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.

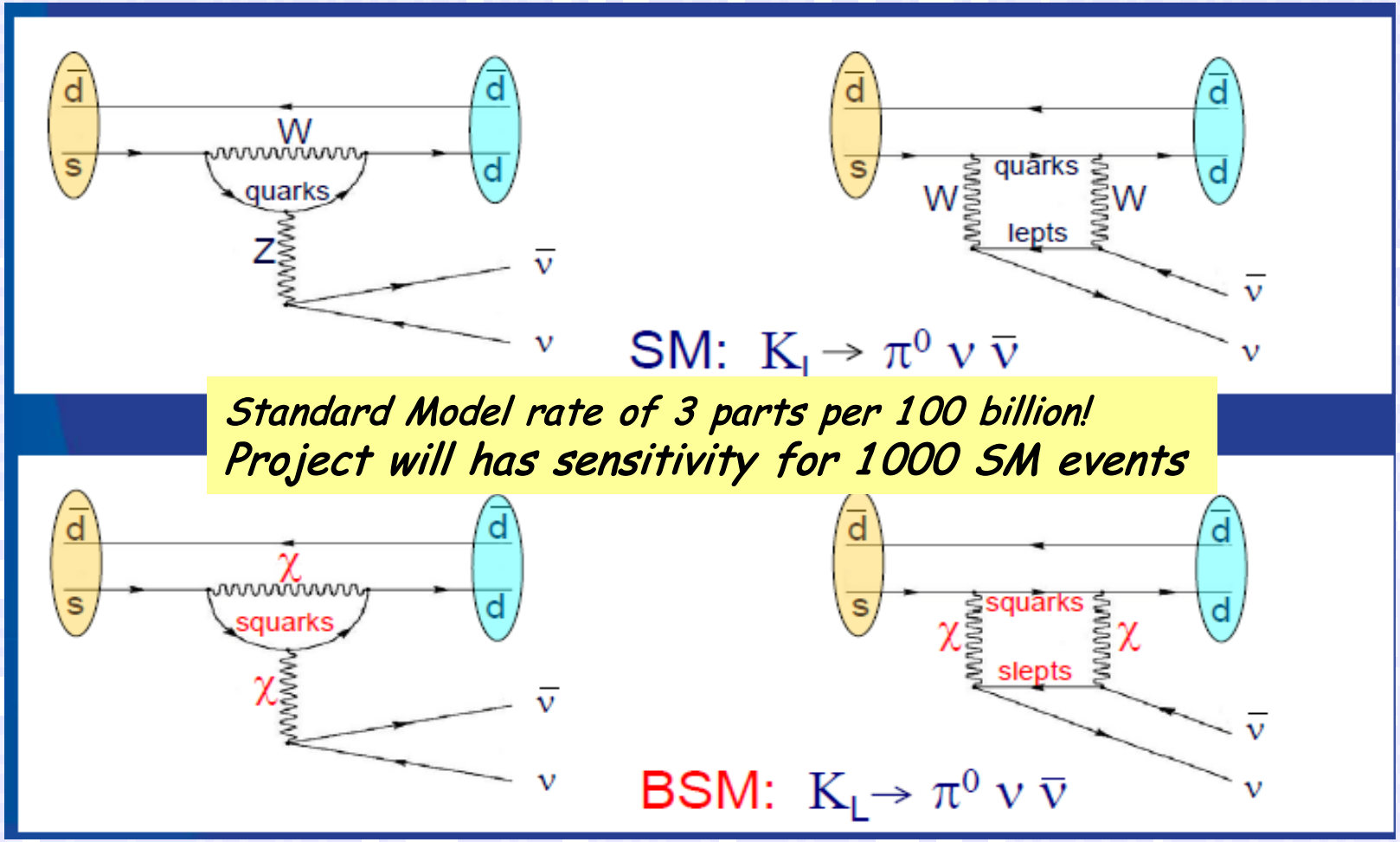
- **November 2009:** 4th Project-X workshop: Produced accelerator and comprehensive research white papers.

- **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 (CD0): Research program briefing November 17th 2010 at Germantown.

The Window of Ultra-rare Kaon Decays in Project X



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

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

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

Day-1 Experiments

Kaon Physics:

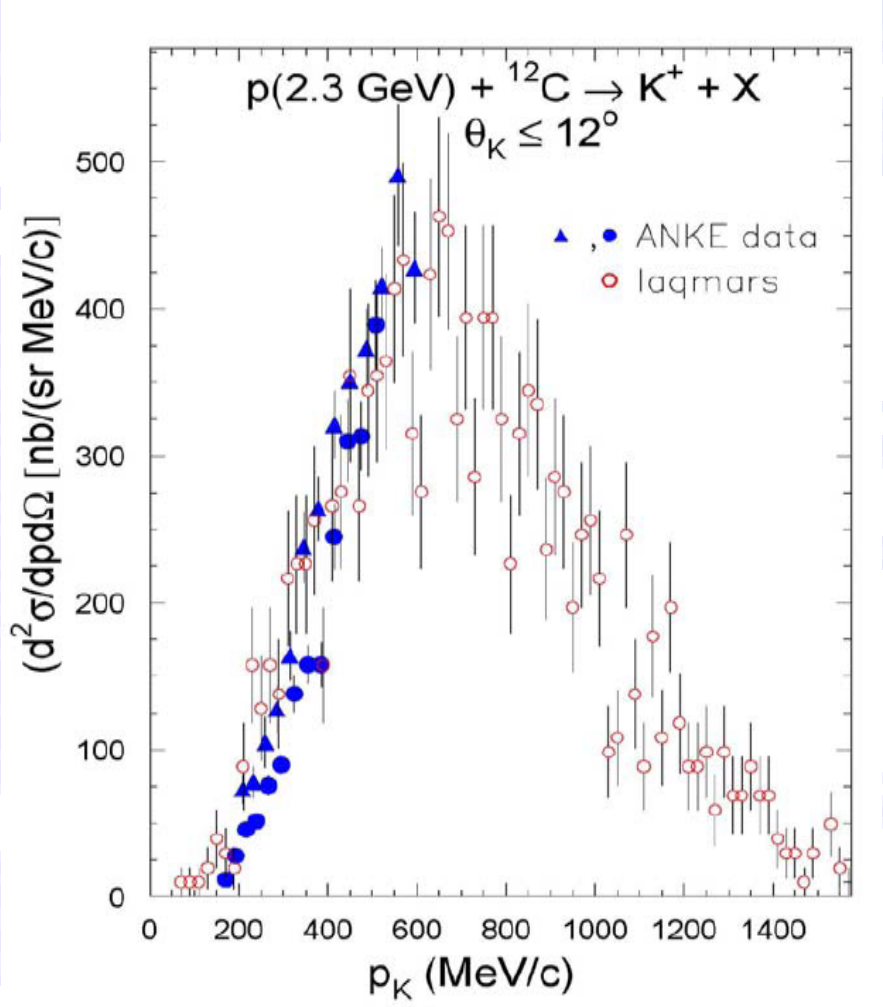
- $K^+ \rightarrow \pi^+\nu\bar{\nu}$: >1000 events, Precision rate and form factor.
- $K_L \rightarrow \pi^0\nu\bar{\nu}$: 1000 events, enabled by high flux & precision TOF.
- $K^+ \rightarrow \pi^0\mu^+\nu$: Measurement of T-violating muon polarization.
- $K^+ \rightarrow (\pi,\mu)^+\nu_x$: Search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

Project-X
Kaon Physics Targets

- $K^+ \to \pi^+ \nu\bar{\nu}$: >1000 events, precision measurement of the rate and form factor, both sensitive to new physics beyond the Standard Model.
- $K^+ \to \pi^0 \mu^+ \nu$: Search for new T-violating phenomena that can affect the transverse muon polarization.
- $K^+ \to (\pi,\mu)^+ \nu_x$: Search for anomalous heavy neutrinos with masses in the 50-250 MeV/c^2 range.
- $K_L \to \pi^0 \nu\bar{\nu}$: 1000 events, precision measurement of the rate is particularly sensitive to new CP violating phenomena.
- $K_L \to \pi^0 e^+ e^-$: <10% measurement of a direct CP violating amplitude, complementary sensitivity to new CP violating physics.
- $K_L \to \pi^0 \mu^+ \mu^-$: <10% measurement of direct CP violating amplitude, complementary sensitivity to new CP violating physics.
- $K^0 \to X$: Precision study of a pure K^0 interferometer, which can be sensitive to new physics out to the Plank scale ($\Delta m_K/m_K \sim 1/M_{Plank}$)
- $K^0, K^+ \to LFV$: Most incisive next-generation search for Lepton Flavor Violating physics in the quark sector.

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

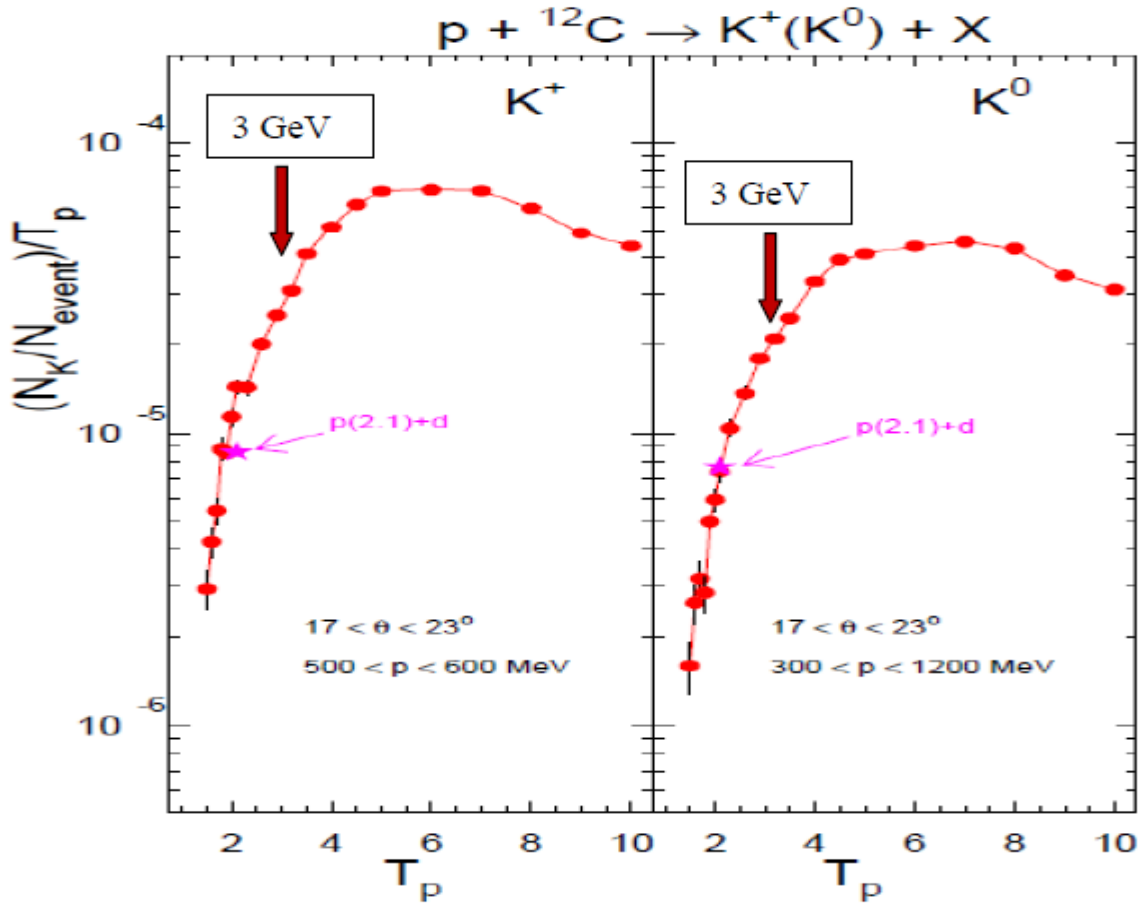


Figure 2: The estimated (LAQGSM/MARS15) kaon yield at constant beam power (yield/T_p) for experimentally optimal angular and energy regions as a function of T_p (GeV).

Stopping charged kaon rates: AGS & Project-X

	Beam Energy T_p	Protons/second (avg) on [target (λ_I)]	$p(K^+)$ (MeV/c)	Stopping K^+/second	K^+/π^+ Production Ratio
BNL AGS (E949)	21 GeV	12×10^{12} on [0.7 λ_I Pt.]	700-730	0.7×10^6 K^+/sec	1:24
Project-X/ K^+ expt	3.0 GeV	$1/2 \times 6000 \times 10^{12}$ on [1.0 λ_I C]	450-570	98×10^6 K^+/sec	1:80

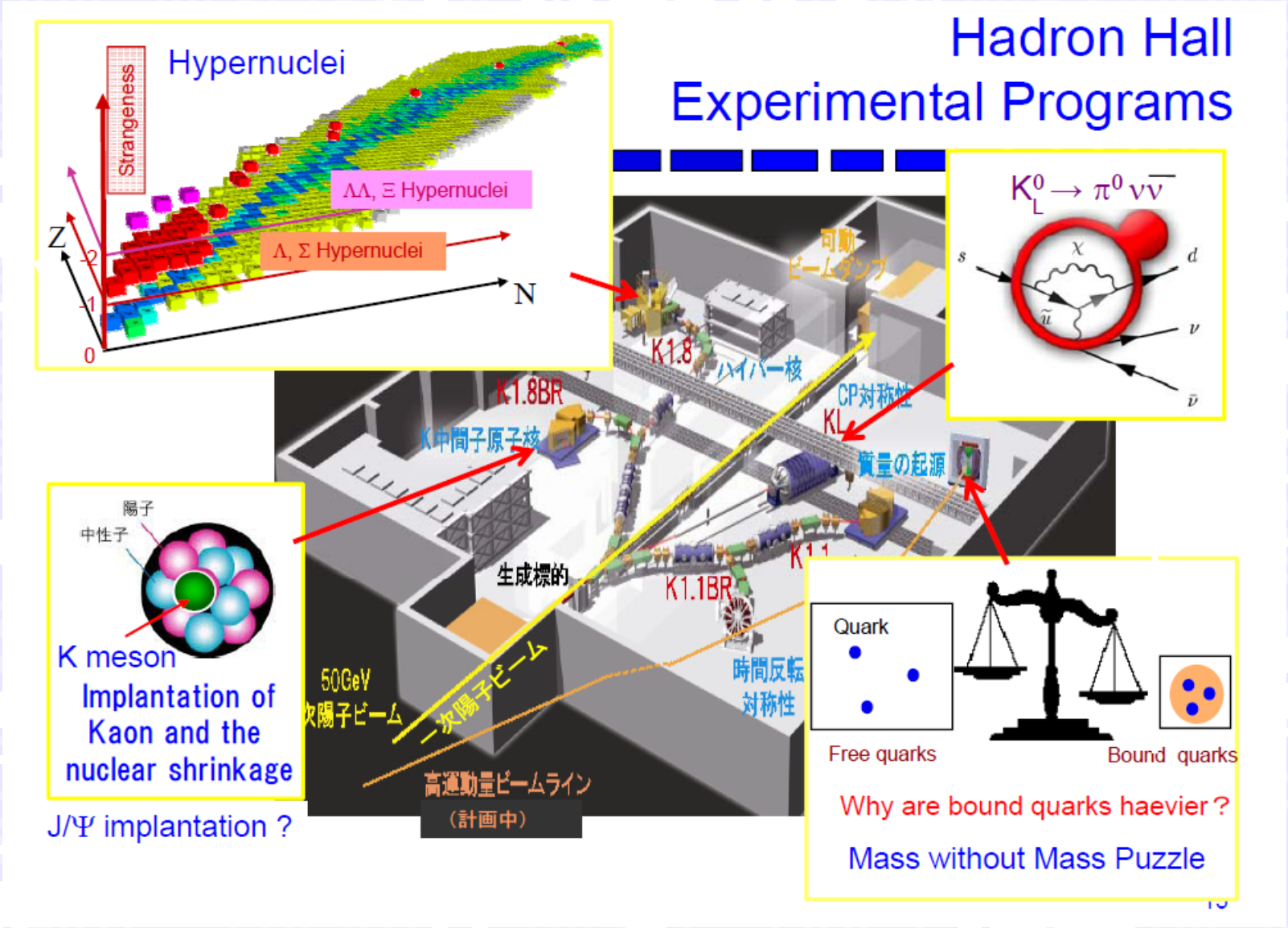
Table 1: Compares the measured rate of stopping K^+ in the BNL-E949 experiment with full LAQGSM/MARS thick-target simulations for Project-X charged kaon yield with ½ of the 1 ma 3.0 GeV proton beam.

Neutral Kaon Beam Rates
AGS & Project-X Rates

	Beam Energy	Target (λ_I)	$p(K^+)$ (MeV/c)	K_L/second (into 500 μsr)	K_L/n Ratio (E_n>10 MeV)
BNL AGS	24 GeV	1.1 Platinum	300-1200	60×10^6 K_L/sec	~1:1000
Project X	3.0 GeV	1.0 Carbon	300-1200	450×10^6 K_L/sec	~1:2700

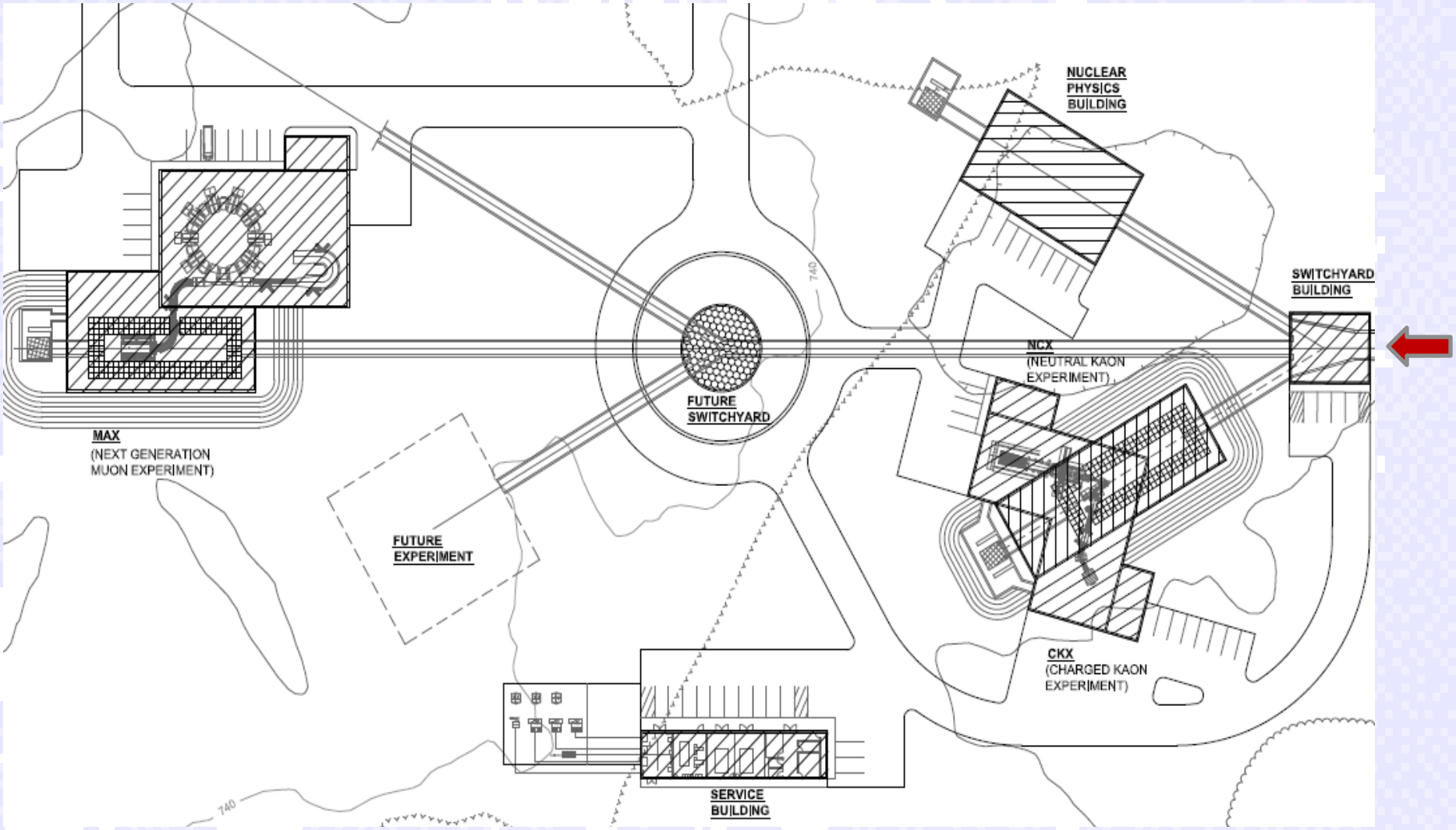
Table 2: Comparison the Project-X K_L production yield from a thick target fully simulated with LAQGSM/MAR15 into the KOPIO beam solid angle and momentum acceptance. The BNL AGS kaon and neutron yields are from RSVP reviews in 2004 (Bryman) and Jaffe (2005).

JPARC Play Book



Courtesy Nagamiya-san

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



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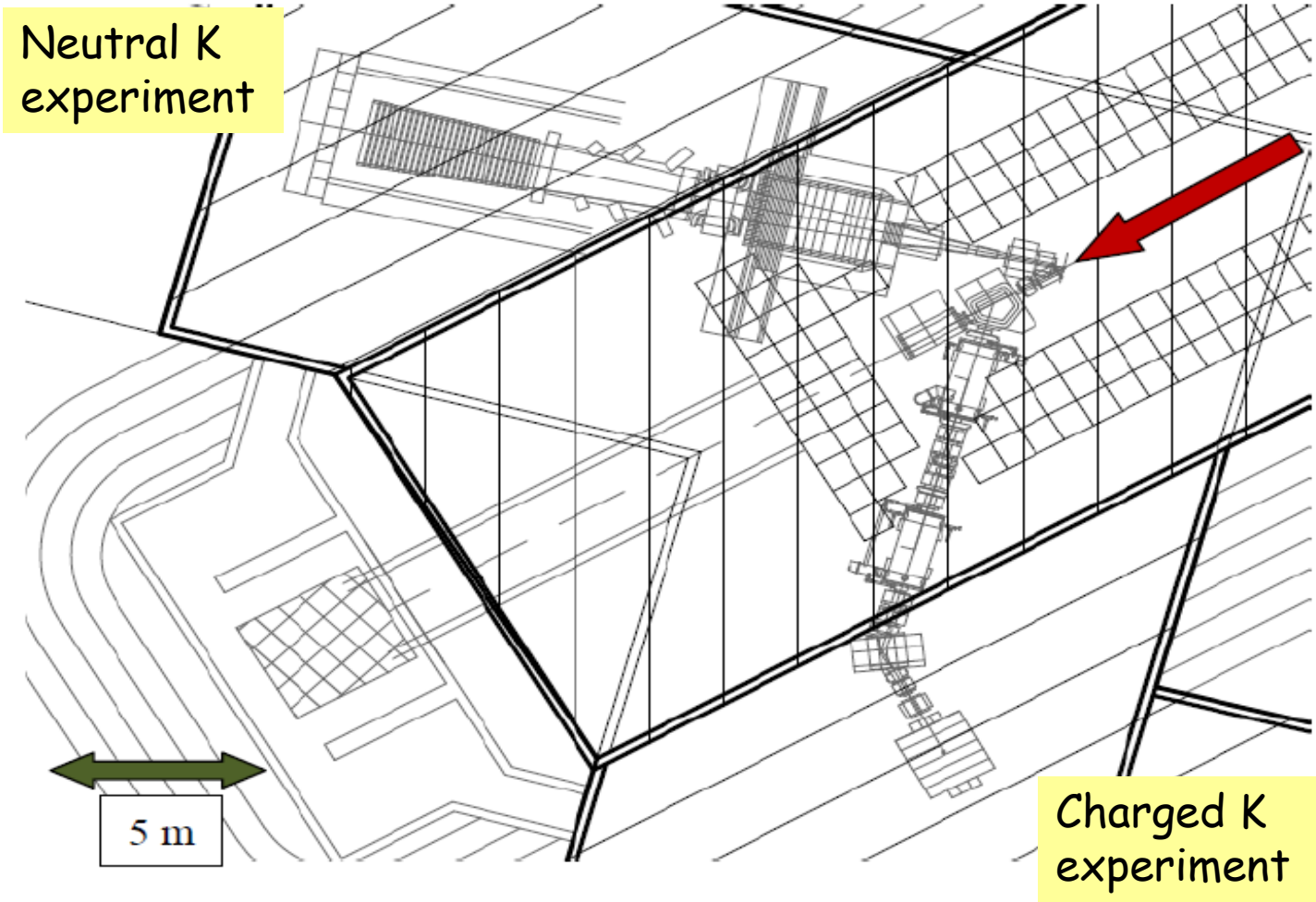
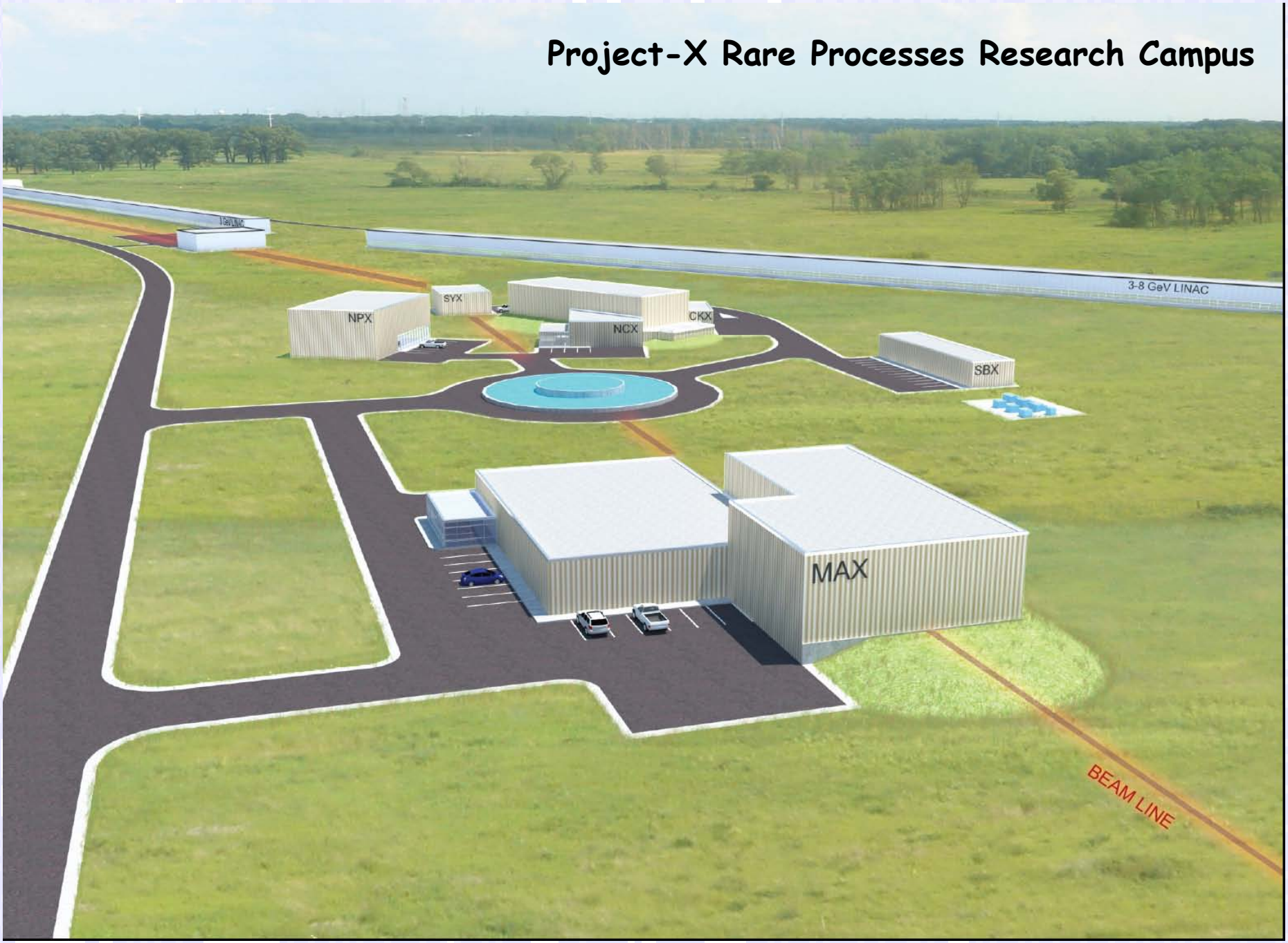
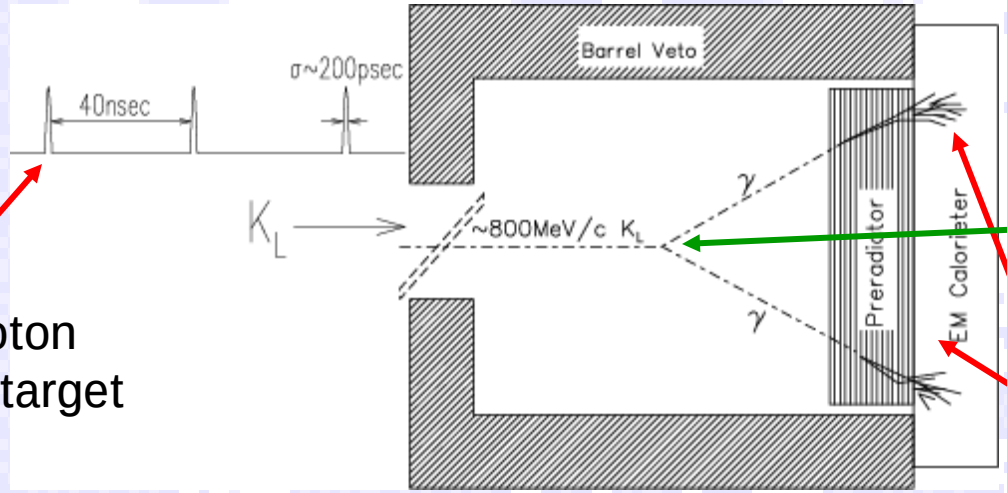


Project-X Rare Processes Research Campus



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.

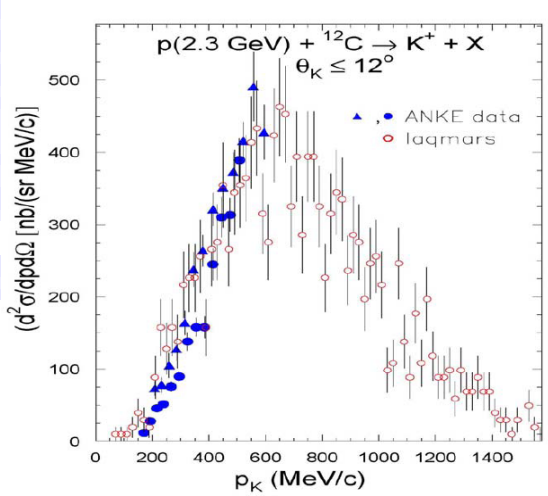


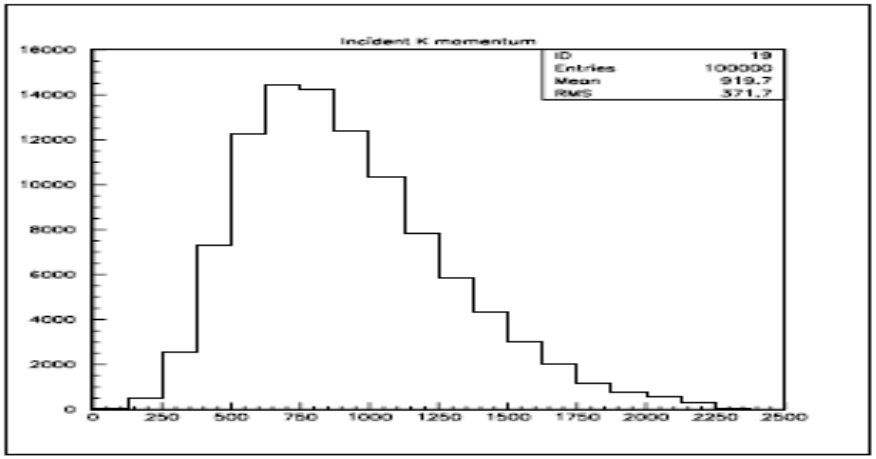
Start when proton beam hits the target

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-AGS and Project-X kaon momentum spectra comparison





KOPIO Proposal

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

Road to Future Progress: Project-X Kaon Research Program

- International community active, Fermilab community is essentially dormant at this point. Buoyed to some extent now by the US quark flavor physics community—but this community is currently under stress regarding futures.

- P996 Fermilab proposal stalled, raises questions.

- A plan for bridging to the Project-X era is needed.

  - Creative funding schemes for P996?
  - Encourage P996 to submit a staged proposal?
  - Greater US collaboration with the JPARC and CERN experiments & initiatives in the near term?

Spare Slides

Project-X Accelerator Functional Requirements

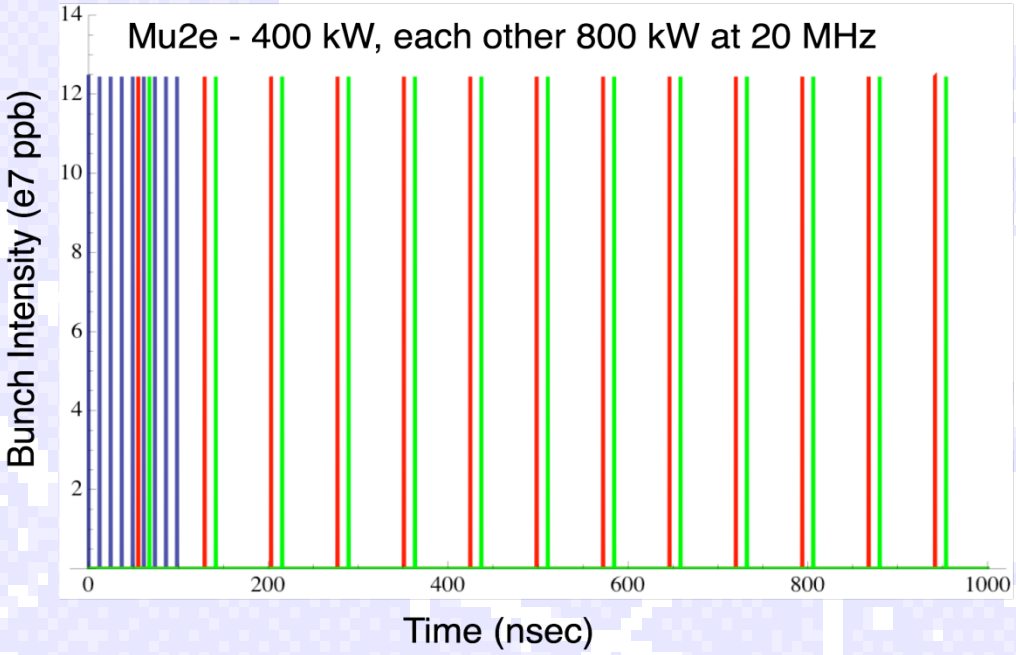
CW Linac		
Particle Type	H^-	
Beam Kinetic Energy	3.0	GeV
Average Beam Current	1	mA
Linac pulse rate	CW	
Beam Power	3000	kW
Beam Power to 3 GeV program	2870	kW
RCS/Pulsed Linac		
Particle Type	protons/H^-	
Beam Kinetic Energy	8.0	GeV
Pulse rate	10	Hz
Pulse Width	0.002/4.3	msec
Cycles to MI	6	
Particles 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

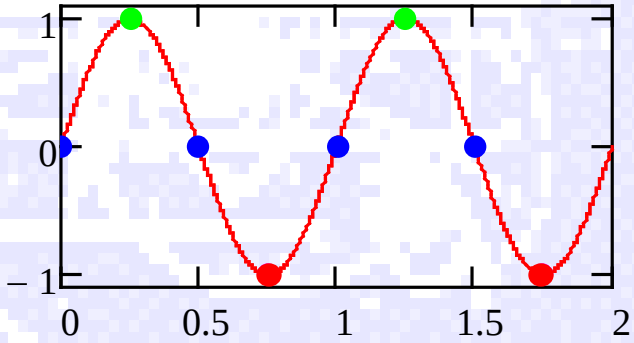
simultaneous

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

1 μsec period at 3 GeV

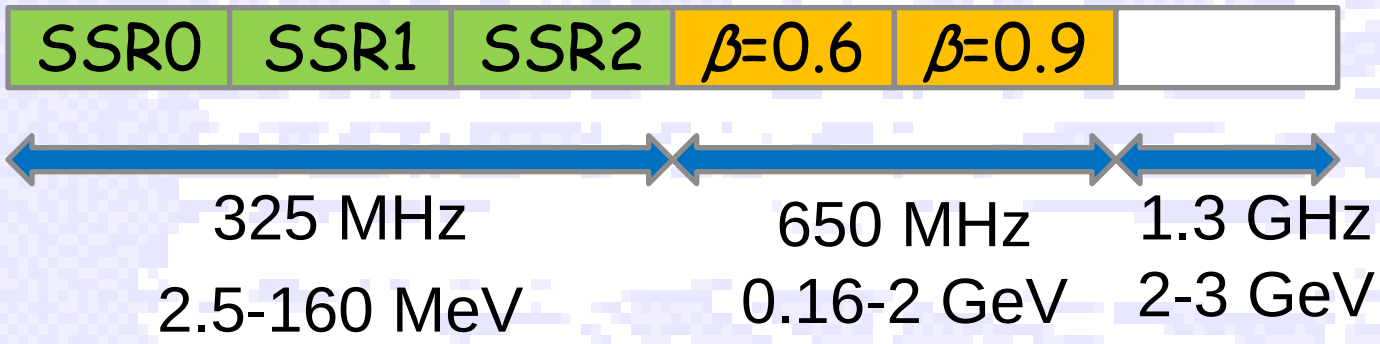
mu2e pulse (9e7) 162.5 MHz, 100 nsec	600 kW
Kaon pulse (9e7) 27 MHz	1200 kW
Nuclear pulse (9e7) 27 MHz	1200 kW





Separation scheme with traverse kicker ala JLAB.

SC CW Linac Technology Map

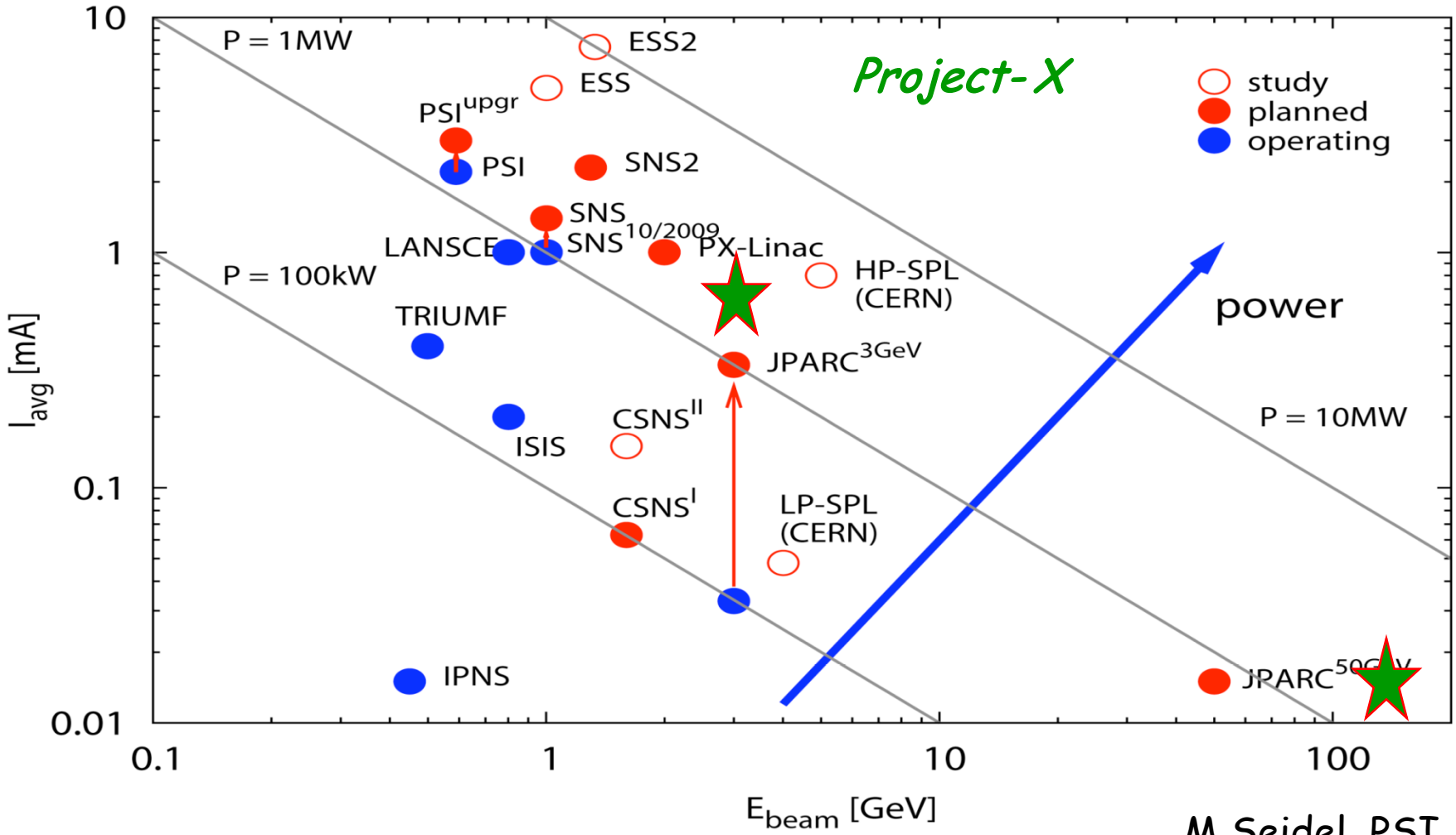


Section	Freq	Energy (MeV)	Cav/mag/CM	Type
SSR0 (β_G=0.11)	325	2.5-10	26 /26/1	SSR, solenoid
SSR1 (β_G=0.22)	325	10-32	18 /18/ 2	SSR, solenoid
SSR2 (β_G=0.4)	325	32-160	44 /24/ 4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-520	42 /21/ 7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	520-2000	96 /12/12	5-cell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

"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 (δt~*20psec*), 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.

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



M Seidel, PSI

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

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 $I^2 x \delta t$, 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.

Sensitivity of Kaon Physics Today

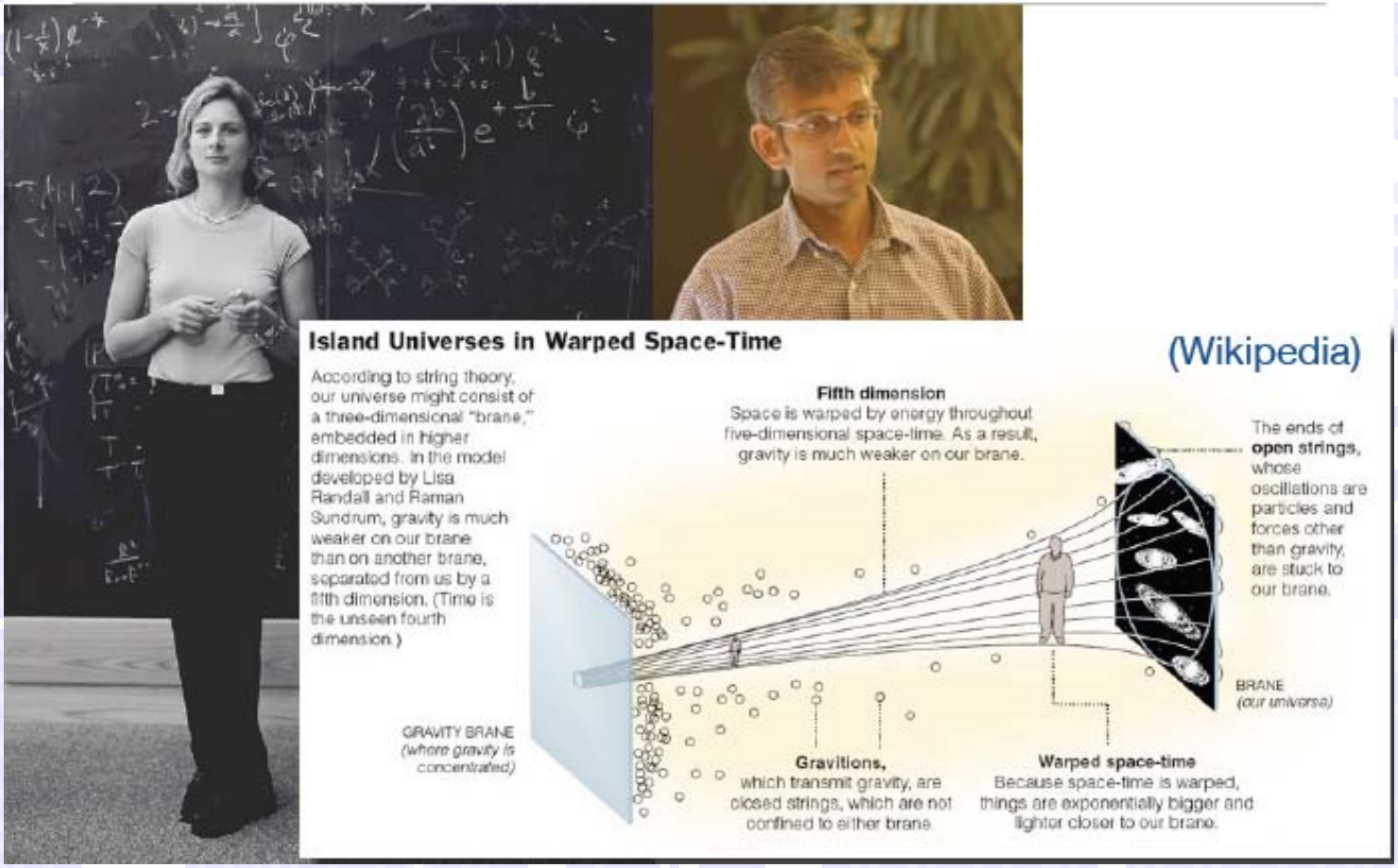
- CERN NA62: 100×10^{-12} measurement sensitivity of $K^+ \to e^+ \nu$
- Fermilab KTeV: 20×10^{-12} measurement sensitivity of $K_L \to \mu\mu ee$
- Fermilab KTeV: 20×10^{-12} search sensitivity for $K_L \to \pi\mu e$, $\pi\pi\mu e$
- BNL E949: 20×10^{-12} measurement sensitivity of $K^+ \to \pi^+ \nu\bar{\nu}$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

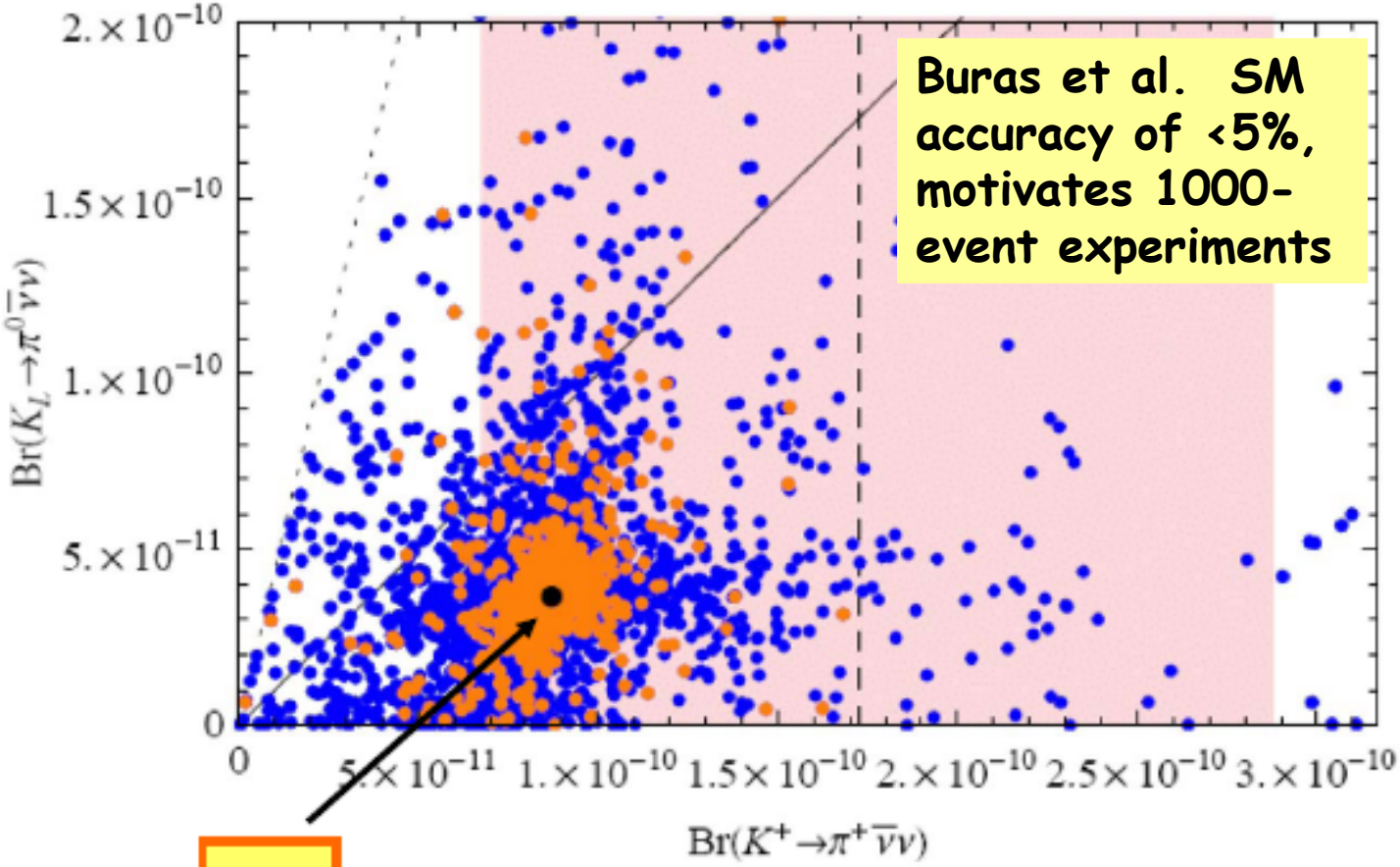
Rates sensitive to other BSMs: Warped Extra Dimensions as a Theory of Flavor??

The Randall-Sundrum (RS) idea



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

(Up to Factor 3 and 2 Enhancements)



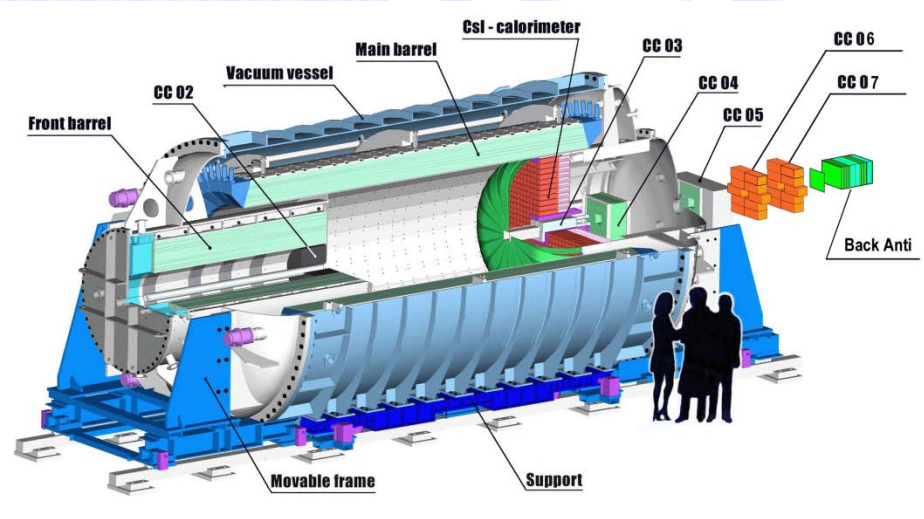
Effect of Warped Extra Dimension Models on Branching Fractions

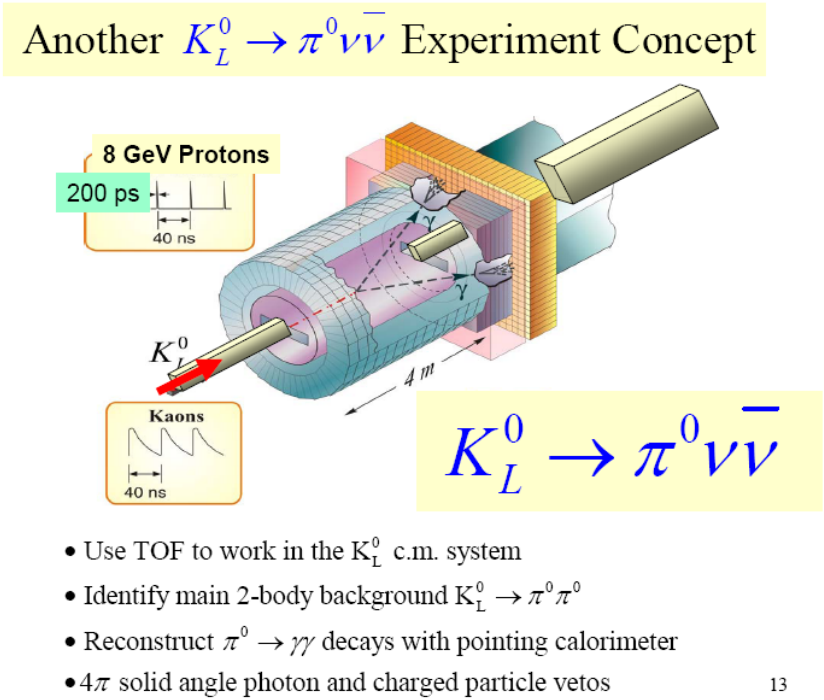
$K_L \to \pi^0 \nu\nu$ Experimental Challenge: "Nothing-in nothing out"

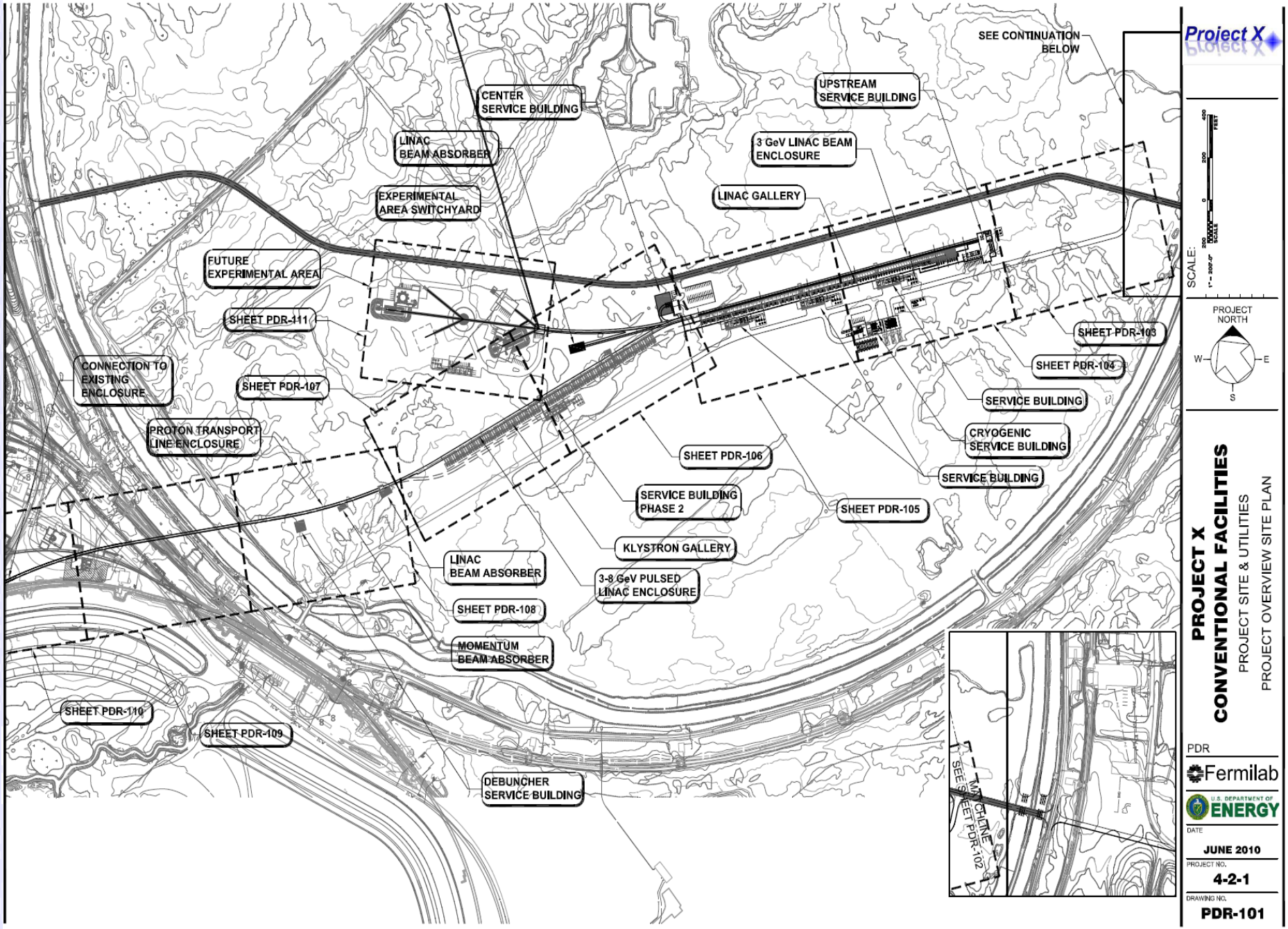
•KEK/JPARC approach emphasizes high acceptance for the two decay photons while vetoing everything else:

A hermetic "bottle" approach.

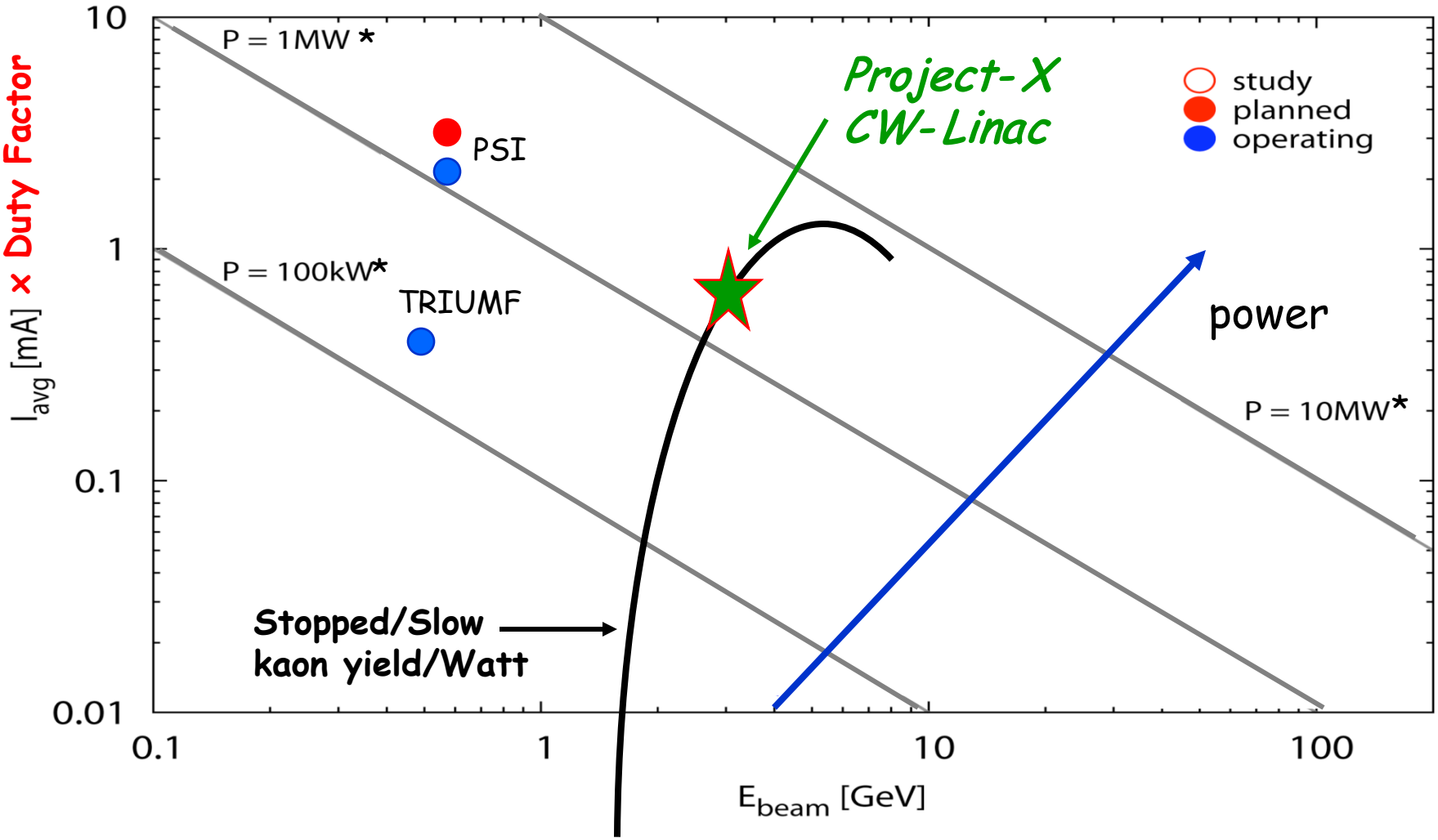
•The original KOPIO concept measures the kaon momentum and photon direction…Good! But costs detector acceptance and requires a large beam to compensate. Project-X Flux can get back to small kaon beam!






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

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



* Beam power x Duty Factor