

# Precision Measurement of $K^+ \rightarrow \pi^+ v \overline{v}$ at Fermilab

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## Outline

- Physics Motivation
- Experimental Background
   BNL E787/E949
- The Opportunity at Fermilab
- Improvements for ORKA
- Status and Timeline
- Summary/Conclusions



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#### $K^+{\rightarrow}\pi^+\nu\overline{\nu}~$ in the Standard Model

 $K \rightarrow \pi v \overline{v}$  decays are among the most precisely calculated FCNC decays.



- A single effective operator  $(\overline{s}_L \gamma^{\mu} d_L) (\overline{v}_L \gamma_{\mu} v_L)$
- Dominated by top quark (charm significant, but controlled)



- Hadronic matrix element shared with  $K \rightarrow \pi e v$
- Largest uncertainty from CKM elements (which will improve)

$$B_{SM}(K^+ \rightarrow \pi^+ \nu \overline{\nu}) = (7.8 \pm 0.8) \times 10^{-11}$$

Brod, Gorbahn, and Stamou, PR D 83, 034030(2011) Remains clean in New Physics models

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#### Sensitive to New Physics



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#### $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ History



## $K^+ \rightarrow \pi^+ v \overline{v}$ Backgrounds



Rejection from:

 Kinematics (tracking) to reject 2-body decays

- Particle ID to select π (reject μ)
- Photon veto (rejection of  $\pi^0$ )

For stopped K's, p = 0. It is not key that the CM is at rest, but that the K's momentum is known when it decays.

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The E949 detector provided

- Measurement of the K-decay vertex in an active (sci-fi) stopping target
- Redundant measurements of pion energy, momentum, and range
- Strong pion identification based on observing the full decay chain  $\pi \rightarrow \mu \rightarrow e$ 
  - Decay history from 500 MHz (8-bit) waveform digitizers on range stack counters
- Nearly  $4\pi$  detection of photons with energy down to a few MeV

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#### E787/E949 Results



 $B_{\rm SM}(K^+ \to \pi^+ \nu \overline{\nu}) = (0.78 \pm 0.08) \times 10^{-10}$ 

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## What is ORKA?

- ORKA will apply the method and techniques that were demonstrated in BNL E878/E949.
  - ORKA does not assume (or require) better background rejection than E949 achieved.
- ORKA will use existing facilities at Fermilab.
  - Main Injector slow extracted beam to produce kaons.
  - Existing infrastructure (e.g., B0 hall).
  - Existing superconducting magnet (from CDF).
- ORKA will be a modern detector based on the E949 concept.
  - E787 was built in the mid-1980's; E949 was an upgrade in late 1990's.
- ORKA will observe about 1000 K<sup>+</sup> → π<sup>+</sup>vv v events in a few years of running (~200 events/yr at SM BF).

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## ORKA vs E949 detector

## ORKA will improve the performance of all detector systems.

- Higher magnetic field (1.0 T → 1.25 T) with superconducting solenoid; better momentum resolution
- Longer drift chamber; larger geometrical acceptance
- Improved scintillating fiber stopping target; smaller fibers and better light collection; better beam K- $\pi$  separation, better vertex position
- Finer segmentation of the range stack, higher QE photodetectors; better dE/dx resolution (better  $\pi$ - $\mu$  separation), reduce accidentals
- Better, thicker  $(17X_0 \rightarrow 23X_0)$  photon veto system; Shashlyk (or other); improved  $\pi^0$  rejection
- Wave form digitizers (500 MHz, 10-bit) on all scintillators (no multiplexing); less sensitive to accidentals
- Modern "triggerless" DAQ system; eliminate deadtime

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#### **Detector Improvements**

#### Estimates based on E949 experience.

Component	Acceptance factor
$\pi  ightarrow \mu  ightarrow e$	$2.24\pm0.07$
Deadtimeless DAQ	1.35
Larger solid angle	1.38
1.25-T B field	$1.12\pm0.05$
Range stack segmentation	$1.12\pm0.06$
Photon veto	$1.65\substack{+0.39 \\ -0.18}$
Improved target	$1.06\pm0.06$
Macro-efficiency	$1.11\pm0.07$
Delayed coincidence	$1.11\pm0.05$
Product ( $R_{\rm acc}$ )	$11.28^{+3.25}_{-2.22}$

## **ORKA Detector**



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#### NA-62



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## Fermilab



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#### **Headline News**

## **Physicists raid Tevatron for parts**

Fermilab icon plundered amid tight budgets and shifting scientific aims.

"... During 26 years of operation at the Fermi National Accelerator Laboratory in Batavia, Illinois, this behemoth, the Collider Detector at Fermilab (CDF), helped to find the top quark and chased the Higgs boson. But since the lab's flagship particle collider, the Tevatron, was switched off in September 2011, the detector has been surplus stock — and it is now slowly being cannibalized for parts.

"... the most ambitious recycling request so far would see it gutted. A proposed experiment called ORKA ... needs a massive solenoid magnet like the one at the CDF's heart.

"Lab management will make a decision about whether ORKA can eviscerate the CDF in about 6 months' time."

Nature 482, 453 (23 February 2012)

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The entire ORKA detector will fit within the CDF tracking volume.

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#### Possible ORKA layout in BO Hall



## ORKA Beam

Main InjectorProton momentum (GeV/c) $21.5$ $95$ Protons/spill $65 \times 10^{12}$ $48 \times 10^{12}$ $75$ kW beam power from Main Injector to ORKA target (versus about 40 kW at BNL)Seperated K+ beamKaon momentum (MeV/c) $710$ $600$ Kaon momentum (MeV/c) $710$ $600$ Lower p improves stopping efficiency; shorter beamline improves K+ survival; larger acceptance improves fluxLower p improves stopping efficiency; shorter beamline improves fluxReaching detector $N_K/sec(inst.)$ $12.8 \times 10^6$ $(88.5 \pm 10.9) \times 10^6$ Reaching detector $N_K/sec(inst.)$ $8.4 \times 10^6$ $26.2 \times 10^6$ Nork/sec(ave.) $2.6 \times 10^6$ $(8.85 \pm 1.09) \times 10^6$ Stopping fraction Nr/sec(ave.) $0.69 \times 10^6$ $(4.78 \pm 1.21) \times 10^6$ ORKA will have x7 more Kstop/s $0$ $0$		Component	E949 "as run"	ORKA	
Main InjectorProtons/spill $65 \times 10^{12}$ $48 \times 10^{12}$ $75 \text{ kW}$ beam power from Main Injector to ORKA target (versus about 40 kW at BNL)Seperated K+ beamKaon momentum (MeV/c) $710$ $600$ $Corrector (Main Injector to Interspill(s))$ Seperated K+ beamKaon momentum (MeV/c) $710$ $600$ $Corrector (Main Injector to Interspill(s))$ Seperated K+ beamKaon momentum (MeV/c) $710$ $600$ $Corrector (Main Injector to Interspill(s))$ Seperated K+ beamKaon momentum (MeV/c) $710$ $600$ $Corrector (Main Injector to Interspill(s))$ Namin Injector $0.41$ $0.44$ $0.44$ $0.44$ protons/sec(inst.) $15.9 \times 10^{12}$ $10.9 \times 10^{12}$ $Corrector (Main Injector to Interspill(s))$ Kaon momentum (MeV/c) $710$ $600$ $Corrector (Main Injector to Interspill(s))$ Kaon momentum (MeV/c) $710$ $600$ $Corrector (Main Injector to Interspill(s))$ K survival factor $0.0372$ $0.0536$ $Corrector (Main Injector to Interspill(s))$ Main Injector $12.2$ $20$ $Corrector (Main Injector to Interspill(s))$ $M_K + stript(m)$ $12.8 \times 10^6$ $(88.5 \pm 10.9) \times 10^6$ $N_K / spill$ $12.8 \times 10^6$ $(88.5 \pm 10.9) \times 10^6$ $N_K / sec(inst.)$ $6.3 \times 10^6$ $(20.1 \pm 2.5) \times 10^6$ $N_K / sec(ave.)$ $2.6 \times 10^6$ $(8.85 \pm 1.09) \times 10^6$ $N_K / sec(ave.)$ $2.6 \times 10^6$ $(4.78 \pm 1.21) \times 10^6$ $N_K / sec(ave.)$ $0.69 \times 10^6$ $(4.78 \pm 1.21) \times 10^6$ <td rowspan="2"></td> <td>Proton momentum <math>(GeV/c)</math></td> <td>21.5</td> <td>95</td> <td></td>		Proton momentum $(GeV/c)$	21.5	95	
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$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$		protons/sec(inst.)	$15.9 \times 10^{12}$	$10.9  imes 10^{12}$	
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Stopping fraction $0.21$ $0.54 \pm 0.12$ ORKA will haveKstop/s(ave.) $0.69 \times 10^6$ $(4.78 \pm 1.21) \times 10^6$ x7 more Kstop/s		$N_K/\text{sec}(\text{ave.})$	$2.6  imes 10^6$	$(8.85 \pm 1.09) \times 10^{-10}$	$10^{6}$
Kstop/s(ave.) $0.69 \times 10^6$ $(4.78 \pm 1.21) \times 10^6$ x7 more Kstop/s		Stopping fraction	0.21	$0.54 \pm 0.12$	ORKA will have
		Kstop/s(ave.)	$0.69 \times 10^{6}$	$(4.78 \pm 1.21) \times 10^{-1}$	<sup>106</sup> x7 more Kstop/s

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#### **ORKA Sensitivity**

ORKA projection: 213 events/year at SM BF for 5000 hours/year running

Where does the improvement come from?

#### **ORKA versus E949**

Net detection efficiency per K-stop	detector	11.3 (+3.3/-2.3)
K-stops per hour	beam	6.9 ± 1.8
5000 hours(per yr)/E949 as run (940	) hours) runi	ning 5.3

#### **ORKA** Projected Precision

Relative uncertainty on  $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ 



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#### $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ Spectrum



ORKA will have some sensitivity for scalar or tensor interactions.

A precise spectrum measurement will require Project-X type statistics.

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#### ORKA will make several measurements.

Process	Current	ORKA
$K^+ \to \pi^+ \nu \bar{\nu}$	7 events	1000 events
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$
$K^+ \to \pi^+ \pi^0 \nu \bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \pi^0 X^0$	$< \sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$
$K^+ \to \mu^+ \nu_{heavy}$	$< 2 \times 10^{-8} - 1 \times 10^{-7}$	$< 1 \times 10^{-10}$
$K^+ \to \mu^+ \nu_\mu \nu \bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$
$K^+ \to \pi^+ \gamma \gamma$	293 events	200,000 events
$\Gamma(Ke2)/\Gamma(K\mu2)$	$\pm 0.5\%$	$\pm 0.1\%$
$\pi^0 \to \nu \bar{\nu}$	$< 2.7  imes 10^{-7}$	$<5\times10^{-8}$ to $<4\times10^{-9}$
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$

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## Status and Timeline

- ORKA (P-1021) received Stage 1 approval from Fermilab in December 2011.
- DOE is cogitating on the issue of "Mission Need" (aka CD-0).

Milestone/Activity	Time Period	
Stage One Approval	Winter 2012	
DOE Approval of Mission Need (CD-0)	Fall 2012	
Beam/Detector Design	2012 - 2013	
Approve Cost Range (CD-1)	early 2013	
Baseline Review/CD-2	End of 2013	
Start Construction (CD-3)	Spring 2014	
Begin Installation	mid-2015	
First Beam/Beam Tests	End of 2015	
Complete Installation	Mid-2016	
First Data (Start Operations/CD-4)	End of 2016	

#### • ORKA could have data in 2017.

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#### **ORKA** Collaboration



The collaboration is growing.

## Summary/Conclusions

- $K^+ \rightarrow \pi^+ v \overline{v}$  is one of the theoretically cleanest FCNC processes.
  - A deviation from the SM branching fraction would be a clear signature for New Physics
- A precision measurement of the  $K^+ \rightarrow \pi^+ v \overline{v}$  branching fraction is a high-priority experiment.
  - Important enough to do twice
- ORKA can exploit existing facilities at Fermilab to make a decisive (~1000 event) measurement by applying the proven BNL E949 method.
  - Can reduce experimental error to the size of the theory error
  - Low risk due to the demonstrated technique