Project-X

Physics Opportunities

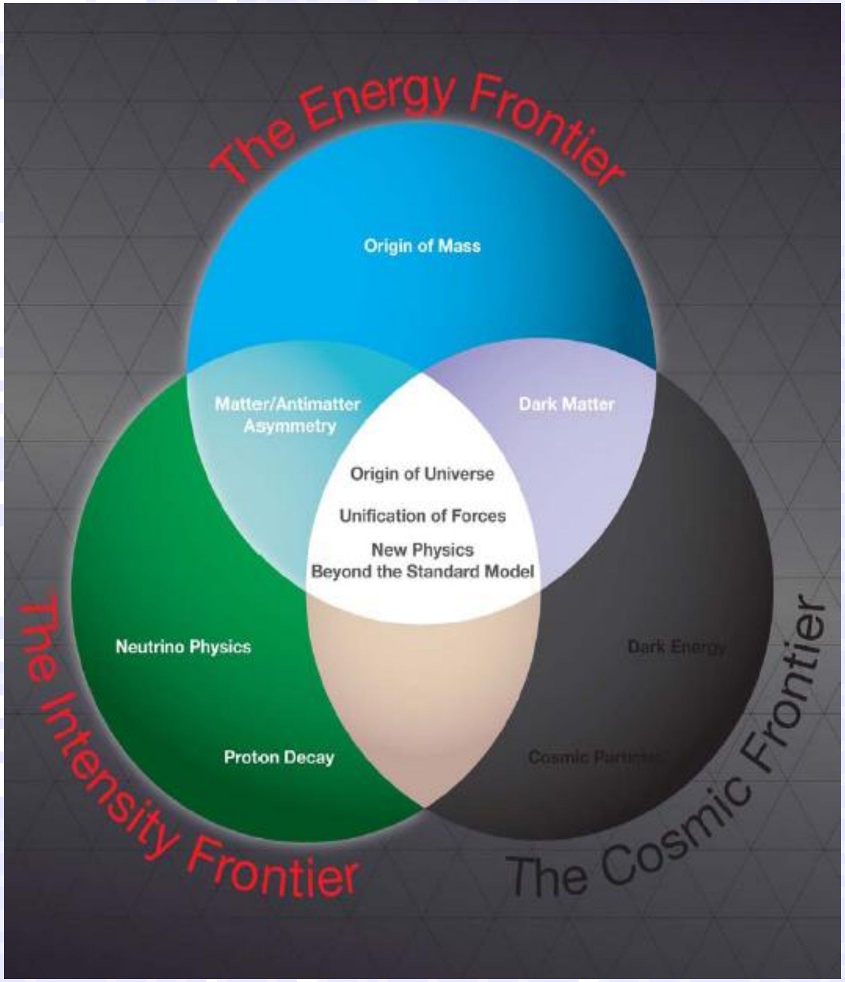
R. Tschirhart
Fermilab

BEACH-2010: Perugia, June 2010

The Promise of the Intensity Frontier

Project-X drives next generation experiments in rare processes neutrino physics that explore:

- ***The origin of the universe***
- ***Unification of Forces***
- ***New Physics Beyond the Standard Model.***



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.

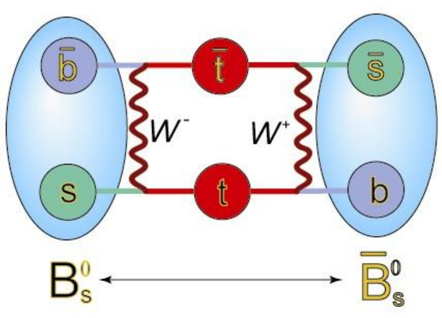
- ***Kaon, muon, nuclei & neutron precision experiments driven by high intensity proton beams running simultaneously with the neutrino program:***

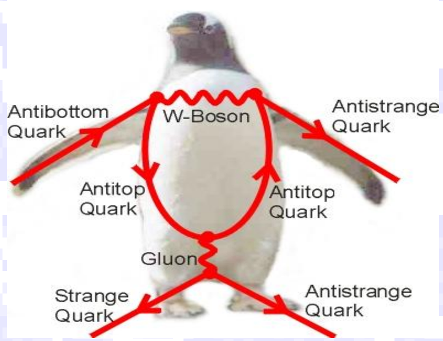
  These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (edms), and world-leading precision measurements of ultra-rare kaon decays.

Detailed Discussion: Project X website

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??

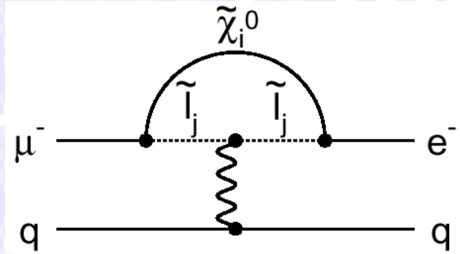


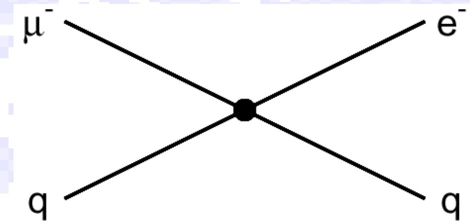


Rare muon decays in Project-X: $\mu^- N \rightarrow e^- N$ Sensitivity to New Physics

Supersymmetry

Predictions at 10^{-15}



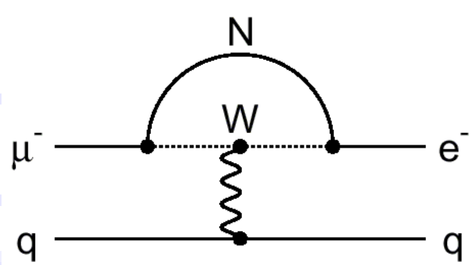


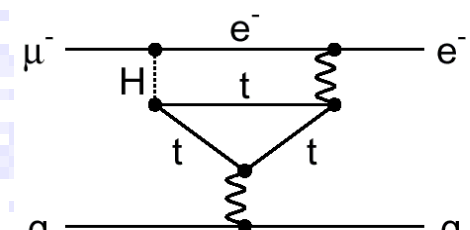
Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

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



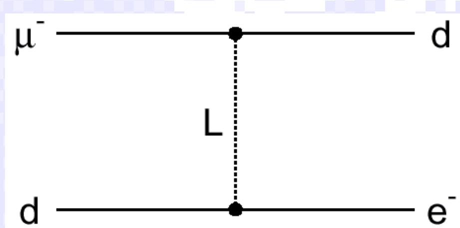


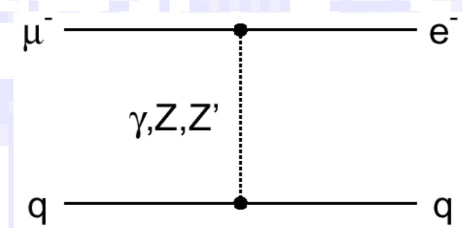
Second Higgs doublet

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

Leptoquarks

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





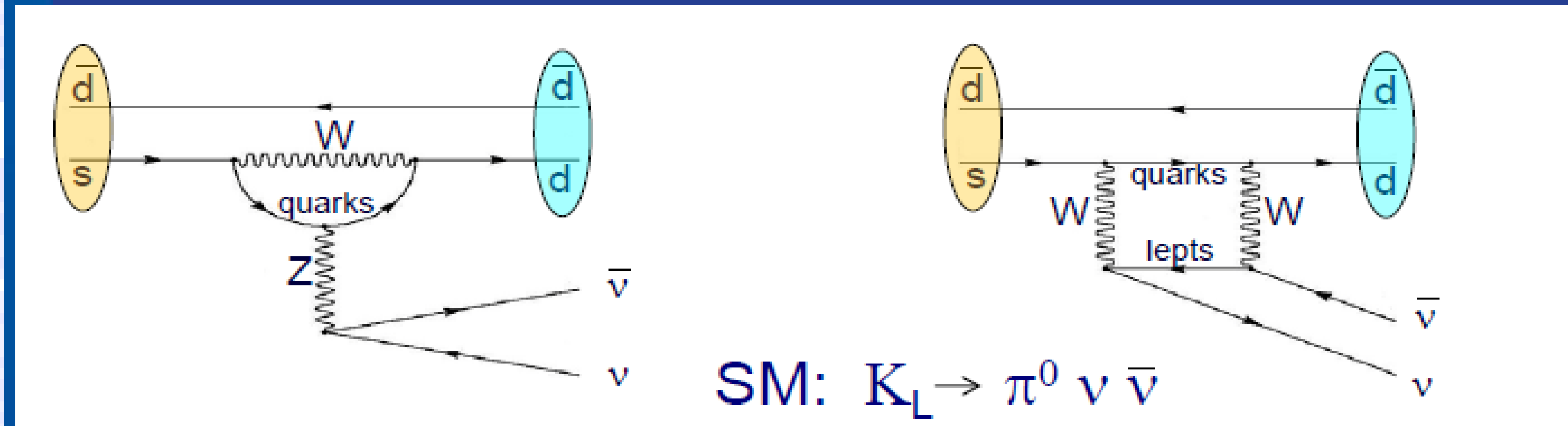
Heavy Z', Anomalous Z coupling

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

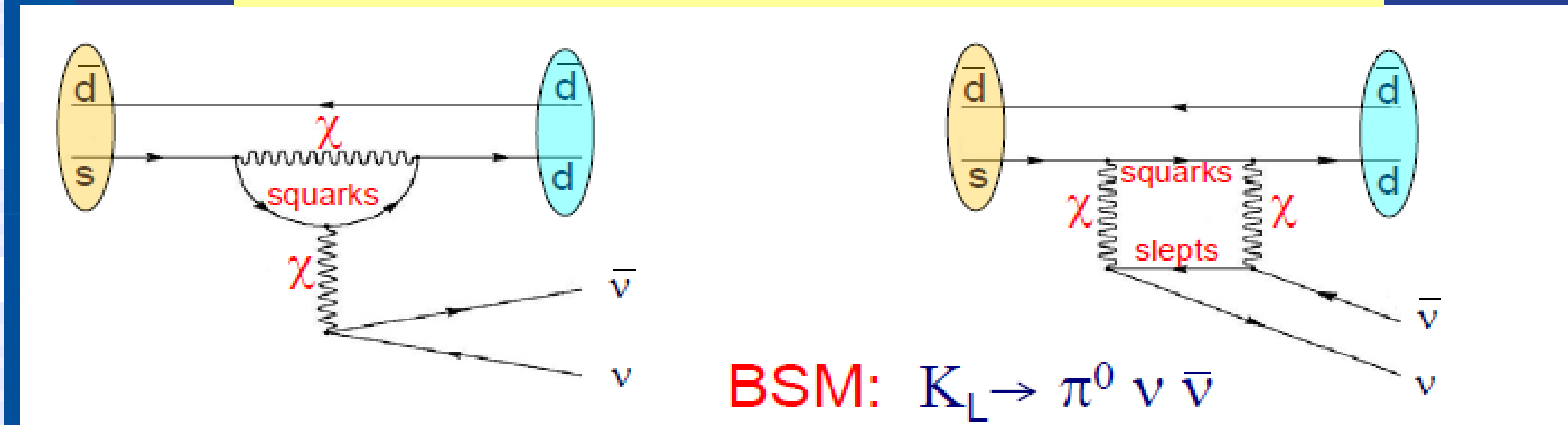
$B(Z \rightarrow \mu e) < 10^{-17}$

After W. Marciano

The Window of Ultra-rare Kaon Decays in Project X



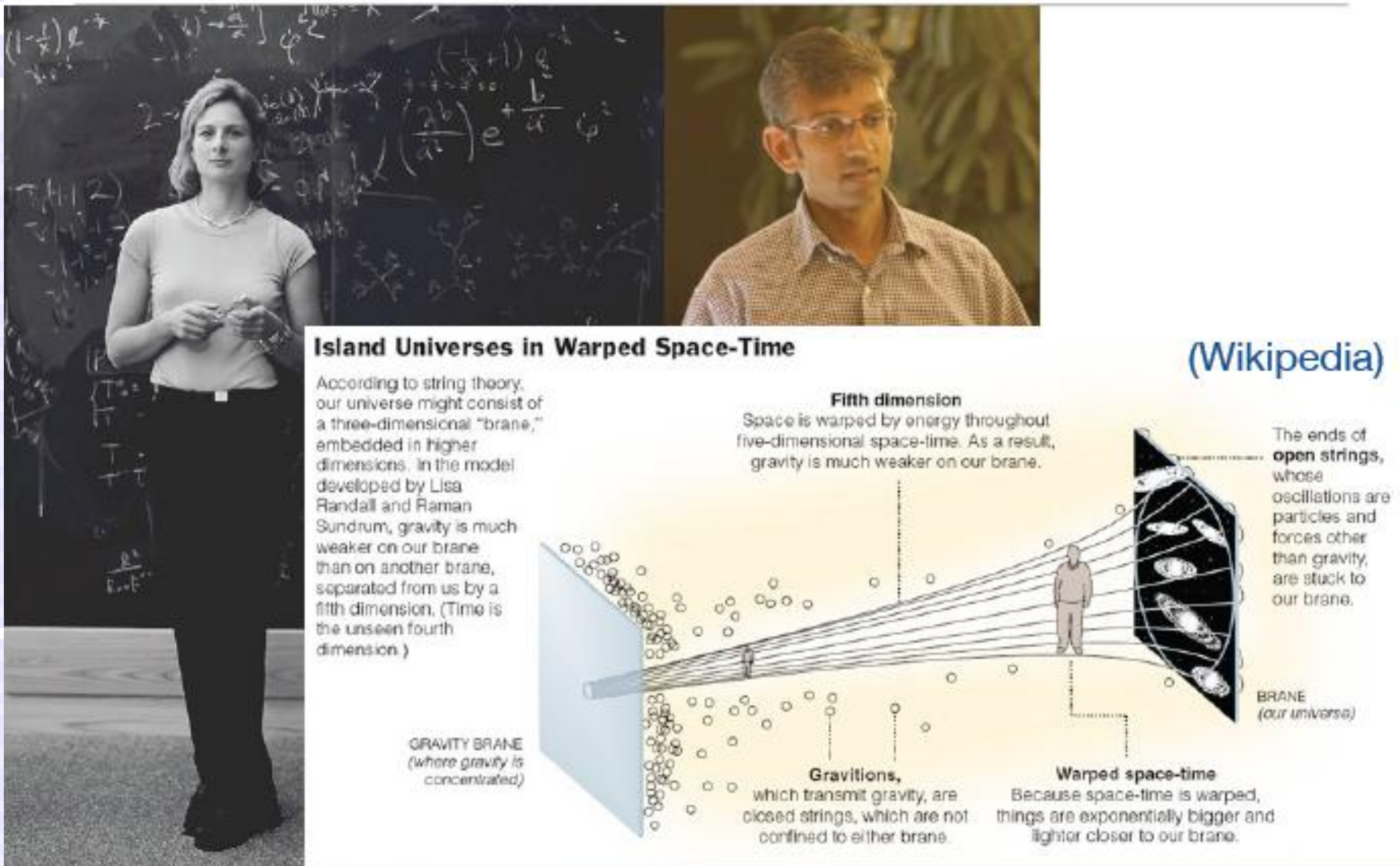
Standard Model rate of 3 parts per 100 billion!



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

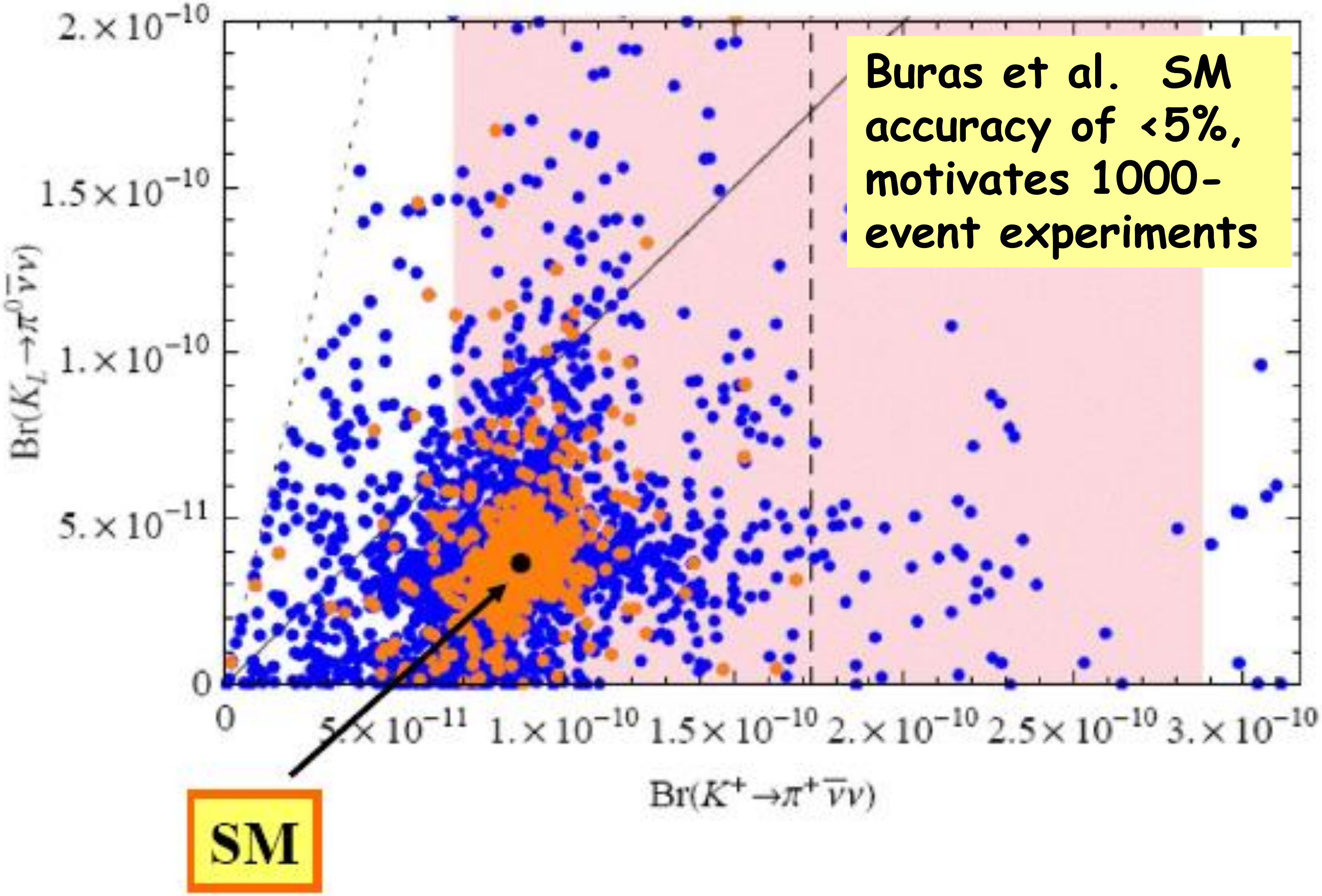
Rates sensitive to other BSMs: Warped Extra Dimensions as a Theory of Flavor??

The Randall-Sundrum (RS) idea



$K_L \to \pi^0 \nu\bar{\nu}$ vs. $K^+ \to \pi^+ \nu\bar{\nu}$ (RS)

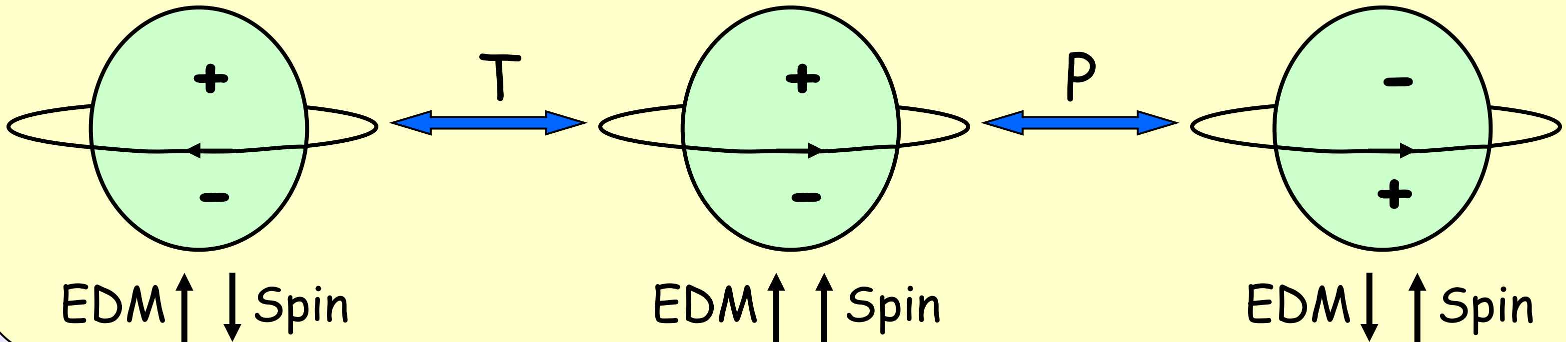
(Up to Factor 3 and 2 Enhancements)



Effect of Warped Extra Dimension Models on Branching Fractions

Search for an electric dipole moment and physics beyond the standard model

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

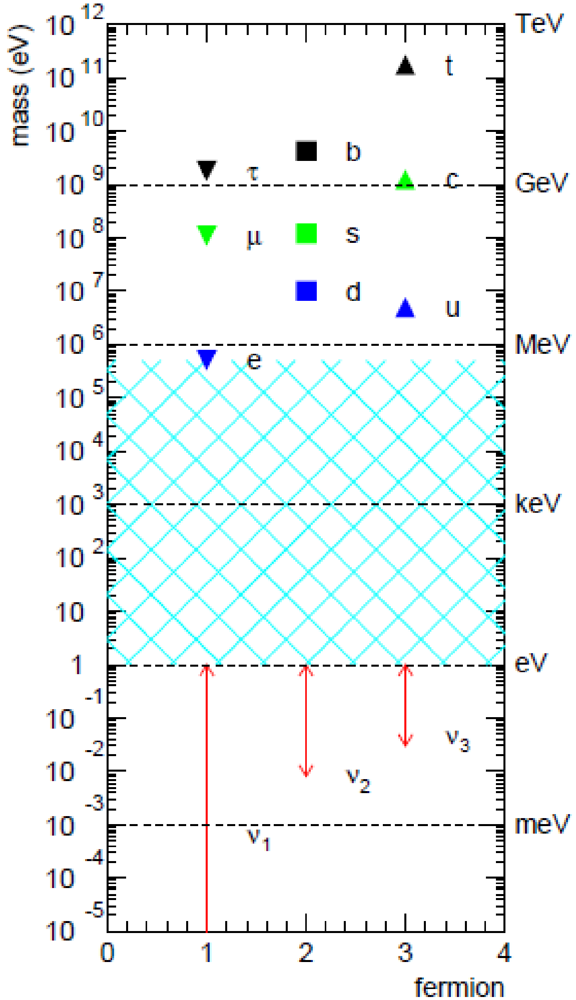
Diamagnetic Atoms (Hg, Xe, Ra, Rn) → Quark Chromo-EDM

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

What are Neutrinos Telling Us?



What We Are Trying To Understand:

⇐ NEUTRINOS HAVE TINY MASSES

⇓ LEPTON MIXING IS "WEIRD" ⇓

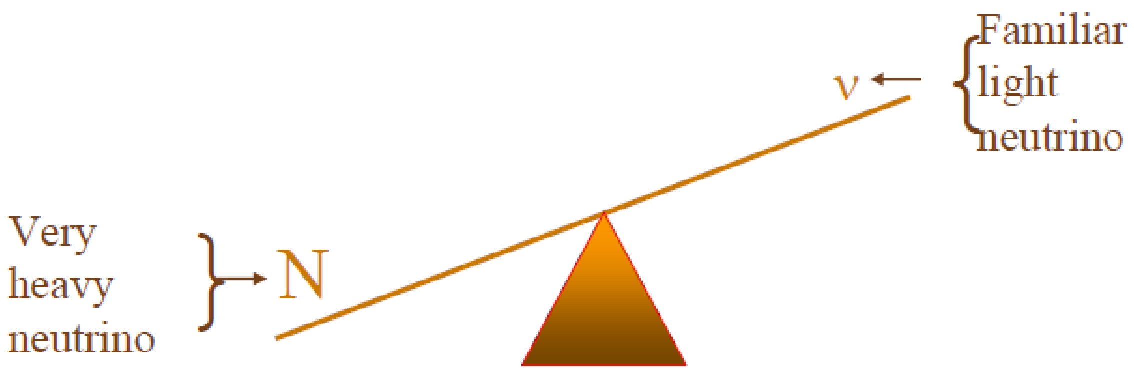
$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

Andre de Gouvea

Leveraging to the Unification Scale

See-Saw Mechanism

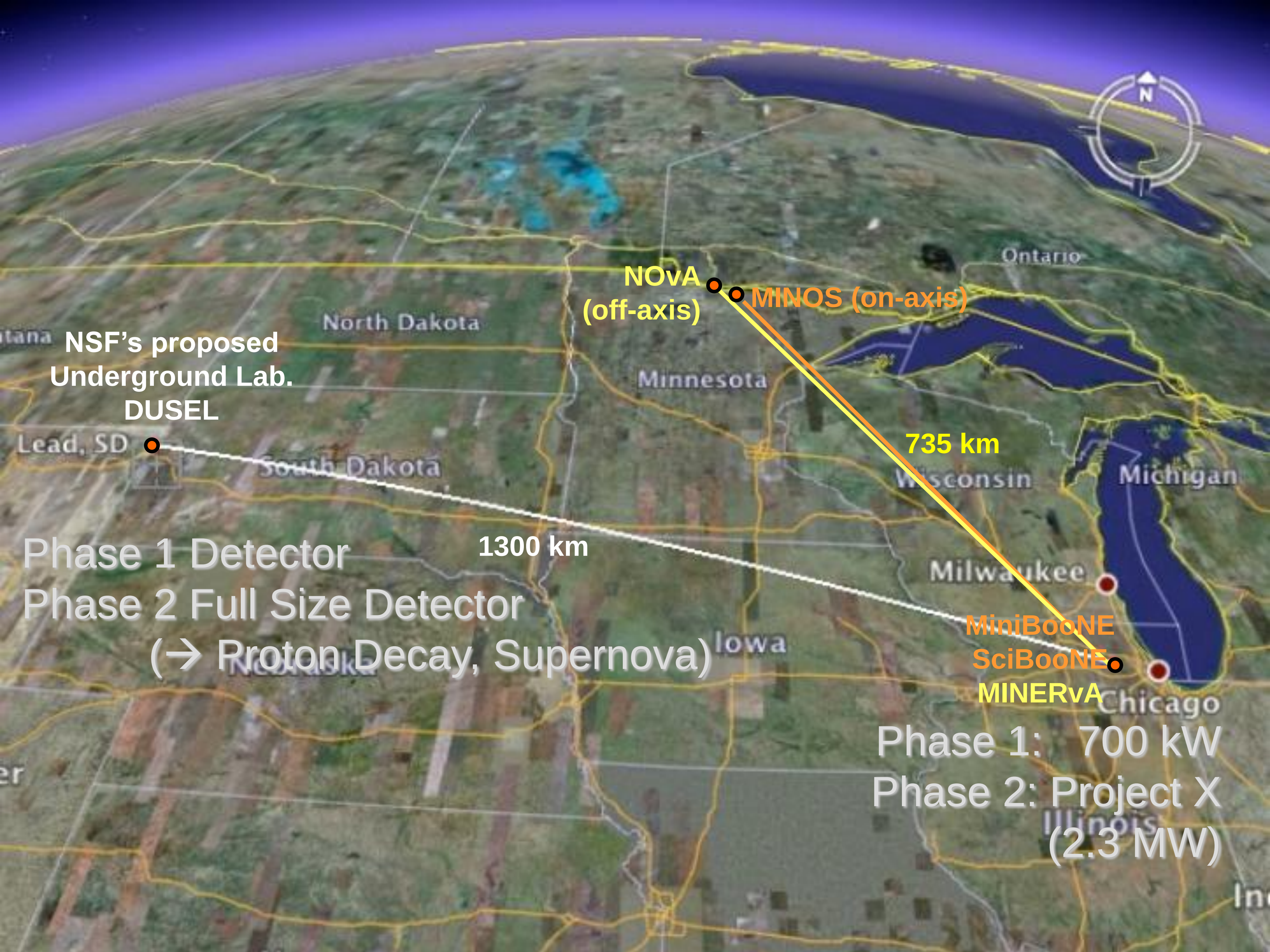


Mass(N) ~ 10^{15} GeV

The strong, EM, and weak forces unify at ~ 10^{16} GeV

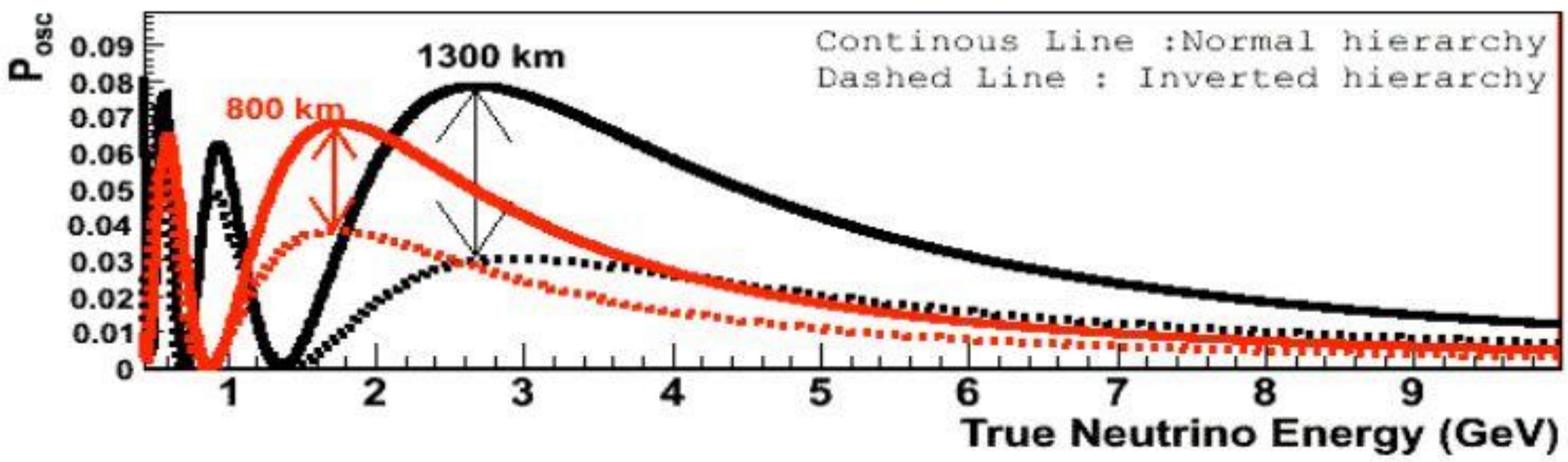
Unification? Leptogenisis?

Boris Kayser


NOvA
(off-axis)
MINOS (on-axis)
Ontario
North Dakota
NSF's proposed
Underground Lab.
DUSEL
Minnesota
Lead, SD
South Dakota
735 km
Wisconsin
Michigan
1300 km
Phase 1 Detector
Phase 2 Full Size Detector
(→ Proton Decay, Supernova)
Milwaukee
MiniBooNE
SciBooNE
MINERvA
Iowa
Nebraska
Chicago
Phase 1: 700 kW
Phase 2: Project X
(2.3 MW)
Illinois

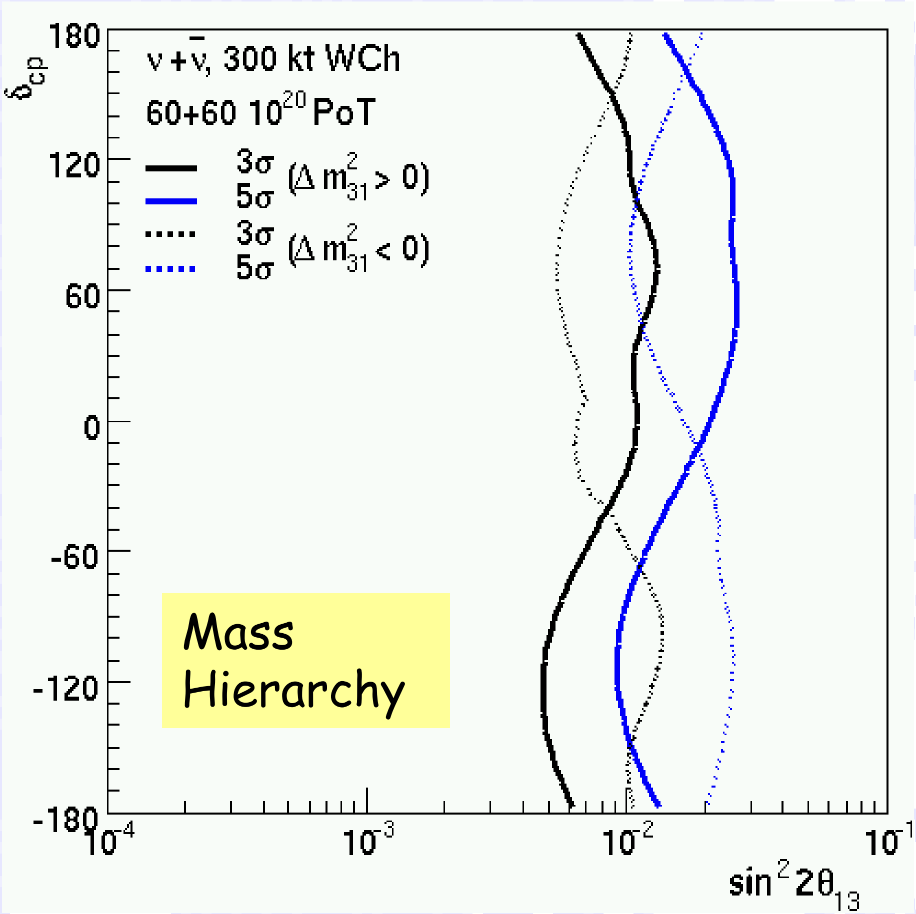
Why DUSEL?

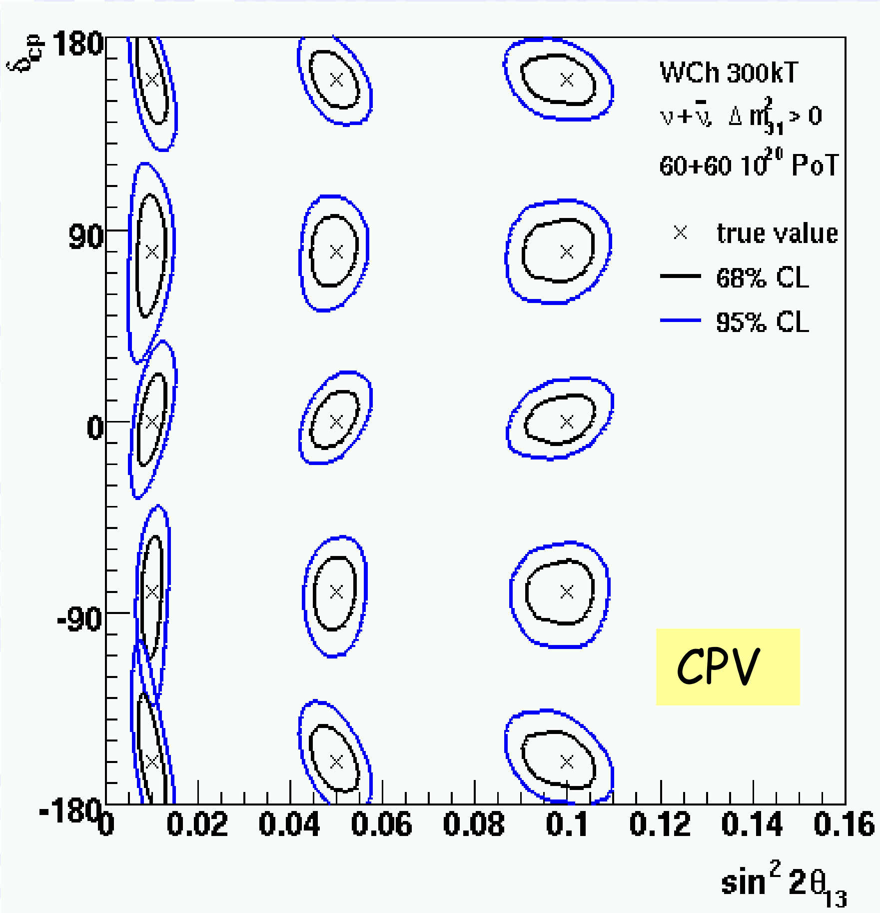
- 1300 km distance is a good compromise of mass-hierarchy and CP violation sensitivities
- Deep underground site allows rich physics program in addition to LB neutrinos



Bob Svoboda, 4th PXP Workshop

DUSEL LBNE Sensitivities

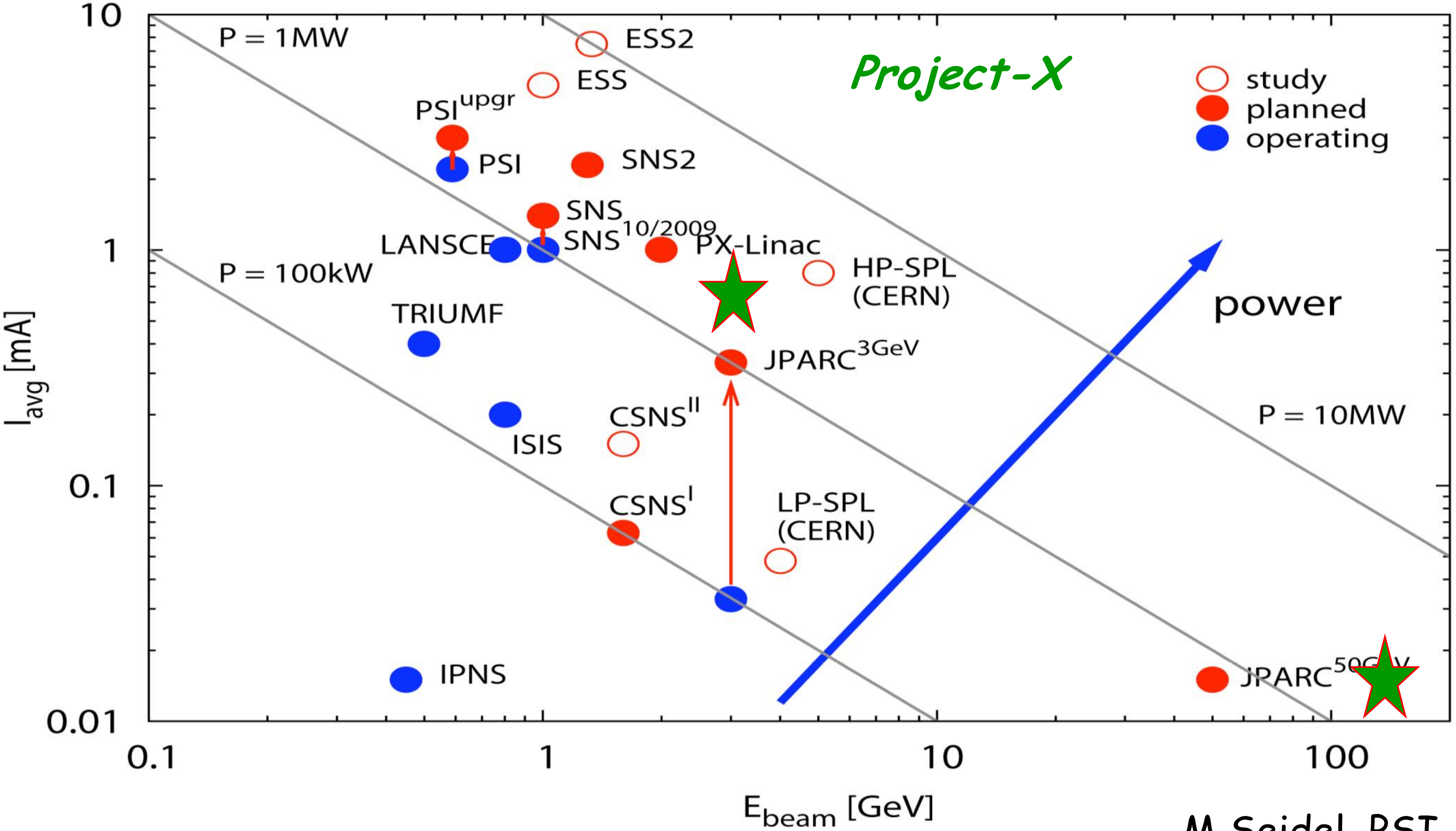




Sensitivities for (300 kT H_2O)×(2 MW)×(3+3 $\nu/\bar{\nu}$ years)

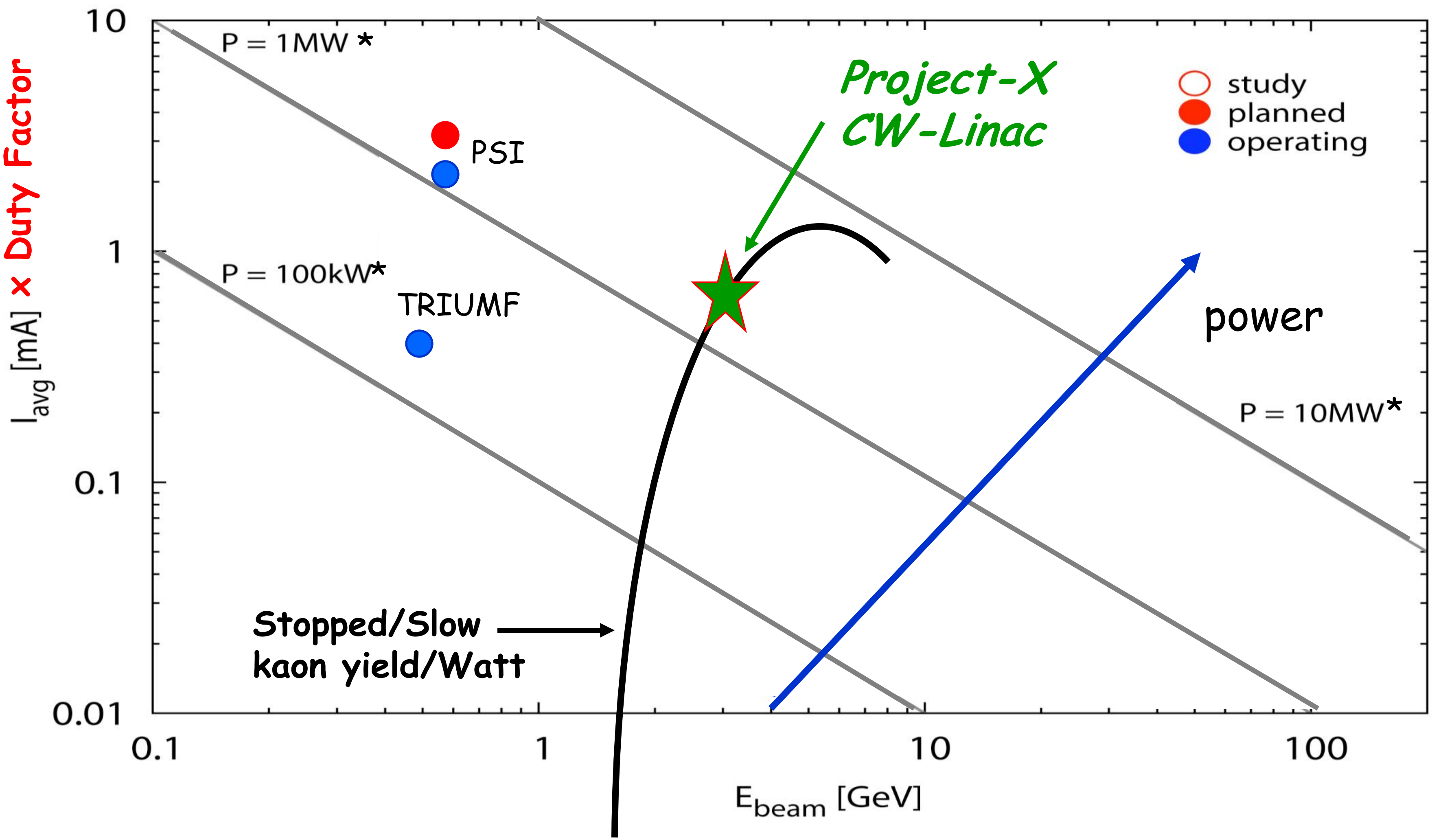
Bob Svoboda, 4th PXP Workshop

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



M Seidel, PSI

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

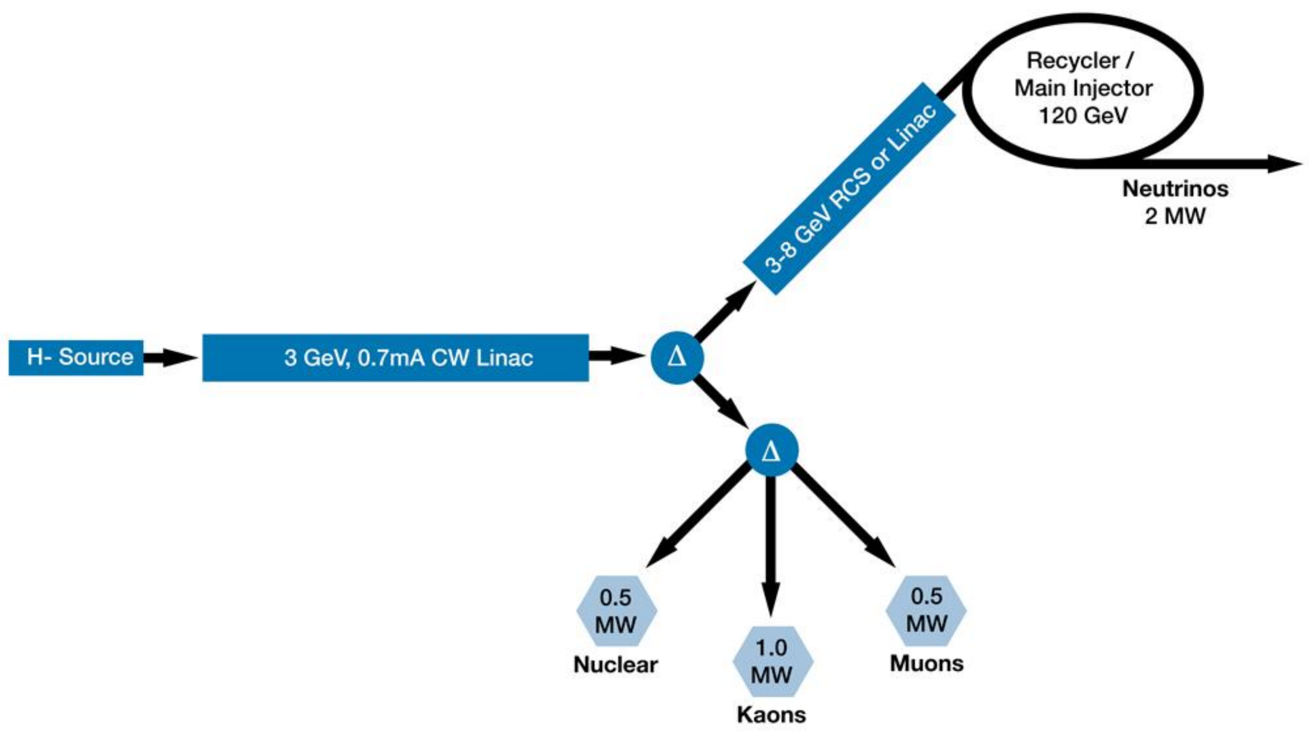


* Beam power × Duty Factor

Project-X, What it's not…

What it is…

- Project X Design Criteria
  - ✓ 2 MW of beam power over the range 60 – 120 GeV;
  - ✓ Simultaneous with 2 MW beam power at 3 GeV;
  - ✓ Compatibility with future upgrades to 2-4 MW at 8 GeV



Steve Holmes, APS Meeting Feb 2010.

"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 ($\delta t \sim 20 psec$) crucial to survival in 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.
- The intrinsic properties of this SCRF CW Linac enables the physics rather than fighting with it. Excellent beam power scaling.

Beam Requirements for a World Leading Rare Processes Program

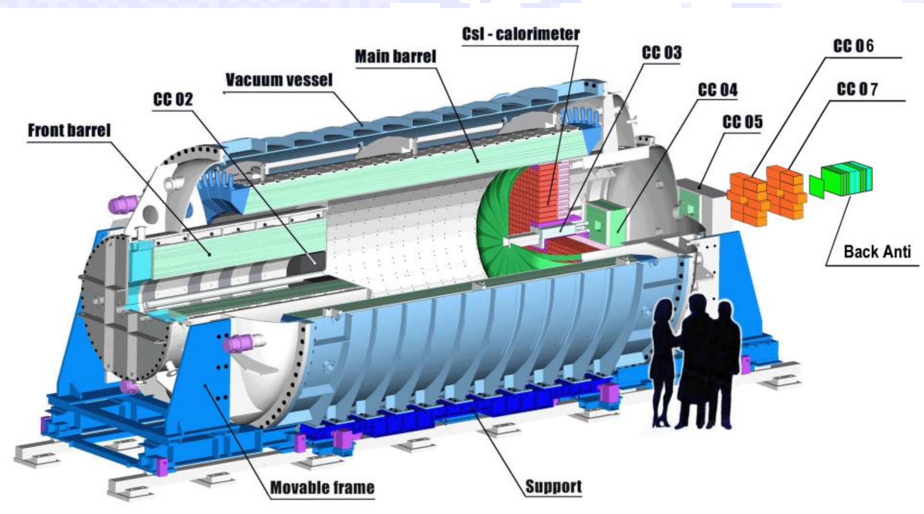
	Proton Energy (kinetic)	Beam Power	Beam Timing
Rare Muon decays	2-3 GeV	>500 kW	1 kHz – 160 MHz
(g-2) measurement	8 GeV	20-50 kW	30- 100 Hz.
Rare Kaon decays	2.6 – 4 GeV	>500 kW	20 – 160 MHz. (<50 psec pings)
Precision K^0 studies	2.6 – 3 GeV	> 200kW (100μA internal target)	20 – 160 MHz. (<50 psec pings)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

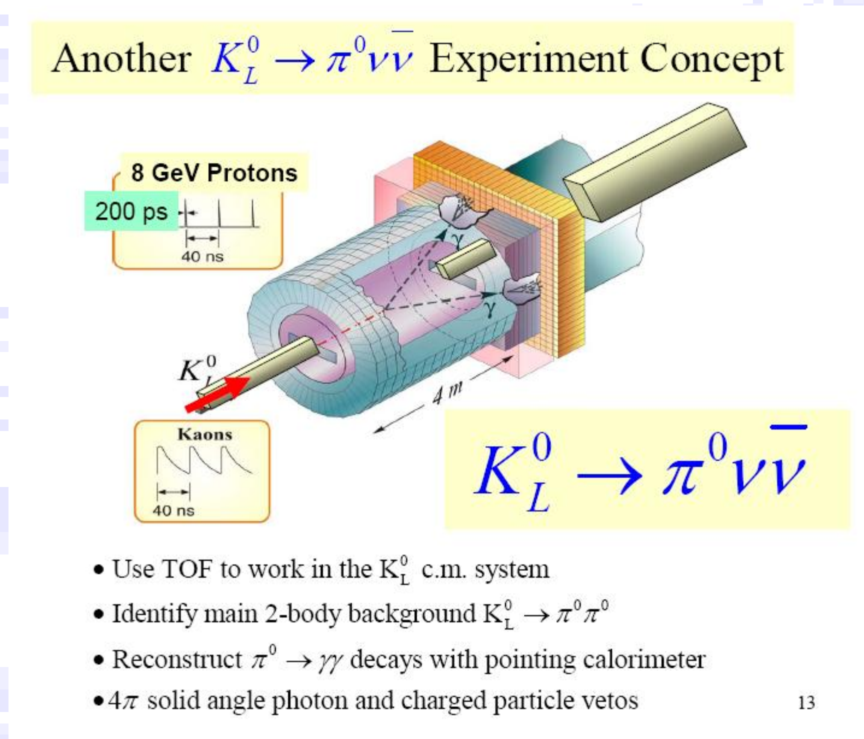
$K_L \to \pi^0 \nu\nu$ Experimental Challenge: "Nothing-in nothing out"

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

A hermetic "bottle" approach.

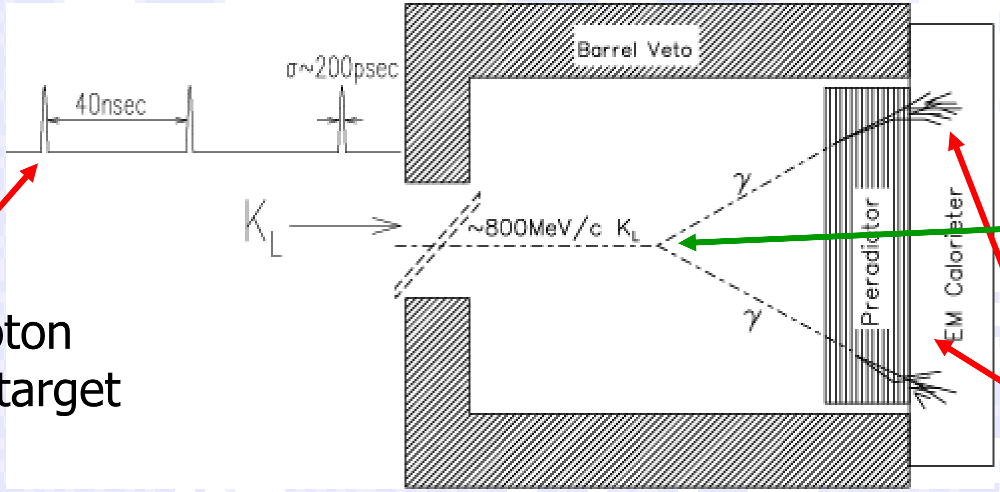
•The original KOPIO concept measures the kaon momentum and photon direction…Good! But costs detector acceptance and requires a large beam to compensate. Project-X Flux can get back to small kaon beam!





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.



Start when proton beam hits the target

End at the decay time and decay point reconstructed from the two photons.

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

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.
- Next generation precision cross section measurements.

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

Muon Physics:

- 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
- $\mu \rightarrow 3e$
- $\mu^+ e^- \rightarrow \mu^- e^+$
- $\mu^- A \rightarrow \mu^+ A'$; $\mu^- A \rightarrow e^+ A'$; $\mu^- \mathbf{e^-}(A) \rightarrow \mathbf{e^-}\ \mathbf{e^-}(A)$
- Systematic study of radiative muon capture on nuclei.

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

Kaon Physics:

- $K^+ \rightarrow \pi^+\nu\nu$: >1000 events, Precision rate and form factor.
- $K^+ \rightarrow \pi^0\mu^+\nu$: Measurement of T-violating muon polarization.
- $K^+ \rightarrow (\pi,\mu)^+\nu_X$: Search for anomalous heavy neutrinos.
- $K_L \rightarrow \pi^0\nu\nu$: 1000 events, enabled by high flux & precision TOF.
- $K_L \rightarrow \pi^0e^+e^-$: <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

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

Baryons:

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

Nuclei:

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

Summary

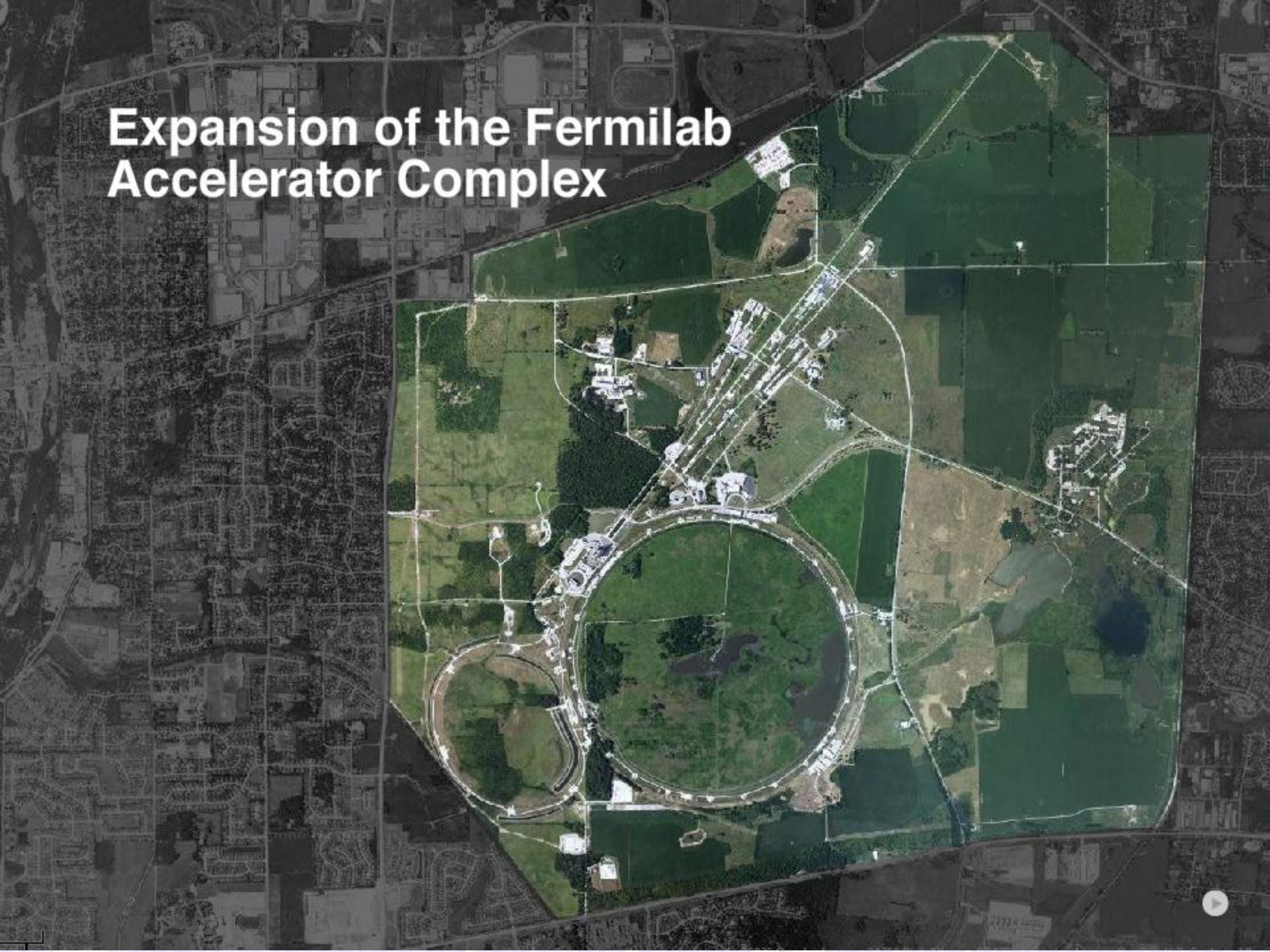
Project-X is a next generation high intensity proton source that can deliver:

Neutrinos: An after-burner for LBNE that reduces the tyranny of (Detector-Mass **x** Running-time) by **x3**, 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.

Prospects: Substantial R&D ongoing now (~$25M/year) on Super Conducting RF accelerator technology supporting Project-X. Earliest construction start of 2015.

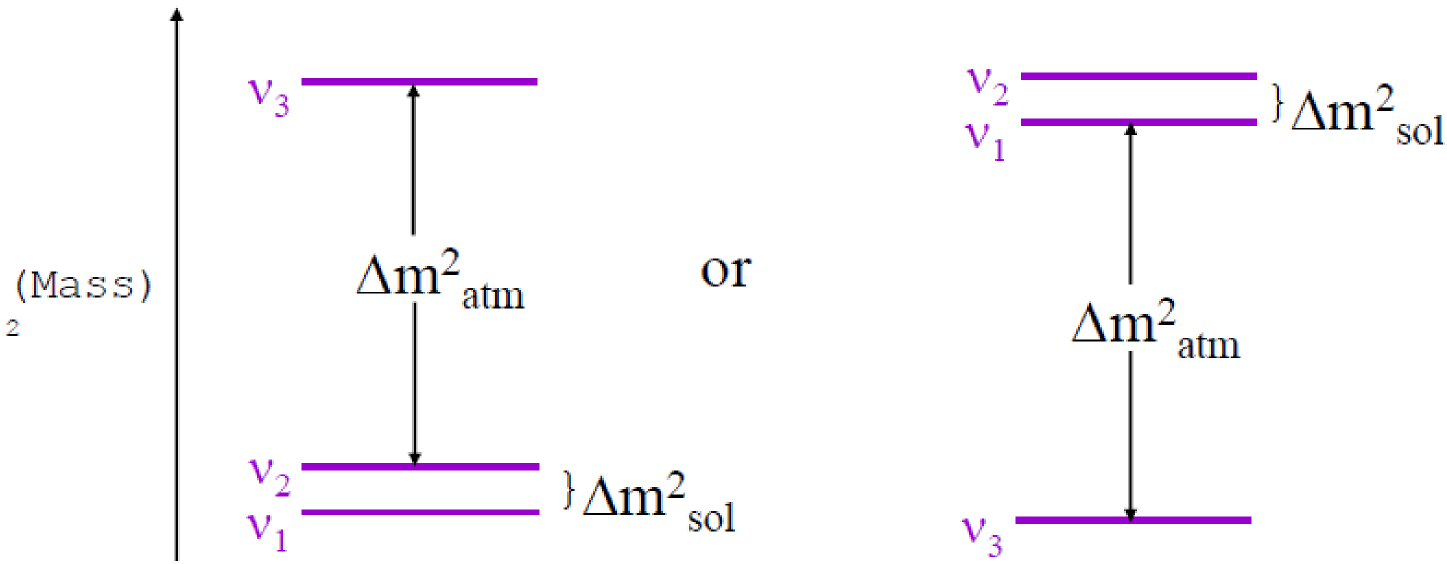
Expansion of the Fermilab Accelerator Complex



Spare Slides

What is Normal?

The (Mass)^2 Spectrum



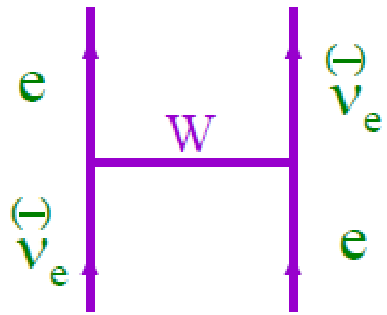
Normal (Quark-like) Inverted

$\Delta m^2_{sol} \cong 7.6 \times 10^{-5}\ eV^2, \quad \Delta m^2_{atm} \cong 2.4 \times 10^{-3}\ eV^2$

Boris Kayser

How To Determine If The Spectrum Is Normal Or Inverted

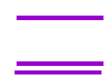
Exploit the fact that, in matter,



raises the effective mass of ν_e , and lowers that of $\bar{\nu}_e$.

This leads to —

$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \begin{cases} > 1 \;; \\ < 1 \;; \end{cases}$$

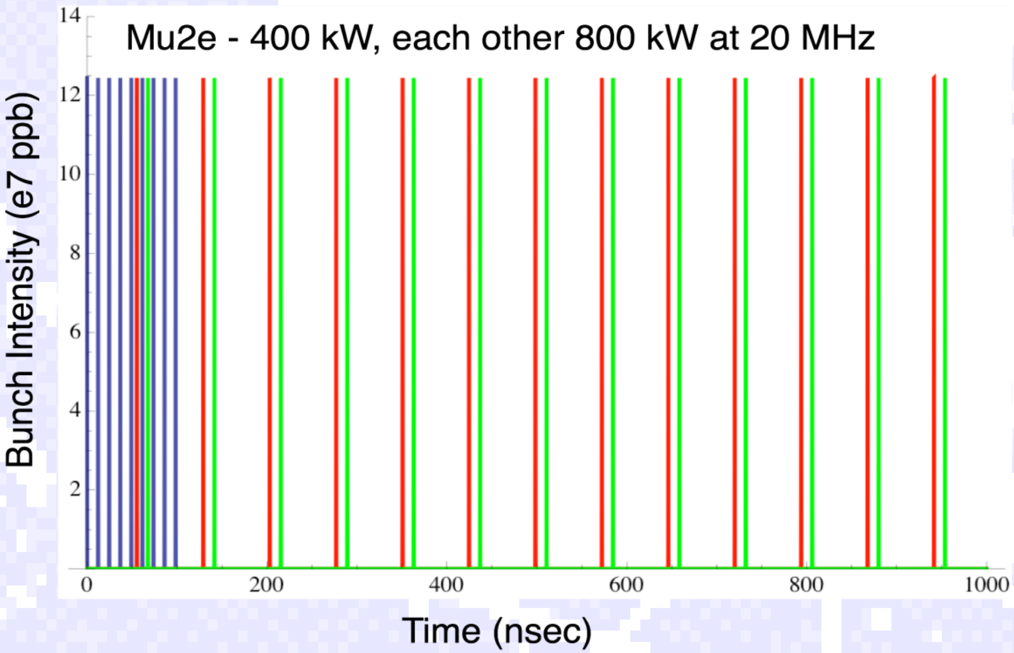


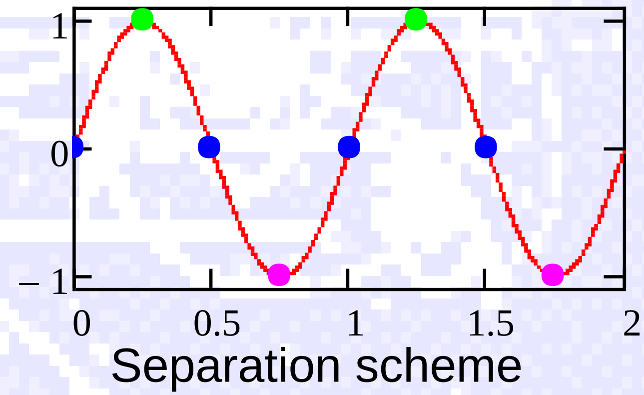
Boris Kayser

Project-X Initial Configuration
Operating Scenario

<u>1 μsec period at 3 GeV</u>

mu2e pulse (9e7) 162.5 MHz, 100 nsec — 400 kW
Kaon pulse (9e7) 27 MHz — 800 kW
Other pulse (9e7) 27 MHz — 800 kW

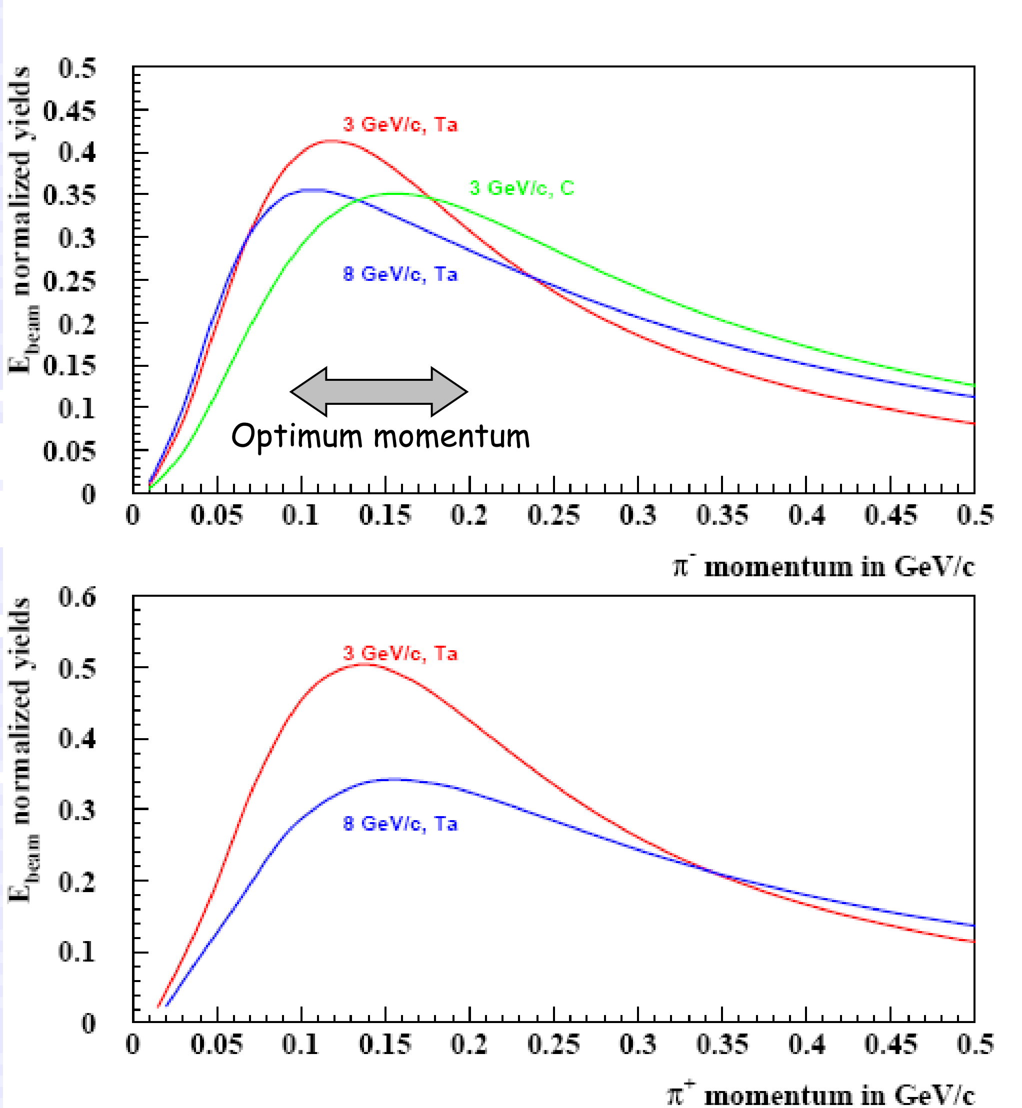




High Duty-Factor Proton Beams
Why is this important of Rare Processes?

- 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

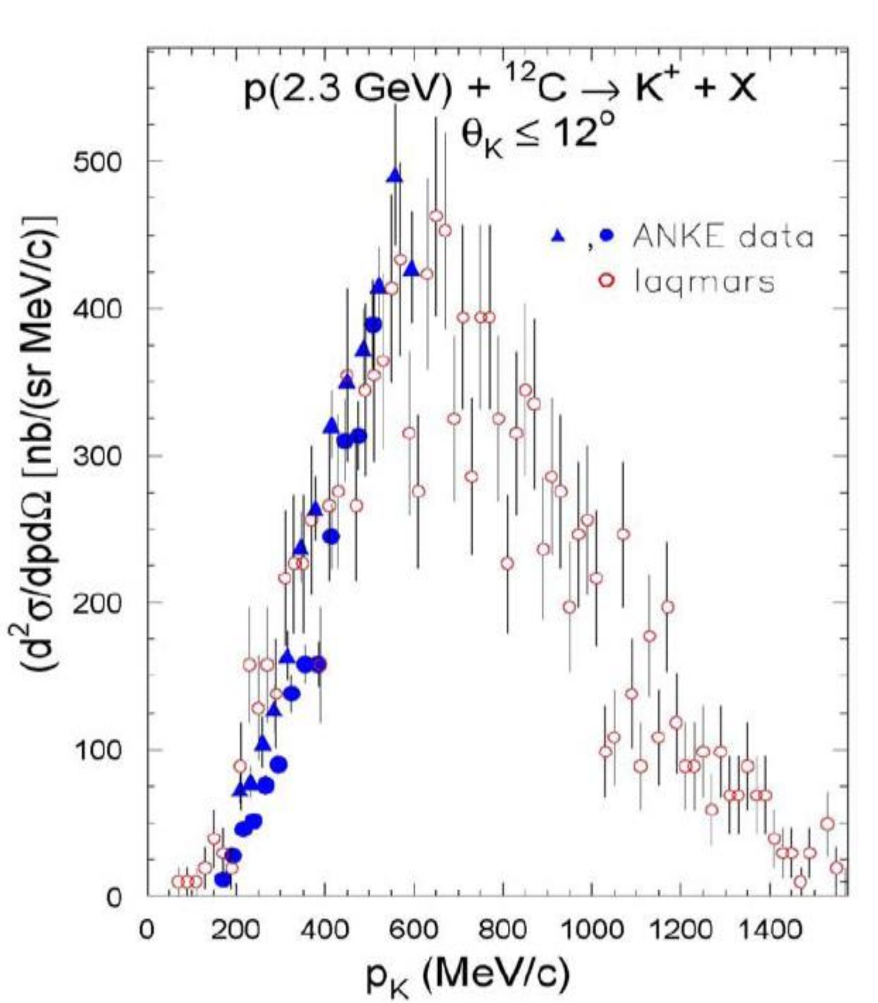
Sensitivity of Kaon Physics Today

- CERN NA62: 100×10^{-12} measurement sensitivity of $K^+ \rightarrow e^+\nu$
- Fermilab KTeV: 20×10^{-12} measurement sensitivity of $K_L \rightarrow \mu\mu ee$
- 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…



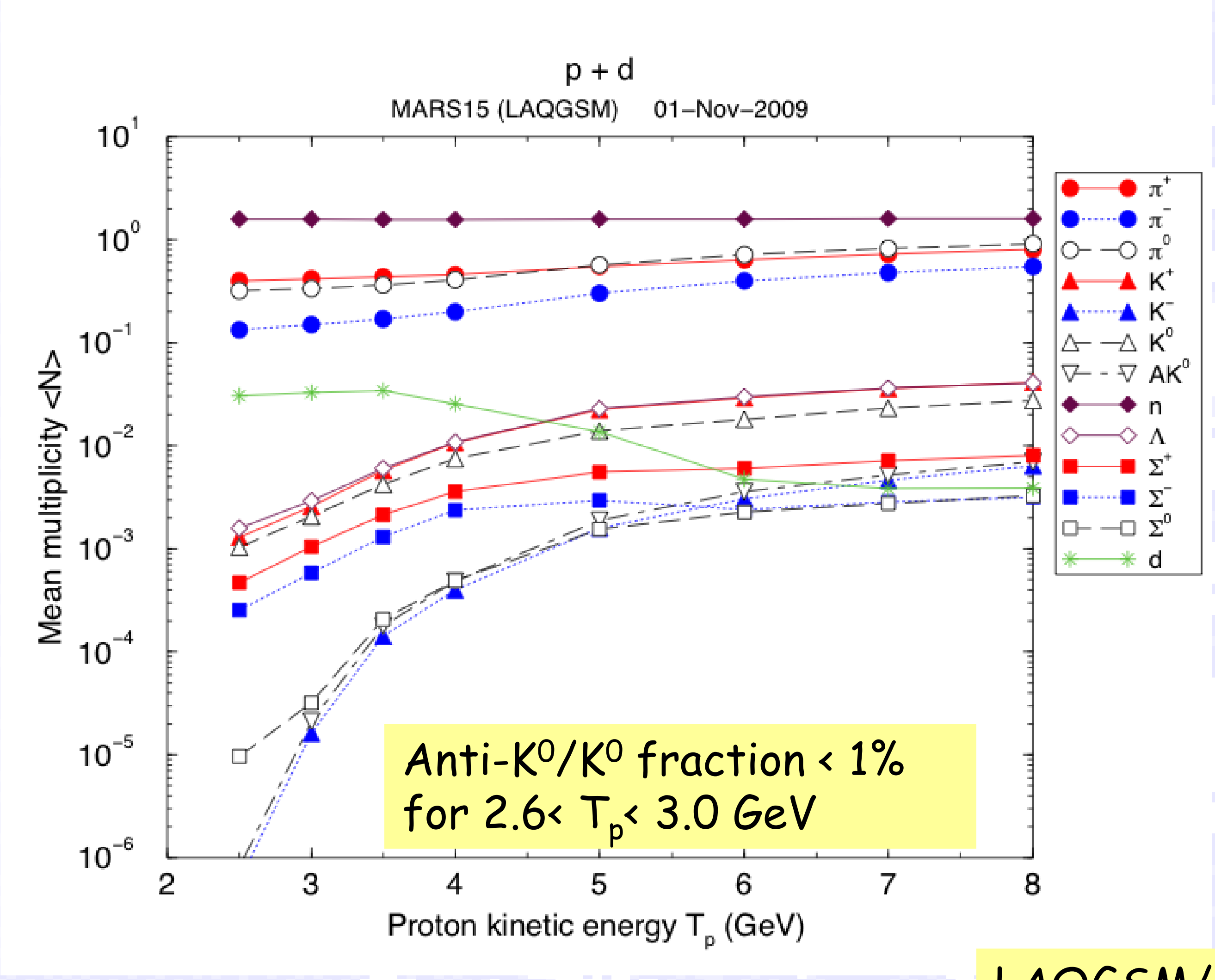
- Los Alamos + MARS simulation suite (LAQGSM + MARS15) is now a state of the art tool set to simulate the challenging region between 1-4 GeV/c proton beam momentum.

[Gudima, Mokhov, Striganov]

- Validated against the high quality data sets from COSY.

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

Project-X is high power, but what about kaon yields??



LAQGSM/MARS-15

Kaon Yields at Constant Beam Power

Optimum yield for IC2 kaon experiments is 4-8 GeV. Minimum for next round of experiments is 2.6 GeV.

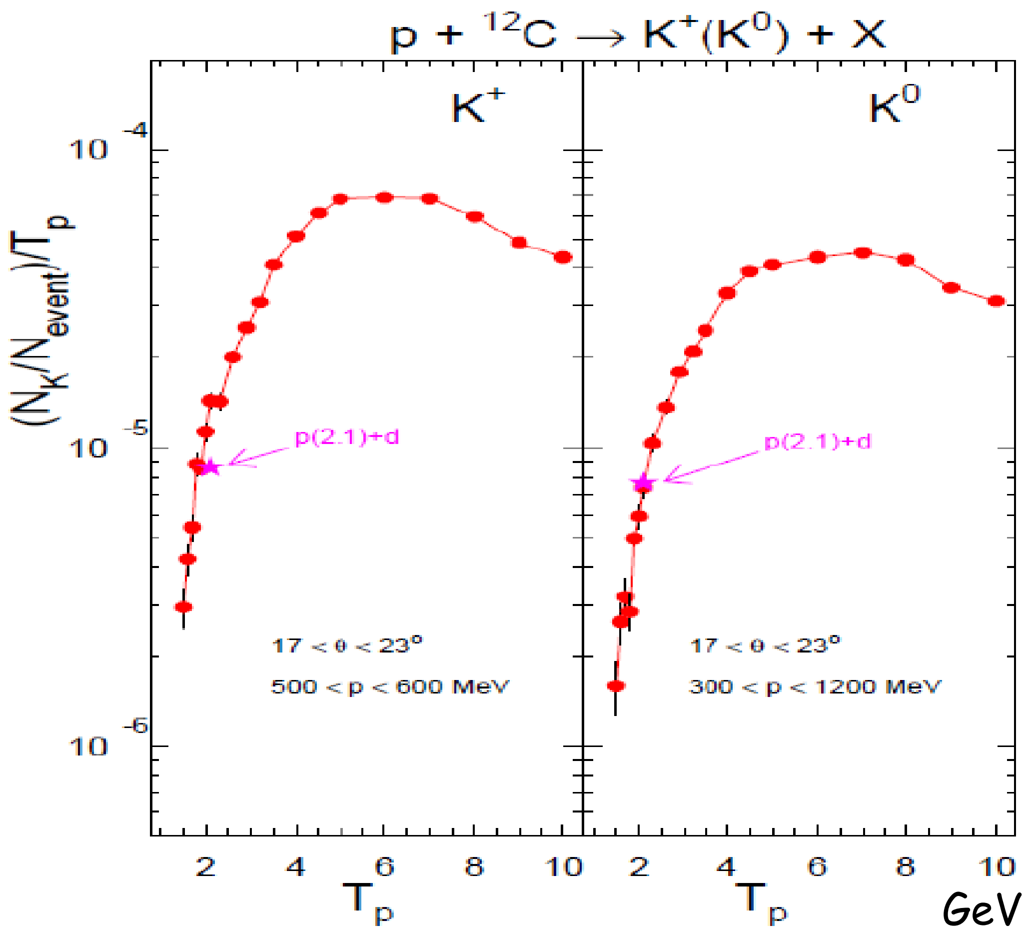


Figure 17: The K → πνν experiment (3.2.3.1 and 3.2.3.2) K^+ and K_L yields at constant beam-power as a function of T_p (GeV).

IC2 Task Force Report

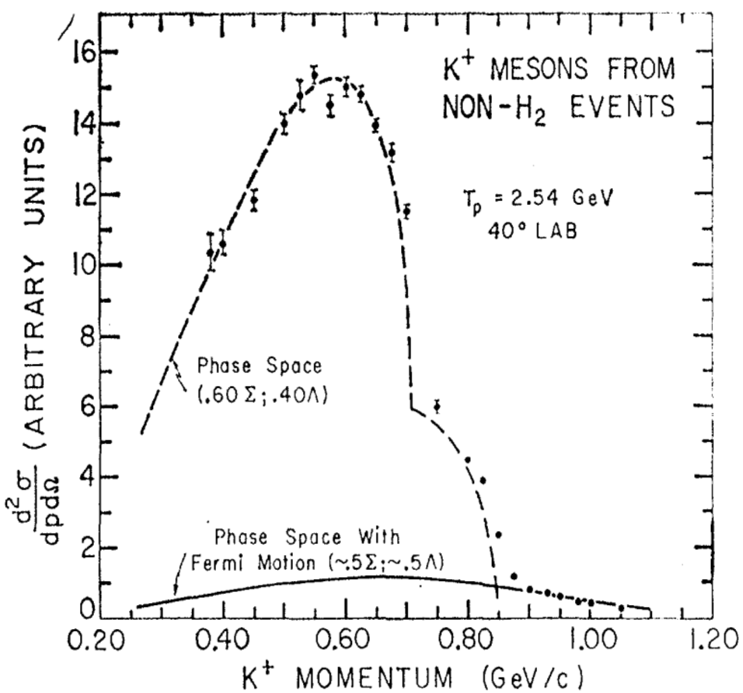
We have been here before: Princeton-Penn Accelerator

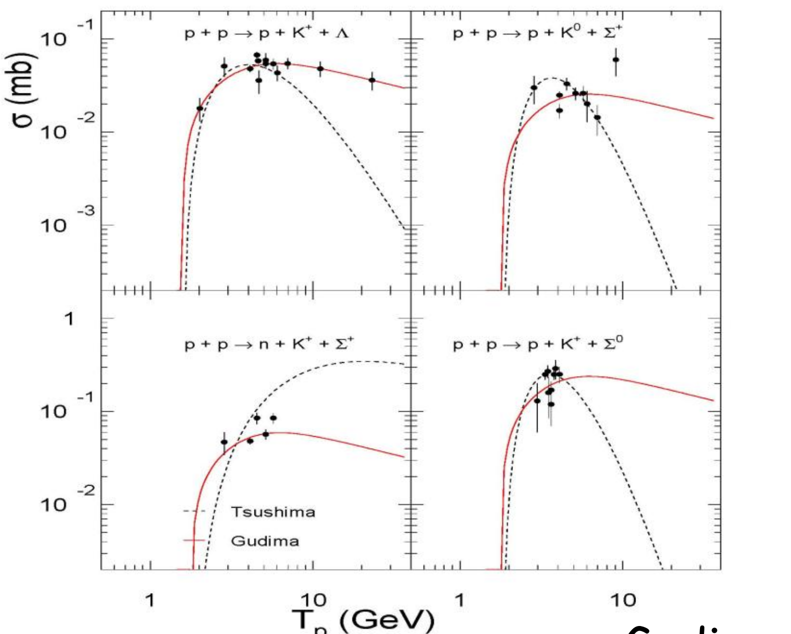
PHYSICAL REVIEW VOLUME 166, NUMBER 5 25 FEBRUARY 1968

K^+-Meson Production in *p*–*p* Collisions at 2.5–3.0 GeV *

W. J. Hogan,† P. A. Piroué, and A. J. S. Smith
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received 24 August 1967)

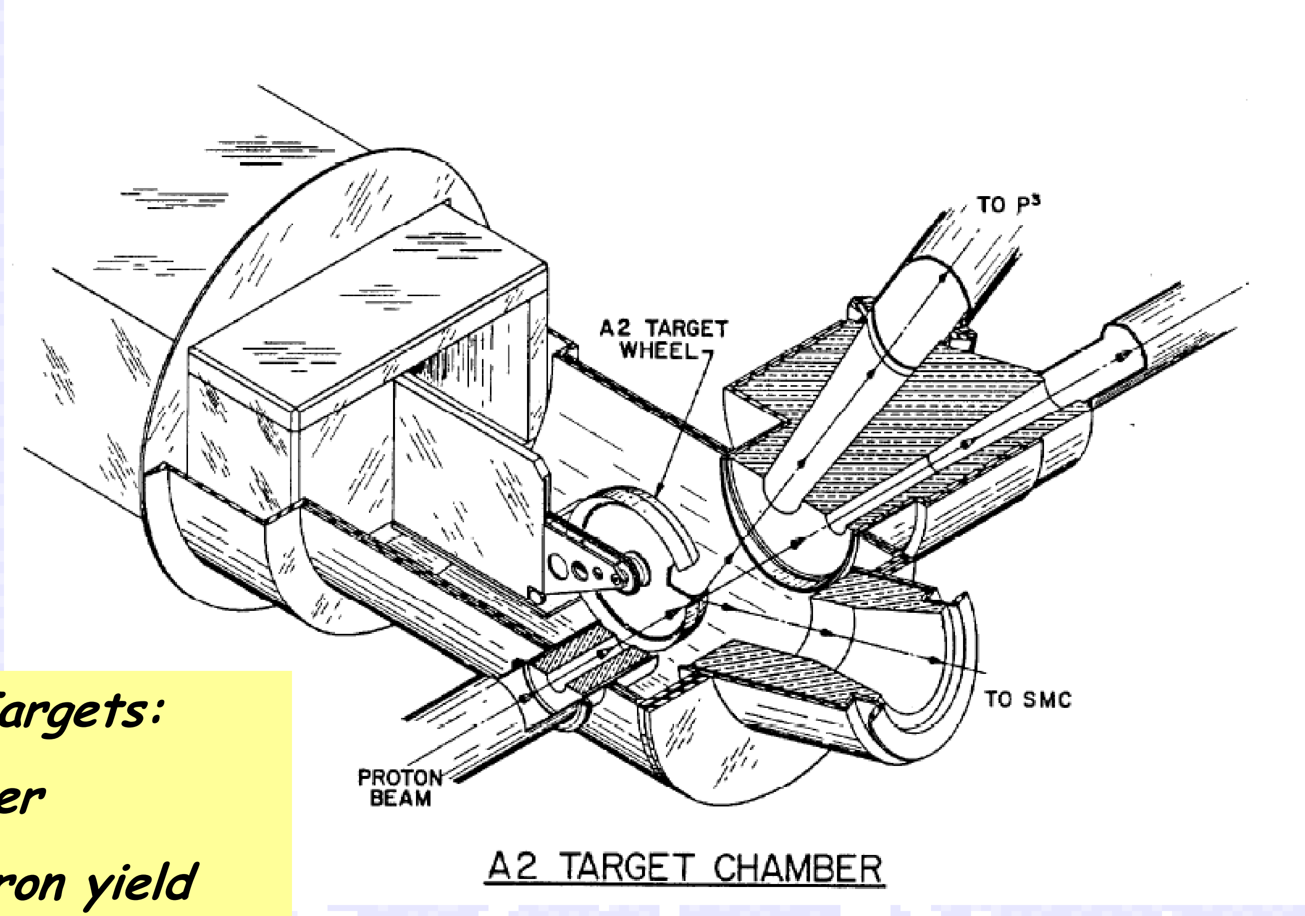




Gudima

Project-X proton flux is x10^8-10^9 higher than the PPA extracted flux.

Real Experience with low-energy, low-Z High-power Targets: LANL



Carbon Targets:

High power

Low neutron yield

Kaon transparency

Back down to Earth: The Challenge of Neutrino Experiments

- The currency is:

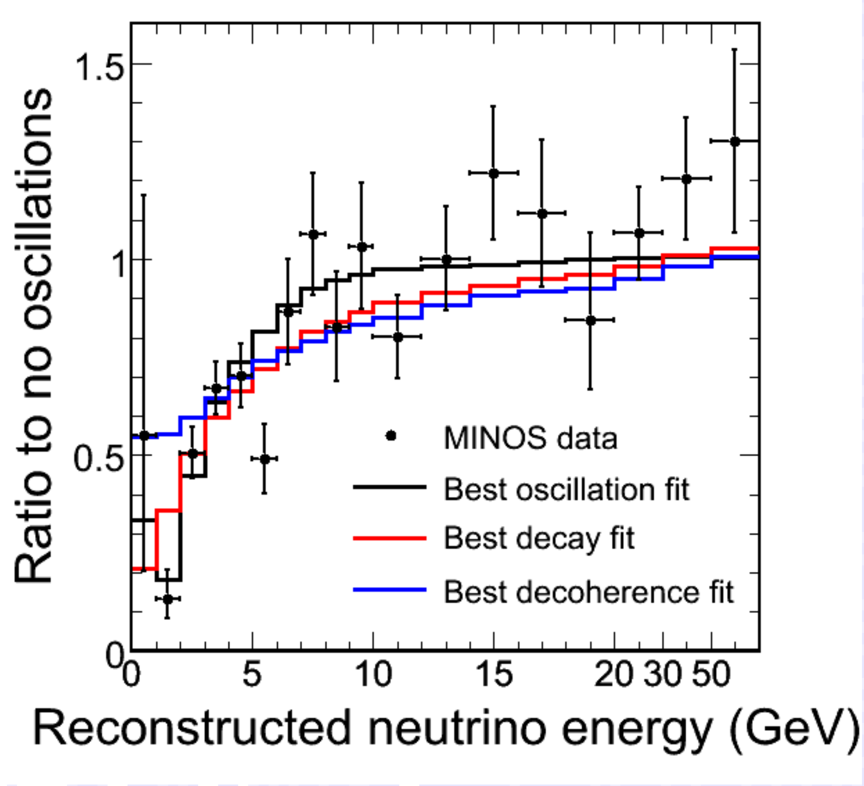
(Beam power)x(Detector Mass)x(Background Rejection)

MINOS is state of the art LB experiment:

Observed 848 events

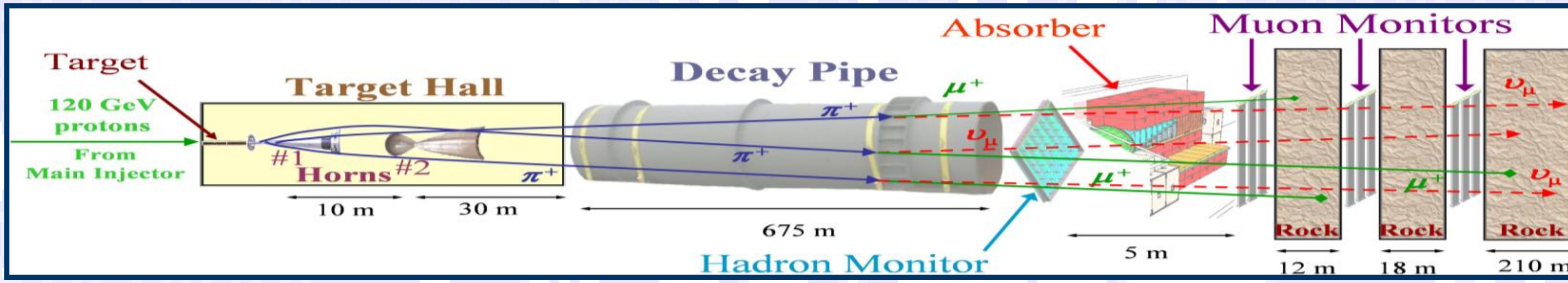
Expect 1060 ± 60 events if no oscillations

•250 kW of beam power
•5-kT detector mass
•Nearly 5 years of data



Why is it Hard? (I)

NuMI (120 GeV protons)



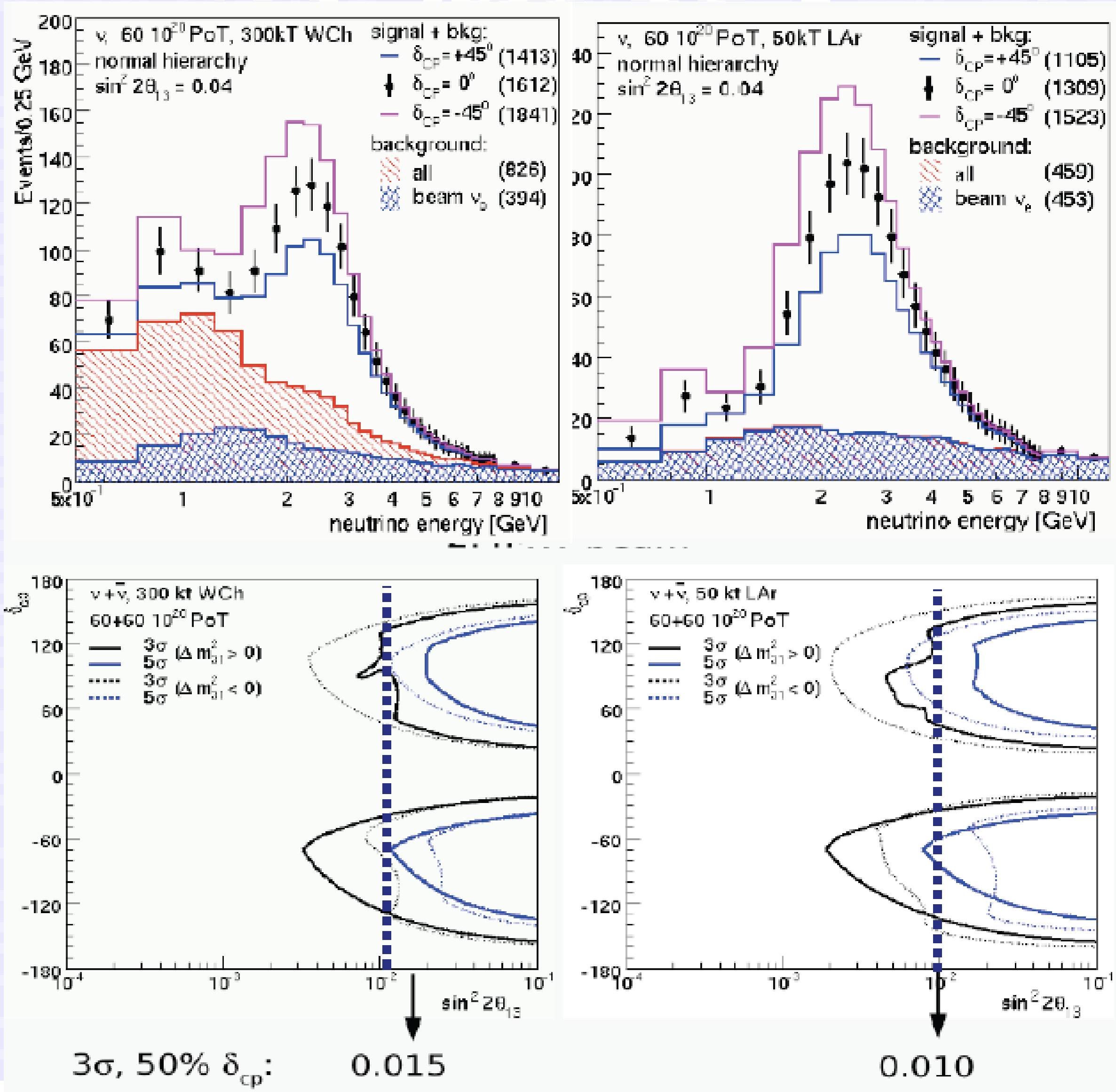
J. Cooper

Why is it Hard? (II): Backgrounds

Water Cerenkov:

(300 kT !!)

“Established” technology but higher backgrounds.



Liquid Argon:

(50 kT !!)

“Reach” technology but lower backgrounds.

G. Rameika

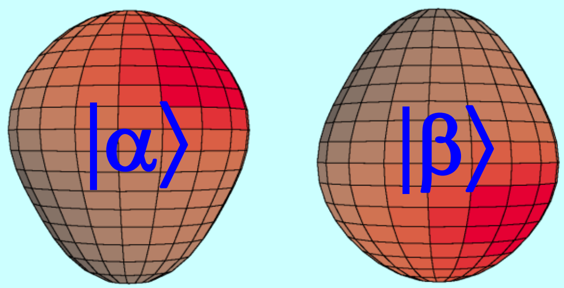
Enhanced EDM of ^{225}Ra

Enhancement mechanisms:

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

Haxton & Henley (1983)
Auerbach, Flambaum & Spevak (1996)
Engel, Friar & Hayes (2000)

Parity doublet



$$\Psi^{-} = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$$

55 keV

$$\Psi^{+} = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$$

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

Skyrme Model	Isoscalar	Isovector	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

Slow Extracted Beam: The Standard Tool to Drive Ultra Rare Decay Experiments

- Techniques developed in the late 1960's to "slow spill" beam from a synchrotron.
- Technique operates at the edge of stability---Betatron oscillations are induced which interact with material in the beam (wire septum) to eject particles from the storage ring beam phase space.
- Technique limited by septum heating & damage, beam losses, and space charge induced instabilities. Works better at higher energies where the beam-power/charge ratio is more favorable.
- Performance milestones:

  Tevatron 800 GeV FT: 64 kW of SEB in 1997.
  BNL AGS 24 GeV beam, 50-70 kW of SEB.

- JPARC Goal: 300 kW of SEB someday, a few kW within reach now.

Spallation neutron yields

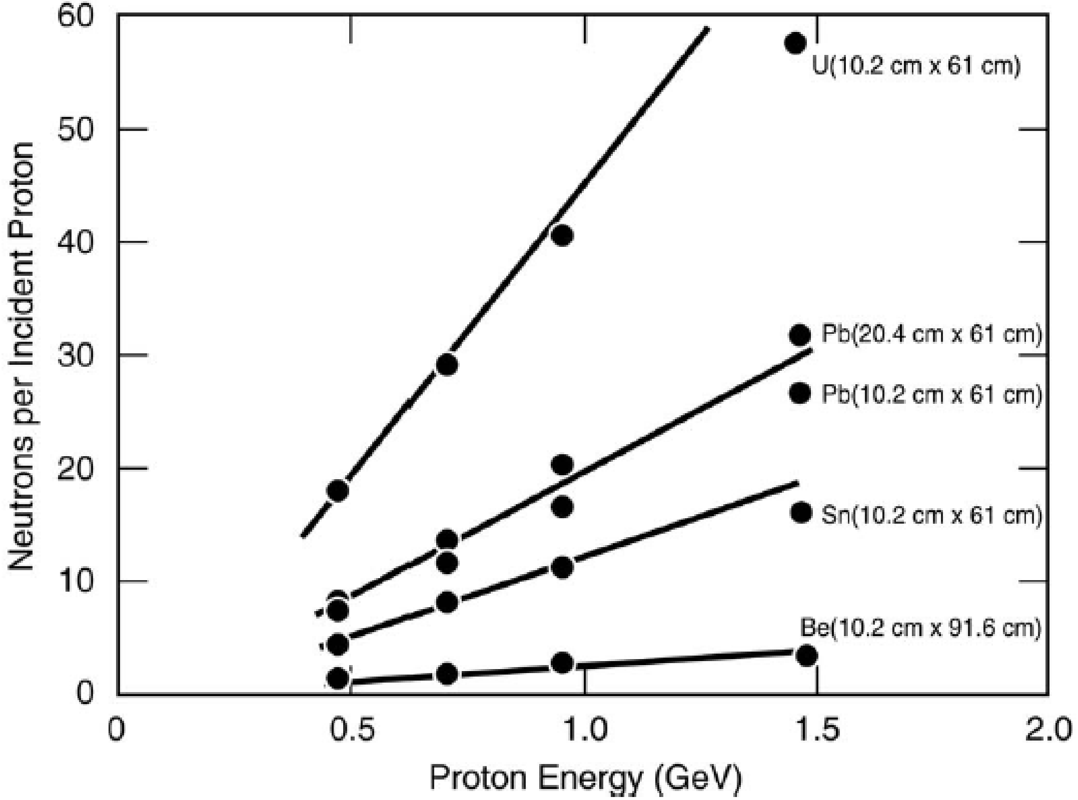
Measured Spallation Neutron Yield vs. Proton Energy for Various Targets, J. Frazer, et al. (1965)

Absolute Global Neutron Yield

Yield (neutrons/proton)

$= 0.1(E_{GeV} - 0.12)(A+20)$, except fissionable materials;

$= 50.(E_{GeV} - 0.12)$, ^{238}U.



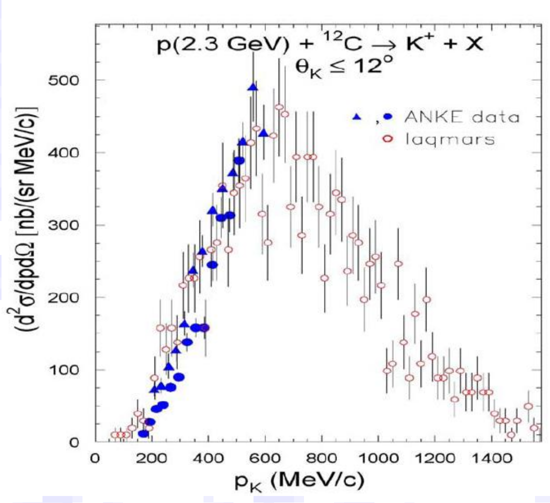
Courtesy John Carpenter, ANL-IPNS/SNS

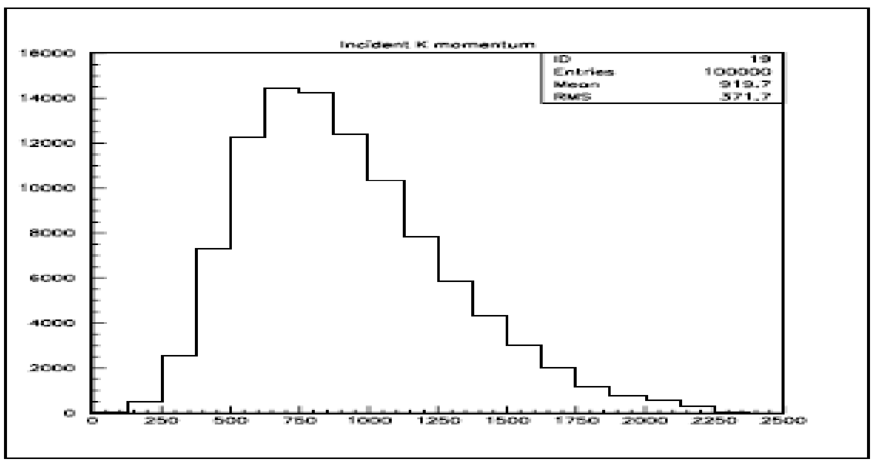
Project-X Sensitivity to $K^+ \rightarrow \pi^+ \nu\nu$

	Beam Energy T_p	Protons/second (avg) on [target (λ_I)]	$p(K^+)$ (MeV/c)	Stopping K^+/second	K^+/π^+ Ratio
BNL AGS (E949)	21 GeV	12×10^{12} on [0.7 λ_I Pt.]	700-730	0.7×10^6	1:24
Tevatron Stretcher Initiative [K.7]	150 GeV	3.6×10^{12} on [1.1 λ_I Pt.]	530-570	$(3\text{-}5) \times 10^6$	1:20
ICD-2 K^+ expt	2.6 GeV	$1/3 \times 6000 \times 10^{12}$ on [1.0 λ_I C]	530-570	43×10^6	1:120

Table 4: Compares the measured rate of stopping K^+ in the BNL-E949 experiment with full LAQGSM/MARS thick-target simulations for stopping rates in the Tevatron Stretcher Initiative and an identical beamline and stopping target with 1/3 of the ICD-2 beam power.

KOPIO-AGS and Project-X kaon momentum spectra comparison





KOPIO Proposal

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

Project-X Sensitivity to $K_L \rightarrow \pi^0 \nu\nu$

	Beam Energy	Target (λ_I)	$p(K^+)$ (MeV/c)	K_L Yield (into 500 μsr)	K_L/n Ratio (E_n>10 MeV)
BNL AGS	24 GeV	1.1 Platinum	300-1200	30×10^{-7} K_L/p	~1:1000
ICD-2	2.6 GeV	1.0 Carbon	300-1200	1×10^{-7} K_L/p	~1:4000

Table 5 Comparison the K_L production from thick targets fully simulated with LAQGSM and MARS into the KOPIO beam and momentum acceptance. The BNL AGS kaon and neutron yields are from RSVP reviews in 2004 (Bryman) and Jaffe (2005).

Table 5 shows that the AGS K_L/p yield is x30 the ICD-2 K_L/p yield. ICD-2 can compensate with a proton flux x300 the AGS RSVP goal of 100×10^{12} protons every 5 seconds. Hence the ICD-2 neutral kaon flux into the KOPIO beam acceptance is x10 the AGS flux goal into the same beam acceptance. The KOPIO initiative had a statistical sensitivity of 100 Standard Model events with about 10,000 hours of running. A nominal five-year run with ICD-2 is x2.5 the duration of the KOPIO AGS initiative and hence the reach of an ICD-2 KOPIO experiment is x25 times the reach of the RSVP goals. An experiment based on 40% of the ICD-2 CW beam flux could have a sensitivity of 1000 Standard Model events with comparable detector rates of the AGS KOPIO design.

After Mu2e, what does more beam power buy you?

- Current Mu2e detector design is rate limited at about 25kW of beam power. Faster detector elements can marginally improve the situation…gains are limited.
- Different experiments, different optimization. e.g: Monochromatic muon beams! Pickup elements of the SINDRUM-II technique, and use the dE/dx difference between pions and muons to separate them. A monochromatic beam also permits a small beam spot on the stopping target which simplifies detector design.

A search for $\mu - e$ conversion in muonic gold

The SINDRUM II Collaboration

W. Bertl[1], R. Engfer[2], E.A. Hermes[2], G. Kurz[2], T. Kozlowski[3], J. Kuth[4], G. Otter[4], F. Rosenbaum[1], N.M. Ryskulov[1], A. van der Schaaf[2], P. Wintz[4], I. Zychor[3]

[1] Paul Scherrer Institut, Villigen, Switzerland
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[3] IPJ Swierk, Swierk, Poland
[4] RWTH Aachen, Aachen, Germany

Received: 13 April 2006 /
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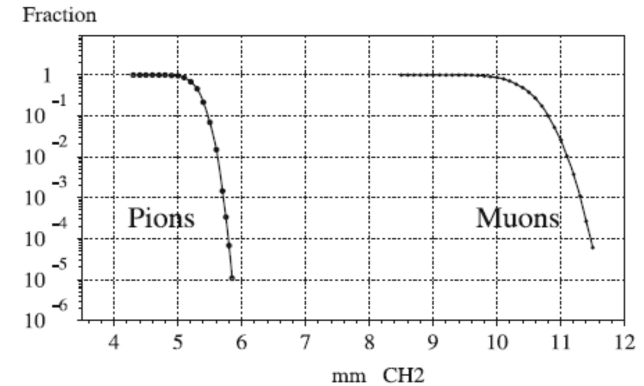
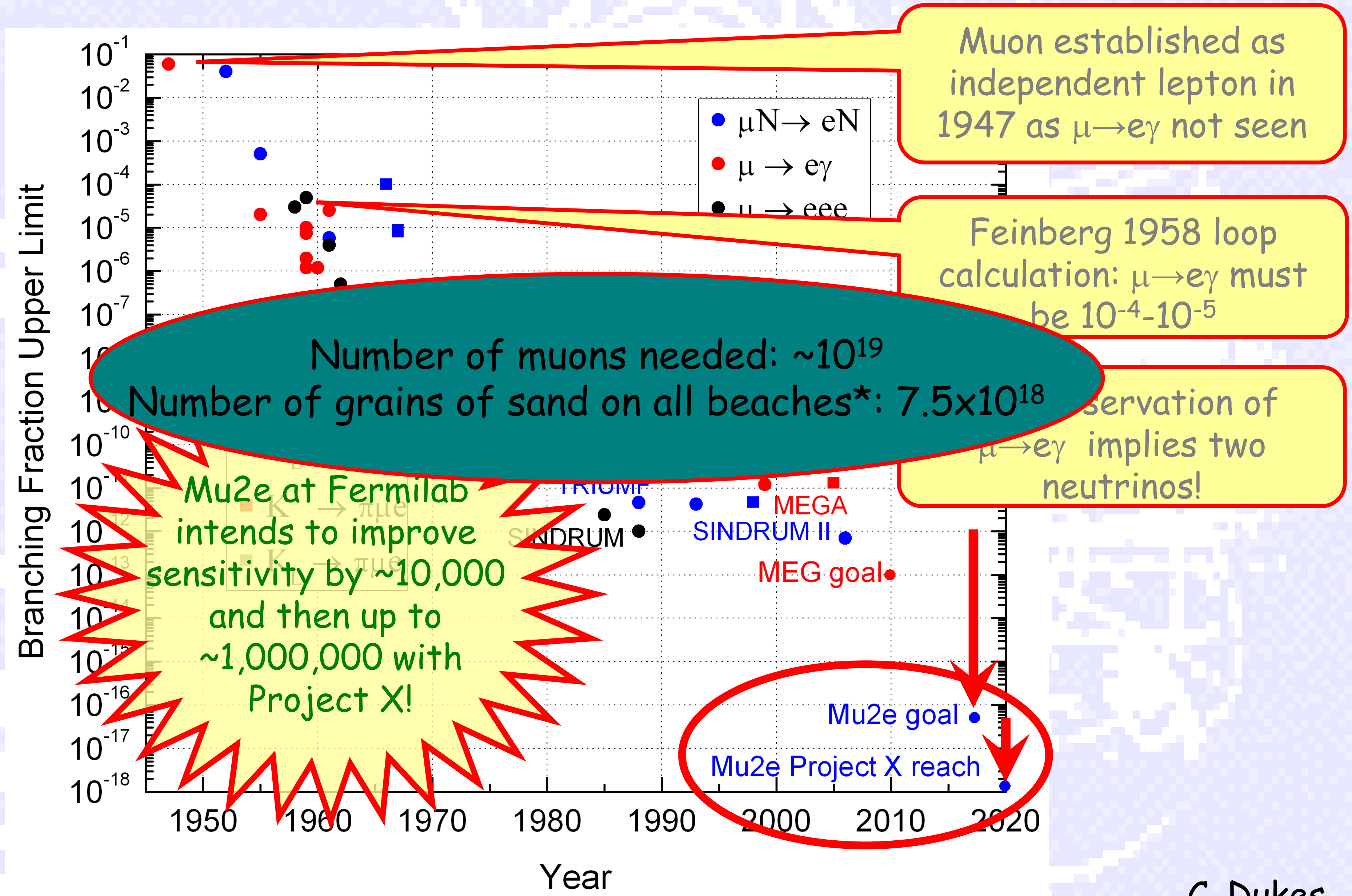


Fig. 1. Fraction of pions and muons with a momentum of 52 MeV/c that cross a CH_2 moderator as a function of the moderator thickness. GEANT [23] simulation

History of Lepton Flavor Violation Searches



C. Dukes

* http://www.hawaii.edu/suremath/jsand.html

Enhanced EDM of ^{225}Ra

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

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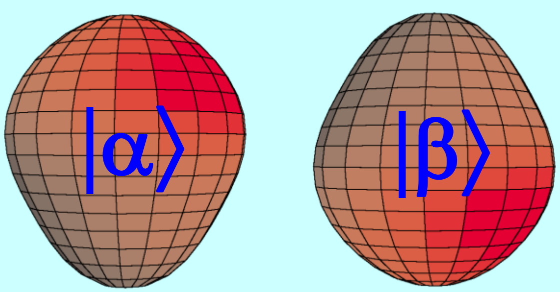
Parity doublet



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$$\Psi^+ = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$$

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

Skyrme Model	Isoscalar	Isovector	Isotensor
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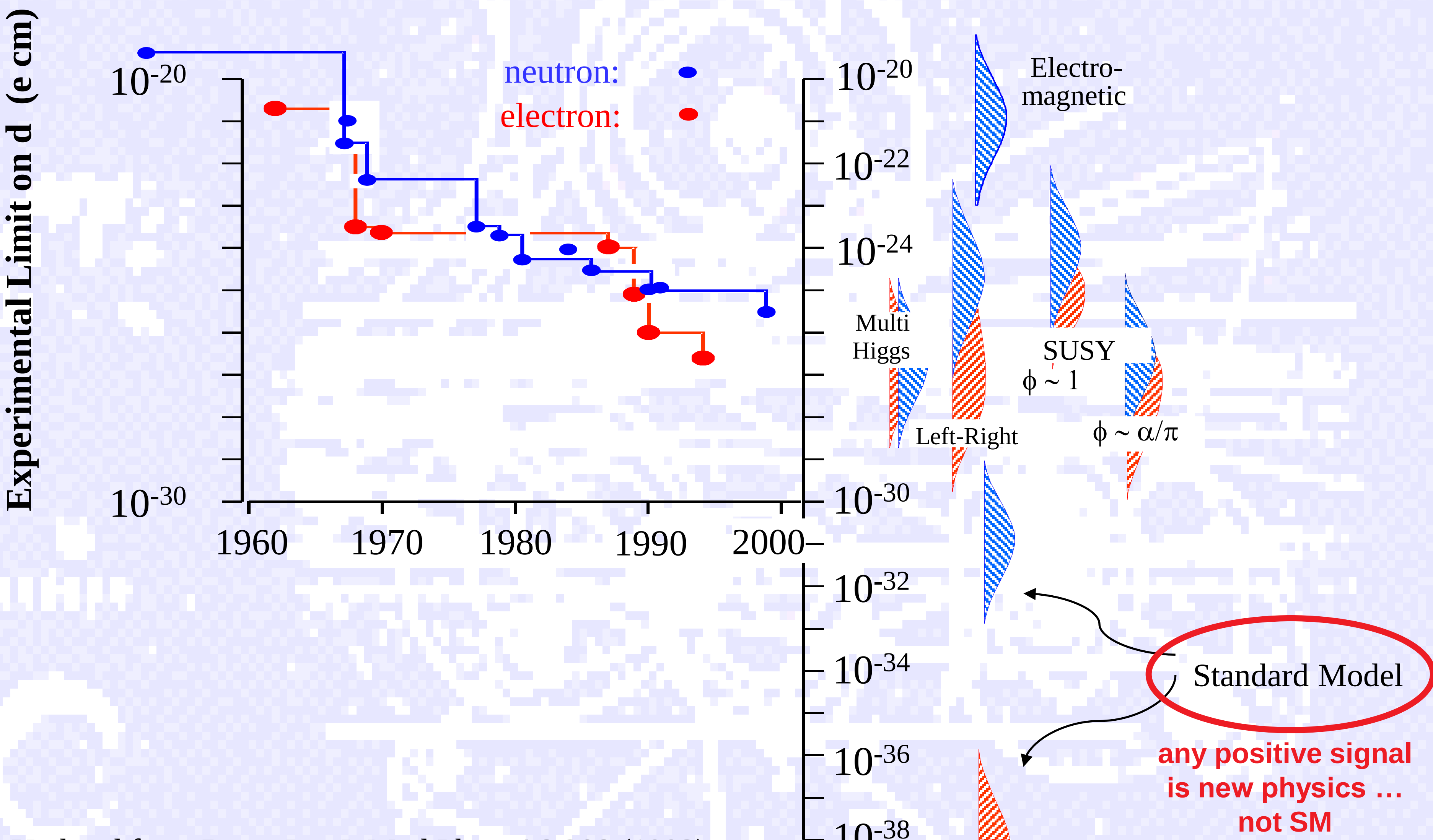
Schiff moment of ^{199}Hg, de Jesus & Engel, PRC (2005)
Schiff moment of ^{225}Ra, Dobaczewski & Engel, PRL (2005)

Guy Savard, ANL

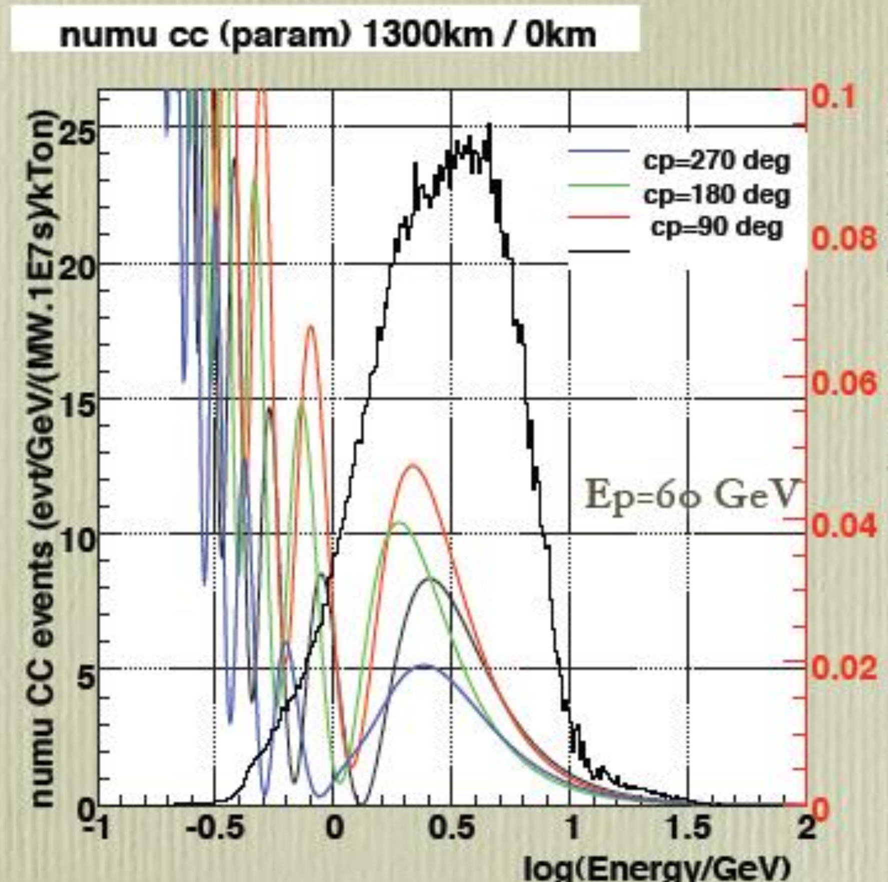
EDM measurements: BSM slayers

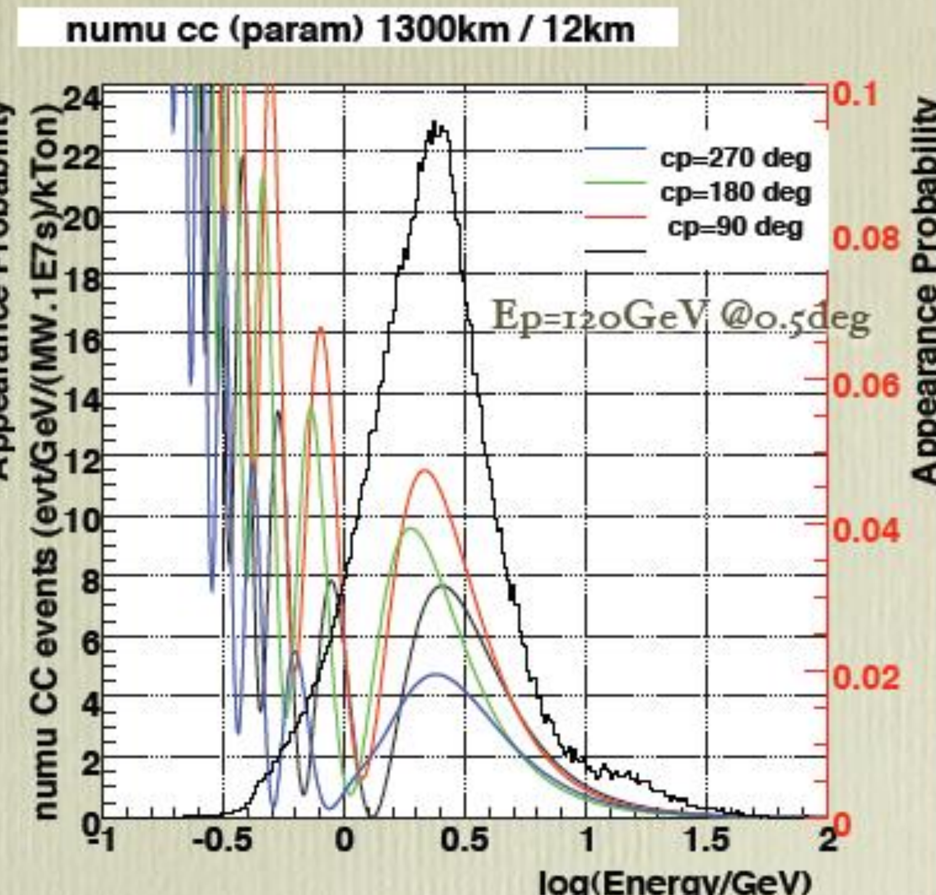


Updated from Barr: Int. J. Mod Phys. A8 208 (1993)

Guy Savard, ANL

Spectra FNAL to DUSEL (WBLE:wide band low energy)





- 60 GeV at 0deg: CCrate: 14 per (kT*10^20 POT)
- 120 GeV at 0.5deg:CCrate: 17 per(kT*10^20POT)

Work of M. Bishai and B. Viren using NuMI simulation tools

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