ORKA: The Golden Kaon Experiment

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

Elizabeth Worcester (BNL)
for the ORKA collaboration
May 2, 2013

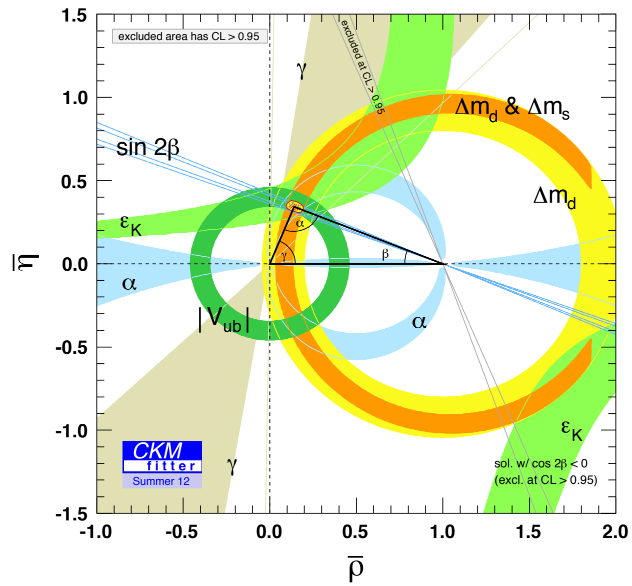
Photo: Life of Sea blogspot

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 candidate events already observed
- High impact measurement

Motivation

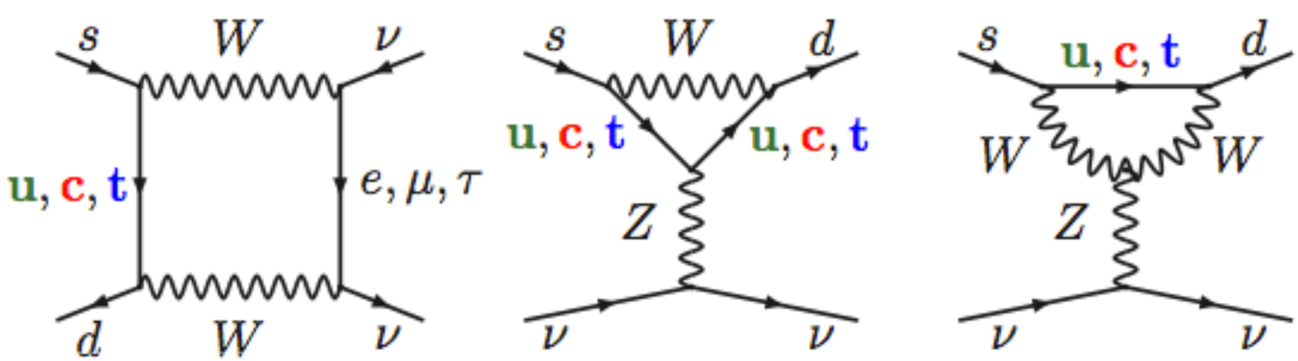
- Flavor problem:
  - We expect new physics at the TeV scale . . .
  - Why don't we see this new physics affecting the flavor physics we study today?



- If (BSM) new physics found in LHC searches:
  - Precision flavor-physics experiments needed to explore flavor- and CP-violating 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

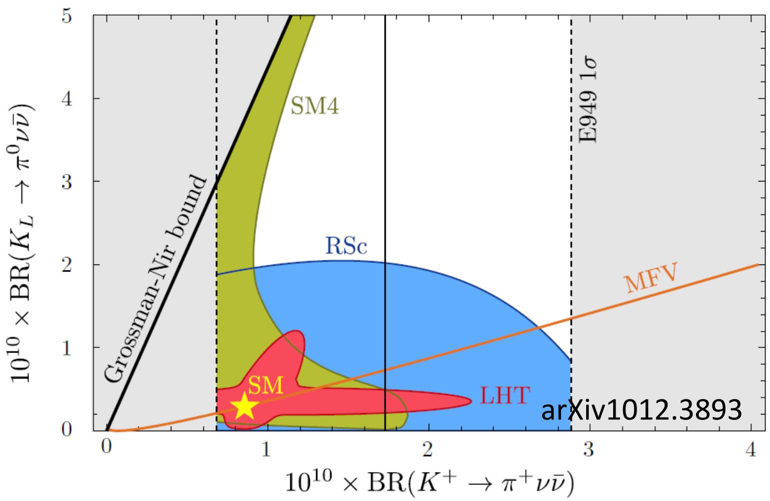
$K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

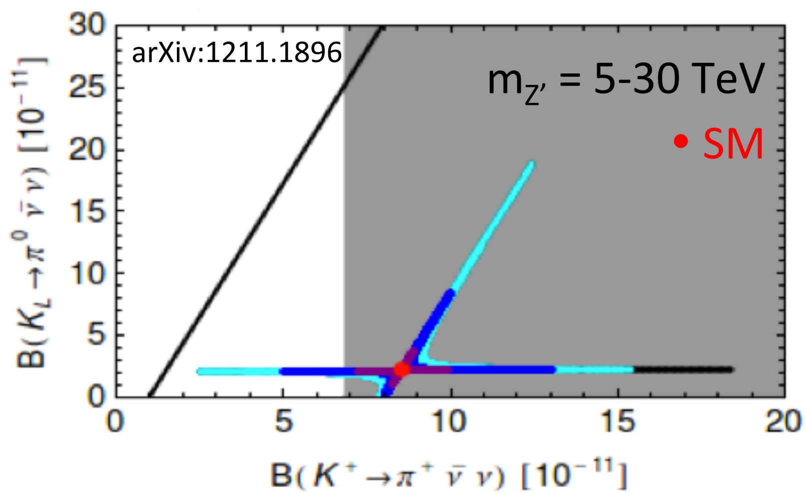
- $K \to \pi\nu\bar{\nu}$ are the most precisely predicted FCNC decays involving quarks
- $B_{SM}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (7.8 \pm 0.8) \times 10^{-11}$

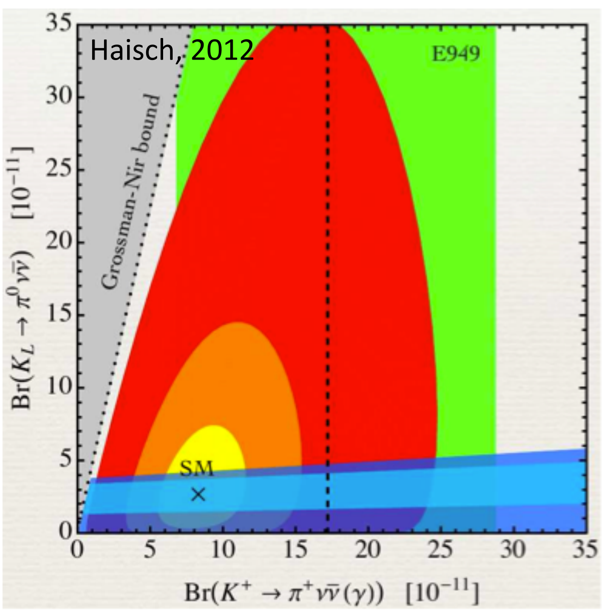


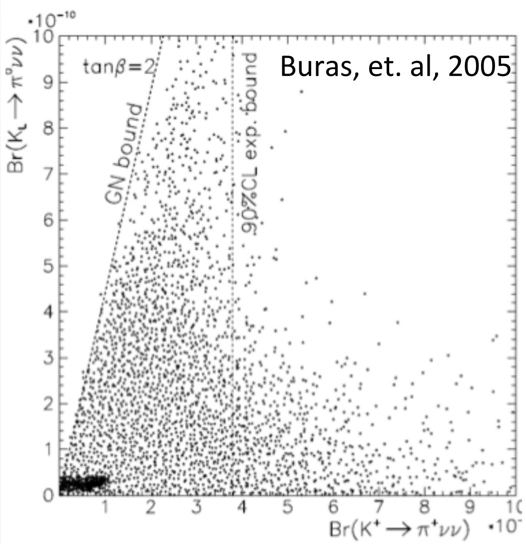
- A single effective operator: $\left(\bar{s}_L \gamma^\mu d_L\right)\left(\bar{\nu}_L \gamma_\mu \nu_L\right)$
- Dominated by top quark
- Hadronic matrix element shared with $K^+ \to \pi^0 e^+ \nu_e$
- Dominant uncertainty from CKM matrix elements (expect prediction to improve to ~5%)

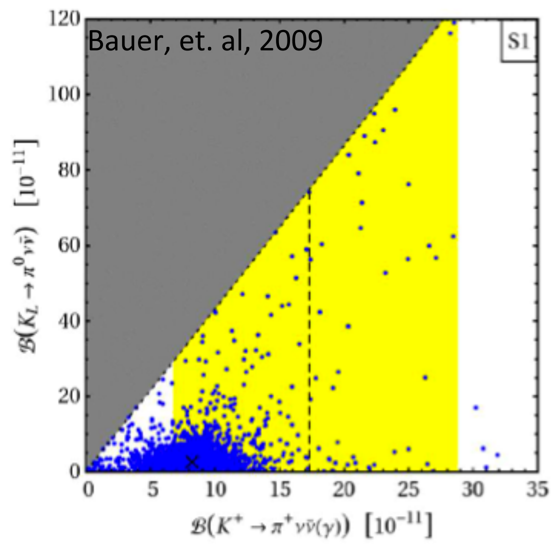
Sensitivity to New Physics



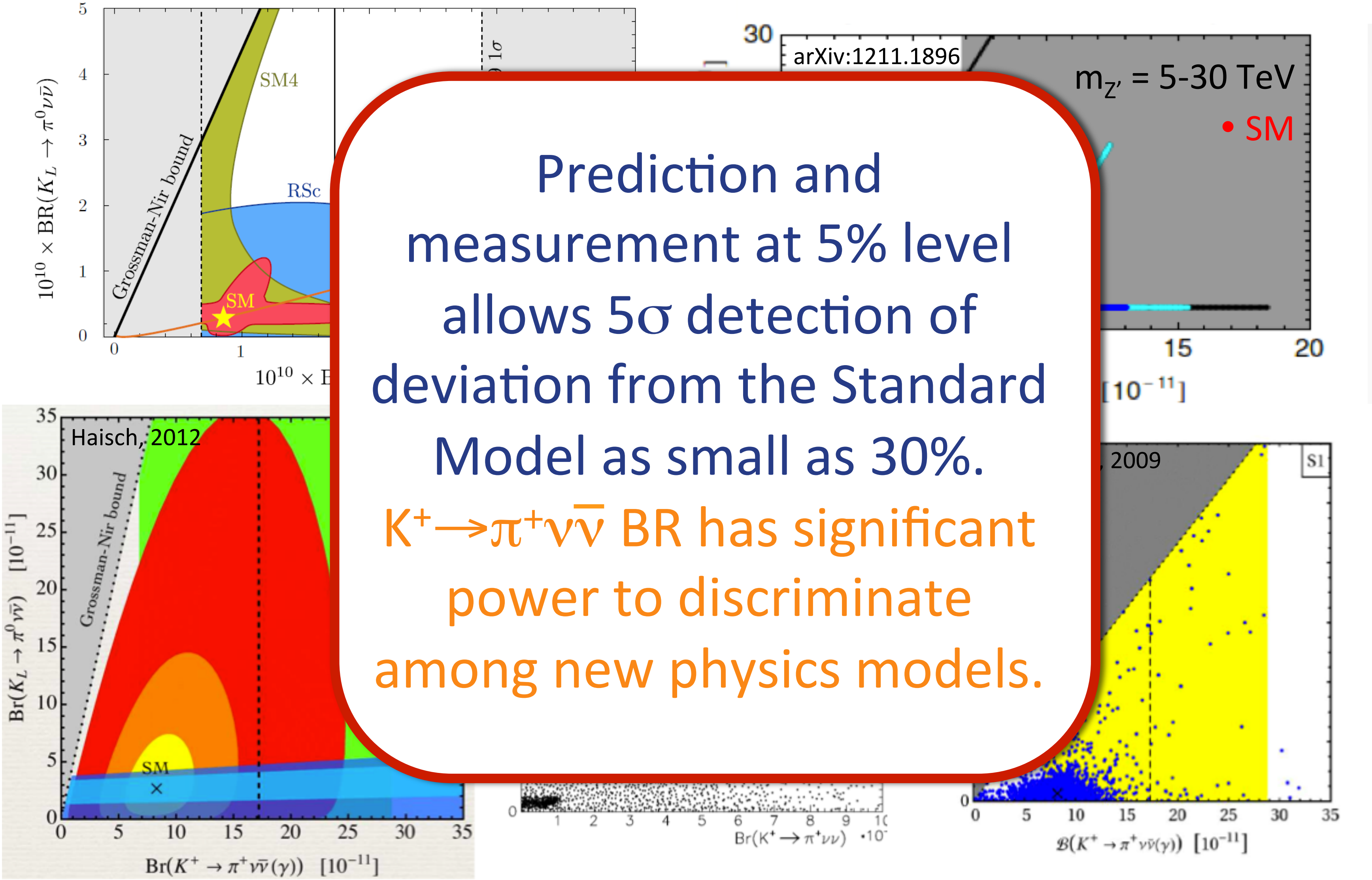








Sensitivity to New Physics

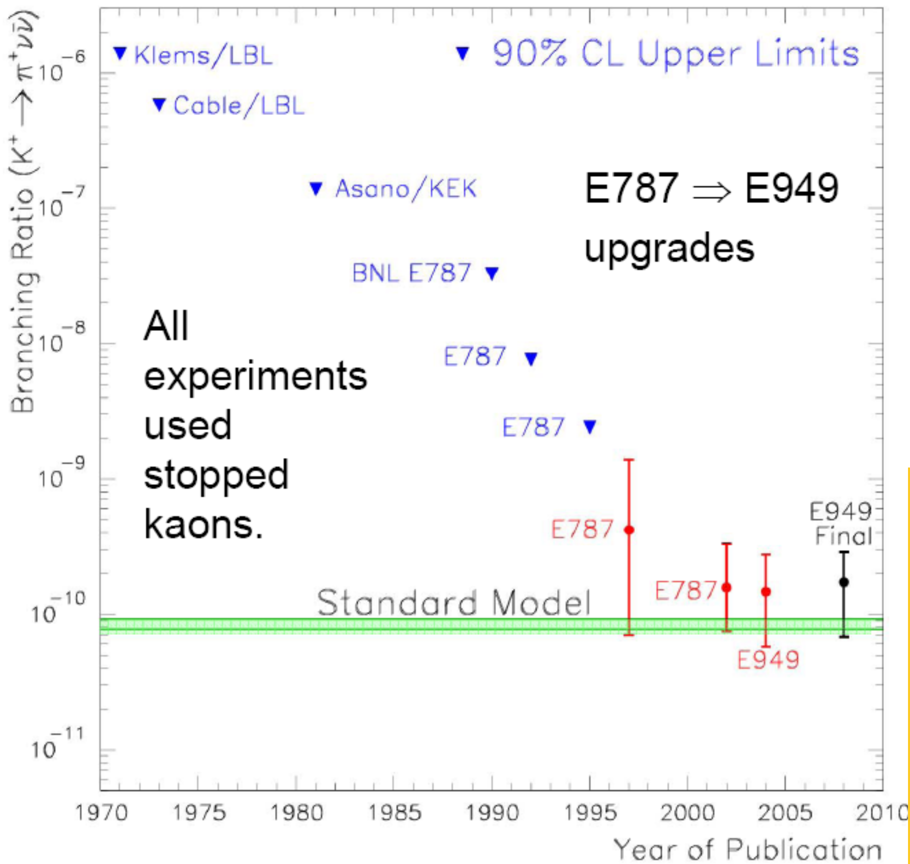


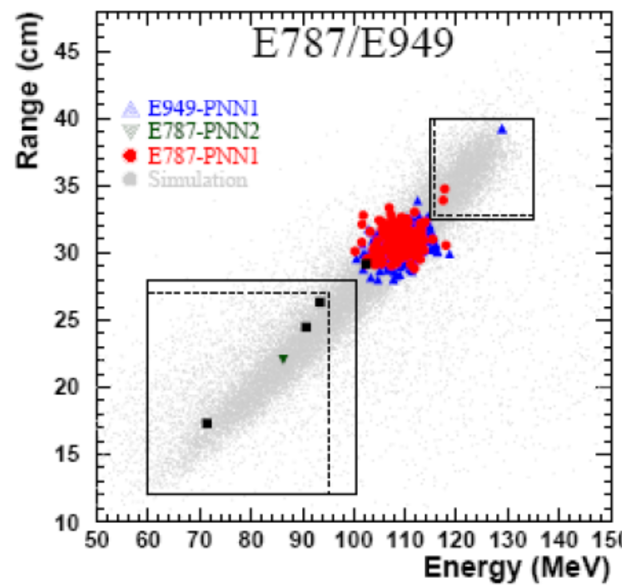
Prediction and measurement at 5% level allows 5σ detection of deviation from the Standard Model as small as 30%.

$K^+ \to \pi^+ \nu\bar{\nu}$ BR has significant power to discriminate among new physics models.

Experimental History

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





E787/E949 Final (7 candidate events observed):

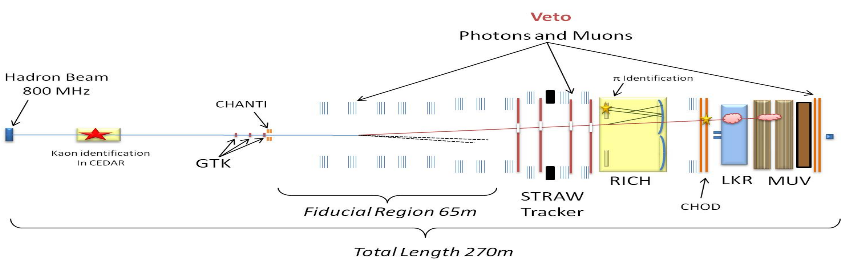
$$B\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$$

Standard Model:

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

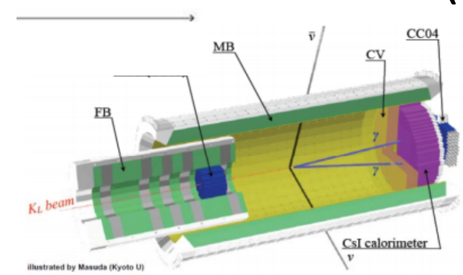
Worldwide Effort

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



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

- J-PARC E14 “KOTO” ($K^0 \to \pi^0 \nu \bar{\nu}$)



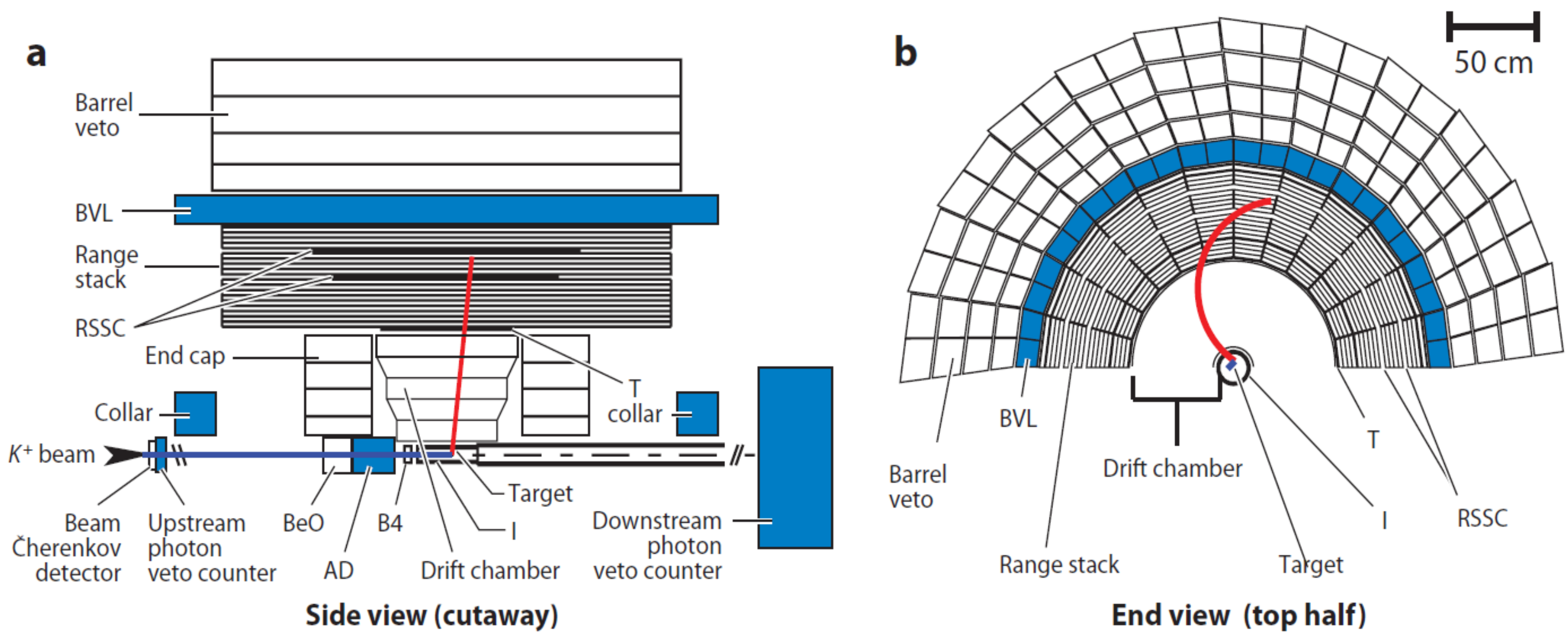
- Pencil beam decay-in-flight experiment
- Improved J-PARC beam line
- 2nd generation detector building on E391 at KEK
- Re-using KTeV CsI crystals to improve calorimeter (better resolution and veto power)
- Expect ~3 $K^0 \to \pi^0 \nu \bar{\nu}$ events (SM)

ORKA at FNAL

- Stopped-kaon technique
- Builds on successful BNL E787/949 experiments
- 17 Institutions in 6 countries: Canada, China, Italy, Mexico, Russia, USA
- 2 US National Labs, 6 US Universities
- Leadership from successful rare kaon decay experiments

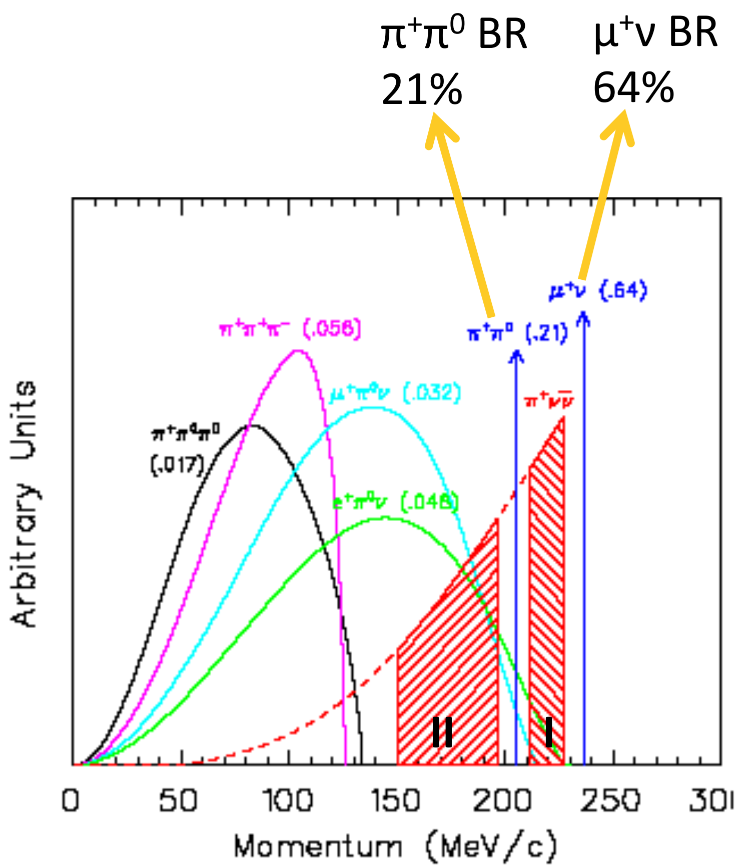
BNL E787/E949 Stopped-Kaon Technique

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

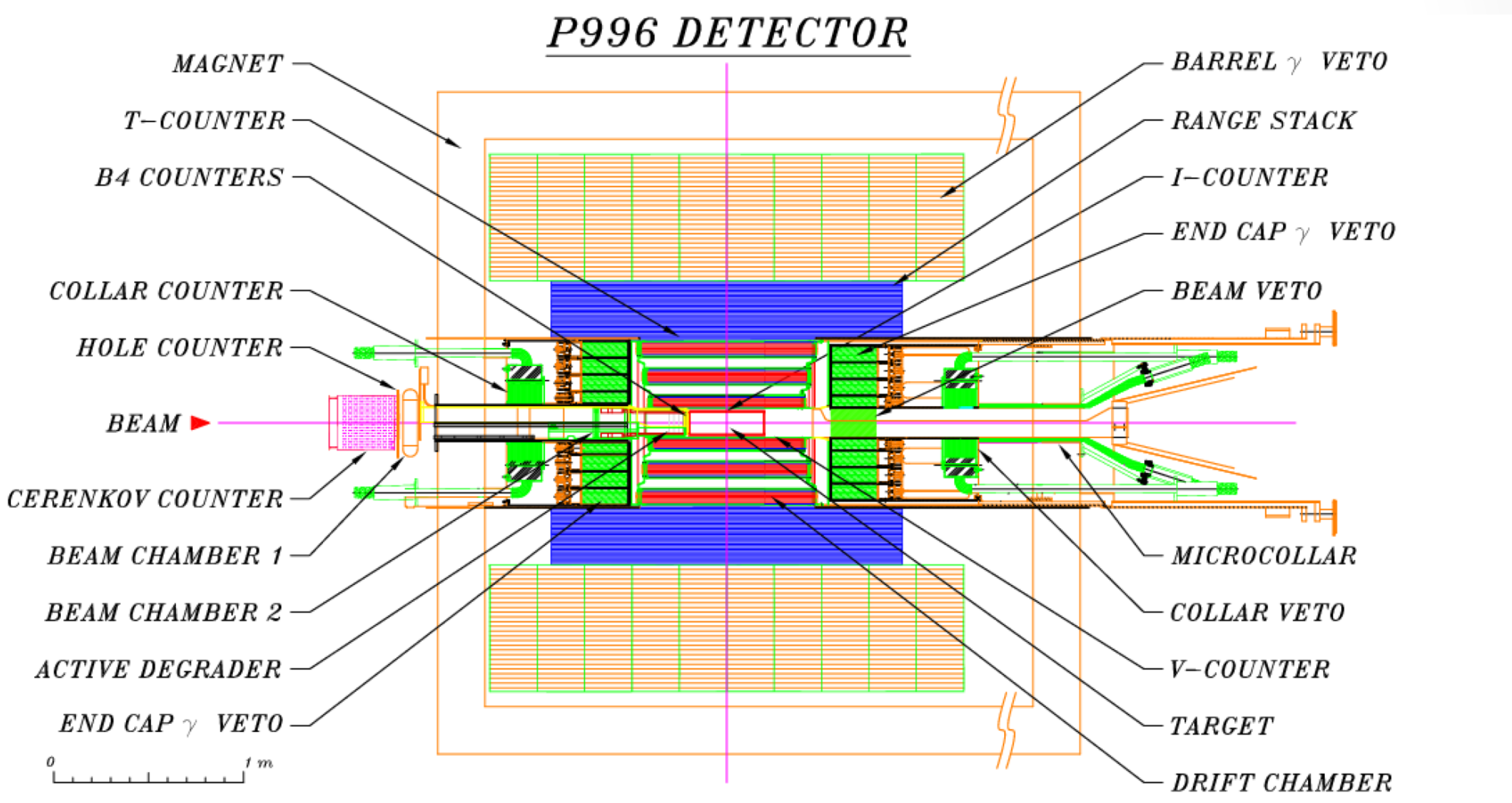
Difficult Measurement



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}

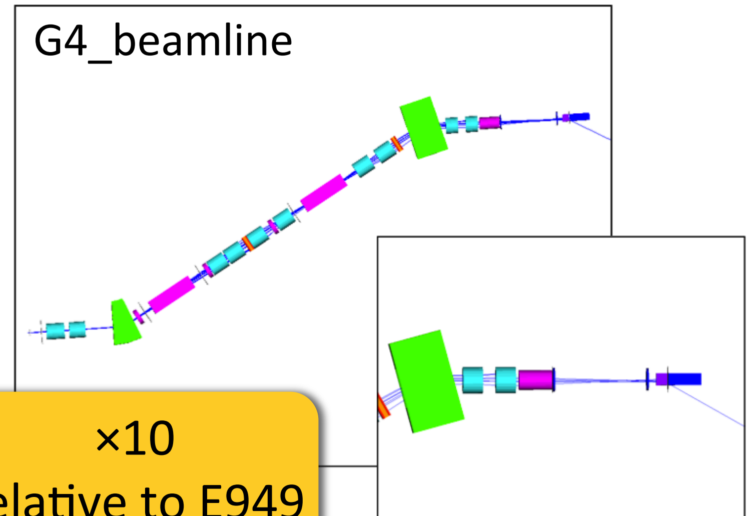
ORKA:
a 4th generation detector



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**)



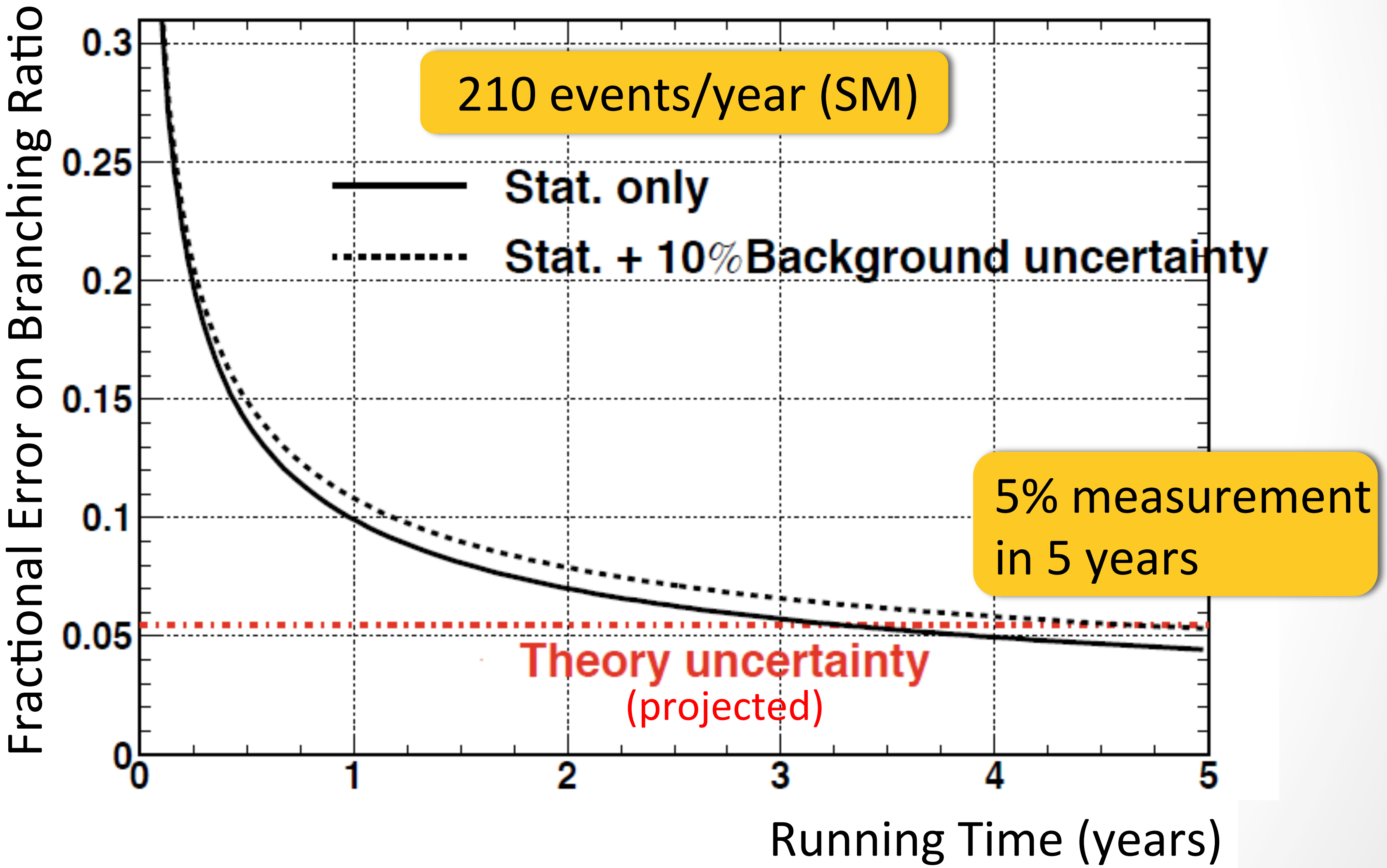
×10
relative to E949

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

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



Other Physics Topics

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

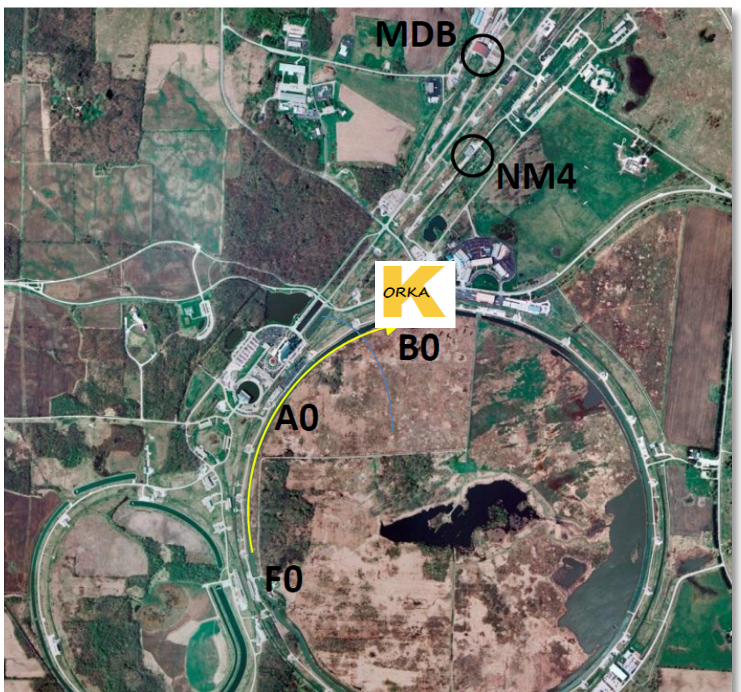
- $K^+ \to \pi^+ \gamma$ ^{TP}
- $K^+ \to \pi^+ \gamma\gamma$ ^{P}
- $K^+ \to \pi^+ \gamma\gamma\gamma$
- $K^+ \to \pi^+ \text{DP};\ \text{DP} \to e^+ e^-$
- K^+ lifetime
- $\mathcal{B}(K^+ \to \pi^+ \pi^0)/\mathcal{B}(K^+ \to \mu^+ \nu)$
- $K^+ \to \pi^+ \pi^0 e^+ e^-$
- $K^+ \to \pi^- \mu^+ \mu^+$ (LFV)
- $\pi^0 \to \text{nothing}$ ^{T,P}
- $\pi^0 \to \gamma \text{DP};\ \text{DP} \to e^+ e^-$
- $\pi^0 \to \gamma X$

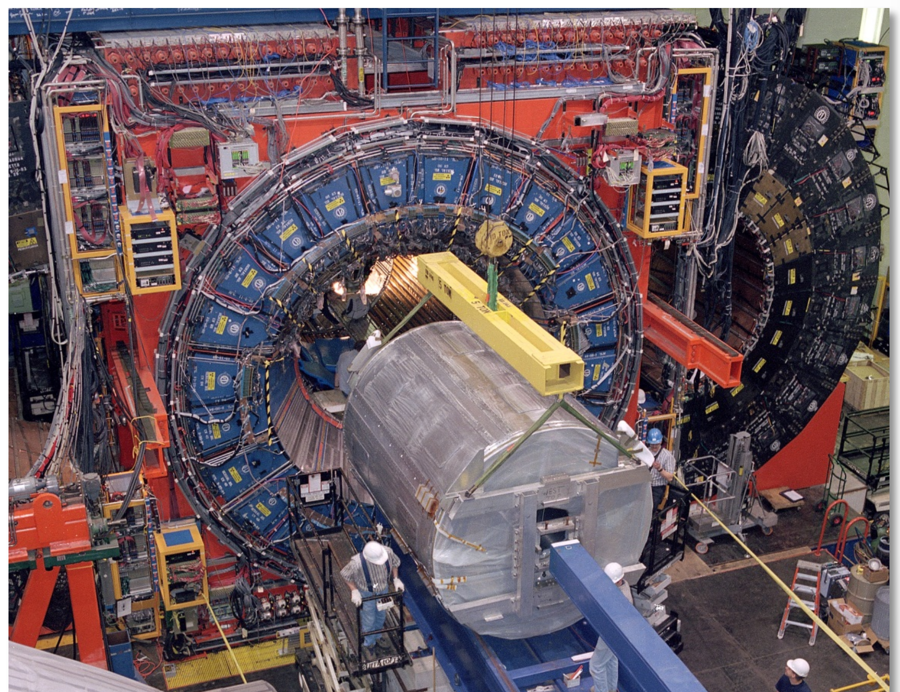
T: E787/949 thesis
P: E787/949 paper
"DP" = dark photon

E787/949: 42 publications, 26 theses
KTeV: 50 publications, 32 theses

Experiment Site: B0 (CDF)

- ORKA detector fits inside CDF solenoid
- Re-use CDF solenoid, cryogenics, infrastructure
- Requires new beam line from A0-B0
- CDF decommissioning in preparation for ORKA ongoing





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
- ORKA proposal:
  - http://www.fnal.gov/directorate/program_planning/Dec2011PACPublic/ORKA_Proposal.pdf

Flavor community and US funding agencies are enthusiastic about ORKA and working to find a way to make it possible.

Extra Slides

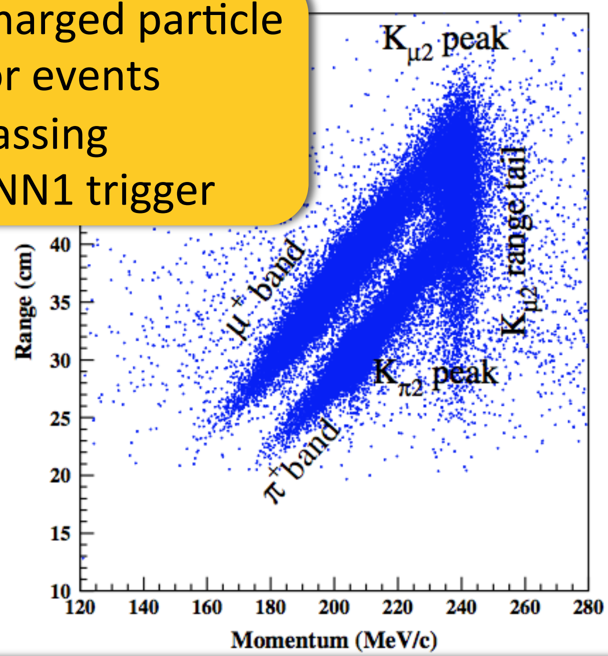
$\pi^+ \to \mu^+ \to e^+$ Acceptance

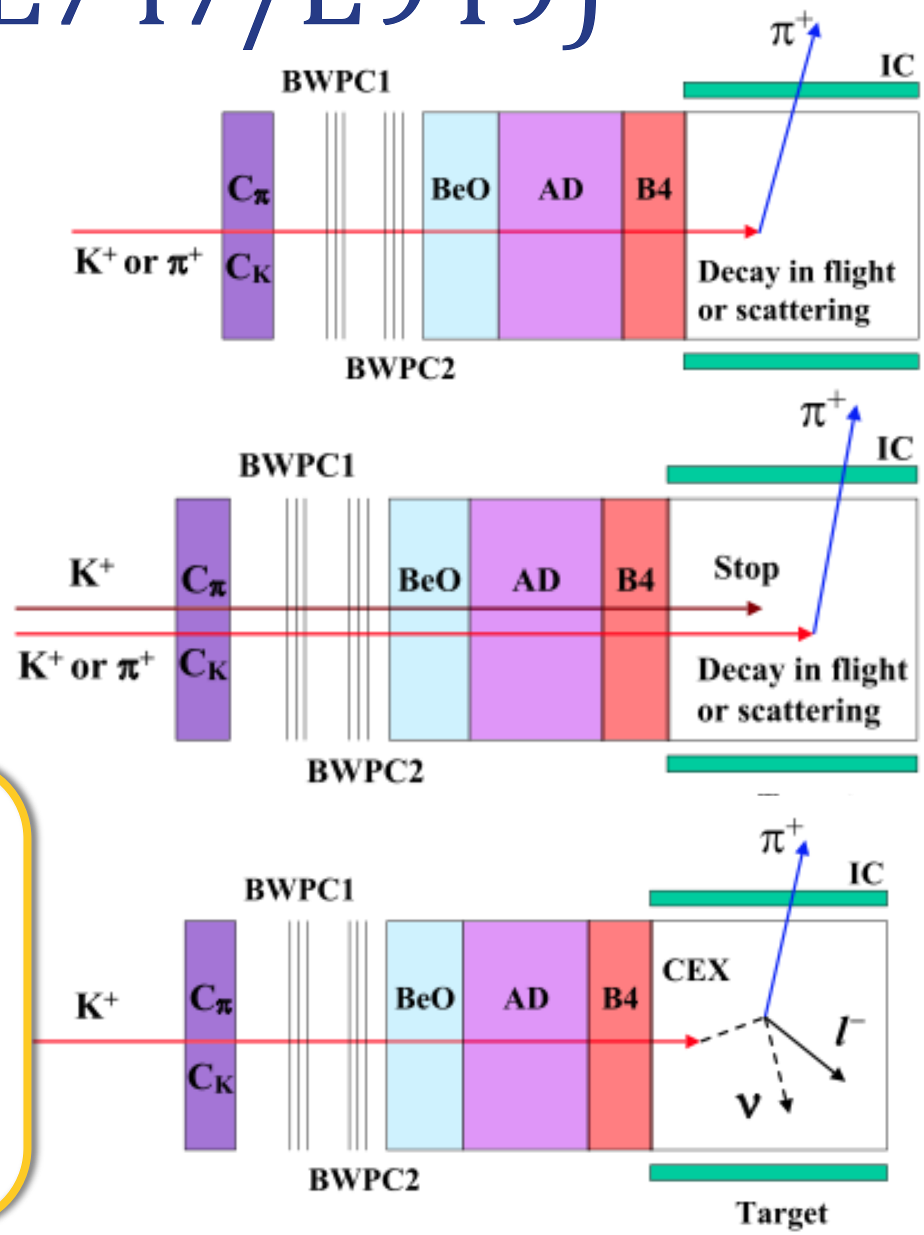
- E949 PNN1 $\pi^+ \to \mu^+ \to e^+$ acceptance: 35%
- Improvements to increase acceptance relative to E949:
  - Increase segmentation in range stack to reduce loss from accidental activity and improve π/μ particle ID
  - Increase scintillator light yield by using higher QE photo-detectors and/or better 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%**

Background (E747/E949)

Charged particle for events passing PNN1 trigger





Stopped kaon background:

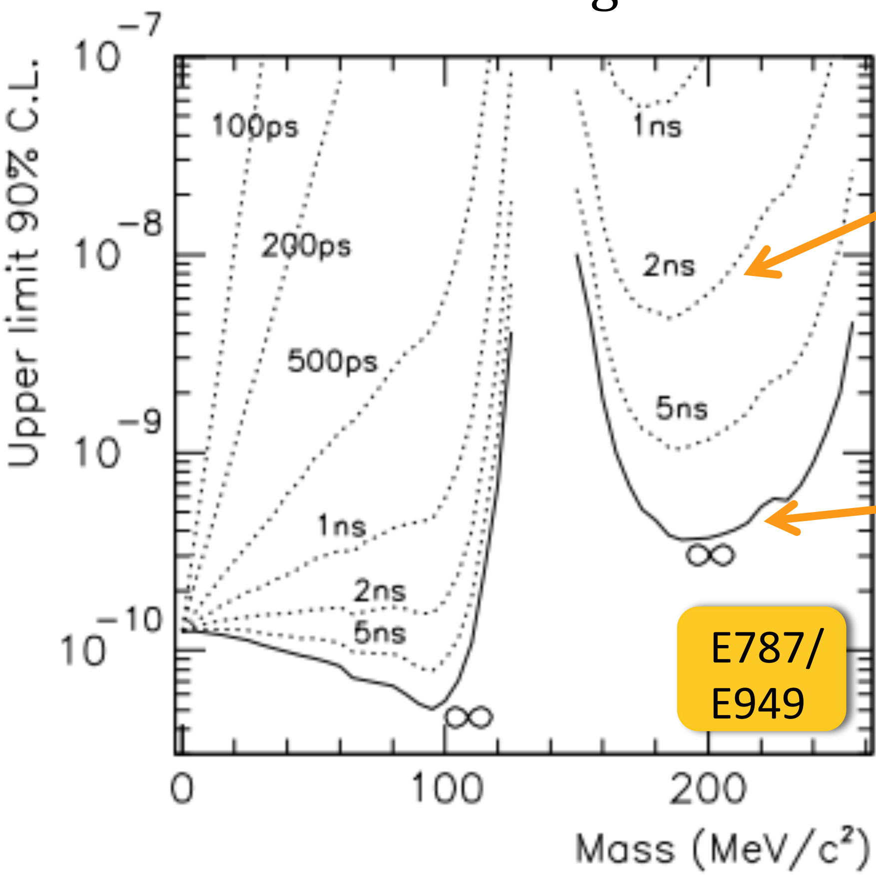
- $K^+ \rightarrow \pi^+\pi^0$
- $K^+ \rightarrow \mu^+\nu$
- μ^+ band
  - $K^+ \rightarrow \mu^+\nu\gamma$
  - $K^+ \rightarrow \mu^+\pi^0\nu$

Beam background:

- Single beam
- Double beam
- Charge exchange

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

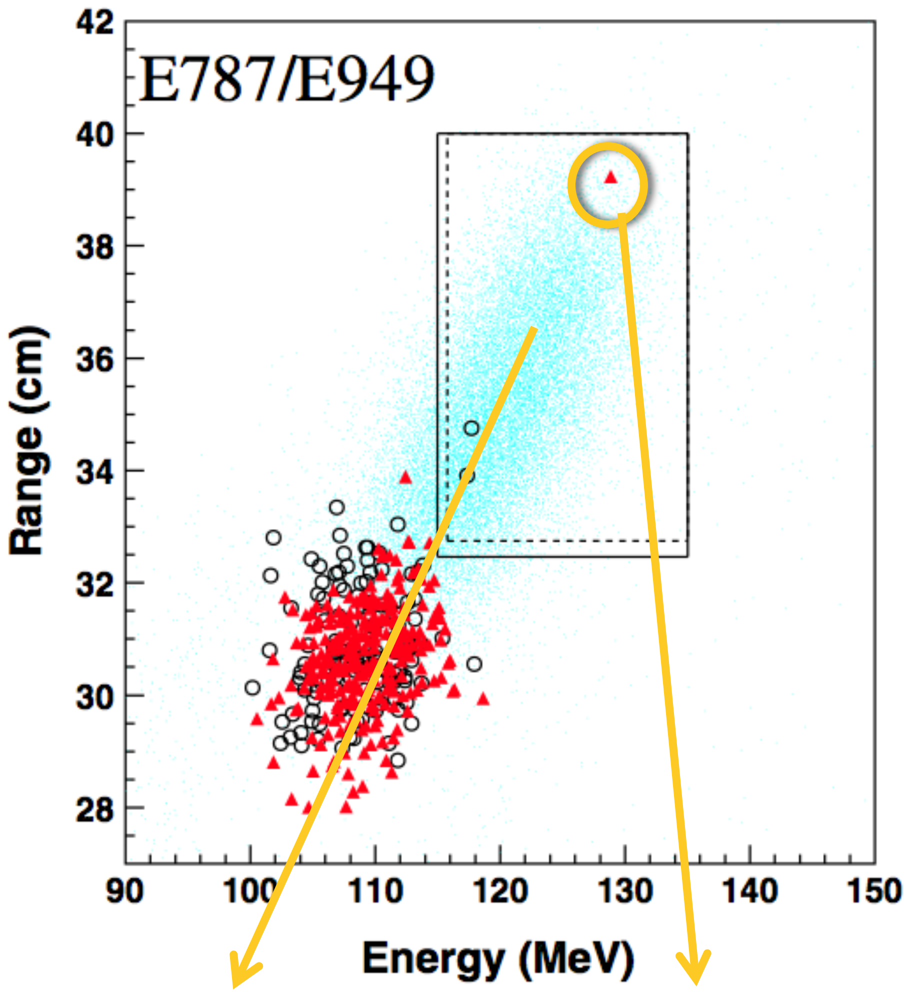
- Many models for X^0: familon, axion, light scalar pseudo-NG boson, sgoldstino, gauge boson corresponding to new U(1) symmetry, light dark matter …
- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is a background



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 of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (MC)

E949 signal event

- One event seen in E949 $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ PNN1 signal region is near kinematic endpoint
- Corresponds to a massless X^0
- Central value of measured $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ BR higher than SM expectation
- Event consistent with SM $K^+ \rightarrow \pi^+ \nu\bar{\nu}$, yet…
- Interesting mode for further study

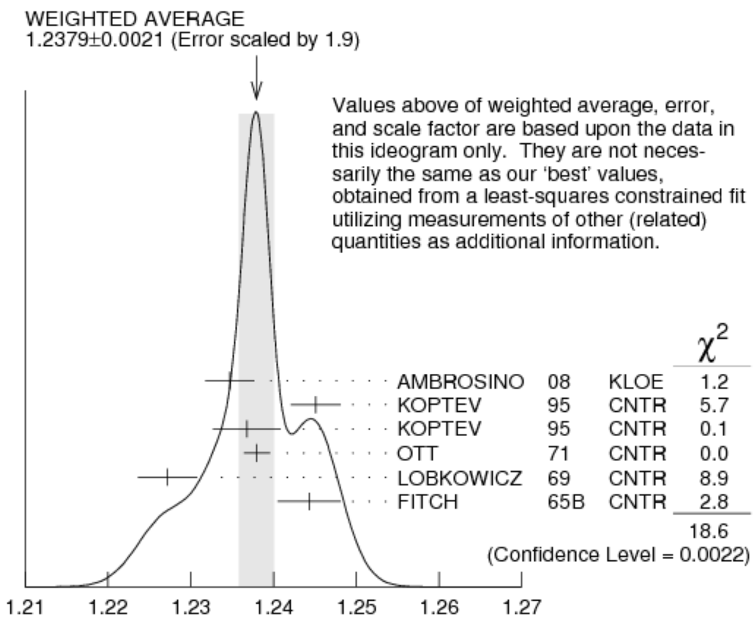
Precision Measurement of K*e*2/Kμ2

$$R_K \equiv \Gamma\left(K^+ \to e^+\nu\right) \Big/ \Gamma\left(K^+ \to \mu^+\nu\right)$$

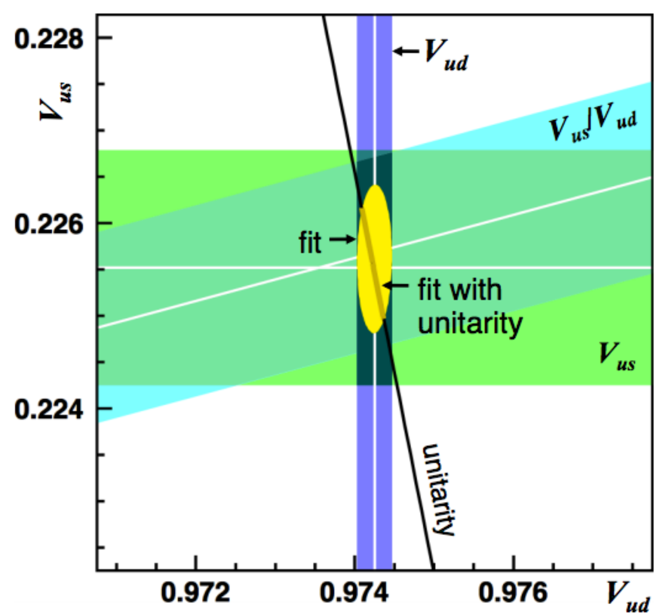
- $R_{SM} = (2.477 \pm 0.001) \times 10^{-5}$
  - Extremely precise because hadronic form factors cancel in ratio
  - Sensitive to new physics effects that do not share V-A structure of SM contribution
- $R = (2.488 \pm 0.010) \times 10^{-5}$ (NA62)
- $R = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$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

Fundamental K^+ Measurements

- K^+ lifetime
  - Not a major source of uncertainty for unitarity tests
  - Some discrepancies among experimental results in PDG
- $B(K^+ \to \pi^+\pi^0)/B(K^+ \to \mu^+\nu)$
  - Contributes to fit for $|V_{us}/V_{ud}|$
  - Expect improvements in lattice calculations so that experimental errors may soon be dominant



x 10^{-8} s



M. Moulson, CIPANP 2012

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

NA62

- 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

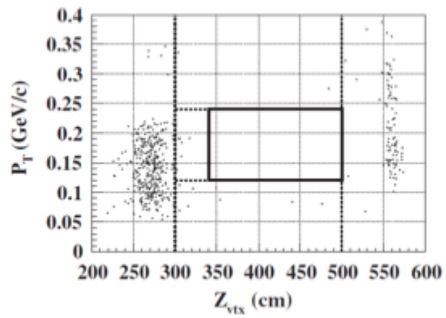
A very rich program in the near future

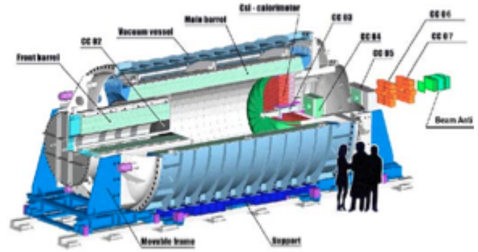
CIPANP 2012 Monica Pepe - INFN Perugia 22

KOTO

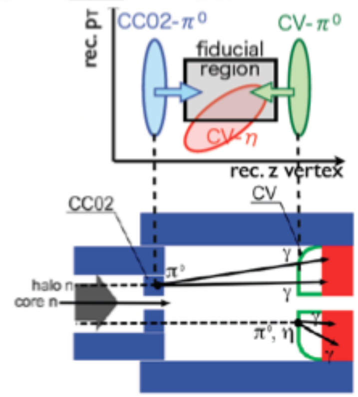
Pilot E391a at KEK(2001-2005) and the challenges

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