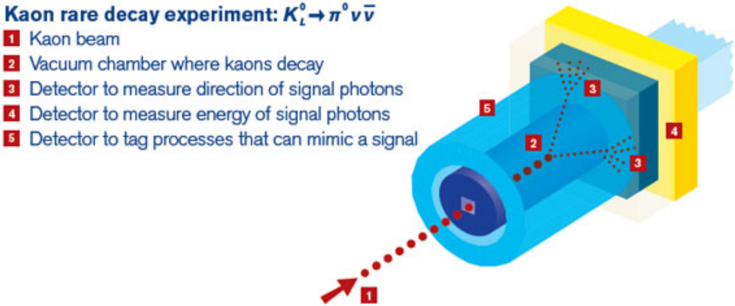
Kaons at Project-X

David Jaffe



April 2013 Intensity Frontier Workshop

Flavor Physics in the LHC Era: Rare Decays

New Physics found at LHC
⇒ New particles with unknown flavor- and CP-violating couplings

Precision flavor-physics experiments needed to help sort out the flavor- and CP-violating couplings of the NP.

New Physics NOT found at LHC

Precision flavor-physics experiments needed -> sensitive to NP at mass scales beyond the reach of the LHC (through virtual effects).

Quark Gen.	Processes to Study NP
1	μ-e Conversion, μ ® $e\gamma$,π ® $e\nu$
2	K^+ ® $\pi^+\nu\bar{\nu}$, K_L^0 ® $\pi^0\nu\bar{\nu}$
3	b ® $s\gamma$, other rare decays

K^+ ® $\pi^+\nu\bar{\nu}$ and K_L^0 ® $\pi^0\nu\bar{\nu}$ have special status because of their small SM uncertainties and large NP reach.

$\mu - e$ Conversion and $K^+ \to \pi^+\nu\bar{\nu}$ are immediate priorities.
* Huge gains in sensitivity are experimentally accessible.
* Smooth transitions to the Day-1 Project-X Intensity Frontier program.

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Rare K physics at Project X

	Current expt
$K^+ \to \pi^+ \nu\bar{\nu}$: Wide range of New Physics accessible	NA62
$K^0_L \to \pi^0 \nu\bar{\nu}$: Wide range of NP including pure CPV effects	KOTO
$K^+ \to \pi^0 \mu^+ \nu$: Transverse polarization, T violation	TREK
$K^+ \to e^+ \nu / K^+ \to \mu^+ \nu$: Universality, LFV	TREK
$K^+ \to \mu^+ \nu_H$: Heavy neutrinos	TREK
$K^0_L \to \pi^0 \ell^+ \ell^-$: CP violation	
$K \to \mu e(X)$: LFV	
K^0-interferometry (Planck scale physics)	

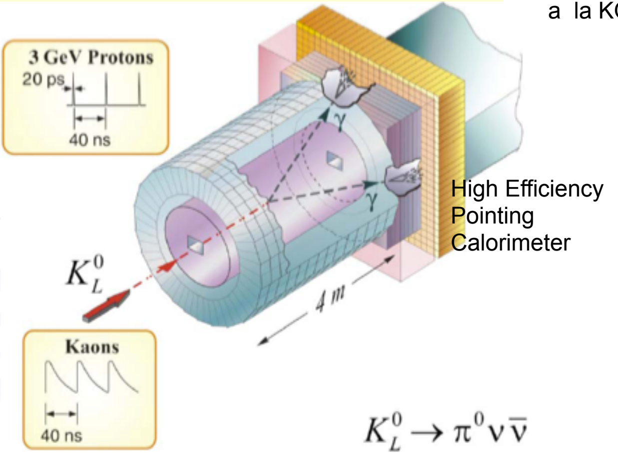
- Pre-Project-X ORKA $K^+ \to \pi^+ \nu\bar{\nu}$ experiment will provide a smooth transition to the premium Day One Project-X experiment to measure $K^0_L \to \pi^0 \nu\bar{\nu}$.
- After ORKA discovers new physics in $K^+ \to \pi^+ \nu\bar{\nu}$, it can move to the Project-X Kaon campus
- I will not totally neglect other kaon physics listed on this page.

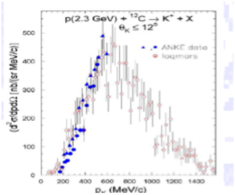
The challenge: Precision measurement of $\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu})$

- In SM, $\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu}) \approx 3 \times 10^{-11}$.
  - To observe 1000 events with 1% efficiency, requires $\sim 3 \times 10^{15}$ K_L^0 or three years at $\sim$100MHz of K_L^0.
- Weak signature
  - Dubbed "Nothing in, nothing out" by many.
- B/S $\approx \mathcal{B}(K_L^0 \to \pi^0 X)/\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu}) \approx 10^{10}$.
  - $K_L^0 \to \pi^0\pi^0$ is the most troublesome.
- Must veto on extra particles with inefficiency $\leq 10^{-4}$
- Most neutral kaon beams have $K_L^0/\mathrm{neutron} \approx 10^{-2}$.
  - Must suppress $n + \mathrm{gas} \to \pi^0 X$ with high vacuum
  - Halo must be small and controlled
  - Hermiticity requires photon veto in the beam
- **Must have convincing measurements of backgrounds**

Project X : K_L^0 ® $\pi^0\nu\nu$ Experiment Concept

a la KOPIO



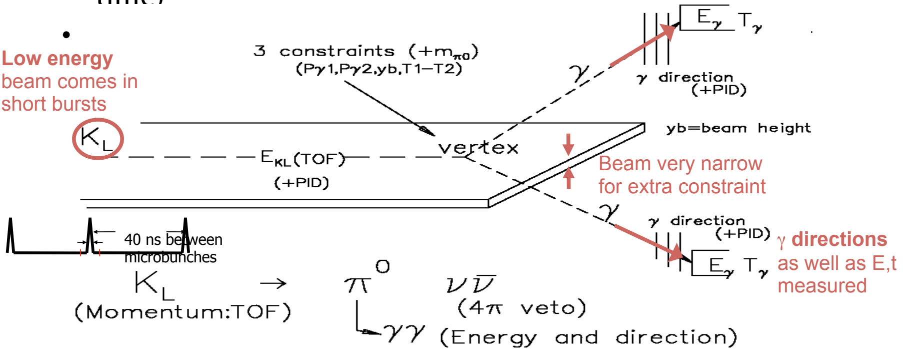


$$K_L^0 \to \pi^0 \nu \bar{\nu}$$

- Use TOF to work in the K_L^0 c.m. system
- Identify and eliminate main 2-body background $K_L^0 \to \pi^0\pi^0$
- Reconstruct $\pi^0 \to \gamma\gamma$ decays with high efficiency pointing calorimeter 30
- 4π solid angle photon and charged particle vetos

KOPIO Technique

- High intensity micro-bunched beam to measure K velocity
- Measure everything! (energy, position, **direction**, time)
-



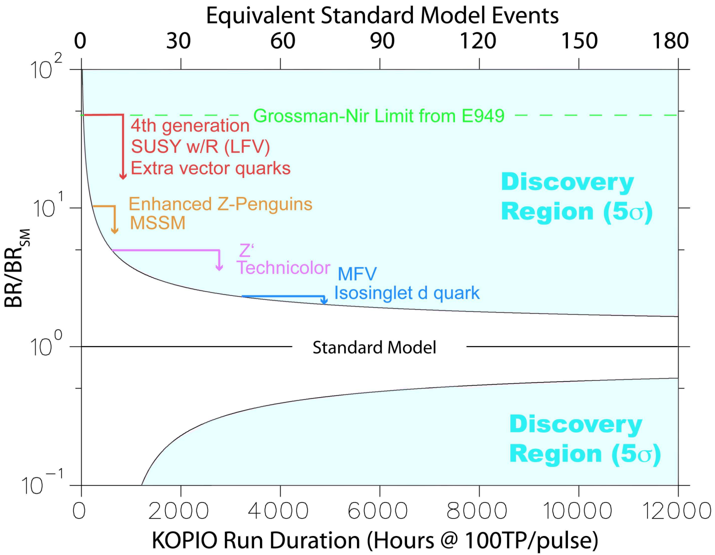
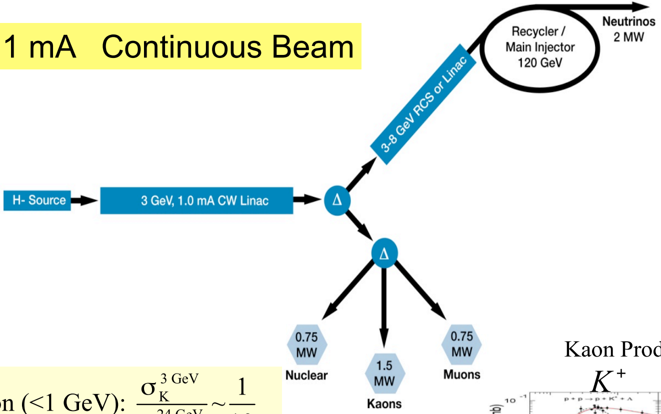


Fig. 1.1. Five-σ upper and lower discovery limits versus running time for the KOPIO experiment as discussed in the text. A branching ratio in the shaded region can be distinguished from the Standard Model prediction by at least 5 σ.

From KOPIO Conceptual Design Report 2005

Fermilab Project X

3 GeV   1 mA   Continuous Beam



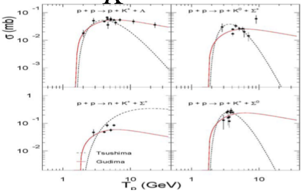
$$\text{K production (<1 GeV):}\quad \frac{\sigma_K^{3\text{ GeV}}}{\sigma_K^{24\text{ GeV}}} \sim \frac{1}{10}$$

$$\text{p beam intensity:}\quad \frac{\text{Proj. X}}{\text{AGS}} \sim 300$$

$$\text{K flux:}\quad \frac{\text{Proj. X}}{\text{AGS}} \sim 30$$

Kaon Production *vs.* T_P

K^+ K^0



Project X for KOPIO-style experiment

Advantages

- 20ps wide proton bunches with $\gg 10^{-3}$ extinction
  - K_L^0 production time distribution would be determined by target size, not proton beam
  - Suppression of interbunch background
- Higher intensity permits “pencil” beam.
  - Simpler beam-line
  - More hermetic detector
  - Increases acceptance because beam hole decreases and detector size increases
  - Improved kinematic contraint increase S/B
  - Background from decays upstream and downstream of the fiducial volume reduced

Challenges

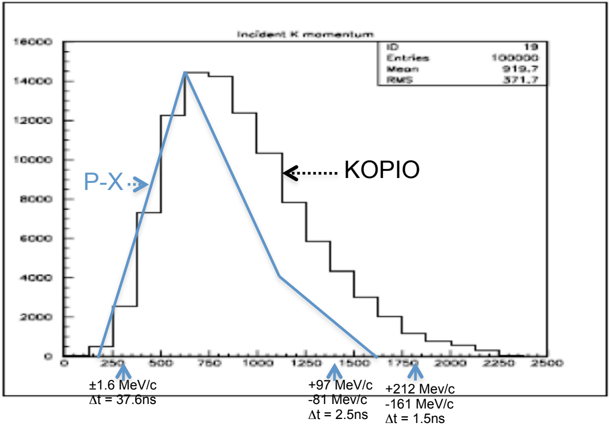
- High neutron rates (lower K/n production ratio)
- High power on target

Compare KOTO, AGS-KOPIO and PX-KOPIO

AGS	PX	KOTO	
24	3	30	T_p GeV
0.05	1.5	0.3	MW
1.1 Pt	1.0 C	? Ni	Target (λ_I)
10.6	38.8	?	Target (cm)
900	750	2100	$\overline{p_K}$ MeV
60	450	—	$10^6 K_L^0$/s/500μSR
360	49	7.8	Acceptance (μSR)
43	44	8	$10^6 K_L^0$/s
1:1000(10)	1:2600(10)	1:26(100)	K_L^0/n ($E_{\rm min}$ MeV)
42°	20°	16°	Beam angle
150/300	200/40	3.5/2.5	S/B per year
KOPIO CDR	Various	Wah's PX talk	References

There are technical issues with the enormous beam power and extended source (the 39cm long graphite target) for the Project-X K_L^0 beam.

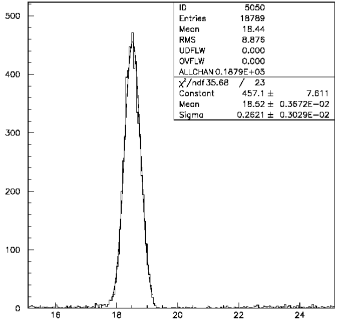
Better K_L Spectrum at Project–X



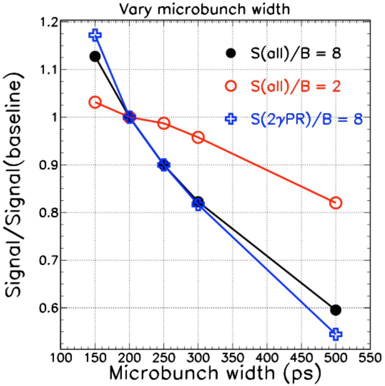
• High momentum events not only have poorer velocity resolution, they come close to the prompt flash of photons & neutrons from the μbunch hit. Unusable K decays hurt the sensitivity since we demand only one decay per μbunch.

Microbunching at Project–X

- KOPIO was designed for 200ps–wide microbunches.
- This was typical detector time–resolution of the era.
- Tests at the AGS achieved 244ps:



- Project–X will be capable of 50ps– wide bunches.
- KOPIO–type experiment can benefit greatly, particularly as detector resolution improves:



Prospects for $K \to \pi\nu\bar{\nu}$

E787/E949: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

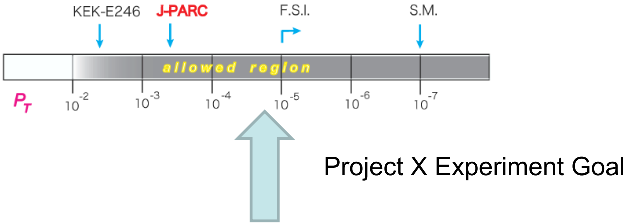
Goals	NA62	ORKA	PX
Events/yr	40	200	340
S/B	5	5	5
Precision	10%	5%	3%

E391a: $\mathcal{B}(K^0_L \to \pi^0\nu\bar{\nu}) < 2.6 \times 10^{-8}$

Goals	KOTO*	PX
Events/yr	1	"200"
S/B	1	5-10
Precision		5%

* Phase II with higher sensitivity planned.

$K_{\mu 3}$ T-Violation at Project X



- Aim for 20-50 x statistics of JPARC – TREK
  ORKA 14 m Beam line at 500MeV
  $K/\pi \sim 4$
- Potential background from π^+ decay in flight
  Need small target, high resolution tracking
- Control of systemmatic effects at 10^{-5} level!
  TREK estimates $<10^{-4}$

$K_L^0 \to \pi^0 \ell^+ \ell^-$ experiments at Project-X

Measurement of direct CPV in $K_L^0 \to \pi^0 \ell^+ \ell^-$ suffers from irreducible $K_L^0 \to \gamma\gamma\ell^+\ell^-$ background and from indirect CPV and non-CPV amplitudes.

- Mitigation by superb π^0 mass resolution and huge statistics, or
- Measuring $\mathrm{Im}(\lambda_t)$ using $K_S^0 - K_L^0$ interference in $K^0 \to \pi^0 e^+ e^-$ (H.Nguyen, Fermilab-TM-2438-PPD). Requires a very compact detector ($c\tau_s = 2.6$cm) and huge proton flux ($\sim 5 \times 10^{23}$, $\sim$10 years at 1.5MW PX) for 5% measurement of $\mathrm{Im}(\lambda_t)$, or
- For $K_L^0 \to \pi^0 \mu^+ \mu^-$, measure muon polarization asymmetries, branching ratio and lepton energy asymmetry to disentangle the CPC and indirect CPV amplitudes and $K_L^0 \to \gamma\gamma\mu^+\mu^-$ background (M.Diwan, H.Ma, L.Trueman, PRD**65** 054020 (2002)), or
- Combine the interference and polarization techniques for $K_L^0 \to \pi^0 \mu^+ \mu^-$ (Bob Tschirhart's idea)

Summary: Kaon physics at Project X

An unprecedented opportunity to find and study new physics with rare kaon decays

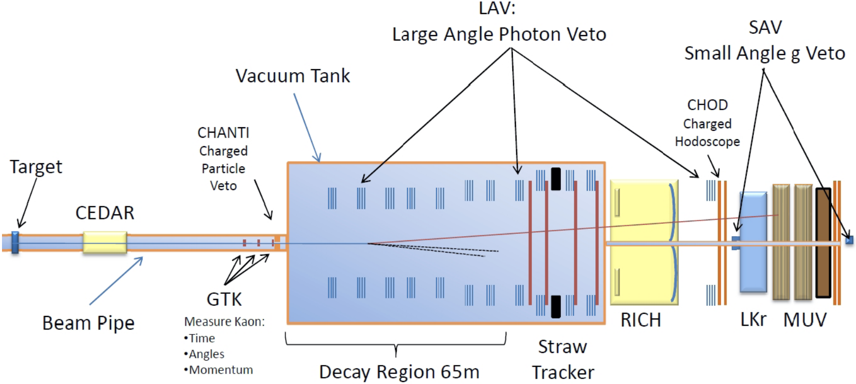
- Measure $K_L^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ with high precision
  - Builds on past and current experiements at BNL, CERN, JPARC and FNAL/MI
  - Achieve the ultimate precision covering all accessible non-SM physics
  - Complementary to LHC for studying flavor interactions at high mass scales
- Project X could explore many rare kaon processes
  - New CP and T violation
  - Lepton universality
  - Lepton flavor violation
  - Searches for scalar and pseudoscalar interactions, exotics....

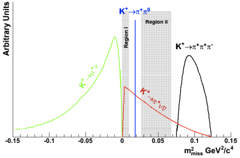
Resources for this talk

1. Project X Kaon Experiments, Douglas Bryman, The Project X Physics Study, June 2012 FNAL.
2. In-flight neutral kaon beams for precision kaon decay studies, Laurence Littenberg, Snowmass Workshop on Frontier Capability, 17-20 April 2013 BNL.
3. The Project X Kaon Physics Research Program Editors: D. Bryman (UBC), R. Tschirhart (Fermilab) August 31st, 2010
4. Design of the neutral K_L^0 beamline for the KOTO experiment, T.Shimogawa, for the J-PARC E14 KOTO collaboration, NIM-A 623 (2010) 585-587
5. The J-PARC KOTO Experiment, Yau WAH, Fermilab Project-X Workshop June 2012
6. Measuring $\mathrm{Im}(\lambda_t)$ using $K_S - K_L$ interference in $\pi^0 e^+ e^-$ Hogan Nguyen, Fermilab Project-X Workshop November 2009
7. Muon decay asymmetries from $K_L^0 \to \pi^0 \mu^+ \mu^-$decays Milind V. Diwan, Hong Ma, and T. L. Trueman, Phys. Rev. D **65** 054020.
8. KOPIO CDR 2005

Current rare K experiments

CERN NA62 -- New Approach to K^+ ® $\pi^+\nu\bar{\nu}$
Decay-in-flight at 75 GeV/c



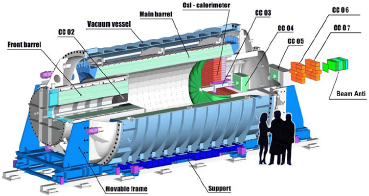


- Builds on NA-31/NA-48
- *Un-separated* GHz beam
- **Aim: 40-50 events/yr at SM**
- Under construction
  Start >2013

K_L^0 ® $\pi^0\nu\bar{\nu}$

KEK PS E391a → JPARC **KOTO** with KTEV CsI

E391a Result: $B(K_L^0$ ® $\pi^0\nu\bar{\nu}) < 2.4\,x10^{-8}$ $(90\%CL)$



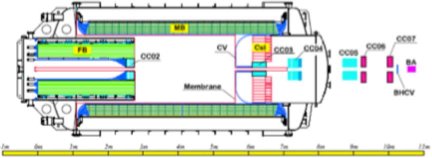


FIG. 1: Cross section of the E391a detector. K_L^0's enter from the left side.

Features:

- Pencil Beam , High P_T selection
- High acceptance
- Reliance on high photon veto efficiency
- Sensitivity goal: ~SM level: 2.8 events S/B~1

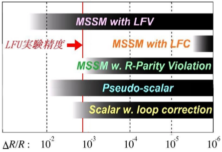
The TREK Program at J-PARC

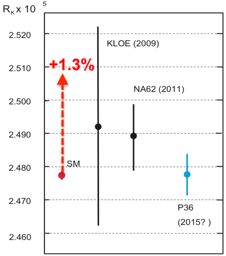
E06: Search for T-Violating Transverse Muon Polarization in $K_{\mu 3}$

Precision Measurement:
Test of Lepton Universality
in $BR(K_{e2})/BR(K_{\mu 2})$

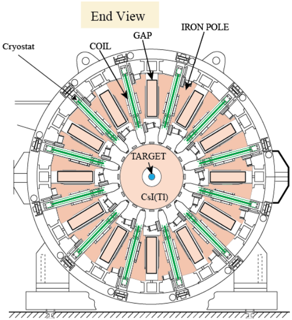
E36

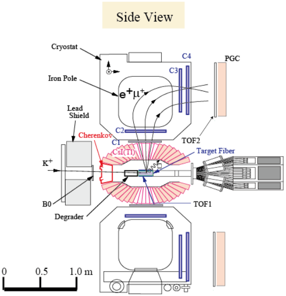
Byproduct Searches:
Heavy Sterile Neutrinos
Dark Photons / U(1) Bosons





Sensitivities: $BR(K^+ \to \mu^+ N) \sim 10^{-8}$
$BR(K^+ \to \mu^+ \nu A')$, $BR(K^+ \to \pi^+ A') \sim 10^{-8}$ $[A' \to e^+ e^-]$





The Secret of Finding Rare Decays