-8 GeV PULSED LINAC ENCLOSURE
SHEET PDR-108
MOMENTUM BEAM ABSORBER
SHEET PDR-110
SHEET PDR-109
DEBUNCHER SERVICE BUILDING
MATCHLINE SEE SHEET PDR-102
Project X
SCALE: 1" = 200'-0"
PROJECT NORTH
W
E
S
PROJECT X
CONVENTIONAL FACILITIES
PROJECT SITE & UTILITIES
PROJECT OVERVIEW SITE PLAN
PDR
Fermilab
U.S. DEPARTMENT OF ENERGY
DATE
JUNE 2010
PROJECT NO.
4-2-1
DRAWING NO.
PDR-101

3 – 8 GeV acceleration

- Pulsed linac based on the ILC technology
  - ✓1.3 GHz, 25 MV/m gradient, ≤5% duty cycle
  - ✓considering 8-30 ms pulse length
  - ✓~250 cavities (28 ILC-type cryomodules) needed.
  - ✓Simple FODO lattice
  - ✓1 Klystron per 2 CM's



Rings' Concepts & Concerns

- Simple numbers to start
  - T_{rev} ~ 800 ns
  - f_{rf} ~ 10 MHz
  - h = 8
  - Injection scheme
    - ~50 ns beam ON followed by ~50 ns NO beam

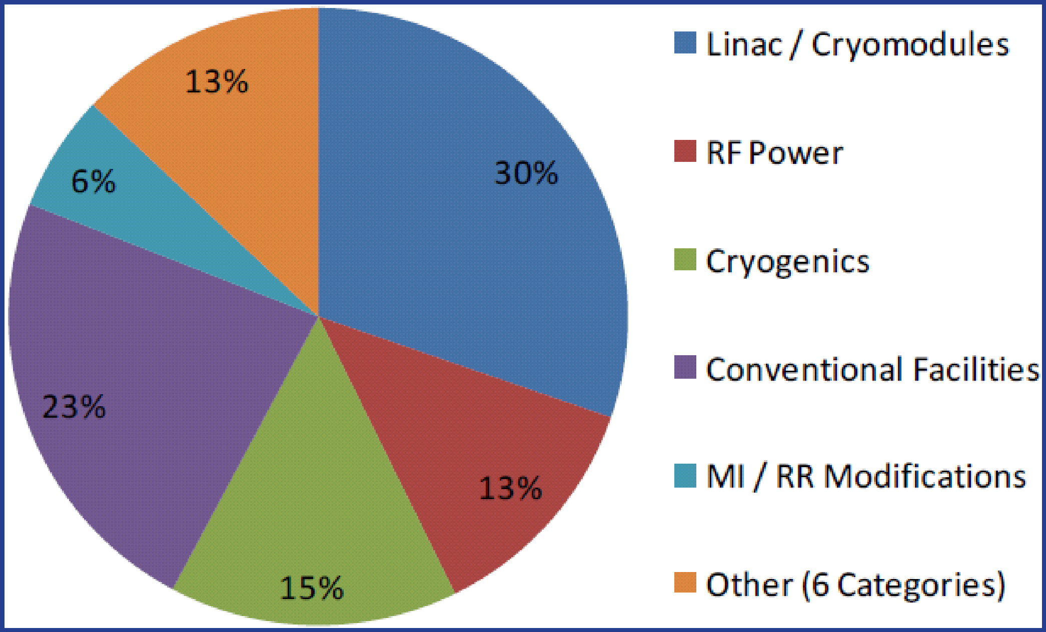
- Evolution of design
  - Increase of circumference (~300m)
  - Space for RF and Injection/Extraction components
  - Several designs and will settle on one
- Concerns
  - Injection: Stripping
  - Instabilities
  - Beam size in Compressor Ring after bunch rotation

Ring Concern: Injection/Stripping

- Stationary foil will not survive
- Solutions are being investigated by other groups; will have to keep informed of progress
  - Will need to build upon Project X R&D for stripping at 8 GeV in to Recycler/Main Injector
  - Rotating foils
  - Laser
- Should not forget about un-stripped beam (~1%) needs to be “absorbed”

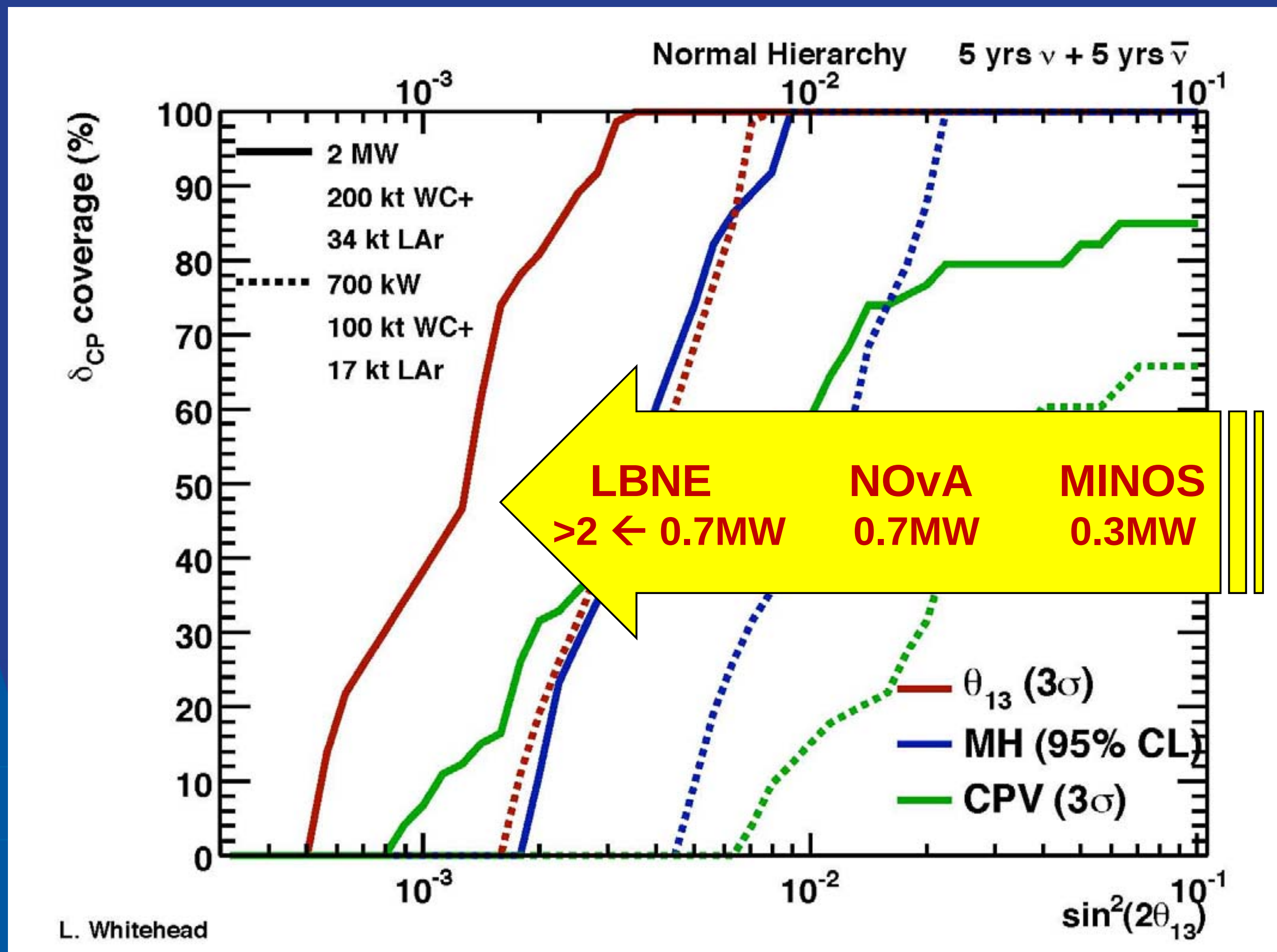
Project X Upgrade Proton Driver - 4

- Conventional facilities
  - More water cooling
  - Building space
    - More cryo capacity
    - More Klystrons



- An upgrade re-uses >75% of RDR cost

Evolution of Neutrino Sensitivities



Fermilab