Project-X

DPF, August 10th 2011
R.Tschirhart
Fermilab

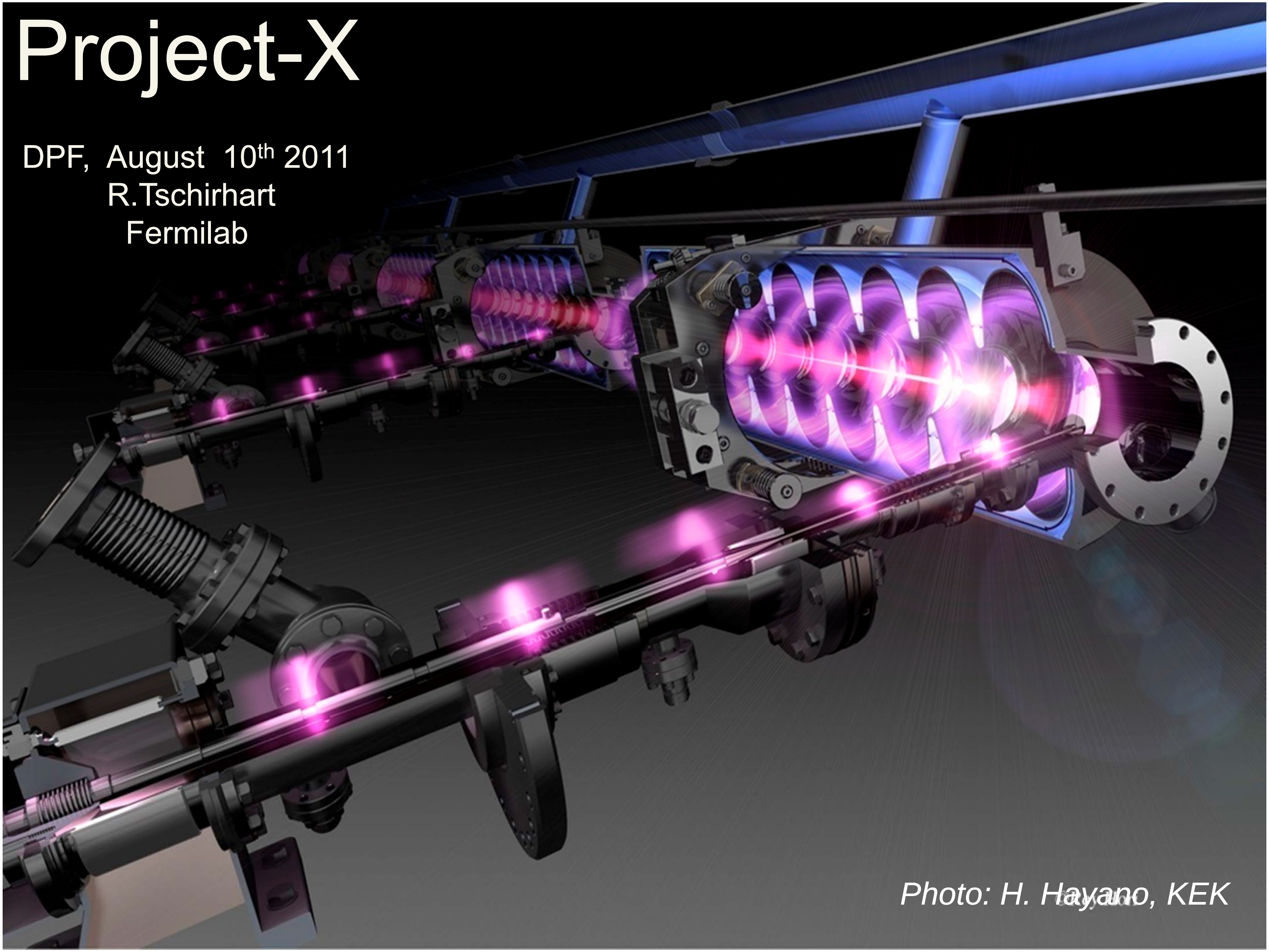


Photo: H. Hayano, KEK

Project-Y:

Origins…

•The Origin of Mass:

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

•The Origin of Matter:

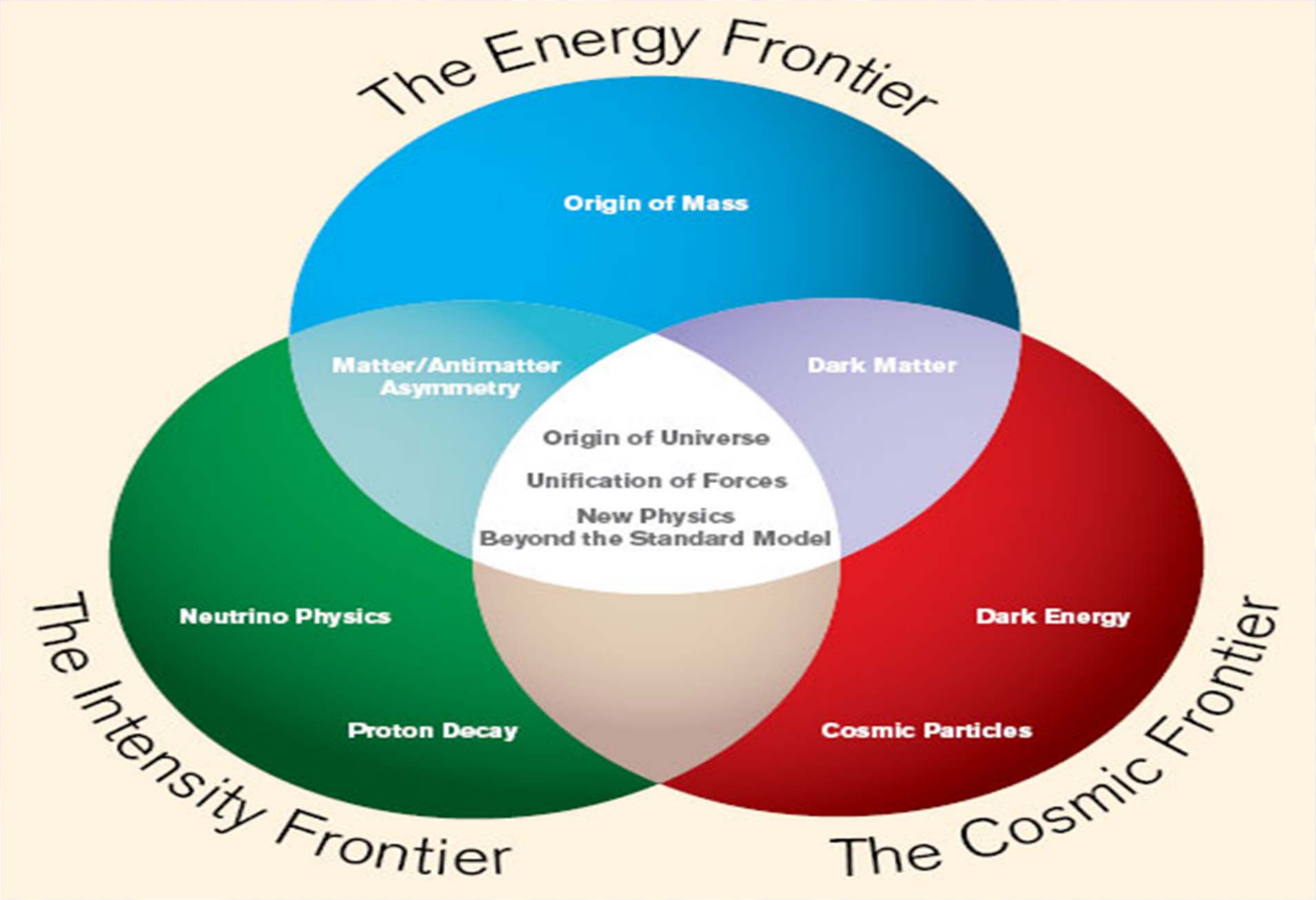
Why are there so many different kinds of matter particles with different properties?
(buzzword: "Flavor")

•The Origin of the Universe:

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

Joe Lykken

An integrated approach to direct and indirect probes in science…



The Project-X Research Program

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

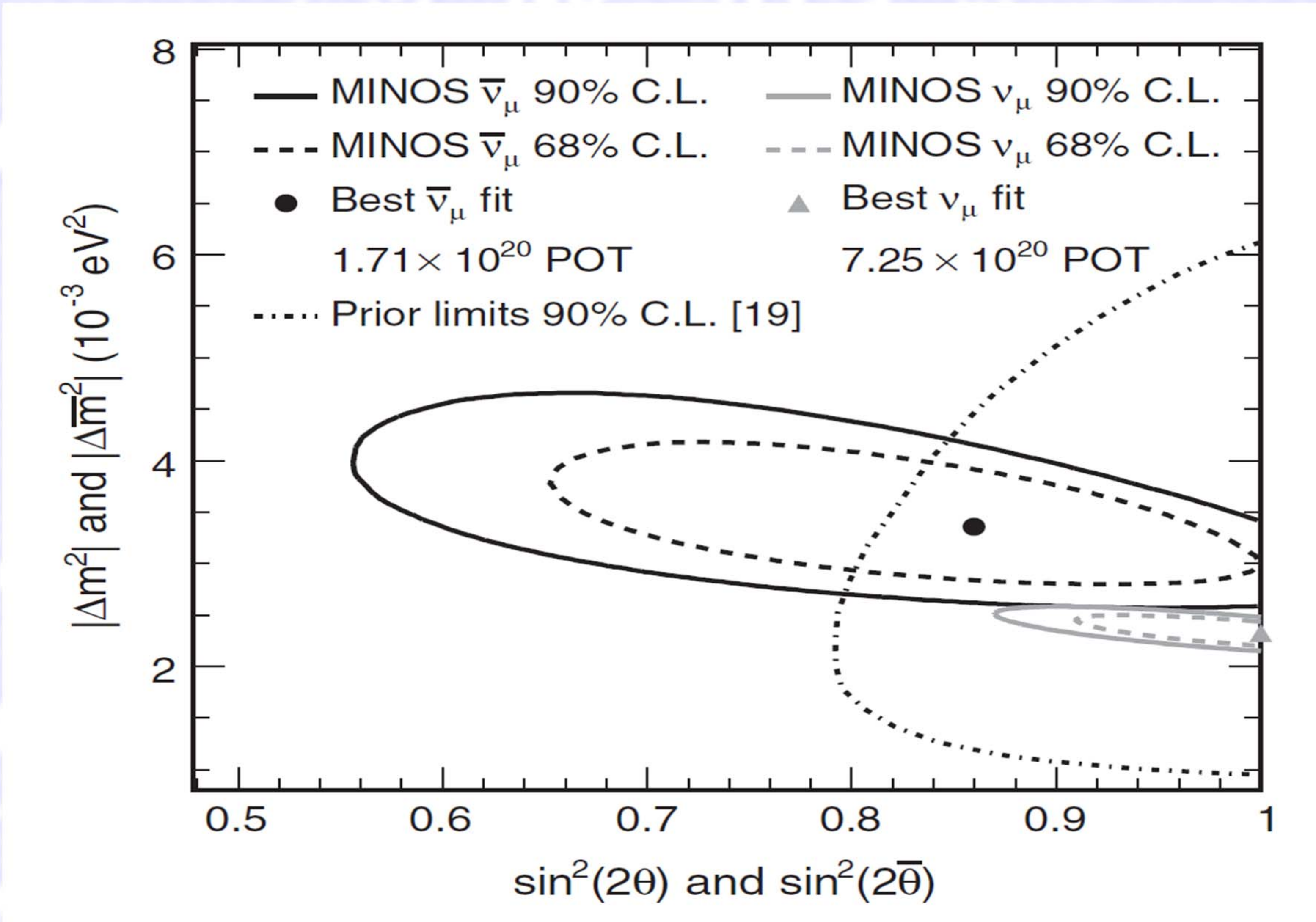
- ***Kaon, muon, nuclei & neutron precision experiments***
- These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (edms), and world-leading precision measurements of ultra-rare kaon decays.

- ***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

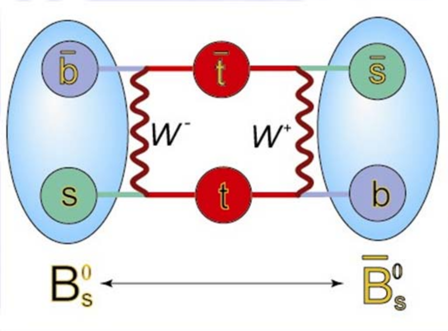
What are Neutrinos Telling Us?

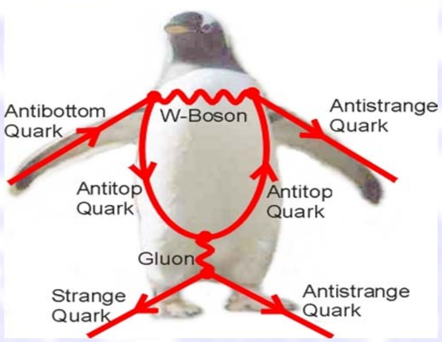


PRL 107 021801 (2011)

Kaon, Muon and EDM Experiments Deeply Attack the "Flavor Problem"

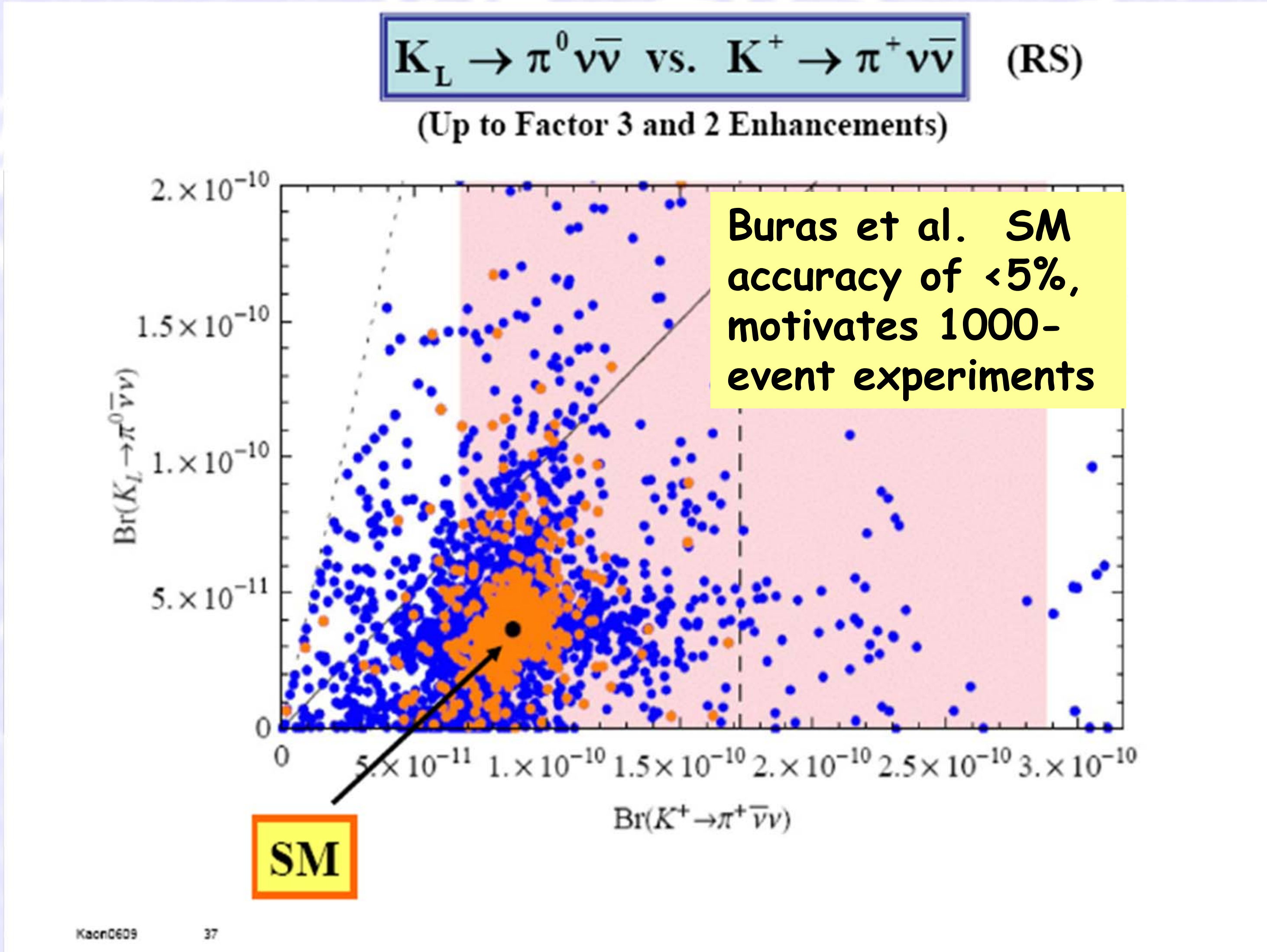
Why don't we see the *Tev-scale Physics we expect* affecting the flavor physics we study today??



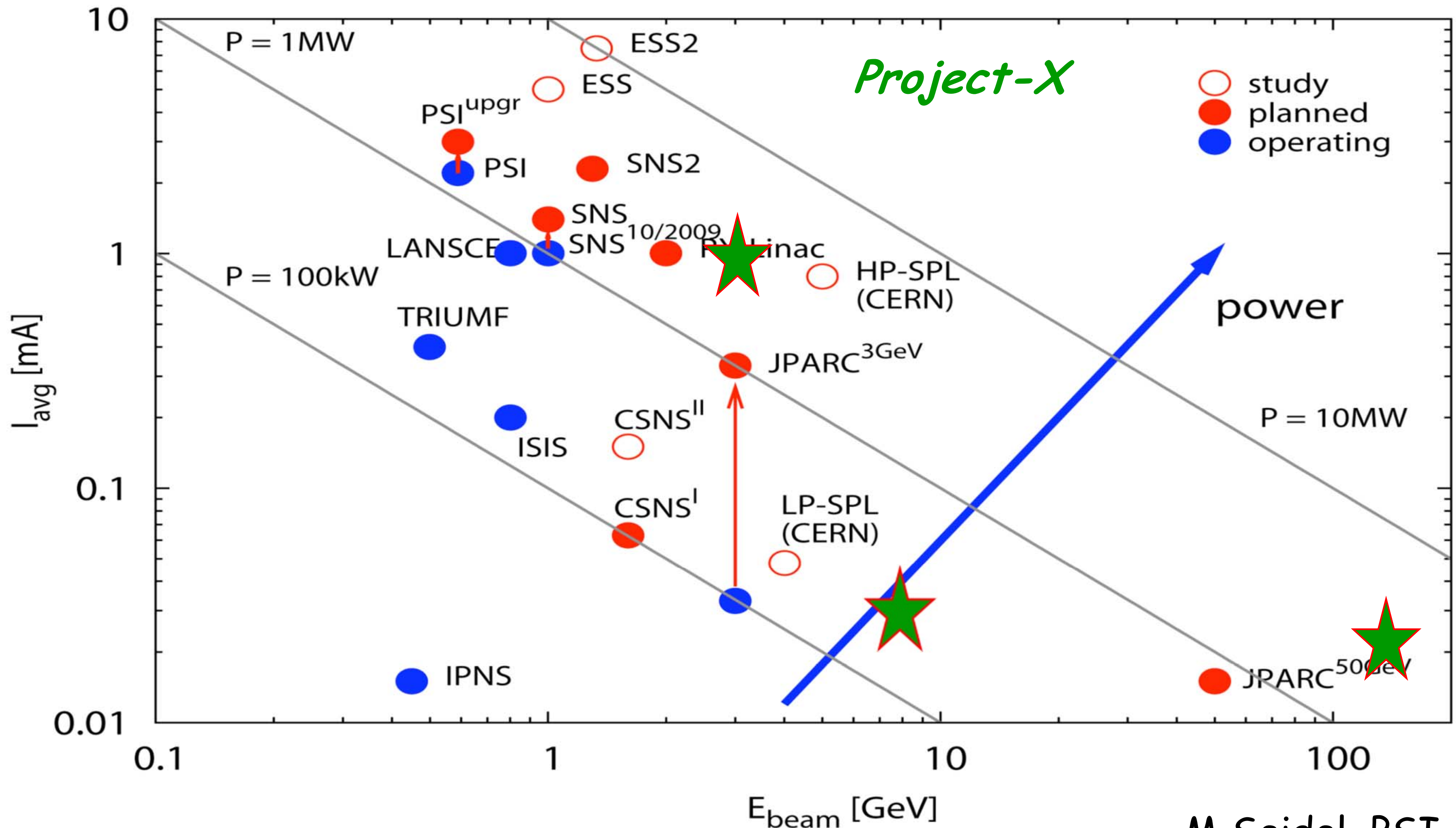


e.g. D0 2μ charge asymmetry arXiv:1106.6308

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

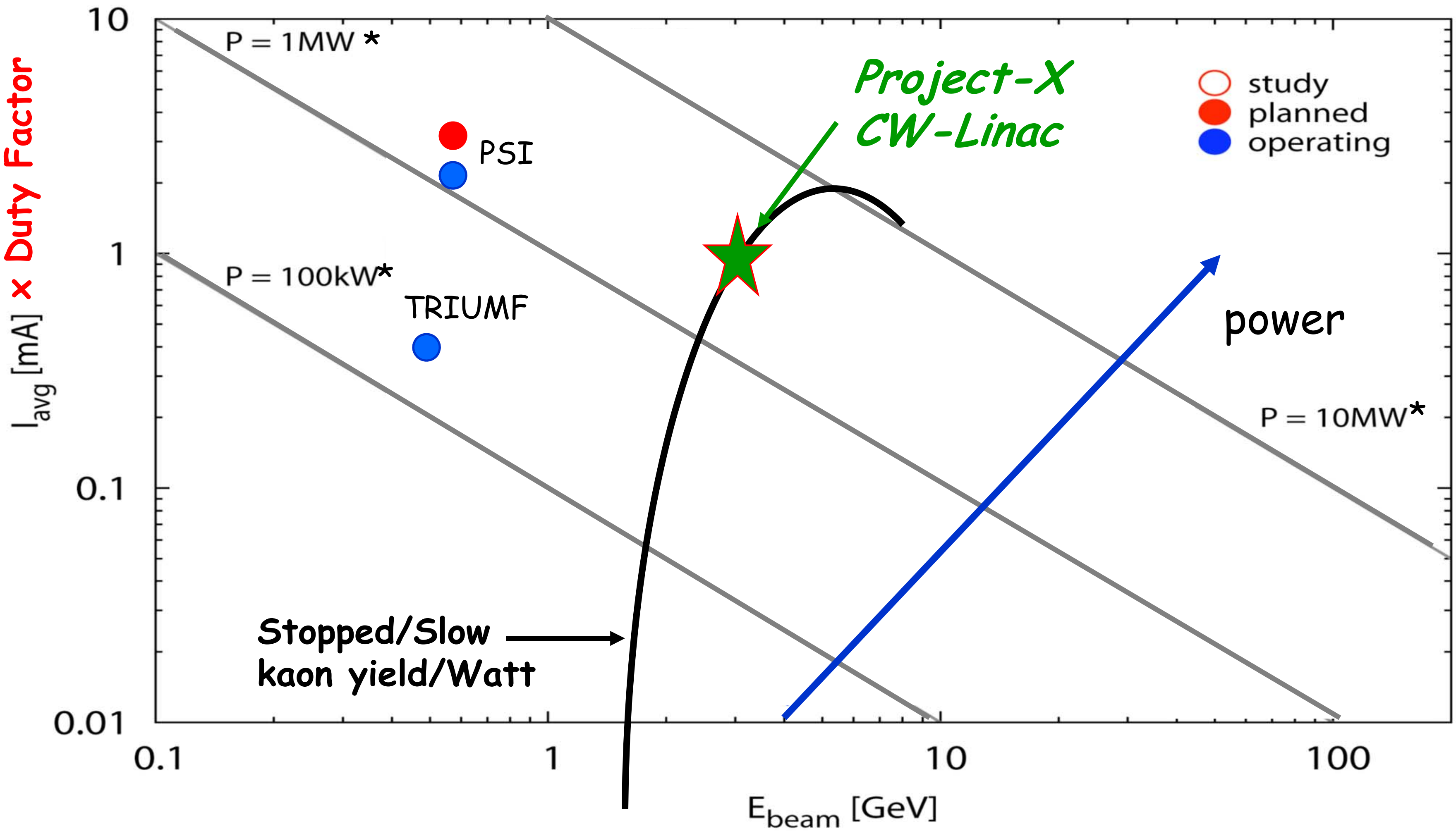


This Science has attracted Competition: The Proton Source Landscape This Decade...



M Seidel, PSI

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



* Beam power x **Duty Factor**

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.

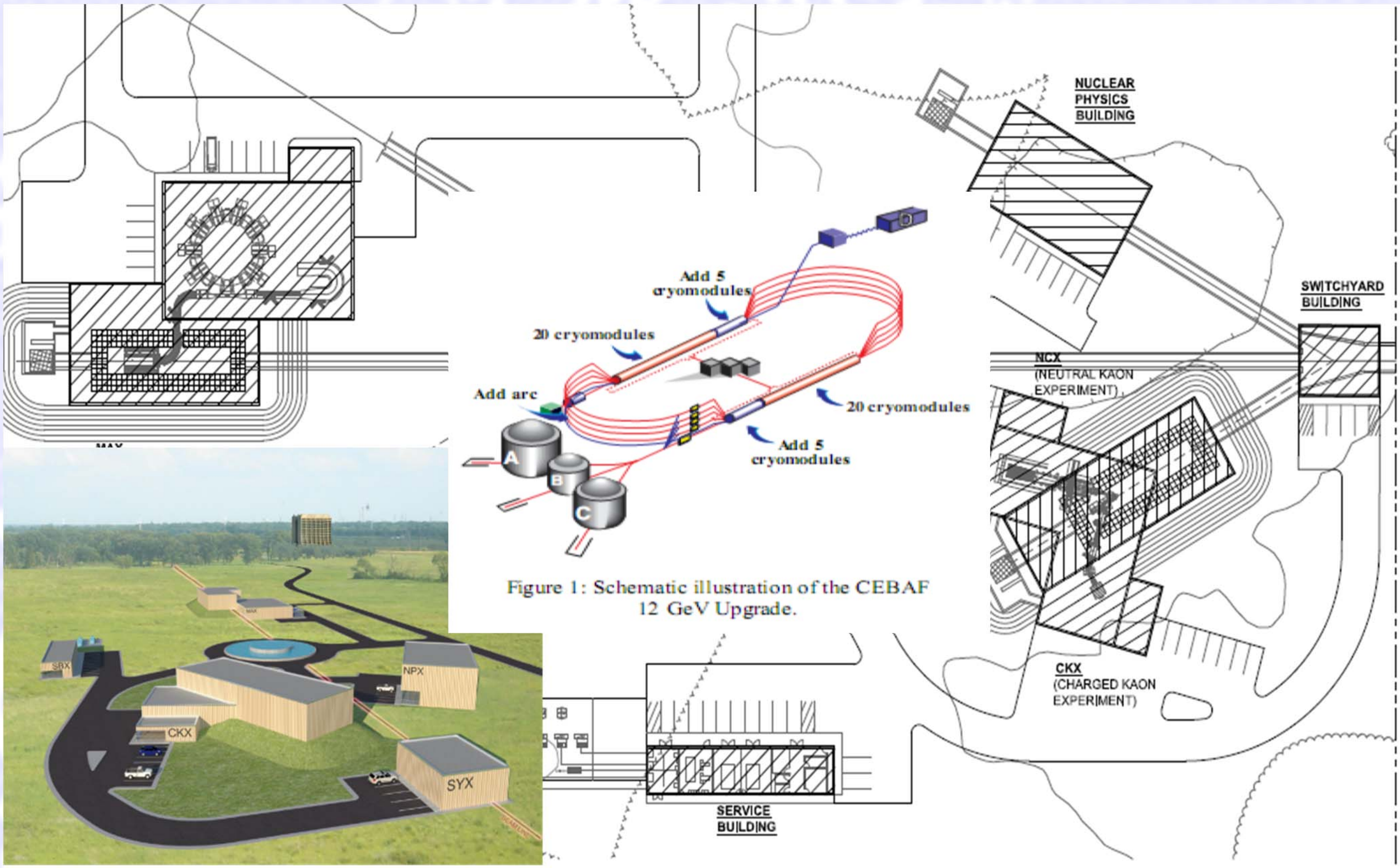
Slow Extracted Beam: The Standard Tool to Drive Ultra Rare Decay Experiments

- 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:

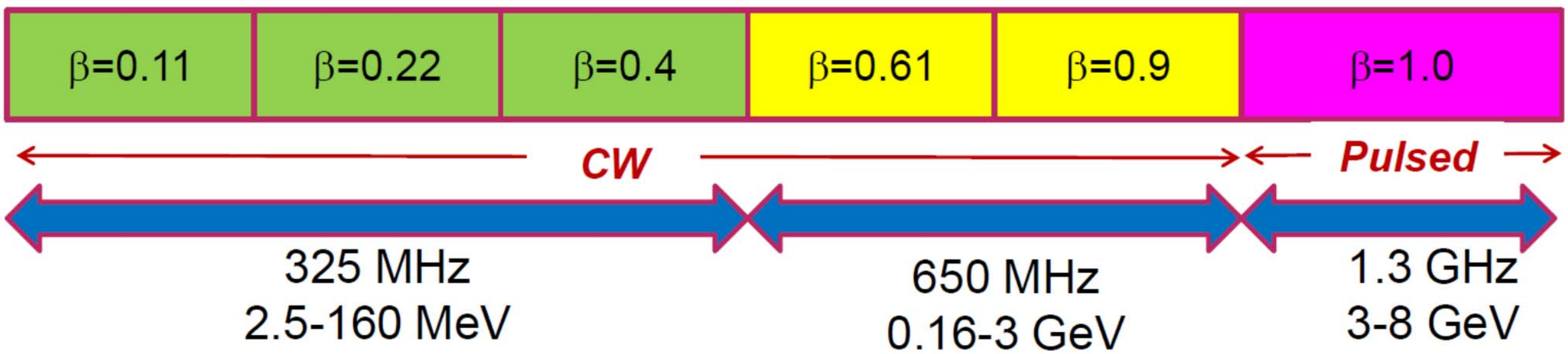
  Tevatron 800 GeV FT: 64 kW of SEB in 1997.
  BNL AGS 24 GeV beam, 50-70 kW of SEB.

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

Project-X High-Intensity Campus



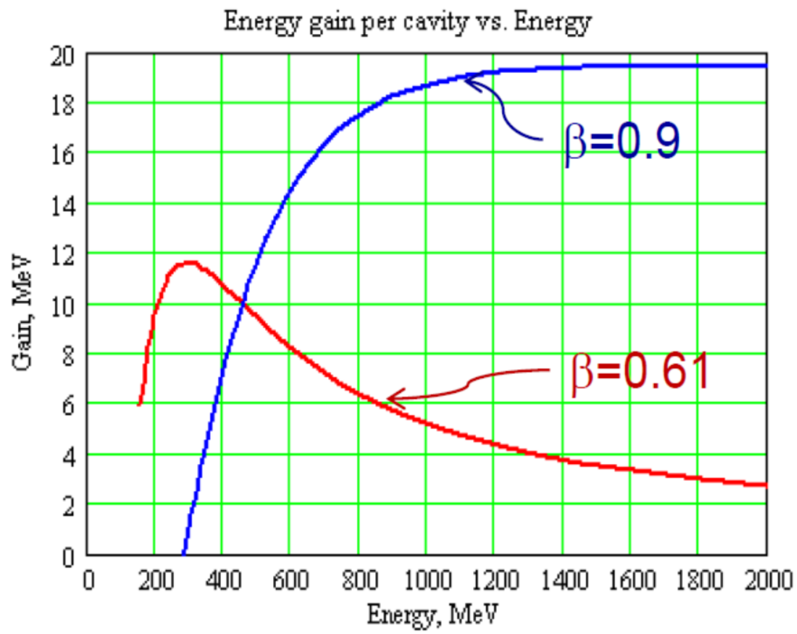
SRF Linac
Technology Map

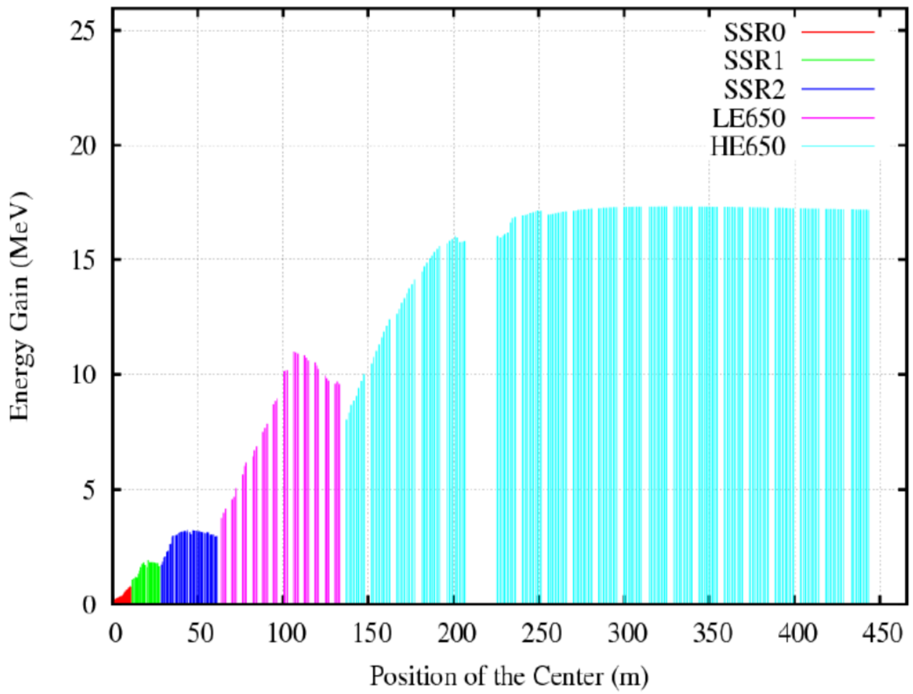


Section	Freq	Energy (MeV)	Cav/mag/CM	Type
SSR0 (β_G=0.11)	325	2.5-10	18 /18/1	SSR, solenoid
SSR1 (β_G=0.22)	325	10-42	20/20/ 2	SSR, solenoid
SSR2 (β_G=0.4)	325	42-160	40/20/4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-460	36 /24/6	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	460-3000	160/40/20	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

Nagaitsev, Telluride

3 GeV CW Linac
Energy Gain per Cavity





- Based on 5-cell 650 MHz cavity
  - Crossover point ~450 - 500 MeV
- Single cavity per power source
  - Solid State, IOT

Nagaitsev, Telluride

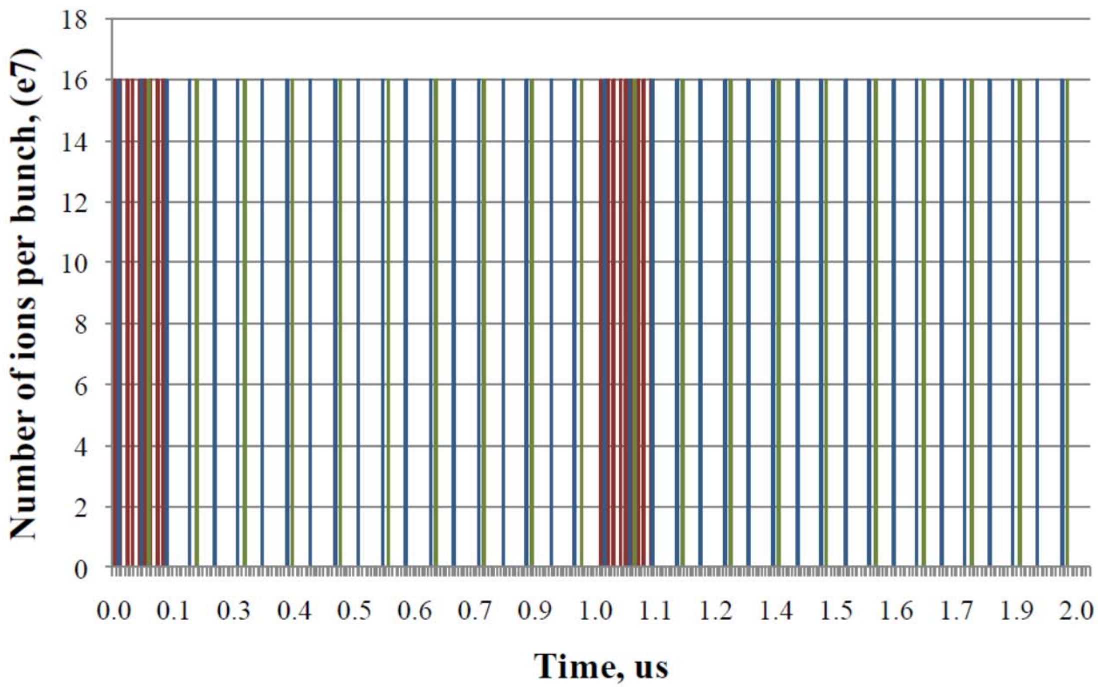
Chopping and splitting for 3-GeV experiments

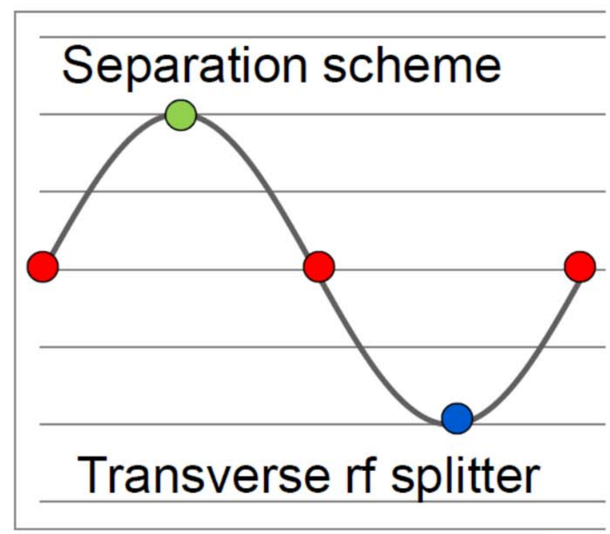
Project X

<u>1 μsec period at 3 GeV</u>

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

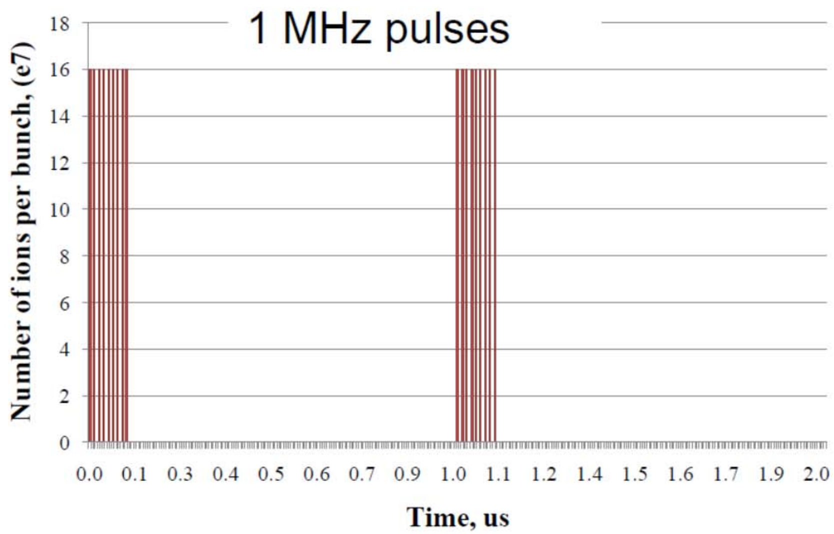
Ion source and RFQ operate at 4.2 mA
75% of bunches are chopped at 2.5 MeV after RFQ

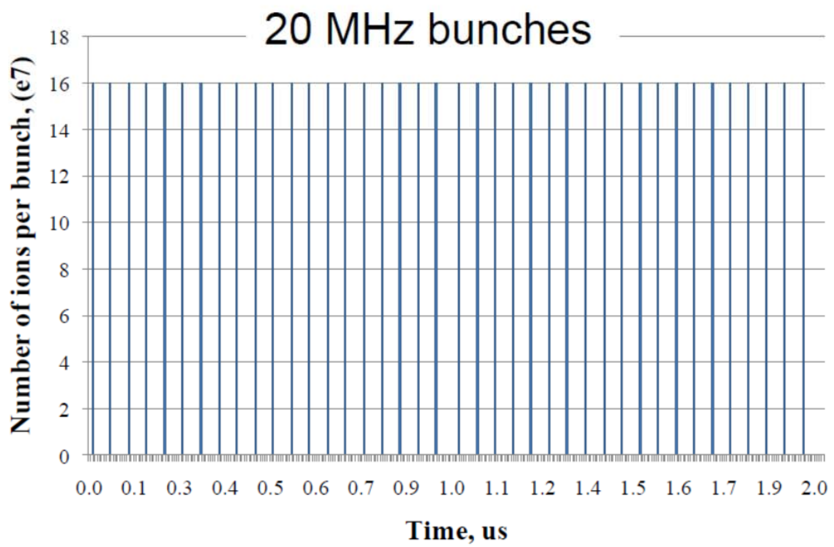


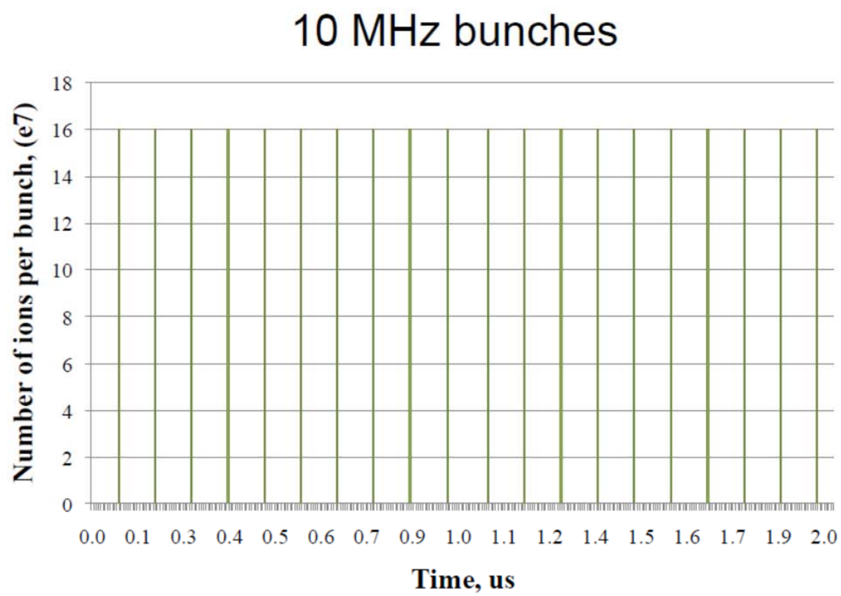


Nagaitsev, Telluride

Beam after splitter







Nagaitsev, Telluride

Performance Goals

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
Pulsed Linac		
Particle Type	H^-	
Beam Kinetic Energy	8.0	GeV
Pulse rate	10	Hz
Pulse Width	4.3	msec
Cycles to MI	6	
Particles per cycle to MI	2.6×10^{13}	
Beam Power to 8 GeV	340	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

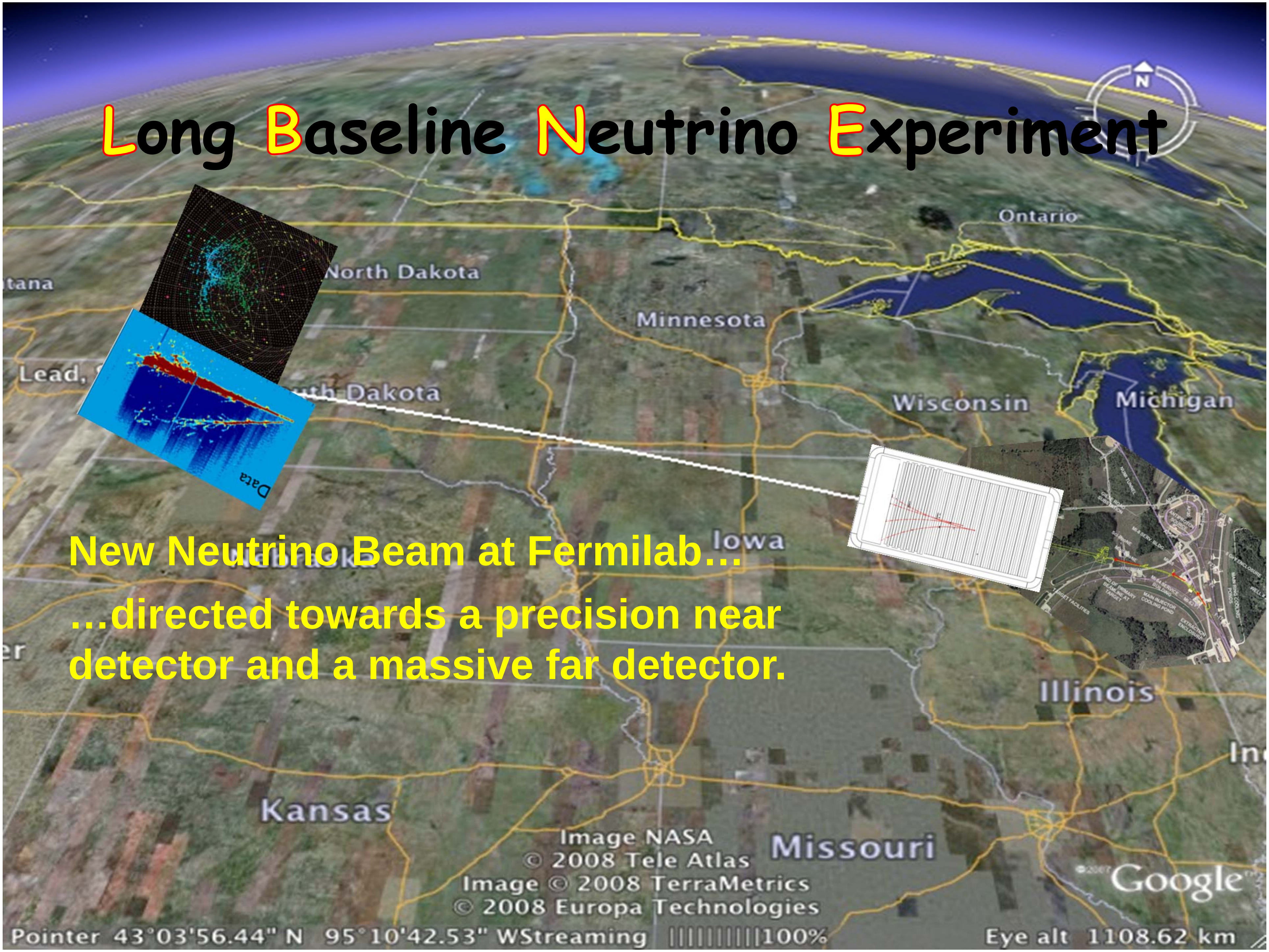
An Incomplete Menu of World Class Research Targets Enabled by Project-X

Neutrino Physics:

Possible Day-1 Experiment

- 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.

Long Baseline Neutrino Experiment



New Neutrino Beam at Fermilab…

…directed towards a precision near detector and a massive far detector.

Project-X and LBNE…

• Project-X makes LBNE a much better experiment! The recent US National Research Council (NRC) report recognized this:

“ The long-baseline neutrino oscillation experiment would provide a great advance in the study of neutrino properties, particularly when coupled with a neutrino beam produced at Fermilab using a new high-intensity proton source under development. ”

• The NRC also recognized that the principal consideration for LBNE is Beam-Power x Detector-Mass.

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

Muon Physics:

Possible 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. continued…

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.
- $K_L \rightarrow \pi^0 e^+ e^-$: <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

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

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.**

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

Collaboration

- A multi-institutional collaboration has been established to execute the Project X RD&D Program.
  - Organized as a "national project with international participation"
    - Fermilab as lead laboratory
    - International participation established via bi-lateral MOUs.
  - Collaboration MOUs for the RD&D phase outlines basic goals, and the means of organizing and executing the work. Signatories:

ANL	ORNL/SNS	BARC/Mumbai
BNL	MSU	IUAC/Delhi
Cornell	TJNAF	RRCAT/Indore
Fermilab	SLAC	VECC/Kolkata
LBNL	ILC/ART	

- Expectation is that collaborators to continue their areas of responsibility into the construction phase.

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.

Lepton Collider: A platform for Muon Collider development.

Energy Studies: A laboratory to develop enabling technologies.

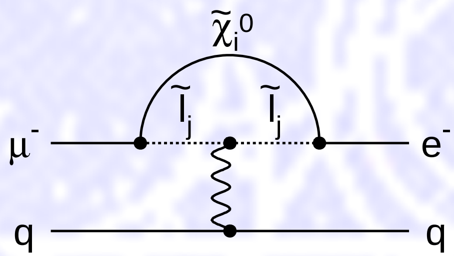
Prospects: International machine collaboration formed, strong bi-lateral collaboration with India. Ongoing substantial US (DOE) investments in R&D (Project-X + SRF + ILC) on Super Conducting RF accelerator technology supporting Project-X. Excellent near-term opportunities for collaborating on the research program.

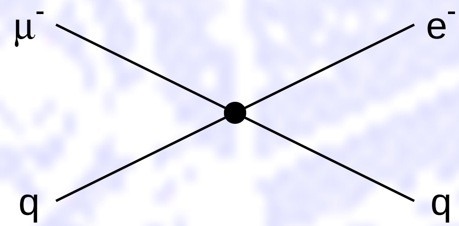
Spare Slides

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

Supersymmetry

Predictions at 10^{-15}



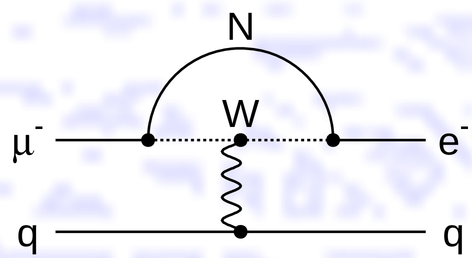


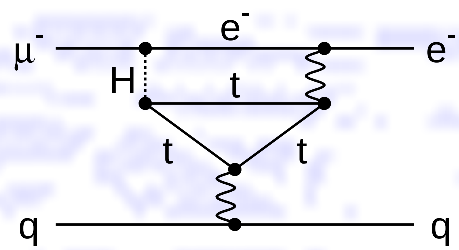
Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

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



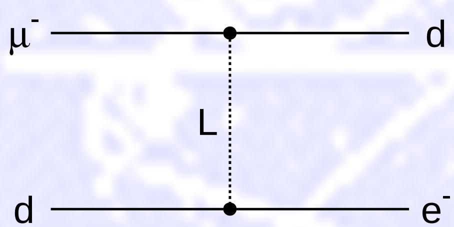


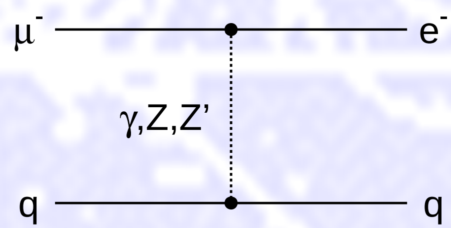
Second Higgs doublet

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

Leptoquarks

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





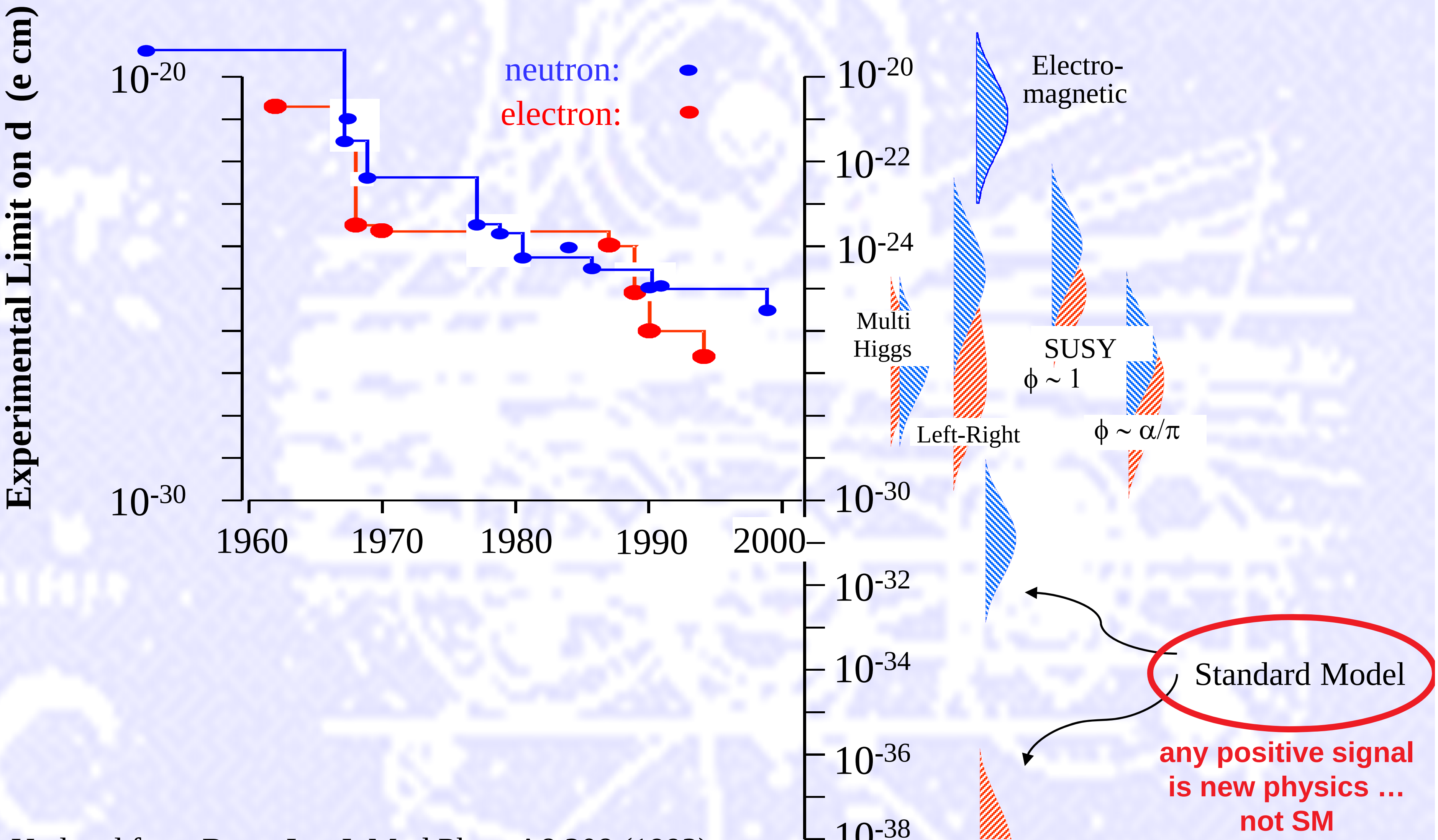
Heavy Z', Anomalous Z coupling

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

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

After W. Marciano

EDM measurements: BSM slayers

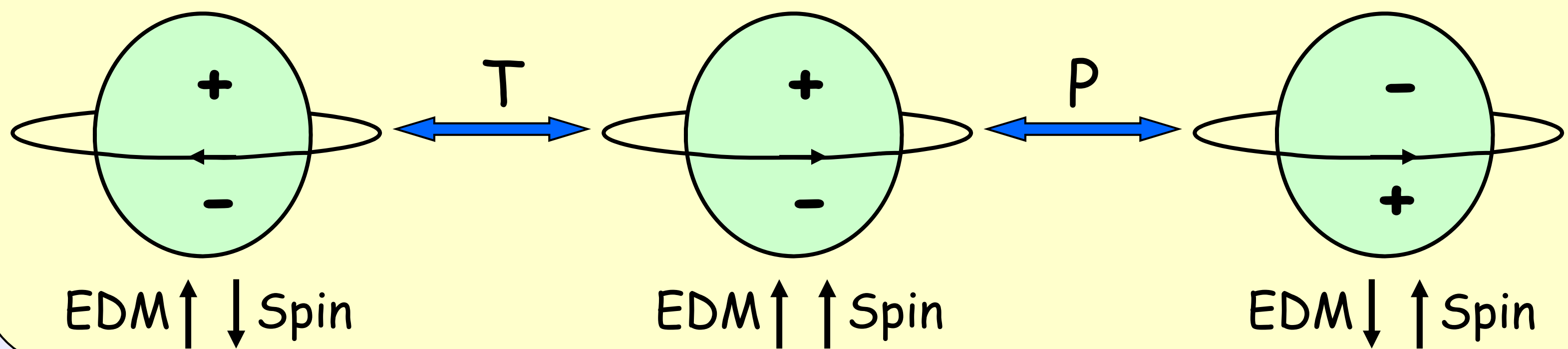


Updated from Barr: Int. J. Mod Phys. A8 208 (1993)

Guy Savard, ANL

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

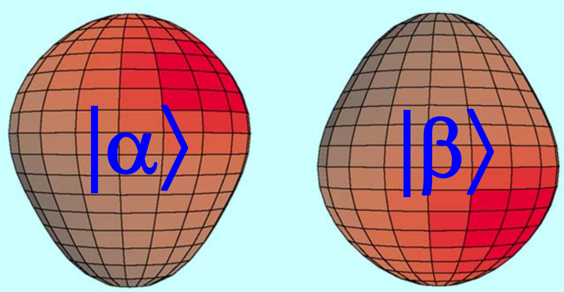
Enhanced EDM of ^{225}Ra

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

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

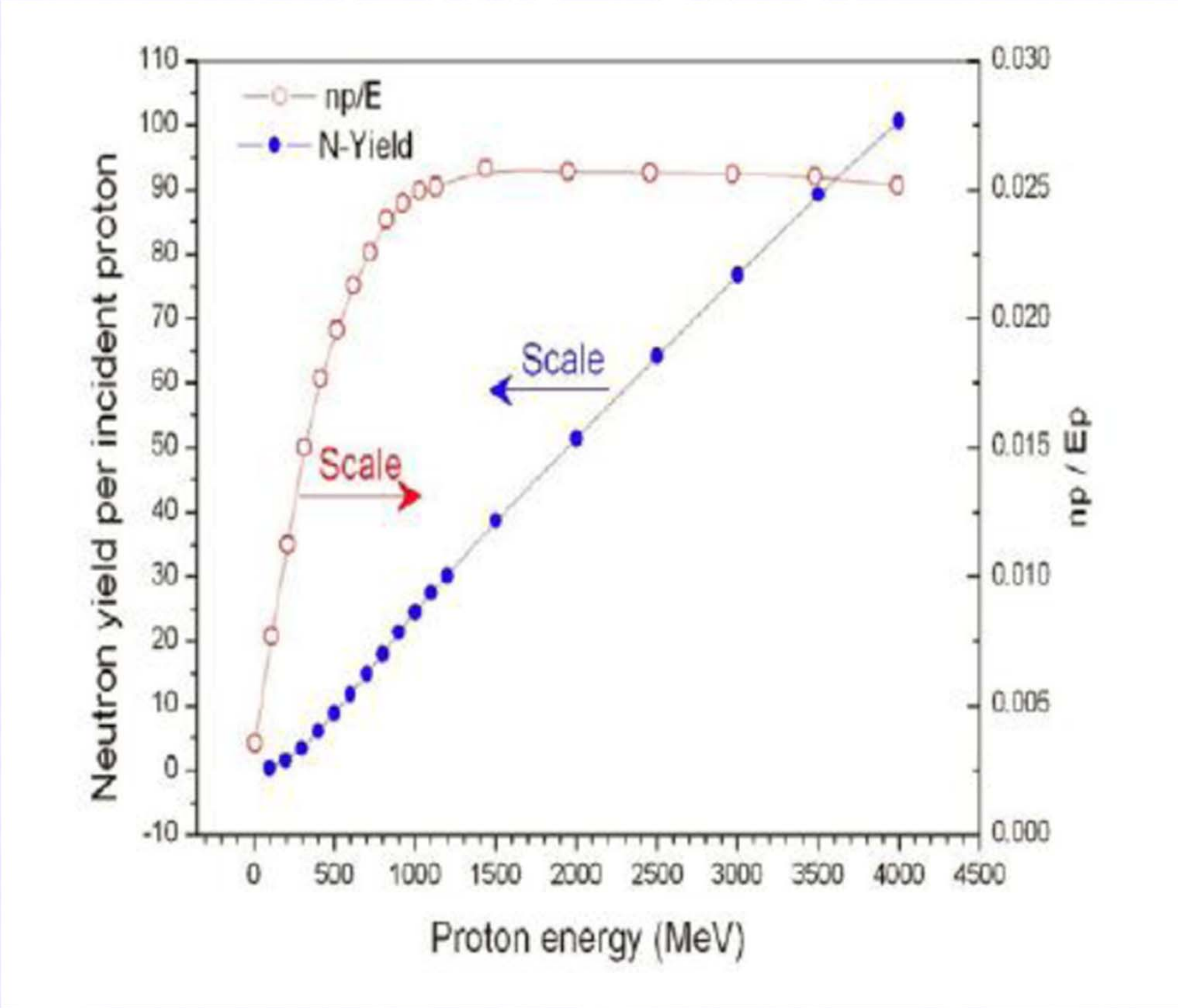
Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

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

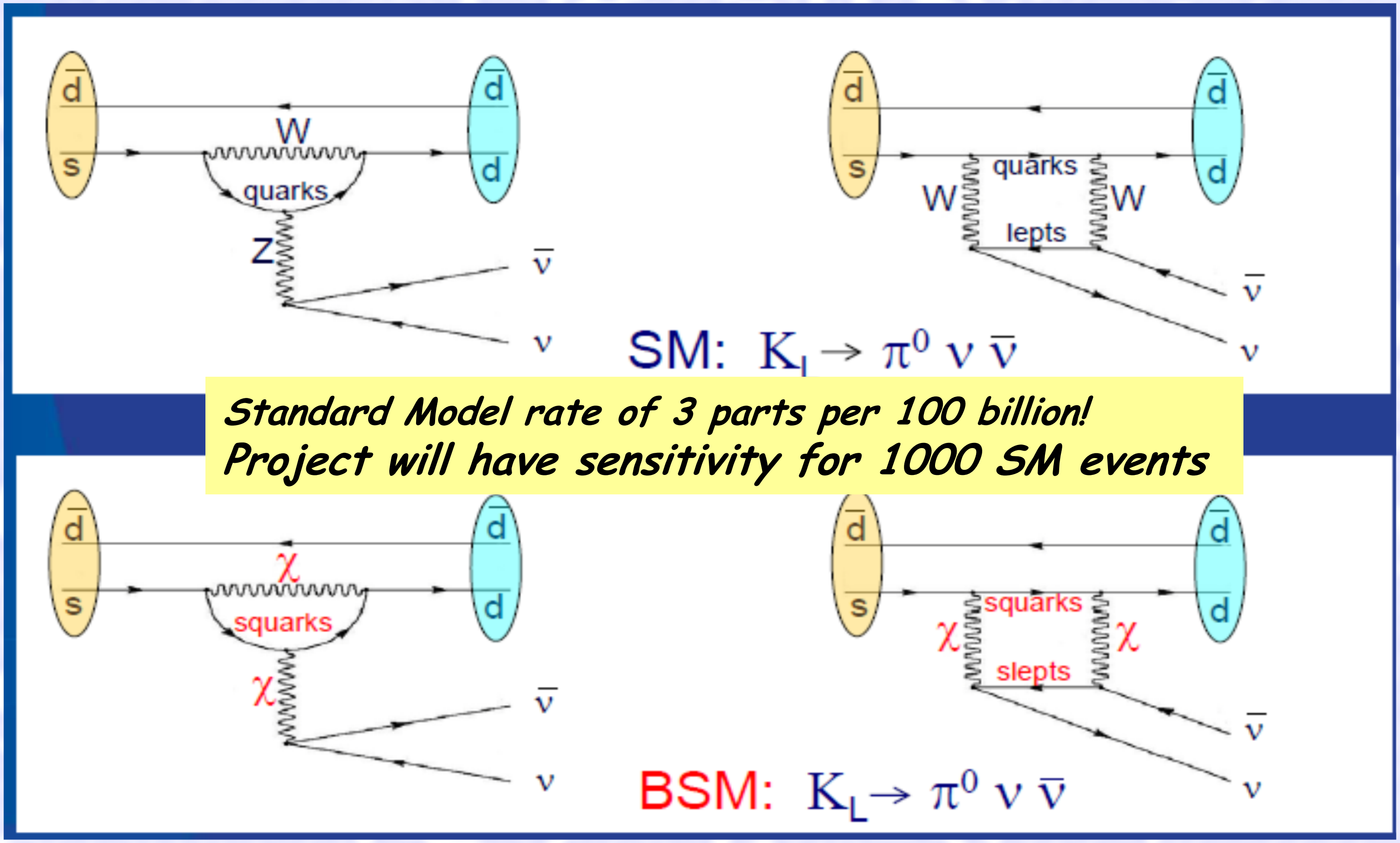
Schiff moment of ^{199}Hg, de Jesus & Engel, PRC (2005)
Schiff moment of ^{225}Ra, Dobaczewski & Engel, PRL (2005)

Guy Savard, ANL

Optimum Energy for ADS R&D



The Window of Ultra-rare Kaon Decays at Project X

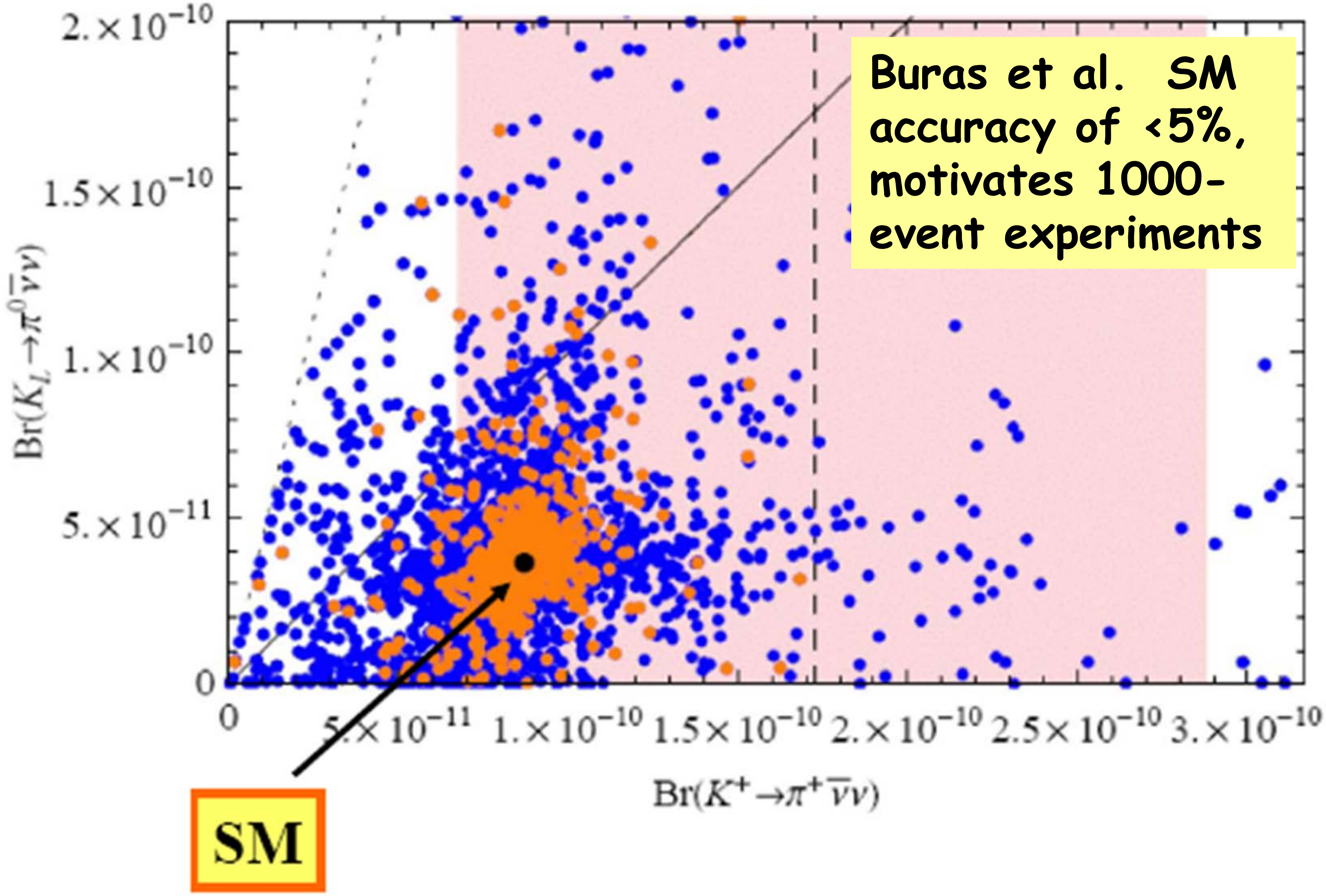


Standard Model rate of 3 parts per 100 billion!
Project will have sensitivity for 1000 SM events

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

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

(Up to Factor 3 and 2 Enhancements)



Effect of Warped Extra Dimension Models on Branching Fractions

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 $K_L \rightarrow \mu e$

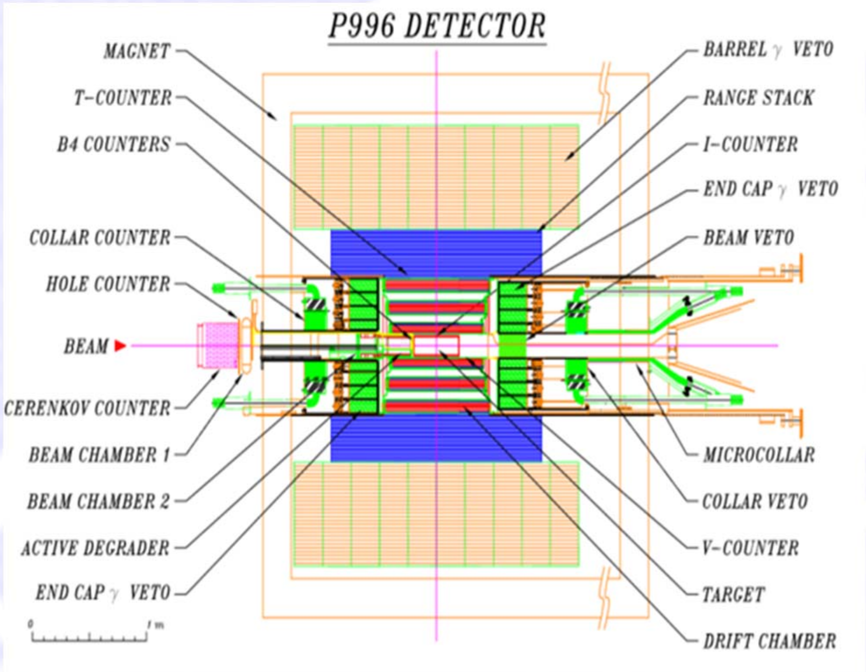
Probing new physics above a 10 TeV scale with 20-50 kW of protons.

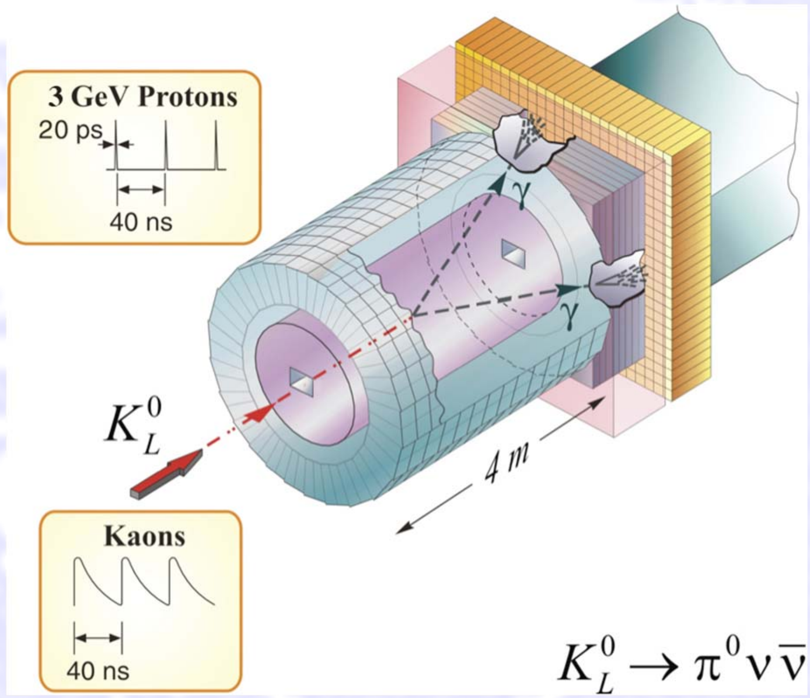
Next goal: 1000-event $\pi\nu\nu$ experiments...10^{-14} sensitivity.

Definitive Measurement of $K \to \pi\nu\bar{\nu}$

In the Project-X era the Fermilab P996 experiment would precisely measure the rate and form-factor of $K^+ \to \pi\nu\bar{\nu}$

The Project-X era presents an opportunity to measure the holy grail of kaon physics with precision: $K_L \to \pi\nu\bar{\nu}$

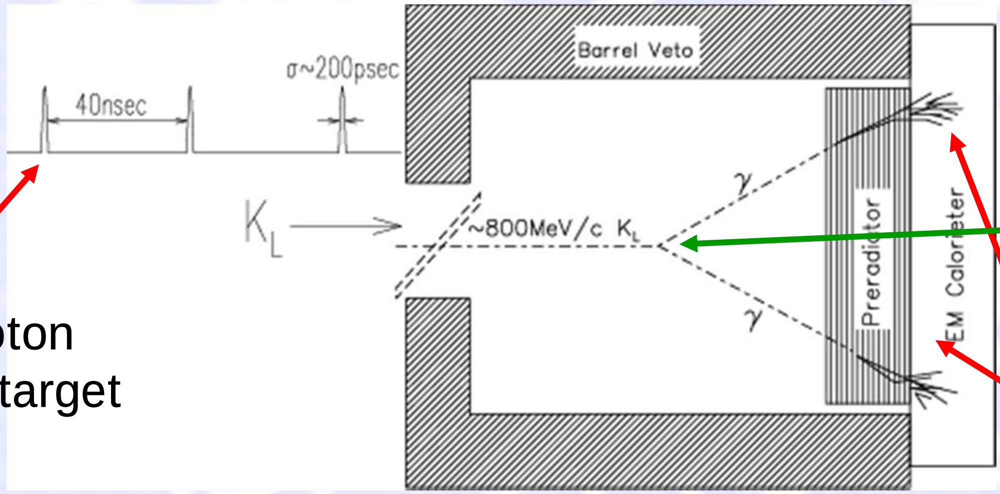




KOPIO inspired: Micro-bunch the beam, TOF determines K_L momentum.

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.

Kaon Yields at Constant Beam Power

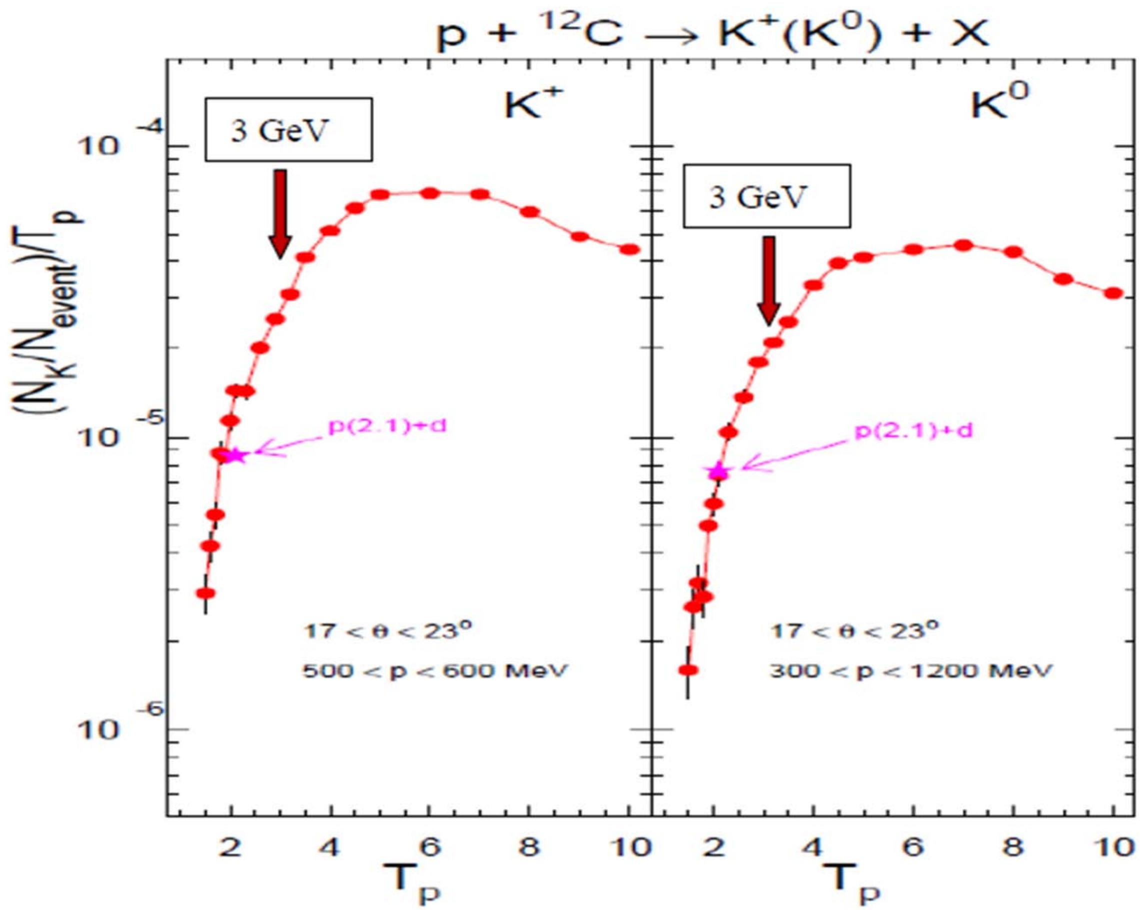
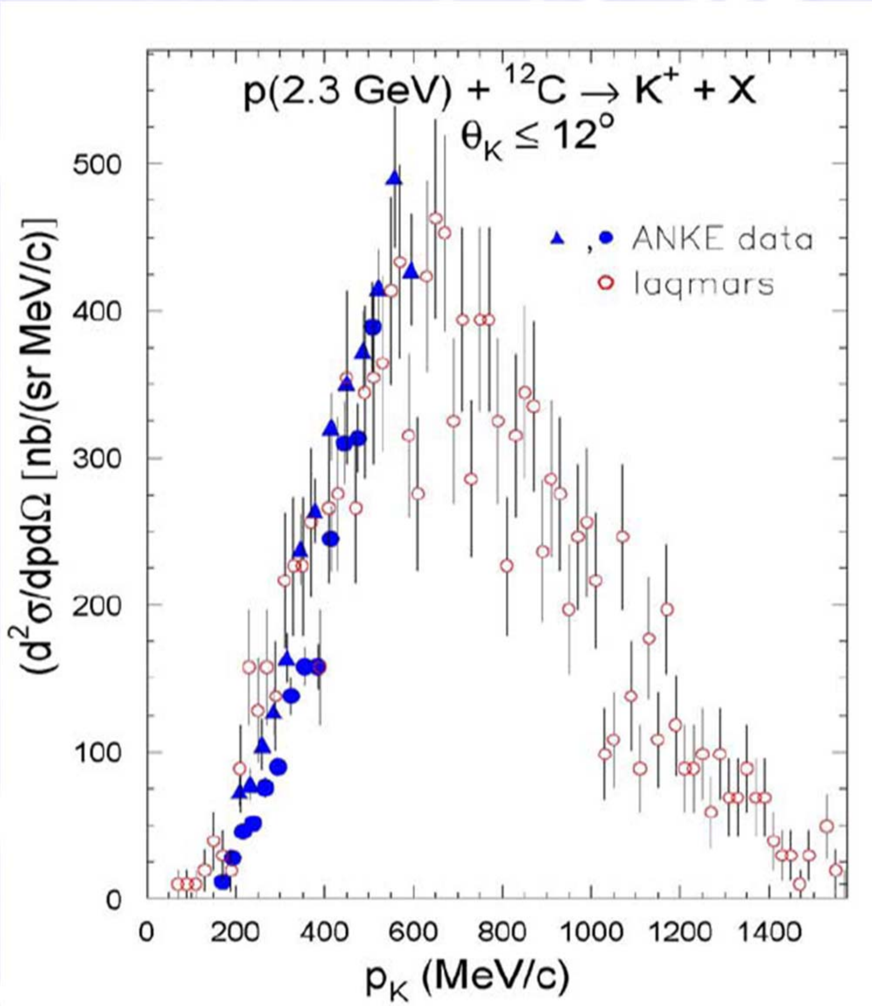


Figure 2: The estimated (LAQGSM/MARS15) kaon yield at constant beam power ($yield/T_p$) for experimentally optimal angular and energy regions as a function of T_p (GeV).

Validating Simulation Tools…



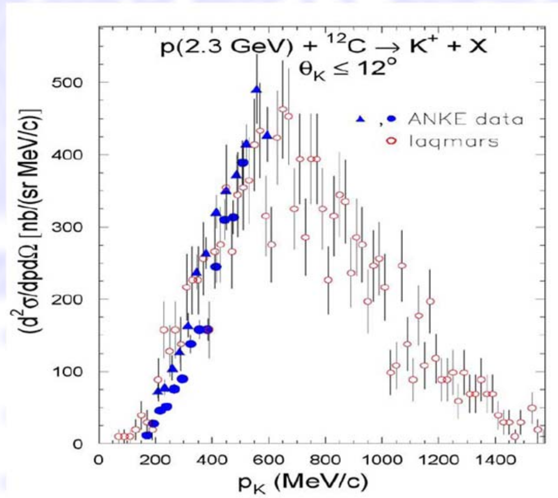
- Los Alamos + MARS simulation suite (LAQGSM + MARS15) is now a state of the art tool set to simulate the challenging region between 1-4 GeV/c proton beam momentum.

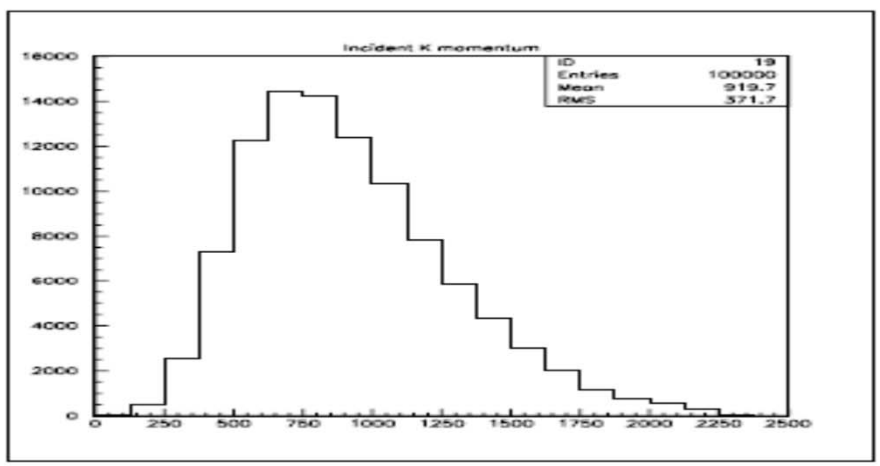
[Gudima, Mokhov, Striganov]

- Validated against the high quality data sets from COSY.

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

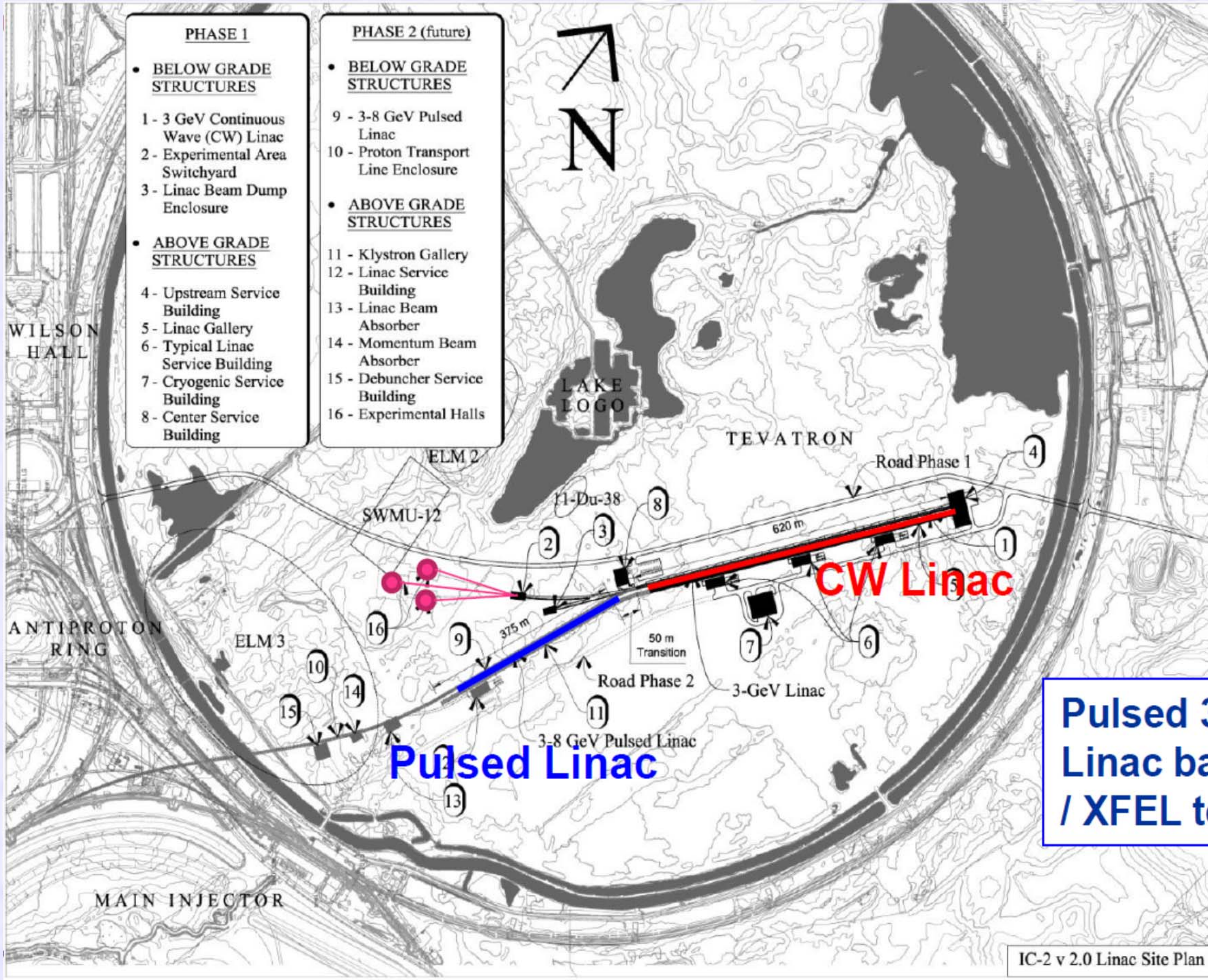
KOPIO-AGS and Project-X kaon momentum spectra comparison





KOPIO Proposal

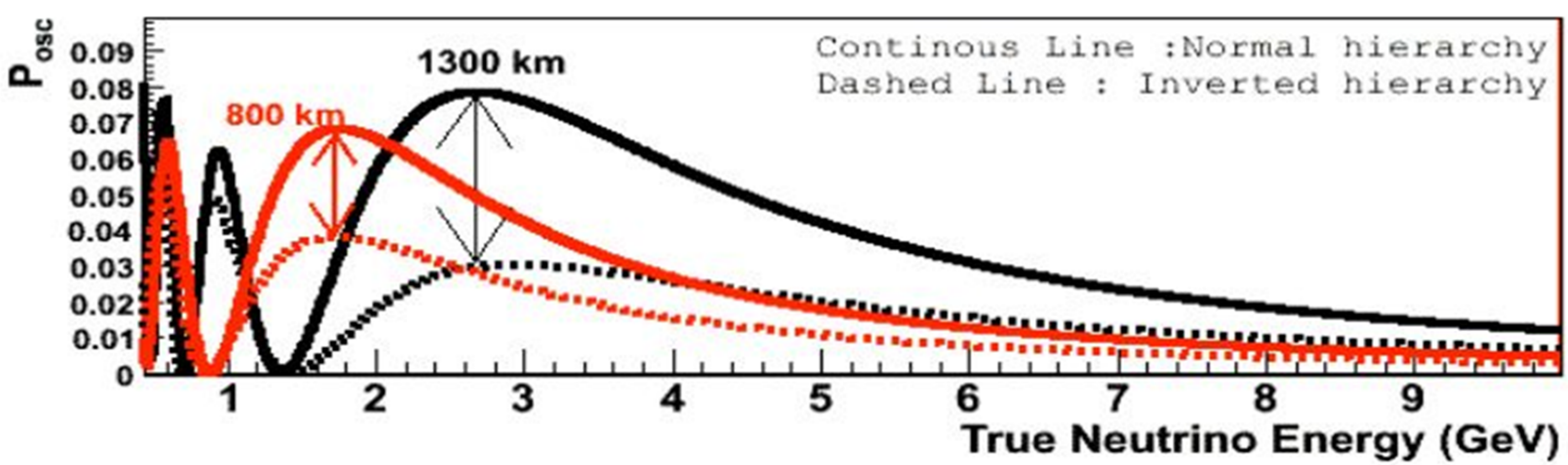
Figure 13: K_L^0 spectrum incident on KOPIO decay volume.



Pulsed 3-8 GeV Linac based on ILC / XFEL technology

Optimal Distance?

- 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