

ORKA: The Golden Kaon Experiment



- Precision measurement of $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ BR with ~1000 expected events at FNAL MI
- Expected BR uncertainty matches Standard Model uncertainty
- Sensitivity to new physics at and beyond LHC mass scale
- Builds on successful previous experiments (BNL E787/E949 – 7 events already seen)
- High impact measurement
- Total estimated cost: \$53M (FY2010)

ORKA

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 (BSM) new physics found in LHC searches:
 - Precision flavor-physics experiments needed to explore flavor- and CPviolating couplings
- If no (BSM) new physics found in LHC searches:
 - Precision flavor-physics experiments needed to search for new physics beyond the reach of direct searches through virtual effects

Some Favorites

Accrately measure sides ranges of Unil. Trobing

CPV in B. - B. (SM "accidentally" small)

K -> Tr VV (ministre in SM + incredibly dean theoretically) · pre, Tre, pr (suggested by big)

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

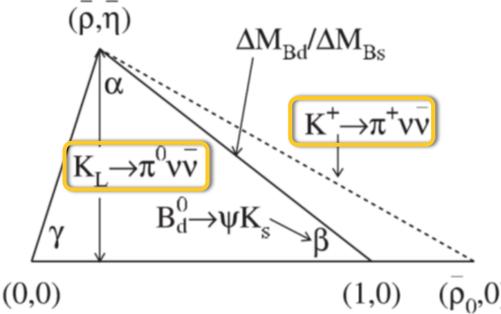
CKM Matrix and Unitarity Triangle





$$\begin{pmatrix} 1 - \lambda^{2} / 2 & \lambda & A\lambda^{3} (\rho - i\eta) \\ -\lambda & 1 - \lambda^{2} / 2 & A\lambda^{2} \\ A\lambda^{3} (1 - \rho - i\eta) & -A\lambda^{2} & 1 \end{pmatrix}$$

CP Violation

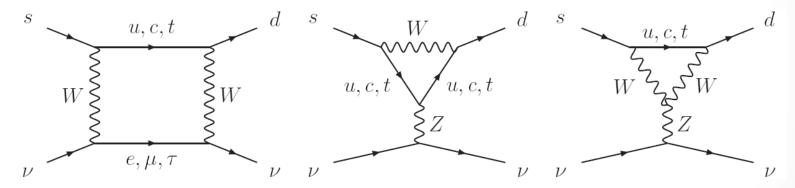


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$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in the Standard Model



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



- A single effective operator: $(\bar{s}_L \gamma^\mu d_L)(\bar{v}_L \gamma_\mu v_L)$
- Dominated by top quark
- Hadronic matrix element shared with Ke3⁺
- Dominant uncertainty from CKM matrix elements (expect prediction to improve to ~5%)

Sensitivity to New Physics



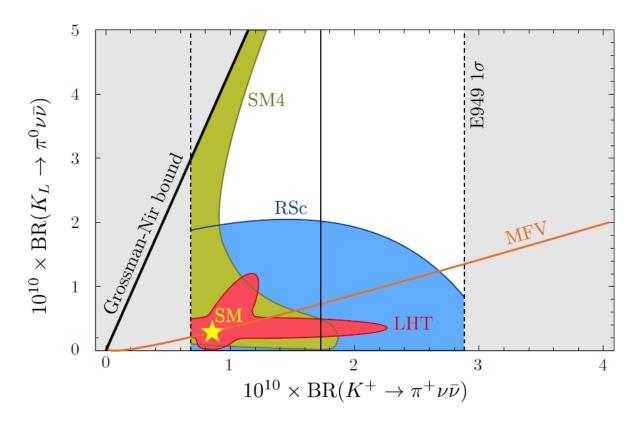
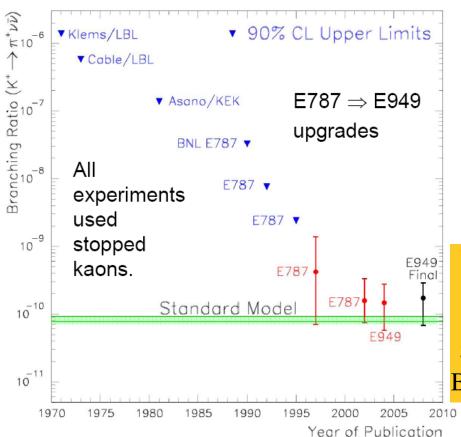


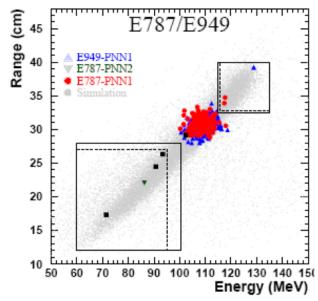
Figure 1: Correlation between the branching ratios of $K_L \to \pi^0 \nu \overline{\nu}$ and $K^+ \to \pi^+ \nu \overline{\nu}$ in MFV and three concrete NP models. The gray area is ruled out experimentally or model-independently by the GN bound. The SM point is marked by a star.

Experimental History



$K^+ \to \pi^+ \nu \overline{\nu}$ History





E787/E949 Final: 7 events observed $B(K^+ \to \pi^+ \nu \bar{\nu}) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$

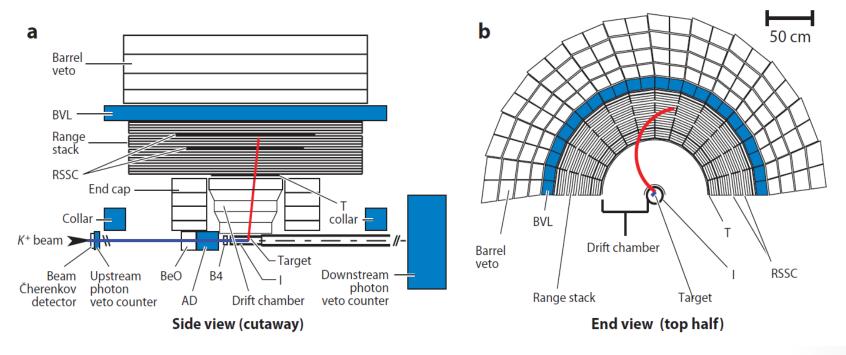
Standard Model:

$$B(K^+ \to \pi^+ \nu \bar{\nu}) = (7.8 \pm 0.8) \times 10^{-11}$$

BNL E787/E949 Stopped Kaon Technique

Measure everything!

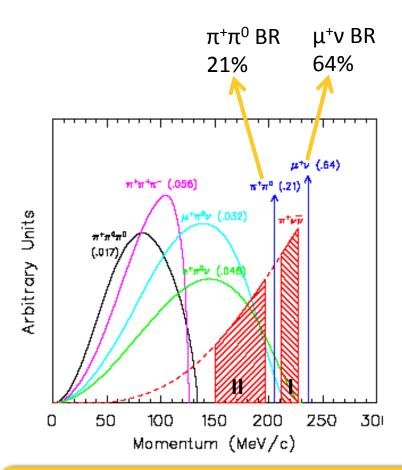




- K⁺ detected and decays at rest in the stopping target
- Decay π^+ track momentum analyzed in drift chamber
- Decay π^+ stops in range stack, range and energy are measured
- Range stack STRAW chamber provides additional π^+ position measurement in range stack
- Barrel veto + End caps + Collar provide 4π photon veto coverage

Difficult Measurement



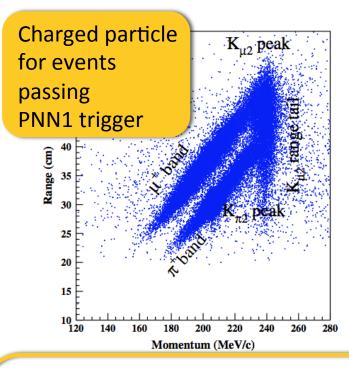


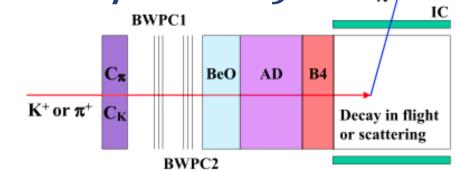
Momentum spectra of charged particles from K⁺ decays in the rest frame

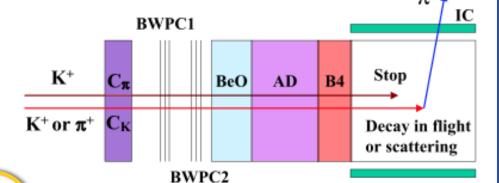
- Observed signal is K⁺→ π⁺→μ⁺→e⁺
- Background exceeds signal by > 10¹⁰
- Requires suppression of background well below expected signal (S/N ~10)
- Requires $\pi/\mu/e$ particle ID > 10^6
- Requires π⁰
 inefficiency < 10⁻⁶









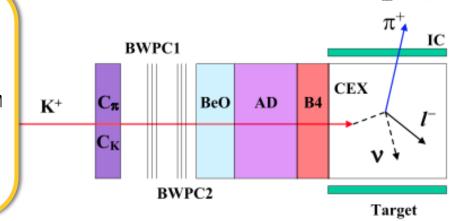


Stopped kaon background:

- $K^+ \rightarrow \pi^+ \pi^0$
- $K^+ \rightarrow \mu^+ \nu$
- μ+ band
 - $K^+ \rightarrow \mu^+ \nu \gamma$
 - $K^+ \rightarrow \mu^+ \pi^0 \nu$

Beam background:

- Single beam
- Double beam
- Charge exchange

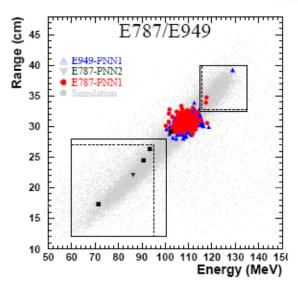


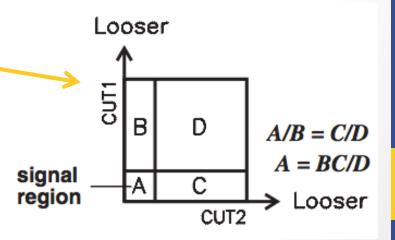
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Analysis Strategy (E747/E949)



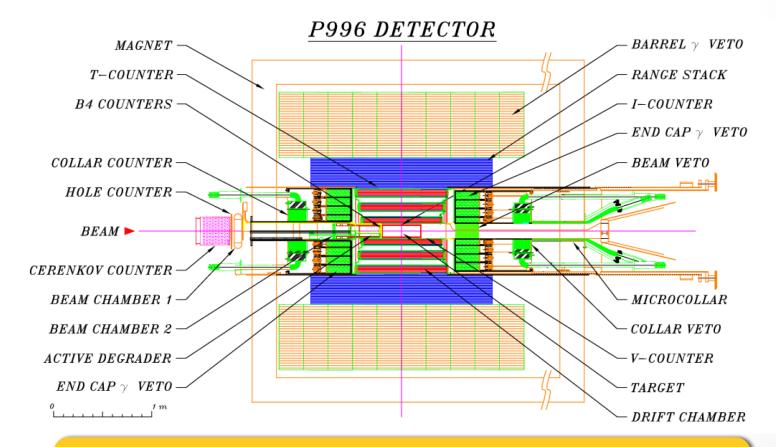
- Measure everything!
- Separate analyses for PNN1 and PNN2 regions
- Blind analysis
 - Blinded signal box
 - Final background estimates obtained from different samples than used to determine selection criteria (1/3 and 2/3 samples)
- Bifurcation method to determine background from data
 - Use data outside signal region
 - Two complementary, uncorrelated cuts
 - Expected background << 1 event
- Measure acceptance from data where possible





ORKA:

a 4th generation detector



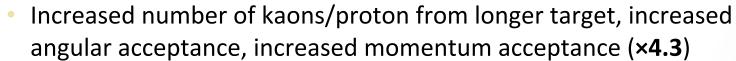
Expect ×100 sensitivity relative to BNL experiment: ×10 from beam and ×10 from detector



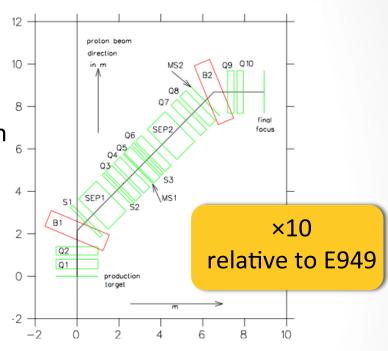
Sensitivity Improvements: Beam



- Main Injector
 - 95 GeV/c protons
 - 50-75 kW of slow-extracted beam
 - 48 × 10¹² protons per spill
 - Duty factor of ~45%
 - # of protons/spill (×0.74)
- Secondary Beam Line
 - 600 MeV/c K⁺ particles



- Larger kaon survival fraction (x1.4)
- Increased fraction of stopped kaons (x2.6)
- Increased veto losses due to higher instantaneous rate (x0.87)



ETW: BEACH Wichita, KS July 27, 2012

Sensitivity Improvements: Acceptance



Component	Acceptance factor
$\epsilon \pi o \mu o e$	2.24 ± 0.07
Deadtimeless DAQ	1.35
Larger solid angle	1.38
1.25-T B field	1.12 ± 0.05
Range stack segmentation	1.12 ± 0.06
Photon veto	$1.65^{+0.39}_{-0.18}$
Improved target	1.06 ± 0.06
Macro-efficiency	1.11 ± 0.07
Delayed coincidence	1.11 ± 0.05
Product (R_{acc})	11.28 ^{+3.25} _{-2.22} rela

×11 relative to E949

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$\pi^+ \rightarrow \mu^+ \rightarrow e^+$ Acceptance



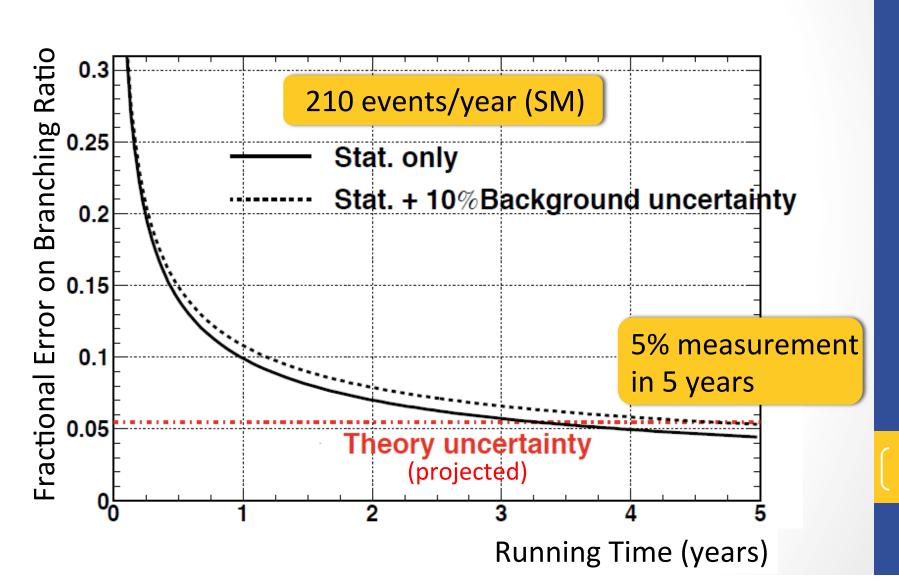
- E949 PNN1 $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ acceptance: 35%
- Improvements to increase acceptance relative to E949:
 - Increase segmentation in range stack to reduce loss from accidental activity and improve π/μ particle ID
 - Increase scintillator light yield by using higher QE photo-detectors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

Irreducible losses:

	Range	Acceptance	
Measured π ⁺ lifetime	3-105 ns	~87%	
Measured μ ⁺ lifetime	0.1-10 ns	~95%	
μ ⁺ escape	n/a	~98%	
Undetectable e ⁺	n/a	~97%	
Total		~78%	

ORKA K⁺ $\rightarrow \pi^+ \nu \bar{\nu}$ Sensitivity

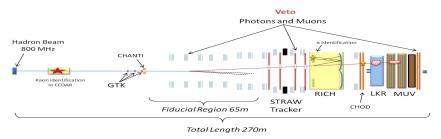




Worldwide Effort

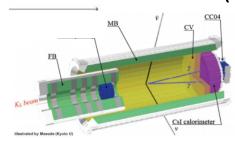


• CERN NA-62 (K⁺ $\rightarrow \pi^+ \nu \bar{\nu}$)



- Decay-in-flight experiment
- Builds on NA-31/NA-48
- Expect ~55 K⁺→π⁺νν events per year (SM) with ~7 bg events per year for ~100 total events
- Expect 10% measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ BR
- Under construction
- Complementary technique to ORKA

• J-PARC E14 "KOTO" $(K^0 \rightarrow \pi^0 \nu \overline{\nu})$



- Pencil beam decay-in-flight experiment
- Improved J-PARC beam line
- 2nd generation detector building on E391 at KEK
- Re-using KTeV CsI crystals to improve calorimeter (better resolution and veto power)
- Expect ~3 K⁰ $\rightarrow \pi^0 \nu \overline{\nu}$ events (SM)
- Under construction

ETW: BEACH Wichita, KS July 27, 2012

Other Physics Topics



- $K^+ \to \pi^+ + \text{missing energy}$
 - $K^+ \rightarrow \pi^+ \nu \bar{\nu}(1)^{T,P}$
 - $K^+ \rightarrow \pi^+ \nu \bar{\nu}(2)^{T,P}$
 - $K^+ \rightarrow \pi^+ \nu \bar{\nu} \gamma$
 - $K^+ \rightarrow \pi^+ X^{P}$
 - $K^+ \rightarrow \pi^+ \tilde{\chi}_0 \tilde{\chi}_0 (FF)^P$
- $K^+ \to \pi^+ \pi^0 + \text{missing energy}$
 - $K^+ \rightarrow \pi^+ \pi^0 \nu \bar{\nu}^{T,P}$
 - $K^+ \rightarrow \pi^+ \pi^0 X$
- $ightharpoonup K^+ o \mu^+ + \text{missing energy}$
 - $K^+ \to \mu^+ \nu_h$ (heavy neutrino) T
 - $ightharpoonup K^+
 ightarrow \mu^+ \nu M \ (M = majoran)$
 - $K^+ \rightarrow \mu^+ \nu \bar{\nu} \nu$

- $K^+ \rightarrow \pi^+ \gamma^{TP}$
- $ightharpoonup K^+ o \pi^+ \gamma \gamma^P$
- $ightharpoonup K^+ o \pi^+ \gamma \gamma \gamma$
- $K^+ \to \pi^+ \mathrm{DP} : \mathrm{DP} \to e^+ e^-$
- ► K⁺ lifetime
- $\blacktriangleright \mathcal{B}(K^+ \to \pi^+ \pi^0)/\mathcal{B}(K^+ \to \mu^+ \nu)$
- $K^{+} \rightarrow \pi^{+}\pi^{0}e^{+}e^{-}$
- $ightharpoonup K^+
 ightarrow \pi^- \mu^+ \mu^+ \text{ (LFV)}$
- $\blacktriangleright \pi^0 \to \text{nothing } T,P$
- ▶ $\pi^0 \rightarrow \gamma DP$; $DP \rightarrow e^+e^-$
- \blacktriangleright $\pi^0 \rightarrow \gamma X$

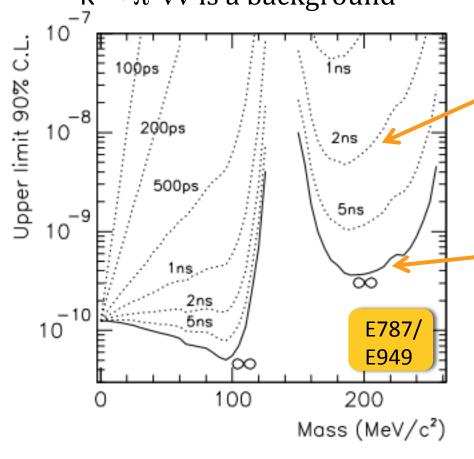
^TE787/E949 Thesis; PE787/E949 Publication; DP≡Dark Photon

$K^+ \rightarrow \pi^+ X^0$



 Many models for X⁰: familon, axion, light scalar pseudo-NG boson, sgoldstino, gauge boson corresponding to new U(1) symmetry, light dark matter ...

• $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ is a background

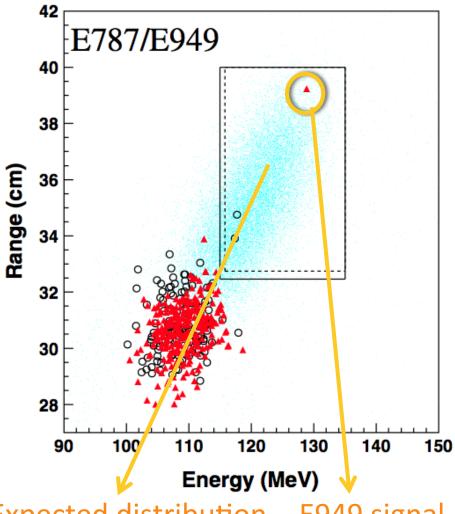


Upper limit on $K^+ \rightarrow \pi^+ X$ where X has listed lifetime

Upper limit on $K^+ \rightarrow \pi^+ X$ where X is stable

$K^+ \rightarrow \pi^+ X^0$ "event"





Expected distribution E949 signal of $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ (MC) event

- One event seen in E949 K⁺→π⁺vv PNN1 signal region is near kinematic endpoint
- Corresponds to a massless X⁰
- Central value of measured K⁺→π⁺νν̄
 BR higher than SM expectation
- Event consistent with SM K⁺ $\rightarrow \pi^+ \nu \bar{\nu}$, yet...
- Interesting mode for further study

Precision Measurement of Ke2/Kµ2



$$R_{K} \equiv \frac{\Gamma(K^{+} \rightarrow e^{+} \nu)}{\Gamma(K^{+} \rightarrow \mu^{+} \nu)}$$

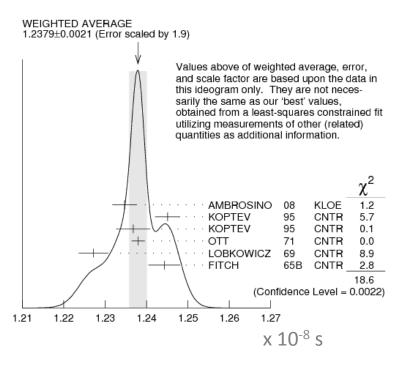
- $R_{SM} = (2.477 \pm 0.001) \times 10^{-5}$
 - Extremely precise because hadronic form factors cancel in ratio
 - Sensitive to new physics effects that do not share V-A structure of SM contribution
- $R = (2.488 \pm 0.010) \times 10^{-5} (NA62)$
- R = $(2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$ (KLOE)
- Expect ORKA statistical precision of ~0.1%
 - More study required to estimate total ORKA uncertainty

July 27, 2012

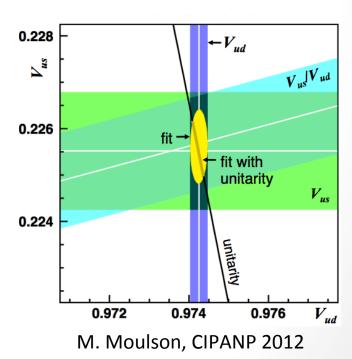
Fundamental K⁺ Measurements



- K⁺ lifetime
 - Not a major source of uncertainty for unitarity tests
 - Some discrepancies among experimental results in **PDG**

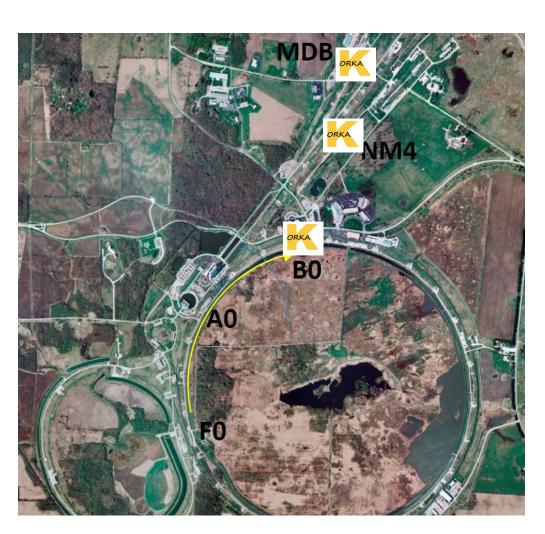


- B(K⁺ $\rightarrow \pi^+\pi^0$)/B(K⁺ $\rightarrow \mu^+\nu$)
 - Contributes to fit for $|V_{us}/V_{ud}|$
 - Expect improvements in lattice calculations so that experimental errors may soon be dominant



Potential Sites

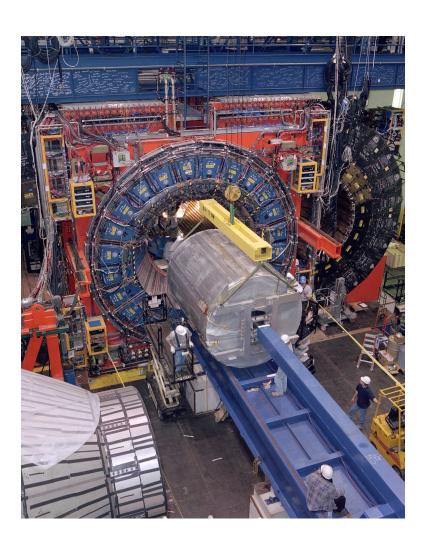




- B0 (CDF)
 - Preferred
 - Re-use CDF solenoid, cryogenics, infrastructure
 - Requires new beam line from A0-B0
 - Decommissioning of CDF in preparation for ORKA beginning 2013
- Other Options
 - Meson Detector Building
 - NM4 (SeaQuest)

ORKA in the CDF Detector





- ORKA detector fits inside CDF solenoid
- Replaces CDF tracker



Steve Kettel with the BNL-E949 central tracker

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

Collaboration



- 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

ORKA Summary

- High precision measurement of $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ at FNAL MI
- Expect ~1000 events and 5% precision on BR measurement with 5 years of data
- Discovery potential for new physics at and above LHC mass scale
- High impact measurement with 4th 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://www.fnal.gov/directorate/program_planning/ Dec2011PACPublic/ORKA_Proposal.pdf



Extra Slides

Cost (FY2010)



	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,

Piermaria Oddone

mara Idas

NA62





CONCLUSIONS



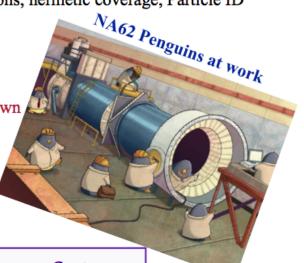
- The $K \rightarrow \pi \nu \nu$ decay: precision physics complementary to high-energy approach for NP search
- **❖ NA62:** Very challenging experiment
 - \rightarrow collect 0(100) events in two years to provide a 10% BR(K⁺ $\rightarrow \pi^+ \nu \bar{\nu}$) measurement
 - → key points: high intensity beams, excellent resolutions, hermetic coverage, Particle ID

❖ Schedule

- → Construction in progress (2010-2013)
- → Dry and Technical runs in summer/falls 2012
- → Ready to take data after CERN accelerator breakdown

❖ More..

The high performances of the detectors can also be the building blocks for a further physics program



A very rich program in the near future

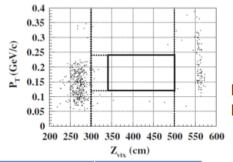
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KOTO

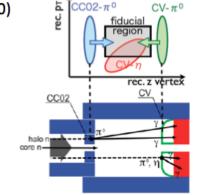


Pilot E391a at KEK(2001-2005) and the challenges

Neutron interactions with detector components close to the beam are the E391a main background sources



Phys. Rev. D 81, 072004(2010
BR<2.6*10 ⁻⁸ at 90% CL



BG	Estimation
CC02- π^0	0.7+/-0.4
CV-η	0.2+/-0.1
CV- π^0	<0.3

At a single event sensitivity of 1.1x10⁻⁸

KOTO goal: improve E391a by 1000 times to reach the SM sensitivity.

- More K_L, less halo neutron → Beam and better measurement of π⁰
- K $_{\rm L}$ ightarrow 2 $\pi^{\rm 0}$ background caused by missing photons is ~0.02 in E391a. But it is the dominant background in KOTO. The calorimeter and the vetoes have major upgrades to reduce it.
- · Higher rate demands new readout electronics

Table 9.4: The E949 experiment "as run" is compared with the proposed experiment. N_K is the number of kaons entering the Cherenkov detector that defines the upstream end of the experiment. Instantaneous is abbreviated as "inst." and average as "ave." in the table. Descriptions can be found in the section indicated in the right hand column.

Component	E949 "as run"	ORKA	Ratio	Section
Proton momentum (GeV/c)	21.5	95		9.2.1
Protons/spill	65×10^{12}	48×10^{12}	$R_{\rm proton} = 0.738$	9.2.1
Spill length(s)	2.2	4.4		9.2.1
Interspill(s)	3.2	5.6		9.2.1
Duty factor	0.41	0.44		9.2.1
protons/sec(ave.)	12×10^{12}	4.8×10^{12}		9.2.1
protons/sec(inst.)	15.9×10^{12}	10.9×10^{12}		9.2.1
Kaon momentum (MeV/c)	710	600		9.2.2
K beamline length(m)	19.6	13.74		9.2.2
Effective beam length(m)	17.6	13.21		9.2.2
K survival factor	0.0372	0.0536	$R_{\rm surv} = 1.4408$	9.2.2
Angular acceptance (msr)	12	20	$R_{\rm ang} = 1.66$	9.2.2
$\Delta p/p(\%)$	4.0	6.0	$R_{\Delta p} = 1.5$	9.2.2
K^+ : π^+ ratio	3	3.31 ± 0.41	_	9.2.2
Relative K/proton			$R_{K/p} = 6.5 \pm 0.8$	9.2.3
N_K/spill	12.8×10^{6}	$(88.5 \pm 10.9) \times 10^6$		9.2.5
$N_K/\mathrm{sec}(\mathrm{inst.})$	6.3×10^{6}	$(20.1 \pm 2.5) \times 10^6$		9.2.5
$N_{K+\pi}/\mathrm{sec(inst.)}$	8.4×10^{6}	26.2×10^{6}		9.2.5
$N_K/\mathrm{sec}(\mathrm{ave.})$	2.6×10^{6}	$(8.85 \pm 1.09) \times 10^6$		9.2.5
Stopping fraction	0.21	0.54 ± 0.12		9.2.4
Kstop/s(ave.)	0.69×10^{6}	$(4.78 \pm 1.21) \times 10^6$		9.2.5
Running time(hr)		5000		9.2.5
Kstop/"year"		$(8.6 \pm 2.2) \times 10^{13}$		9.2.5
$\mathcal{S}'_{\mathrm{loss}}$			0.77 ± 0.02	9.2.5



ORKA

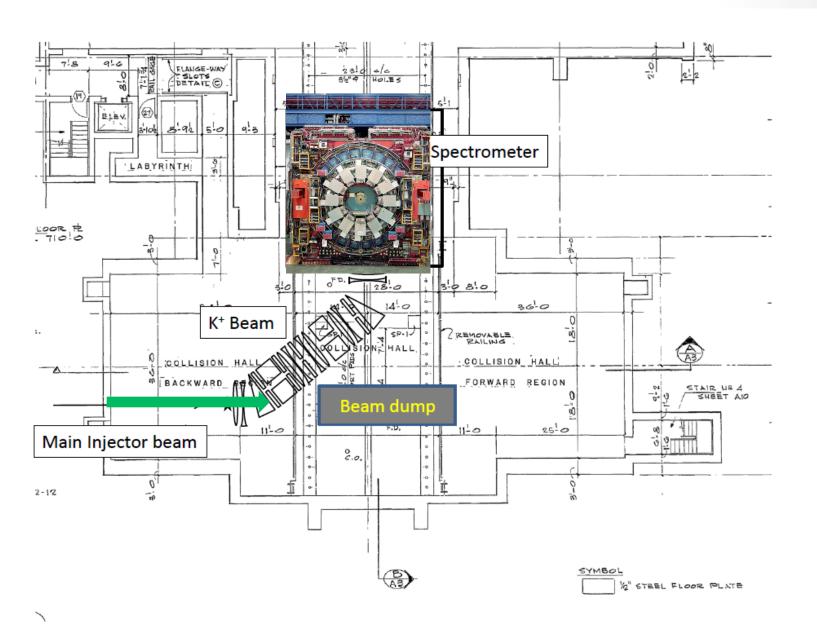


Figure 5.3: Illustration of the ORKA beam line and detector sited within the B0 collision hall.

G4Beamline dog-leg design underway to preserve CDF detector orientation.

