Probing New Physics with ORKA

Elizabeth Worcester (BNL) for the ORKA collaboration

Snowmass on the Mississippi

August 2, 2013

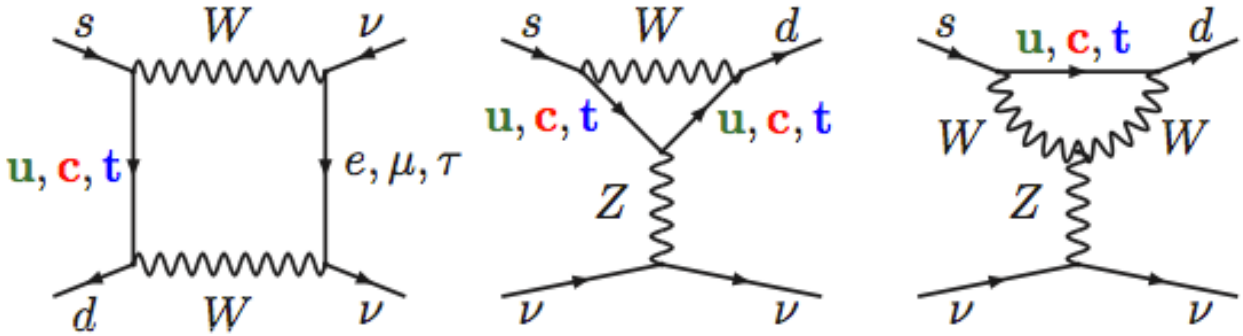
Photo: Life of Sea blogspot

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
- Detector R&D and site preparation underway

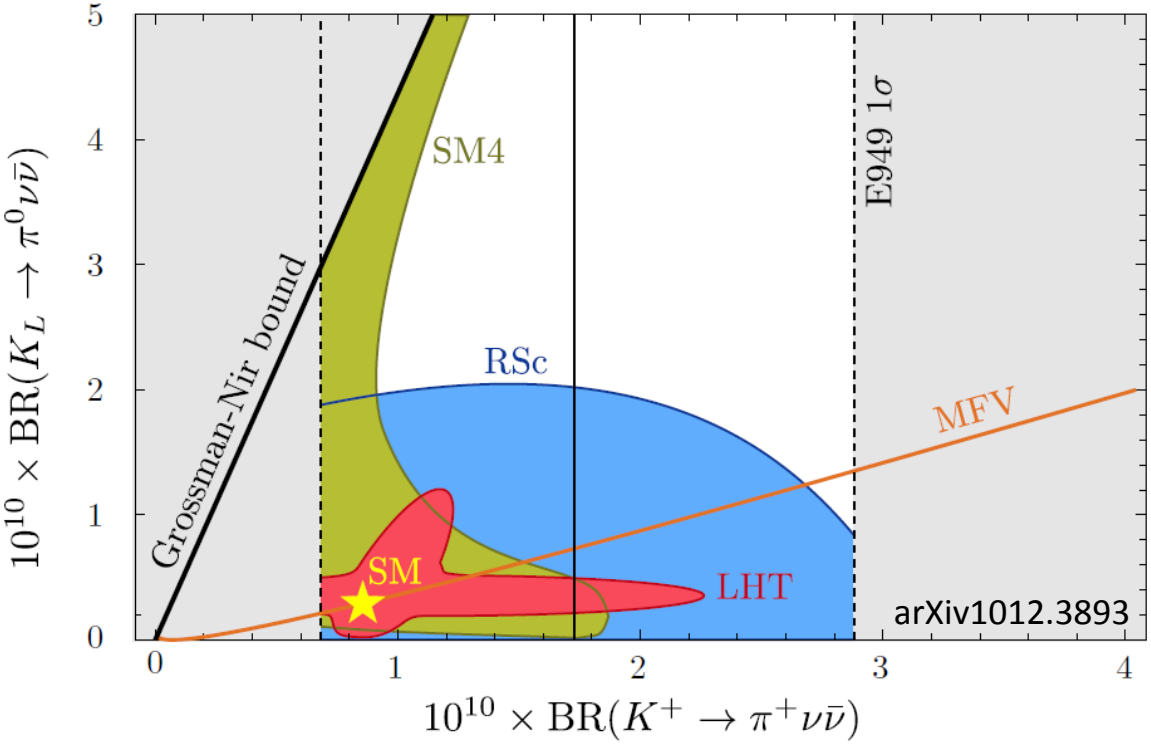
$K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

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



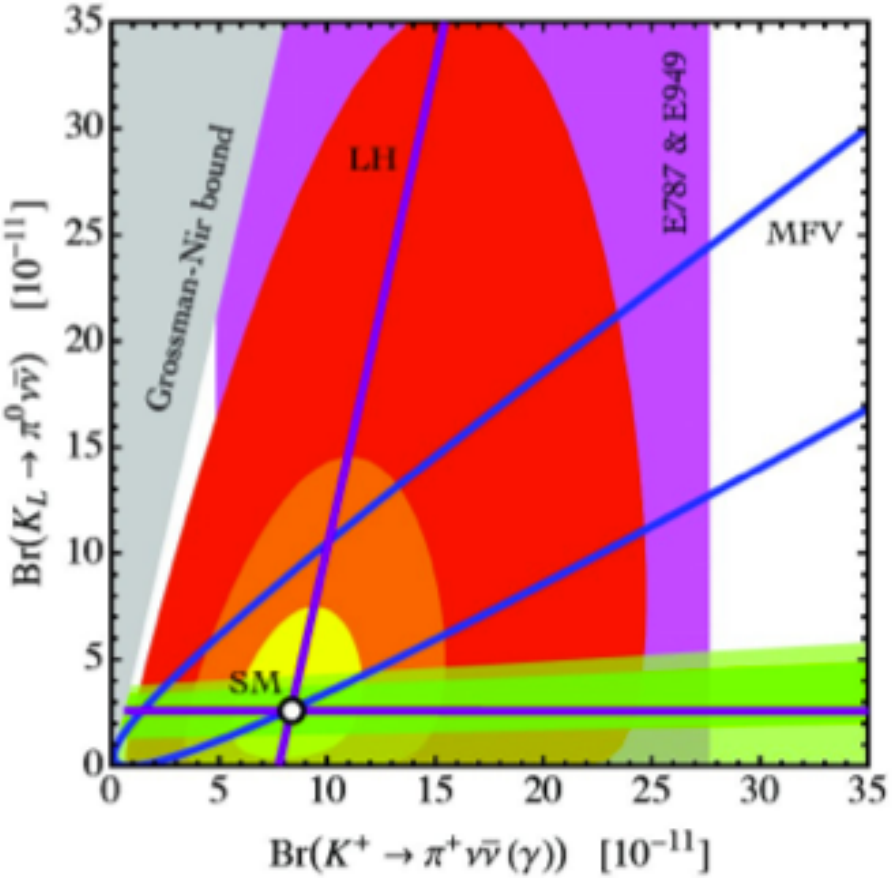
- A single effective operator: $\left(\bar{s}_L \gamma^\mu d_L\right)\left(\bar{\nu}_L \gamma_\mu \nu_L\right)$
- Dominated by top quark
- Hadronic matrix element shared with $K^+ \to \pi^0 e^+ \nu_e$
- Dominant uncertainty from CKM matrix elements
  - Expect prediction to improve to ~5%

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.

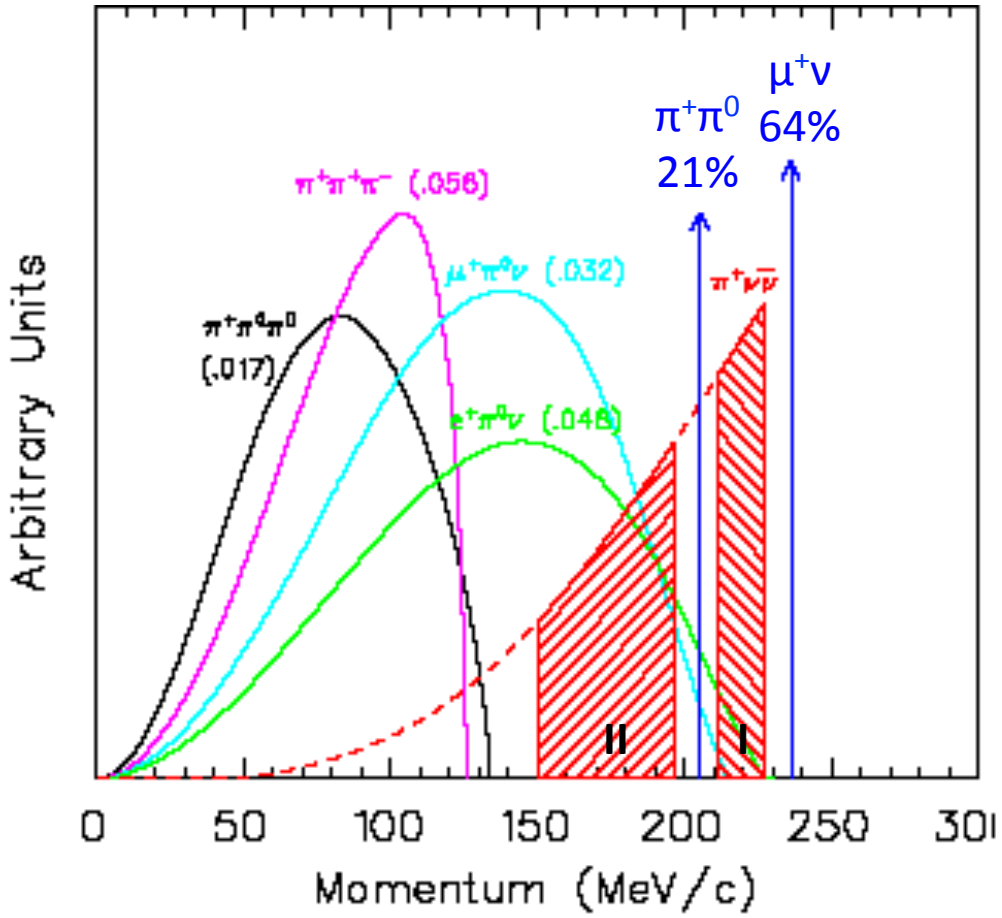
Constraint on New Physics



- Flavor-changing Z-penguin operators are leading effect in many BSM models
- When Z-penguins dominate, experimental value of ε'/ε constrains possible enhancements to $K_L \to \pi^0 \nu\bar{\nu}$ branching ratio
- Four-fermion operators not subject to this constraint

More details:
http://indico.cern.ch/getFile.py/access?contribId=5&resId=0&materialId=slides&confId=65927

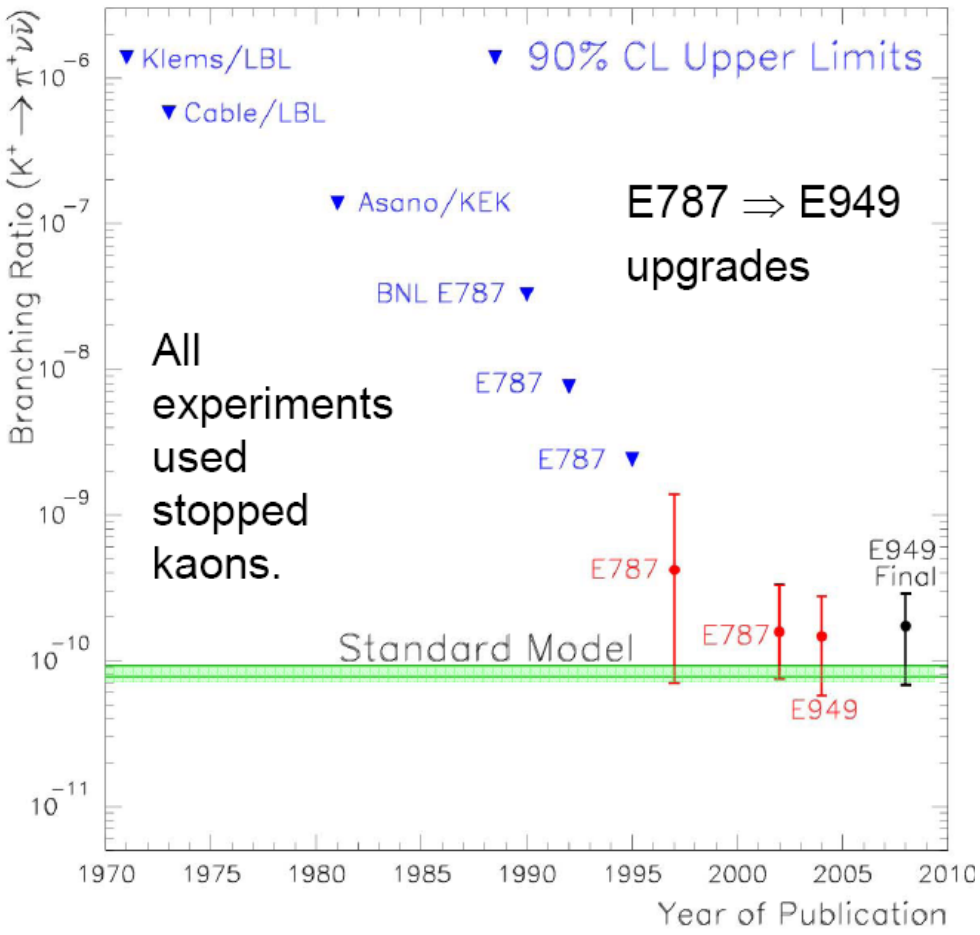
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ Measurement

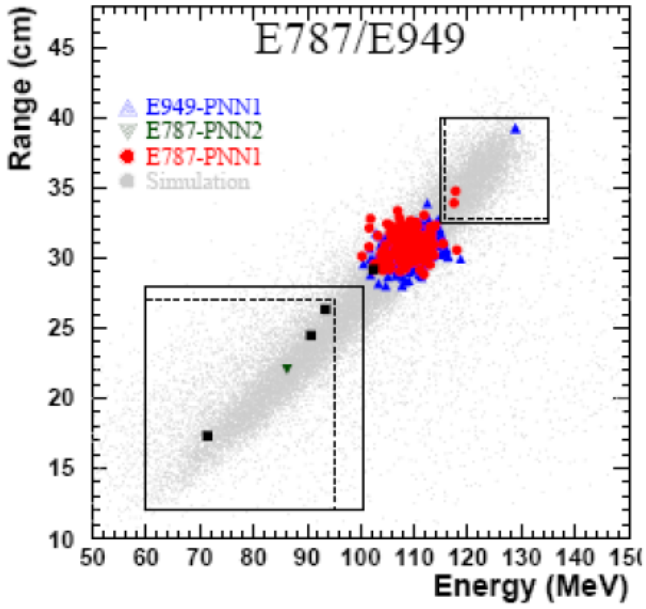


Momentum spectra of charged particles from K^+ decays in the rest frame

- 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 $\pi/\mu/e$ particle ID $> 10^6$
- Requires π^0 inefficiency $< 10^{-6}$

Experimental History





E787/E949 Final (7 candidate events observed):

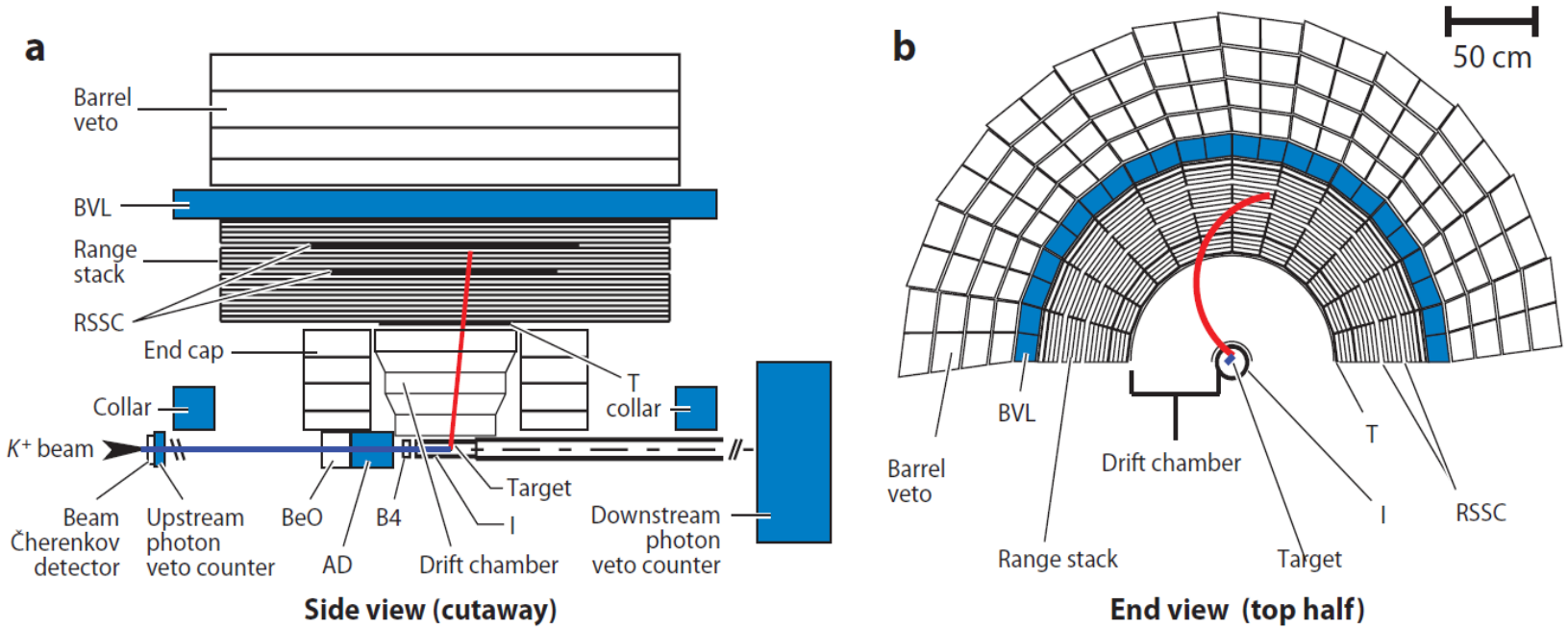
$$B\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$$

Standard Model:

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

BNL E787/E949 Stopped-Kaon Technique

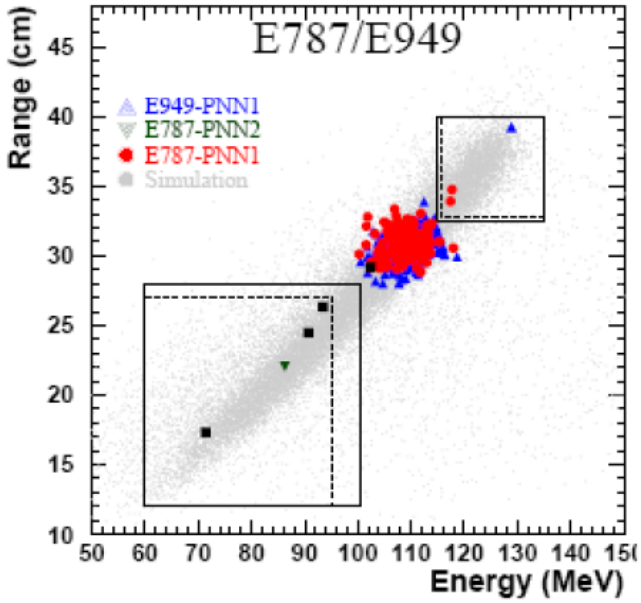
Measure everything!

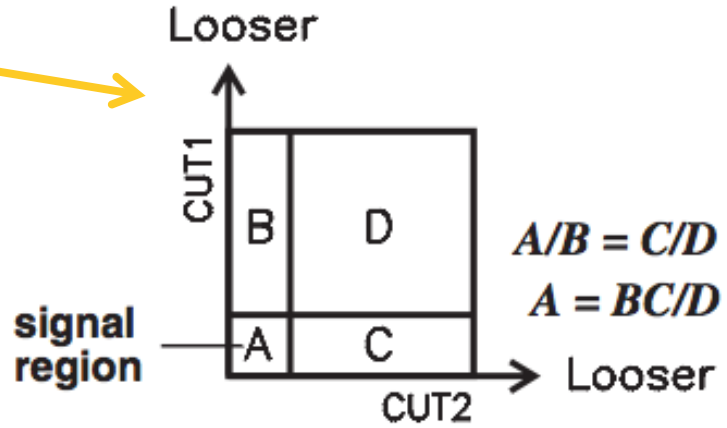


- K^+ detected and decays at rest in the stopping target
- Decay π^+ track momentum analyzed in drift chamber
- Decay π^+ stops in range stack, range and energy are measured
- Range stack straw chamber provides additional π^+ position measurement in range stack
- Barrel veto + End caps + Collar provide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

Analysis Strategy (E747/E949)

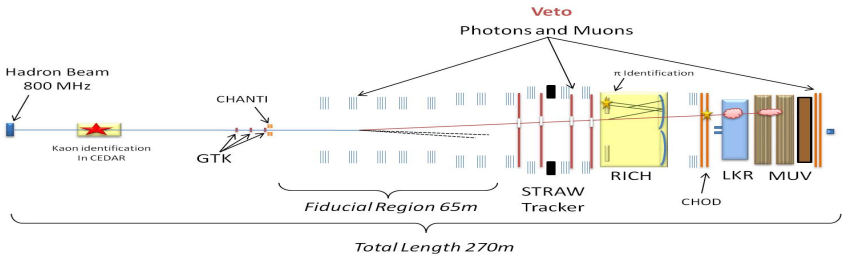
- Measure everything!
- Separate analyses for PNN1 and PNN2 regions
- Blind analysis
  - Blinded signal box
  - Final background estimates obtained from different samples than used to determine selection criteria (1/3 and 2/3 samples)
- Bifurcation method to determine background from **data**
  - Use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





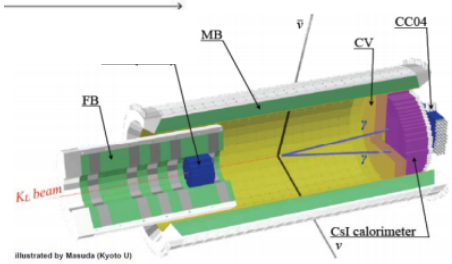
Worldwide Effort

- 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" ($K_L \to \pi^0 \nu\bar{\nu}$)

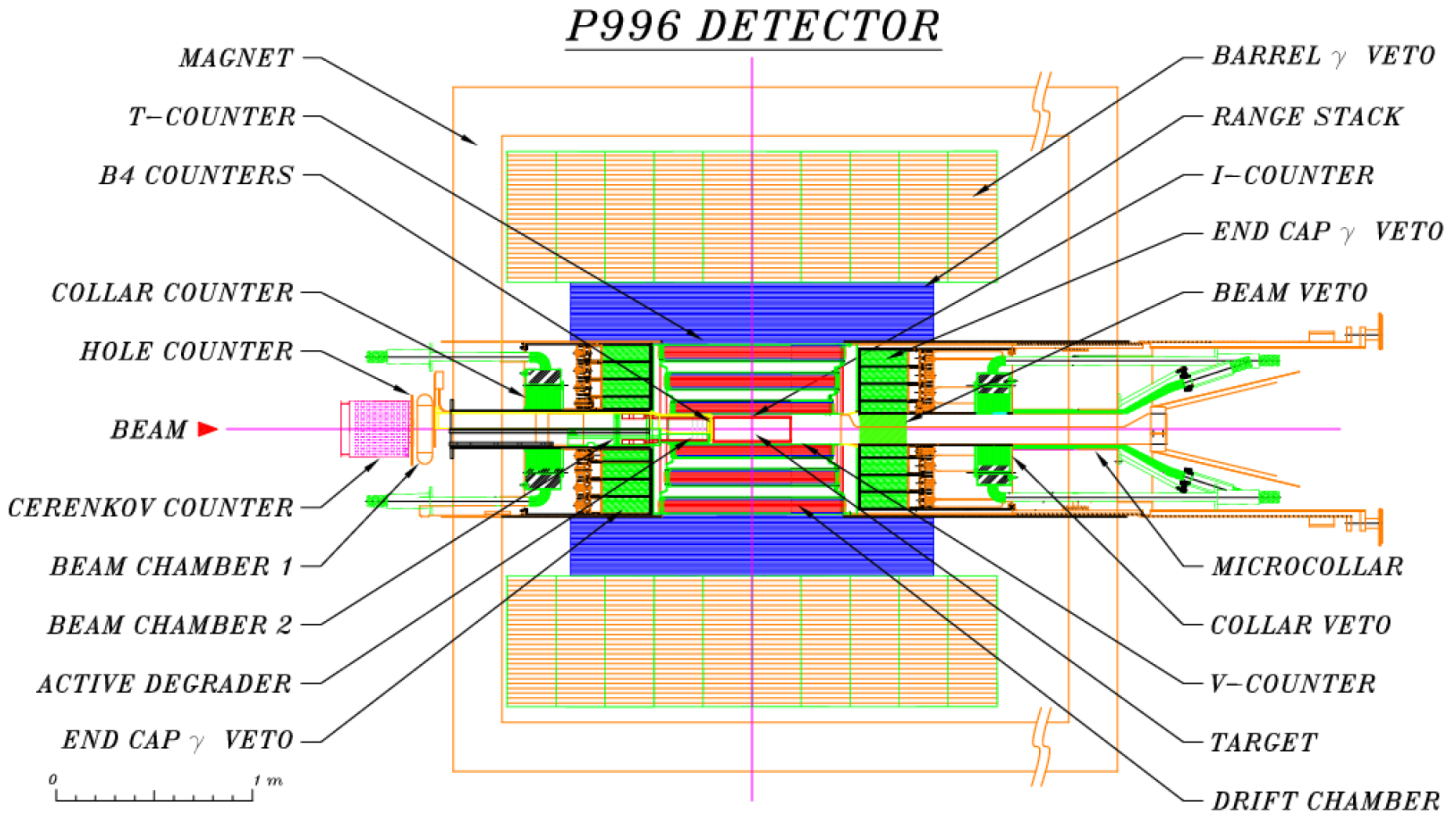


- Pencil beam decay-in-flight experiment
- Improved J-PARC beam line
- 2nd generation detector building on E391 at KEK
- Re-using KTeV CsI crystals to improve calorimeter (better resolution and veto power)
- Expect ~3 $K_L \to \pi^0 \nu\bar{\nu}$ events (SM) with S/B ~ 1

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

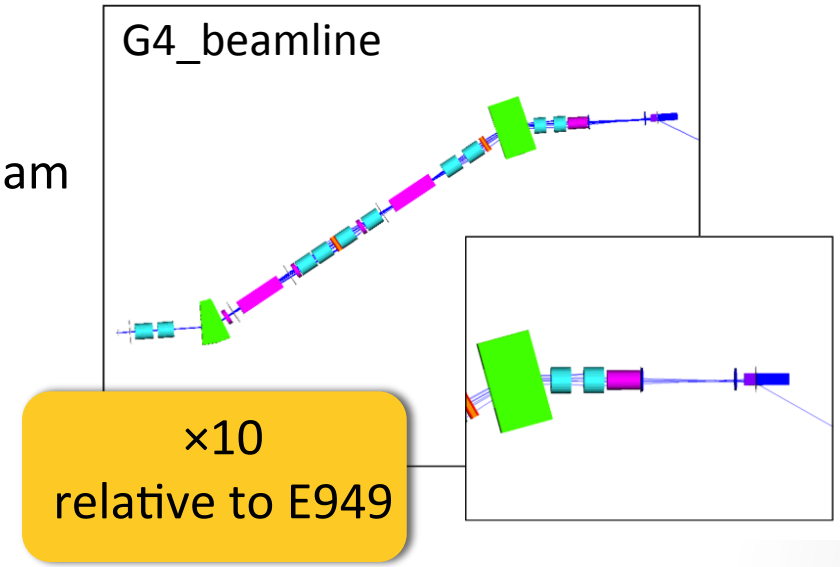
ORKA:
a 4th generation detector



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**)

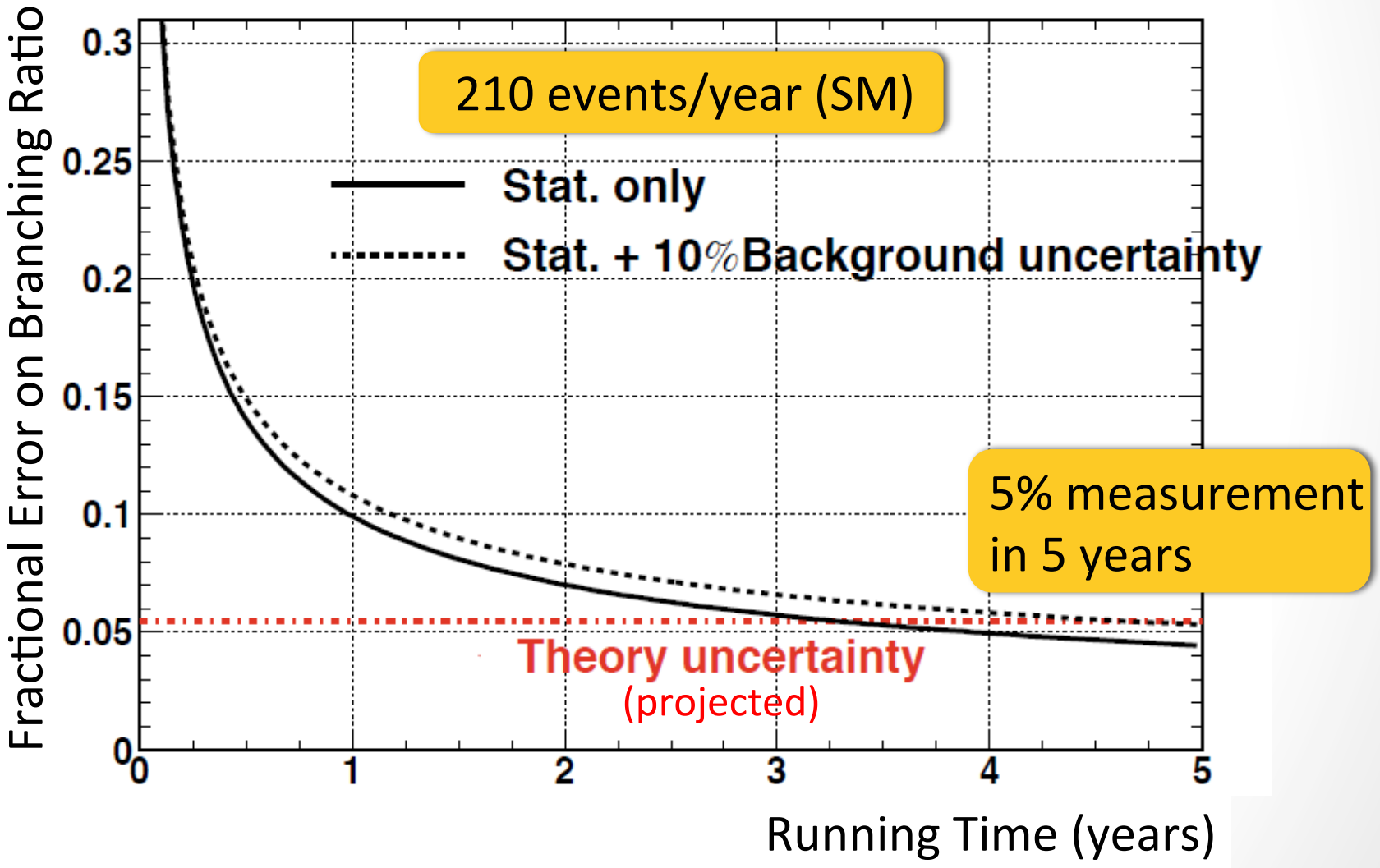


Sensitivity Improvements: Acceptance

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 ($R_{\rm acc}$)	$11.28^{+3.25}_{-2.22}$

×11 relative to E949

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



ORKA Physics Topics

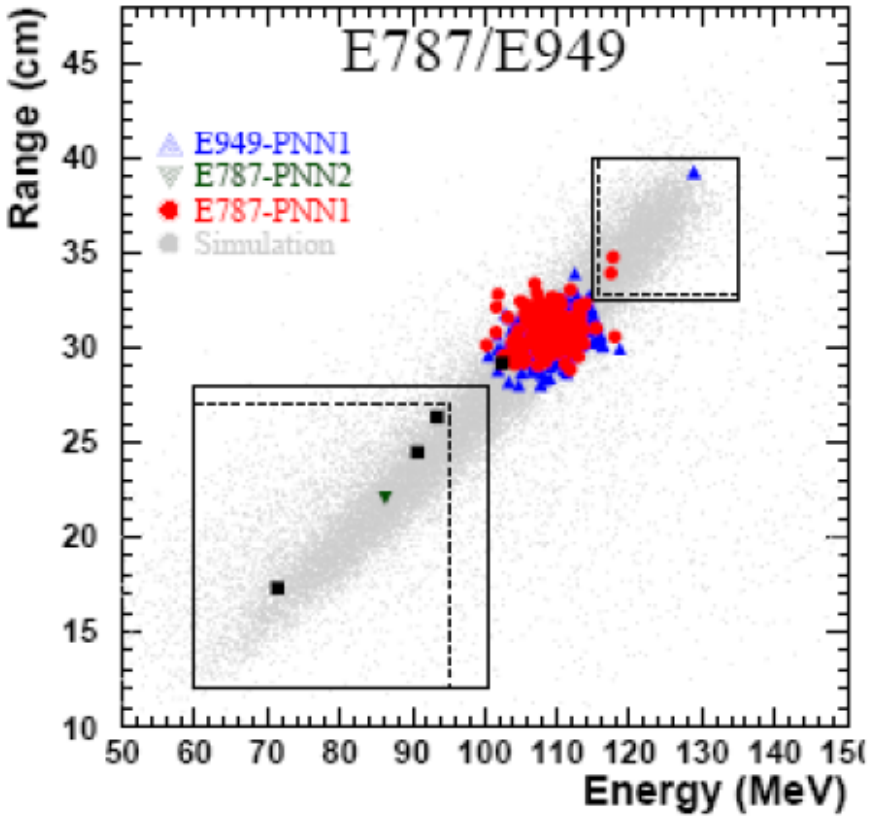
- $K^+ \to \pi^+ +$ missing energy
  - $K^+ \to \pi^+ \nu\bar{\nu}(1)$ ^{T,P}
  - $K^+ \to \pi^+ \nu\bar{\nu}(2)$ ^{T,P}
  - $K^+ \to \pi^+ \nu\bar{\nu}\gamma$
  - $K^+ \to \pi^+ X$ ^{P}
  - $K^+ \to \pi^+ \tilde{\chi}_0 \tilde{\chi}_0$(FF) ^{P}
- $K^+ \to \pi^+\pi^0 +$ missing energy
  - $K^+ \to \pi^+\pi^0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

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

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

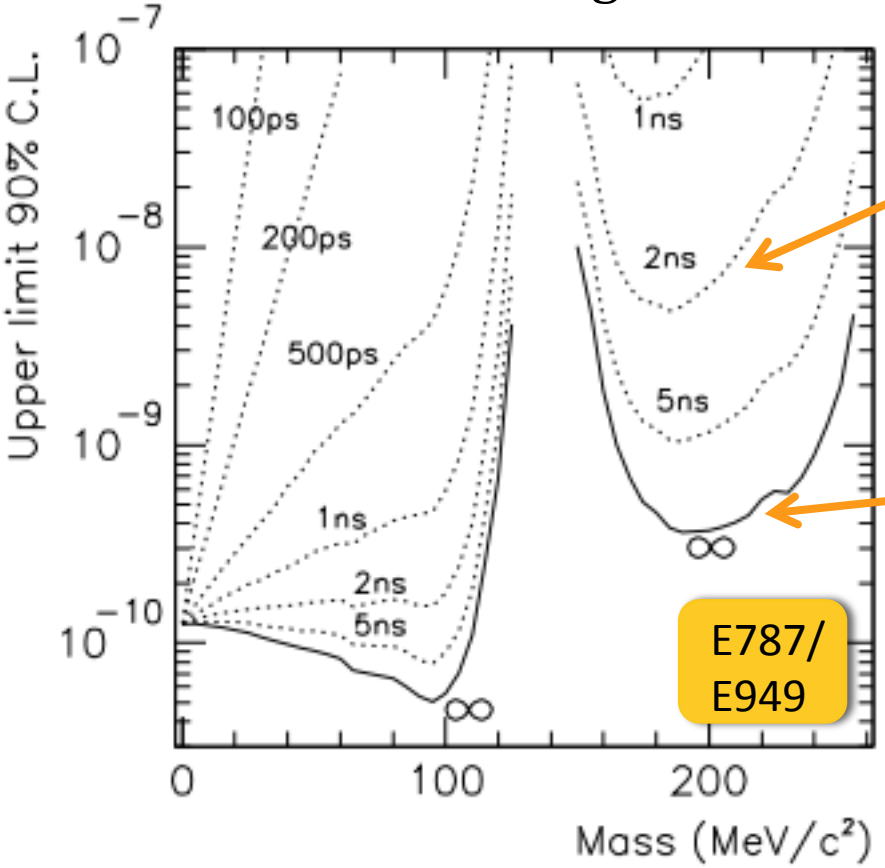
$K^+ \to \pi^+ \nu\bar{\nu}$ PNN1/PNN2 ratio

- PNN1 and PNN2 kinematic regions analyzed separately
- Different background and acceptance issues
- If ratio of BRs measured in the two regions differs from SM, could indicate new physics
  - ex: unparticles



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

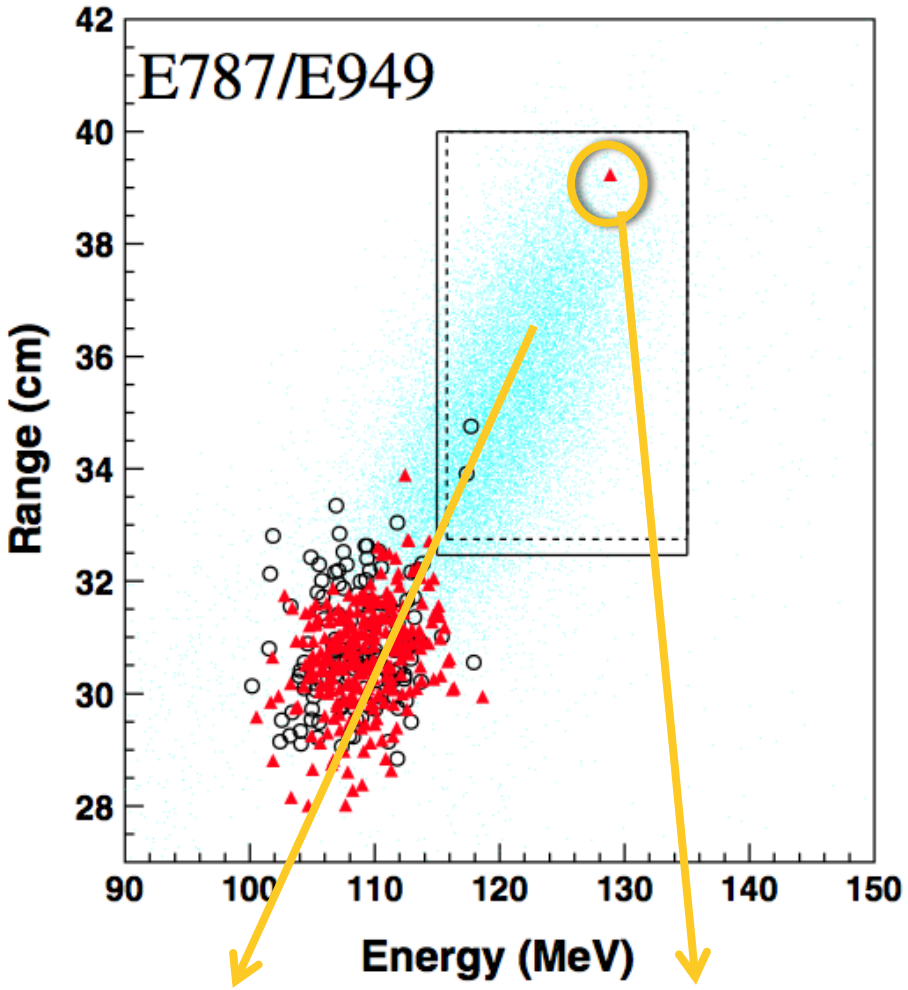
- Many models for X^0: familon, axion, light scalar pseudo-NG boson, sgoldstino, gauge boson corresponding to new U(1) symmetry, light dark matter …
- $K^+ \to \pi^+ \nu\bar{\nu}$ is a background



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

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

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



Expected distribution of $K^+ \to \pi^+ \nu\bar{\nu}$ (MC)

E949 signal event

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

$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$

- Ke4 BR allows firm SM prediction (1-2 × 10^{-14})
- New physics from axial-vector in addition to vector currents
- E787: B($K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$) < 4.3 × 10^{-5}
  - Limited by trigger bandwidth and detector resolution
- Expect × 1000 improvement at ORKA

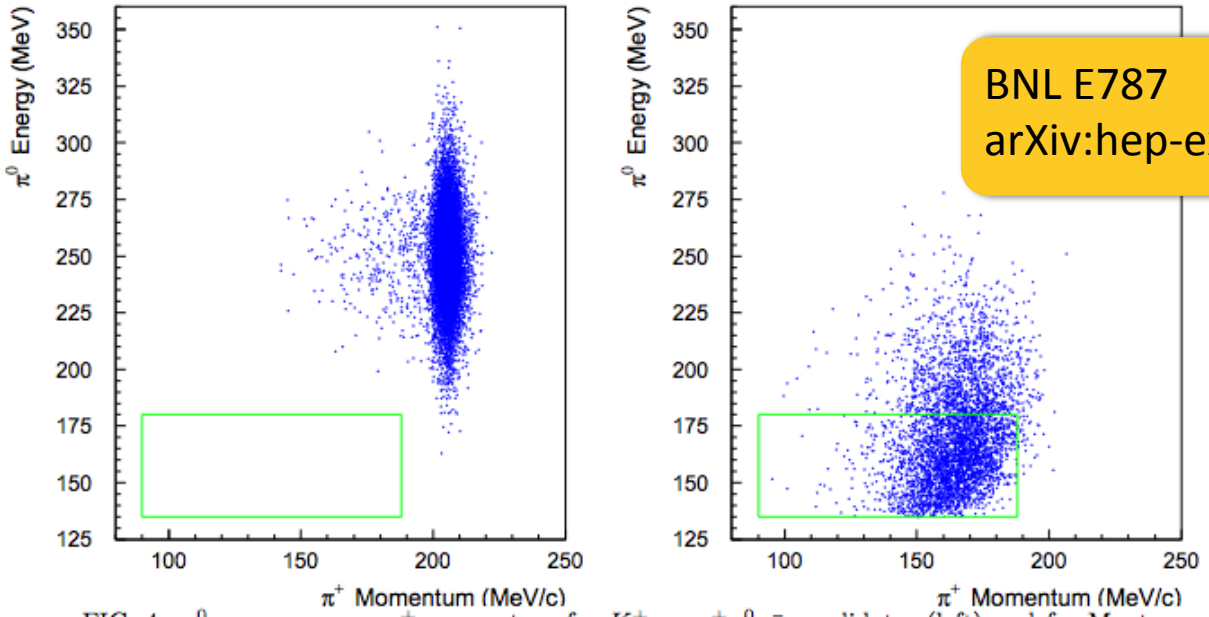
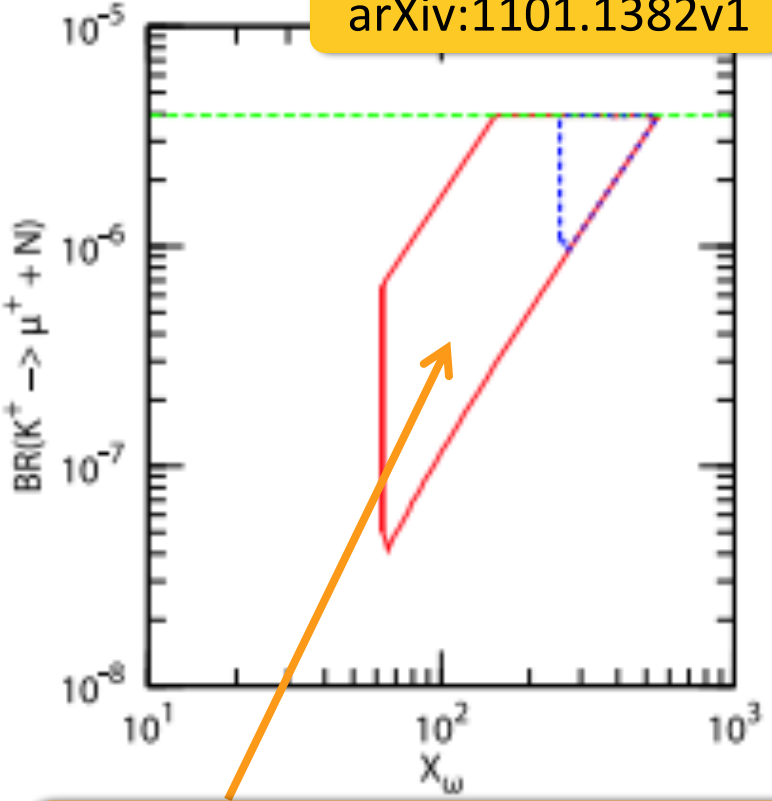


FIG. 4. π^0 energy versus π^+ momentum for $K^+ \to \pi^+\pi^0\nu\bar{\nu}$ candidates (left) and for Monte Carlo signal events (right). Box indicates the signal acceptance region. $K_{\pi 2}$ events cluster at the upper right in the top plot.

BNL E787
arXiv:hep-ex/0009055v1

Heavy Neutrinos: $K^+ \to \mu^+ X^0$

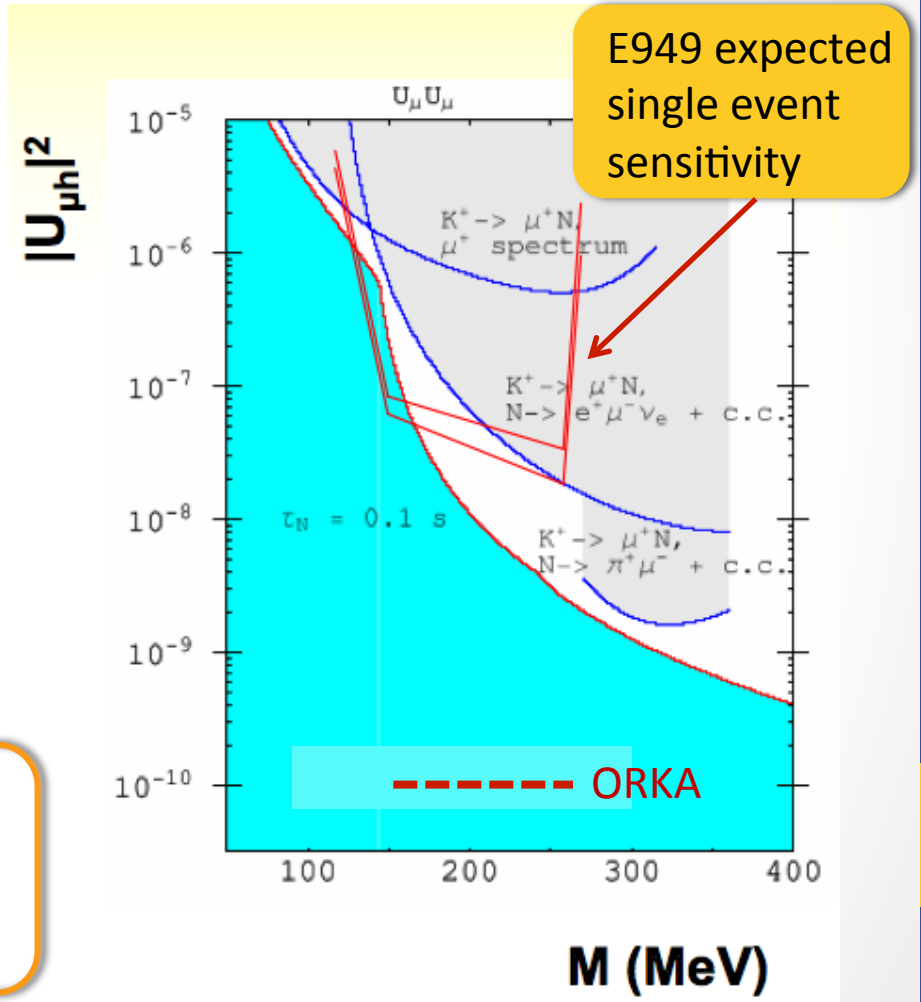
arXiv:1101.1382v1



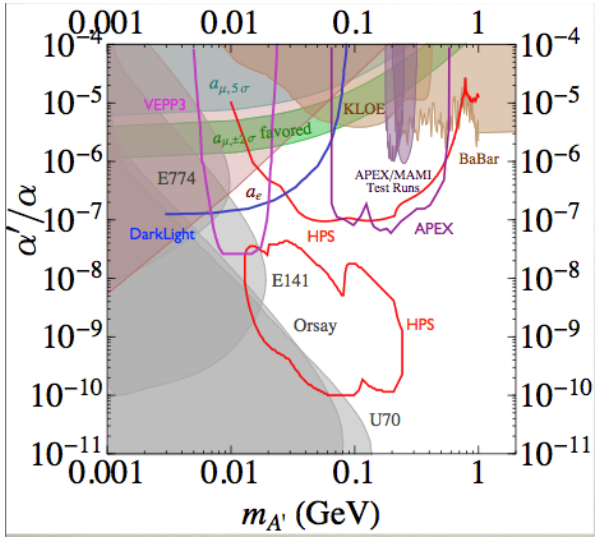
Ex: Allowed BR($K^+ \to \mu^+ N_{2,3}$) for NH in νMSM, M_N=120 MeV: ~4×10^{-8} to ~4×10^{-6}

Ongoing E949 analysis (A. Shaykhiev, INR)

E949 expected single event sensitivity



Heavy Photons



- A´: same interactions as SM photon with reduced coupling
- Dark matter candidate
- Multiple dedicated experiments

ORKA Search

- $K^+ \rightarrow \pi^+ A' \rightarrow \pi^+ e^+ e^-$ and $\pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$
- Signal would appear as resonance above continuum in e^+e^- invariant mass distribution
- Electron resolution and background from conversion could be a problem
- No ORKA sensitivity estimate yet

Precision Measurement of Ke2/Kμ2

$$R_K \equiv \frac{\Gamma\left(K^+ \to e^+\nu\right)}{\Gamma\left(K^+ \to \mu^+\nu\right)}$$

- $R_{SM} = (2.477 \pm 0.001) \times 10^{-5}$
  - 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

ORKA Sensitivity Summary

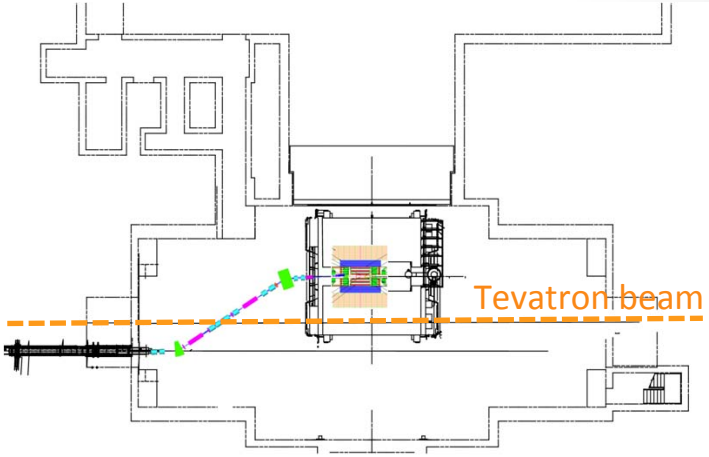
(preliminary estimate of sensitivity)

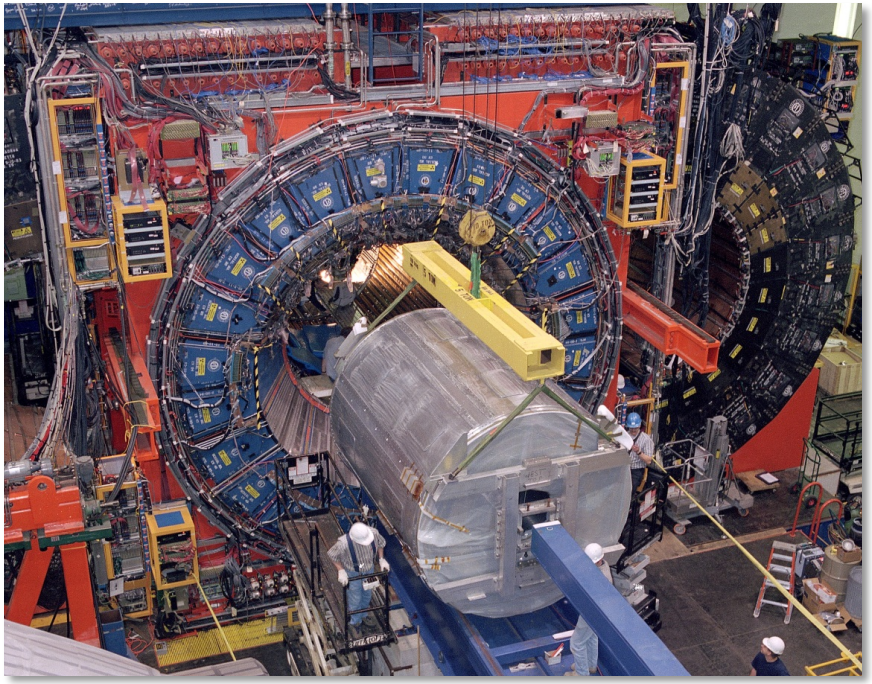
Process	Current	ORKA	Comment
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events	
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$	$K^+ \to \pi^+ \nu\bar{\nu}$ is a background
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+ \pi^0 X^0$	$<\sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$	
$K^+ \to \mu^+ \nu_{heavy}$	$< 2 \times 10^{-8} - 1 \times 10^{-7}$	$< 1 \times 10^{-10}$	150 MeV $< m_\nu <$ 270 MeV
$K^+ \to \mu^+ \nu_\mu \nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$	
$K^+ \to \pi^+ \gamma\gamma$	293 events	200,000 events	
$\Gamma(Ke2)/\Gamma(K\mu 2)$	$\pm 0.5\%$	$\pm 0.1\%$	
$\pi^0 \to \nu\bar{\nu}$	$< 2.7 \times 10^{-7}$	$< 5 \times 10^{-8}$ to $< 4 \times 10^{-9}$	depending on tech nique
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$	

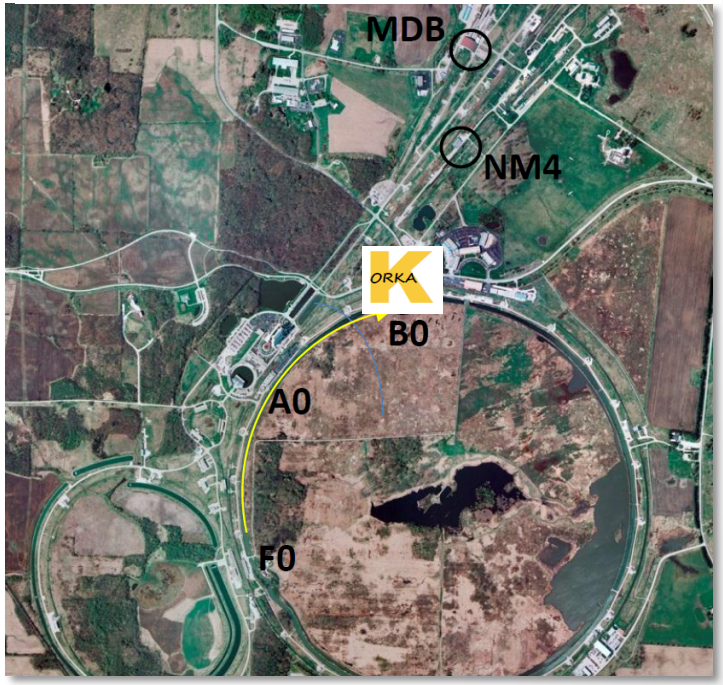
- ORKA, while highly optimized for $K^+ \to \pi^+ \nu\bar{\nu}$, is capable of making important, precise measurements of many other physics processes.
  - Real discovery potential
  - Training ground for next generation of US flavor physicists

Experiment Site: B0 (CDF)

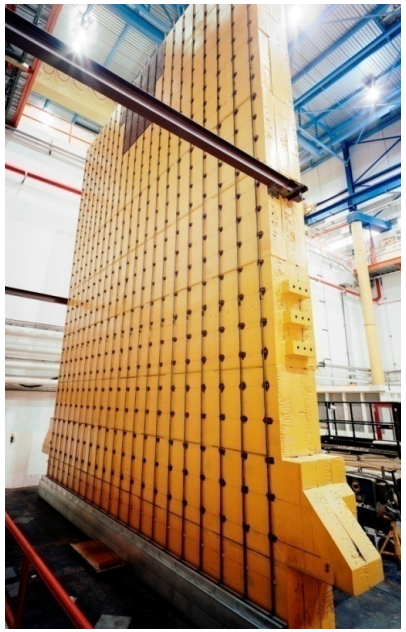
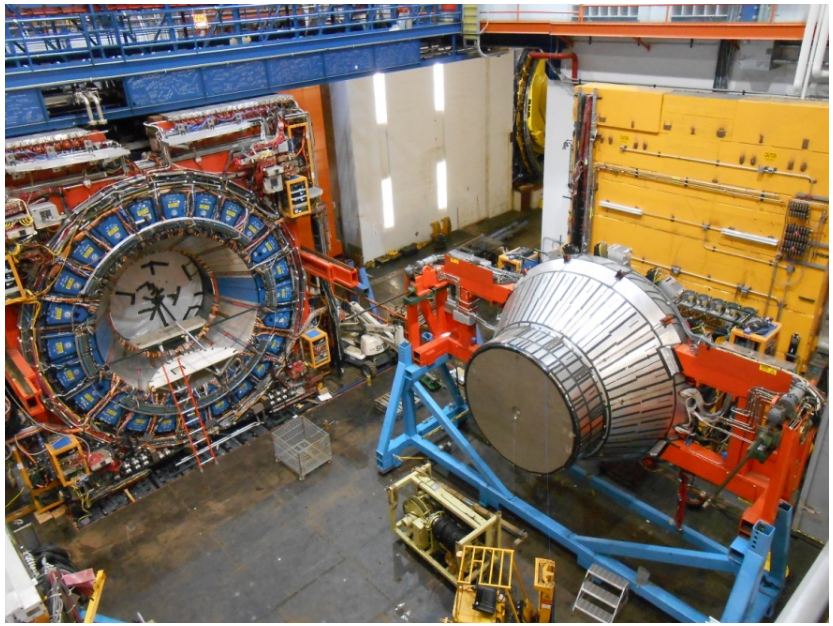
- ORKA detector fits inside CDF solenoid
- Re-use CDF solenoid, cryogenics, infrastructure
- Requires new beam line from A0-B0





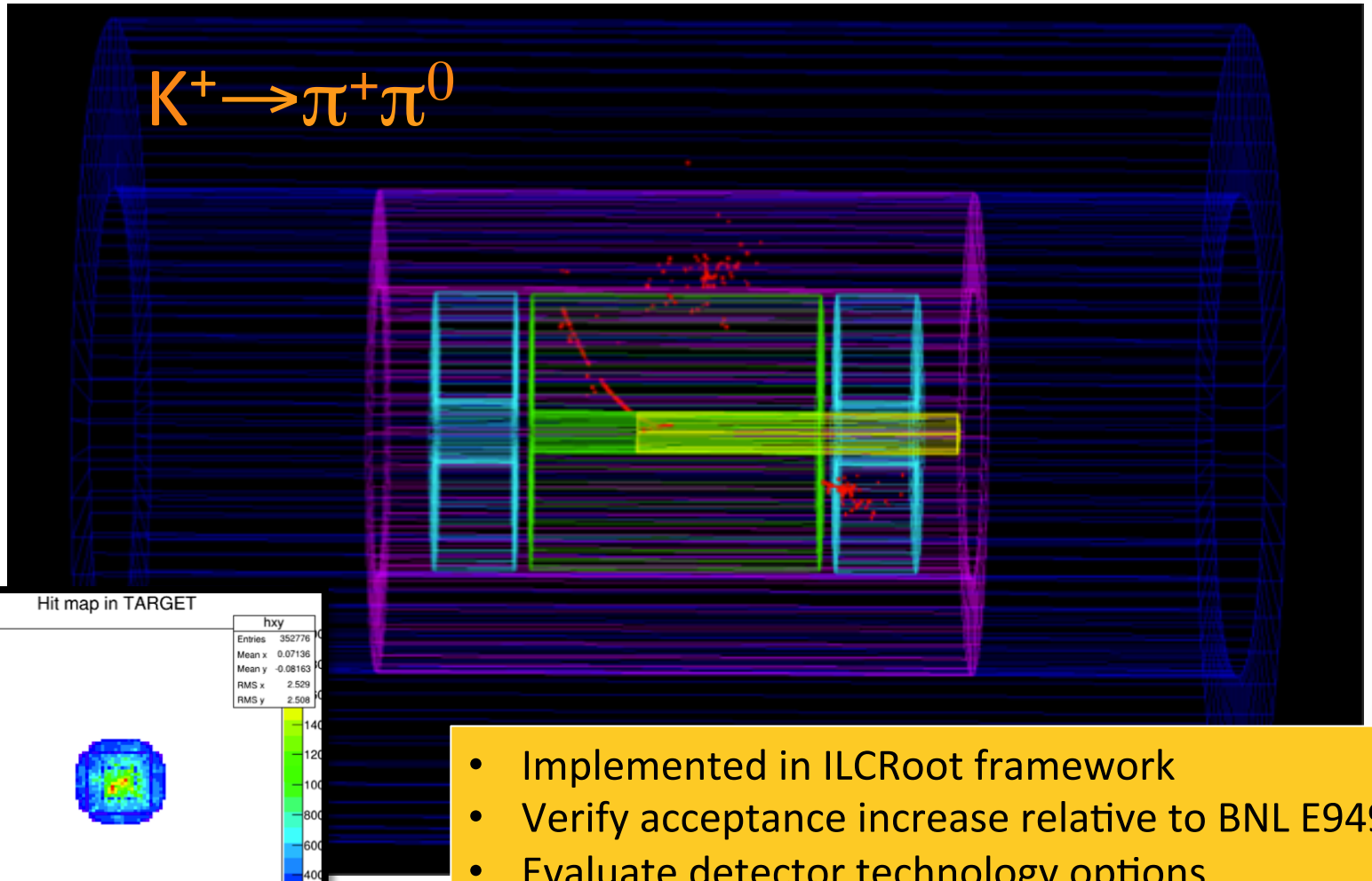


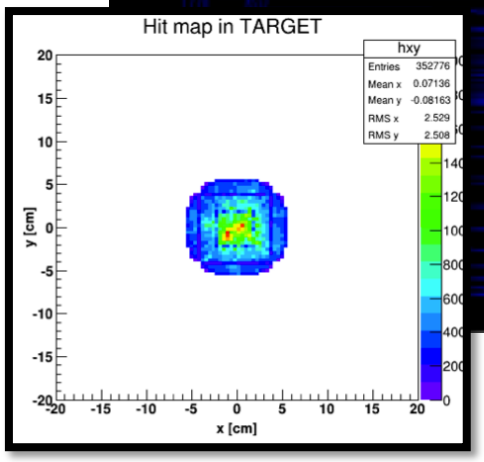
ORKA Site Preparation

- Central detector and muon walls now in assembly area
- Removal of cables, electronics, and PMTs almost complete
- Tracker removal planned for this month
- Outer muon system demolition ongoing

ORKA Simulations



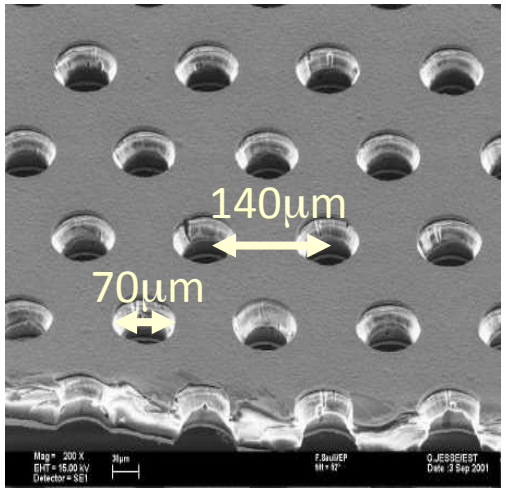


- Implemented in ILCRoot framework
- Verify acceptance increase relative to BNL E949
- Evaluate detector technology options
- Optimize detector design

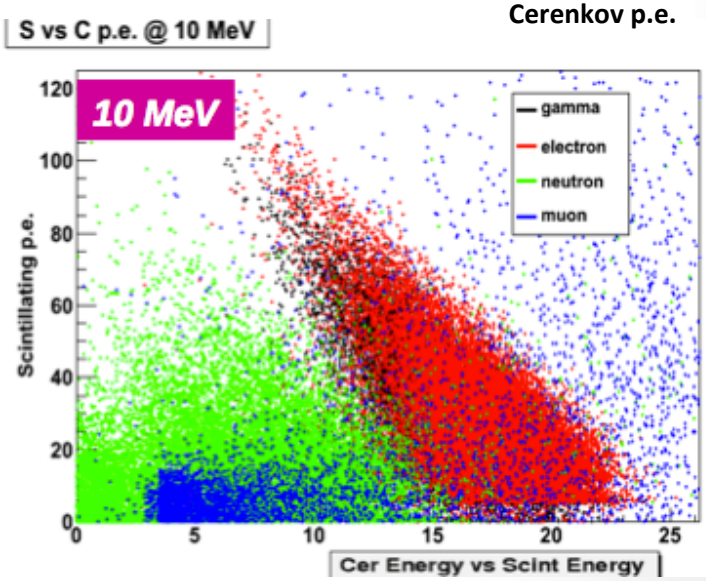
ORKA Detector R&D

- In progress: see S. Kettell's talk in this session
- R&D topics
  - SiPM readout
  - Front-end electronics for SiPMs
  - Trigger-less DAQ
  - ADRIANO fully-active calorimeter
  - GEM tracking
  - Detector optimization
  - K^+ beam line design

GEM foil:



Cerenkov p.e.



ORKA Cost & Schedule

- System-by-system review of cost estimate conducted by ORKA collaboration in 2012-2013
  - Input from external experts
  - Much more detailed understanding of expected costs relative to 2011 proposal
- ORKA total project cost: ~$50M
- Beam line costs covered by FNAL AIPs
  - AIP: Accelerator Improvement Project
  - Similar strategy to muon campus
- FNAL Stage 1 Approval: 2011
- R&D to optimize detector design underway
- Working with DOE to determine best timing for CD-0

ORKA Summary

- High precision measurement of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at FNAL MI
- Expect ~1000 events and 5% precision on BR measurement with 5 years of data
- Significant measurements with real potential for discovery of new physics
- 4^{th} generation detector using a combination of known techniques and modern detector technology
- 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

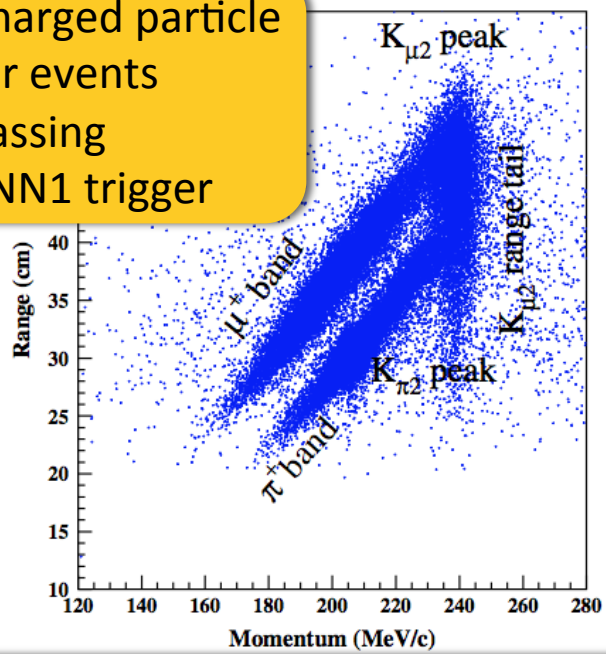
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$ Acceptance

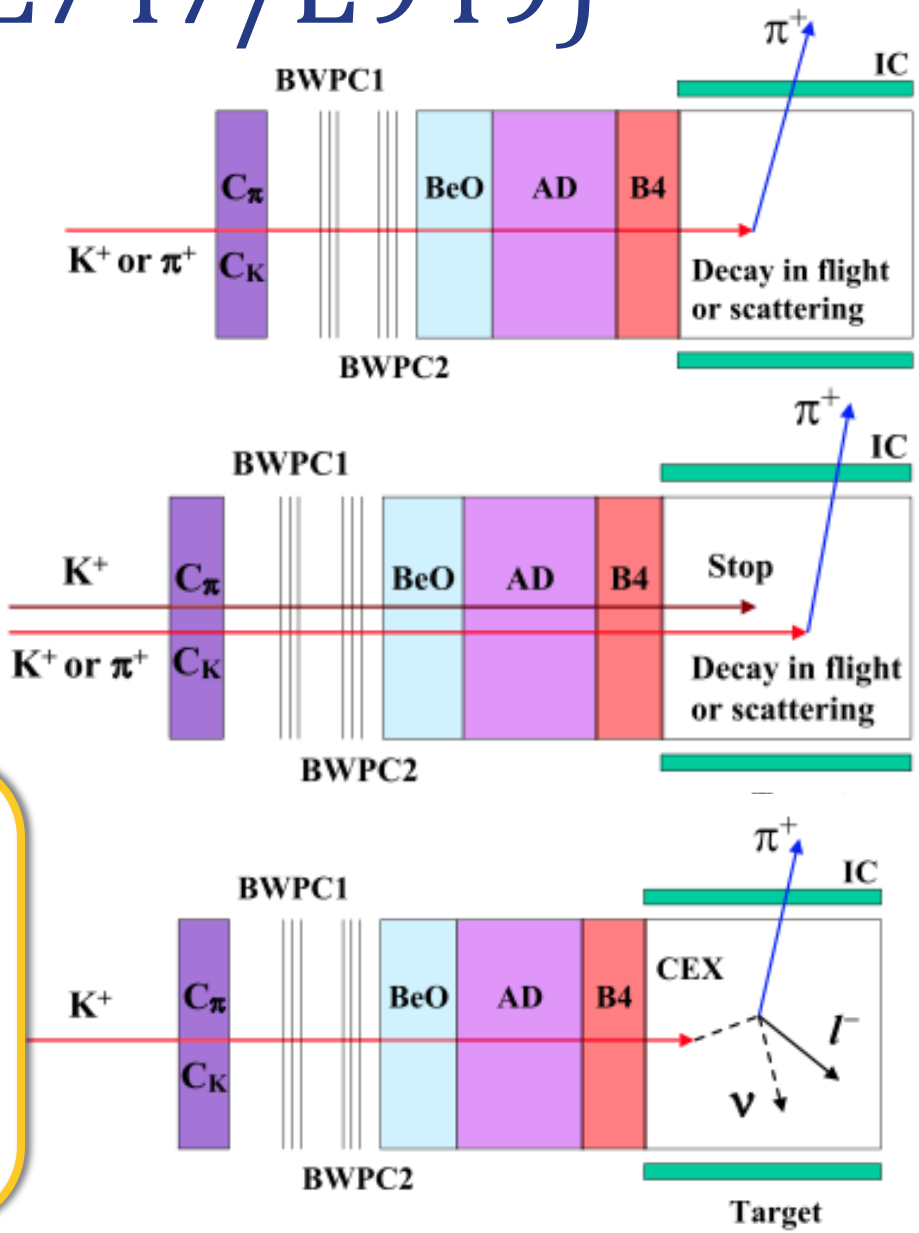
- E949 PNN1 $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ acceptance: 35%
- Improvements to increase acceptance relative to E949:
  - Increase segmentation in range stack to reduce loss from accidental activity and improve π/μ particle ID
  - Increase scintillator light yield by using higher QE photo-detectors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

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

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
$\mathcal{S}'_{\text{loss}}$			0.77 ± 0.02	9.2.5