

Project-X

Fermilab PAC, Nov 2010
R. Tschirhart

Fermilab

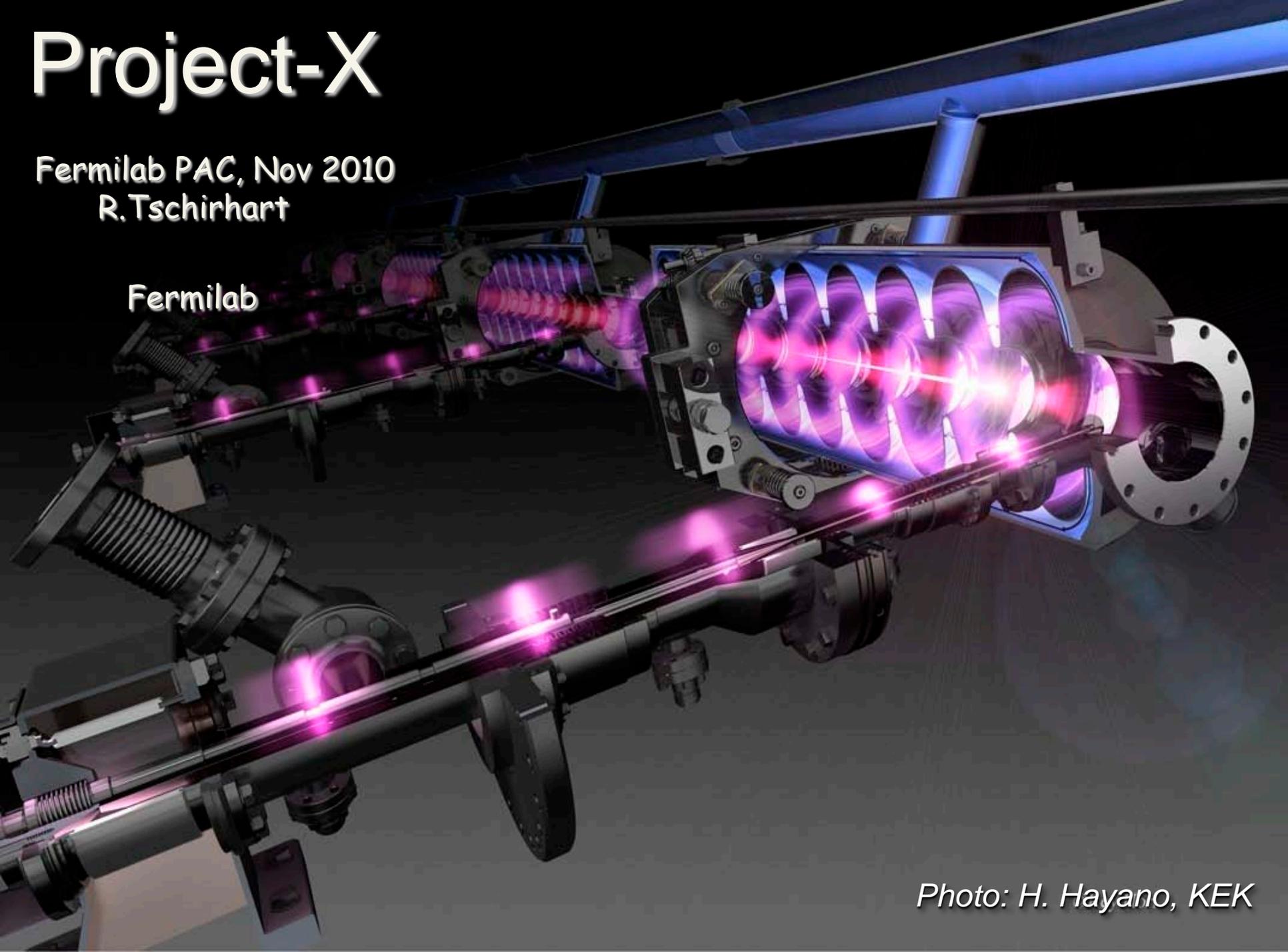


Photo: H. Hayano, KEK

The Project-X Research Program

- *Long baseline neutrino oscillation experiments:*

Driven by a high-power proton source with proton energies between 50 and 120 GeV that would produce intense neutrino beams directed toward massive detectors at a distant deep underground laboratory.

- *Kaon, muon, nuclei & neutron precision experiments driven by high intensity proton beams running simultaneously with the neutrino program:*

These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (edms), and world-leading precision measurements of ultra-rare kaon decays.

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

Detailed Discussion: [Project X website](#)

Progress since Aspen 2009

- **October 2009:** Workshop on the Application of High Intensity Proton Accelerators (AHIPA) October 2009: Excellent cross-cut, exploration of common ground.

- **November 2009:** 4th Project-X workshop: Produced accelerator and comprehensive research white papers.

- **January - August 2010:**
 - Development of thrust specific white papers.
 - Accelerator configuration refined and defined in a Functional Requirements document.
 - Emergence of Nuclear Energy R&D as part of the Project-X portfolio.

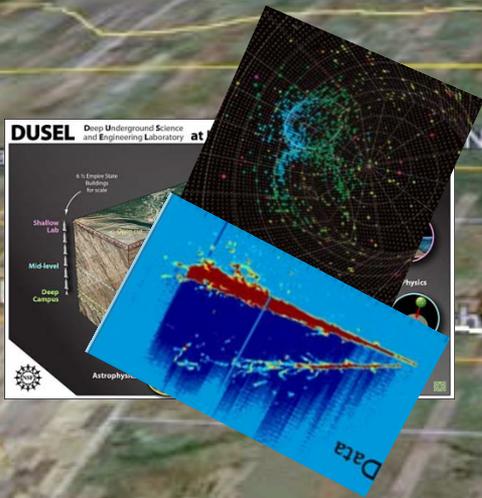
- **November 2010:** 5th Project-X Physics Workshop, focused forums on refining white papers of research thrusts.

- **November 2010:** OHEP expresses interest in advancing case and basis for Critical Decision Zero (CDO): Research program briefing November 17th 2010 at Germantown.

Expansion of the Fermilab Accelerator Complex



Long Baseline Neutrino Experiment



New Neutrino Beam at Fermilab...

...Directed towards NSF's proposed DUSEL

Precision Near Detector on the Fermilab site

100 kT fiducial volume Water Cherenkov Far Detector

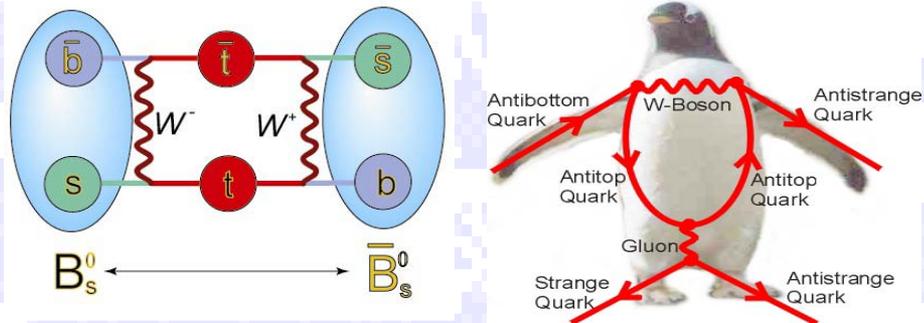
17 kT fiducial volume Liquid Argon TPC Far Detector

Image NASA
© 2008 Tele Atlas
Image © 2008 TerraMetrics
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Google

Kaon, Muon and EDM Experiments Deeply Attack the Flavor Problem

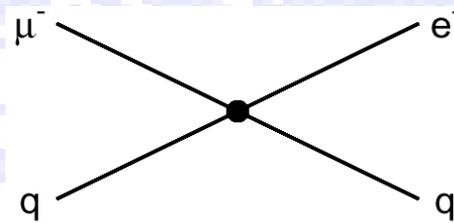
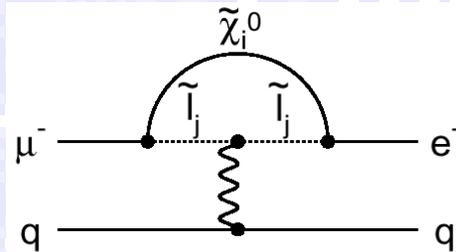
Why don't we see the
Terascale Physics we expect
affecting the flavor physics
we study today??



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

Supersymmetry

Predictions at 10^{-15}

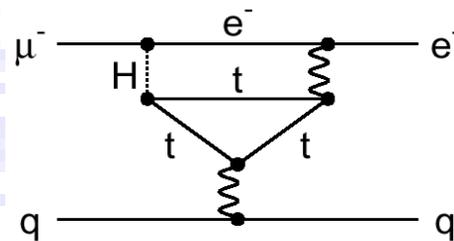
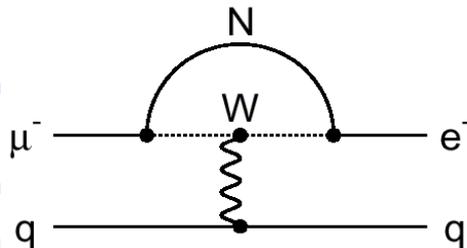


Compositeness

$$\Lambda_C = 3000 \text{ TeV}$$

Heavy Neutrinos

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

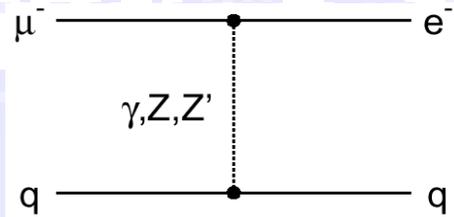
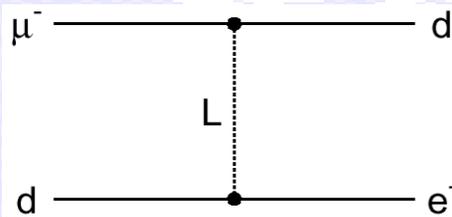


Second Higgs doublet

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

Leptoquarks

$$M_L = 3000 \sqrt{\lambda_{\mu d} \lambda_{e d}} \text{ TeV}/c^2$$



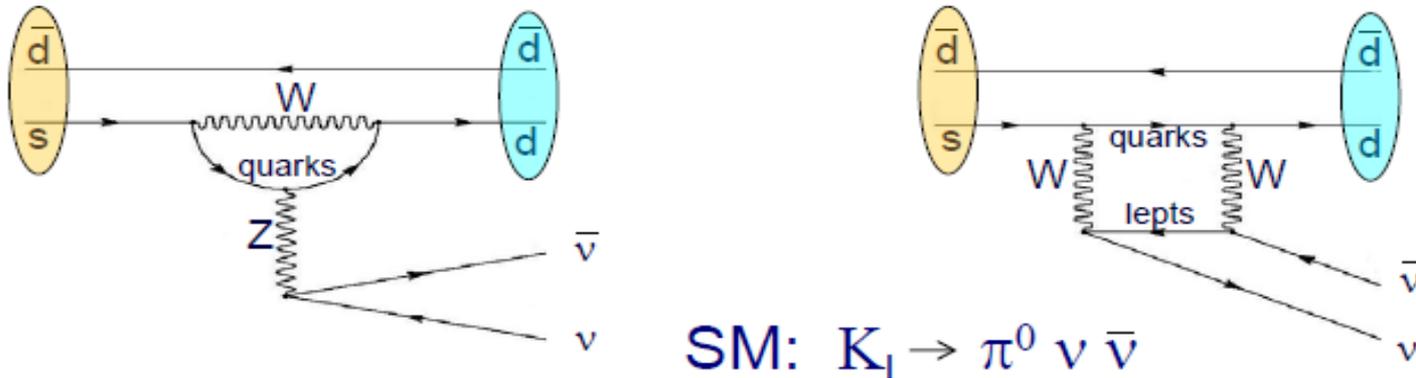
Heavy Z' ,
Anomalous Z
coupling

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

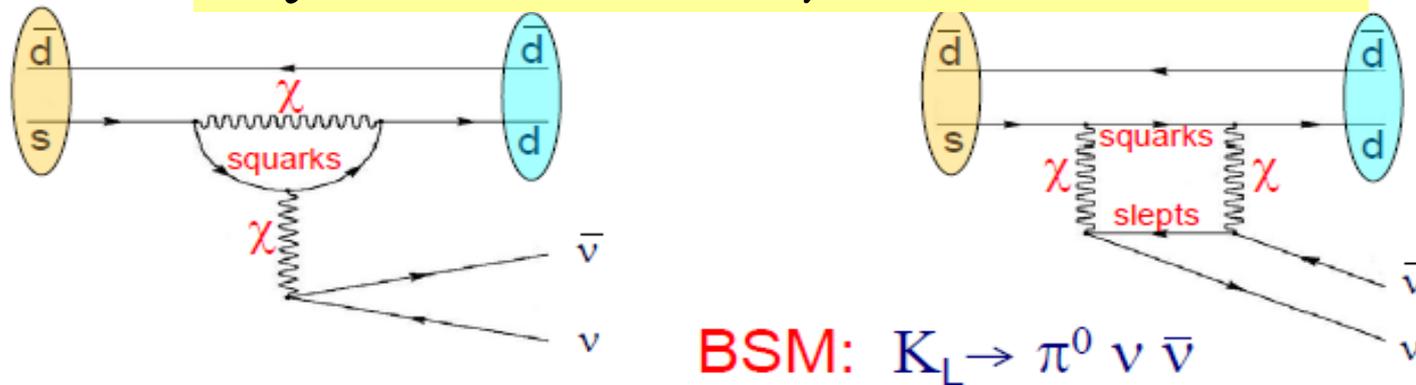
$$B(Z\mu e) < 10^{-17}$$

After W. Marciano

The Window of Ultra-rare Kaon Decays at Project X



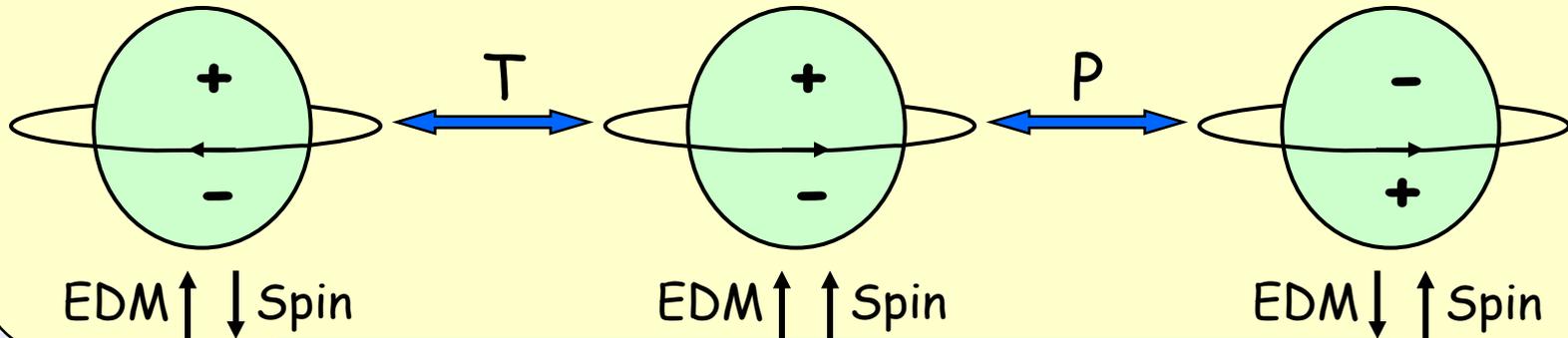
*Standard Model rate of 3 parts per 100 billion!
Project will have sensitivity for 1000 SM events*



BSM particles within loops can increase the rate by x10 with respect to SM.

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

Diamagnetic Atoms
(Hg, Xe, Ra, Rn)

Quark Chromo-EDM

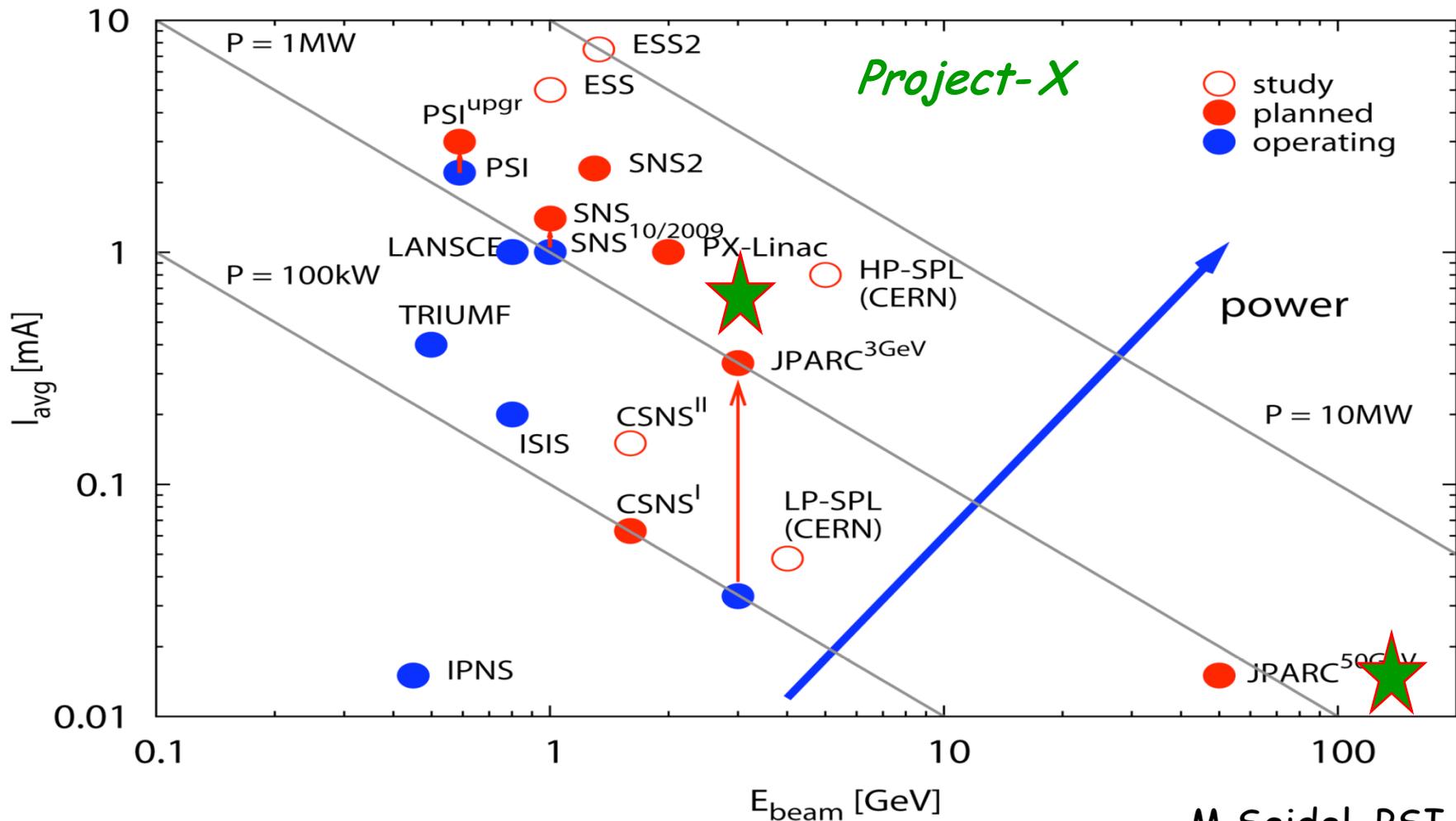
Physics beyond
the Standard
Model:
SUSY, Strings ...

Paramagnetic Atoms (Tl, Fr)
Molecules (PbO)

Electron EDM

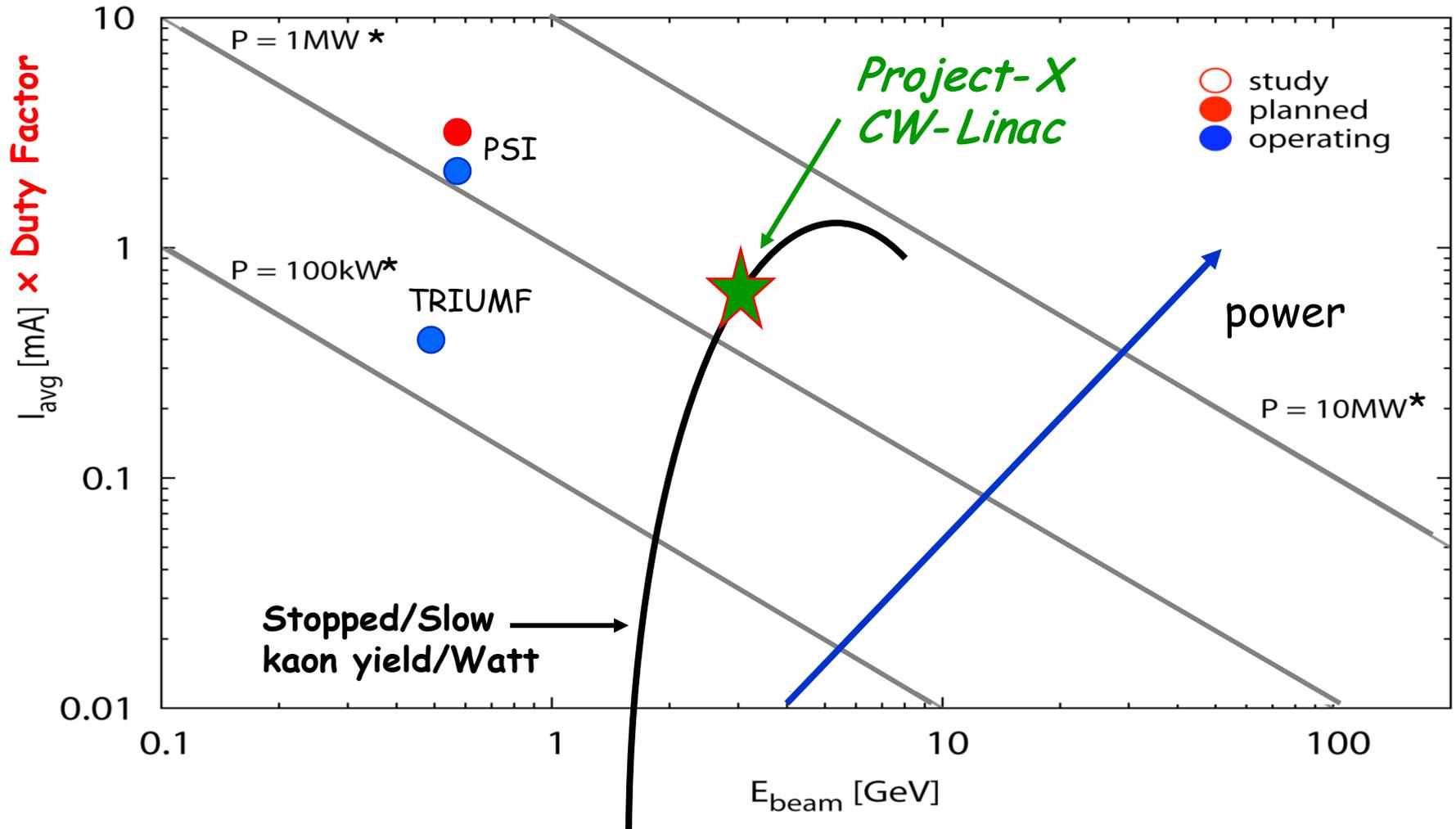
Guy Savard, ANL

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



M Seidel, PSI

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



* Beam power \times **Duty Factor**

"Continuous Wave" (CW) Linac for Rare Processes...

- Beam extraction challenge is finessed.
- Duty factor is very high.
- The high frequency bandwidth intrinsic to a Linac can be exploited to generate excellent time resolution ($\delta t \sim 20 \text{ psec}$), a very powerful tool to face a high intensity environment.
- JLAB has demonstrated that beam can be cleanly multiplexed between many targets with minimal losses. These "touchless" RF beam multiplexers are enabled by the high linac bandwidth.
- Excellent beam power scaling.

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

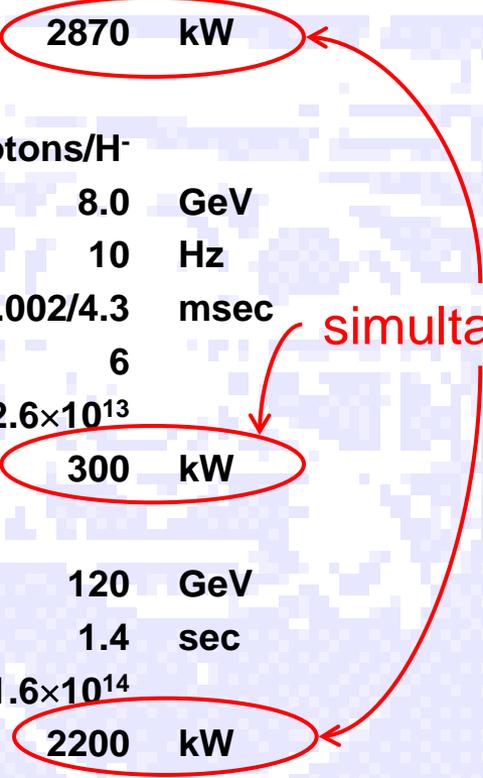
RCS/Pulsed Linac

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	300 kW

Main Injector/Recycler

Beam Kinetic Energy (maximum)	120 GeV
Cycle time	1.4 sec
Particles per cycle	1.6×10^{14}
Beam Power at 120 GeV	2200 kW

simultaneous



3 GeV Super-conducting CW Linac: High Power and High Duty Factor

1 μ sec period at 3 GeV

mu2e pulse (9e7) 162.5 MHz, 100 nsec

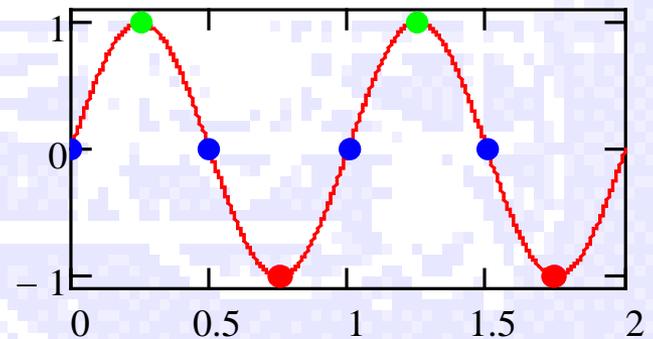
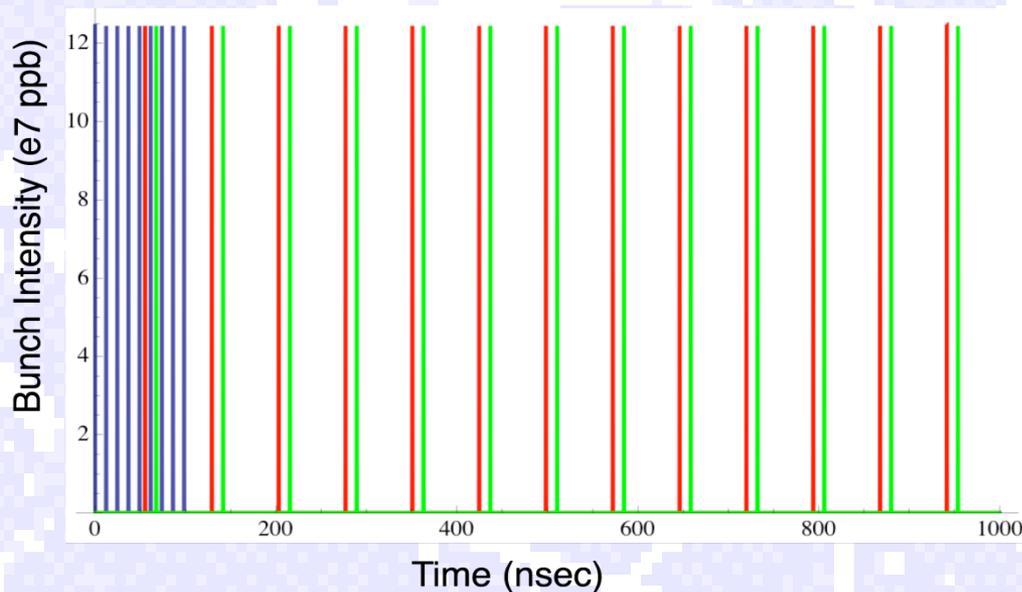
600 kW

Kaon pulse (9e7) 27 MHz

1200 kW

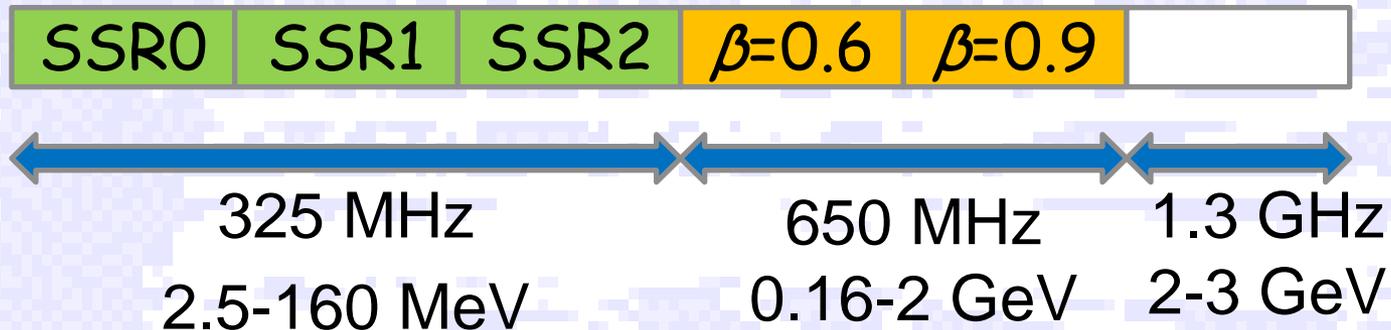
Nuclear pulse (9e7) 27 MHz

1200 kW



Separation scheme with
traverse kicker ala JLAB.

SC CW Linac Technology Map

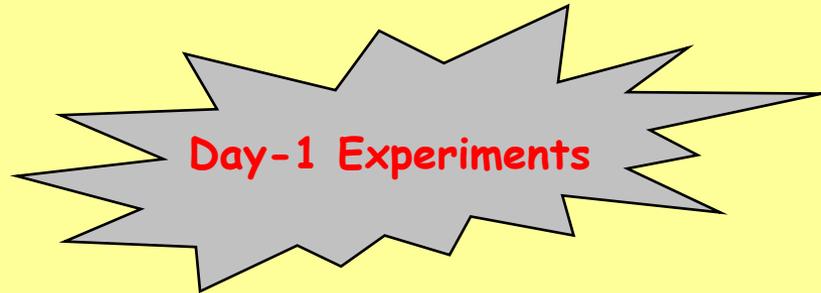


Section	Freq	Energy (MeV)	Cav/mag/CM	Type
SSR0 ($\beta_G=0.11$)	325	2.5-10	26 /26/1	SSR, solenoid
SSR1 ($\beta_G=0.22$)	325	10-32	18 /18/ 2	SSR, solenoid
SSR2 ($\beta_G=0.4$)	325	32-160	44 /24/ 4	SSR, solenoid
LB 650 ($\beta_G=0.61$)	650	160-520	42 /21/ 7	5-cell elliptical, doublet
HB 650 ($\beta_G=0.9$)	650	520-2000	96 /12/12	5-cell elliptical, doublet
ILC 1.3 ($\beta_G=1.0$)	1300	2000-3000	64 / 8/ 8	9-cell elliptical, quad

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

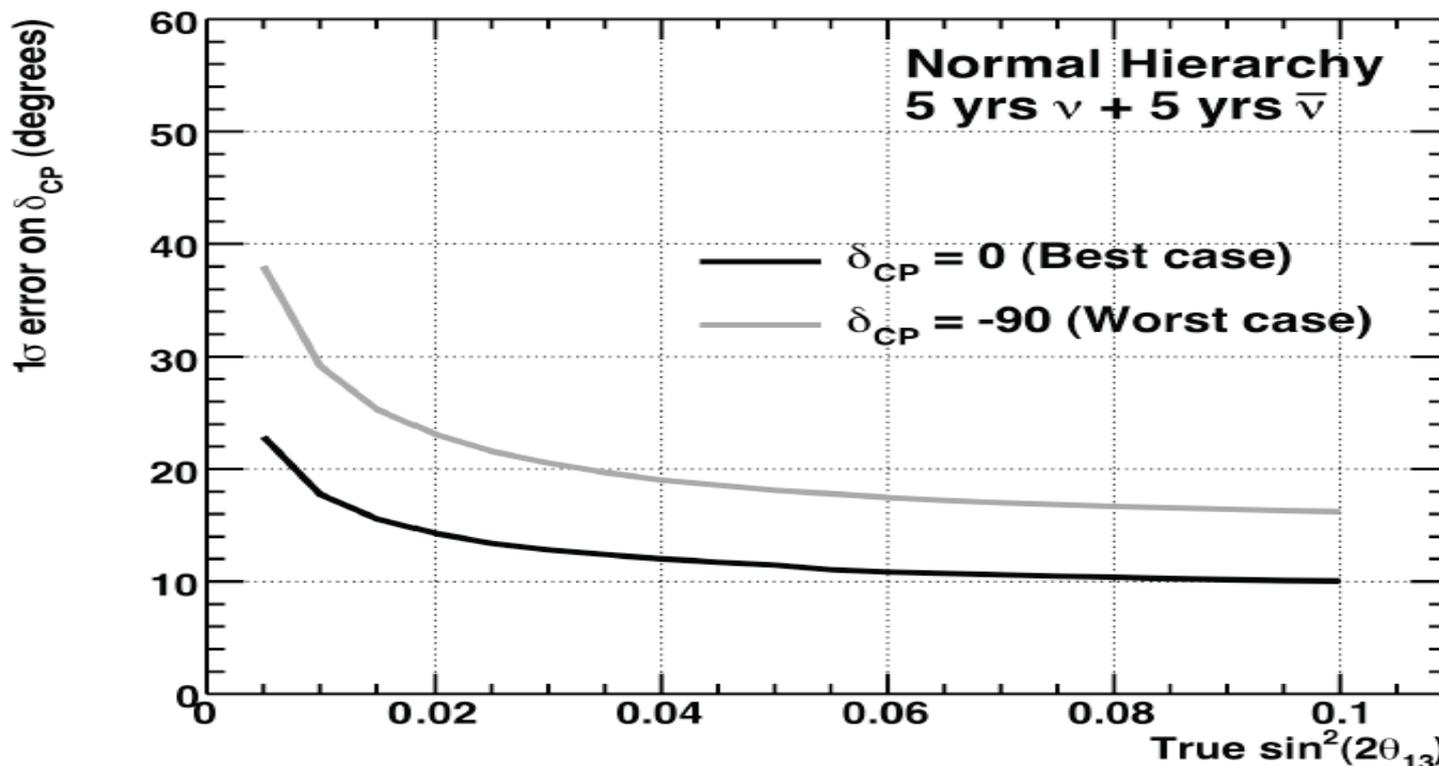
Neutrino Physics:

- **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 $\nu_e, \nu_e^{-} \rightarrow X$ experiments....x3 beam power @ 120 GeV, x10-x20 power @ 8 GeV.
- Next generation precision cross section measurements.



Pursuing next-generation neutrino parameters is beam-power hungry: Project-X *Triples* the Sensitivity

100 kton WC + 17 kton LAr



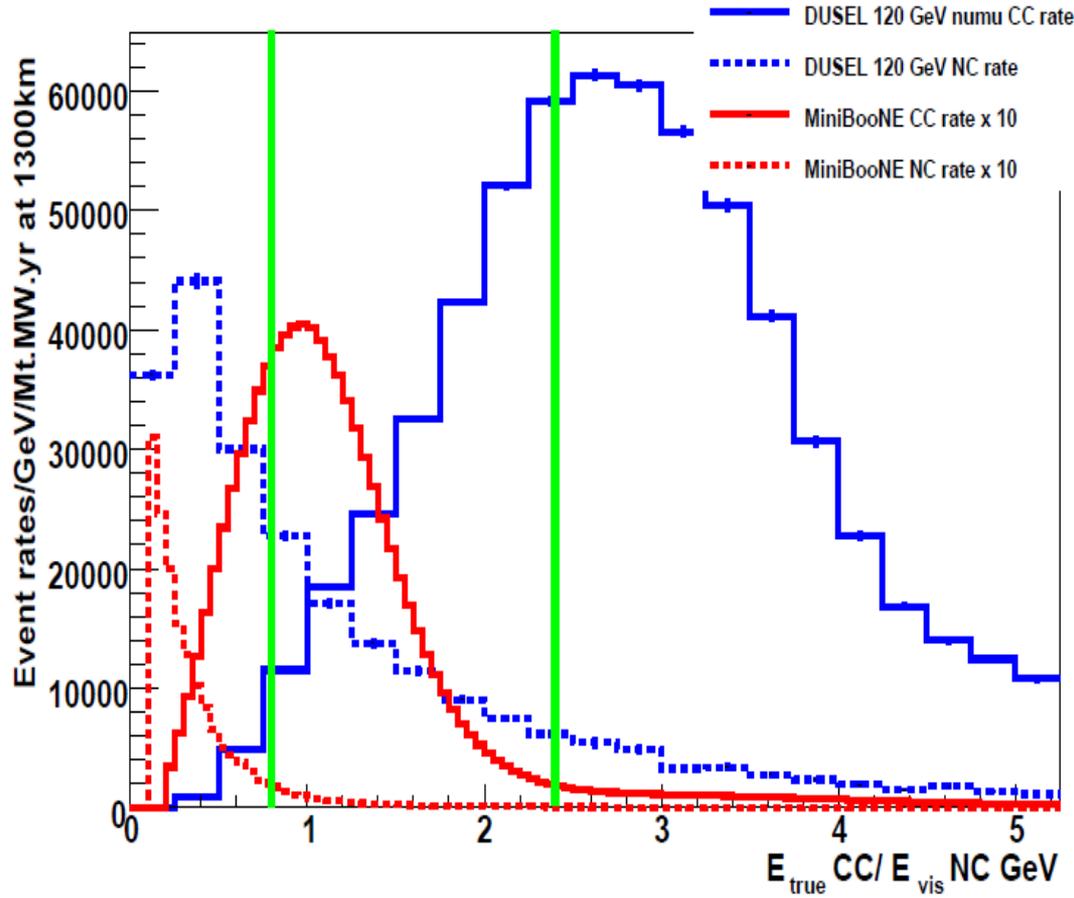
From the
neutrino
white
paper

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]

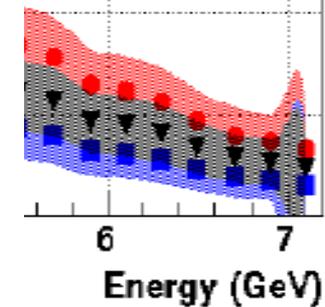
Can we use "excess" 8 GeV pulsed power to drive LBNE as well??

October 20, 2009

DUSEL 120 GeV numu CC rate



normal hierarchy
normal hierarchy
inverse hierarchy



A wide-band beam at 1300km

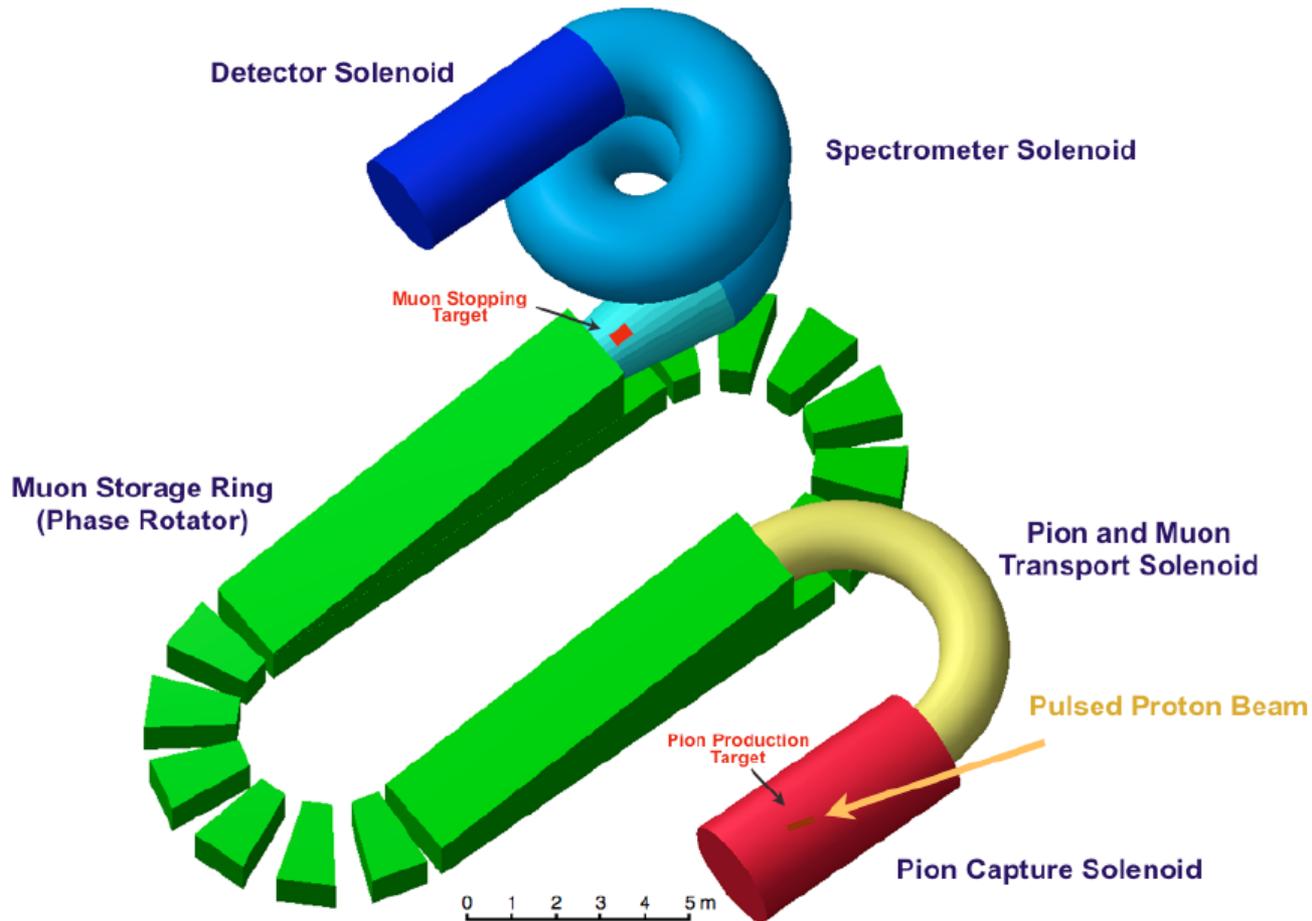
An Incomplete Menu of World Class Research Targets Enabled by Project-X. continued...

Muon Physics:

Day-1 Experiment

- Next generation muon-to-electron conversion experiment, new techniques for higher sensitivity and/or other nuclei.
- Next generation $(g-2)_\mu$ 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.

Pursuing the Holy Grail of Stopped Muon Experiments: A High Acceptance Mono-energetic muon source



From
the
muon
white
paper

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

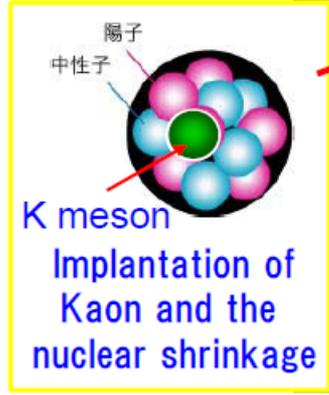
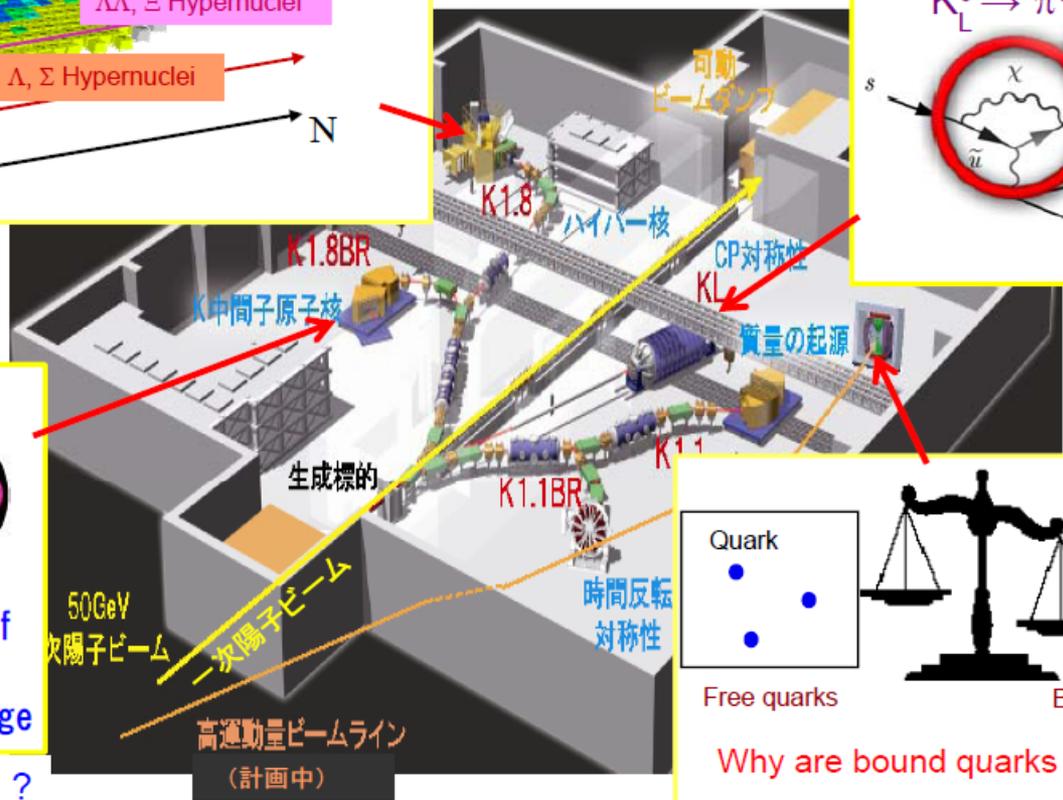
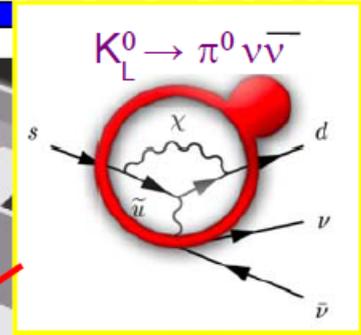
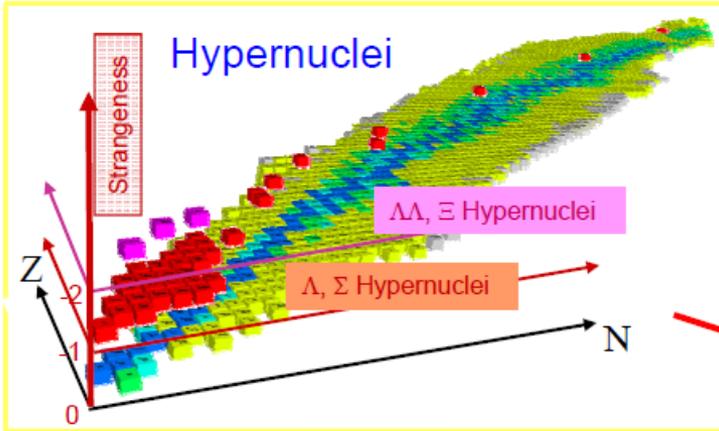
Kaon Physics:

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.
- $K^+ \rightarrow (\pi, \mu)^+ \nu_\chi$: Search for anomalous heavy neutrinos.
- $K_L \rightarrow \pi^0 e^+ e^-$: <10% measurement of CP violating amplitude.
- $K_L \rightarrow \pi^0 \mu^+ \mu^-$: <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

JPARC Play Book

Hadron Hall Experimental Programs

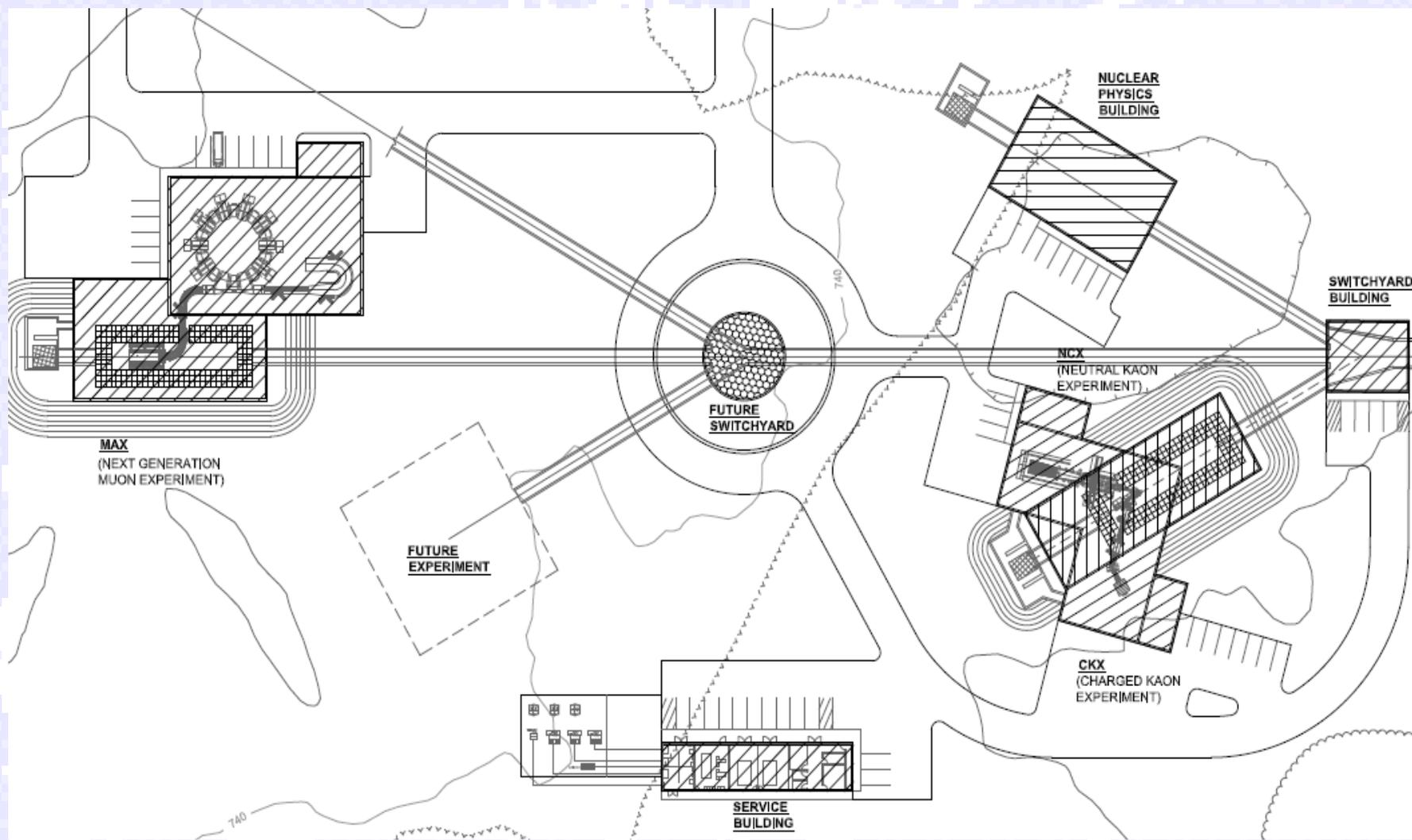


Implantation of Kaon and the nuclear shrinkage

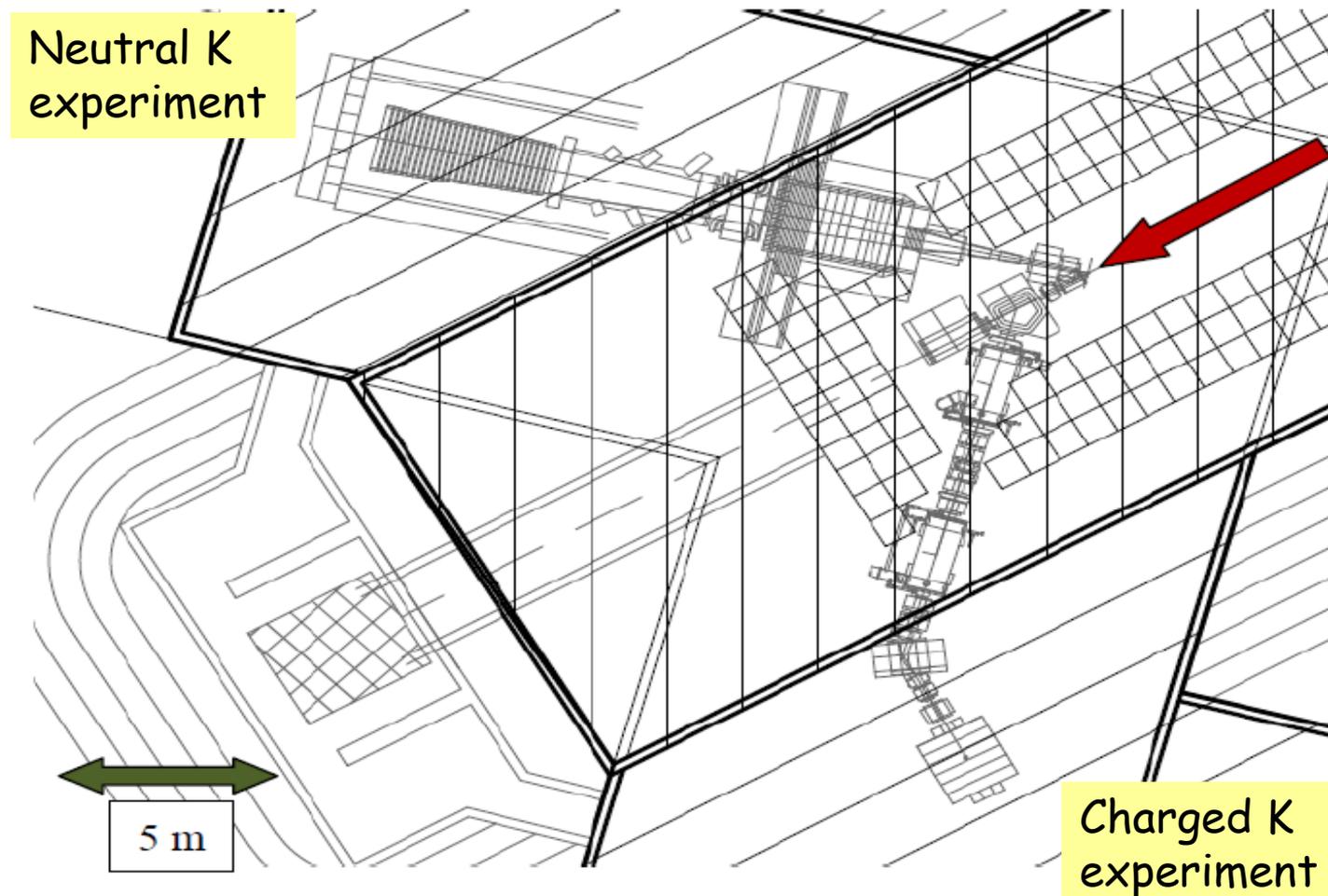
J/ψ implantation ?

Courtesy Nagamiya-san

Taking a page from the JPARC hadron hall playbook: One target can serve multiple kaon experiments.

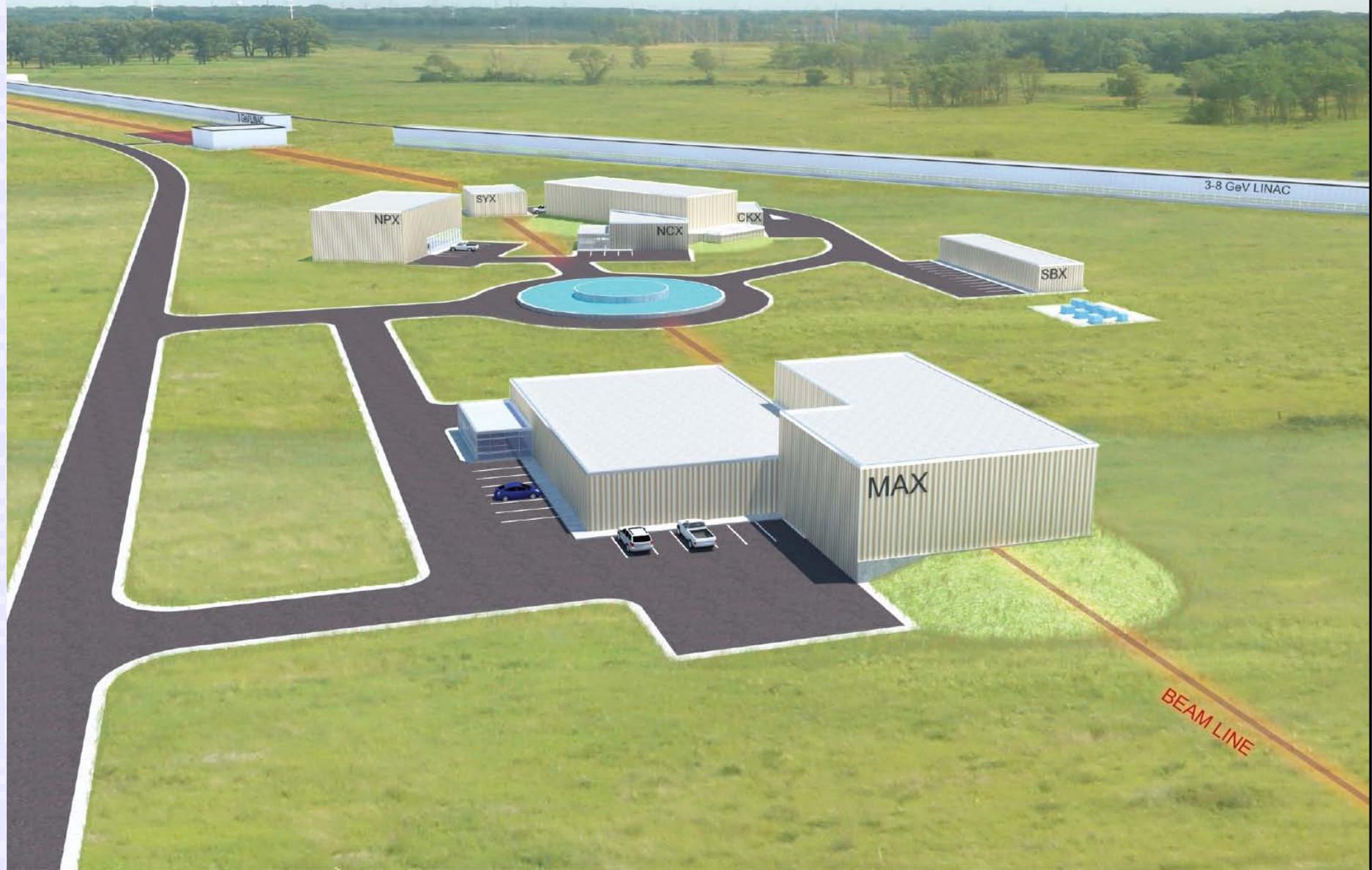


Taking a page from the JPARC hadron hall playbook: One target can serve multiple kaon experiments.



From the kaon white paper

Project-X Rare Processes Research Campus



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

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.

Baryon Physics:

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

Road to Future Progress: Neutrino Research Program

- Strong international community. US community is healthy and growing.
- Value of higher beam power from the Main Injector is clear in principle. However, there is a need to develop and promote the research program strategy that addresses θ_{13} , opportunities of near-term measurements, etc. **Progress on Project-X need not be contingent on the magnitude of θ_{13} .**
- Explicitly engage the Neutrino Factory community to explore and develop the low-energy conceptual design from Project-X to DUSEL.
- Investigate opportunities that may exist with an 8 GeV neutrino program, including long-baseline beam to DUSEL.

Road to Future Progress: Muon Research Program

- International community active, US community is small, but growing with Mu2e and $(g-2)_\mu$.
- $(g-2)_\mu$. Let's do it!
- No conceptual accelerator & beam design yet for driving next-generation $\mu \rightarrow e$ conversion experiment. A PRISM (FFAG) based solution needs further accelerator design work. Interesting synergies with Muon Collider cooling concepts are being explored that would clearly exploit Project-X. *This work should be encouraged to answer the question:*

PSI has a 1-2 MW source for muon physics now...why & how is Project-X better??

- Good opportunity for Intensity Frontier fellows.

Road to Future Progress: Kaon Research Program

- International community active, Fermilab community essentially dormant now. Buoyed to some extent now by the US quark flavor physics community—but this community is currently under stress regarding futures.
- Excellent basis for 1000 event $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ experiment now.
- P996 Fermilab proposal stalled, raises questions in community.
- A plan for bridging to the Project-X era is needed.
 - Push for kaon experiment CDO @ Project-X ASAP.
 - Meaningful collaboration with JPARC and CERN initiatives in the near term?

Road to Future Progress: Nuclear-Particle Physics

- Strong international community. US community is healthy and growing.
- No historical context for Fermilab. Some sensitivities with other labs and agencies.
- Working closely with Argonne National Lab is a great opportunity to bridge into this community.
- Should explore Intensity Frontier Fellows, Joint positions and Fellowships between ANL and FNAL, possibly University of Chicago.

Summary

Project-X is a next generation high intensity proton source that can deliver:

Neutrinos: An after-burner for LBNE that reduces the tyranny of (Detector-Mass \times Running-time) by $\times 3$, and a foundation for a Neutrino Factory.

Rare Processes: Game-changing beam power and timing flexibility that can support a broad range of particle physics experiments.

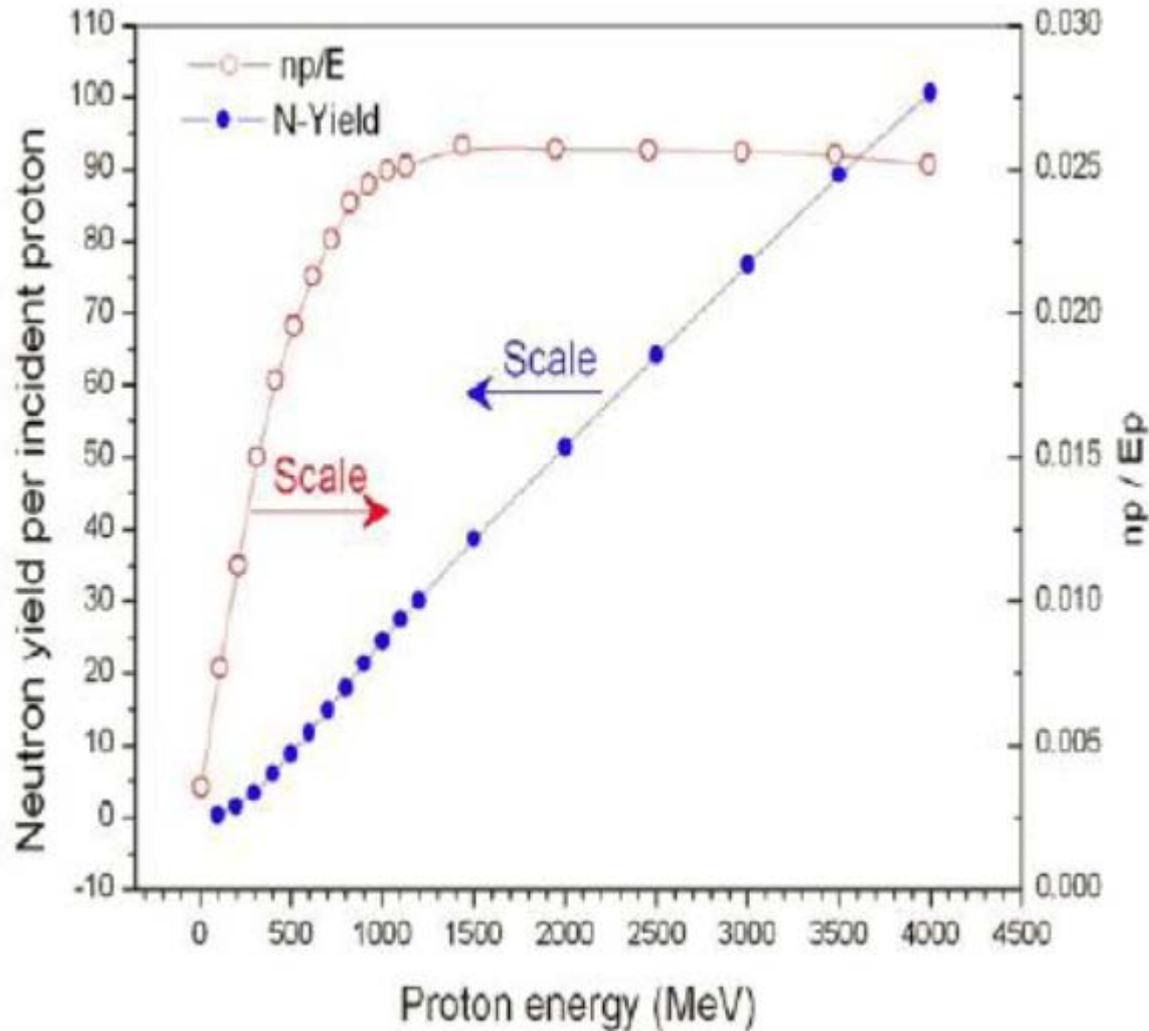
Lepton Collider: A platform for Muon Collider development.

Prospects: International collaboration formed, ongoing substantial US (DOE) investments in R&D (Project-X + SRF + ILC) on Super Conducting RF accelerator technology supporting Project-X.

Earliest construction start of 2015, operations in 2020.

Spare Slides

Optimum Energy for ADS R&D



Beam Requirements for a World Leading Rare Processes Program

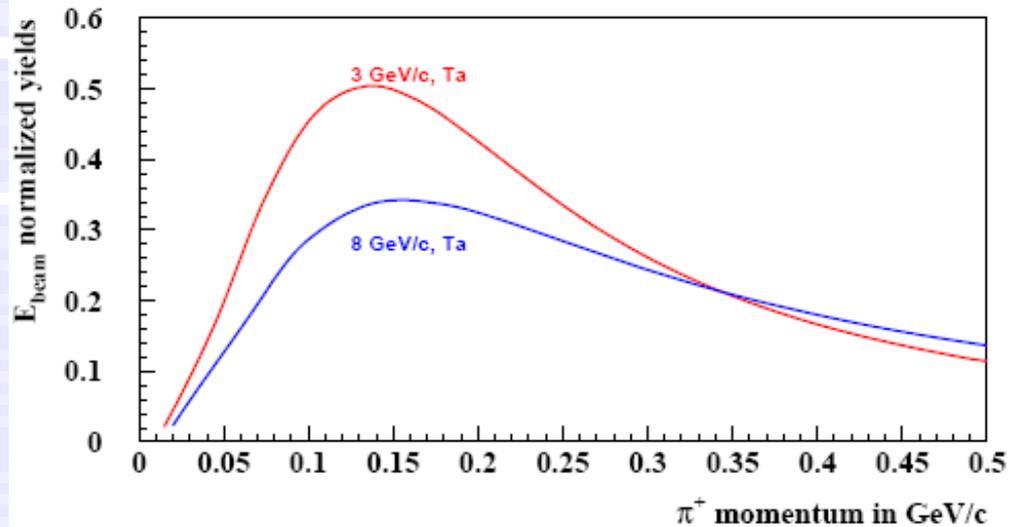
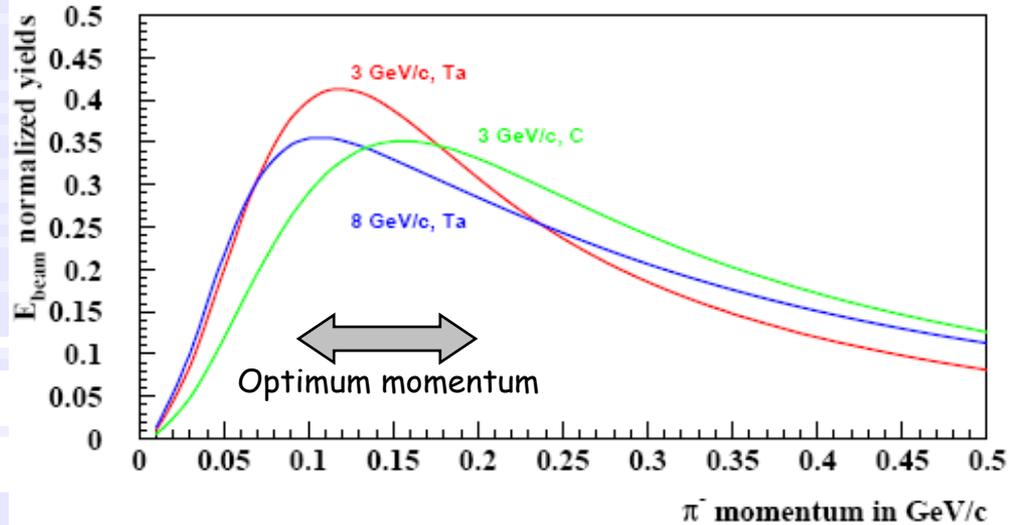
	Proton Energy (kinetic)	Beam Power	Beam Timing
Rare Muon decays	2-3 GeV	>500 kW	1 kHz - 160 MHz
(g-2) measurement	8 GeV	20-50 kW	30- 100 Hz.
Rare Kaon decays	2.6 - 4 GeV	>500 kW	20 - 160 MHz. (<50 psec pings)
Precision K^0 studies	2.6 - 3 GeV	> 200kW (100 μ A internal target)	20 - 160 MHz. (<50 psec pings)
Neutron and exotic nuclei EDMs	1.5-2.5 GeV	>500 kW	> 100 Hz

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.

What is the optimum energy for producing low-energy muons?



LAQGSM/MARS
simulation
validated with
HARP data

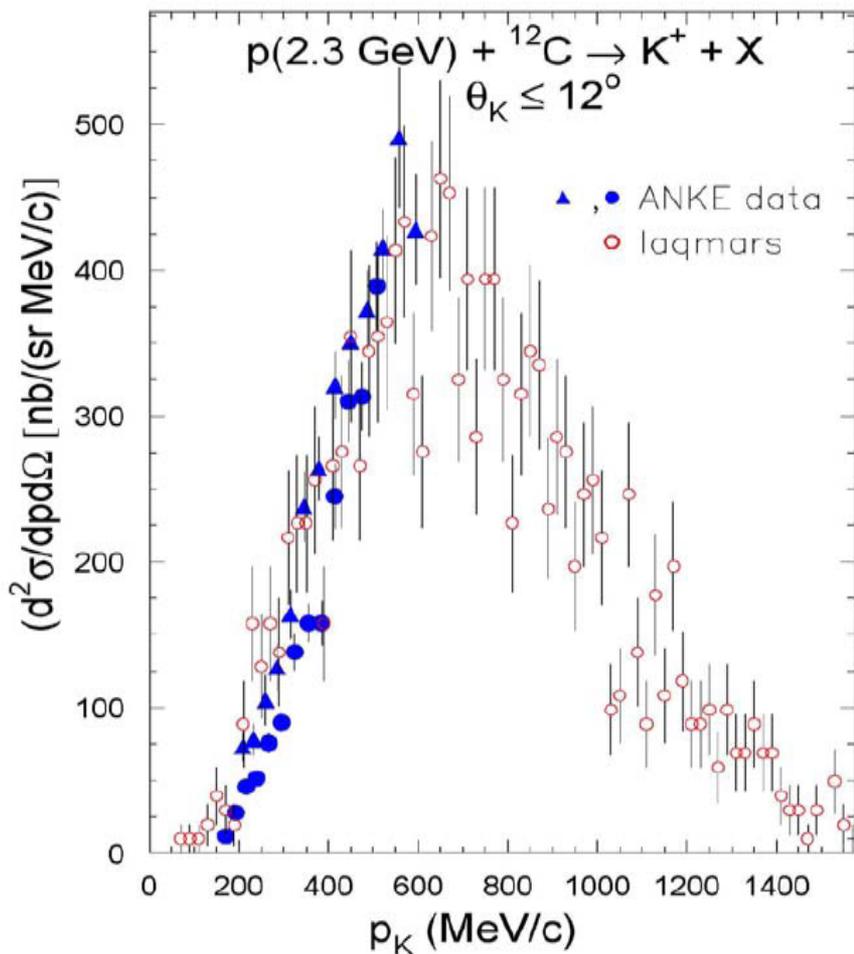
Sensitivity of Kaon Physics Today

- CERN NA62: 100×10^{-12} measurement sensitivity of $K^+ \rightarrow e^+ \nu$
- Fermilab KTeV: 20×10^{-12} measurement sensitivity of $K_L \rightarrow \mu \mu e e$
- Fermilab KTeV: 20×10^{-12} search sensitivity for $K_L \rightarrow \pi \mu e, \pi \pi \mu e$
- BNL E949: 20×10^{-12} measurement sensitivity of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- BNL E871: 1×10^{-12} measurement sensitivity of $K_L \rightarrow e^+ e^-$
- BNL E871: 1×10^{-12} search sensitivity for $K_L \rightarrow \mu e$

Probing new physics above a 10 TeV scale with 20-50 kW of protons.

Next goal: 1000-event $\pi \nu \nu$ experiments... 10^{-14} sensitivity.

Validating Simulation Tools...



- Los Alamos + MARS simulation suite (LAQGSM + MARS15) is now a state of the art tool set to simulate the challenging region between 1-4 GeV/c proton beam momentum.

[Gudima, Mokhov, Striganov]

- Validated against the high quality data sets from COSY.

- Data shown: Buscher et al (2004) ANKE experiment at COSY, absolutely normalized.

Kaon Yields at Constant Beam Power

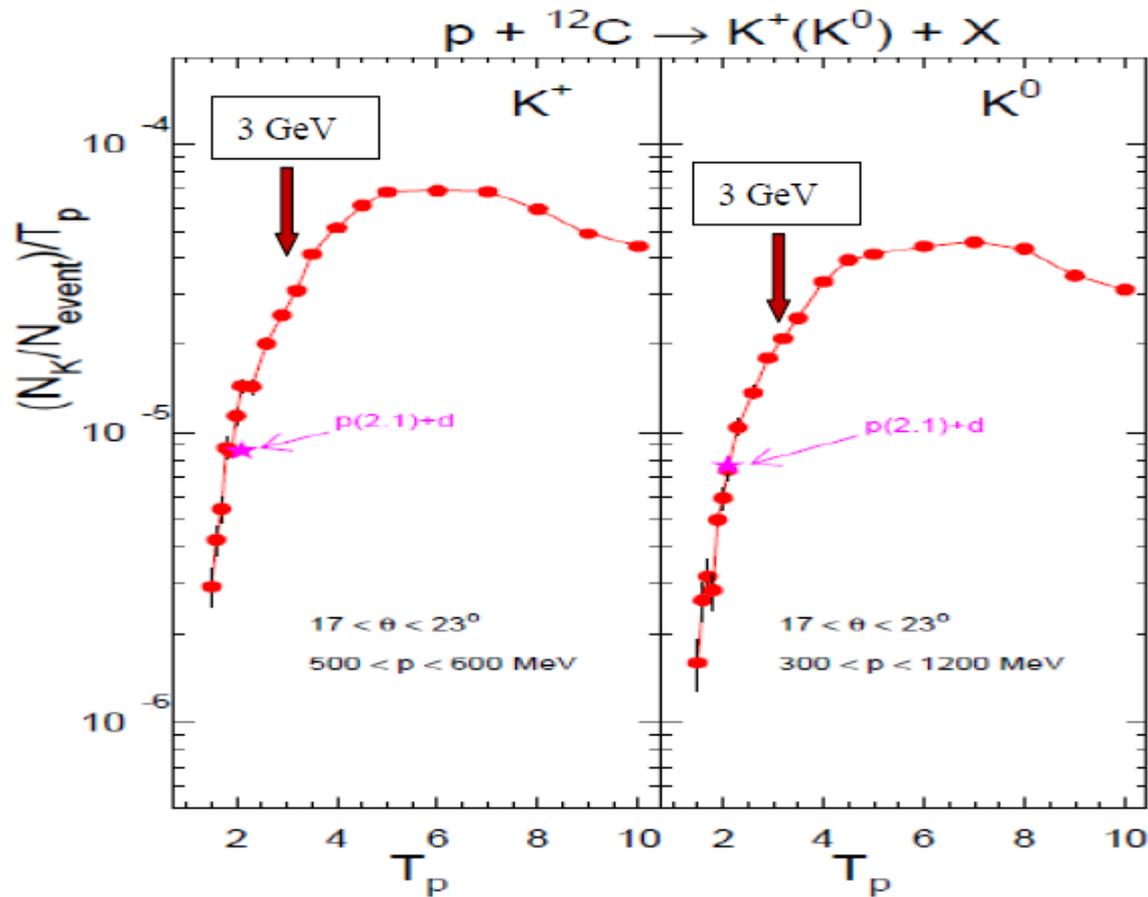
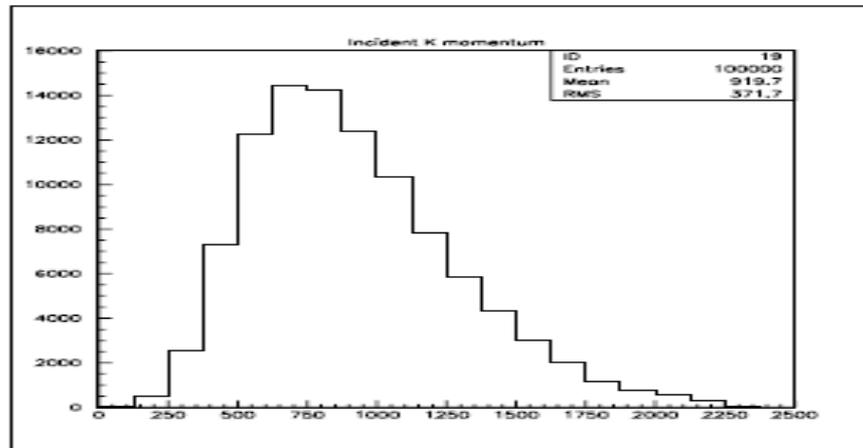
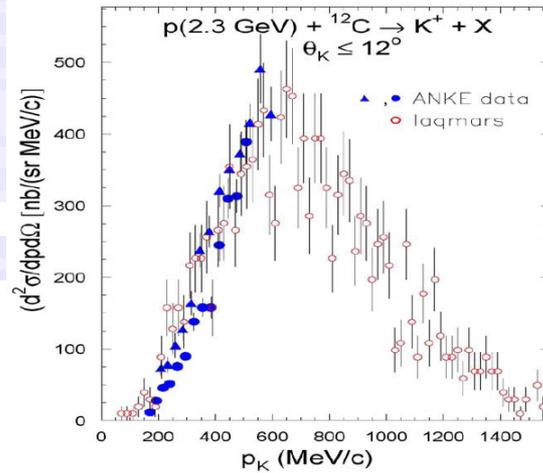


Figure 2: The estimated (LAQGSM/MARS15) kaon yield at constant beam power (yield/ T_p) for experimentally optimal angular and energy regions as a function of T_p (GeV).

KOPIO-AGS and Project-X kaon momentum spectra comparison

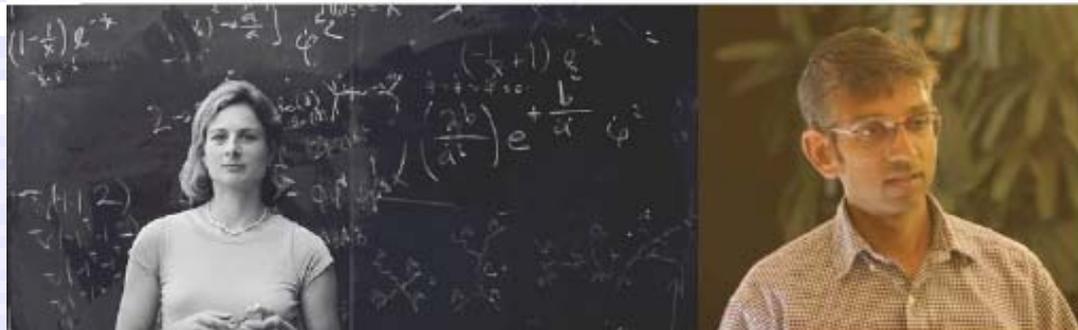


KOPIO
Proposal

Figure 13: K_L^0 spectrum incident on KOPIO decay volume.

Rates sensitive to other BSMs: Warped Extra Dimensions as a Theory of Flavor??

The Randall-Sundrum (RS) idea



Island Universes in Warped Space-Time

According to string theory, our universe might consist of a three-dimensional "brane," embedded in higher dimensions. In the model developed by Lisa Randall and Raman Sundrum, gravity is much weaker on our brane than on another brane, separated from us by a fifth dimension. (Time is the unseen fourth dimension.)

GRAVITY BRANE
(where gravity is concentrated)

Fifth dimension
Space is warped by energy throughout five-dimensional space-time. As a result, gravity is much weaker on our brane.

Gravitons,
which transmit gravity, are closed strings, which are not confined to either brane.

Warped space-time
Because space-time is warped, things are exponentially bigger and lighter closer to our brane.

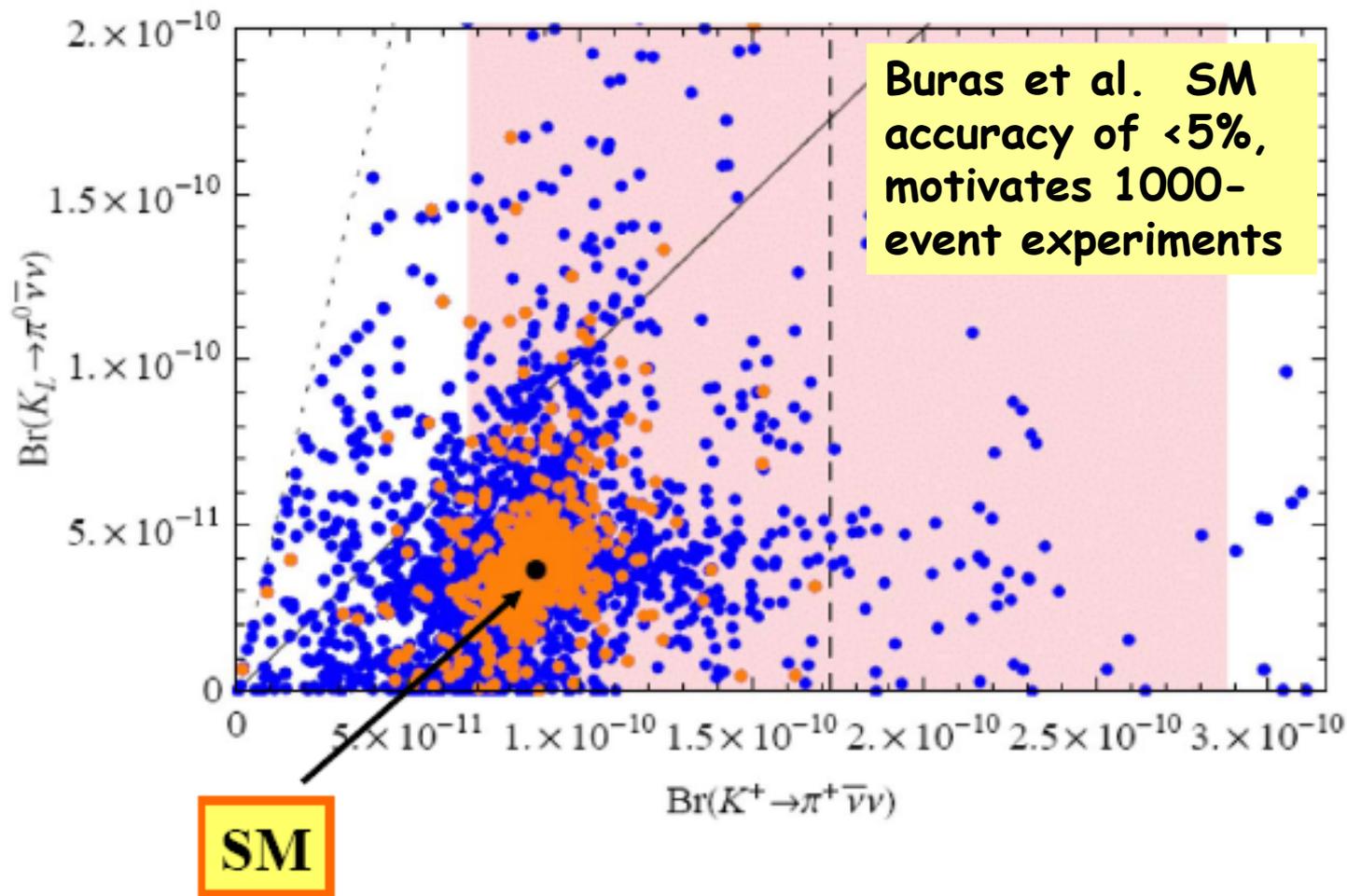
BRANE
(our universe)

The ends of **open strings**, whose oscillations are particles and forces other than gravity, are stuck to our brane.

(Wikipedia)

$$\mathbf{K_L \rightarrow \pi^0 \nu\bar{\nu} \text{ vs. } K^+ \rightarrow \pi^+ \nu\bar{\nu}} \quad (\text{RS})$$

(Up to Factor 3 and 2 Enhancements)



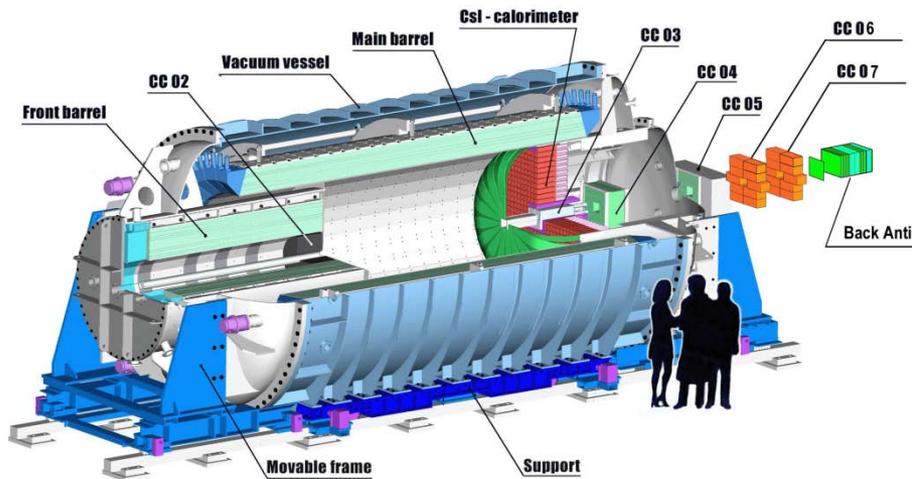
Effect of Warped Extra Dimension Models on Branching Fractions

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ Experimental Challenge: "Nothing-in nothing out"

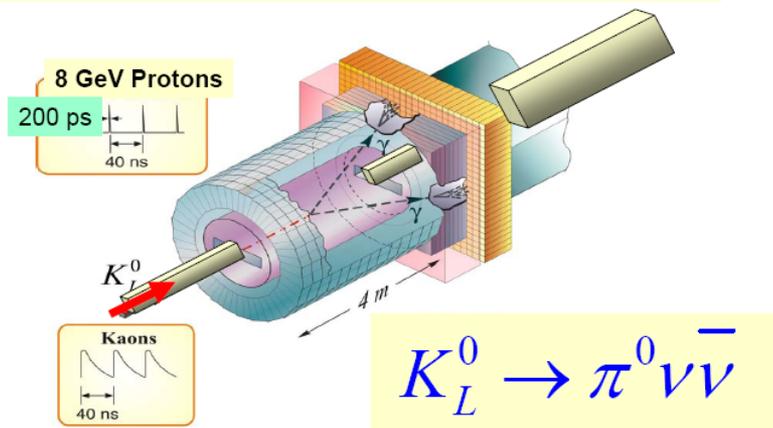
- KEK/JPARC approach emphasizes high acceptance for the two decay photons while vetoing everything else:

A hermetic "bottle" approach.

- The original KOPIO concept measures the kaon momentum and photon direction... Good! But costs detector acceptance and requires a large beam to compensate. Project-X Flux can get back to small kaon beam!



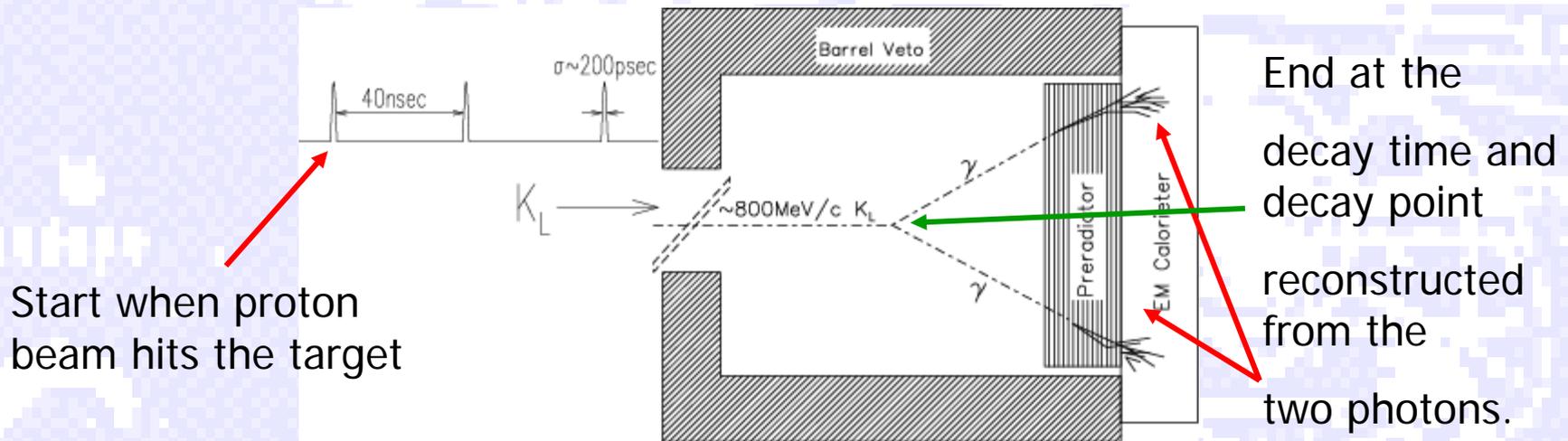
Another $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ Experiment Concept



- Use TOF to work in the K_L^0 c.m. system
- Identify main 2-body background $K_L^0 \rightarrow \pi^0 \pi^0$
- Reconstruct $\pi^0 \rightarrow \gamma \gamma$ decays with pointing calorimeter
- 4π solid angle photon and charged particle vetos

KOPIO inspired: Micro-bunch the beam, TOF determines K_L momentum.

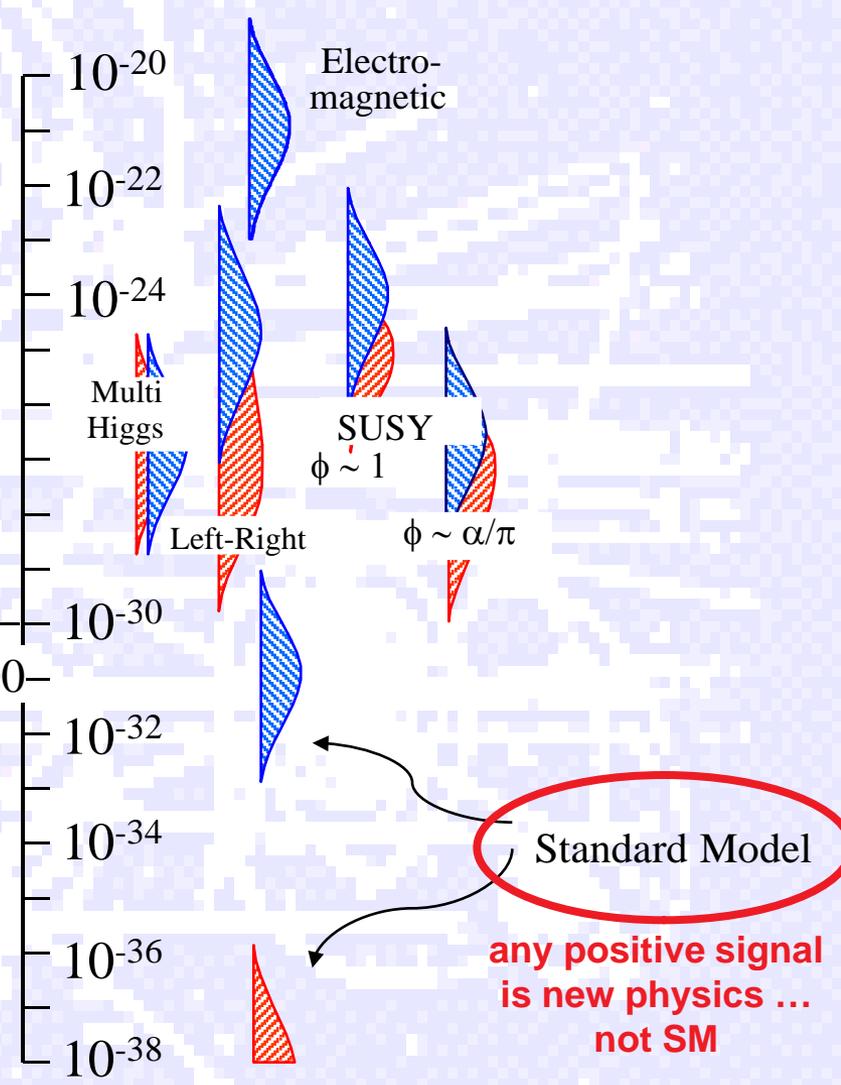
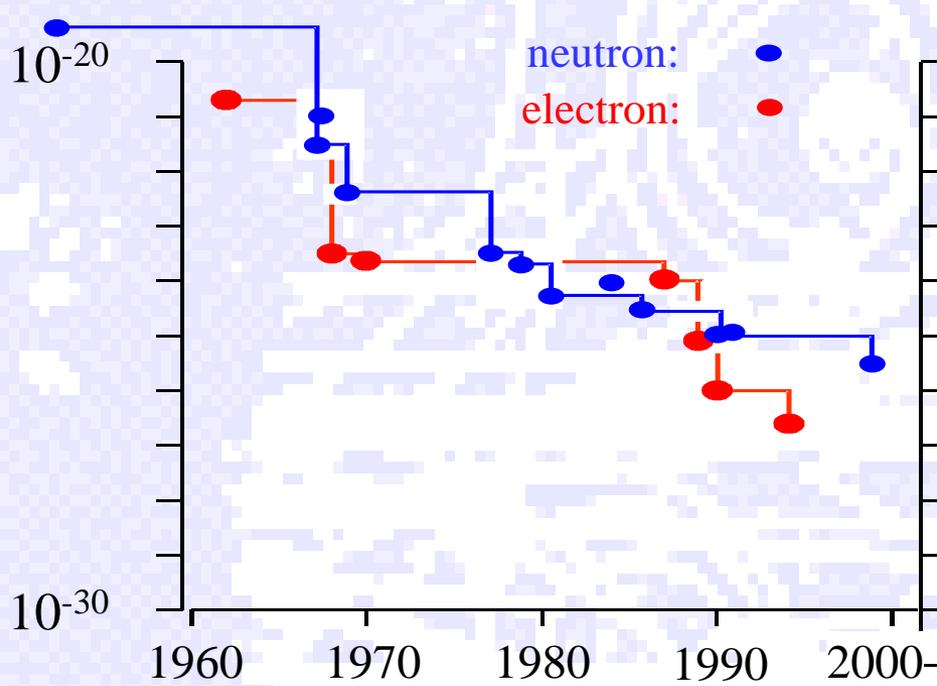
Fully reconstruct the neutral Kaon in $K_L \rightarrow \pi^0 \nu \bar{\nu}$ measuring the Kaon momentum by time-of-flight.



Timing uncertainty due to microbunch width should not dominate the measurement of the kaon momentum; requires RMS width < 200 ps. CW linac pulse timing of less than 50ps is intrinsic.

EDM measurements: BSM slayers

Experimental Limit on d (e cm)



Updated from Barr: Int. J. Mod Phys. A8 208 (1993)

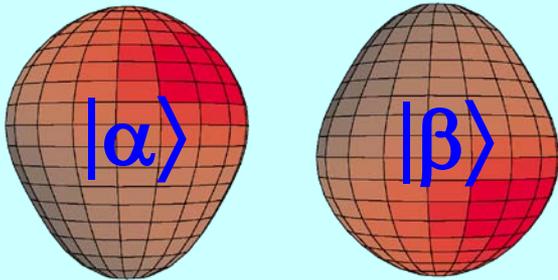
Guy Savard, ANL

Enhanced EDM of ^{225}Ra

Enhancement mechanisms:

- Large intrinsic Schiff moment due to octupole deformation;
- Closely spaced parity doublet;
- Relativistic atomic structure.

Parity doublet



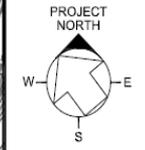
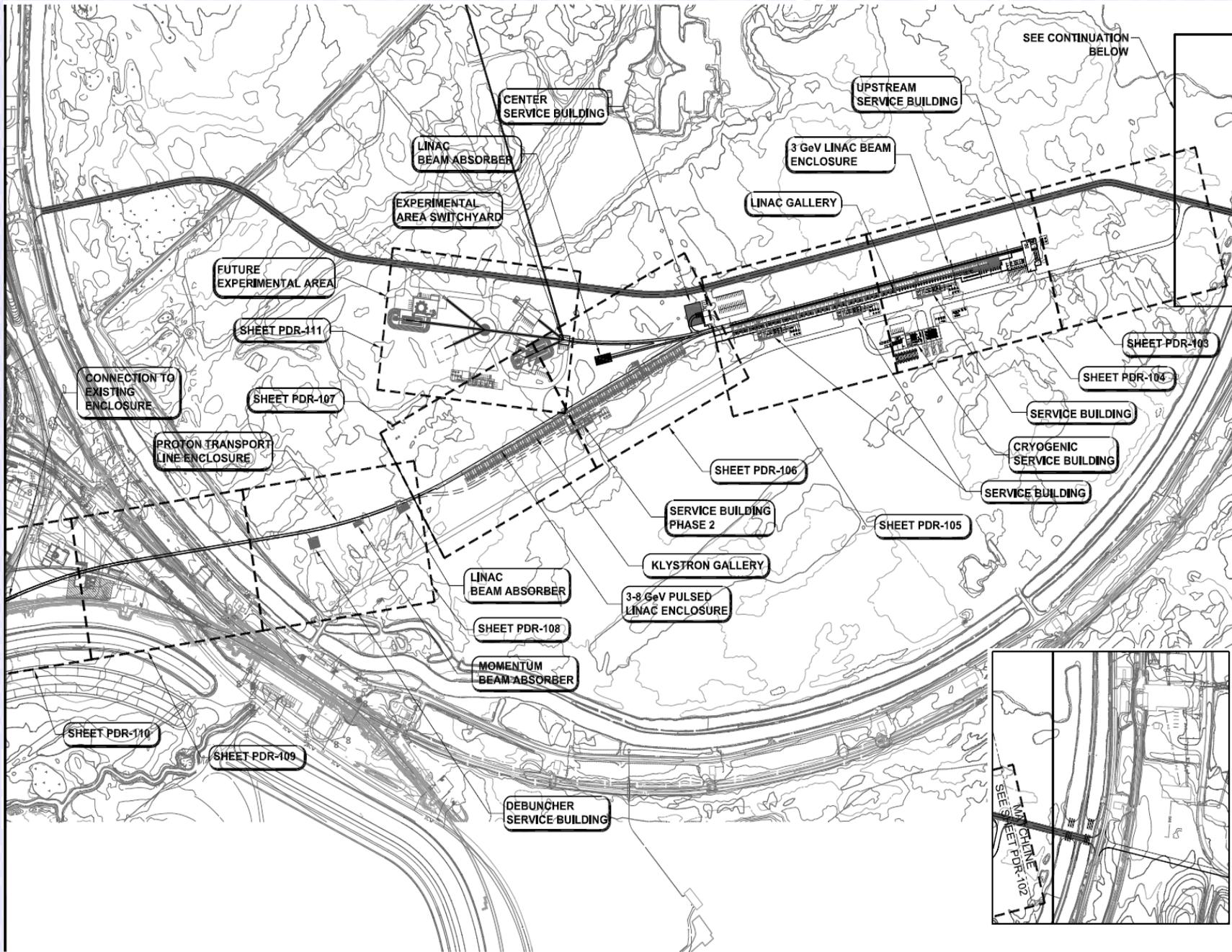
Enhancement Factor: $\text{EDM}(^{225}\text{Ra}) / \text{EDM}(^{199}\text{Hg})$

Skyrme Model	Isoscalar	Isvector	Isotensor
SkM*	1500	900	1500
SkO'	450	240	600

Schiff moment of ^{199}Hg , de Jesus & Engel, PRC (2005)

Schiff moment of ^{225}Ra , Dobaczewski & Engel, PRL (2005)

Guy Savard, ANL



PROJECT X
CONVENTIONAL FACILITIES
PROJECT SITE & UTILITIES
PROJECT OVERVIEW SITE PLAN

PDR
Fermilab



DATE

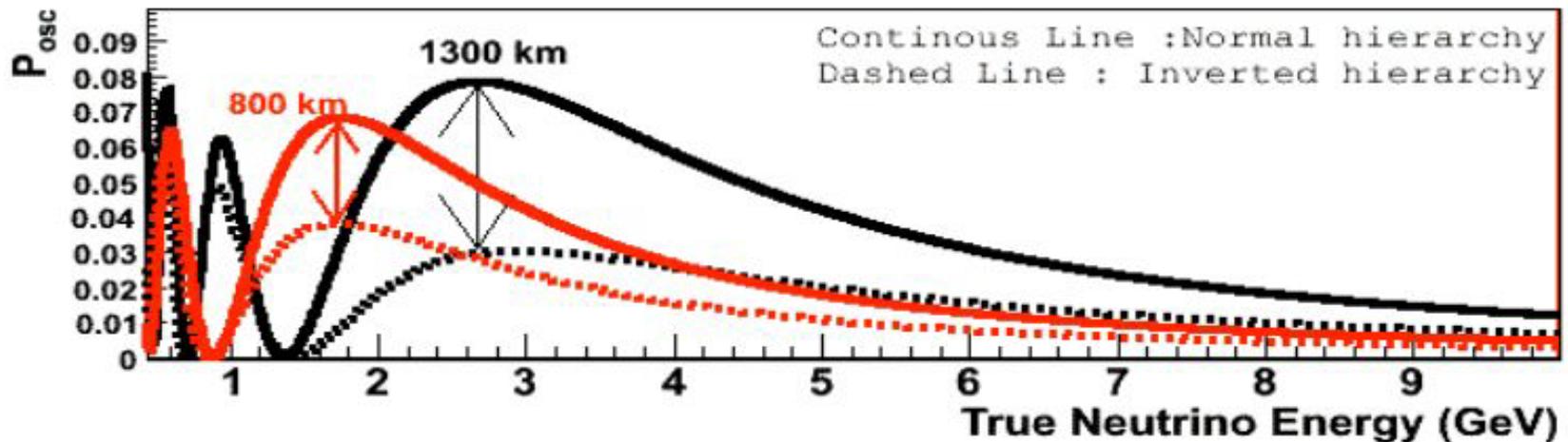
JUNE 2010

PROJECT NO.
4-2-1

DRAWING NO.
PDR-101

Why DUSEL?

- 1300 km distance is a good compromise of mass-hierarchy and CP violation sensitivities
- Deep underground site allows rich physics program in addition to LB neutrinos



Bob Svoboda, 4th PXP Workshop