Probing New Physics with ORKA

Elizabeth Worcester (BNL) for the ORKA collaboration
University of Virginia, HEP Seminar
September 18, 2013

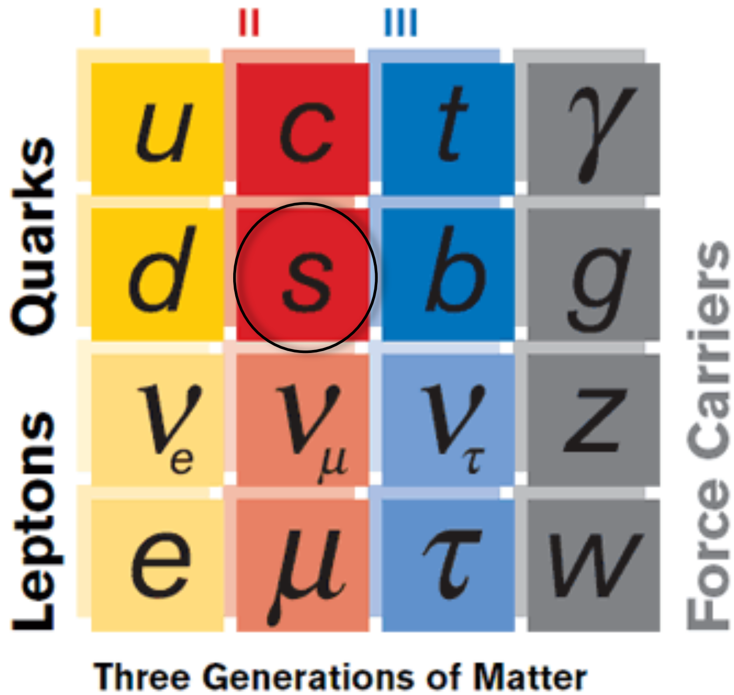
Photo: Life of Sea blogspot

Overview

- Some Kaon History
- $K \to \pi\nu\bar{\nu}$ Sensitivity to New Physics
- Experimental Status of $K \to \pi\nu\bar{\nu}$
- ORKA Detector & $K^+ \to \pi^+\nu\bar{\nu}$ Analysis
- Other Physics with ORKA
- ORKA Status
- Kaon Physics at Project X

Kaons in the Standard Model

Standard Model of
Particle Physics



Quark Charge: u,c,t = 2/3
d,s,b = -1/3

K^+: $u\bar{s}$

K^-: $\bar{u}s$

K^0: $d\bar{s}$

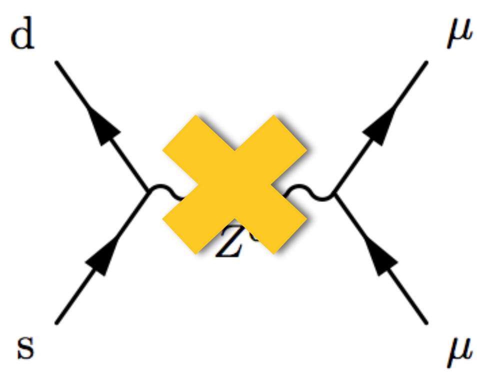
$\overline{K}^0$: $\bar{d}s$

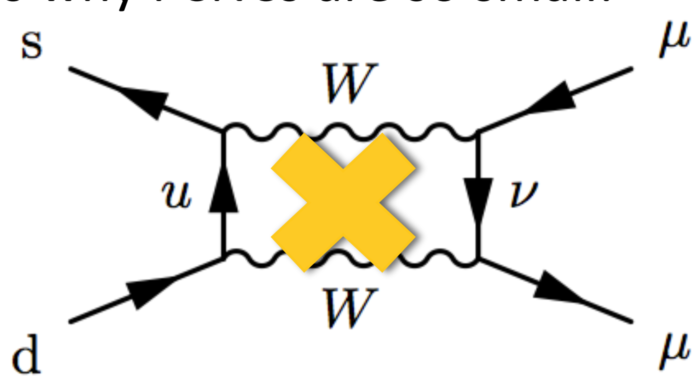
Flavor Changing Neutral Currents

- FCNC highly suppressed in the Standard Model:

$$\frac{\Gamma\left(K_L \to \mu^+\mu^-\right)}{\Gamma\left(K_L \to \mu^+\bar{\nu}_\mu\right)} = 2.60\times10^{-9}$$ (Current measurement)

- In 1960s, it was not obvious why FCNCs are so small:

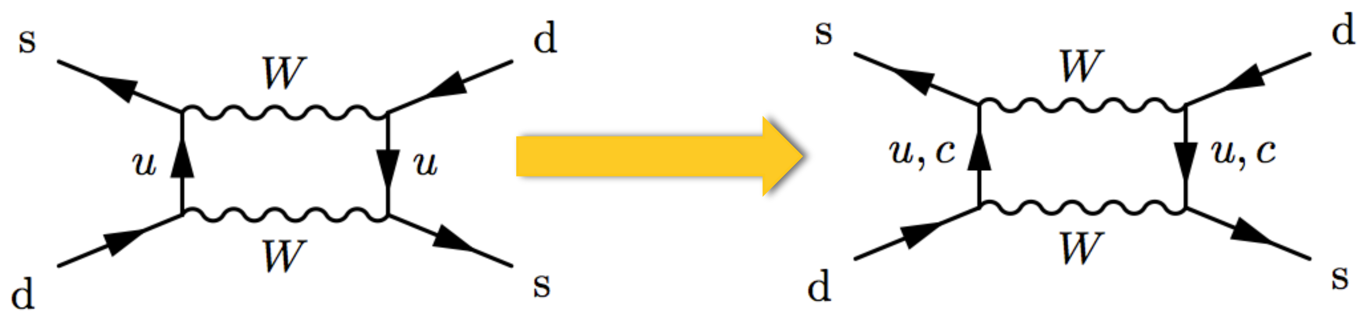




These diagrams each predict a BR already excluded by experimental limits in the 60s!

GIM Mechanism

- In 1960s, only up, down, and strange quarks were known
- With only 3 quarks, neutral-kaon mixing has divergent amplitude

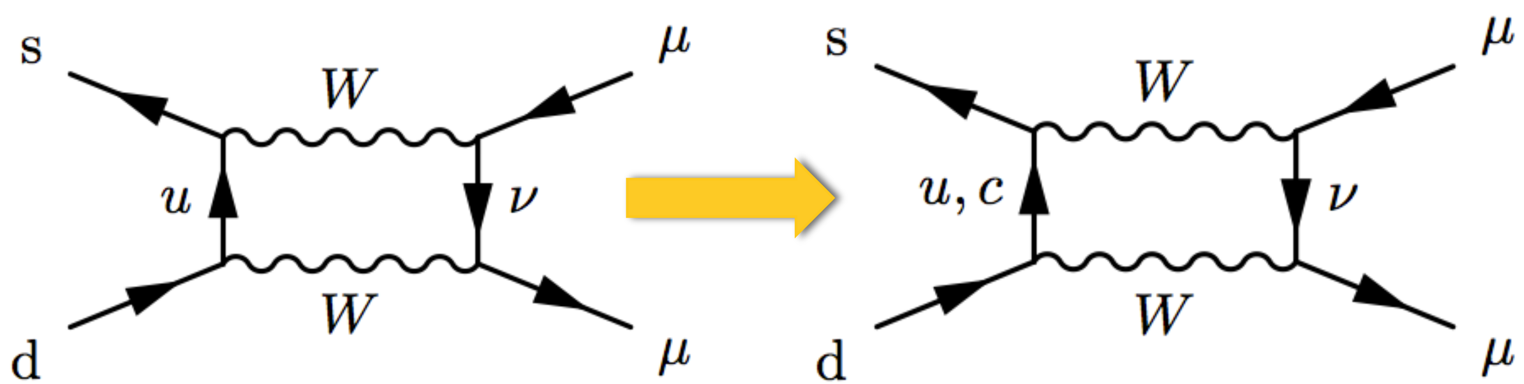


- Glashow, Iliopoulos, Maiani (1970): coupling to a 4th quark (charm) enters with opposite sign as coupling to up quark
- If $m_c = m_u$, cancellation is perfect. Actual rate is proportional to $m_c^2 - m_u^2$.

Predicted existence and mass of charm quark!

Back to $K_L \to \mu^+\mu^-$

- With addition of charm quark, Yang-Mills theory based on $SU(2) \otimes U(1)$ is possible
- Tree-level flavor-changing neutral currents forbidden by weak isospin
- Suppression of higher-order FCNC processes explained by GIM mechanism



Discussion of GIM mechanism and FCNC follows: L. Maiani, *The GIM Mechanism: origin, predictions and recent uses*, arXiv:1303.6154 (2013).

CP Violation & CKM Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

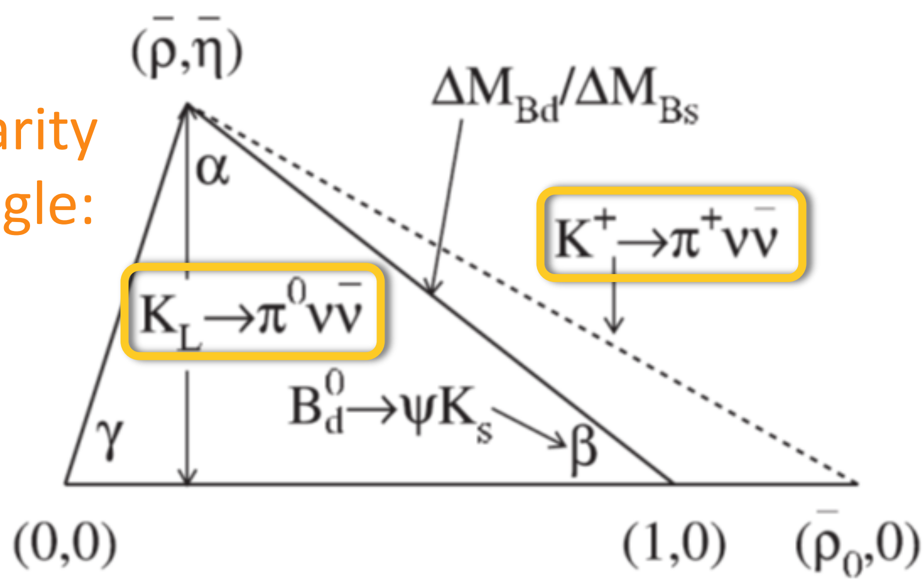
weak eigenstates — Cabibbo Kobayashi Maskawa (CKM) matrix — mass eigenstates

Wolfenstein Parameterization:

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

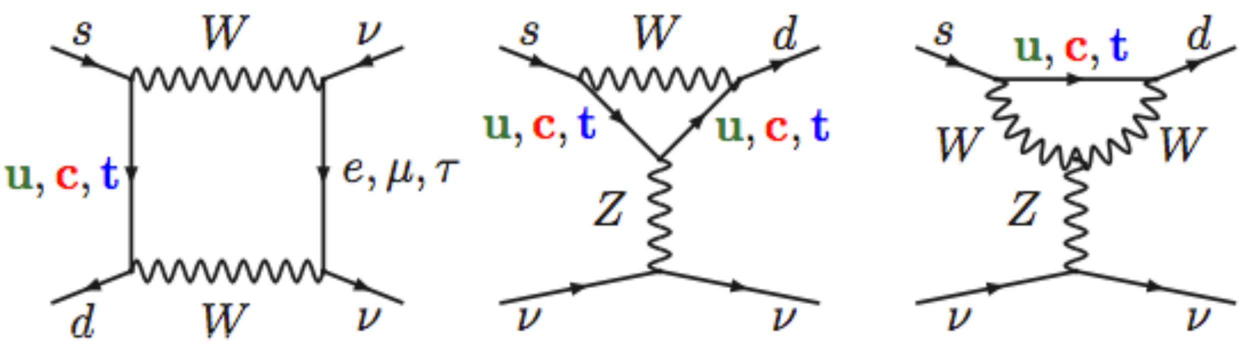
CP Violation

Unitarity Triangle:



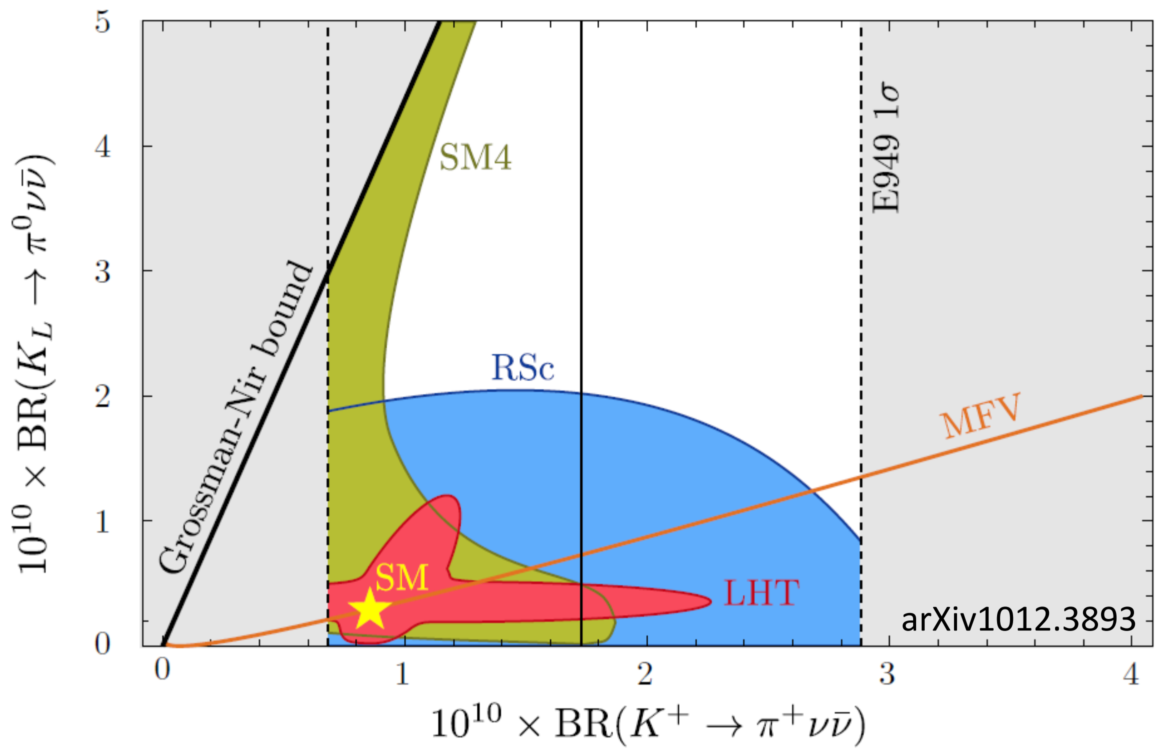
$K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

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



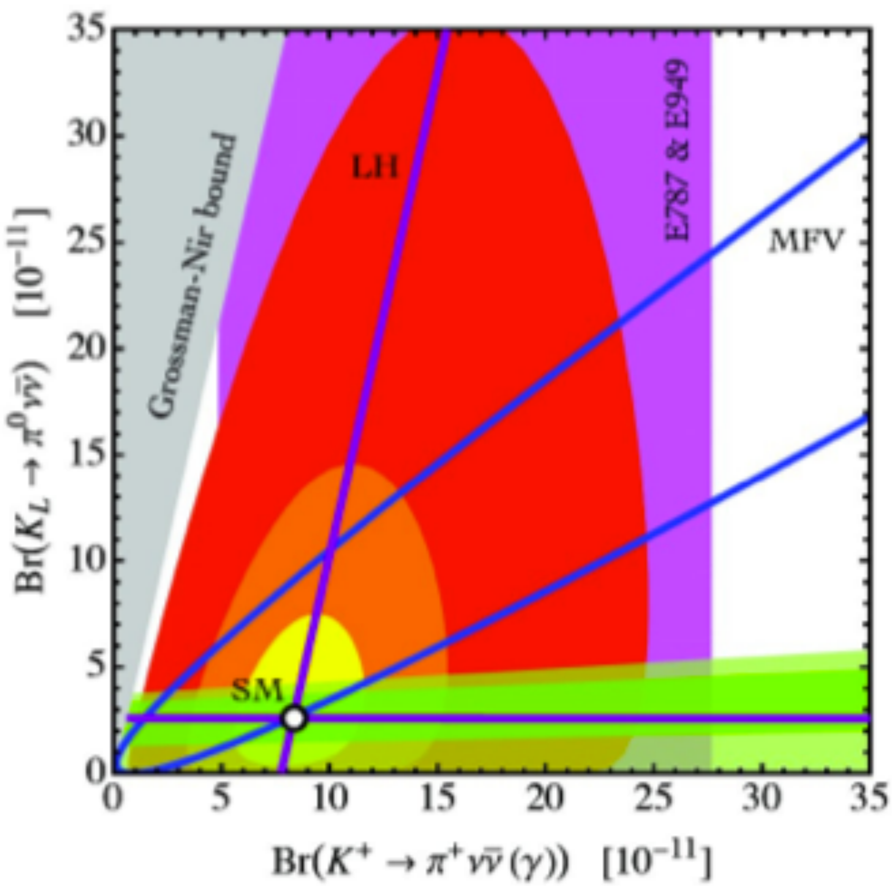
- A single effective operator: $\left(\bar{s}_L \gamma^\mu d_L\right)\left(\bar{\nu}_L \gamma_\mu \nu_L\right)$
- Dominated by top quark
- Hadronic matrix element shared with $K^+ \to \pi^0 e^+ \nu_e$
- Dominant uncertainty from CKM matrix elements
  - Expect prediction to improve to ~5%

Sensitivity to New Physics



- Prediction and measurement at 5% level allows 5σ detection of deviation from the Standard Model as small as 35%.
- $K^+ \to \pi^+ \nu\bar{\nu}$ BR has significant power to discriminate among new physics models.

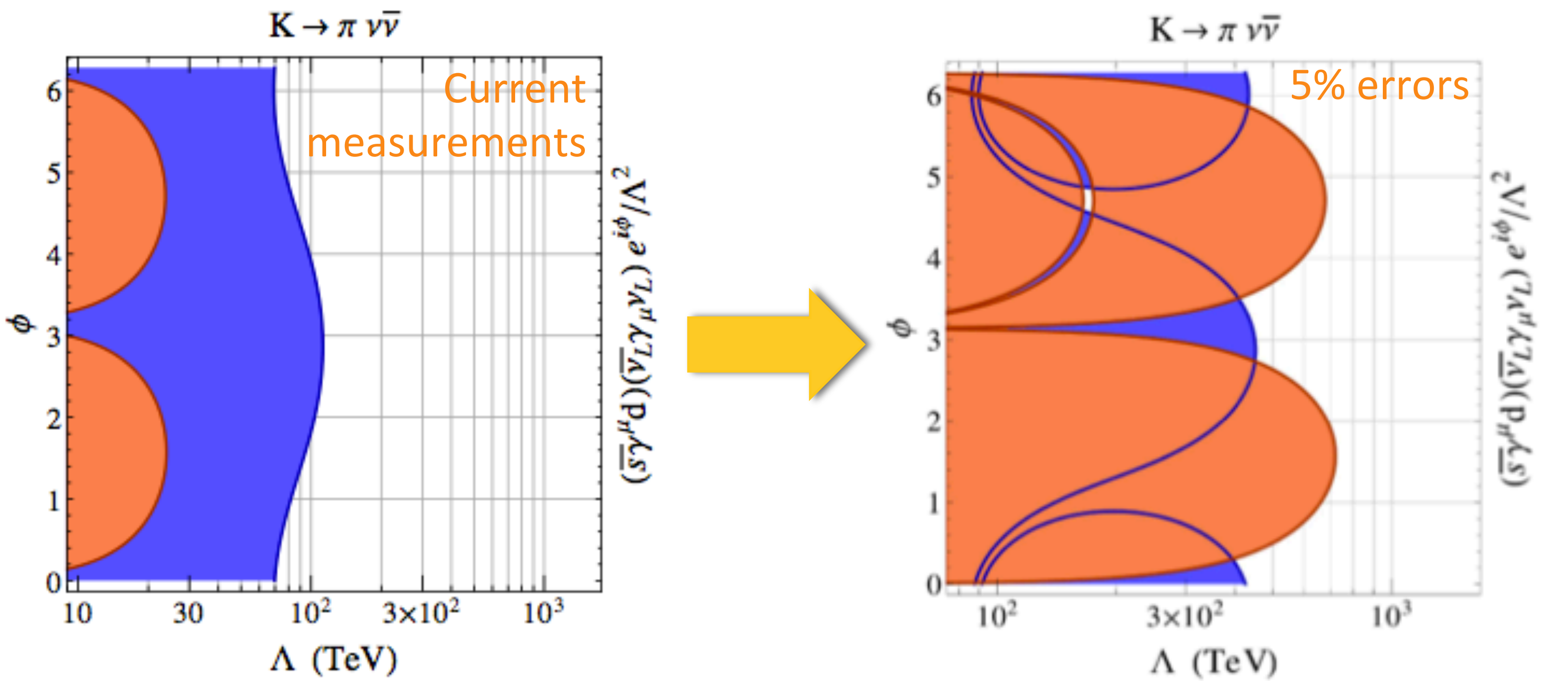
Constraint on New Physics



- 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 $K_L \rightarrow \pi^0 \nu\bar{\nu}$ branching ratio
- Four-fermion operators not subject to this constraint

See S. Jager's talk at NA62 book workshop: http://indico.cern.ch/getFile.py/access?contribId=5&resId=0&materialId=slides&confId=65927

New Physics Scales



- $K^+ \to \pi^+ \nu\bar{\nu}$ already constrains scales of ~100 TeV
- $K_L \to \pi^0 \nu\bar{\nu}$ does not yet add to constraints
- With 5% measurement of both charged and neutral modes, probes scales up to 700 TeV!

See W. Altmannshofer's talk at Argonne Intensity Frontier Workshop: https://indico.fnal.gov/contributionDisplay.py?contribId=64&sessionId=0&confId=6248

Flavor of New Physics

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

★★★ Large effects

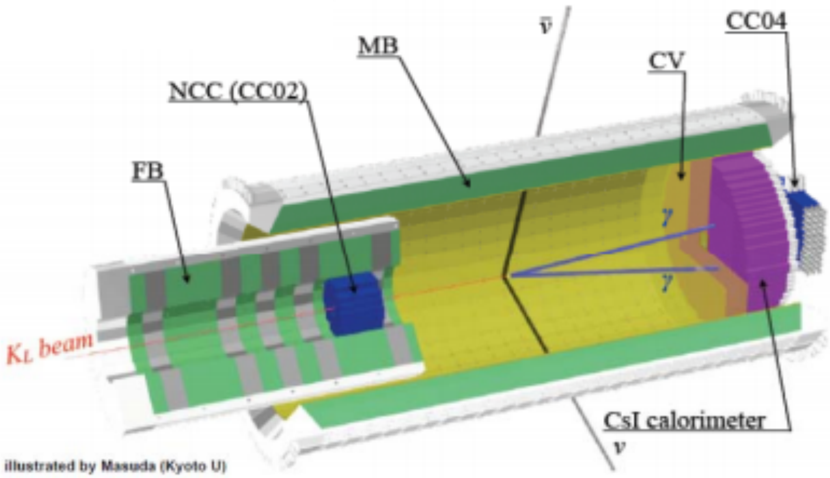
★★ Small observable effects

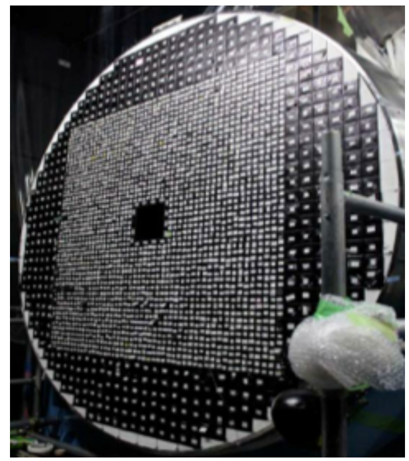
★ Unobservable effects

Models	
AC	RH currents and U(1) flavor symmetry
RVV2	SU(3)-flavored MSSM
AKM	RH currents & SU(3) family symmetry
δLL	CKM-like currents
FBMSSM	Flavor-blind MSSM
LHT	Little Higgs with T Parity
RS	Warped Extra Dimensions

W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi and D.M. Straub, Anatomy and Phenomenology of FCNC and CPV Effects in SUSY Theories. Nucl.Phys. B830,17 (2010).

Worldwide Effort: KOTO



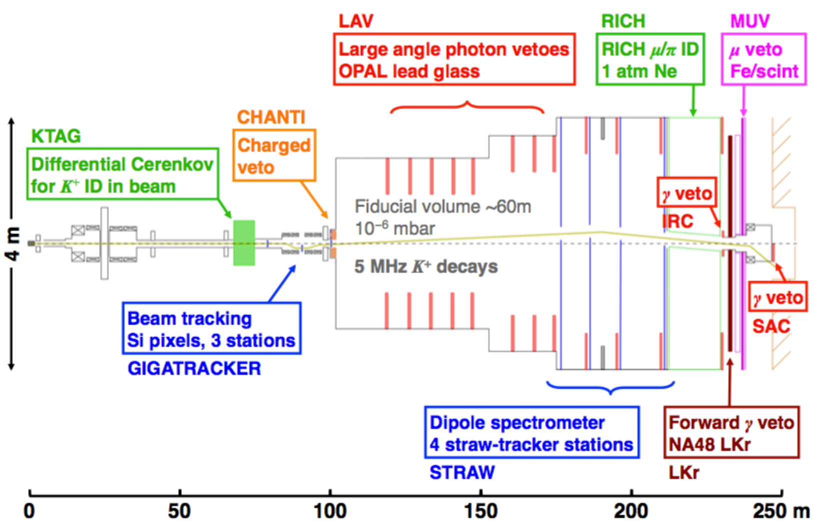


- Pencil beam decay-in-flight experiment at J-PARC to measure $K_L \to \pi^0 \nu \bar{\nu}$
- 2^{nd} generation detector building on E391 at KEK
- Re-using KTeV CsI crystals to improve calorimeter
- Expect ~3 $K_L \to \pi^0 \nu \bar{\nu}$ events (SM) with S/B ~ 1
- 2013 physics run interrupted by J-PARC radiation accident

See J.Xu's talk at DPF 2013: https://indico.bnl.gov/contributionDisplay.py?sessionId=11&contribId=100&confId=603

Worldwide Effort: NA-62

- Decay-in-flight experiment at CERN to measure $K^+ \to \pi^+ \nu \bar{\nu}$
- Building on NA-31/NA-48
- Expect ~45 $K^+ \to \pi^+ \nu \bar{\nu}$ events per year (SM) with <10 bg events per year (~100 total events)
- Expect ~10% measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ BR
- Complementary technique to ORKA
- Data starting late 2014

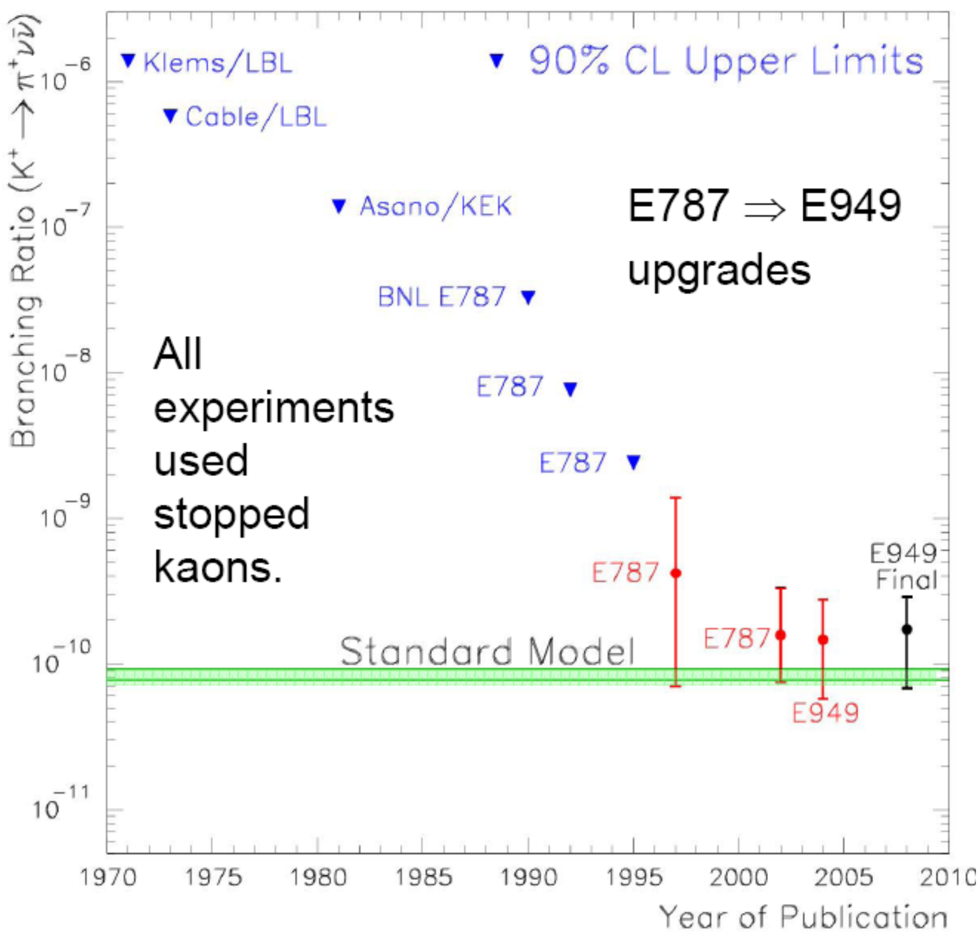


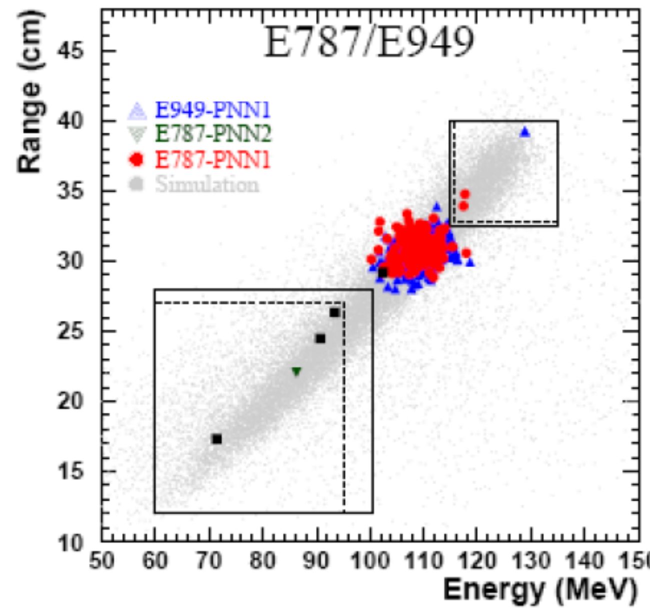
See M. Moulson's talk at DPF 2013: https://indico.bnl.gov/contributionDisplay.py?sessionId=11&contribId=103&confId=603

ORKA: The Golden Kaon Experiment

- Precision measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ BR with ~1000 expected events using protons from FNAL Main Injector
- Expected BR uncertainty matches Standard Model uncertainty
- Builds on successful previous experiments BNL E787/E949
  - 7 candidate events already observed
- Detector R&D and site preparation underway
- Collaboration:
  - 17 Institutions, 6 countries
  - 2 US National Labs, 6 US Universities
  - Leadership from successful rare kaon decay experiments

Experimental History





E787/E949 Final (7 candidate events observed):

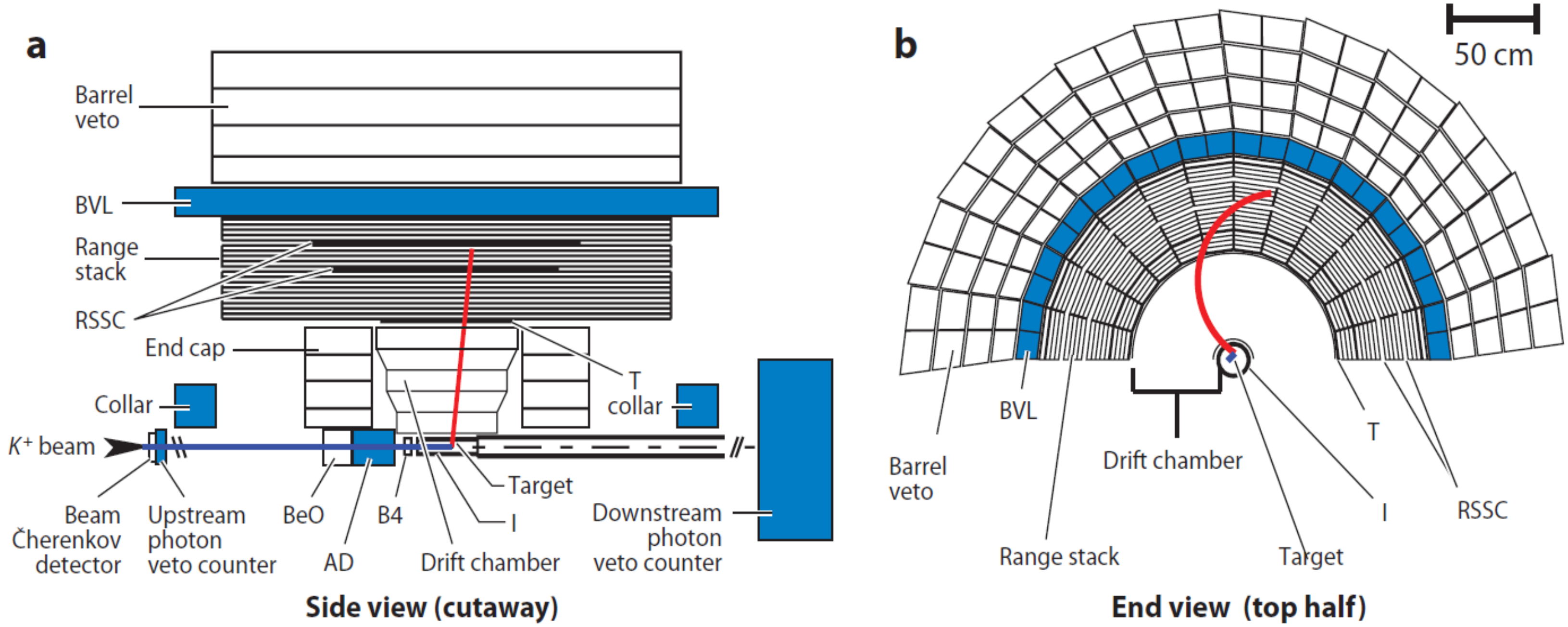
$$B\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$$

Standard Model:

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

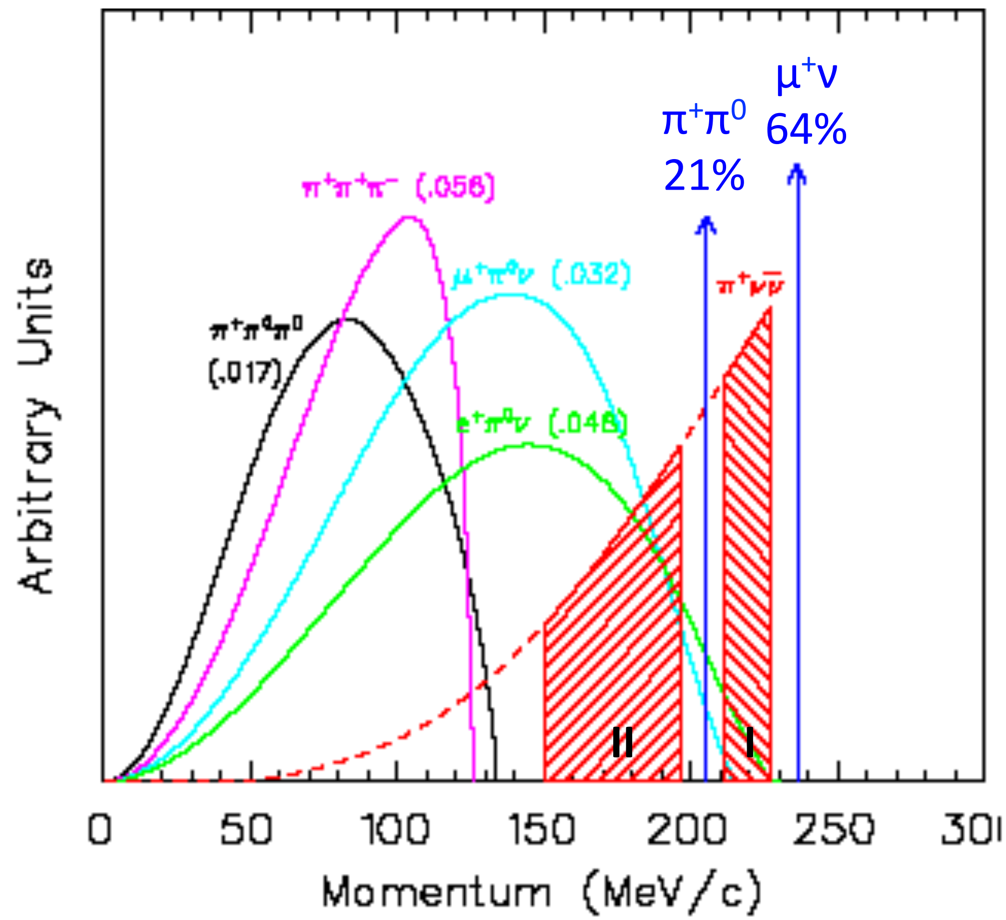
BNL E787/E949 Stopped-Kaon Technique

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

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

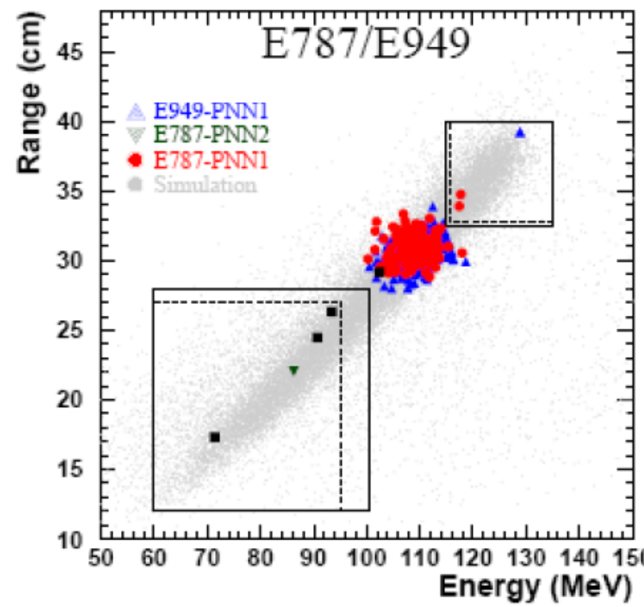


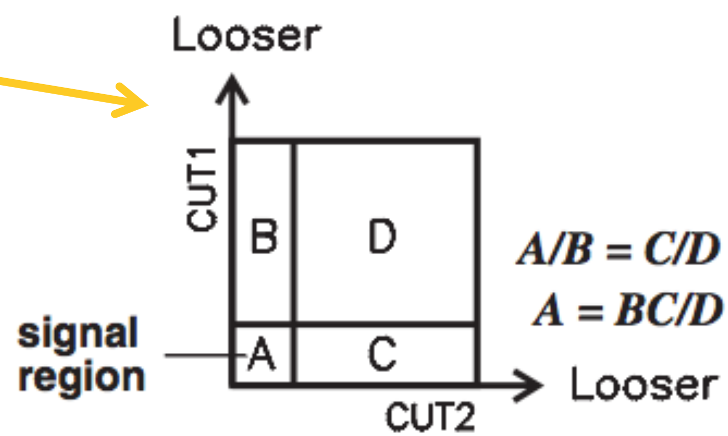
Momentum spectra of charged particles from K^+ decays in the rest frame

- Observed signal is $K^+ \to \pi^+ \to \mu^+ \to e^+$
- 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 $< 10^{-6}$

Analysis Strategy (E787/E949)

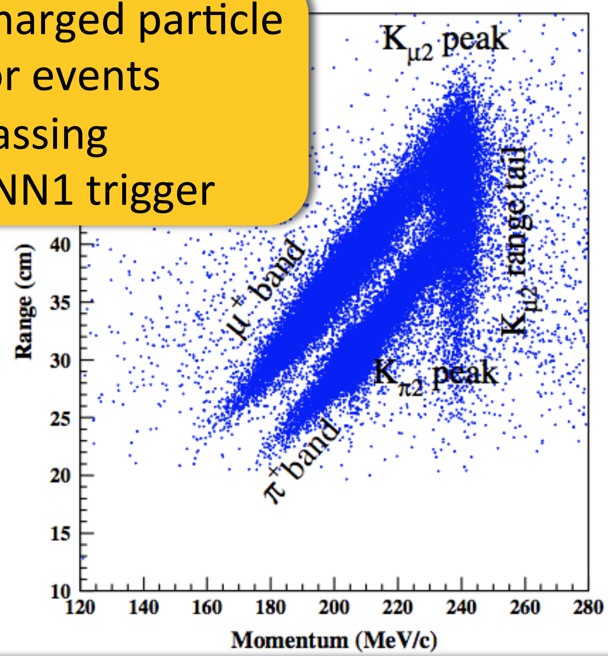
- Measure everything!
- Separate analyses for PNN1 and PNN2 regions
- Blind analysis
  - Blinded signal box
  - Final background estimates obtained from different samples than used to determine selection criteria (1/3 and 2/3 samples)
- Bifurcation method to determine background from **data**
  - Use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

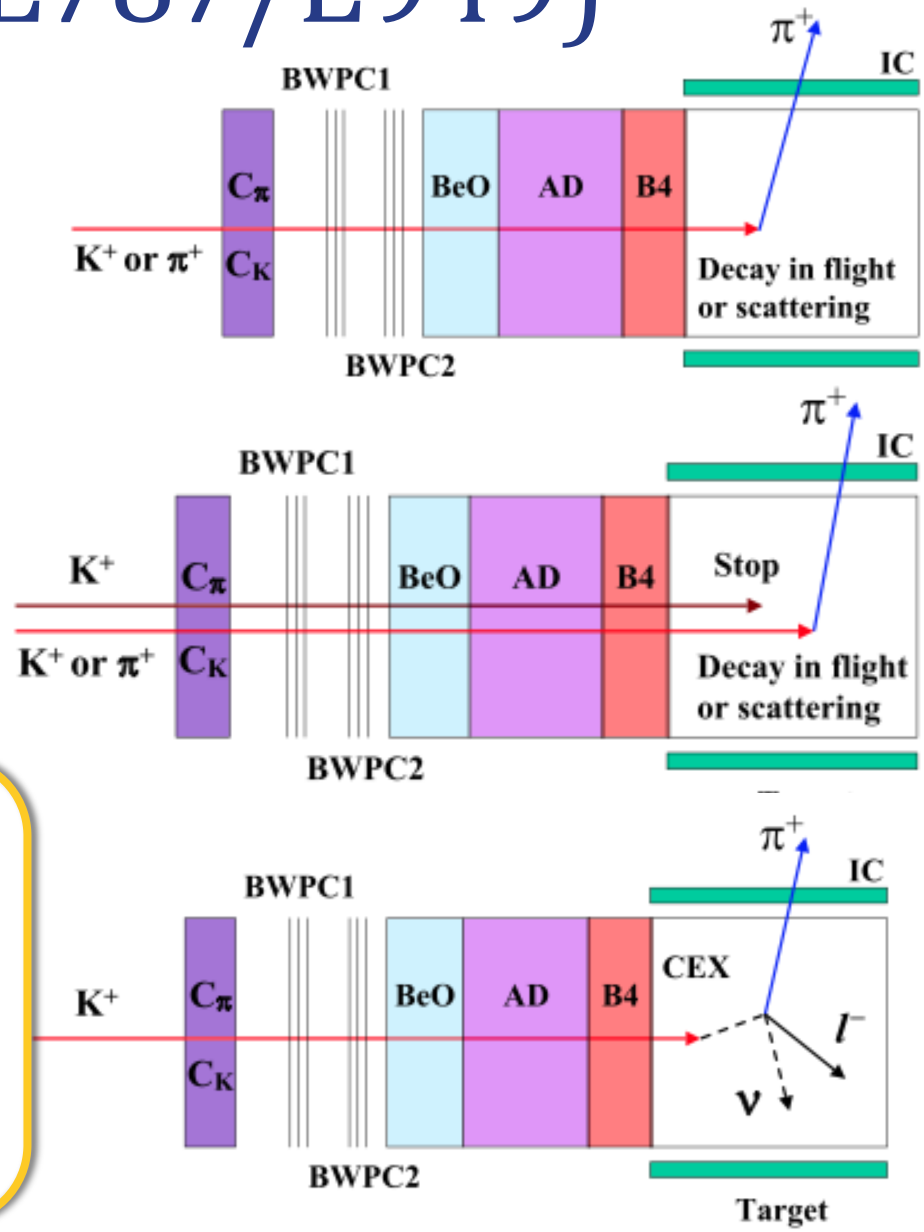




Background (E787/E949)

Charged particle for events passing PNN1 trigger





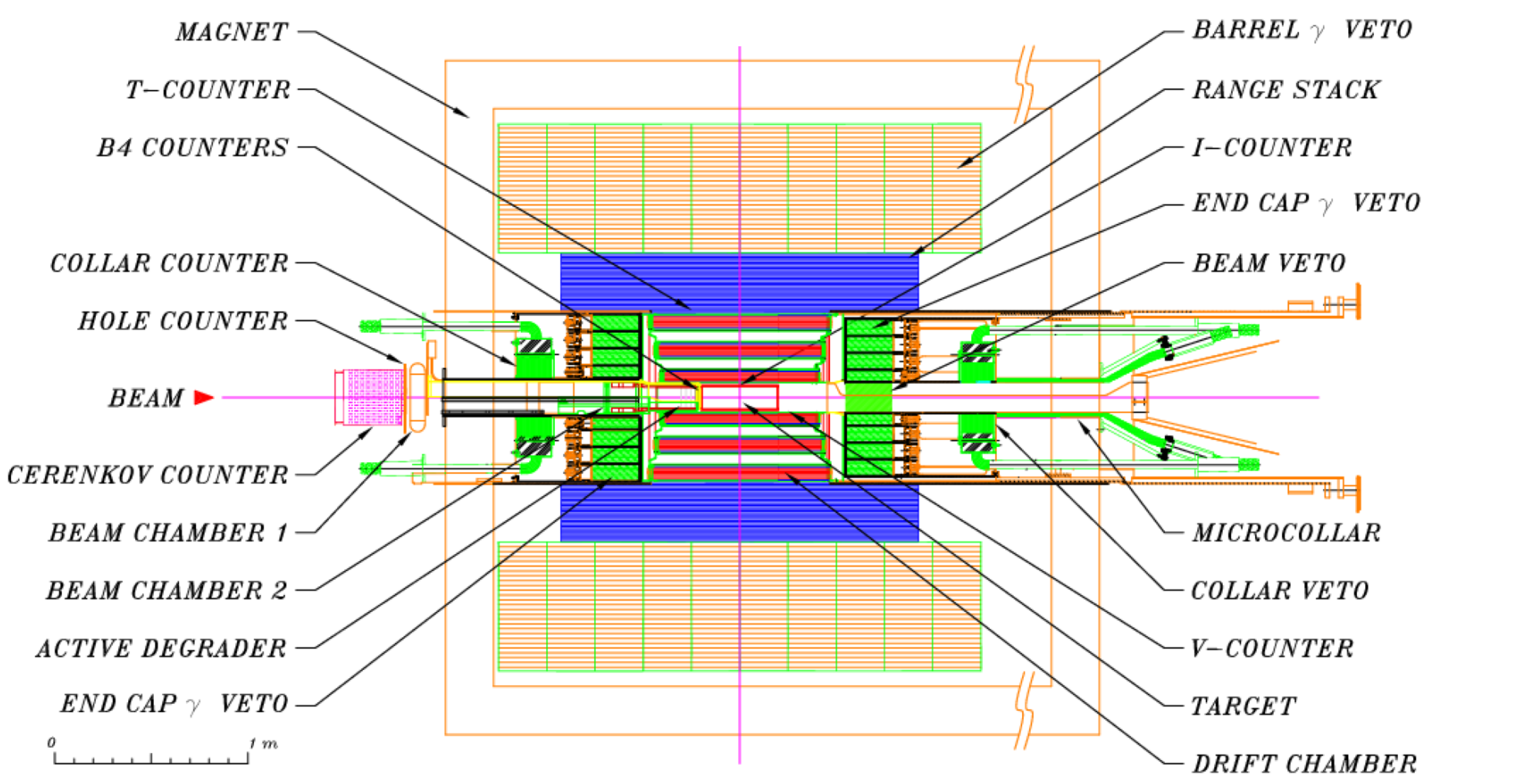
Stopped kaon background:

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

Beam background:

- Single beam
- Double beam
- Charge exchange

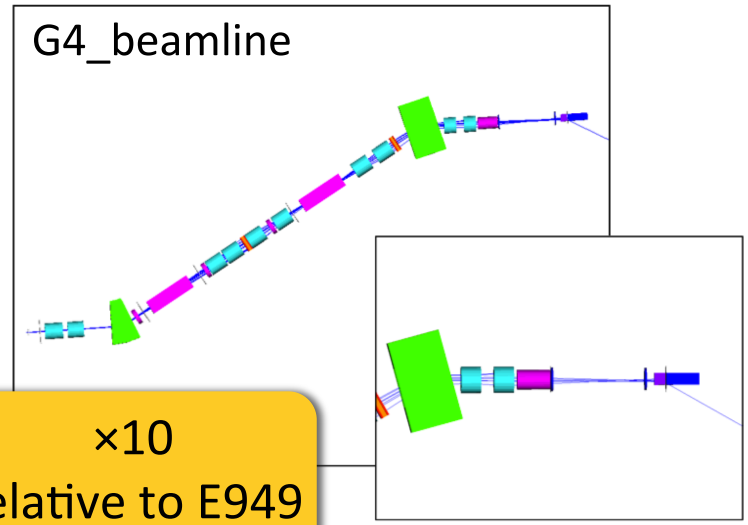
ORKA:
a 4th generation detector



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
$\pi \rightarrow \mu \rightarrow e$	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})	$11.28^{+3.25}_{-2.22}$

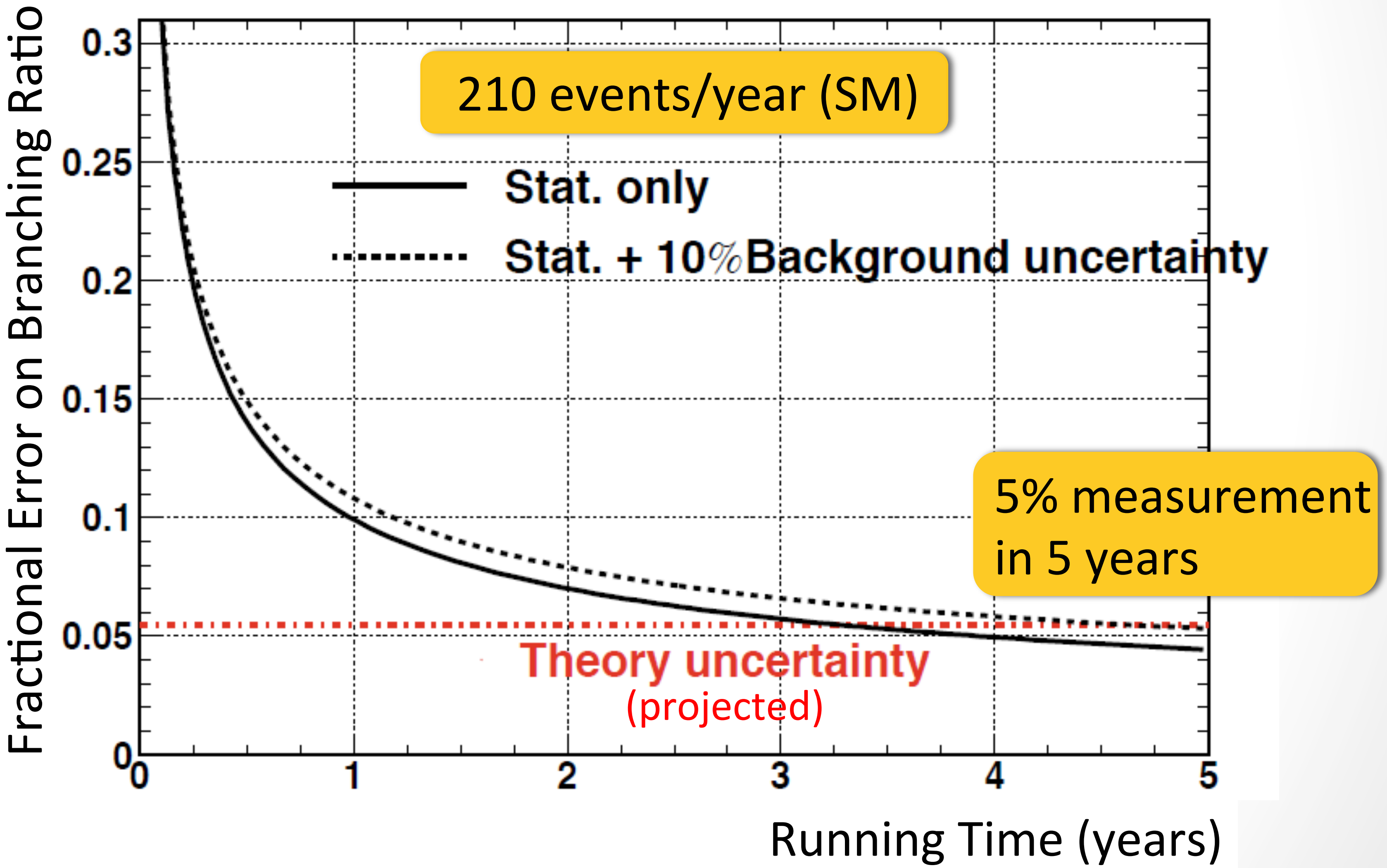
×11 relative to E949

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



ORKA Physics Topics

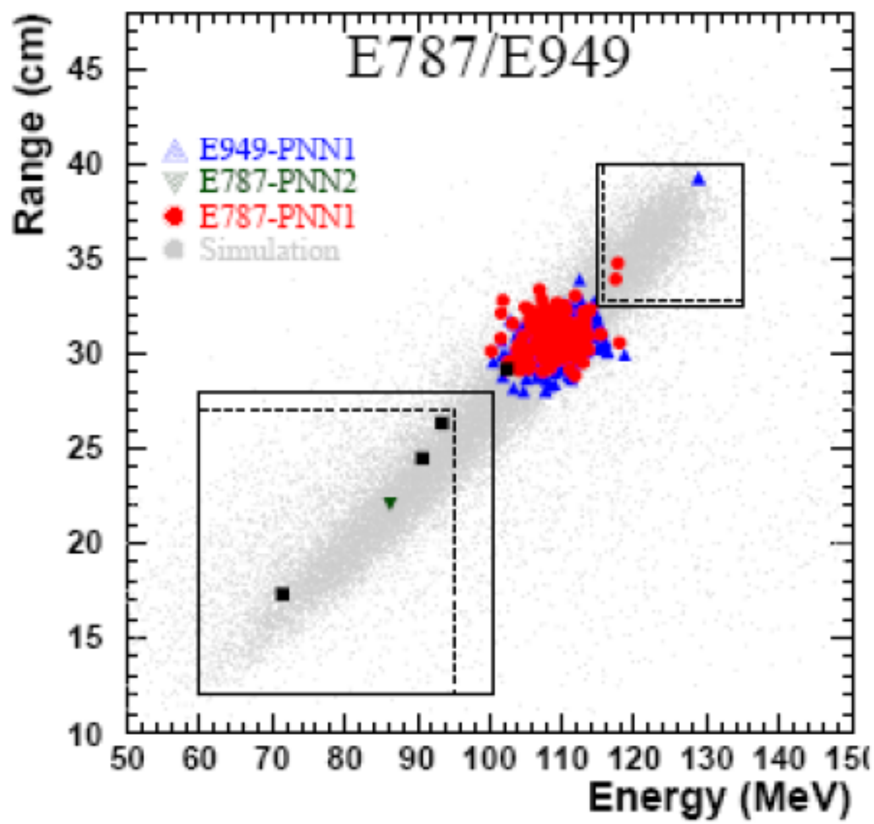
- $K^+ \to \pi^+ + \text{missing energy}$
  - $K^+ \to \pi^+ \nu\bar{\nu}(1)$ ^{T,P}
  - $K^+ \to \pi^+ \nu\bar{\nu}(2)$ ^{T,P}
  - $K^+ \to \pi^+ \nu\bar{\nu}\gamma$
  - $K^+ \to \pi^+ X$ ^{P}
  - $K^+ \to \pi^+ \tilde{\chi}_0 \tilde{\chi}_0 (\mathrm{FF})$ ^{P}
- $K^+ \to \pi^+ \pi^0 + \text{missing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

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

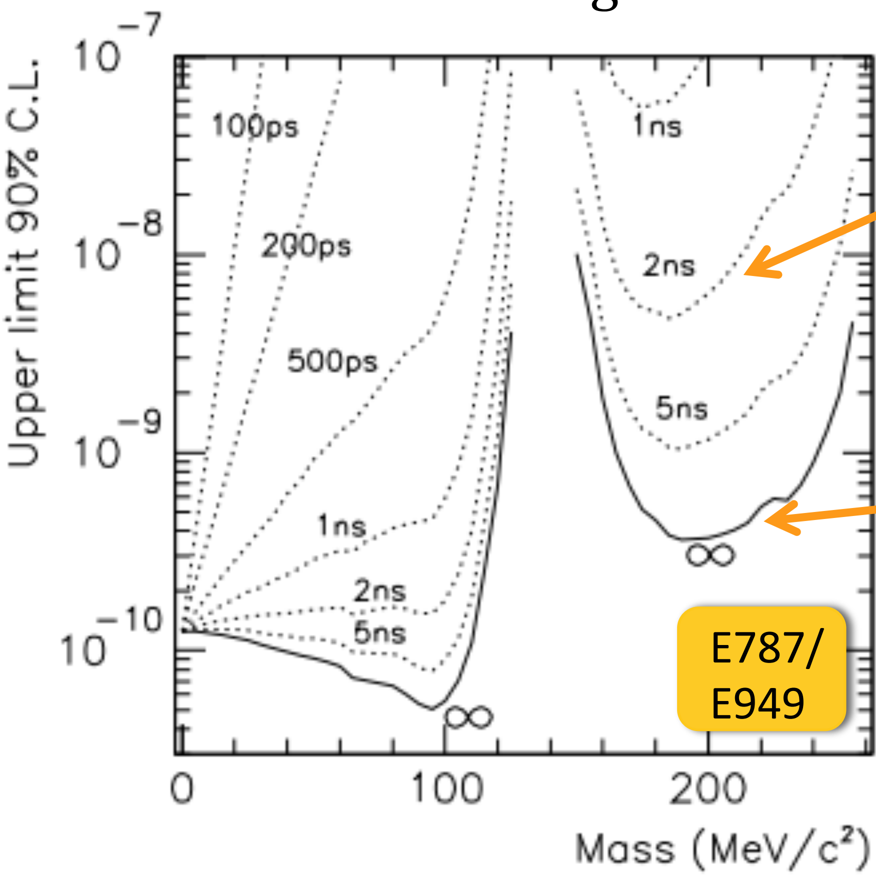


ORKA

ETW: UVA HEP Seminar September 18, 2013

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

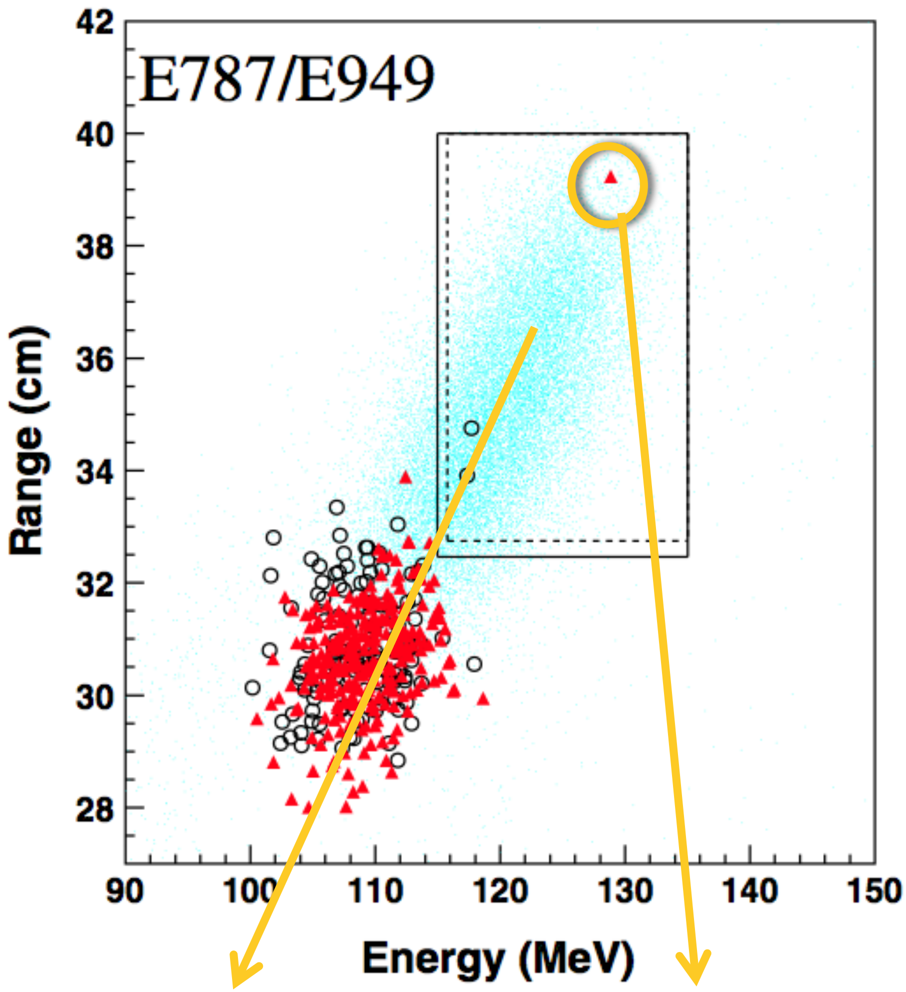
- Many models for X^0: familon, axion, light scalar pseudo-NG boson, sgoldstino, gauge boson corresponding to new U(1) symmetry, light dark matter …
- $K^+ \to \pi^+ \nu\bar{\nu}$ is a background



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

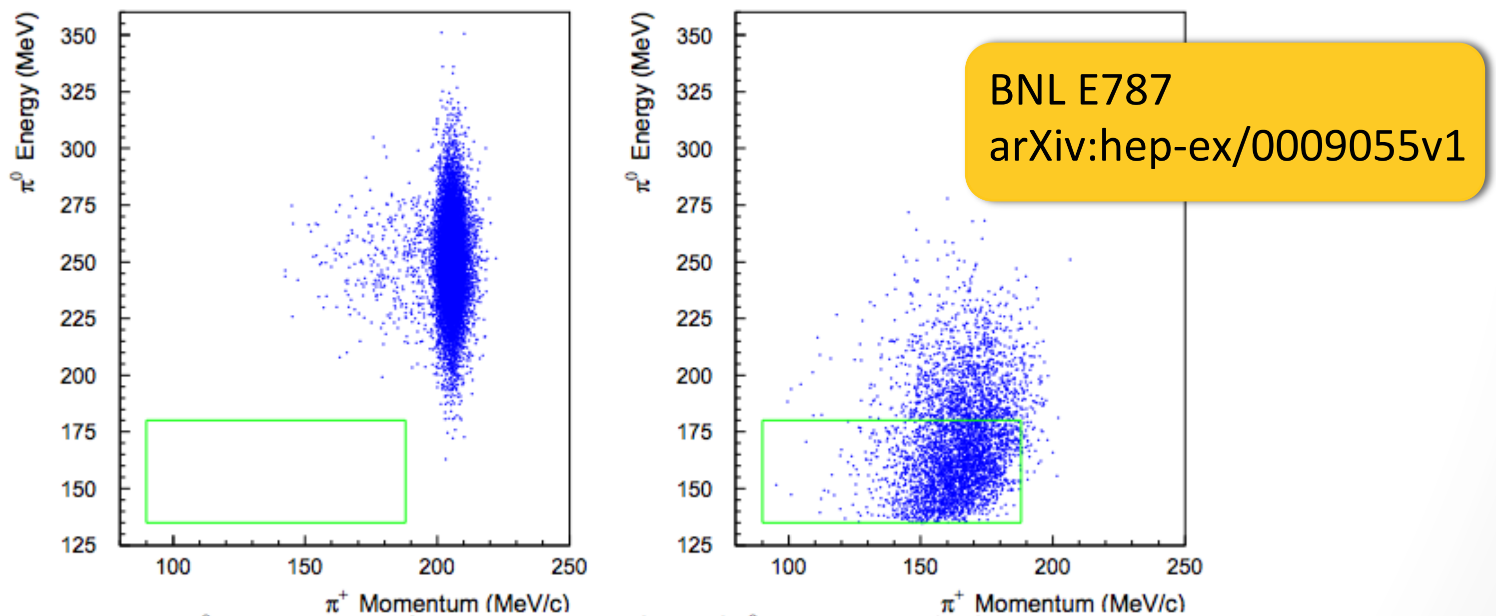
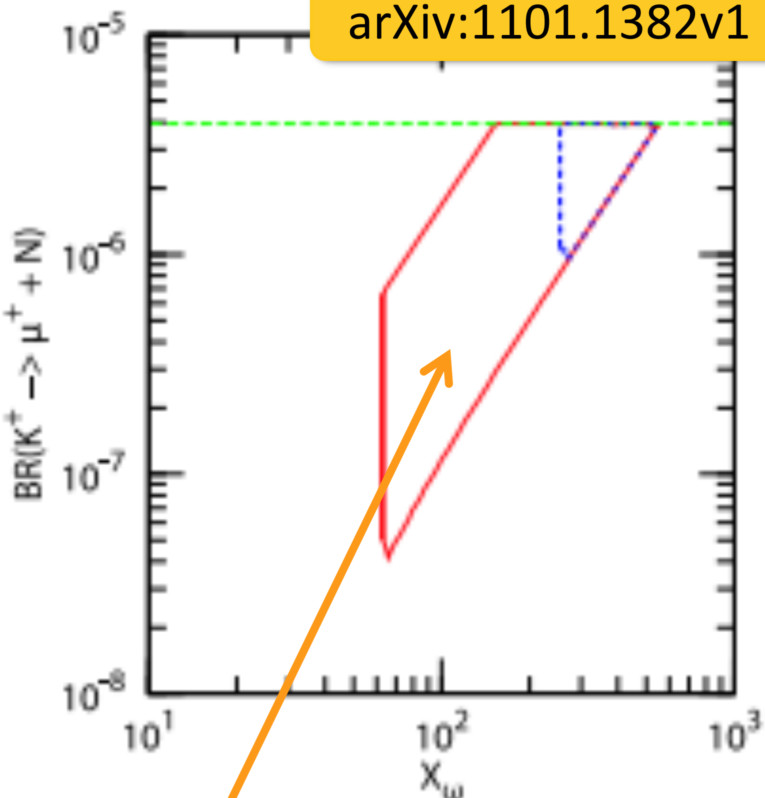


FIG. 4. π^0 energy versus π^+ momentum for $K^+ \to \pi^+\pi^0\nu\bar{\nu}$ candidates (left) and for Monte Carlo signal events (right). Box indicates the signal acceptance region. $K_{\pi 2}$ events cluster at the upper right in the top plot.

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

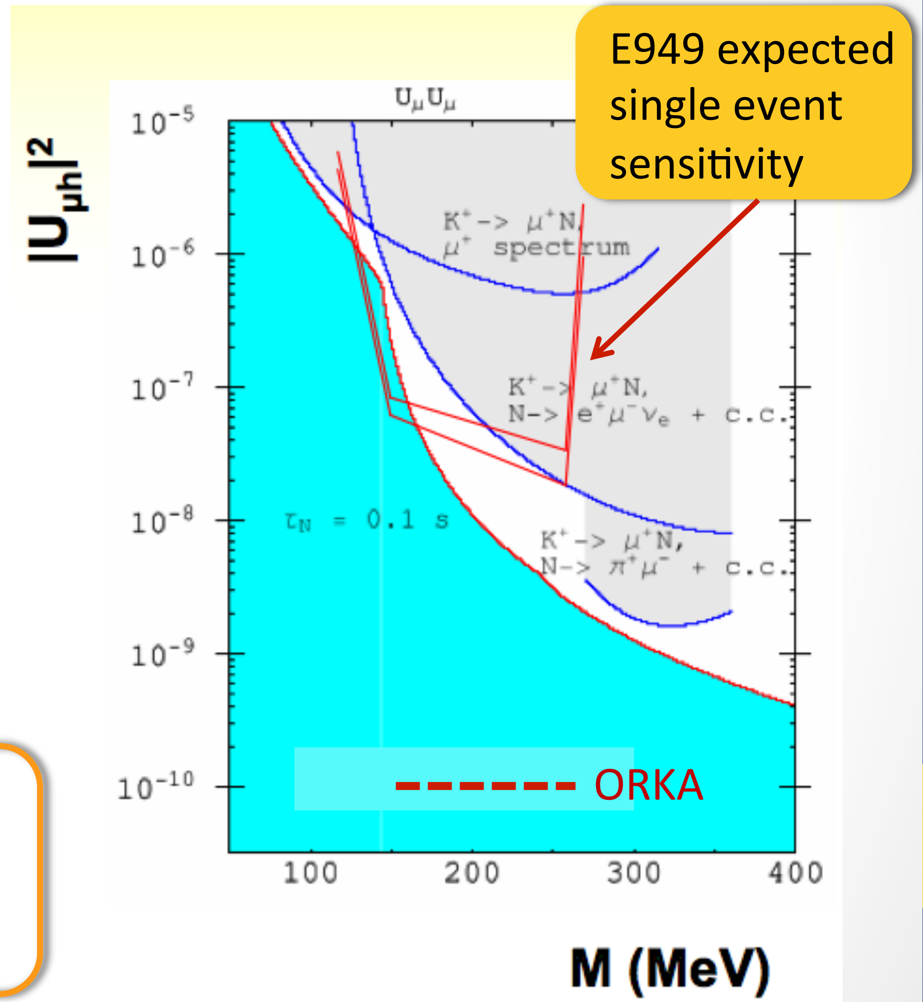
arXiv:1101.1382v1



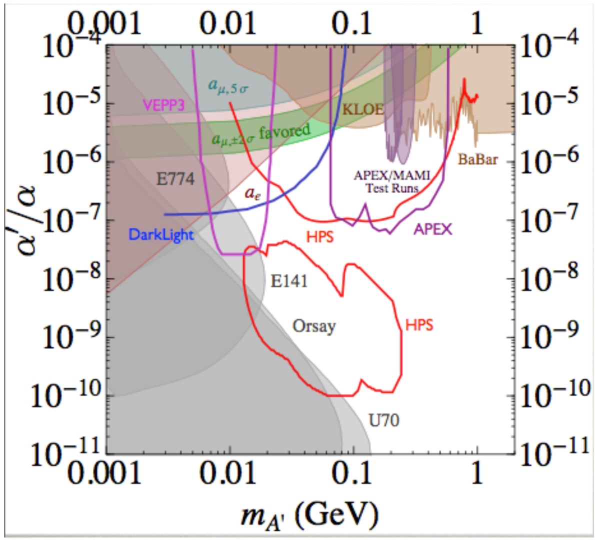
Ex: Allowed $BR(K^+ \to \mu^+ N_{2,3})$ for NH in νMSM, M_N=120 MeV: ~4×10^{-8} to ~4×10^{-6}

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

- $K^+ \to \pi^+ A' \to \pi^+ e^+ e^-$ and $\pi^0 \to \gamma A' \to \gamma e^+ e^-$
- 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

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

- $R_{SM} = (2.477 \pm 0.001) \times 10^{-5}$
  - 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) ⟶ 0.4% precision
- $R = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$ (KLOE)
- Expect ORKA statistical precision of ~0.1%
  - More study required to estimate total ORKA uncertainty

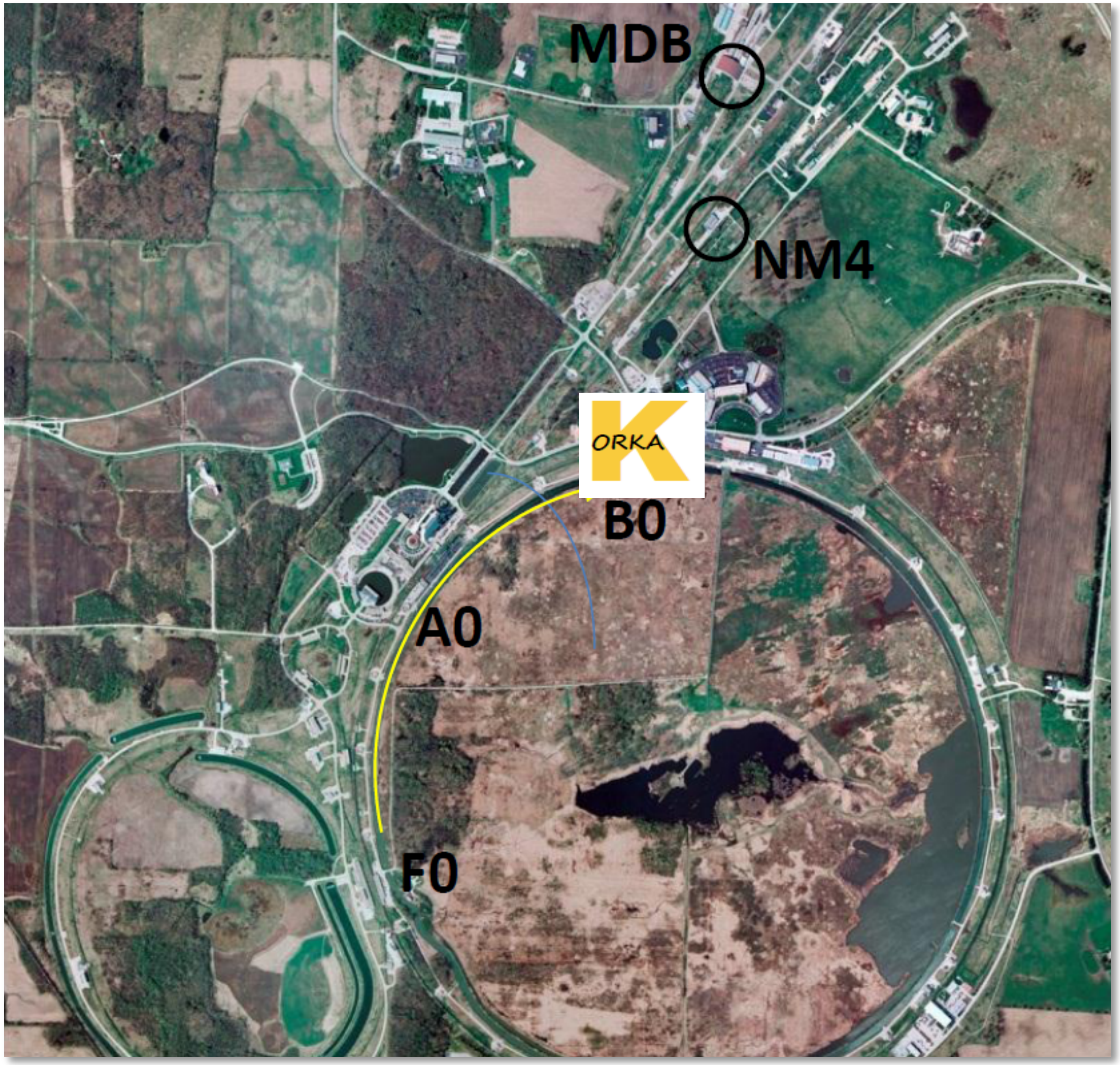
ORKA Sensitivity Summary

(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	
$\Gamma(Ke2)/\Gamma(K\mu2)$	$\pm 0.5\%$	$\pm 0.1\%$	
$\pi^0 \to \nu\bar{\nu}$	$< 2.7 \times 10^{-7}$	$< 5 \times 10^{-8}$ 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

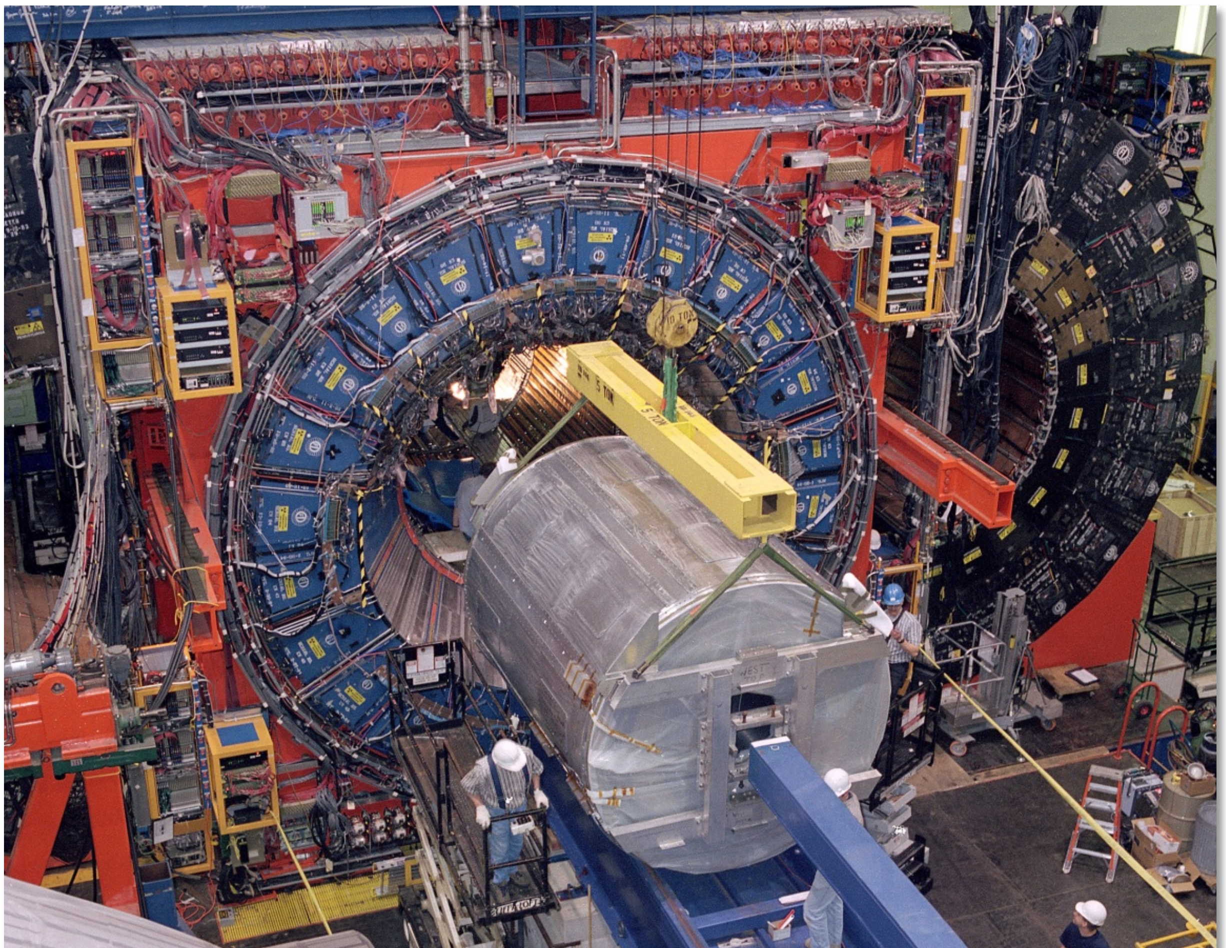
Experiment Site: B0 (CDF)



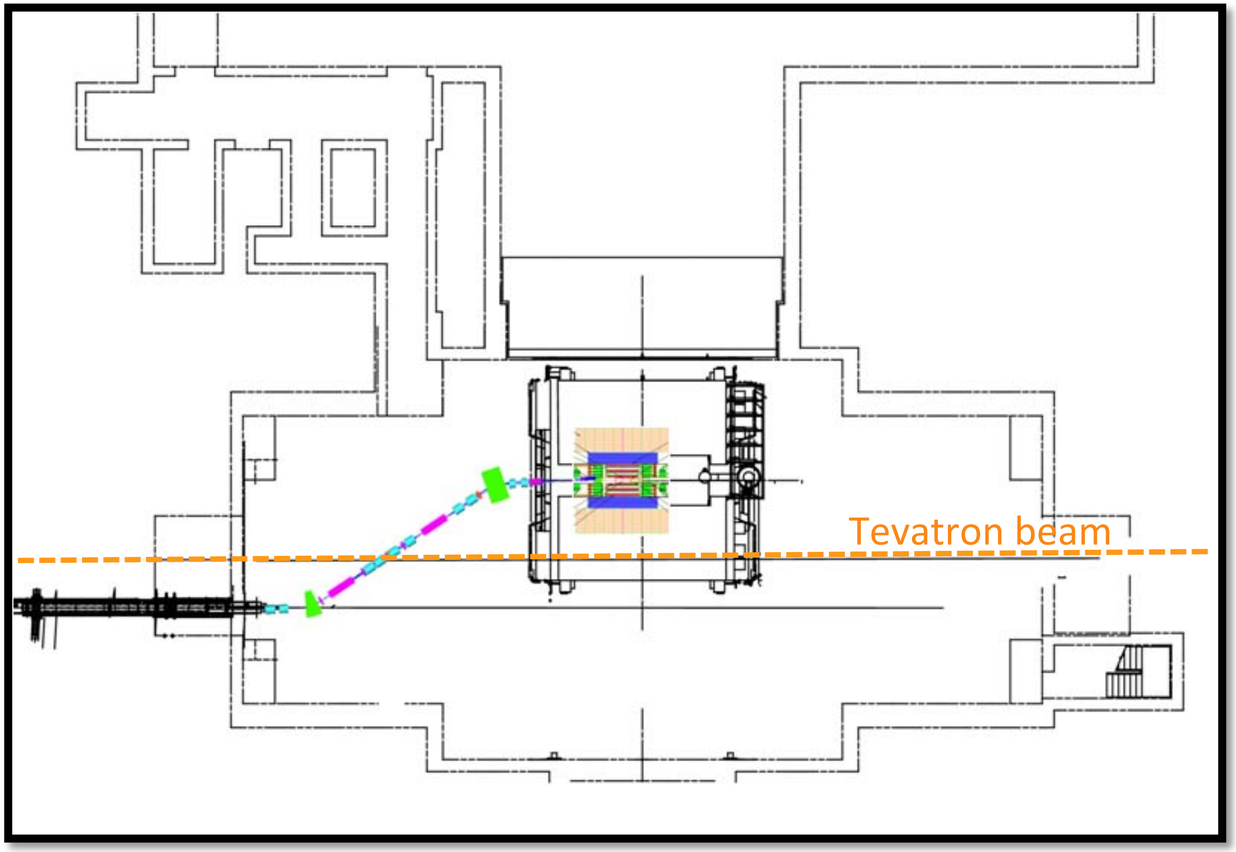
- Requires new beam line from A0-B0
- Re-use Tevatron tunnel
- No civil construction required

Experiment Site: B0 (CDF)

- ORKA detector fits inside CDF solenoid
- Re-use CDF solenoid, cryogenics, infrastructure

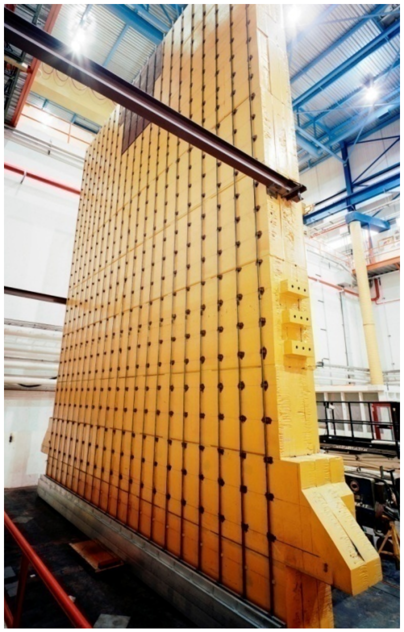


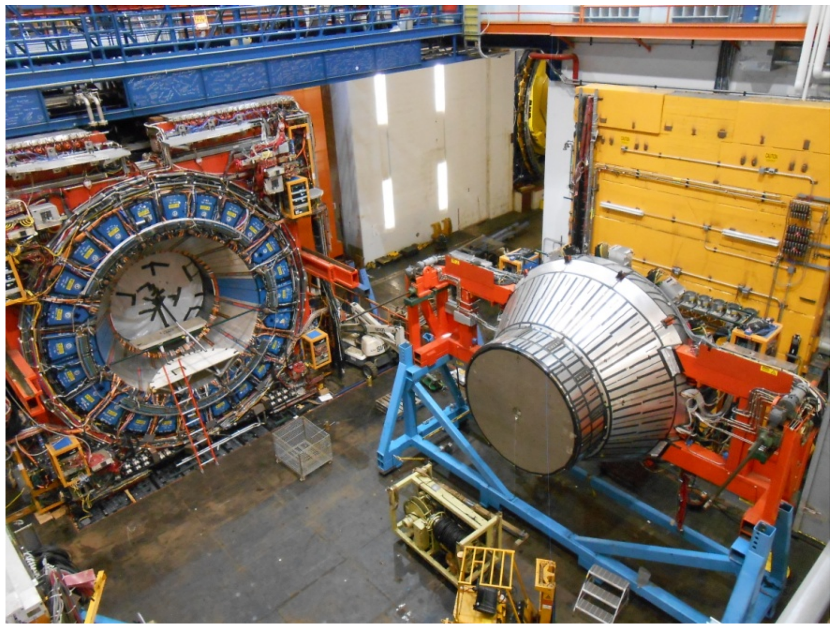
Experiment Site: B0 (CDF)

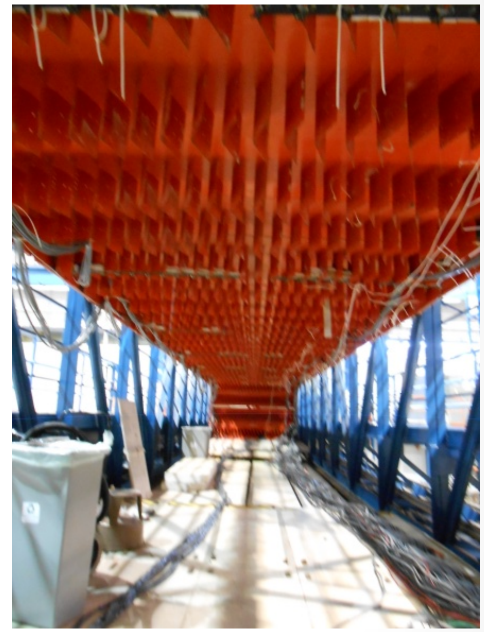


- Proton beam slightly south of Tevatron beam line
- Dog-leg kaon beam line
- Magnet shifted slightly to the north

ORKA Site Preparation

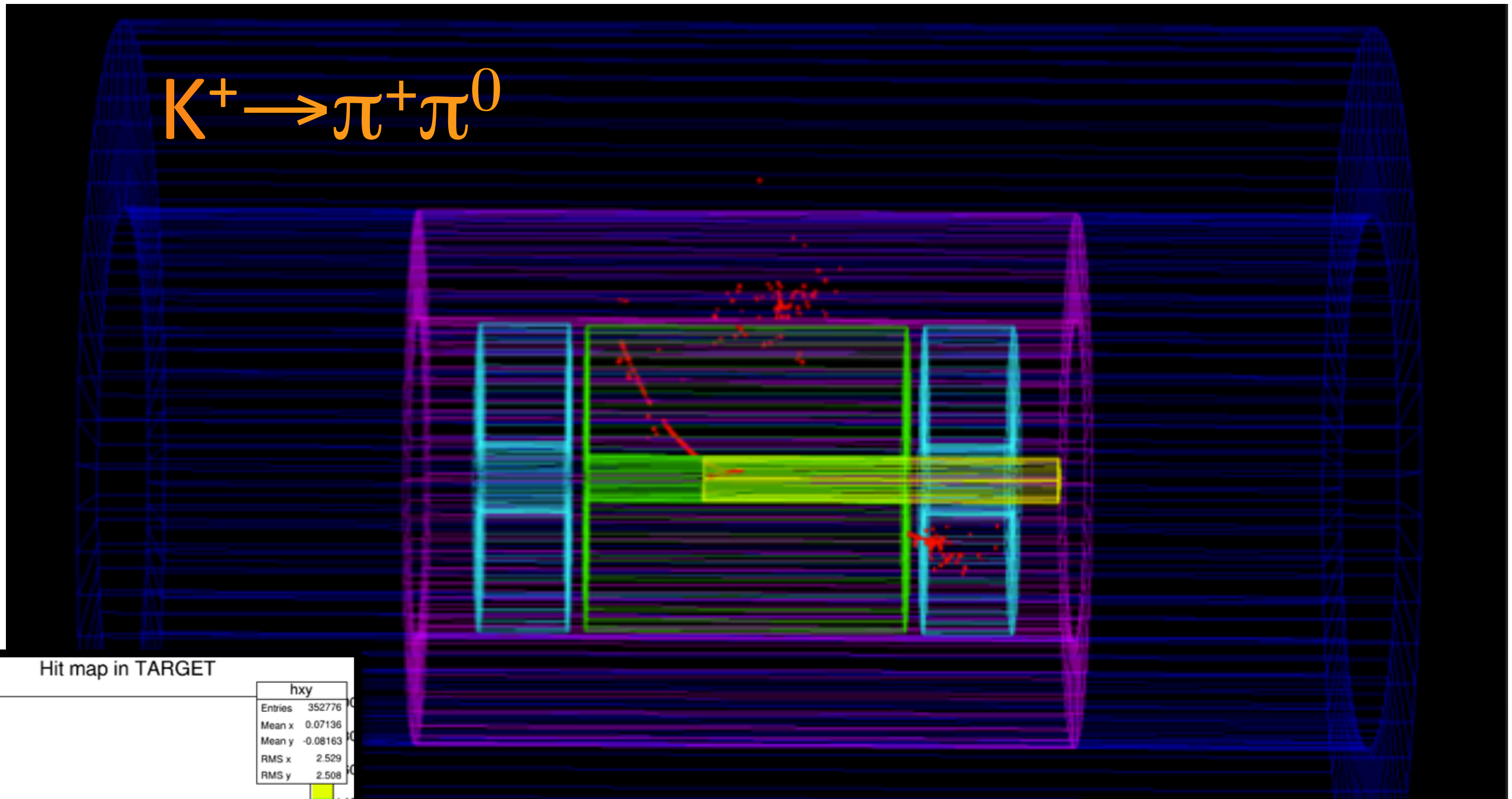


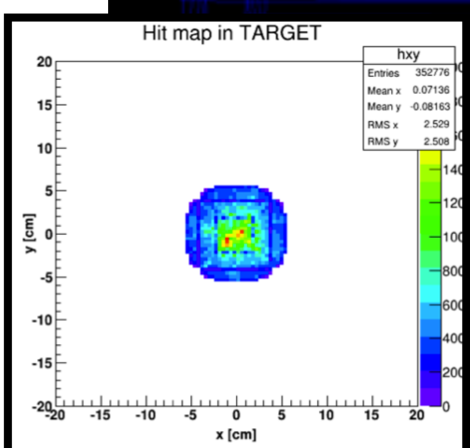




- Central detector and muon walls now in assembly area
- Removal of cables, electronics, and PMTs almost complete
- Tracker removal this month
- Outer muon system demolition ongoing

ORKA Simulations



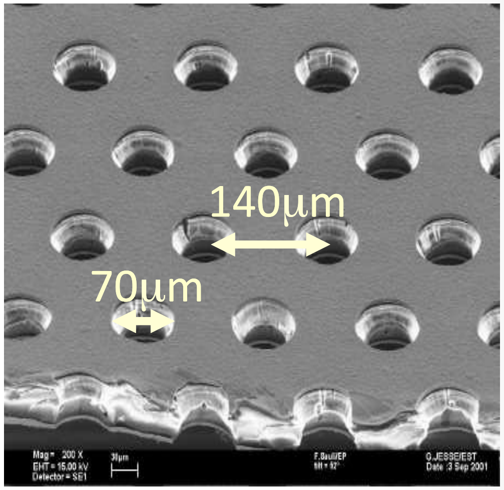


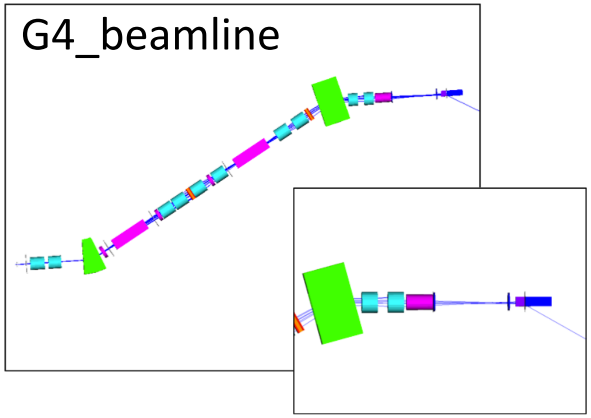
- Implemented in ILCRoot framework
- Verify acceptance increase relative to BNL E949
- Evaluate detector technology options
- Optimize detector design

ORKA R&D

- Improvement in sensitivity relative to BNL-E949 depends upon FNAL beam & modernization of experiment design
- Detector refinements:
  - Efficient photon detectors (ADRIANO/Shashlik)
  - Solid state photo-sensors (SiPMs)
  - Range-stack tracking (GEM/straw)
  - Low-mass drift chamber optimization
- Common front-end electronics for SiPM readout of stopping target, range stack, photon veto, beam monitors
- Fully-streaming, deadtimeless DAQ
- K^+ beam-line design

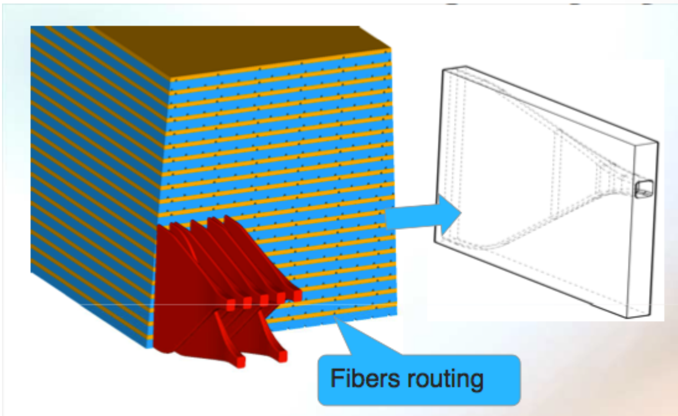
GEM foil:

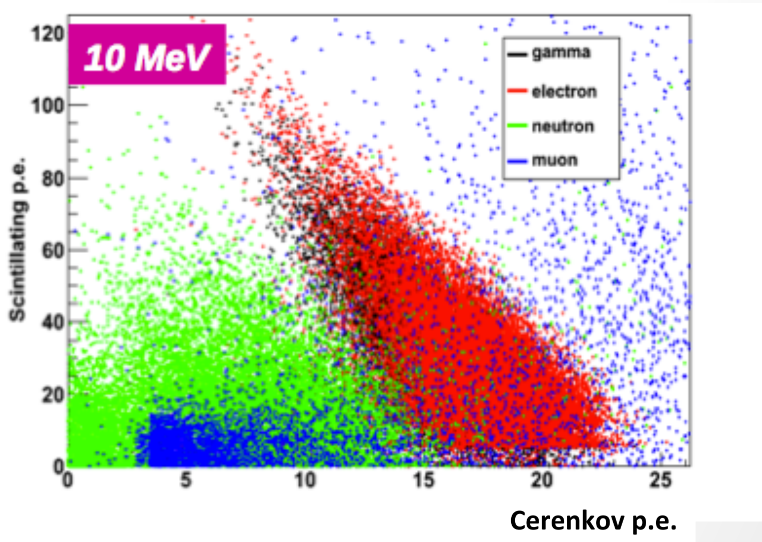




Fully-active Photon Veto

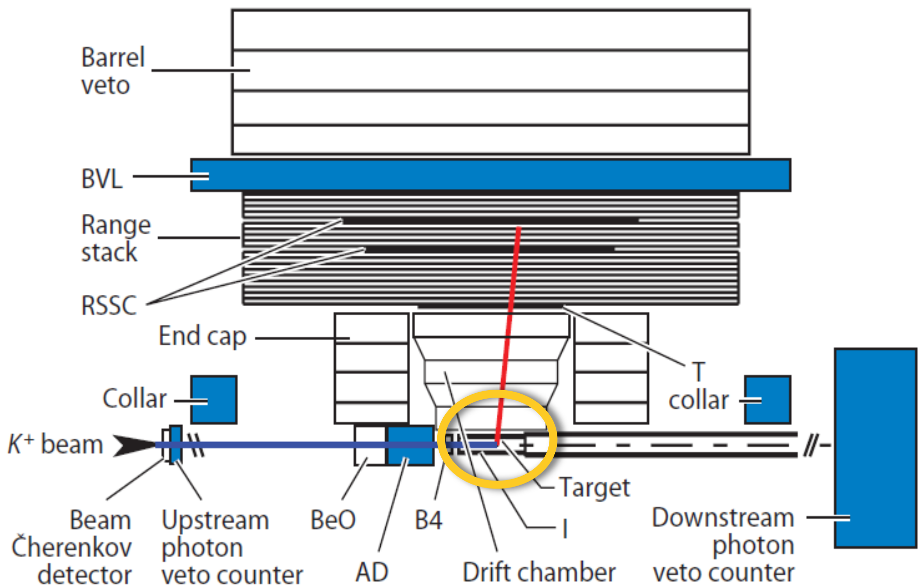
- E949 barrel-veto detector was Shashlik detector (lead-scintillator sandwich)
- ADRIANO (A Dual-Readout Integrally Active Non-segmented Option) under consideration for ORKA barrel-veto detector
  - Optically-separated layers of lead glass and plastic scintillator
  - Cerenkov light from lead glass
  - Scintillation light from plastic scintillator
  - Potential to improve photon-veto efficiency
  - Potential for particle identification



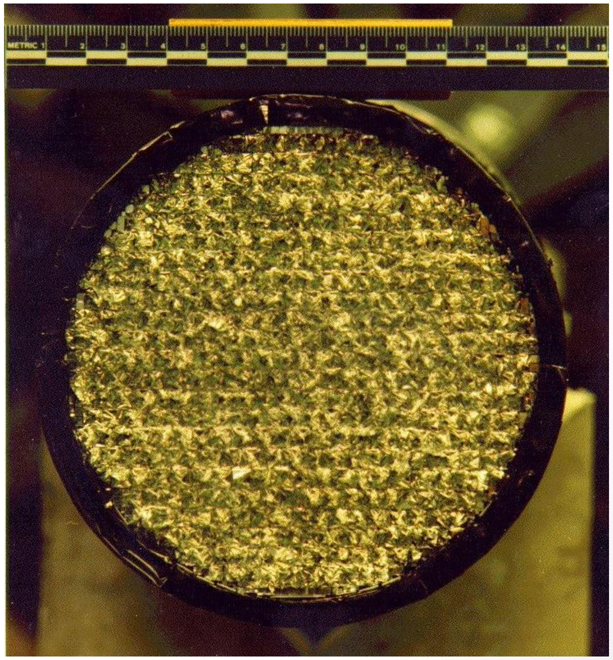


Scintillating-fiber Stopping Target

- E949 target:
  - 413 5-mm-square, 310-cm-long scintillating fibers (+"edge" fibers)
  - Read out by 1" PMTs
- ORKA target:
  - Similar design with shorter fibers (100-200 cm), finer segmentation?
  - Read out by SiPMs



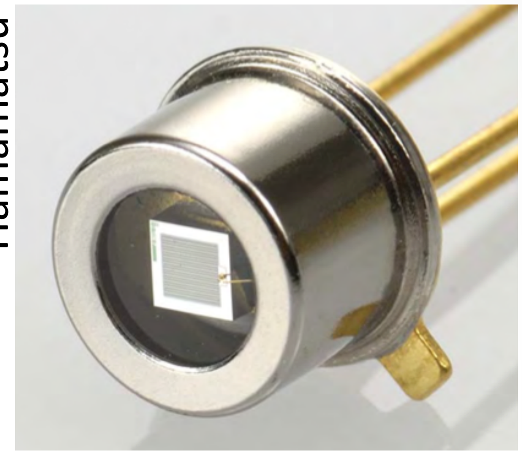
Side view (cutaway)

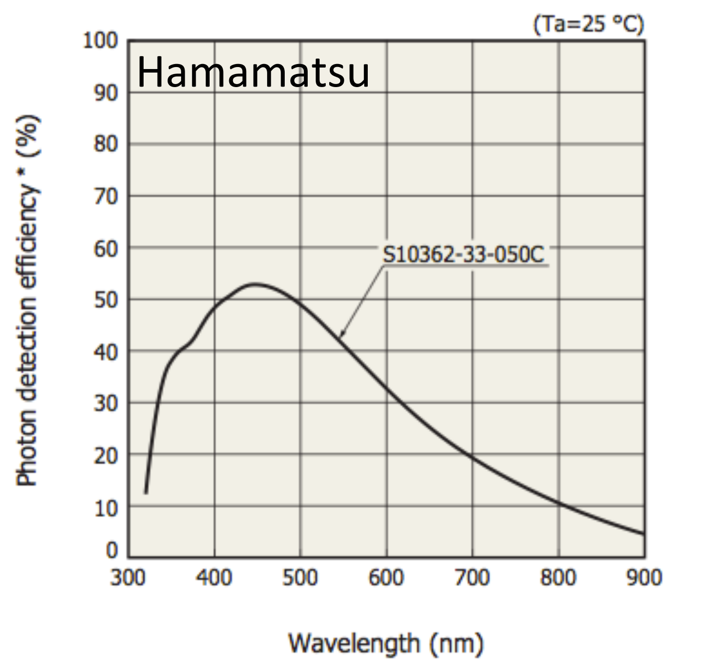


Silicon PhotoMultiplier (SiPM)

- Multi-pixel photo-detector
- Each pixel consists of an avalanche photodiode operating in Geiger mode
- Advantages
  - High gain, excellent time resolution (~500 ps)
  - Small size & insensitivity to magnetic fields allow direct coupling to detector: improved time resolution and light-collection efficiency
  - Relatively low cost: increased segmentation possible

Hamamatsu

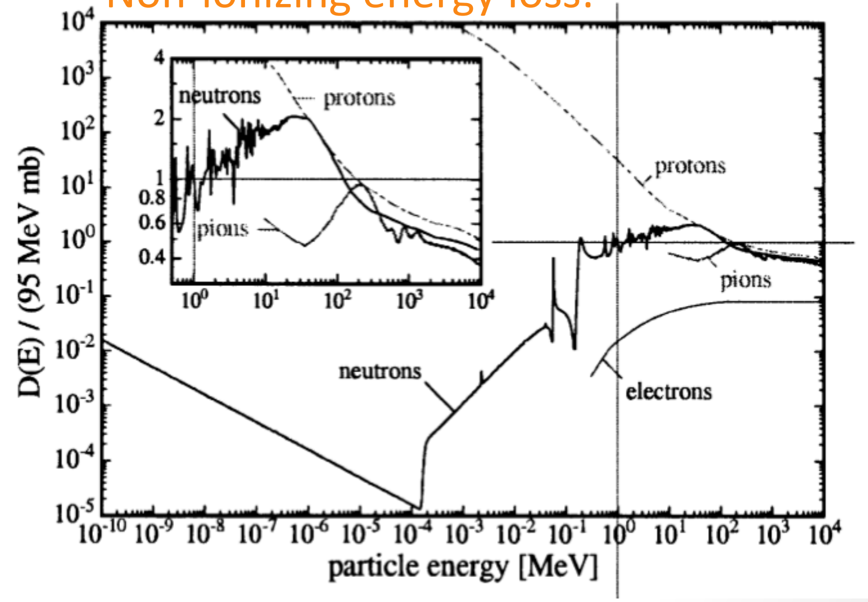




SiPM Radiation Damage

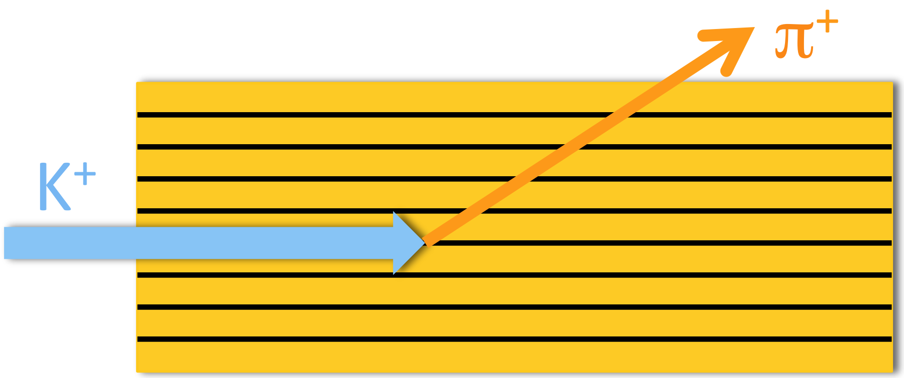
- Desirable to read out scintillating-fiber stopping target at both ends
  - Higher light-collection efficiency
  - Redundancy
  - More information about longitudinal position
- Convert particle fluence at upstream end of target to 1-MeV neutron equivalent: Φ_{eq}~10^{13} n/year-cm^2
- Compare to other HEP environments:
  - ATLAS inner detector Φ_{eq}~10^{13} n/cm^2
  - CMS Hcal Φ_{eq}~10^{12} n/cm^2
  - JLab test sees SiPM performance degradation at much lower levels of particle fluence.

Non-ionizing energy loss:

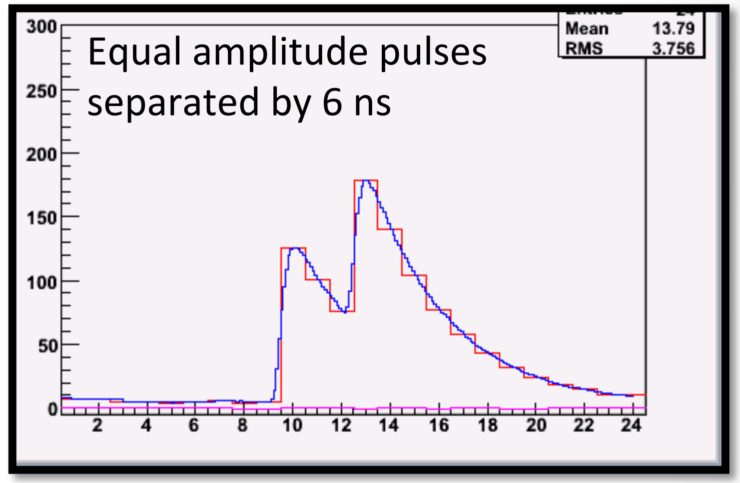


Further investigation needed!

SiPM Double-Pulse Resolution



SiPM pulse simulation, B. Kiburg (g-2):



- Incoming kaon: 1-100 MeV/fiber
- Outgoing pion: ~1 MeV/fiber
- K^+ lifetime: 12 ns
- Intrinsic SiPM pulse width: ~0.5 ns

Goal: ~2-ns double-pulse resolution for pulses with very different amplitudes

- SiPM pulse requires amplification (can degrade time resolution)
- Study using laser-diode with filters and delay lines to simulate kaon signal followed by pion signal

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

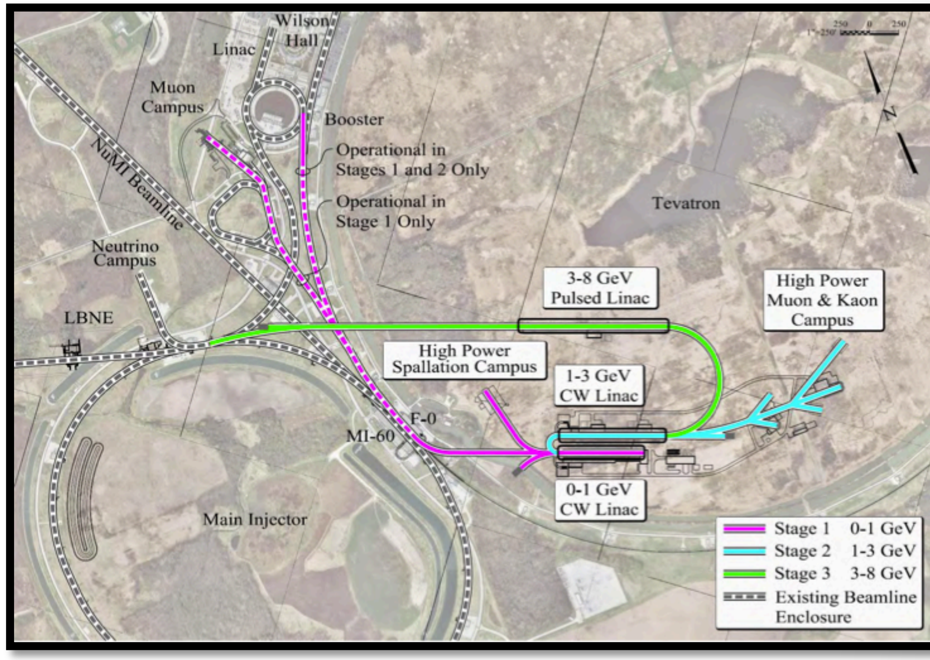
ORKA Summary

- 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
- 4th 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.

Project X at FNAL

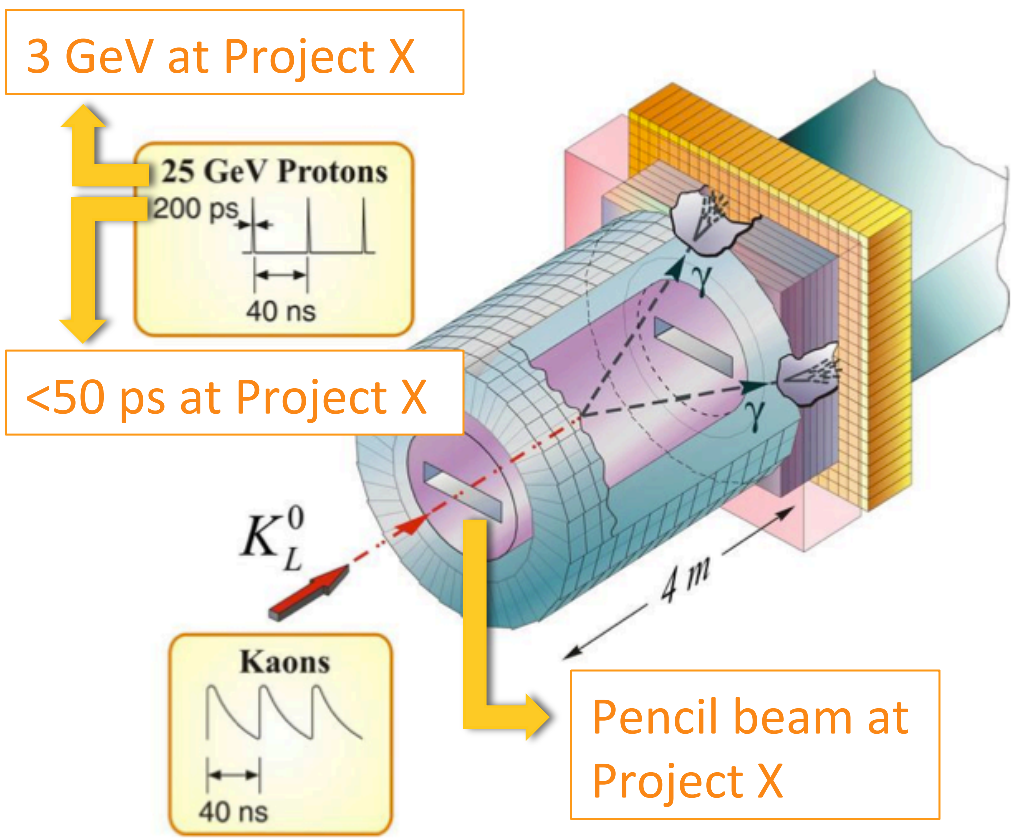
- Stage 1: 1-GeV CW linac providing beams to the existing 8-GeV booster, the muon campus, and a new 1-GeV experimental facility
- Stage 2: Addition of 1-3-GeV linac providing beam to a new 3-GeV experimental facility; upgrades of the 1-GeV linac and the Booster
- Stage 3: Addition of 3-8-GeV pulsed linac; upgrades to the Recycler and Main Injector



Project X Accelerator Reference Design: arXiv:1306.5022
Project X Physics Opportunities: arXiv:1306.5009

Kaon Physics at Project X

KOPIO Concept for $K_L \to \pi^0 \nu \bar{\nu}$ Experiment at AGS



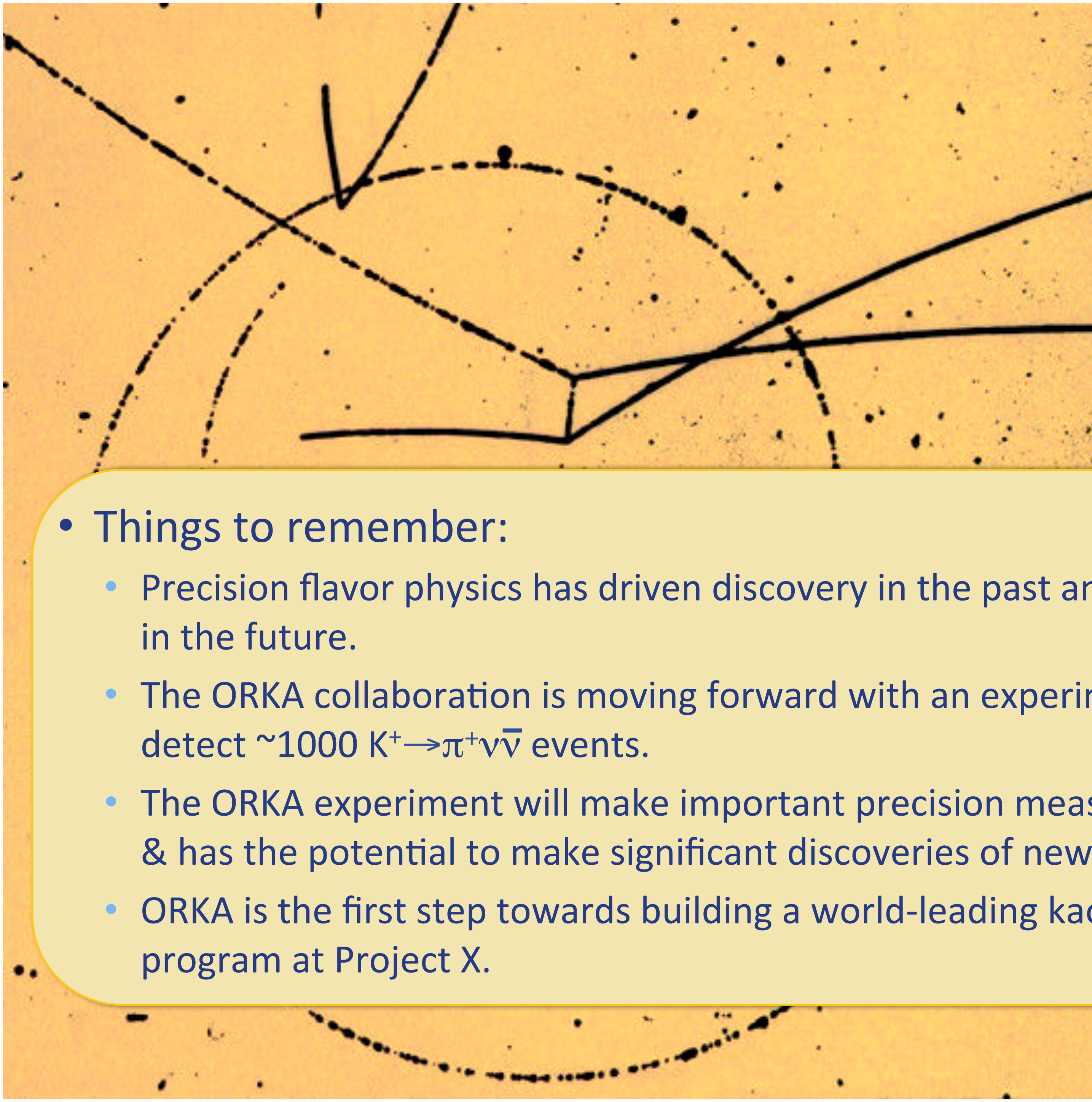
- Use time-of-flight to work in kaon center-of-mass system
- Requires micro-bunched beam
- KOPIO proposal was well-developed and thoroughly reviewed
- Higher intensity and tighter bunching at Project X allows for 1000-event $K_L \to \pi^0 \nu \bar{\nu}$ experiment

Kaon Physics at Project X

- 5% measurement of $K_L \to \pi^0 \nu\bar{\nu}$
- 2% measurement of $K^+ \to \pi^+ \nu\bar{\nu}$
- World-leading kaon-physics program!

Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$7.81(75)(29) \times 10^{-11}$	$1.73^{+1.15}_{-1.05} \times 10^{-10}$ E787/E949	$\sim$10% at NA62 $\sim$5% at ORKA $\sim$2% at Project-X
$\mathcal{B}(K^0_L \to \pi^0 \nu\bar{\nu})$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a	1st observation at KOTO $\sim$5% at Project-X
$\mathcal{B}(K^0_L \to \pi^0 e^+ e^-)$	$(3.23^{+0.91}_{-0.79}) \times 10^{-11}$	$< 2.8 \times 10^{-10}$ KTeV	$\sim$10% at Project-X
$\mathcal{B}(K^0_L \to \pi^0 \mu^+ \mu^-)$	$(1.29^{+0.24}_{-0.23}) \times 10^{-11}$	$< 3.8 \times 10^{-10}$ KTeV	$\sim$10% at Project-X
$\lvert P_T \rvert$ in $K^+ \to \pi^0 \mu^+ \nu$	$\sim 10^{-7}$	< 0.0050	< 0.0003 at TREK < 0.0001 at Project-X
$\Gamma(K_{e2})/\Gamma(K_{\mu 2})$	$2.477(1) \times 10^{-5}$	$2.488(12) \times 10^{-5}$ (NA62, KLOE)	$\pm 0.0054 \times 10^{-5}$ at TREK $\pm 0.0025 \times 10^{-5}$ at Project-X
$\mathcal{B}(K^0_L \to \mu^\pm e^\mp)$	$< 10^{-25}$	$< 4.7 \times 10^{-12}$	$< 2 \times 10^{-13}$ at Project-X

See *Report of Quark Flavor Physics Working Group* in Snowmass CSS2013 Proceedings (coming soon).



- Things to remember:
  - Precision flavor physics has driven discovery in the past and can do so in the future.
  - The ORKA collaboration is moving forward with an experiment to detect ~1000 $K^+ \to \pi^+ \nu \bar{\nu}$ events.
  - The ORKA experiment will make important precision measurements & has the potential to make significant discoveries of new physics.
  - ORKA is the first step towards building a world-leading kaon-physics program at Project X.