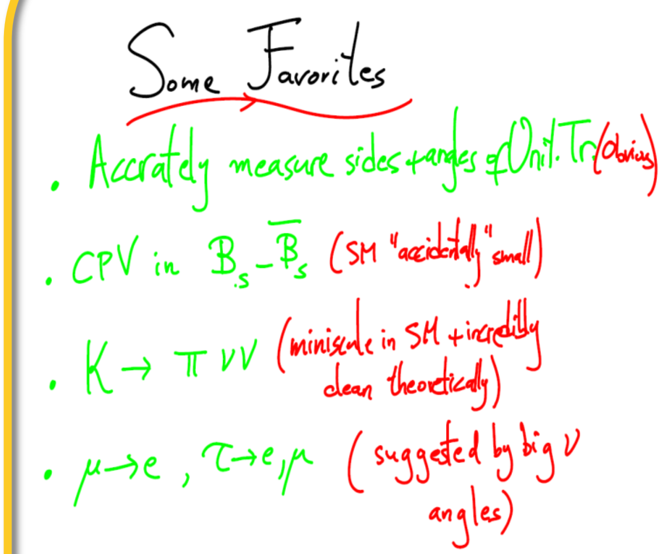

ORKA: The Golden Kaon Experiment
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$
Elizabeth Worcester (BNL)
for the ORKA collaboration
June 13, 2012
Photo: Life of Sea blogspot

ORKA: The Golden Kaon Experiment

- Precision measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ 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)

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 CP-violating 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



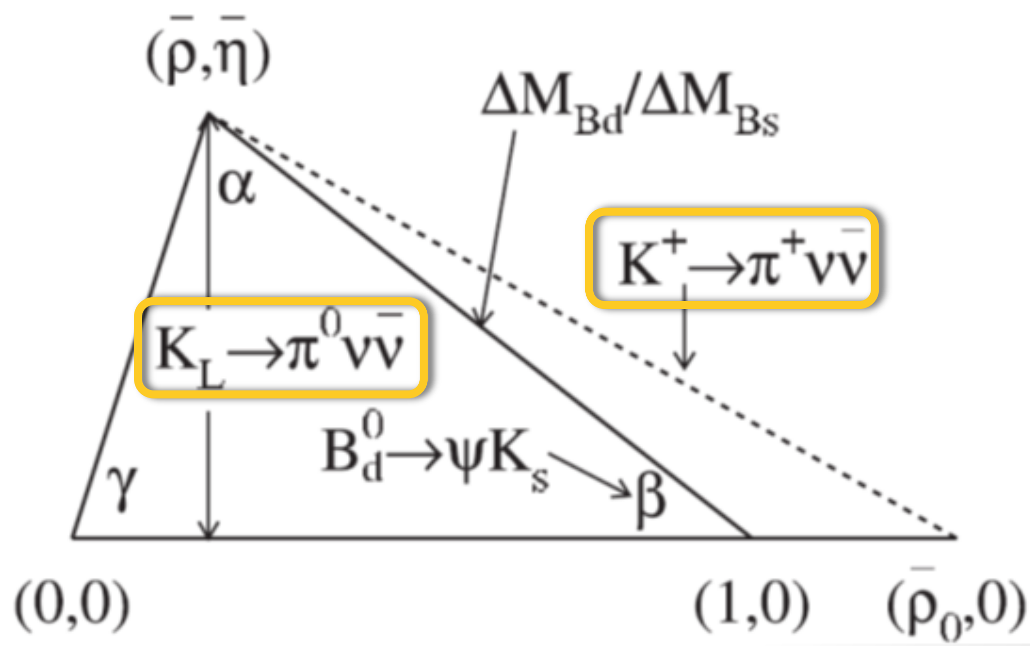
Flavor Physics: Pushing Beyond the LHC.
Intensity Frontier Workshop
Nima Arkani-Hamed (Princeton, IAS)

CKM Matrix and Unitarity Triangle

Wolfenstein Parameterization

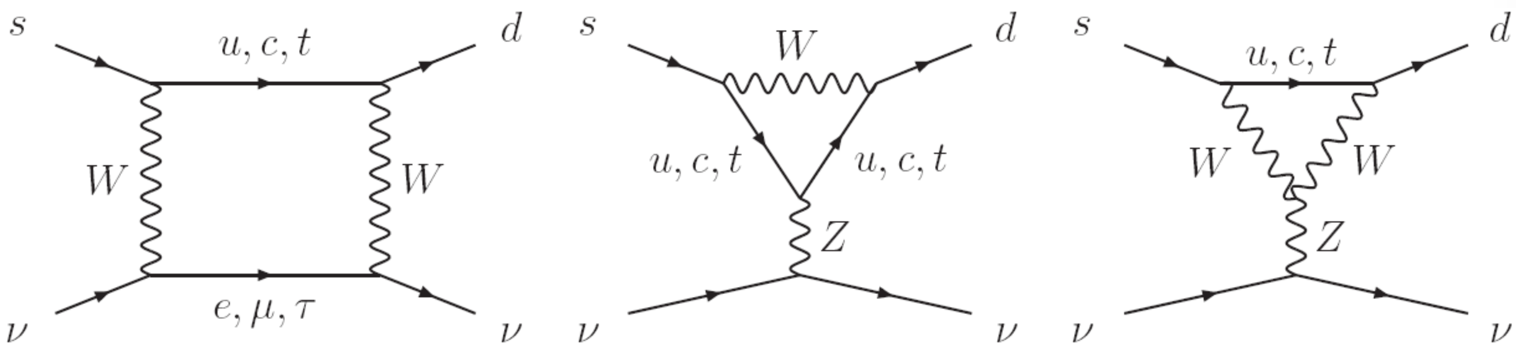
$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CP Violation



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

- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is the most precisely predicted FCNC decay involving quarks
- $B_{SM}\left(K^+ \rightarrow \pi^+ \nu\bar{\nu}\right) = \left(7.8 \pm 0.8\right) \times 10^{-11}$



- A single effective operator: $\left(\bar{s}_L \gamma^\mu d_L\right)\left(\bar{\nu}_L \gamma_\mu \nu_L\right)$
- 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

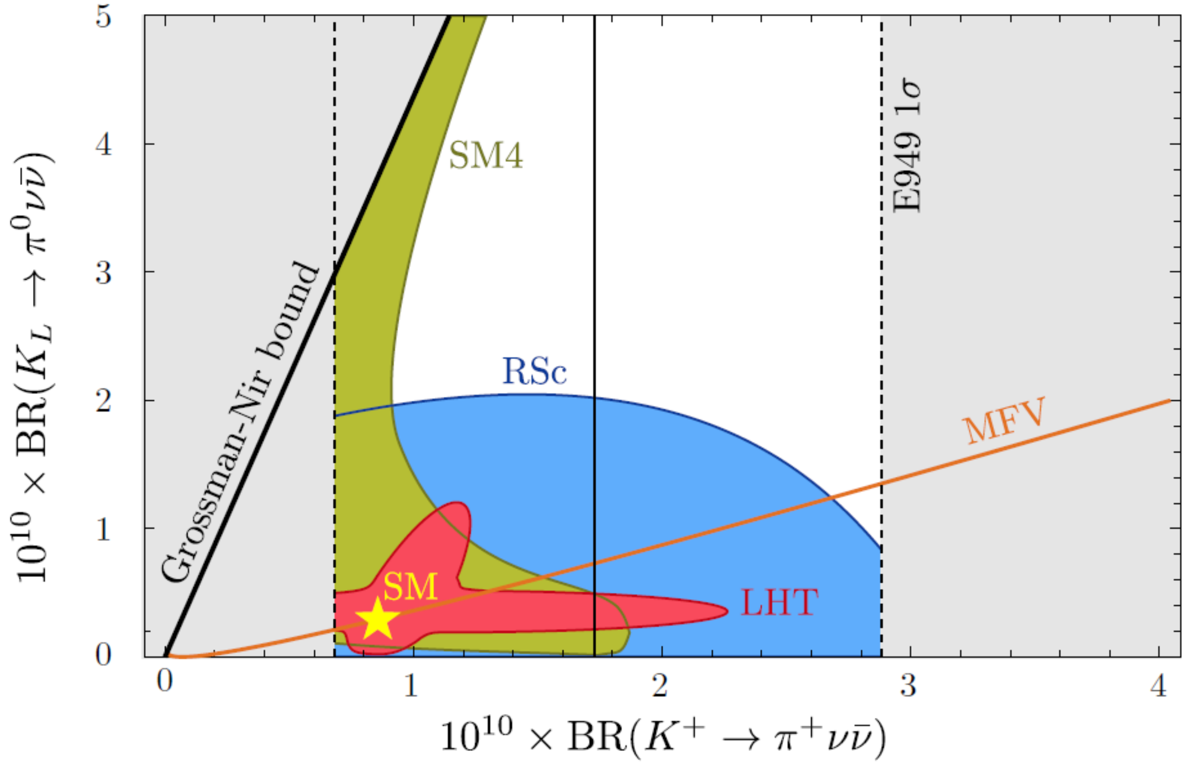
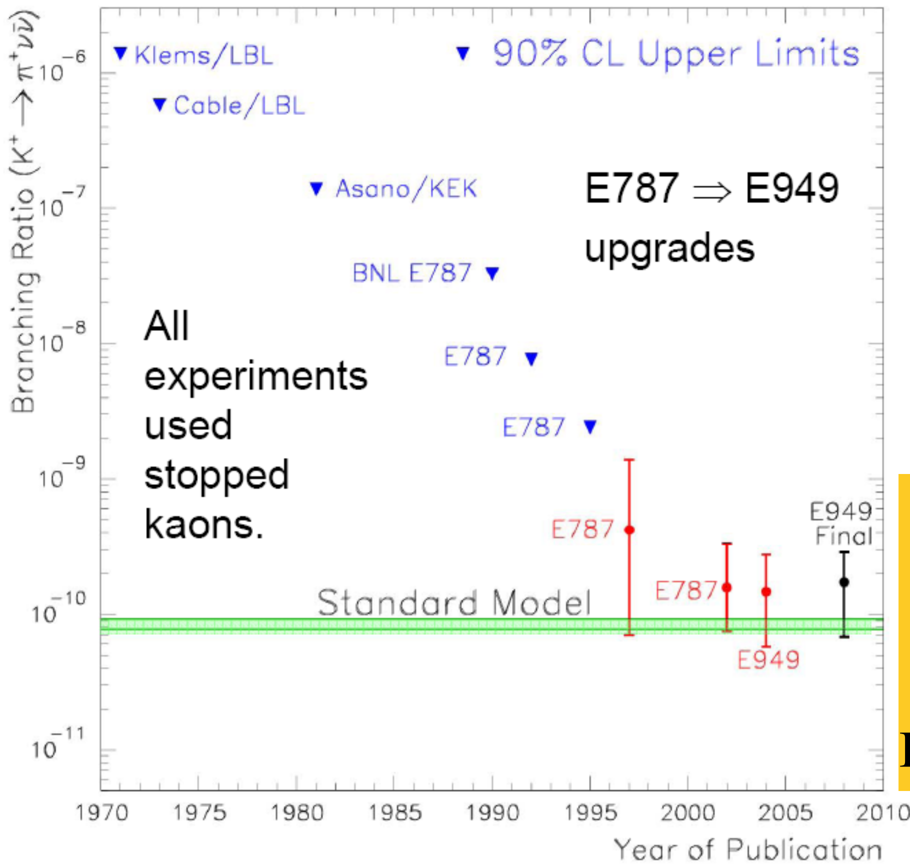


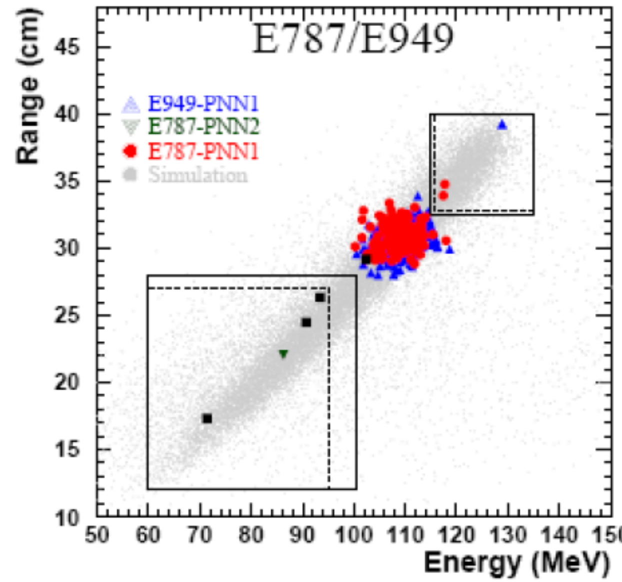
Figure 1: Correlation between the branching ratios of $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ in MFV and three concrete NP models. The gray area is ruled out experimentally or model-independently by the GN bound. The SM point is marked by a star.

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

Experimental History

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





E787/E949 Final: 7 events observed

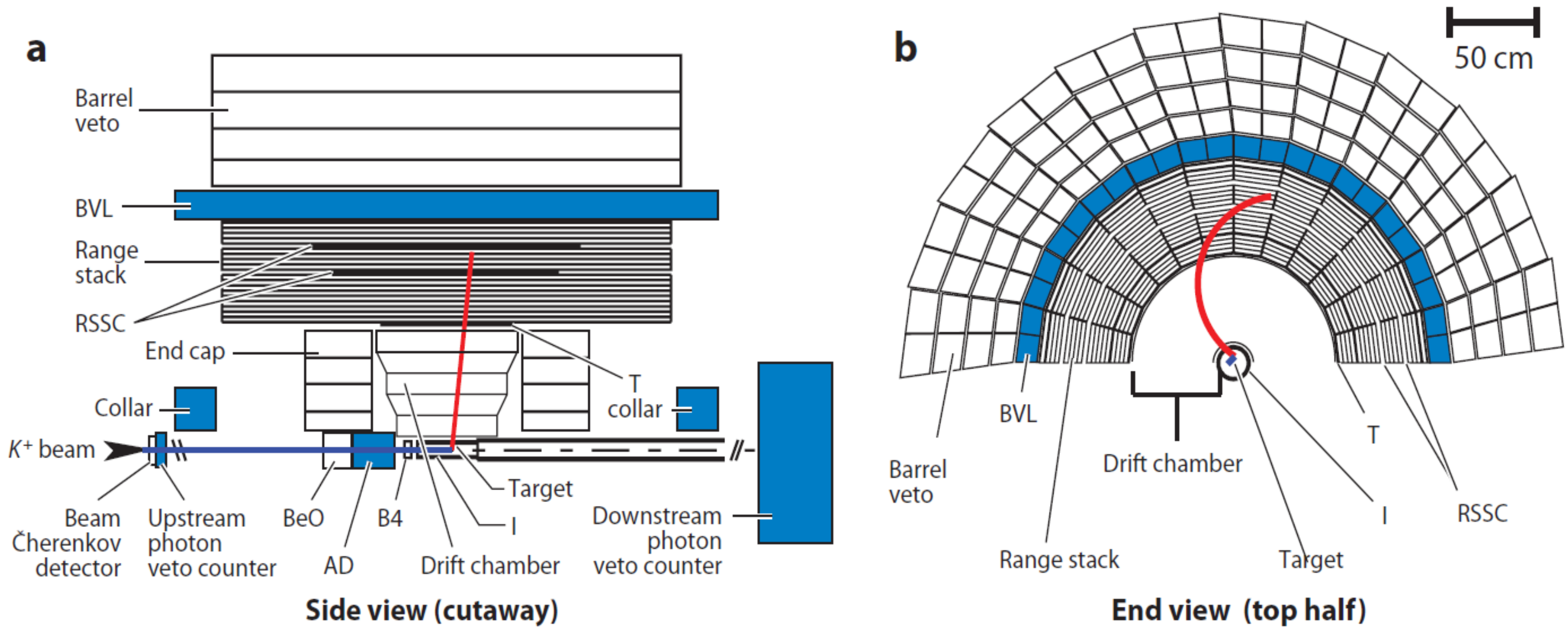
$$B\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$$

Standard Model:

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

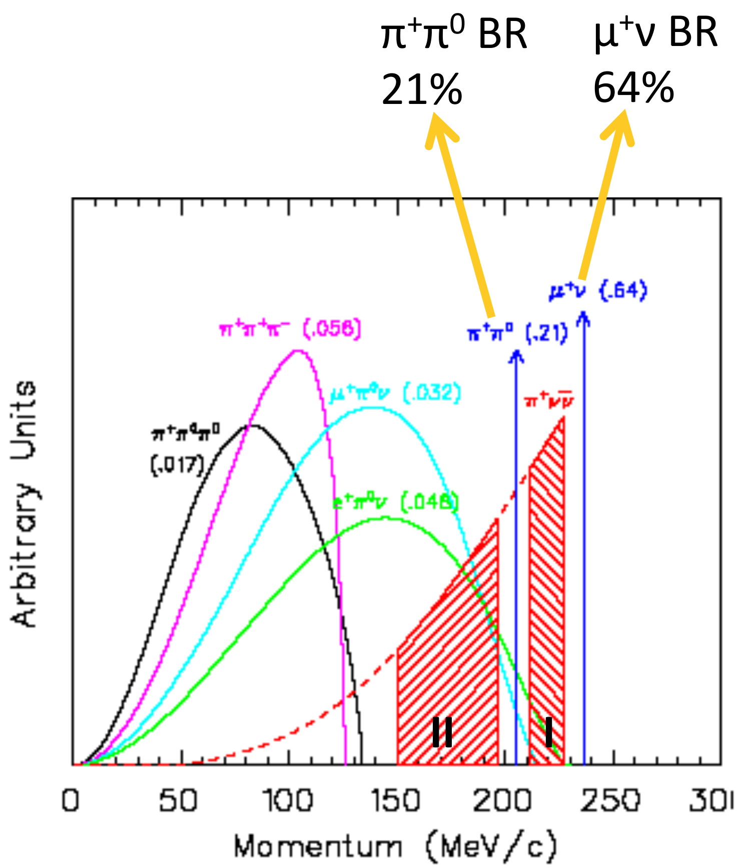
BNL E787/E949 Stopped Kaon Technique

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

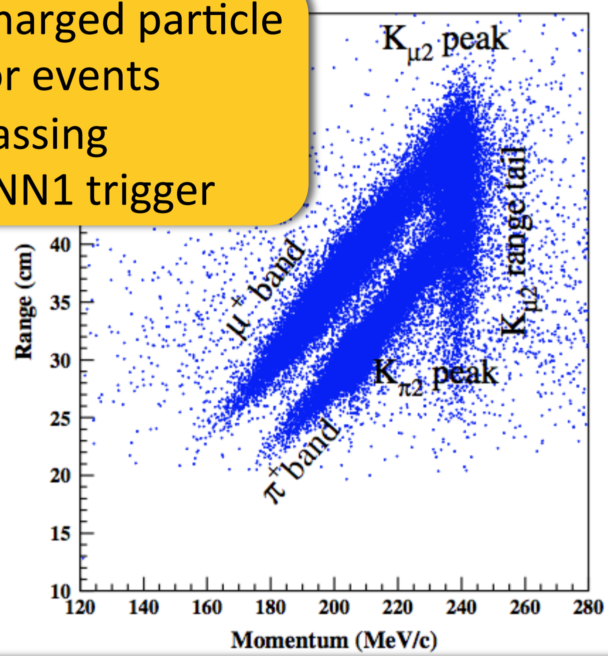


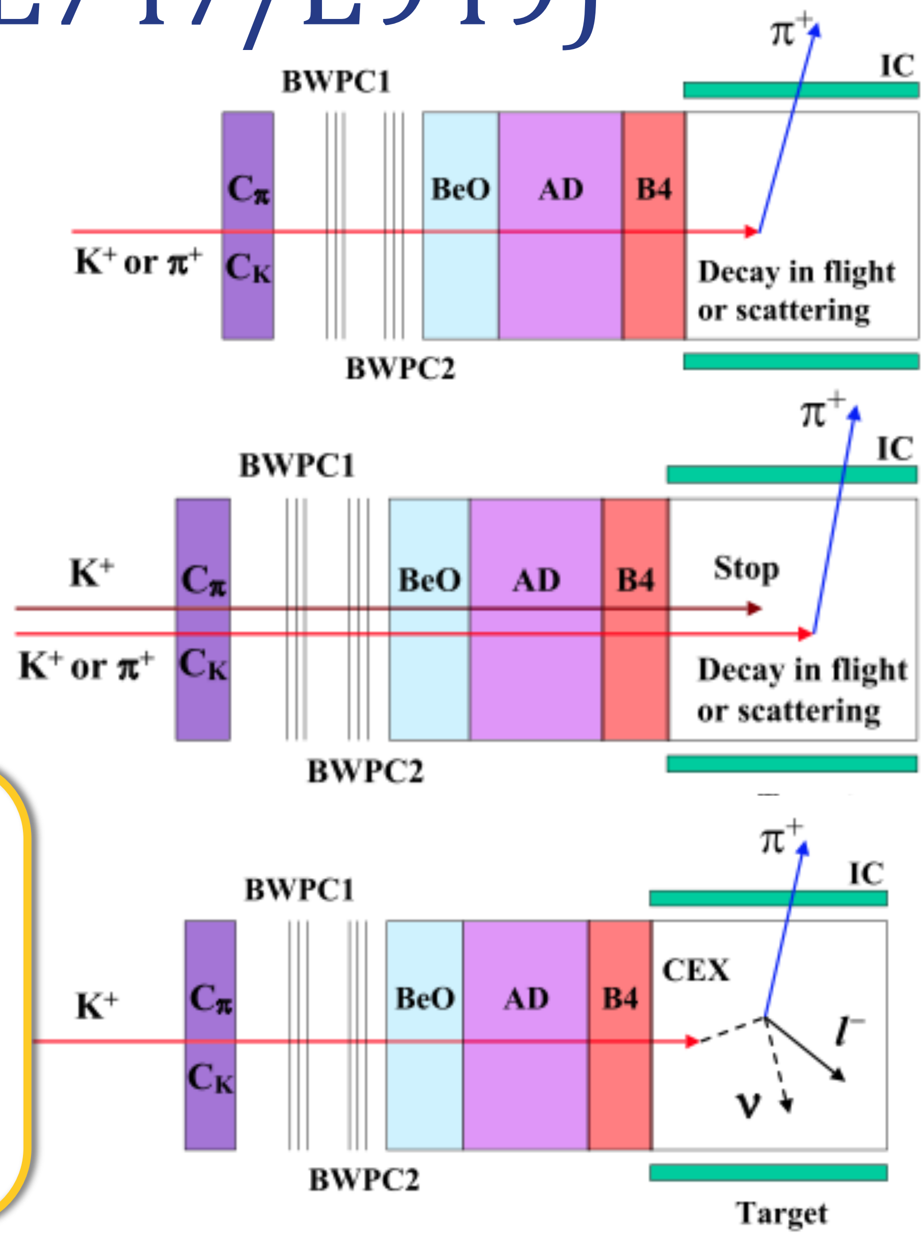
Momentum spectra of charged particles from K^+ decays in the rest frame

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

Background (E747/E949)

Charged particle for events passing PNN1 trigger





Stopped kaon background:

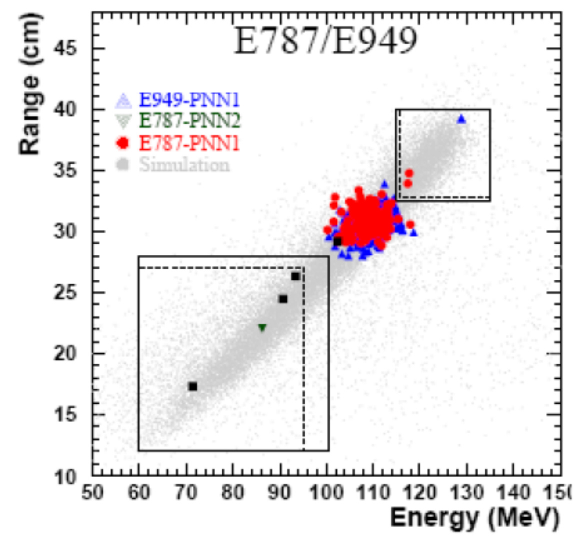
- $K^+ \to \pi^+\pi^0$
- $K^+ \to \mu^+\nu$
- μ^+ band
  - $K^+ \to \mu^+\nu\gamma$
  - $K^+ \to \mu^+\pi^0\nu$

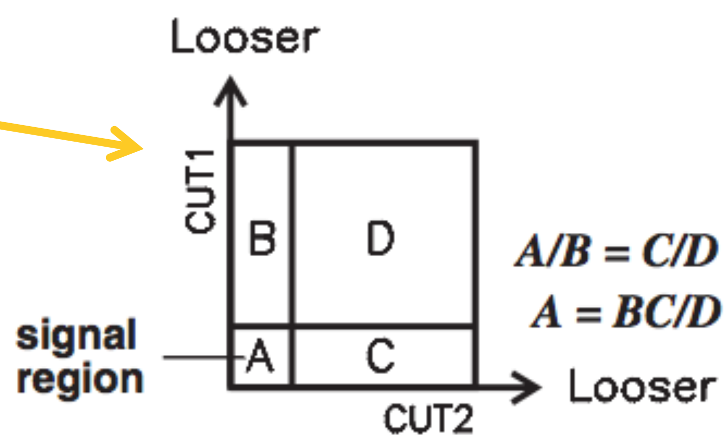
Beam background:

- Single beam
- Double beam
- Charge exchange

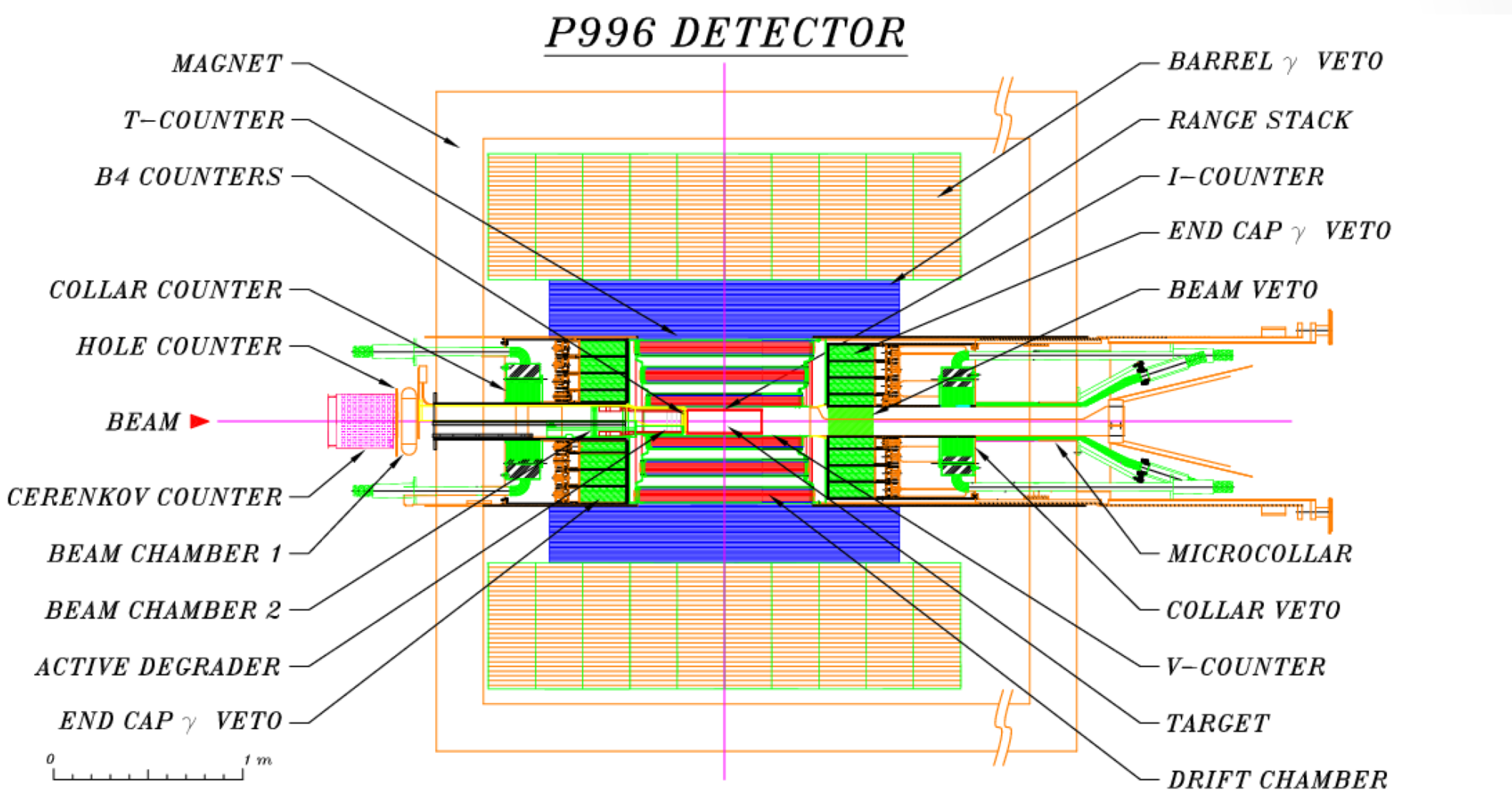
Analysis Strategy (E747/E949)

- 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





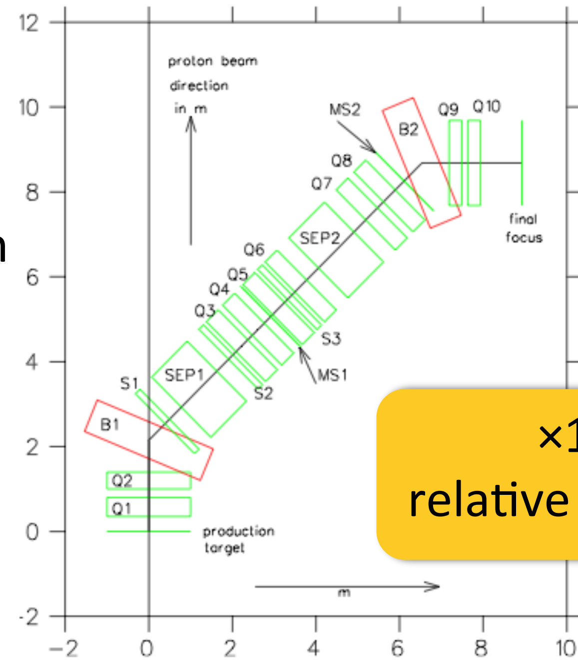
ORKA:
a 4th generation detector



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
  - 48×10^{12} protons per spill
  - Duty factor of ~45%
  - # of protons/spill (**×0.74**)
- Secondary Beam Line
  - 600 MeV/c K^+ 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**)



×10
relative to E949

Sensitivity Improvements: Acceptance

Component	Acceptance factor
$\pi \to \mu \to e$	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})	$11.28^{+3.25}_{-2.22}$

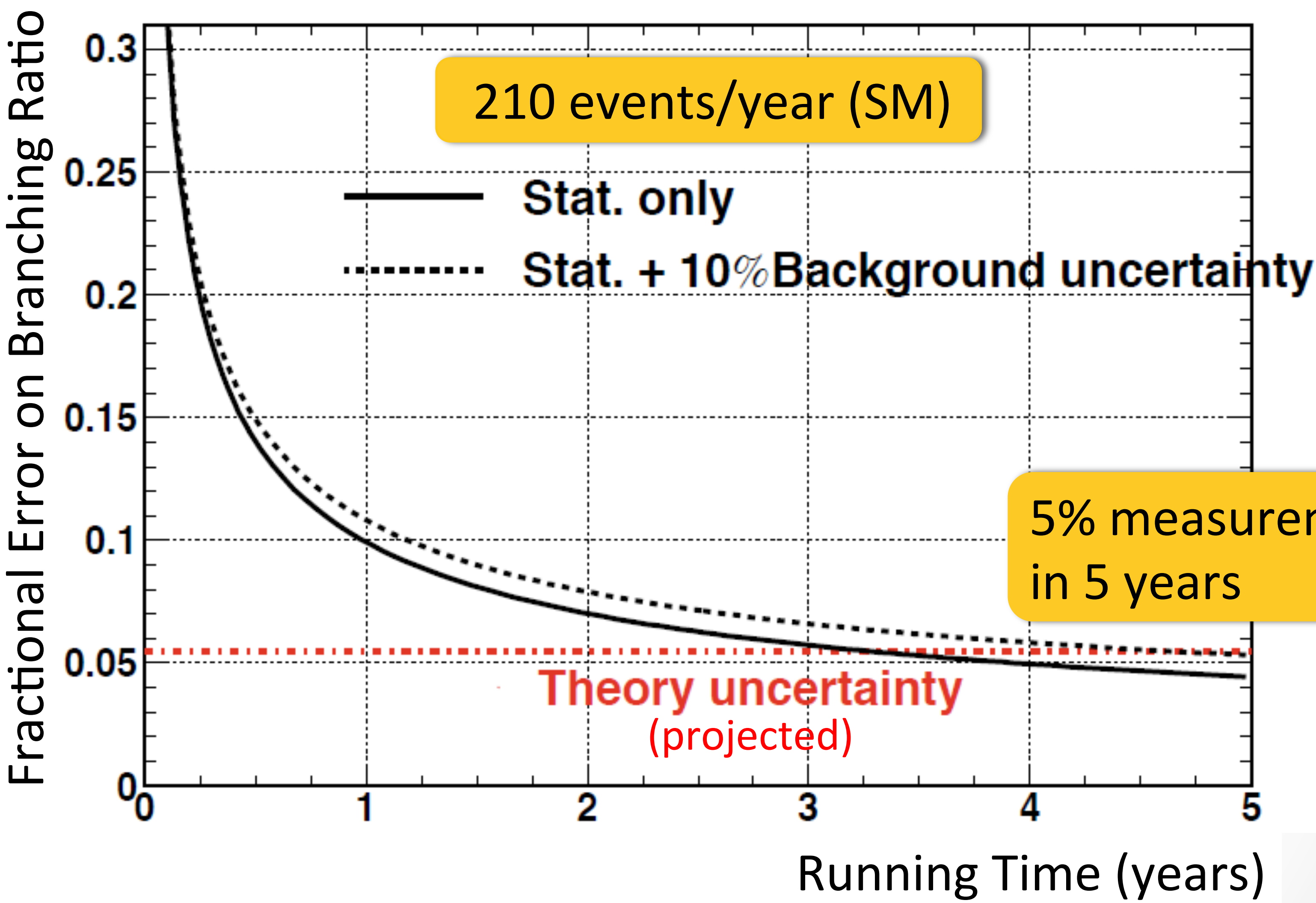
×11 relative to E949

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

- E949 PNN1 $\pi^+ \to \mu^+ \to e^+$ 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:

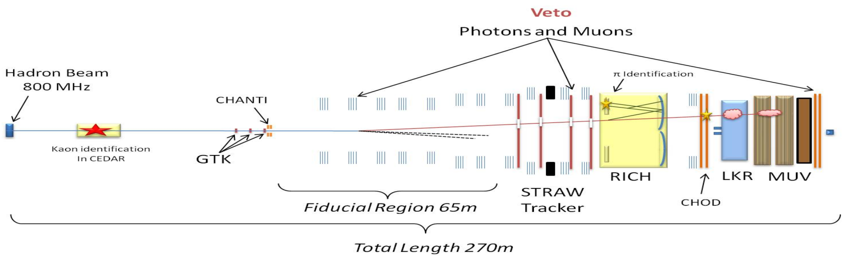
	Range	Acceptance
Measured π^+ lifetime	3-105 ns	~87%
Measured μ^+ lifetime	0.1-10 ns	~95%
μ^+ escape	n/a	~98%
Undetectable e^+	n/a	~97%
Total		**~78%**

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



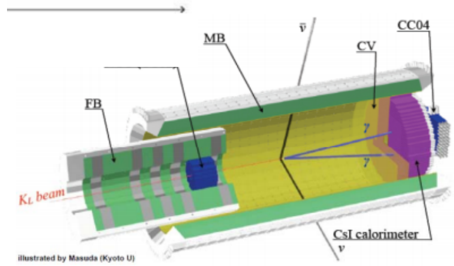
Worldwide Effort

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



- Decay-in-flight experiment
- Builds on NA-31/NA-48
- Expect ~55 $K^+\rightarrow\pi^+\nu\bar{\nu}$ 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 measurement to ORKA

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



- 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 $K^0\rightarrow\pi^0\nu\bar{\nu}$ events (SM)
- Under construction

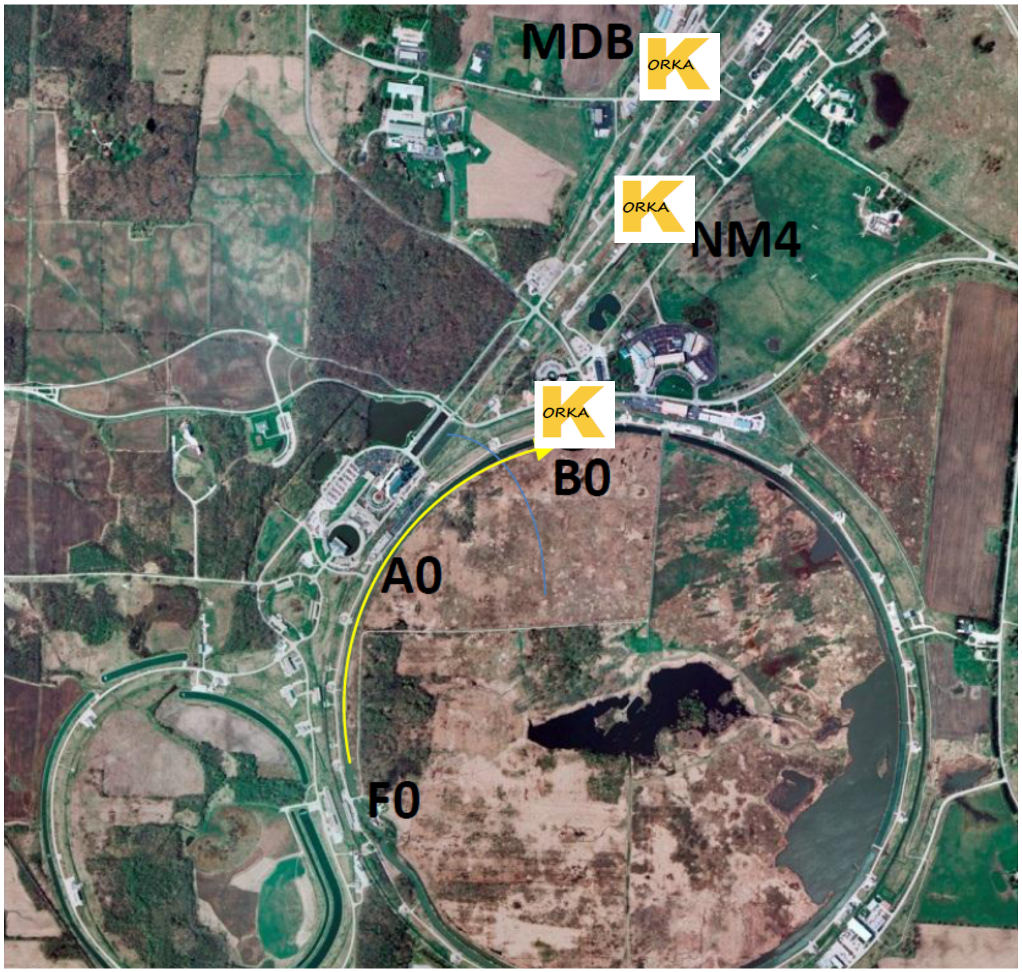
Other Physics Topics

- $K^+ \to \pi^+ +$ missing energy
  - $K^+ \to \pi^+\nu\bar{\nu}(1)$ ^{T,P}
  - $K^+ \to \pi^+\nu\bar{\nu}(2)$ ^{T,P}
  - $K^+ \to \pi^+\nu\bar{\nu}\gamma$
  - $K^+ \to \pi^+X$ ^{P}
  - $K^+ \to \pi^+\tilde{\chi}_0\tilde{\chi}_0(\mathrm{FF})$ ^{P}
- $K^+ \to \pi^+\pi^0 +$ missing energy
  - $K^+ \to \pi^+\pi^0\nu\bar{\nu}$ ^{T,P}
  - $K^+ \to \pi^+\pi^0X$
- $K^+ \to \mu^+ +$ missing energy
  - $K^+ \to \mu^+\nu_h$ (heavy neutrino) ^{T}
  - $K^+ \to \mu^+\nu M$ (M =majoran)
  - $K^+ \to \mu^+\nu\bar{\nu}\nu$
- $K^+ \to \pi^+\gamma$ ^{TP}
- $K^+ \to \pi^+\gamma\gamma$ ^{P}
- $K^+ \to \pi^+\gamma\gamma\gamma$
- $K^+ \to \pi^+\mathrm{DP}$; $\mathrm{DP} \to e^+e^-$
- K^+ lifetime
- $\mathcal{B}(K^+ \to \pi^+\pi^0)/\mathcal{B}(K^+ \to \mu^+\nu)$
- $K^+ \to \pi^+\pi^0e^+e^-$
- $K^+ \to \pi^-\mu^+\mu^+$ (LFV)
- $\pi^0 \to$ nothing ^{T,P}
- $\pi^0 \to \gamma\mathrm{DP}$; $\mathrm{DP} \to e^+e^-$
- $\pi^0 \to \gamma X$

^{T}E787/E949 Thesis ; ^{P}E787/E949 Publication; DP≡Dark Photon

More info in my talk at Project X Physics Study: June 19

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)

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!

ASU UNBC INFN INFN Ole Miss
ILLINOIS UBC THE UNIVERSITY OF TEXAS AT AUSTIN TSING HUA UNIVERSITY UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ
BROOKHAVEN NATIONAL LABORATORY JOINT INSTITUTE FOR NUCLEAR RESEARCH TRIUMF

ORKA Summary

- High precision measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ 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

More ORKA: See David Jaffe's talk June 18 at PXPS

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

NA62

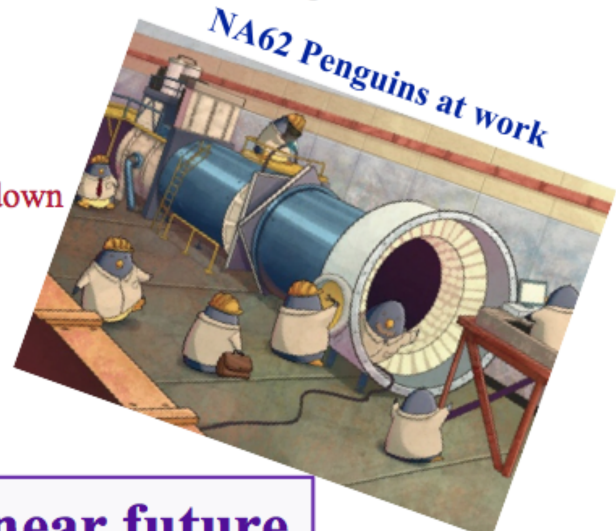
CONCLUSIONS

- The $K \rightarrow \pi\nu\bar{\nu}$ decay : precision physics complementary to high-energy approach for NP search

- **NA62:** Very challenging experiment
  - ➔ 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

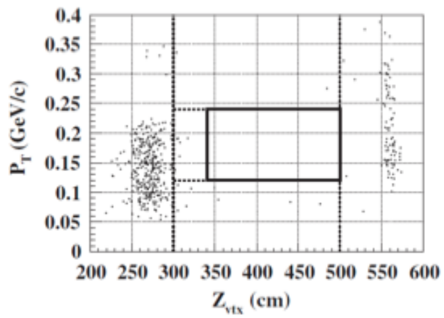


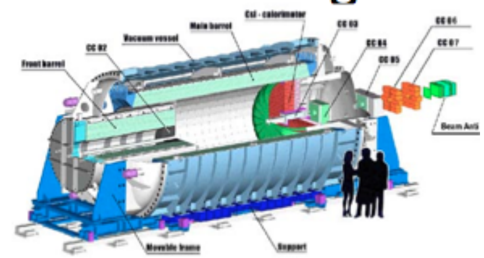
A very rich program in the near future

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

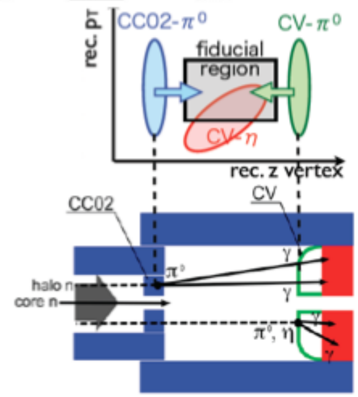




Phys. Rev. D 81, 072004(2010)
BR<2.6*10^{-8} at 90% CL

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 π^0**
- **$K_L \rightarrow 2\,\pi^0$ 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**

7

Jiasen Ma, APS Meeting, March 2012

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}	$R_{\text{proton}} = 0.738$	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	$R_{\text{surv}} = 1.4408$	9.2.2
Angular acceptance (msr)	12	20	$R_{\text{ang}} = 1.66$	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/sec(inst.)	6.3×10^6	$(20.1 \pm 2.5) \times 10^6$		9.2.5
$N_{K+\pi}$/sec(inst.)	8.4×10^6	26.2×10^6		9.2.5
N_K/sec(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
S'_{loss}			0.77 ± 0.02	9.2.5

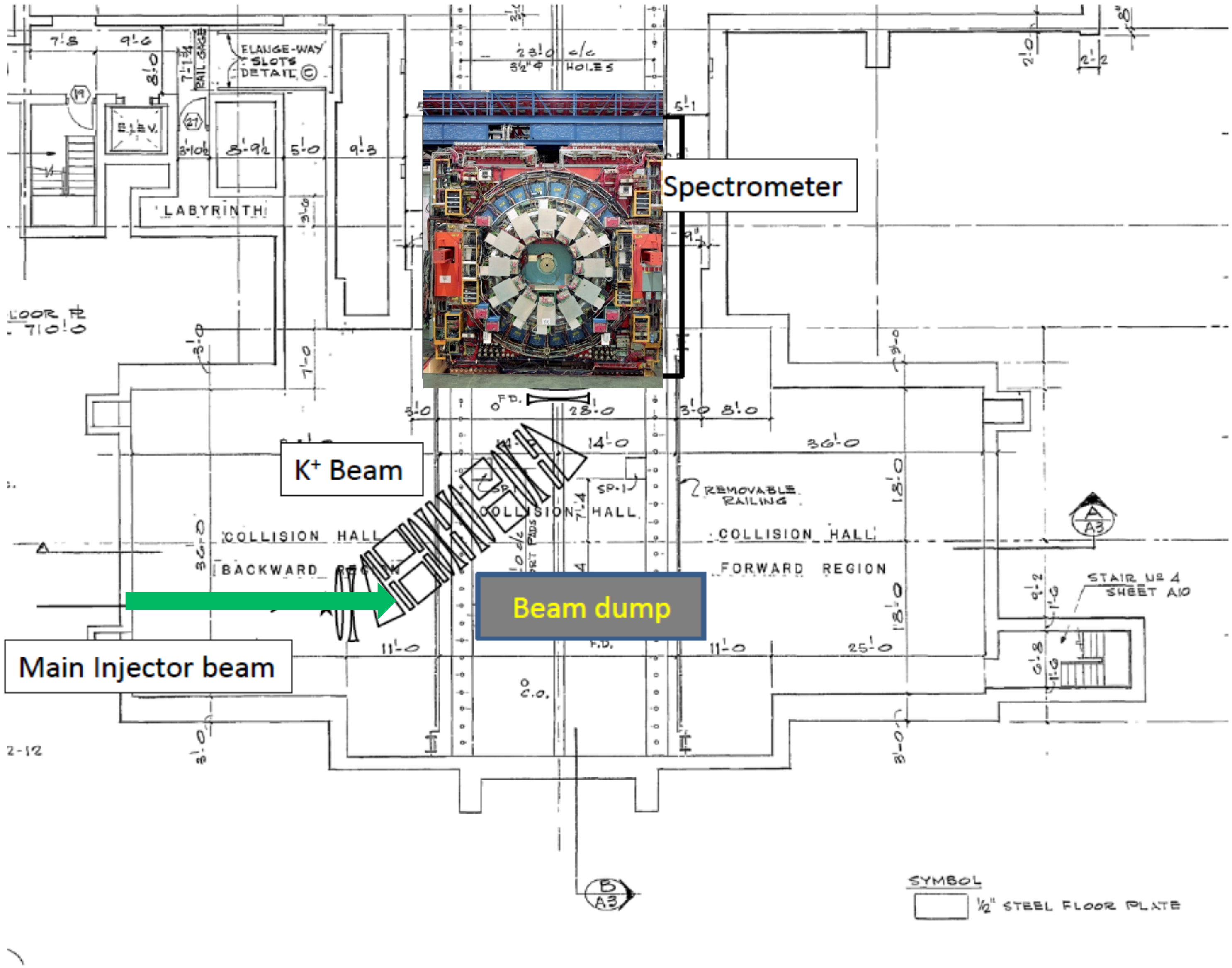


Figure 5.3: Illustration of the ORKA beam line and detector sited within the B0 collision hall.

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