The Project-X Research Program

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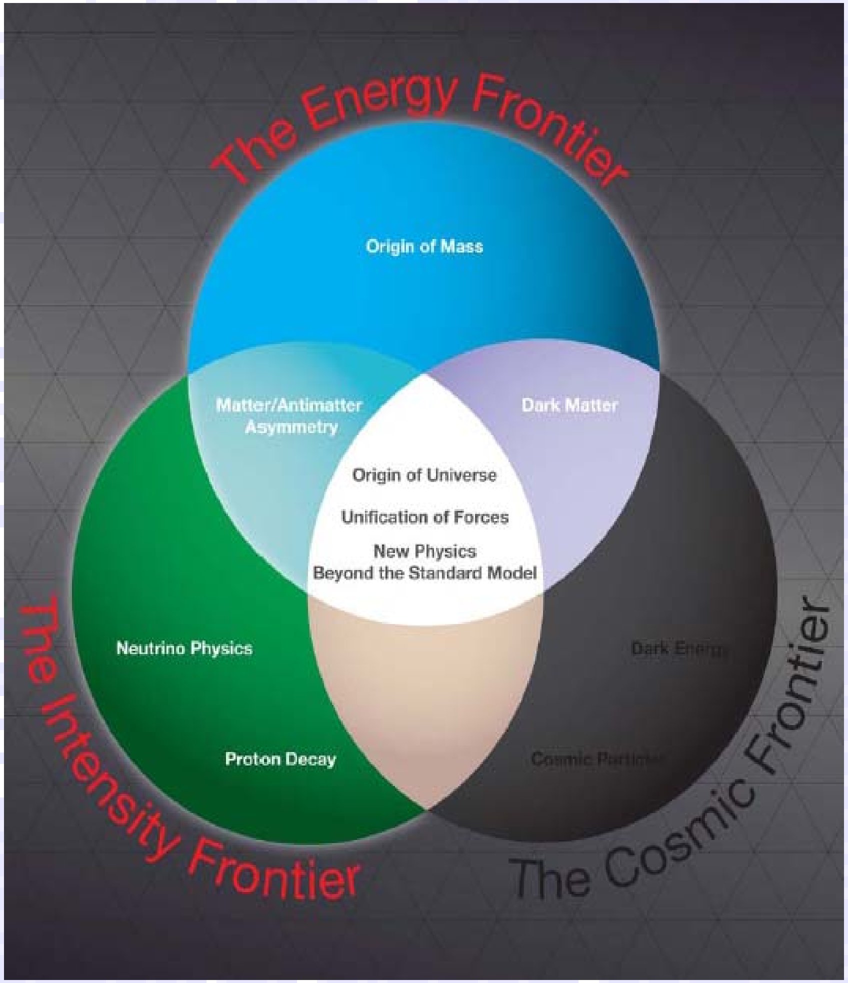
Fermilab

September 11th , 2009

The Promise of the Intensity Frontier

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

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

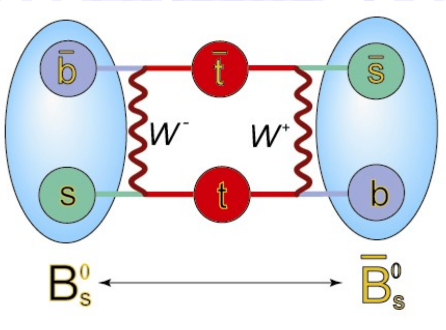


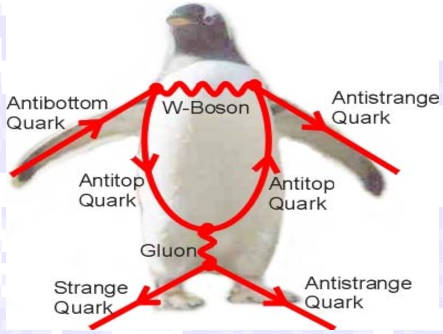
Project-X Research Program

- ***A neutrino beam for long baseline neutrino oscillation experiments.*** A new two or more megawatt proton source with proton energies between 50 and 120 GeV that would produce intense neutrino beams, directed toward a large detector located in a distant underground laboratory.
- ***Kaon and muon based precision experiments driven by high intensity proton beams running simultaneously with the neutrino program.*** These could include a world leading muon-to-electron conversion experiment and world leading rare kaon decay experiments.
- ***A path toward a muon source for a possible future neutrino factory and, potentially, a muon-collider at the Energy Frontier.*** This path requires that the new proton source have significant upgrade potential.

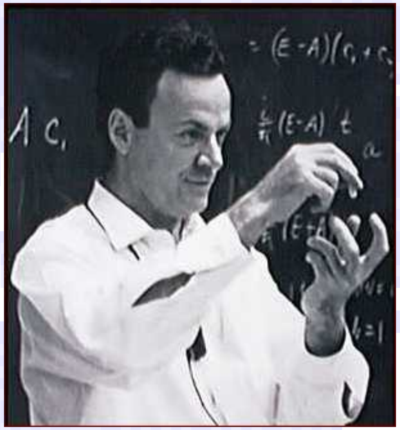
Kaon and Muon Experiments Deeply Attacks The Flavor Problem

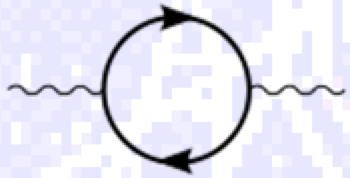
Why don't we see the *Terascale Physics we expect* affecting the flavor physics we study today??



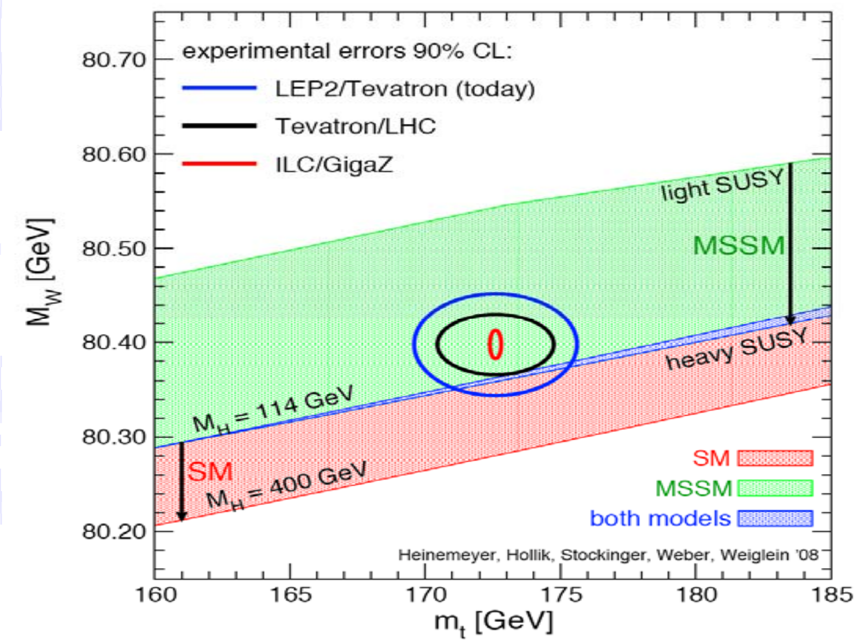


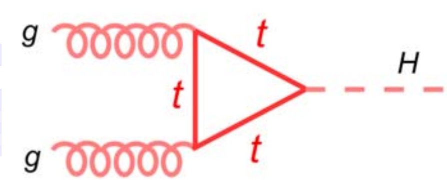
Why we believe in loops…

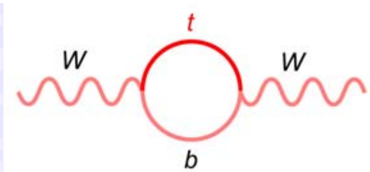




QED! Lamb Shift, $(g-2)_e$, α_{EM}, etc.







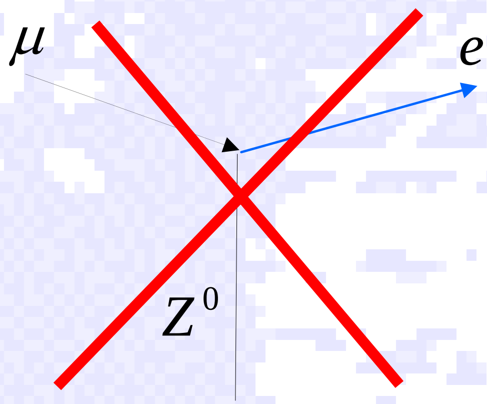
- Suppressed Flavor Changing Neutral Currents in kaon decays predicted the charm quark and the right mass range for m_c.

- Precision measurement of W and top masses predicts a low mass Higgs.

- Critical in New Physics frameworks such as Super-Symmetry.

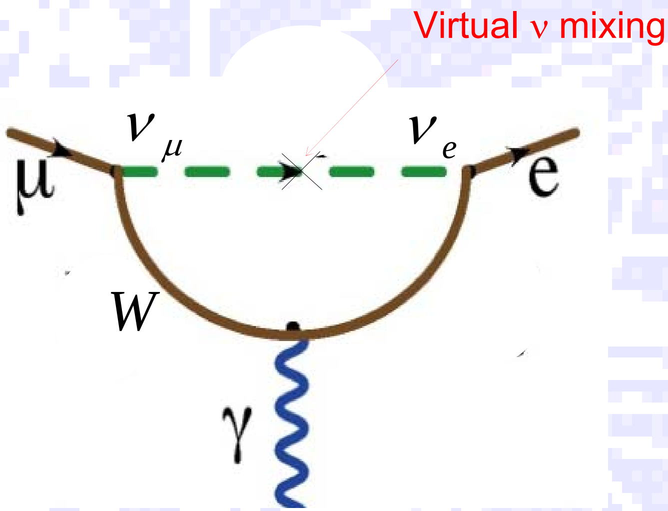
The deepest probe of Lepton Flavor Physics: Ultra-rare μ-Decays:

First Order FCNC:



- **Forbidden in Standard Model**

Higher order dipole "penguin":



- **Observation of neutrino mixing shows this can occur at a very small rate**
- **Photon can be real (μ->eγ) or virtual (μN->eN)**

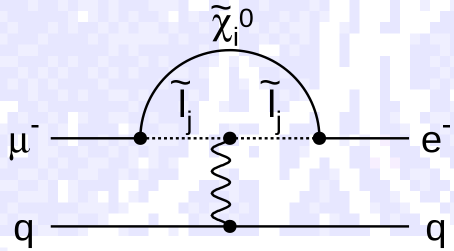
$$Br(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

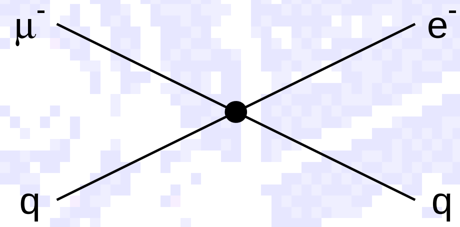
The MEG(PSI) experiment sensitivity is in the 10^{-11} range.

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

Supersymmetry

Predictions at 10^{-15}



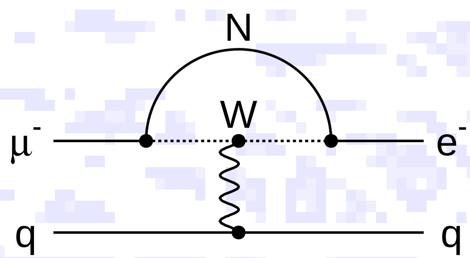


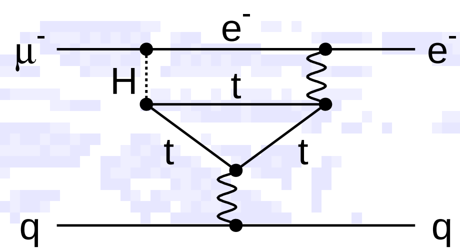
Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

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



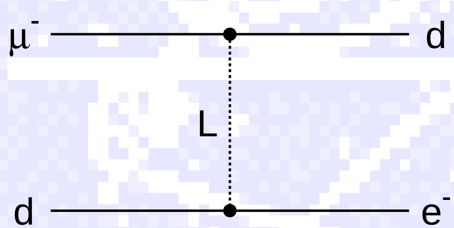


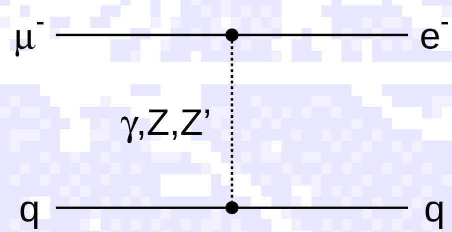
Second Higgs doublet

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

Leptoquarks

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





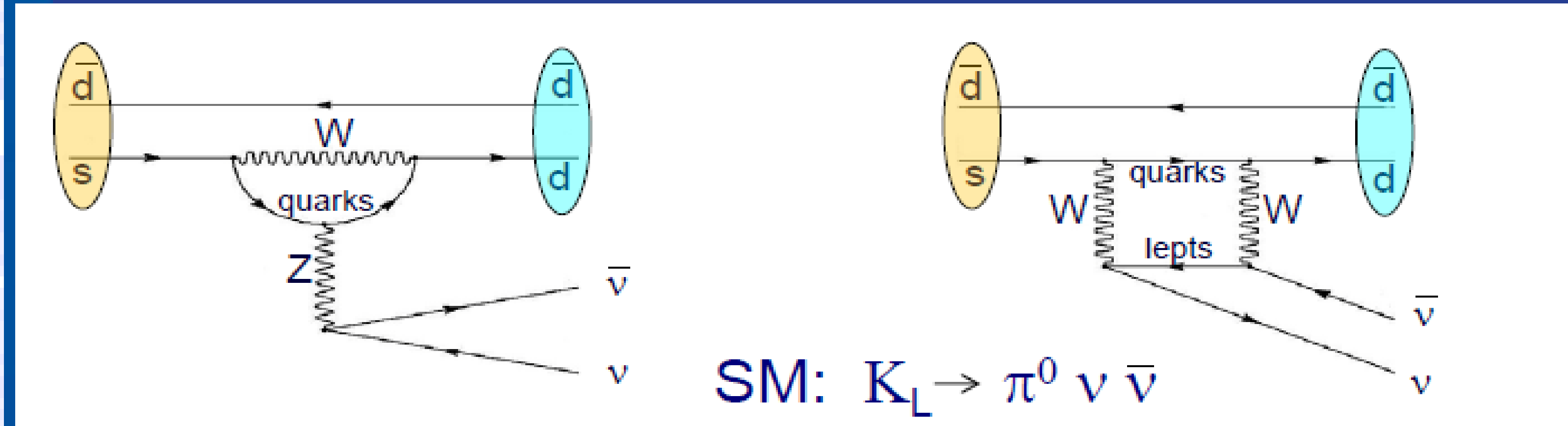
Heavy Z', Anomalous Z coupling

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

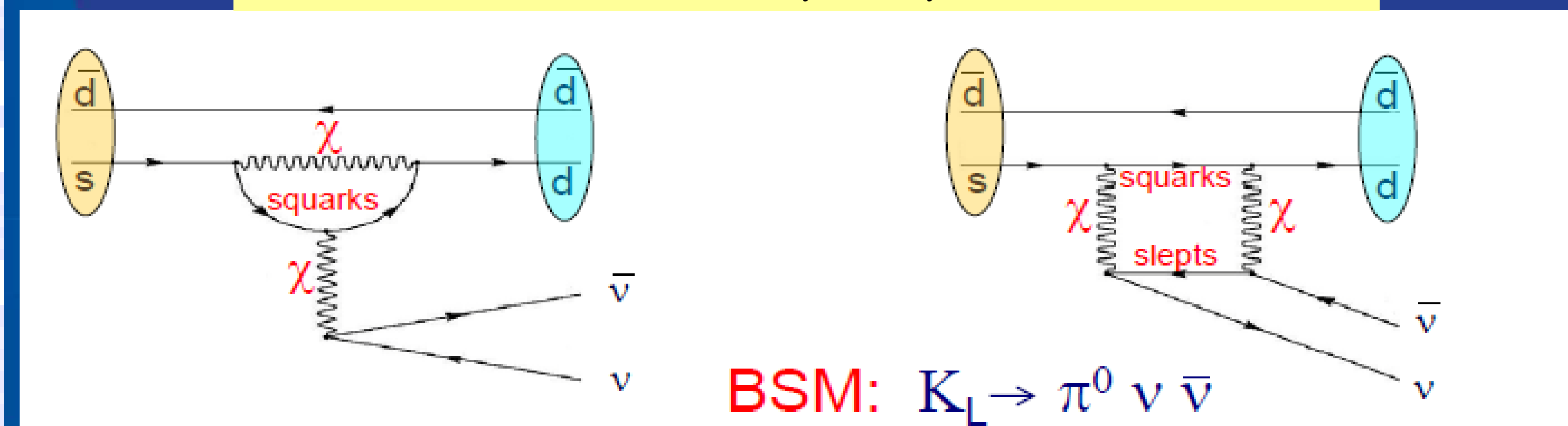
$B(Z \to \mu e) < 10^{-17}$

After W. Marciano

The Window of Ultra-rare Kaon Decays



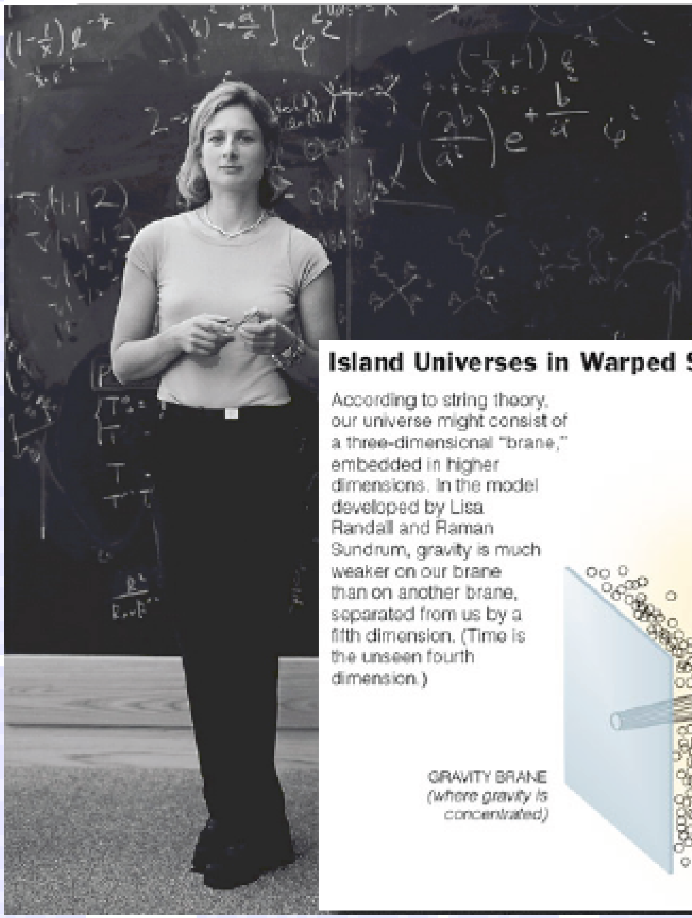
Standard Model rate of 3 parts per 100 billion!

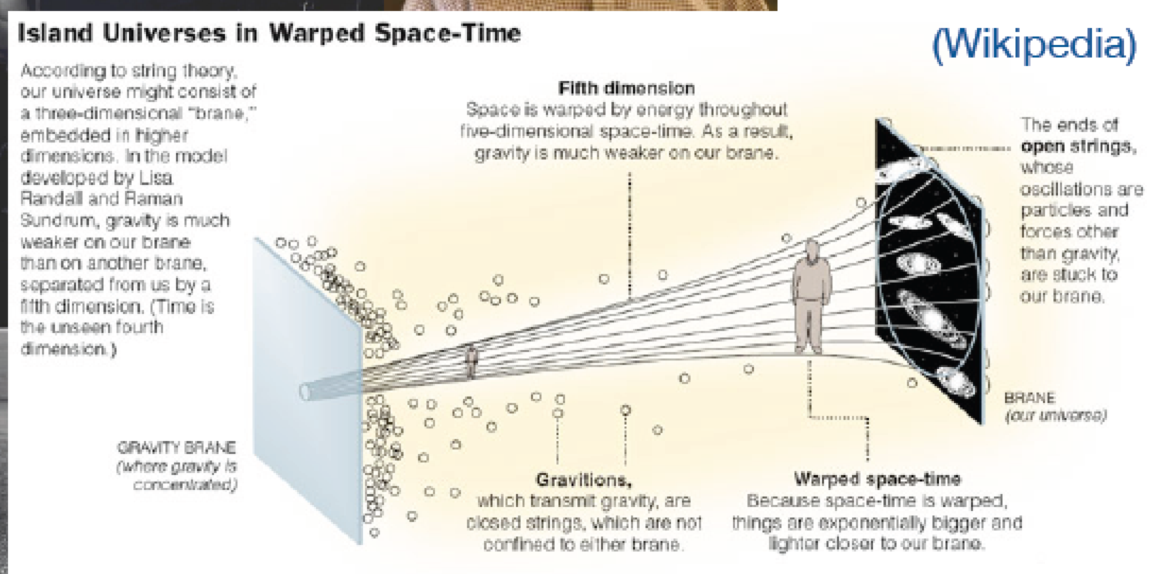


BSM particles within loops can increase the rate by x10 with respect to SM.

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

The Randall-Sundrum (RS) idea

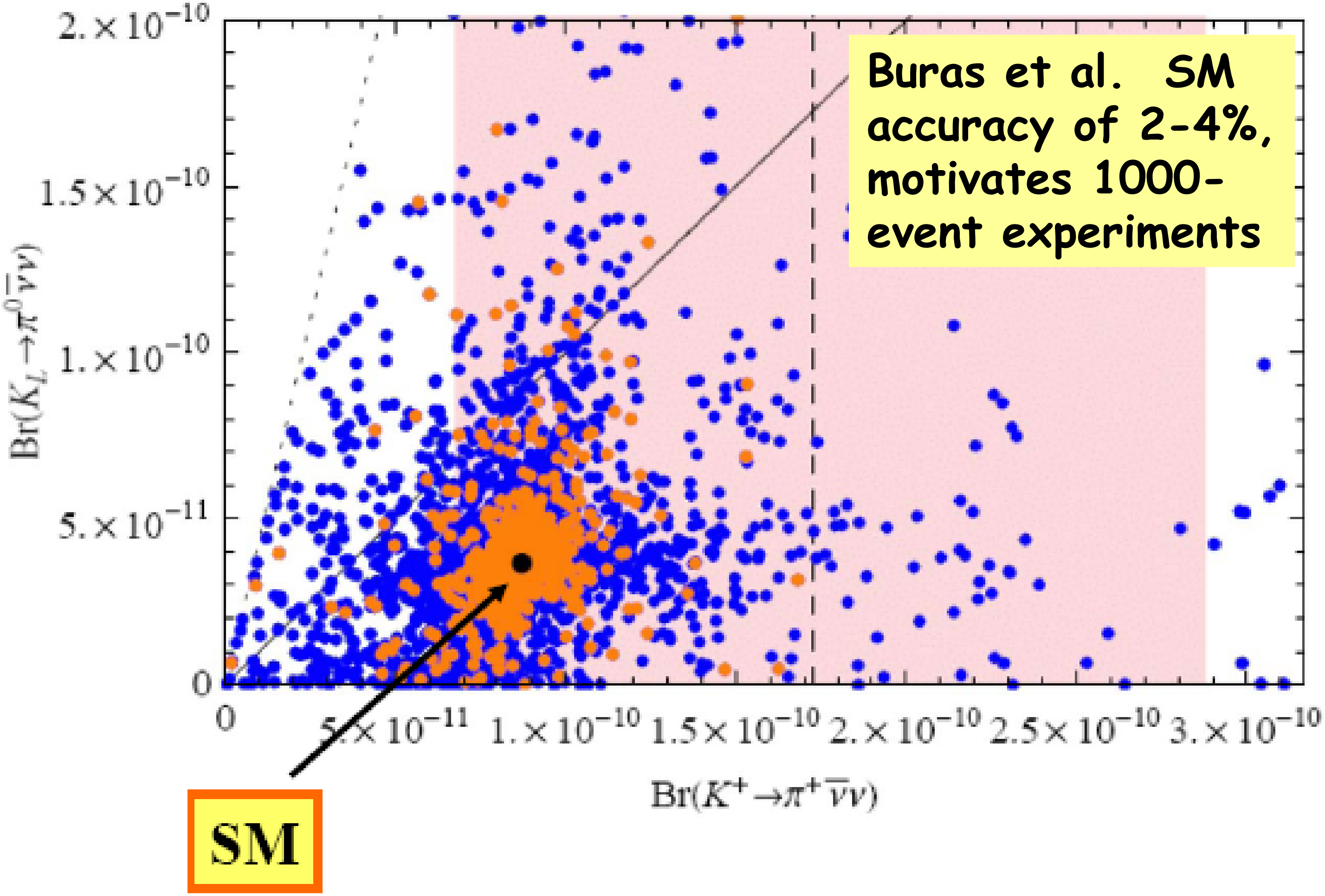




(Wikipedia)

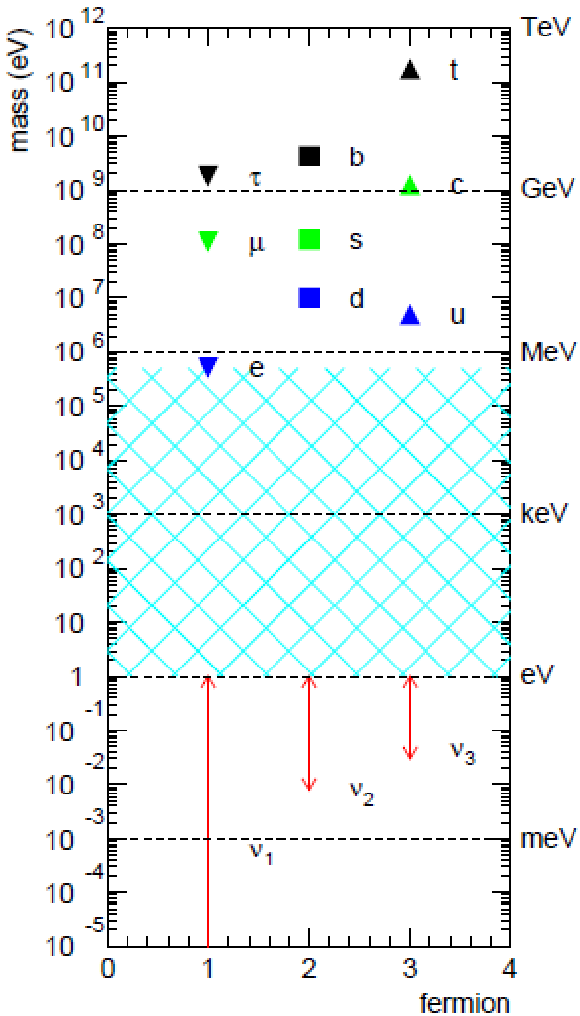
$K_L \rightarrow \pi^0 \nu\bar{\nu}$ vs. $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (RS)

(Up to Factor 3 and 2 Enhancements)



Effect of Warped Extra Dimension Models on Branching Fractions

What are Neutrinos Telling Us?



What We Are Trying To Understand:

⇐ NEUTRINOS HAVE TINY MASSES

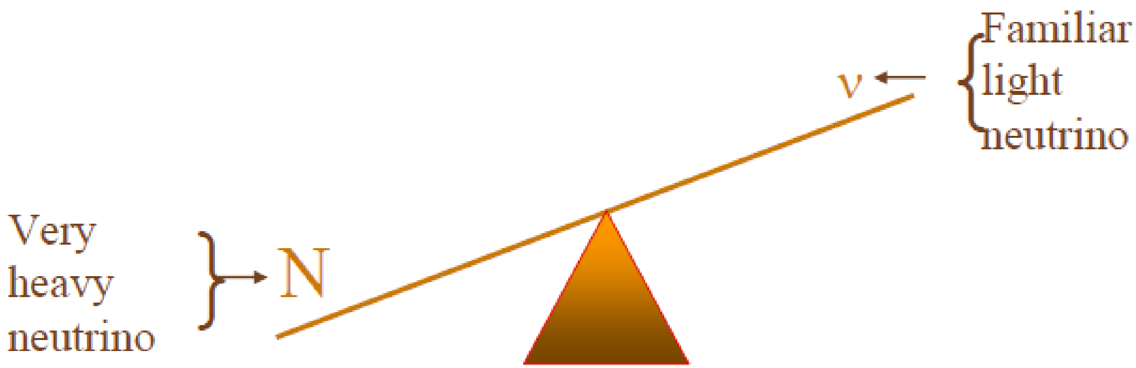
⇓ LEPTON MIXING IS "WEIRD" ⇓

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

What Does It Mean?

Leveraging to the Unification Scale

See-Saw Mechanism



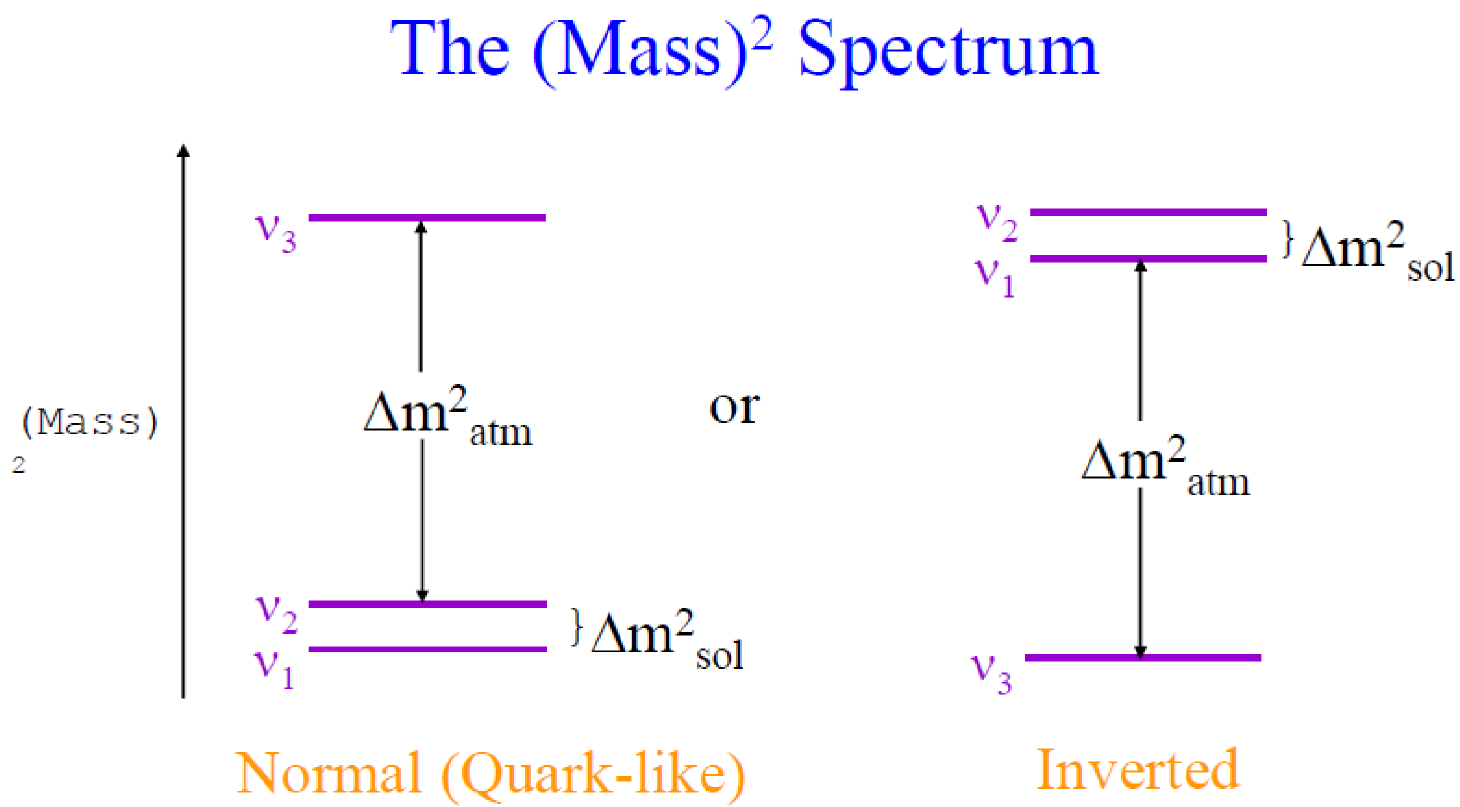
Mass(N) ~ 10^{15} GeV

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

Coincidence??

Boris Kayser

What is Normal?

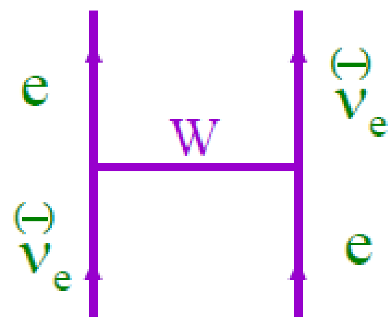


$\Delta m^2_{sol} \cong 7.6 \times 10^{-5}\ eV^2$, $\Delta m^2_{atm} \cong 2.4 \times 10^{-3}\ eV^2$

Boris Kayser

How To Determine If The Spectrum Is Normal Or Inverted

Exploit the fact that, in matter,

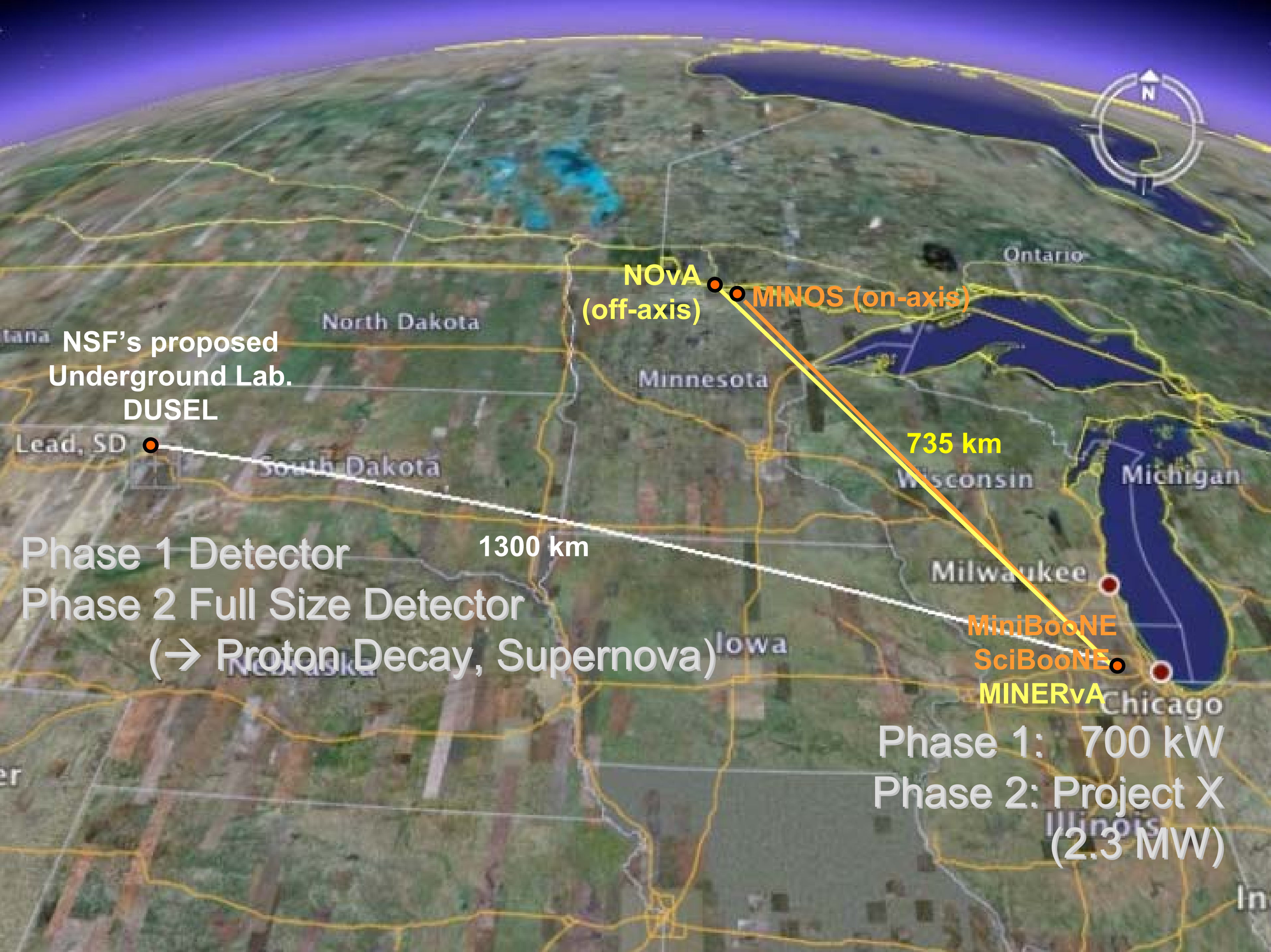


raises the effective mass of ν_e , and lowers that of $\bar{\nu}_e$.

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


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

Back down to Earth: The Challenge of Neutrino Experiments

- The currency is:

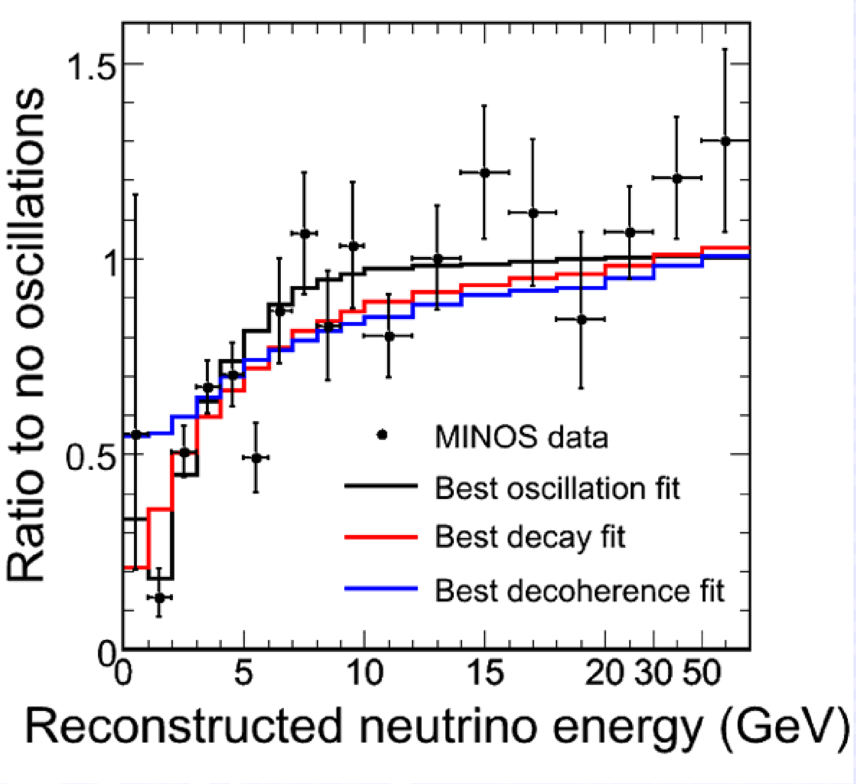
(Beam power)x(Detector Mass)x(Background Rejection)

MINOS is state of the art:

Observed 848 events

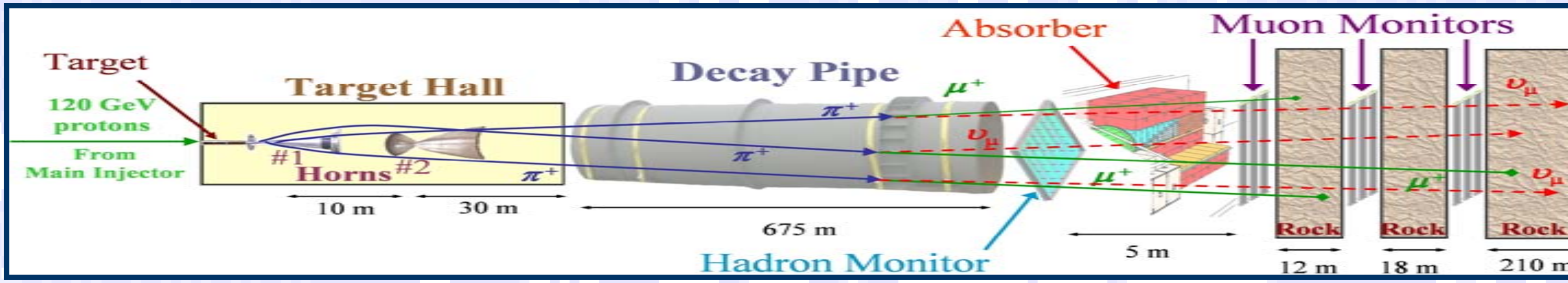
Expect 1060 ± 60 events if no oscillations

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



Why is it Hard? (I)

NuMI (120 GeV protons)



NOvA 14 kt & deep pit of building in "a" football stadium

(wire frame of loading dock in black hangs out over the stands by 30 yards)

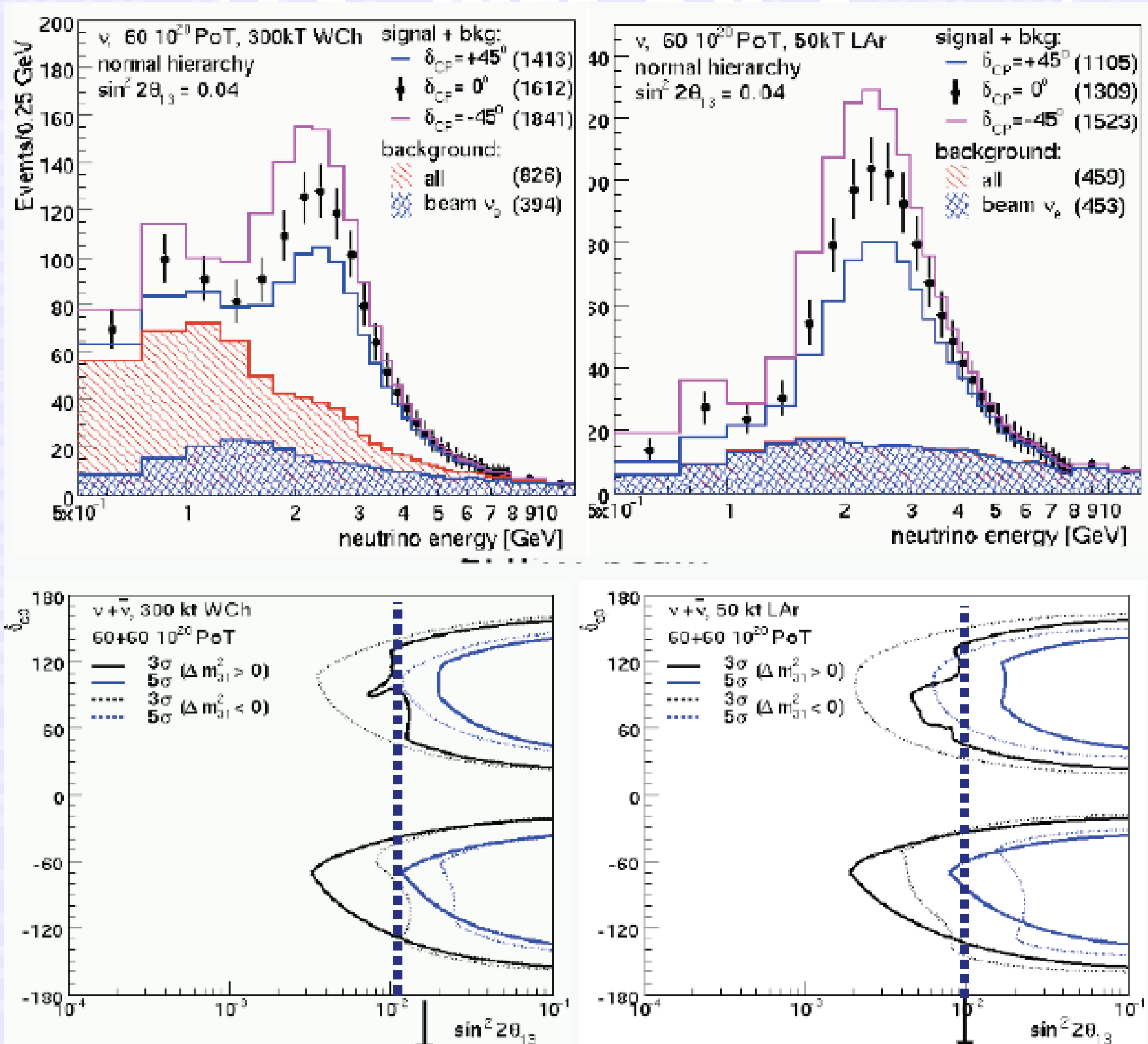
J. Cooper

Why is it Hard? (II): Backgrounds

Water Cerenkov:

(300 kT !!)

"Established" technology but higher backgrounds.



3σ, 50% δ_{cp}: 0.015 0.010

Liquid Argon:

(50 kT !!)

"Reach" technology but lower backgrounds.

G. Rameika

Driving a Future Fermilab Program in Rare-Processes

Before Project-X:

- A conceptual design exists to drive a next generation muon-to-electron conversion experiment (mu2e) with about 25kW of 8 GeV protons through an evolution of the Debuncher/Accumulator. The experiment design is rate limited at about 50kW.
- An initiative has developed to mount a next-generation (g_μ-2) experiment driven with an evolution of the Debuncher/Accumulator.
- A new initiative is being explored to pursue a stopped K^+ experiment driven with 120 GeV beam from the Tevatron Stretcher*.

Project-X:

- Pion and kaon yield, *what we learned in school:* The production of pions and kaons becomes proportional to proton beam power at proton energies above about 5 GeV. ICD-1 (8 GeV) OK, ICD-2?? (2.x GeV).
- Concepts have been developed for 1000-event stopped K^+ and low-energy K_L experiments driven by high duty-factor ICD-1 8-GeV proton beam, using all the beam (200 kW). http://project-x-kaons.fnal.gov/

*Syphers, AD-DocDB 2222, 2849

Project-X Research Program Task Force Members

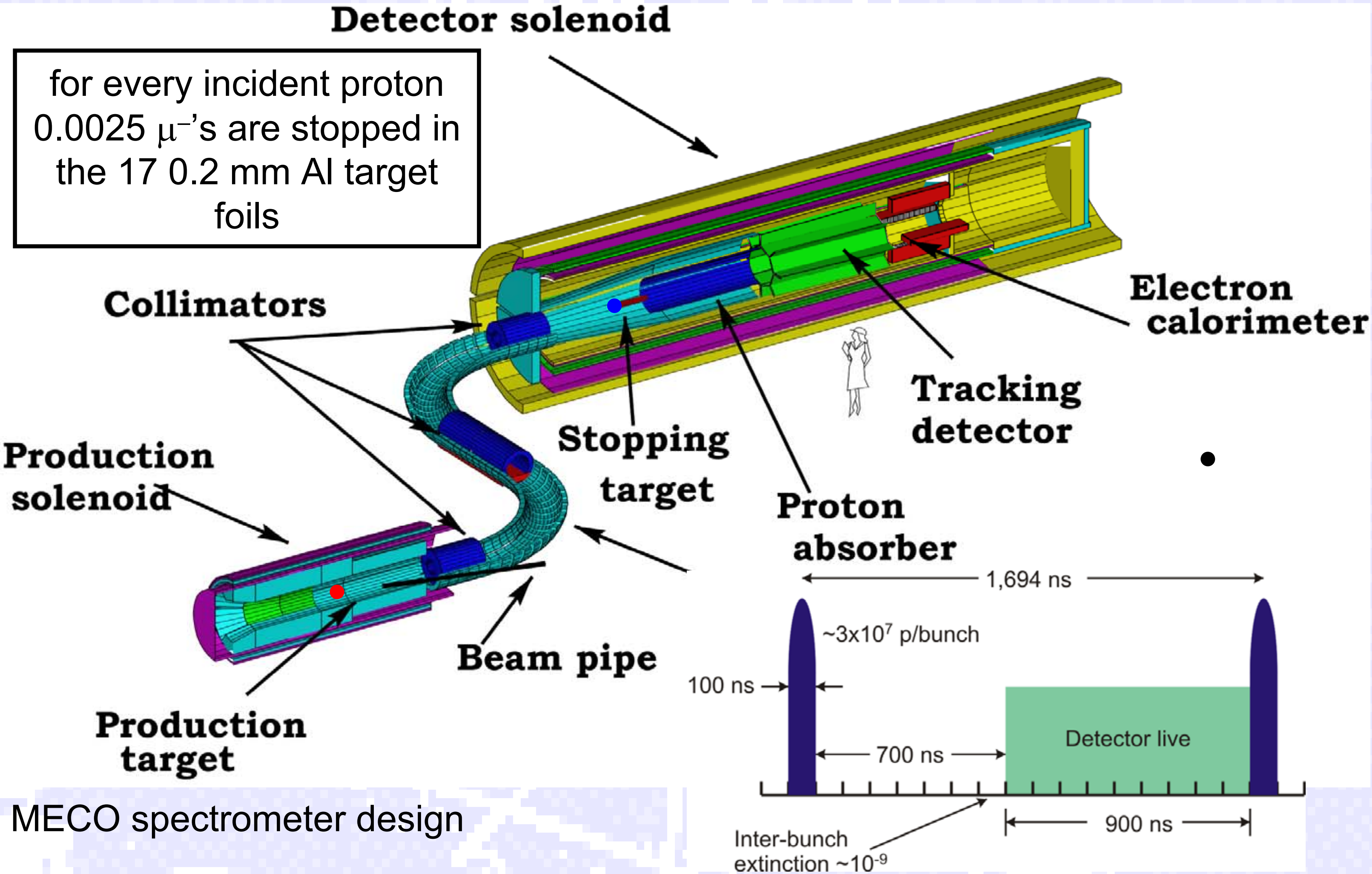
• D. Bryman	UBC/TRIUMF
• M. Campbell	University of Michigan
• D. Christian	Fermilab, PPD
• P. Cooper	Fermilab, CD
• D. Glenzinski	Fermilab, PPD
• V. Lebedev	Fermilab, AD
• N. Mokhov	Fermilab, APC
• S. Nagaitsev	Fermilab, AD
• J. Peoples	Fermilab, Emeritus
• S. Striganov	Fermilab, APC
• M. Syphers	Fermilab, AD
• R. Tschirhart	Fermilab, CD (chair)
• Y Kuno	Osaka University
• Y. Wah	University of Chicago

This committee wrote an interim report that was presented to the June PAC, Final writing in progress.

mu2e Muon Beam and Detector

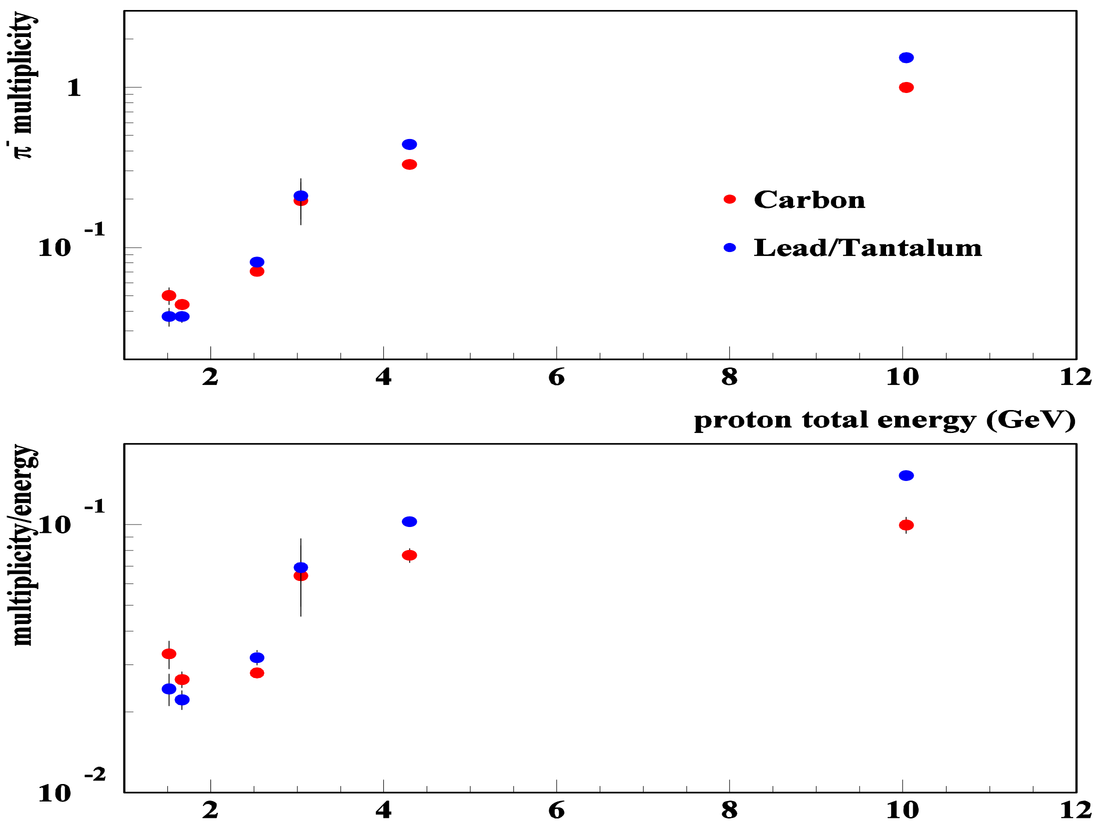
C. Dukes

for every incident proton 0.0025 μ^{-}'s are stopped in the 17 0.2 mm Al target foils



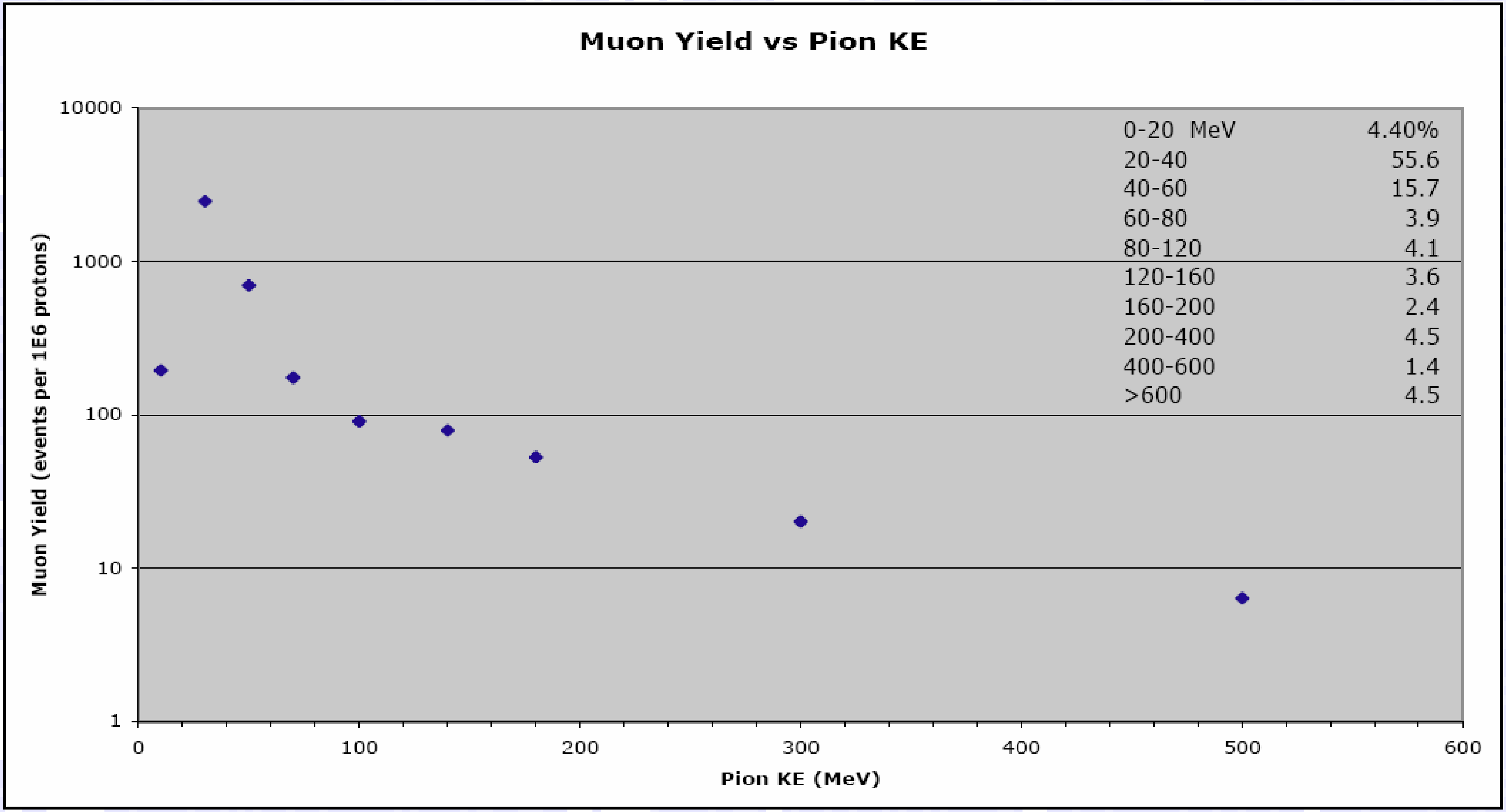
MECO spectrometer design

Charged Pion Yield vs Energy



Experimental data on π^- multiplicity in proton-nucleus interactions

Low energy pions make muons that can be stopped, Consider Mu2e…



R. Coleman

The Next $\mu \rightarrow e$ Conversion Experiment: What are the weapons?

- Beam Power to drive a new technique, possibly a PRISM-FFAG based design.

- ICD-1 runs out of gas at 200 kW, and we don't know how to extract beam above 100 kW from any evolution of the Debuncher/Accumlator Complex.

- High Duty Factor at High Power.

- Additional techniques to deliver higher beam extinction.

- All this motivates consideration of ICD-2 which has a much higher beam power ceiling.

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.

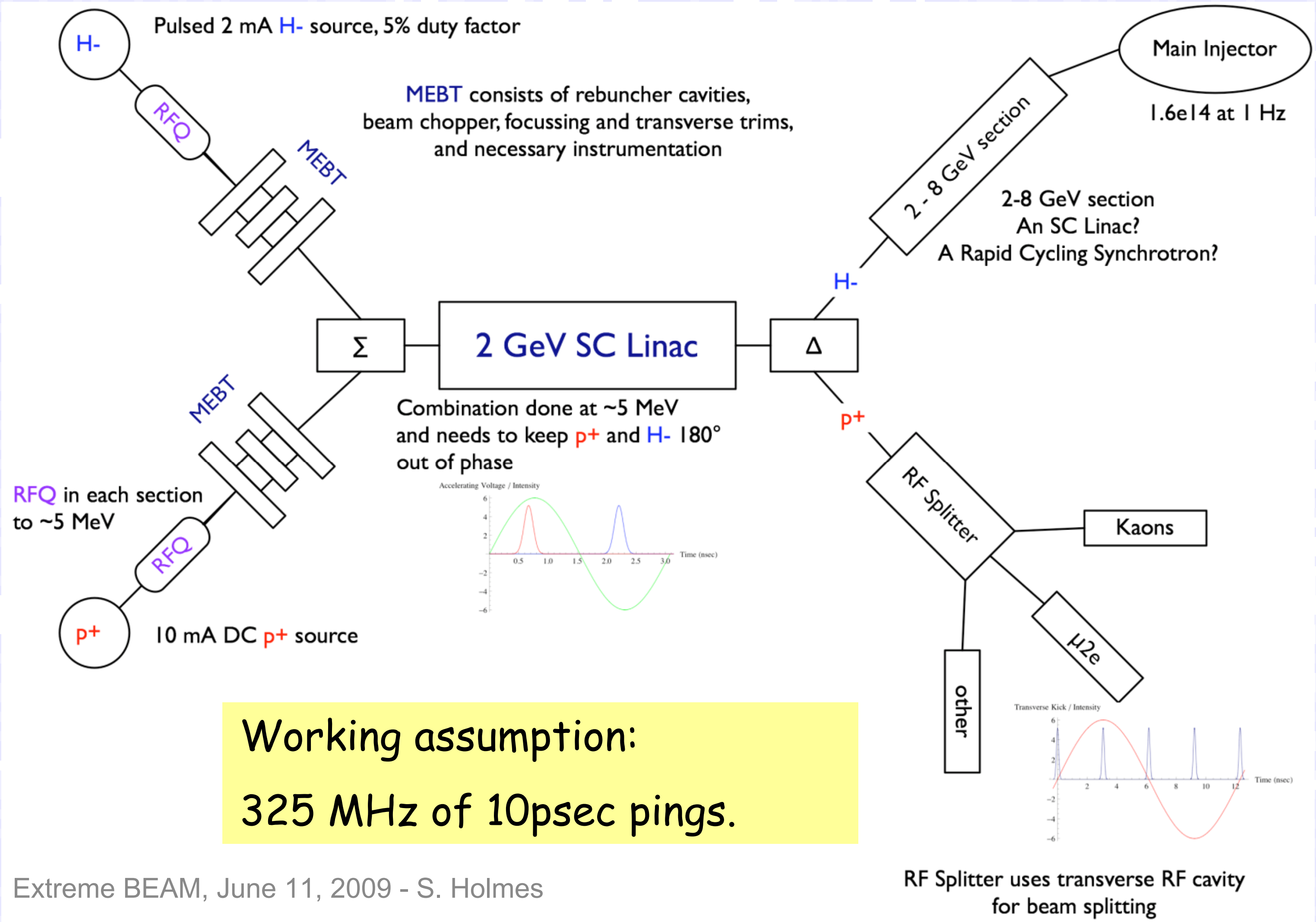
Slow Extracted Beam: The Standard Tool to Drive Ultra Rare Decay Experiments

- 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.

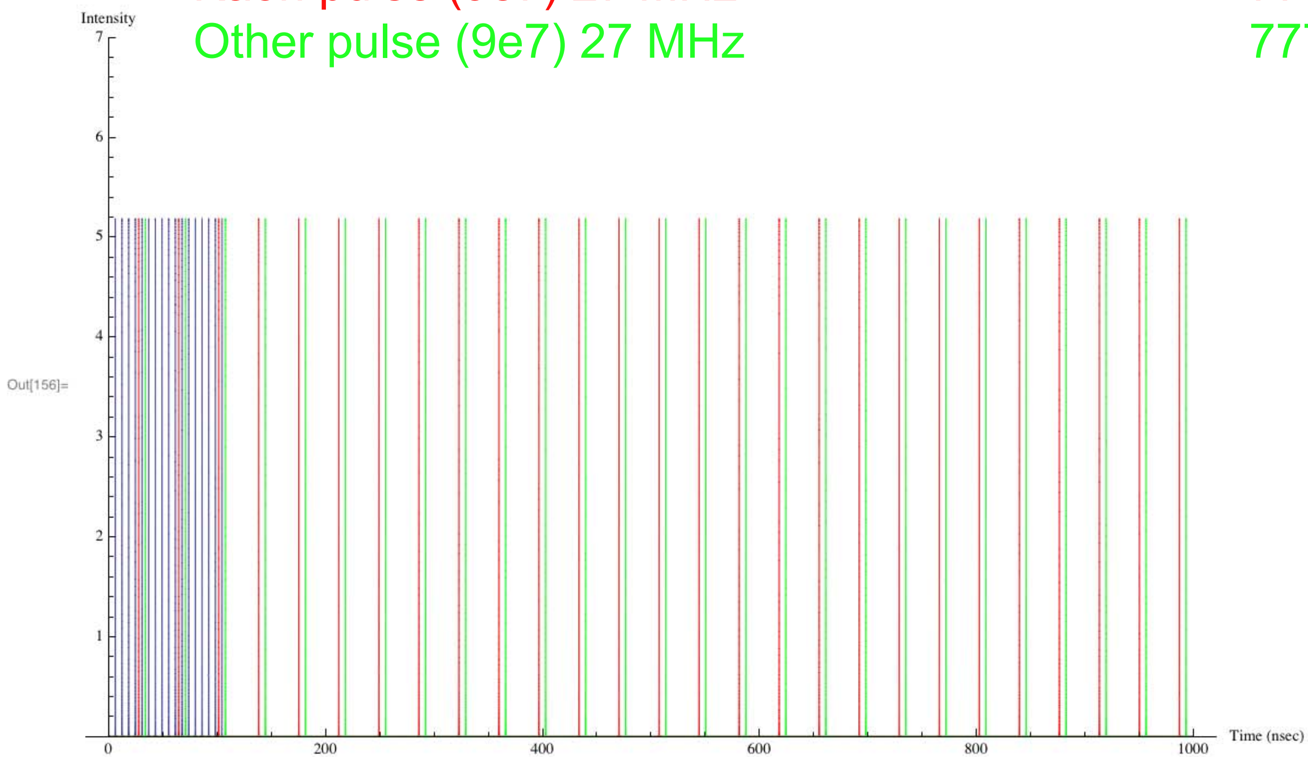
The ICD-2 Concept



Example of an ICD-2 Operating Scenario

1 μsec period at 2 GeV

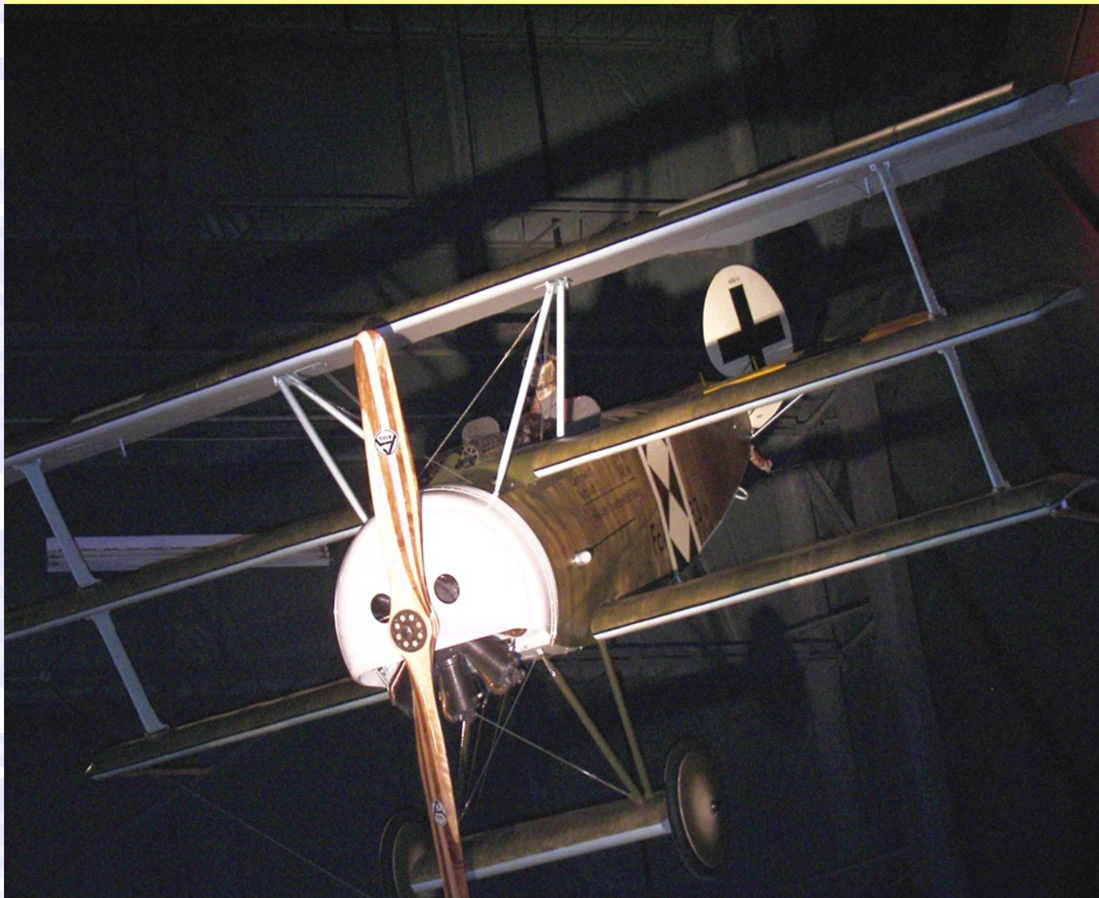
mu2e pulse (9e7) 162.5 MHz, 100 nsec	518 kW
Kaon pulse (9e7) 27 MHz	777 kW
Other pulse (9e7) 27 MHz	777 kW

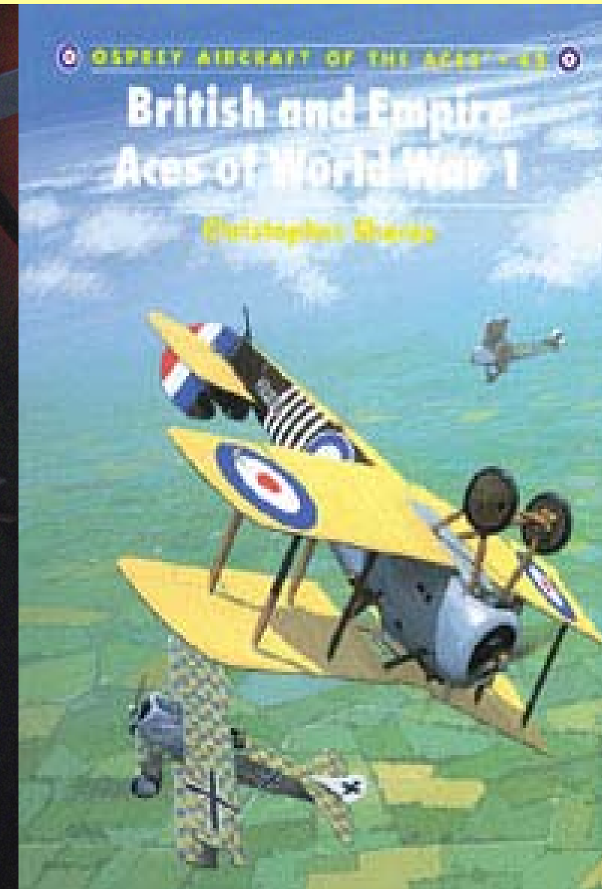


Extreme BEAM, June 11, 2009 - S. Holmes

What is good about a CW Linac

- Beam extraction challenge is finessed.





Thumbnail of muon physics Research Opportunities driven with the 2.x GeV CW Linac

- Next generation muon-to-electron conversion experiment, new techniques for higher sensitivity and/or other nuclei.

- $\mu \rightarrow 3e$
- Next generation (g-2) if motivated by theory, next round, LHC.
- μ edm.
- $\mu^+ e^- \rightarrow \mu^- e^+$
- $\mu^- A \rightarrow \mu^+ A'$
- Systematic study of radiative muon capture on nuclei.

Despite current yield uncertainties, there are in-principle advantages in driving future stopping muon experiments with a 2 GeV CW linac. These are:

1) The CW linac proton beam can directly impinge on the production target with a very high duty factor which finesses the substantial challenge of extracting high power beam from a synchrotron.

2) Production model uncertainties in the low energy π^- yield from 2.x GeV proton drive beam can be compensated with the large beam power reserve of the CW linac. Best estimate today is that the *relevant* π^- yield (30-70 MeV T) scales with beam power, possibly better.

3) The extraordinary intra-pulse extinction required by stopping muon experiments (10^{-9}) is intrinsic to the CW linac accelerating structure. *A* secondary extinction channel may not be necessary.

4) Experimental backgrounds from kaons and anti-protons produced in the production target will be substantially reduced (eliminated in the case of anti-protons) with a 2.x GeV drive beam.

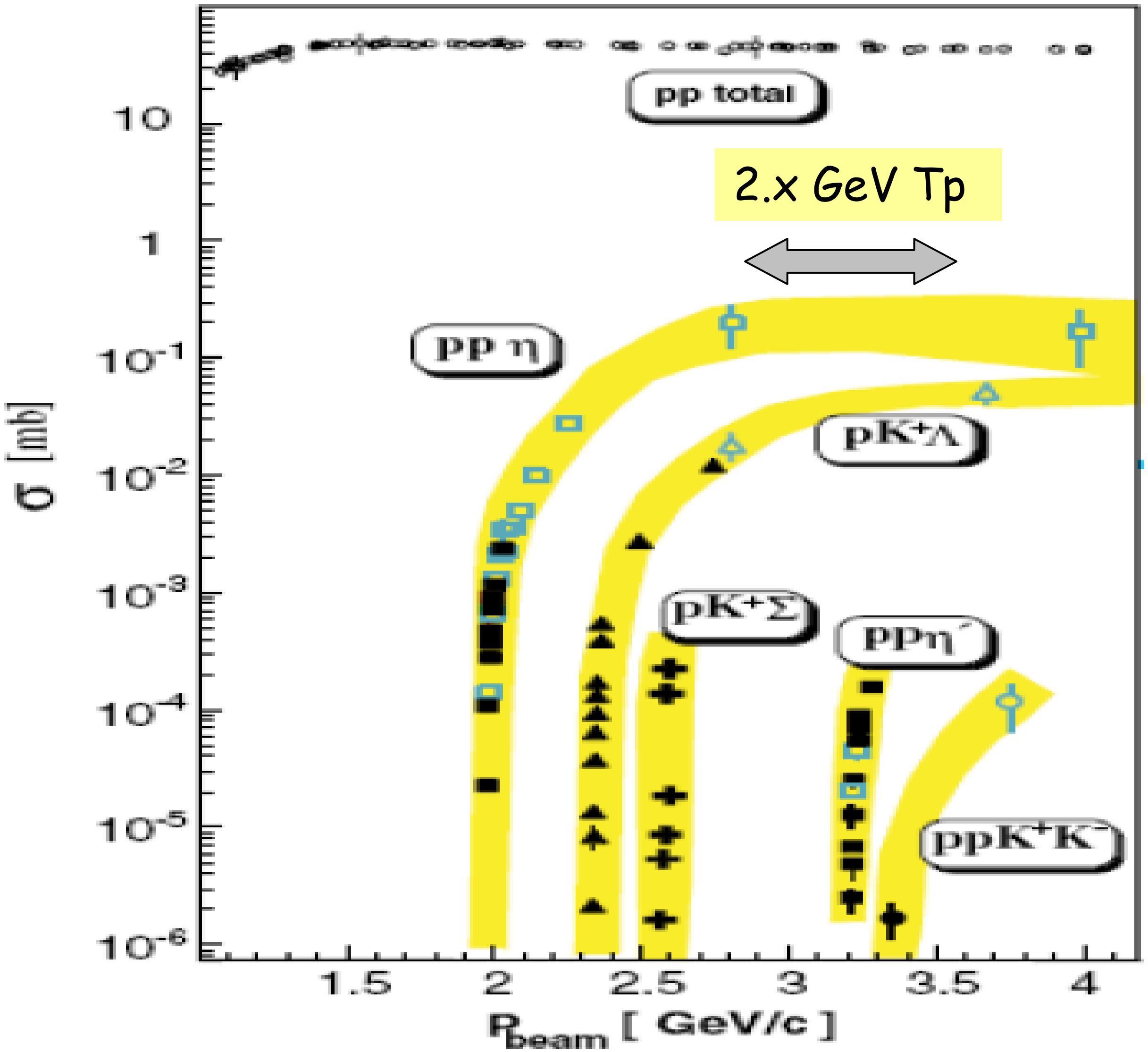
Sensitivity of Kaon Physics Today

- CERN NA62: 100×10^{-12} measurement sensitivity of $K^+ \to e^+ \nu$
- Fermilab KTeV: 20×10^{-12} measurement sensitivity of $K_L \to \mu\mu ee$
- Fermilab KTeV: 20×10^{-12} search sensitivity for $K_L \to \pi\mu e$, $\pi\pi\mu e$
- BNL E949: 20×10^{-12} measurement sensitivity of $K^+ \to \pi^+ \nu\bar{\nu}$
- BNL E871: 2×10^{-12} measurement sensitivity of $K_L \to e^+ e^-$
- BNL E871: 1×10^{-12} search sensitivity for $K_L \to \mu e$

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

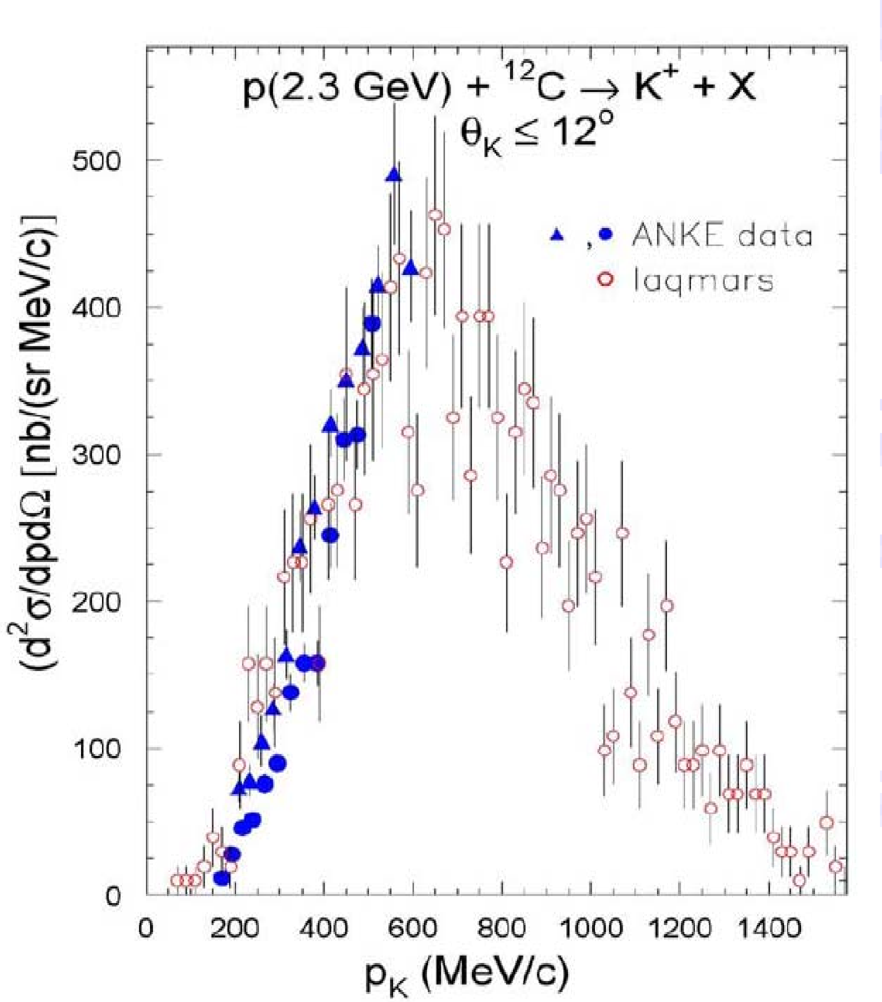
Next goal: 1000-event **$\pi\nu\nu$ experiments...10^{-14} sensitivty.**

Kaons at ICD-2, When Does the World Become Strange?



COSY Program, ANKE & other expts

Validating Simulation Tools…



- Los Alamos + MARS simulation suite (LAQMARS) is the 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.

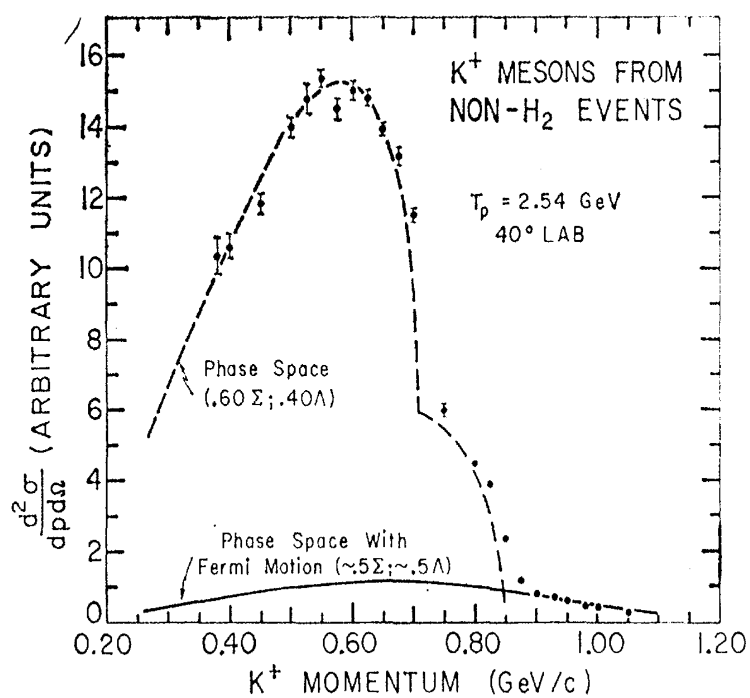
- Data shown: Buscher et al (2004) ANKE experiment at COSY, absolutely normalized.

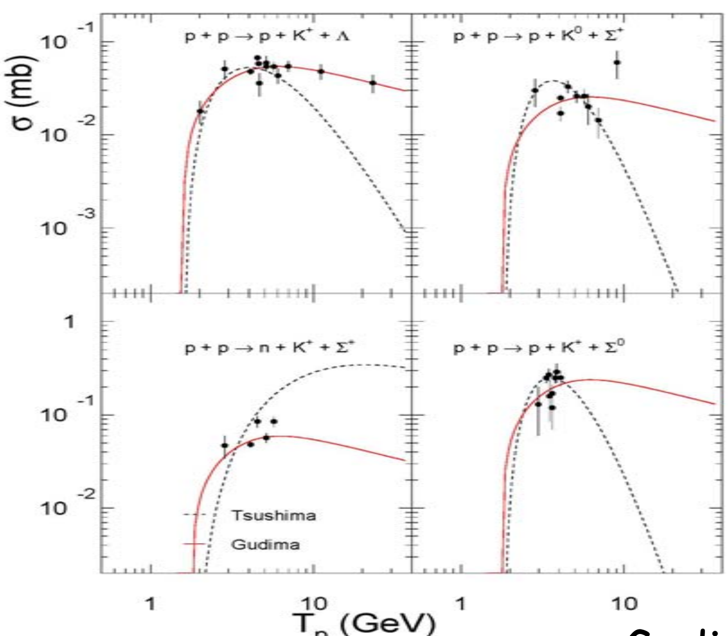
We have been here before: Princeton-Penn Accelerator

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)

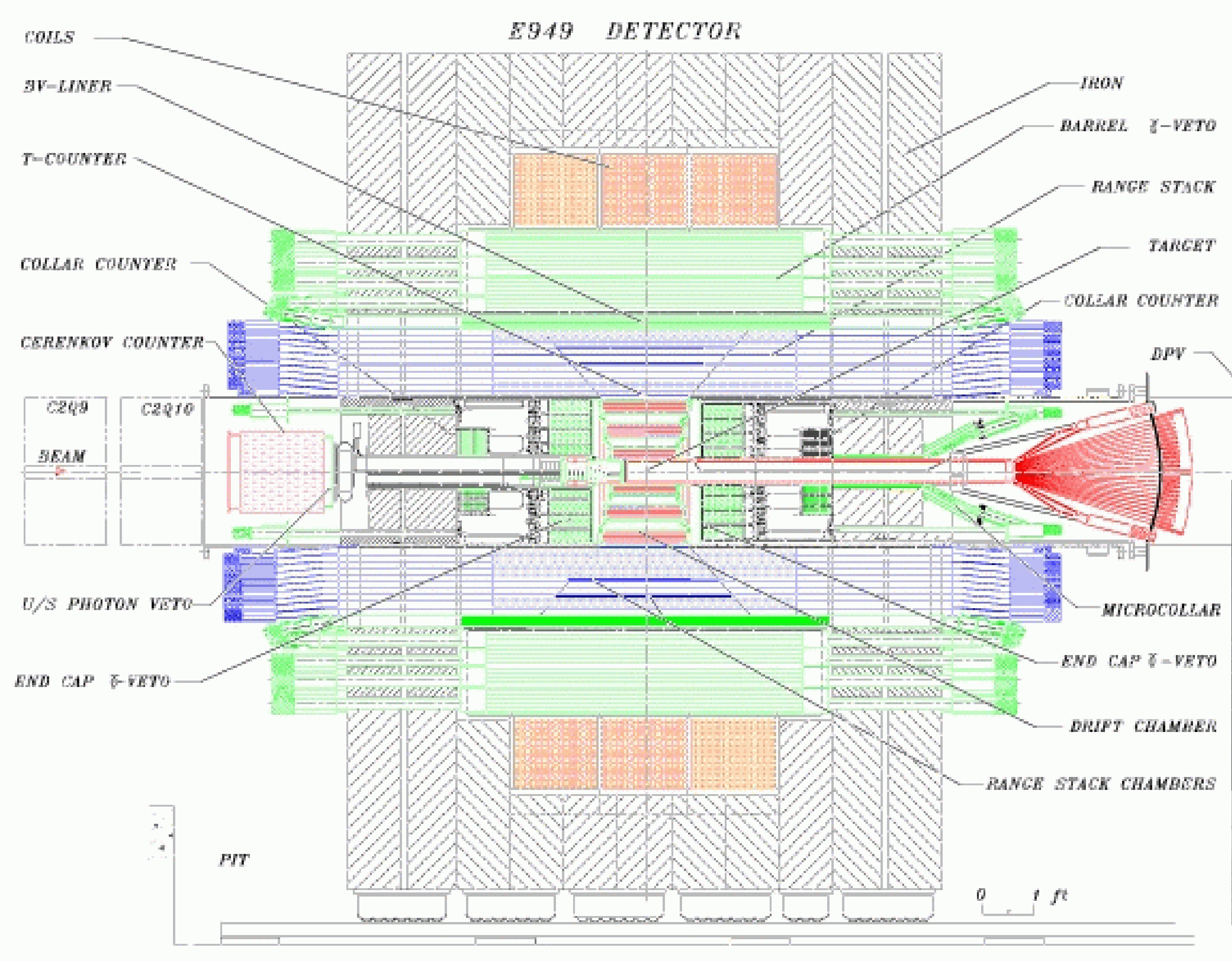




Gudima

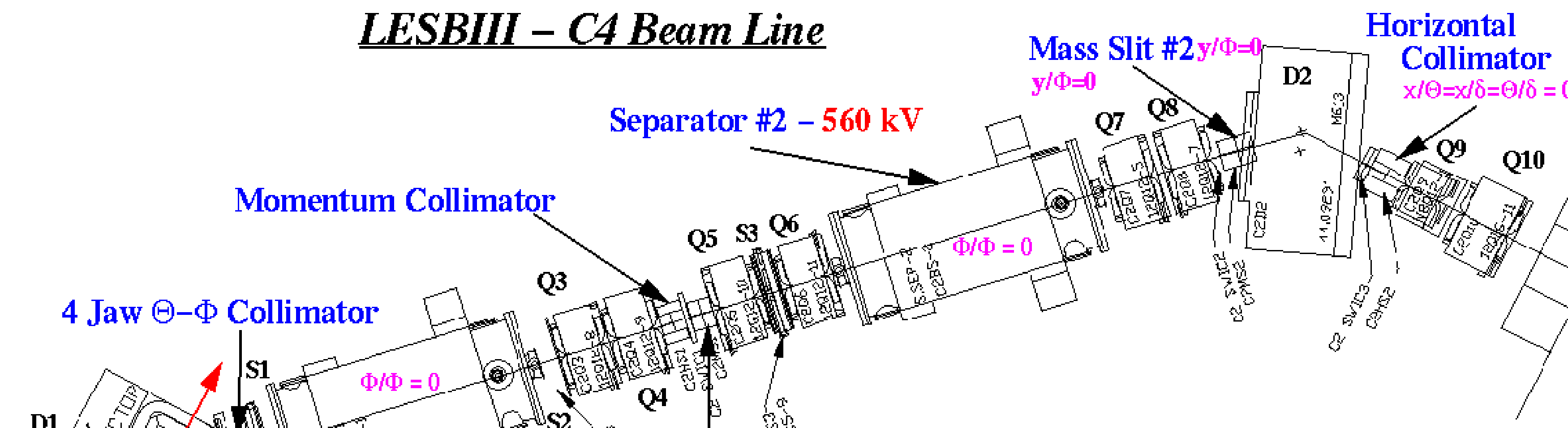
ICD-2 proton flux is x10^8-10^9 higher than the PPA extracted flux.

BNL E787/E949: Stopping K^+ Experiment that discovered the $K^+ \rightarrow \pi^+ \nu\nu$ process.

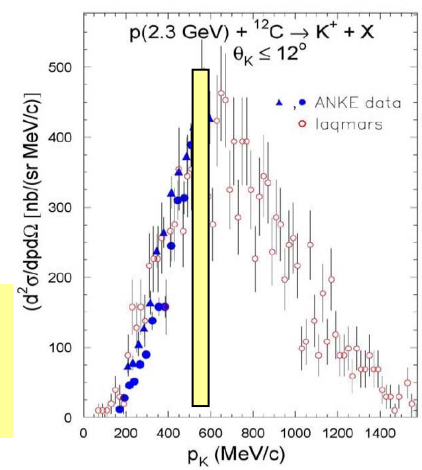


Elevation view of the E949 detector.

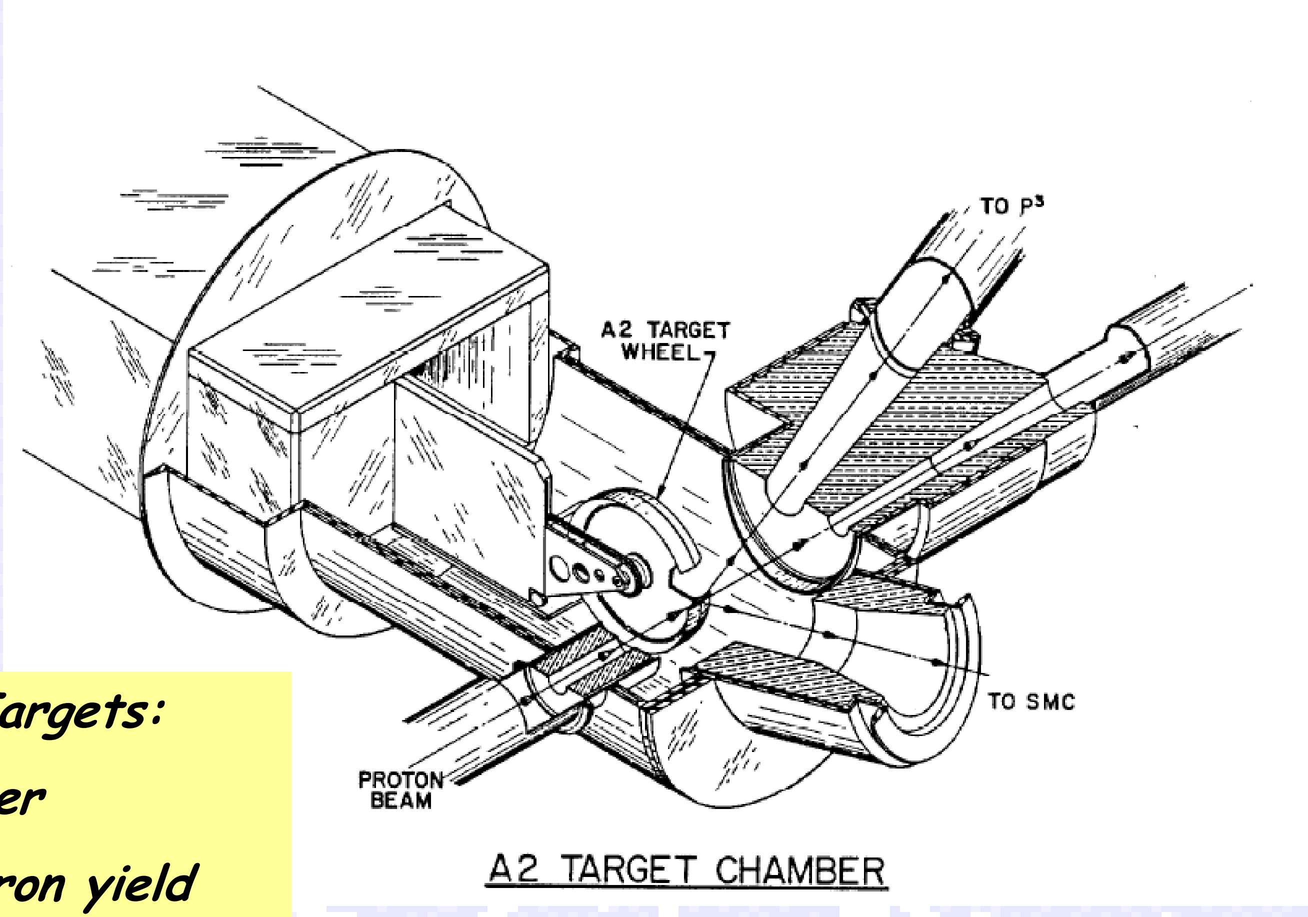
BNL Charged K+ Beamline: Channel a low energy *separated* charged beam to a stopping target: Measure kaon decays at Rest!



Stopped K+ experiment requires separated beam. ExB system optimizes with an incident kaon momentum of 500-600 MeV, 4% FWHM Δp bite



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



Carbon Targets:

High power

Low neutron yield

Kaon transparency

Spallation neutron yields

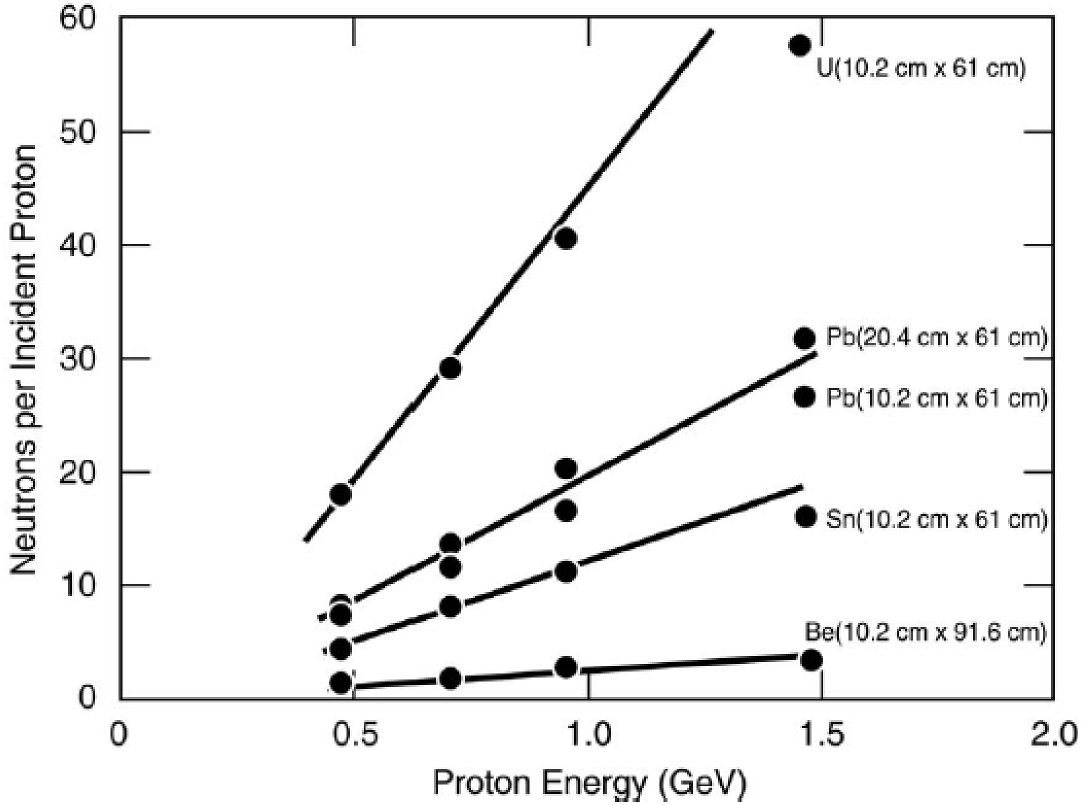
Measured Spallation Neutron Yield vs. Proton Energy for Various Targets, J. Frazer, et al. (1965)

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

Stopped K^+ experiment (based on BNL-E949) is driven by 550 MeV/c K^+ into $\theta<100$mR

- ICD-2: (2.1 GeV, thin-Carbon, $\theta<100$mR, 4% ($\Delta P_K/P_K$)) = 1.5×10^{-6} K^+/p
- AGS: (24 GeV, thin-Platinum, $\theta<100$mR, 4% ($\Delta P_K/P_K$)) = 8.0×10^{-6} K^+/p

ICD-2 thin-target 550 MeV K^+ yield/watt is x2.2 better than the BNL AGS (24 GeV). Thick carbon target studies in progress, assume practical thick target yield will be 50% of a thick Pt AGS target.

AGS maximum proton flux goal was 1×10^{14} p/5-sec vs ICD-2 design of 60×10^{14} p/sec: Proton flux ratio of x300. ICD2 design K^+ flux is x30 of the Max AGS goal, x40 the K^+ flux of the Tevatron Stretcher initiative.

ICD-2 K^+/π^+ is worse than the AGS, excellent ICD-2 TOF will help here.

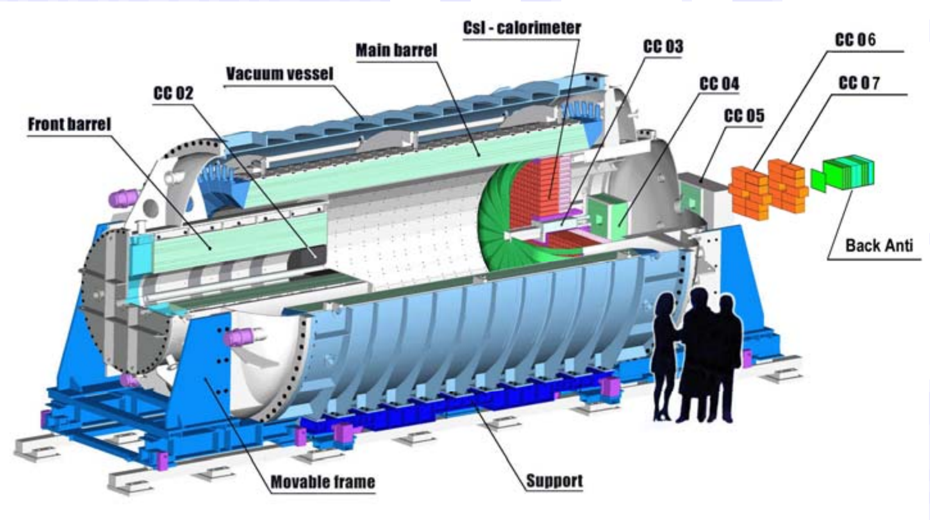
1000-event $K^+\rightarrow\pi^+\nu\nu$ experiment plausible with both ICD-2 and ICD-1 .

* LAQGSM estimate, scaling from 10cm Pt target measurements.

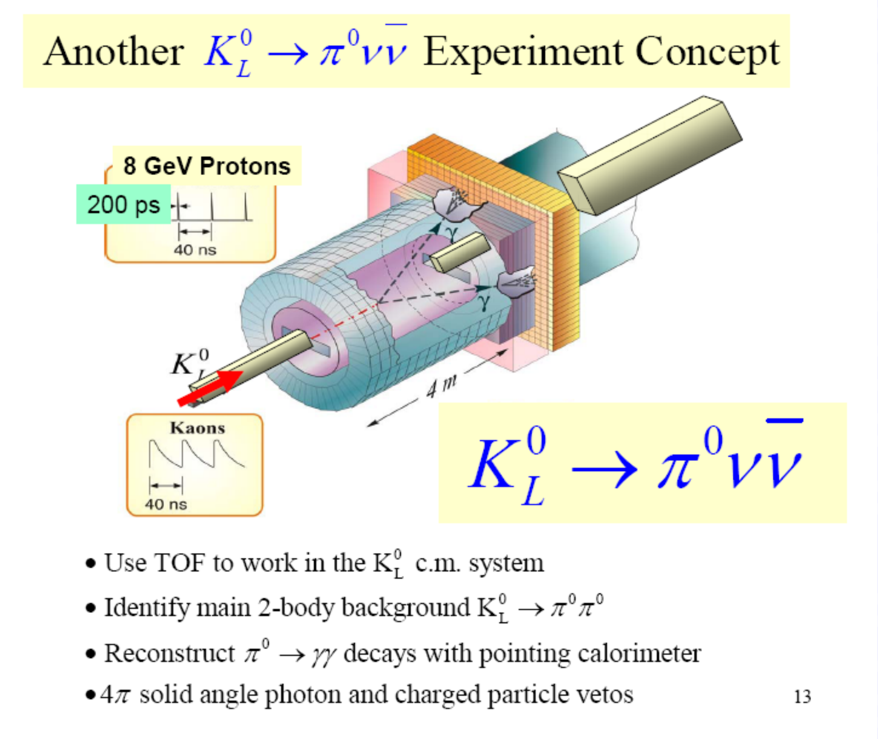
$K_L \to \pi^0 \nu\nu$ Experimental Challenge: "Nothing-in nothing out"

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

A hermetic "bottle" approach.

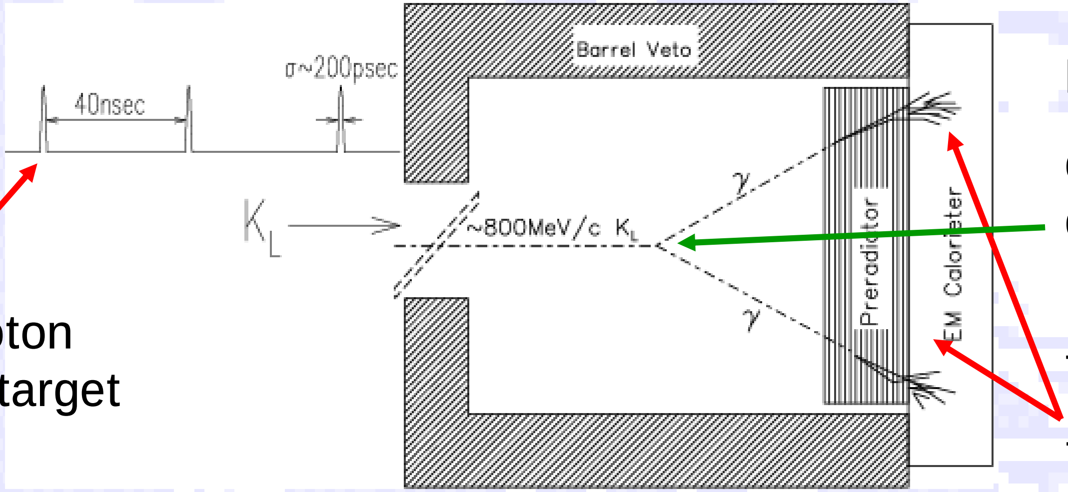


•The original KOPIO concept measures the kaon momentum and photon direction…Good! But costs detector acceptance and requires a large beam to compensate. Project-X Flux can get back to small kaon beam!



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.

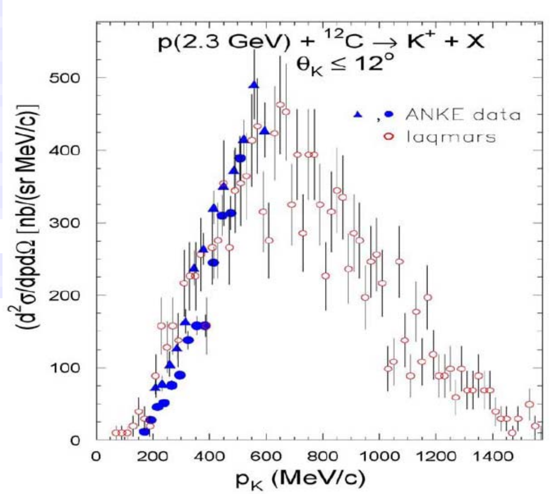


Start when proton beam hits the target

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

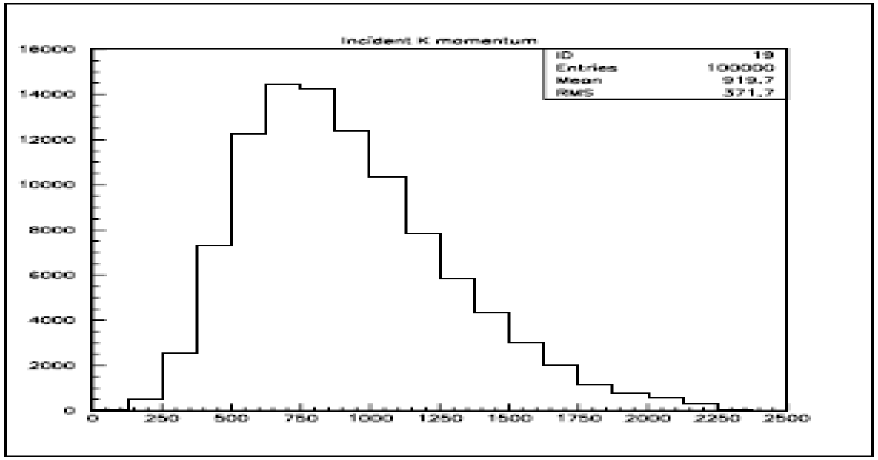
Timing uncertainty due to microbunch width should not dominate the measurement of the kaon momentum; requires RMS width < 200ps. CW linac pulse timing of less than 50ps is intrinsic.

KOPIO and ICD-2 kaon momentum spectra comparison



Sensitivity Studies in Progress. What we know now:

- K_L p_K spectrum favorable.
- ICD-2 KL/n ratio similar to AGS.
- Very high ICD-2 flux permits consideration of a pencil beam.



KOPIO Proposal

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

What the ICD-2 could offer Rare-Process Experimenters

- ICD-2 has the potential to support a broad program of quark flavor physics, charged lepton flavor physics and nuclear physics. Without much effort we have identified more than 10 possible world-class particle physics experiments worth exploring.

What ICD-2 could offer particle *and* nuclear experimenters:

Very high flux of low energy muons with flexible timing and high df.

Very high flux of low energy K^+ with flexible timing and high df.

Very high flux of $\overline{K^0}$ and K_L with flexible timing and high df.

High flux of tagged $\overline{K^0}$, Σ^+, and Λ^0 with flexible timing and high df.

Very high flux of π^- and π^+ beams with flexible timing and high df.

Threshold studies of strangeness production on nuclei.

Negligible background of anti-baryons, Very deep direct B-violation searches.

Break-through Time-of-Flight resolution. (~ 10 psec)

Research Program Summary

- Both ICD-1 and ICD-2 can adequately drive the 2+ MW of beam power for the LBNE program. Major beamline and detector challenges exist, and there is an excellent team growing nationally and internationally to meet these challenges.

ICD-1 Rare Processes:

- The 200 kW can drive a world class program of experiments.
- The scope will however be limited by available beam power and there is not a scheme today to extract 100-200 kW of 8 GeV beam power with the required RF structure.

ICD-2 Rare Processes:

- The 2MW of beam power available at 2.x GeV can drive a broad program of world-class experiments. Work continues on refining concepts for muon and kaon experiments which look promising at this point.
- Not another rendition of the BNL AGS. The AGS was a venerable machine, which has had it's day.
- The properties of the Super Conducting CW high bandwidth linac are enabling this new approach to the high sensitivity frontier.

Spare Slides

Other Lepton Number Violation Experiments driven with 2.x GeV CW Linac

- **Lepton Number Violation:**

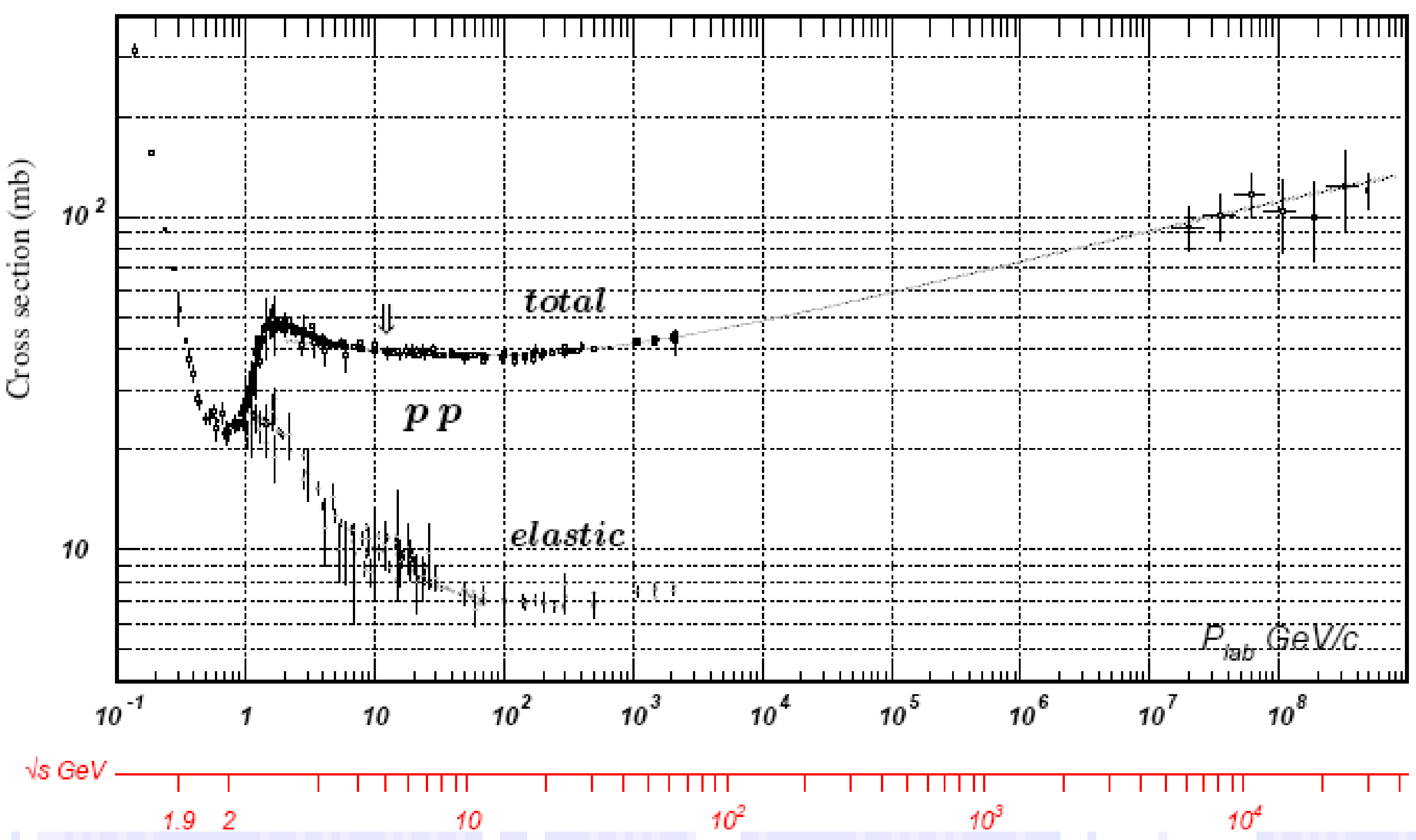
Reaching beyond 10^{-12} branching fraction sensitivity $K_L \rightarrow \mu e$, $\pi\mu e$, $K^+ \rightarrow \pi^-\mu^+\mu^+$, $K^+ \rightarrow \pi^- e^+ e^+$

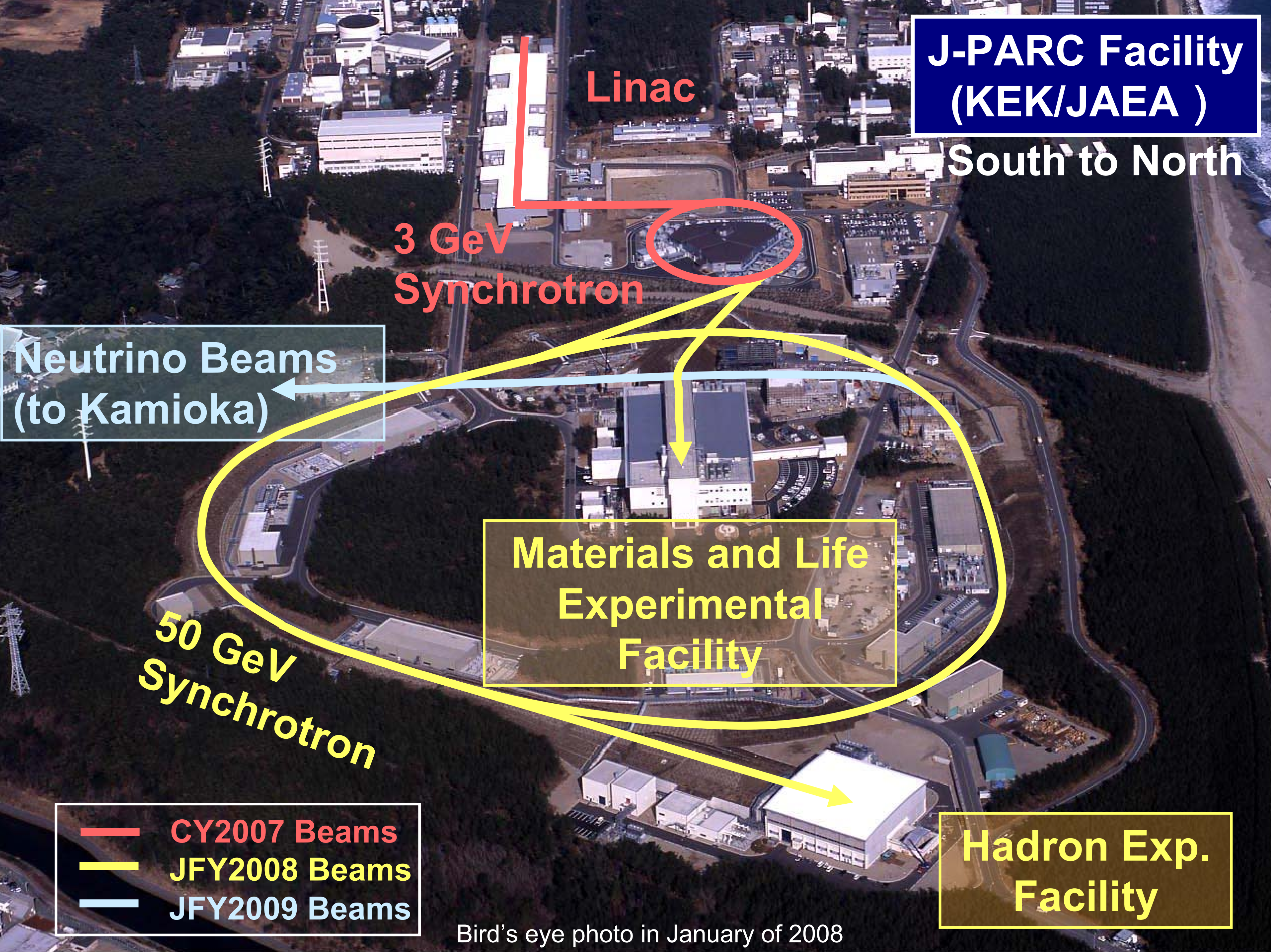
Experiments have been limited by kaon flux and the background rejection (e.g. $K_L \rightarrow \pi e \nu_e$; $(\pi \rightarrow \mu), e$ + soft νs ; $\rightarrow \mu e$)

TOF is an additional handle to measure K_L momentum, tag the $\pi \rightarrow \mu$ decay to fight backgrounds. High kaon flux enables much more tightly controlled pencil beams.

One can imagine pushing to the 10^{-14} level, raise limits on tree couplings from ~50 TeV to ~150 TeV.

Consider Low-Energy High Power Beam with ICD-2. First, what is the pp Cross Section?




J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental
Facility
50 GeV
Synchrotron
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

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

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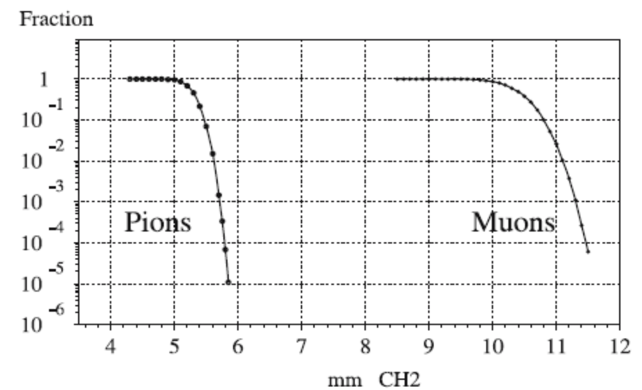
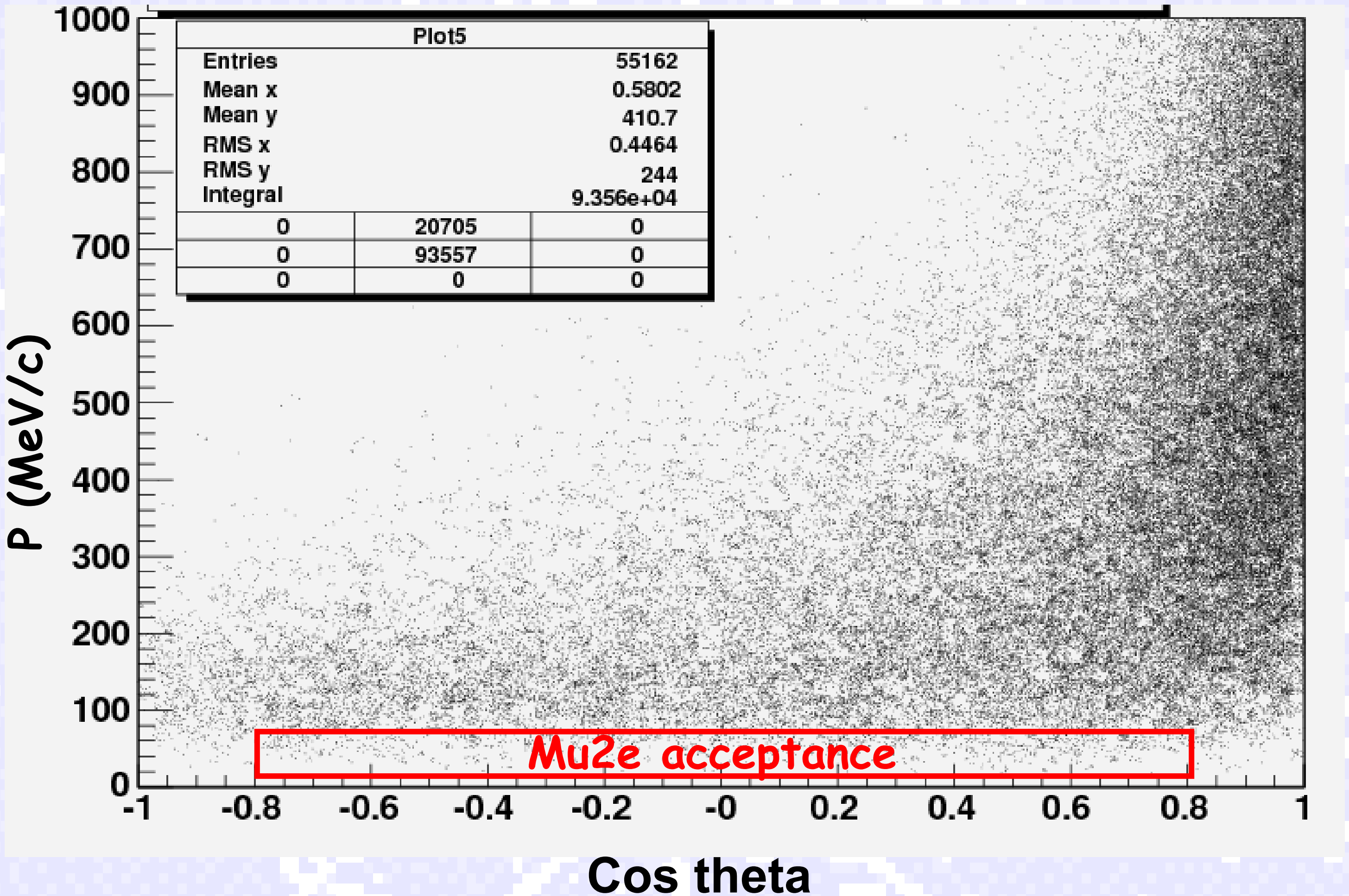


Fig. 1. Fraction of pions and muons with a momentum of 52 MeV/c that cross a CH_2 moderator as a function of the moderator thickness. GEANT [23] simulation

π^- Momentum vs. Cosine of production angle with 8 GeV proton drive beam.



(from C. Yoshikawa, courtesy C. Anklebrandt)