Prospects for Precise Measurements of $K^+ \to \pi^+ \nu \bar{\nu}$ at Fermilab Project X

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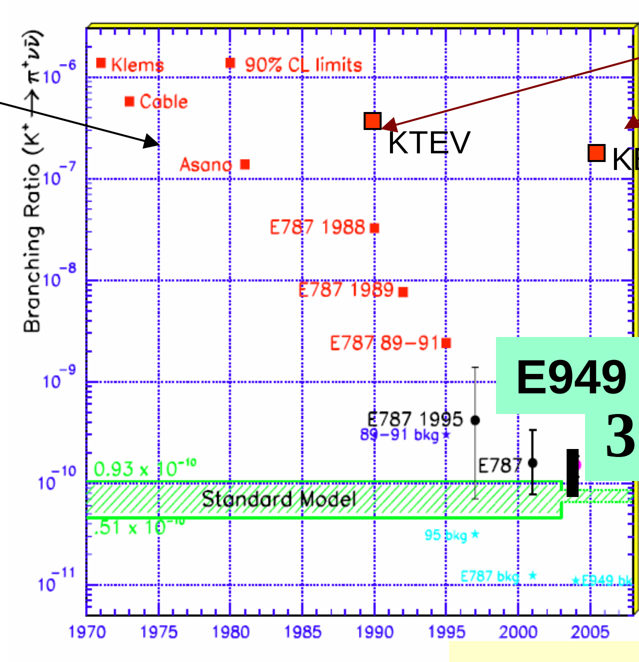
Experiments

$K^+ \to \pi^+ \nu \bar{\nu}$

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



E949

3

KEK-> J-PARC?

NA62? **100**

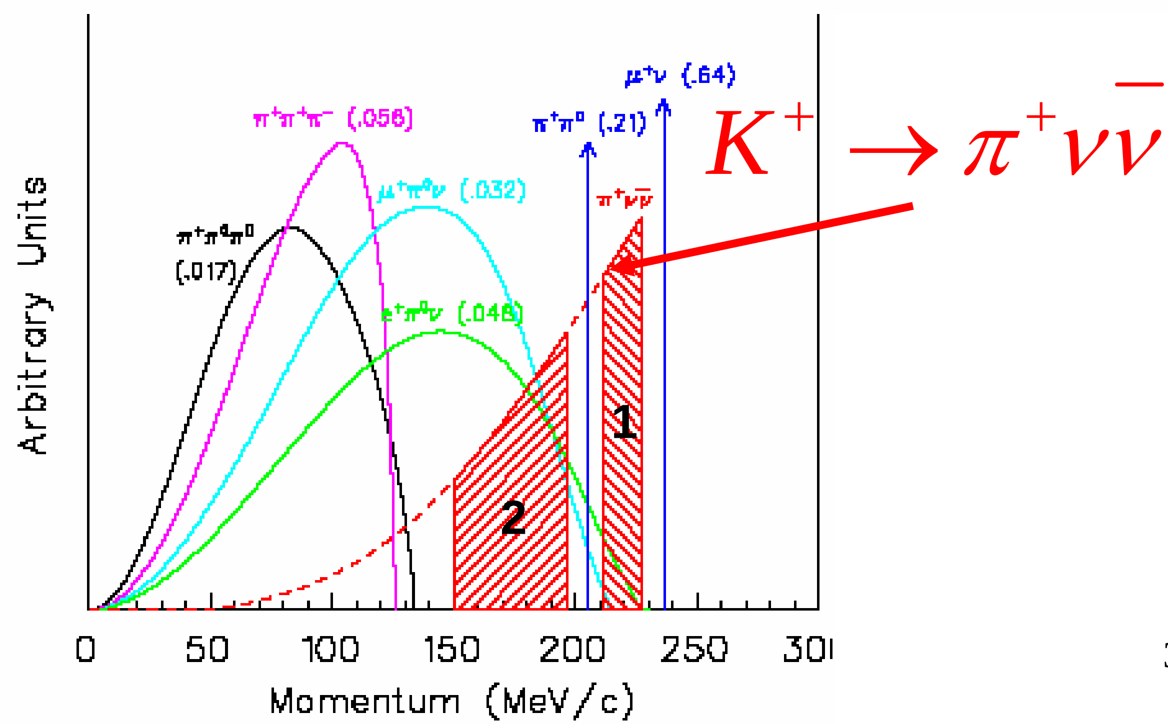
Project X?
1000???

Know the enemy.

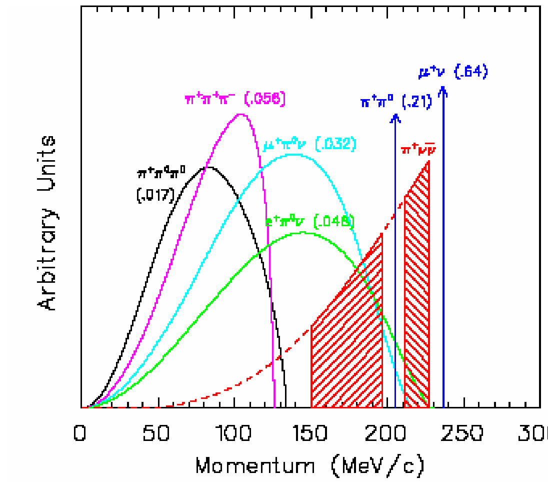
K^+ Decay Modes $\tau_{K^+} = 12.4ns$

Decay Mode	Branching Ratio	Background Rejection
$K^+ \to \mu^+\nu$	63% (called $K_{\mu 2}$)	μ PID, Two-Body Kinematics
$K^+ \to \pi^+\pi^0$	21%	Photon Veto, Two-Body Kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	Charged Particle Veto, Kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	Photon Veto, Kinematics
$K^+ \to \pi^0\mu^+\nu$	3% (called $K^+_{\mu 3}$)	Photon Veto, μ PID
$K^+ \to \pi^0 e^+\nu$	5% (called K^+_{e3})	Photon veto, E/p

Background processes exceed signal by $>10^{10}$



Approaching
$K^+ \to \pi^+ \nu \bar{\nu}$



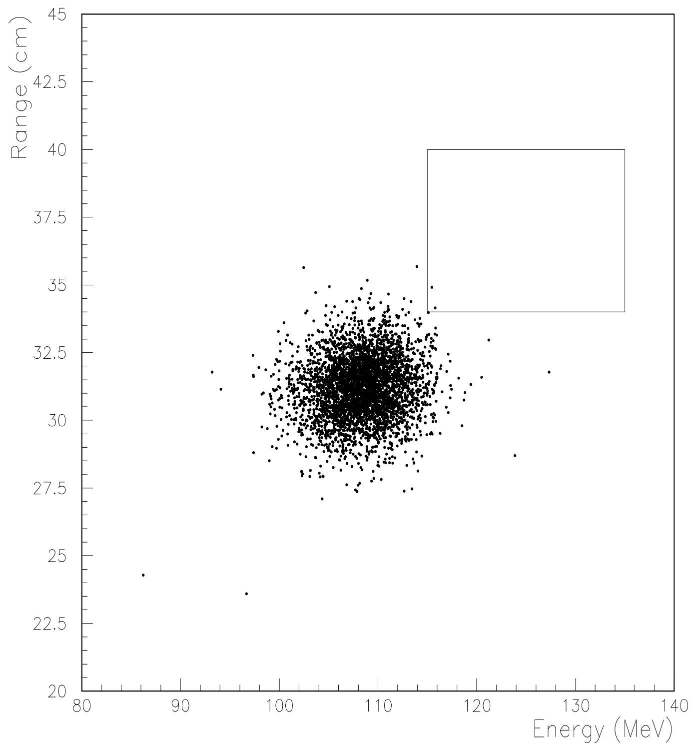
- Determine everything possible about the K^+ and π^+
  - * π^+/μ^+ particle ID better than 10^6 (π^+-μ^+-e^+)
- Eliminate events with extra charged particles or ***photons***
  - * π^0 inefficiency < 10^{-6}
- Suppress backgrounds well below the expected signal (S/N~10)
  - * Predict backgrounds *from data*: dual independent cuts
  - * Use "Blind analysis" techniques
  - * Test predictions with "outside-the-box" measurements
- Evaluate candidate events with Signal/Noise function

$\mathbf{K}^+ \to \pi^+\pi^0$ Background Suppression

Dual cuts: γ Veto and Kinematics (P,R,E...)

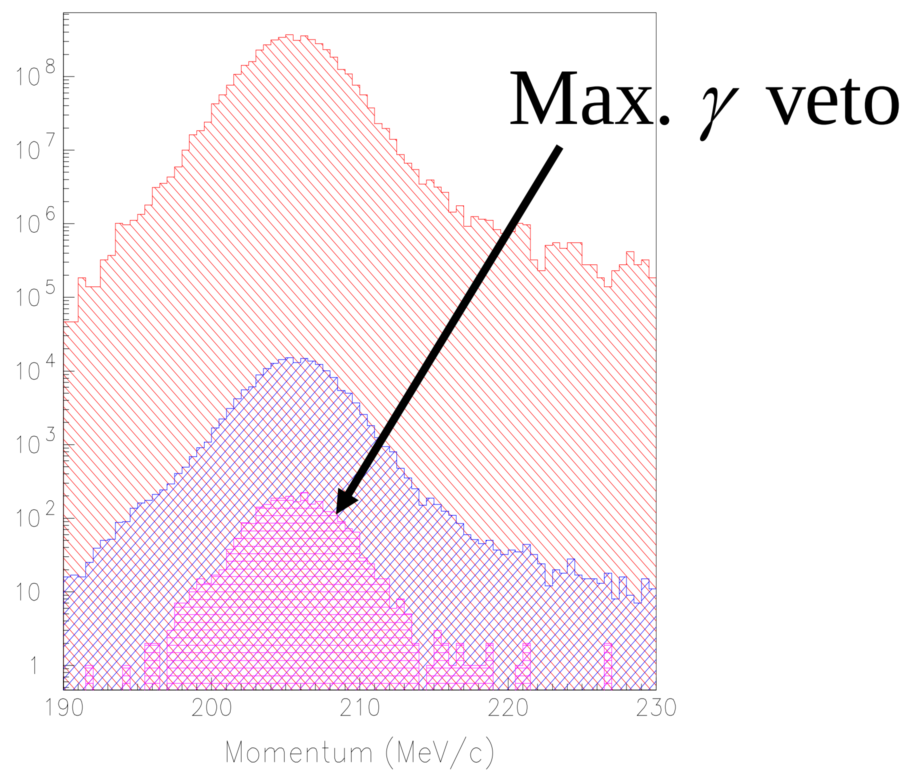
γ Veto Reversed

Range vs. Energy



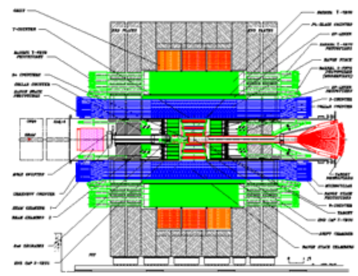
γ Veto Applied

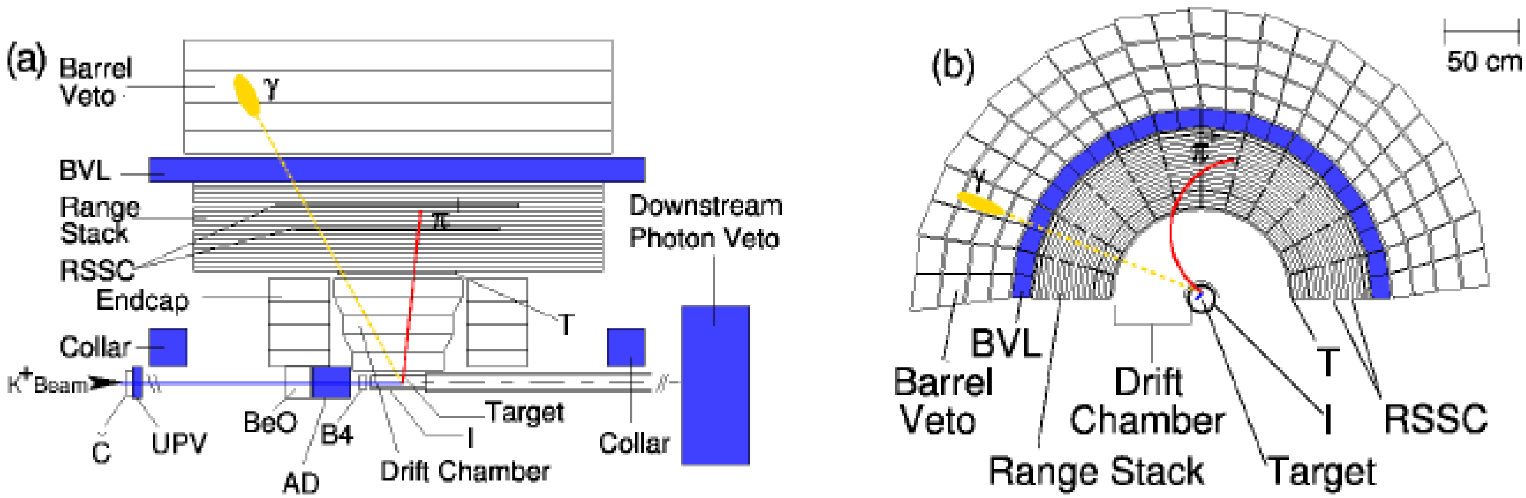
Momentum



Important step: Check for correlations.

E949

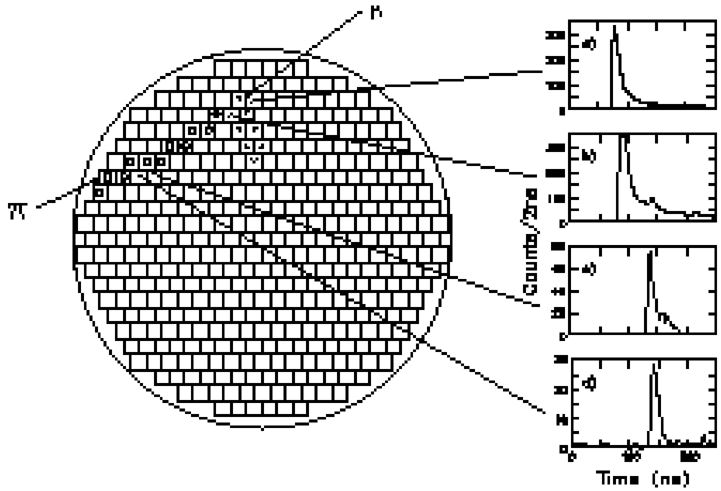




Acceptance: 0.002; major factor in small acceptance was due to suppression of muon backgrounds;
Accidental spoiling of events (photon veto) limited the rate capability.

Special Instruments Required: 500 MHz Transient Digitizers

$K \rightarrow \pi$



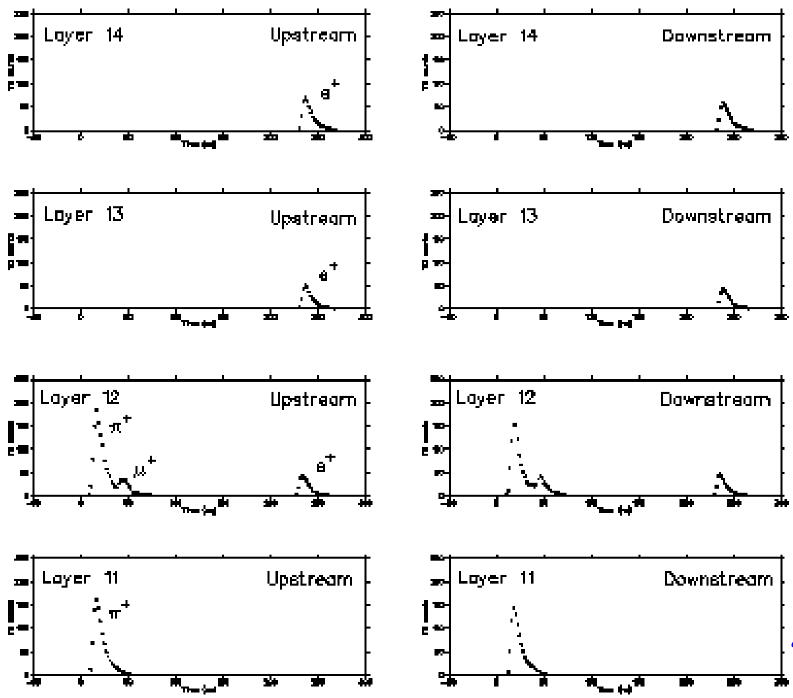
K stop

$K \rightarrow \pi$

π

π

$\pi \rightarrow \mu \rightarrow e$



$e \Uparrow$

$e \Uparrow$

$\pi \rightarrow \mu \,/\, \mu \rightarrow e$

π enters $\uparrow$

Background Suppression:

E949 Photon (π^0) Detection Efficiency

Photon Detection Efficiency limited by

- Photonuclear interactions ("$\gamma \to$ n")
- Sampling Fluctuations
- Punch-through

π^0 Rejection: >10^6

(for $K^+ \to \pi^+\pi^0$ background)

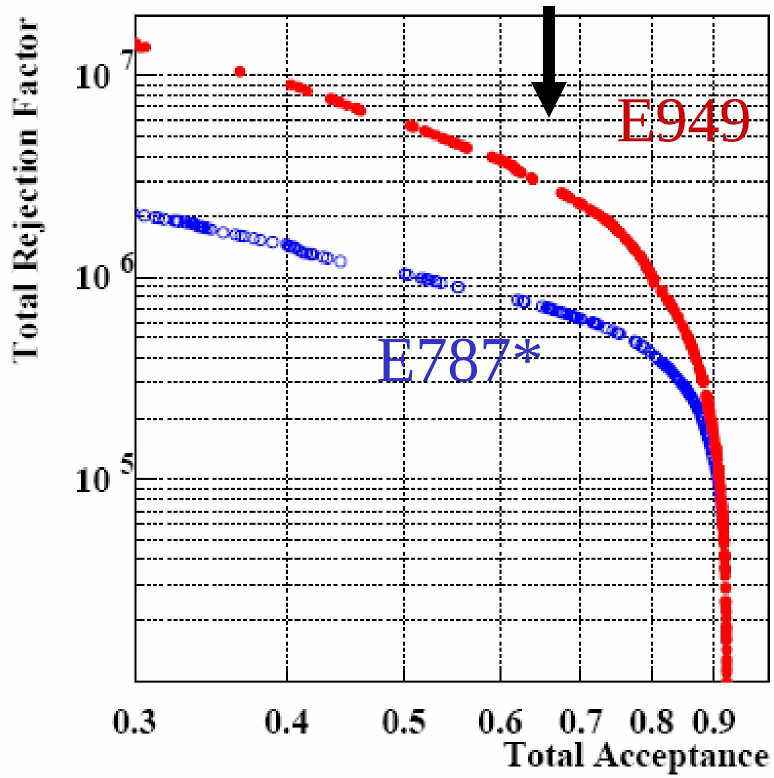
Twice the rejection

of π^0 backgrounds

at comparable acceptance

for $K^+ \to \pi^+\nu\bar{\nu}$.

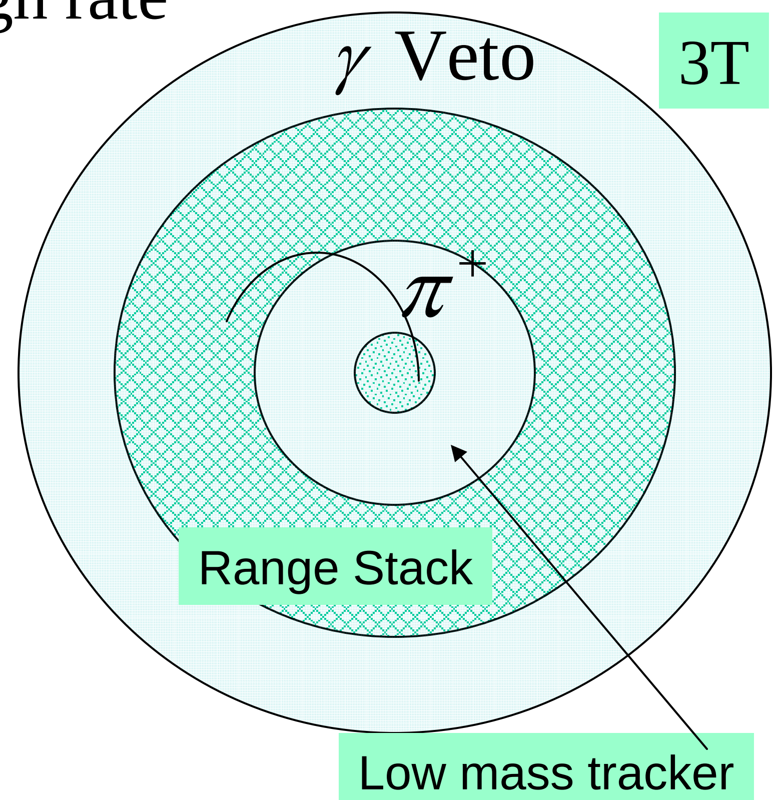
Rejection vs. Acceptance



* E787 was a previous version of E949.

Compact High Field System for $K^+ \to \pi^+ \nu \bar{\nu}$

- Low P_K ~400 MeV/c for high stopping efficiency
- Sci-Fi target and range stack for high rate $\pi \to \mu \to e$ measurements
- High acceptance and precise momentum measurement to suppress $K^+ \to \pi^+ \pi^0, K^+ \to \mu^+ \nu$ backgrounds
- "Ideal" homogeneous photon veto e.g. LXe 20 X_0



Assumptions and Issues for High Precision $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Measurement at Project X

- **Project X primary beam properties.** 10 x Booster at 8 GeV; 5000 hrs./yr. with 100% duty factor.
- **K Production Cross Sections at 8 GeV.** 8 GeV yields at 450 and 400 MeV/c relative to 21.5 GeV at 710 MeV/c were estimated by Sergei Striganov: 0.16 and 0.11.
- **Kaon beam** (E949): 13 (19) m; 25 (12) msr; 400 (710) MeV/c
  1.2 x momentum acceptance relative to LESB3 at the AGS;
  4 x efficiency for stopping kaons
- **Detector Improvements.** 3 (1) T field: Fine segmentation of RS (e.g. 5 mm x 5 mm (20mm x 200 mm))- factor 100-150 suppression of muon background; 2x better momentum resolution; high quality non-sampling photon veto detector. ***Overall, assume 2.5 x acceptance of E949.***
- A**ccidental losses due to photon veto hits – reduced significantly due to low momentum**

Estimates by DB and Laurie Littenberg

$K^+ \rightarrow \pi^+ \nu \overline{\nu}$	**BNL "E949"**	**FNAL Booster X0**	**FNAL Proj X1**	**FNAL Proj X2**
Beam Power(kW)	39	21	206	2057
Protons/pulse	6.5E+13	2.25E+13	2.25E+14	2.25E+15
Pulse lenth (s)	4.1	1.26	1.4	1.4
Interspill (s)	2.3	0.14	0	0
Duty Factor	0.6	0.9	1.0	1.0
Proton energy (GeV)	24.0	8.0	8.0	8.0
Pk(MeV/c)	710	450	425	400
Ek	371	174	157	141
Cross Sect.(K/p) (est.)	1	0.157	0.13	0.111
Decay factor (X=13 m)	0.03	0.02	0.015	0.01
Beam Accept.(X=13m)	1	2.2	2.2	2.2
Stop Efficiency (est.)	0.20	0.65	0.70	0.75
P accept.	1.00	1.20	1.20	1.20

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	**BNL**	**FNAL**	**FNAL**	**FNAL**
	"E949"	**Booster X0**	**Proj X1**	**Proj X2**
K/s (inst.)	1	0.3	1.8	11.2
hr/yr	2500	5000	5000	5000
p/yr(E20)	0.9	2.9	28.9	289.3
Kstop/yr.	1	3	23	157
Detect. "Accept."	1	2.50	2.50	2.50
Accidental 'losses'	0.20	0.04	0.06	0.24

$K^+ \to \pi^+ \nu \bar{\nu}$	**BNL "E949"**	**FNAL Booster X0**	**FNAL Proj X1**	**FNAL Proj X2**
Events/yr	5	38	268	1487
Events/5yr		189	1341	7433
5 yr. Precision(%)		7.3	2.7	1.2
Precision w/bckgnd*		8.4	3.2	1.3

**** Includes separate estimates of backgrounds in Regions I (10%) and 2(75%)***.

Concluson: A precise (~few %) measurement of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ appears to be feasible at Fermilab Project X