# **ORKA**: The Golden Kaon Experiment $K^+ \rightarrow \pi^+ \nu \bar{\nu}$



36th International Conference on High Energy Physics

4 – 11 July 2012 Melbourne Convention and Exhibition Centre Mike Hildreth, University of Notre Dame for the ORKA collaboration July 6, 2012





#### **ORKA: The Golden Kaon Experiment**

- Precision measurement of the branching ratio for  $K^+ \rightarrow \pi^+ v \overline{v}$ , with ~1000 event Standard Model sensitivity
  - aim for 5% measurement of Branching Ratio
- Located at FNAL Main Injector
- Expected uncertainty matches theoretical uncertainty from the Standard Model
- Sensitivity to new physics at and beyond LHC mass scale
  - Contributions of >40% to BR(K<sup>+</sup> $\rightarrow \pi^+ \nu \overline{\nu}$ ) still possible
- Builds on successful previous experiments (BNL E787/ E949 – 7 events already seen)
- High impact measurement
- Modest total estimated cost: \$53M (FY2010\$)





#### Motivation

- Flavor problem:
  - We expect new physics at the TeV scale . . .
  - Why don't we see this new physics affecting the flavor physics we study today?
- If new^physics found at LHC:
  - Precision flavor-physics experiments needed to explore flavor- and CPviolating couplings
- If no new^physics found at LHC:
  - Precision flavor-physics experiments needed to search for new physics beyond the reach of the LHC through virtual effects

Some Favoriles Accrately measure sides ranges g(Unit. Tr(Owing) . CPV in B<sub>s</sub>-B<sub>s</sub> (SM "accidentally" small)  $K \rightarrow \pi \nu \nu$  (miniscule in SM + incredily dean theoretically) · prie, Trie, p (suggested by big V

Flavor Physics: Pushing Beyond the LHC. Intensity Frontier Workshop Nima Arkani-Hamed (Princeton, IAS)

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#### K⁺→π⁺v⊽ in the Standard Model

•  $K^+ \rightarrow \pi^+ \sqrt{\nu}$  is the most precisely predicted FCNC decay involving quarks Brod, Gorbahn, Stamou PR **D83**, 034030 (2011)



- A single effective operator:  $(\bar{s}_L \gamma^{\mu} d_L) (\bar{v}_L \gamma_{\mu} v_L)$
- Amplitude dominated by top quark loop
  - charm significant, but controlled
- Hadronic matrix element shared with  $K \rightarrow \pi e v$  (Ke3) decay
- Dominant uncertainty from CKM elements
  - expect prediction to improve to ~5%







#### **CKM Matrix and Unitarity Triangle**

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = \frac{\alpha^2 BR(K^+ \to \pi^0 e^+ \nu)}{V_{us}^2 2\pi^2 \sin^4 \theta_W} \cdot |V_{cs}^* V_{cd} X_{NL}^l + V_{ts}^* V_{td} X(x_t)|^2$$

Wolfenstein Parametrization:

e.g.: Buras, Lautenbacher, Ostermaier, Phys. Rev. D 50:3433 (1994)

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) \propto A^4 X^2(x_t) \frac{1}{\sigma} \left[ (\sigma \bar{\eta})^2 + \frac{2}{3} \left( \varrho_0^e - \bar{\varrho} \right)^2 + \frac{1}{3} \left( \varrho_0^\tau - \bar{\varrho} \right)^2 \right]$$

with:

$$\varrho_0^l = 1 + \frac{P_0^l}{A^2 X(x_t)} \quad P_0^l = \frac{X_{NL}^l}{\lambda^4} \quad \sigma = \left(\frac{1}{1 - \frac{\lambda^2}{2}}\right)^2$$

Measurements of BR's for ultra-rare Kaon decays will allow independent, highprecision tests of Unitarity







#### **Sensitivity to New Physics**



Figure 1: Correlation between the branching ratios of  $K_L \to \pi^0 \nu \overline{\nu}$  and  $K^+ \to \pi^+ \nu \overline{\nu}$ in MFV and three concrete NP models. The gray area is ruled out experimentally or model-independently by the GN bound. The SM point is marked by a star.

#### D.M. Straub, CKM 2010 Workshop, arXiv:1012.3893[hep-ph]







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#### **Experimental History**









#### **Difficult Measurement**



from K<sup>+</sup> decays in the rest frame

- Observed signal is  $K^+ \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$
- Background more than 10<sup>10</sup> larger than signal
- Requires suppression of background well below expected signal (S/N ~10)
- Requires  $\pi/\mu/e$  particle ID > 10<sup>6</sup>
- Requires  $\pi^0$  inefficiency <  $10^{-6}$





#### BNL E787/E949 Stopped Kaon Technique



- K<sup>+</sup> detected and decays at rest in the stopping target
- Decay  $\pi^+$  track momentum analyzed in drift chamber
- Decay π<sup>+</sup> stops in range stack, range and energy are measured
- Range Stack Straw Chamber provides additional  $\pi^{\scriptscriptstyle +}$  position measurement in range stack
- Barrel veto + End caps + Collar provide 4π photon veto coverage

Measure everything!

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#### ORKA: a 4<sup>th</sup> generation detector



Expect ×100 sensitivity relative to BNL experiment: ×10 from beam and ×10 from detector

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#### **Sensitivity Improvements: Beam**

- Main Injector
  - 95 GeV/c protons
  - 50-75 kW of slow-extracted beam
  - 48 × 10<sup>12</sup> protons per spill
  - Duty factor of ~45%
  - # of protons/spill (×0.74)
- Secondary Beam Line
  - 600 MeV/c K<sup>+</sup> particles
  - Increased number of kaons/proton from longer target, increased angular acceptance, increased momentum acceptance (×4.3)
  - Larger kaon survival fraction (×1.4)
  - Increased fraction of stopped kaons (×2.6)
- Increased veto losses due to higher instantaneous rate (×0.87)







#### **Sensitivity Improvements: Acceptance**

Component	Acceptance fac	ctor
$ \pi \rightarrow \mu \rightarrow e $	2.24 ± 0.07	
Deadtimeless DAQ	1.35	
Larger solid angle	1.38	
1.25-T B field	$1.12 \pm 0.05$	
Range stack segmentation	$1.12 \pm 0.06$	
Photon veto	$1.65^{+0.39}_{-0.18}$	
Improved target	$1.06 \pm 0.06$	
Macro-efficiency	$1.11 \pm 0.07$	×11
Delayed coincidence	1.11 ± 0.05	relative to
Product (R <sub>acc</sub> )	$11.28^{+3.25}_{-2.22}$	E949





#### **π**<sup>+</sup>→µ<sup>+</sup>→e<sup>+</sup> Acceptance

- E949 PNN1  $\pi^+ \rightarrow \mu^+ \rightarrow e^+$  acceptance: 35%
- Improvements to increase acceptance relative to E949:
  - Increase segmentation in range stack to reduce loss from accidental activity and improve  $\pi/\mu$  particle ID
  - Increase scintillator light yield by using higher QE photo-detectors and/or better optical coupling to improve μ identification
  - Deadtime-less DAQ and trigger so online  $\pi/\mu$  particle ID unnecessary
- Irreducible losses:

	Range	Acceptance
Measured $\pi^+$ lifetime	3-105 ns	~87%
Measured $\mu^+$ lifetime	0.1-10 ns	~95%
µ⁺ escape	n/a	~98%
Undetectable e <sup>+</sup>	n/a	~97%
Total		~78%







#### **ORKA K<sup>+</sup>** $\rightarrow \pi^+ \sqrt{\nu}$ Sensitivity







#### **Worldwide Effort**



. Total Length 270m

- Decay-in-flight experiment
- Builds on NA-31/NA-48
- Expect ~40 K<sup>+</sup> $\rightarrow \pi^+ \nu \nu$  events per year (SM)
- Under construction
- Complementary measurement to ORKA
  - different techniques, systematics

KOTO ( $K^0 \rightarrow \pi^0 \nu \nu$ )



- Pencil beam decay-in-flight experiment
- Improved J-Parc beam line
- 2<sup>nd</sup> generation
- Expect ~3  $K^0 \rightarrow \pi^0 \nu \nu$  events (SM)
- Under construction





#### **Other Physics Topics**

- K<sup>+</sup>  $\rightarrow \pi^+ \nu \bar{\nu}(1)$  <sup>T,P</sup>
- K<sup>+</sup>  $\rightarrow \pi^+ \nu \bar{\nu}$ (2) <sup>T,P</sup>
- $K^+ \to \pi^+ \nu \bar{\nu} \gamma$
- $K^+ \rightarrow \pi^+ X^P$
- $K^+ \rightarrow \pi^+ \tilde{\chi}_0 \tilde{\chi}_0 (FF) P$
- $\blacktriangleright \ K^+ \to \pi^+ \pi^0 \nu \bar{\nu} \ ^{T,P}$
- $K^+ \rightarrow \pi^+ \pi^0 X$
- $K^+ \rightarrow \mu^+ \nu_h$  (heavy neutrino) <sup>T</sup>
- $K^+ \rightarrow \mu^+ \nu M \ (M = majoran)$
- $\blacktriangleright \ K^+ \to \mu^+ \nu \bar{\nu} \nu$

- $\blacktriangleright \ K^+ \to \pi^+ \gamma \ ^{TP}$
- $\blacktriangleright \ K^+ \to \pi^+ \gamma \gamma \ ^P$
- $\blacktriangleright \ K^+ \to \pi^+ \gamma \gamma \gamma$
- $K^+ \rightarrow \pi^+ \text{DP}$ ;  $\text{DP} \rightarrow e^+ e^-$
- $\blacktriangleright \ \Gamma(K^+ \to e^+ \nu) / \Gamma(K^+ \to \mu^+ \nu)$
- $\Gamma(K^+ \to \pi^+ \pi^0) / \Gamma(K^+ \to \mu^+ \nu)$
- K<sup>+</sup> lifetime
- $\blacktriangleright \ K^+ \to \pi^+ \pi^0 e^+ e^-$
- $K^+ \rightarrow \pi^- \mu^+ \mu^+$  (LFV)
- $\pi^0 \rightarrow \text{nothing } T, P$
- ►  $\pi^0 \rightarrow \gamma \text{DP}$ ;  $\text{DP} \rightarrow e^+ e^-$
- ►  $\pi^0 \to \gamma X$

<sup>*T*</sup>E787/E949 Thesis ; <sup>*P*</sup>E787/E949 Publication; DP=Dark Photon







#### **Potential Sites**



- B0 (CDF)
  - Preferred
  - Re-use CDF solenoid, cryogenics, infrastructure
  - Requires new beam line from A0-B0
- Also considering Meson Detector Building and NM4 (SeaQuest)





#### **ORKA in the CDF Detector**



- Full ORKA detector payload fits inside of CDF solenoid
  - longer barrel improves detector acceptance



Steve Kettell with the BNL-E949 Central tracker (similar diameter to ORKA proposal)

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#### **Possible Schedule**

Milestone	Time
Stage One Approval	Winter 2012 🗸
DOE Approval of Mission Need (CD-0)	Fall 2012
Beam/Detector Design	2012-2013
DOE Approval of Cost Range (CD-1)	Early 2013
DOE 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







- 2 US National Labs, 5 US Universities
- 16 Institutions spanning 6 countries: Canada, China, Italy, Mexico, Russia, USA
- Leadership from successful rare kaon decay experiments
- Many sub-systems: excellent opportunity for universities
- New collaborators welcome!







## **ORKA Summary**

- High precision measurement of  $K^+ \rightarrow \pi^+ \nu \overline{\nu}$  at FNAL MI
- Expect ~1000 events and 5% BR precision with 5 years of data
- Discovery potential for new physics at and above LHC mass scale
- High impact measurement with 4<sup>th</sup> generation detector
- Requires modest accelerator improvements and no civil construction
- Total cost \$53M (FY2010)
- Construction by 2014, data by 2017 is plausible
- ORKA proposal:
  - http://projects-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1365





## **Extra Slides**



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#### $\pi \rightarrow \mu \rightarrow e$ Acceptance Factors

- 1. Identify range stack counter where  $\pi^+$  stops
- 2. Detect  $\pi \rightarrow \mu$  decay in stopping counter
- 3. Detect  $\mu \rightarrow e$  in stopping counter and neighboring counters

Quantity	Acceptance	Range
$\pi$ decay	0.8734	(3,105) ns
$\mu$ decay	0.9450	$(0.1,10)~\mu s$
$\mu$ escape	0.98	
e <sup>+</sup> detection	$0.97\pm0.03$	
Product	$0.78\pm0.02$	
E949 acceptance	0.35	
Improvement factor	$2.24\pm0.07$	





#### Detector Improvements and $\pi \rightarrow \mu \rightarrow e$ Acceptance

- 1. Eliminate 4x multiplexing of range stack (RS) waveform digitizers used in E949.
  - Reduced loss due to accidentals
- 2. E949 RS: 19 layers (1.9cm thick), 24 azimuthal sectors. ORKA RS: 30 layers (0.95cm thick), 48 sectors.
  - Reduced accidental veto loss (µ<sup>+</sup> and e<sup>+</sup>)
  - Improved discrimination of  $\pi$  and  $\mu$
- Increased RS scintillator light yield by higher QE photodetectors and/or better optical coupling.
  - Improved  $\mu$  identification
- Deadtime-less DAQ and trigger: π → μ → e acceptance improvements; rudimentary π → μ identification was an essential component of the K<sup>+</sup> → π<sup>+</sup>νν̄ trigger in E787/E949.





#### Livetime and Delayed-Coincidence Acceptance

			Macro-efficiency			
	Livetime			E949	average	0.76
E949	livetime	0.74		E949	best week	0.84
ORKA	estimate	1.00		MiniB	BooNE (FY08)	0.85
Accep	otance increase	1.35		ORKA	estimate	$\textbf{0.85} \pm \textbf{0.05}$
				Accep	tance increase	$1.11\pm0.07$

E949 required a delayed coincidence of 2 ns between the stopped kaon and the outgoing pion to suppress prompt backgrounds.

Delayed coincidence			
E949	acceptance	0.763	
ORKA	estimate	$0.851\pm0.035$	
Accep	otance increase	$1.11\pm0.05$	





# Improved Momentum and Range Resolution and Increased Solid Angle

ORKA	/E949 momentum resolution	0.90	
Acce	otance increase	$1.12\pm0.05$	
ORKA	/E949 range resolution	$0.87\pm0.05$	
Accep	otance increase	$1.12\pm0.06$	
E949/E787 energy resolution 0.93			
Accep	otance increase	1.12	



		Solid angle increase	
		Drift chamber	Range Stack
	E949	50.8	180
	ORKA	84.7	250
Acceptance in	ncrease	1.38	



#### Photon Veto and Target Improvements

Photon veto			
E949		17.3 radiation lengths	
ORKA		23.0 radiation lengths	
Accep	otance increase	$1.65^{+0.39}_{-0.18}$	

Estimated increase taken from simulated KOPIO PV performance. KOPIO simulation was adjusted to agree with E949 PV efficiency.

	Target
E949	3.1 m long, single-end readout
ORKA	1.0 m long, double-end readout
Acceptance increase	$1.06\pm0.06$





## Comparison of ORKA and BNL E949

	E949	ORKA
P <sub>p</sub> (GeV/c)	21.5	95
Duty Factor (%)	41	44
P <sub>K</sub> (MeV/c)	710	600
Fraction of kaons that stop in target (%)	21	54
Average rate of stopping kaons/s (10 <sup>6</sup> )	0.69	4.78
Accidental loss (%)	23	28
Events/yr (SM)	1.3	210





#### Cost

	Cost (million)	w/ 60% contingency
Accelerator and Beams	7.5	12
A0 to B0 transport	2.2	3.5
Target and Dump	0.9	1.5
Kaon Beam	4.4	7.0
Detector	22.4	35.8
Magnet	0.5	0.8
Beam and Target	0.6	1.0
Drift Chamber	1.9	3.0
Range Stack	2.5	4.0
Photon Veto	3.0	4.8
Electronics	4.0	6.4
Trigger and DAQ	2.0	3.2
Software and Computing	2.0	3.2
Installation and Integration	5.9	9.4
Project Management	2.7	4.4
Total	33	53





#### Stage One Approval (Excerpt)

As you see, the PAC recommended Stage I approval, and I accept that recommendation. Nevertheless, as also noted by the PAC, we need to understand better the possible site of the experiment, technical issues associated with use of the Main Injector as proposed, and how we might fit the cost of ORKA into anticipated budgets of the Laboratory. All of these issues will be necessary before Stage II approval might be given.

We look forward to working with you to resolve these issues, recognizing that even working on them now will be difficult, given our severely constrained resources. At the same time, the Stage I approval I am granting now should help in finding additional collaborators, outside resources, and help within the Laboratory.

Sincerely,

emana Idae

Piermaria Oddone

