ORKA
A Golden Kaon Experiment at Fermilab

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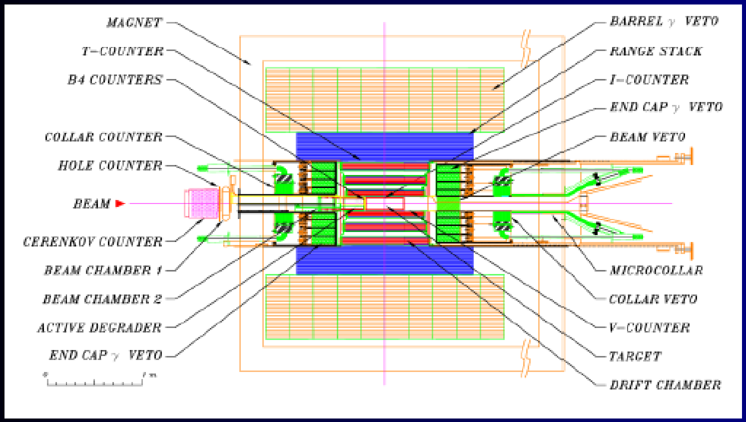
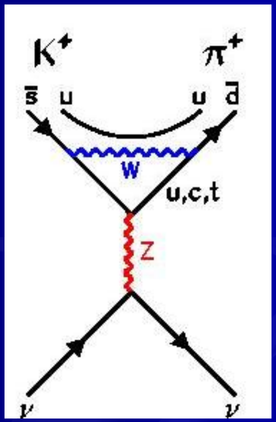
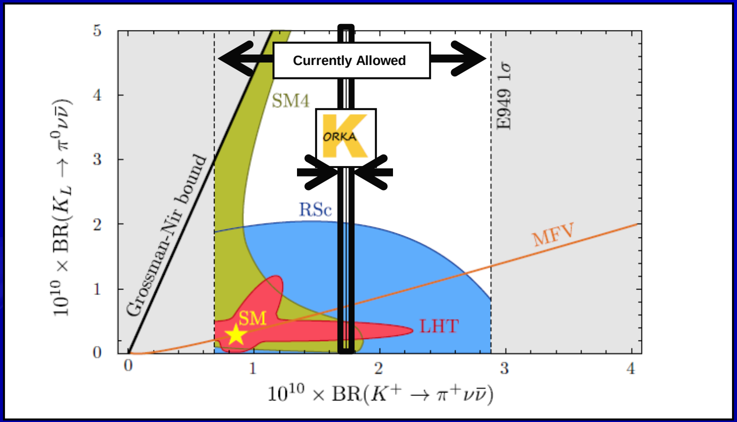


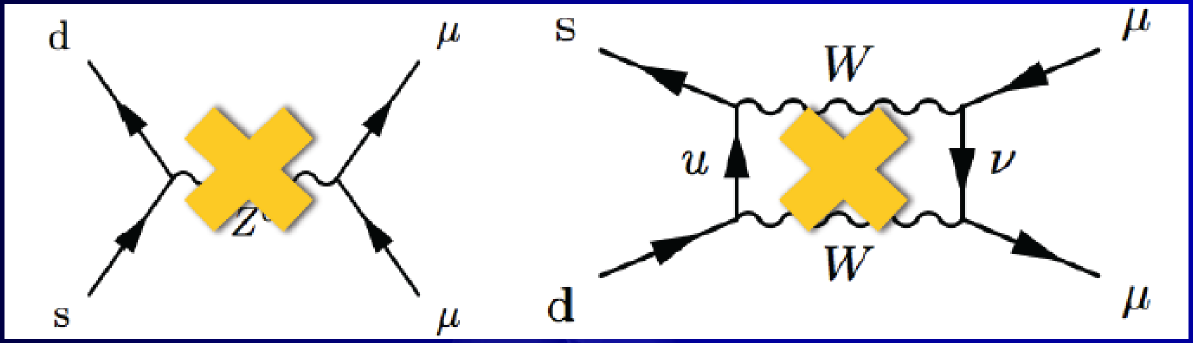




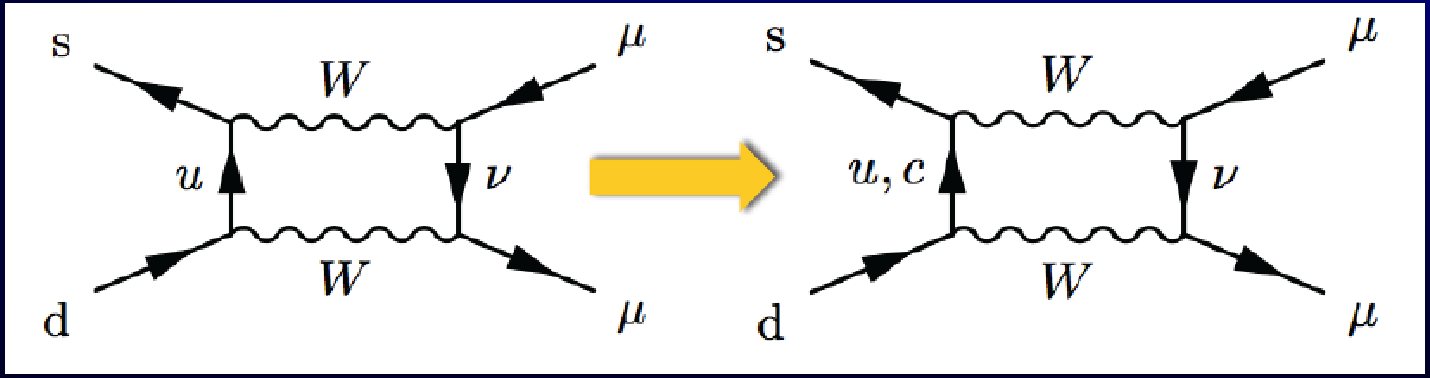
- **Precision measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ BR at FNAL MI**
  - Observe ~1000 events
  - Expected BR uncertainty matches Standard Model uncertainty: 5σ reach for 35% deviation from BR_{SM}.
- **Sensitivity to new physics at and beyond LHC mass scale**
  - New Physics at LHC → Explore its flavor structure
  - No New Physics at LHC → Explore higher mass scales
- **Builds on successful previous experiments**
  - BNL E787/E949: 7 candidate events observed

FCNC

- **Highly suppressed in SM:** $\frac{BR(K_L \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu)} \sim 10^{-8}$

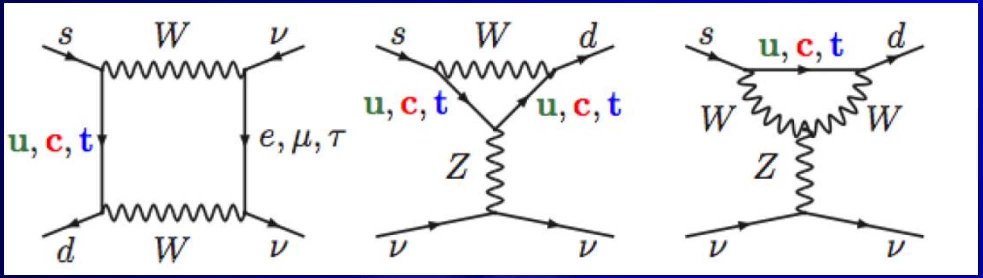


- **Tree level forbidden by weak isospin**
- **Higher order loops suppressed by GIM mechanism**
  - Coupling to 4th quark, c, with opposite sign to u coupling



So Why $K^+ \to \pi^+ \nu\bar{\nu}$?

- **$K \to \pi\nu\nu$ "Golden decays" are the most precisely predicted FCNC decays involving quarks**



- A single effective operator: $(\bar{s}_L \gamma^\mu d_L)(\overline{\nu_L} \gamma_\mu \nu_L)$
- Dominated by top quark
- Hadronic matrix element from well-measured $K^+ \to \pi^0 e^+ \nu_e$
- Dominant uncertainty from CKM matrix elements

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

* Expect prediction to improve to ~5%

CKM Matrix and CP Violation

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

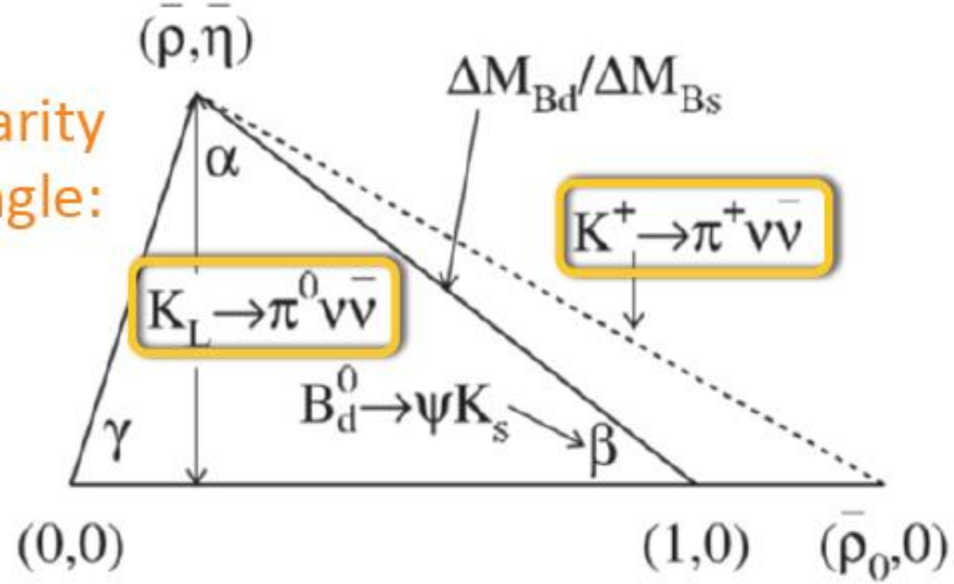
weak eigenstates — Cabibbo Kobayashi Maskawa (CKM) matrix — mass eigenstates

Wolfenstein Parameterization:

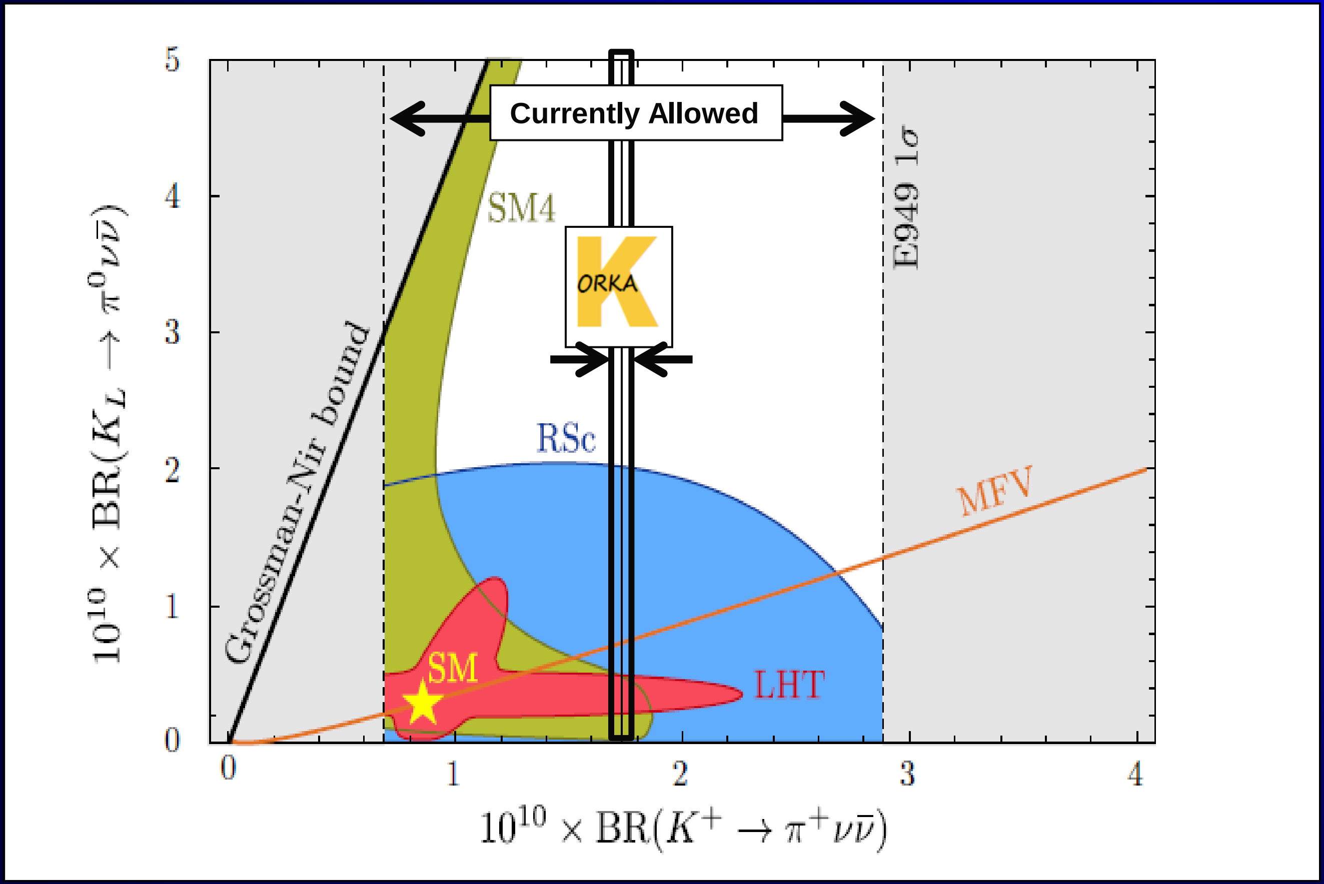
$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CP Violation

Unitarity Triangle:



Sensitivity to New Physics



D. M. Straub, arXiv:1012.3893

- **With prediction and measurement at the 5% level, deviations from the SM as small as 35% can be detected at 5σ**

New Physics Flavor…

	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

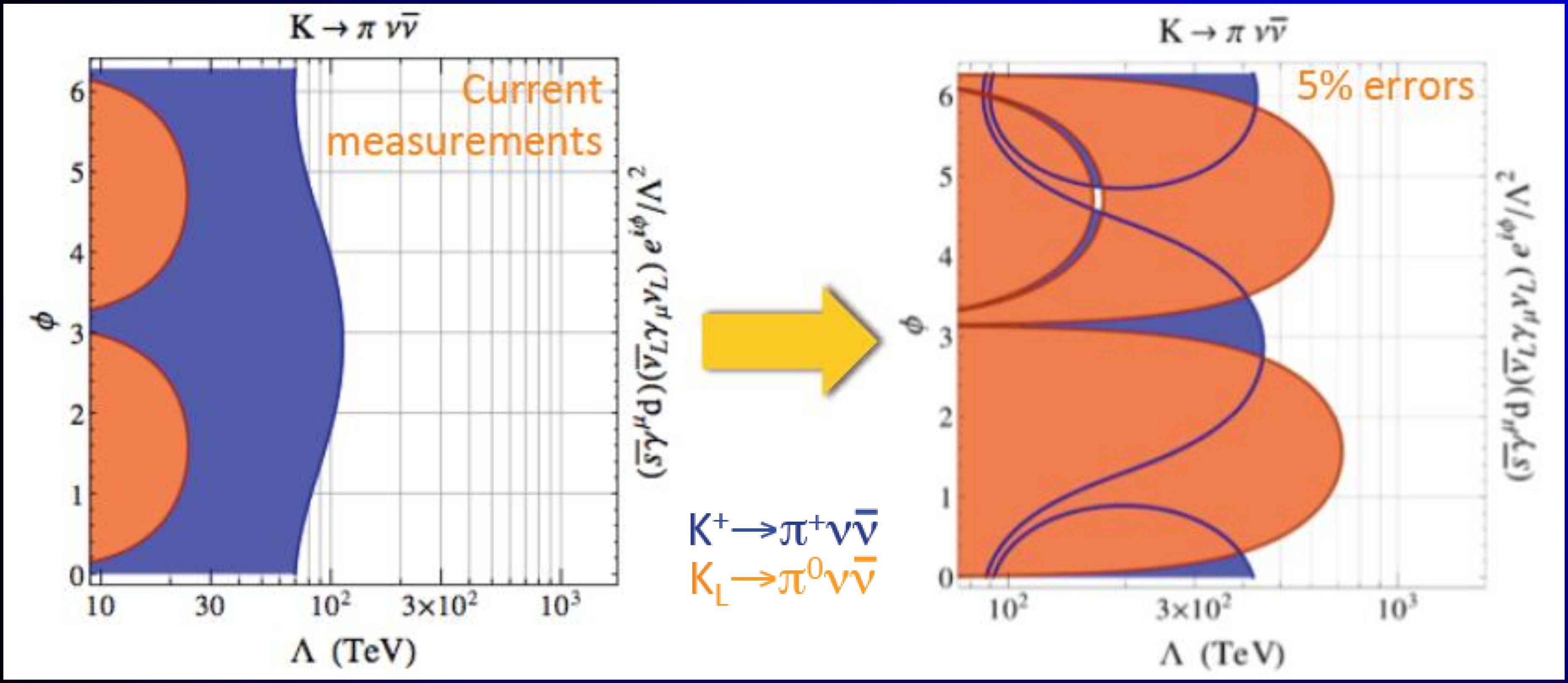
Models

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).

- **Complementary to B and lepton flavor studies**

High Mass Scales



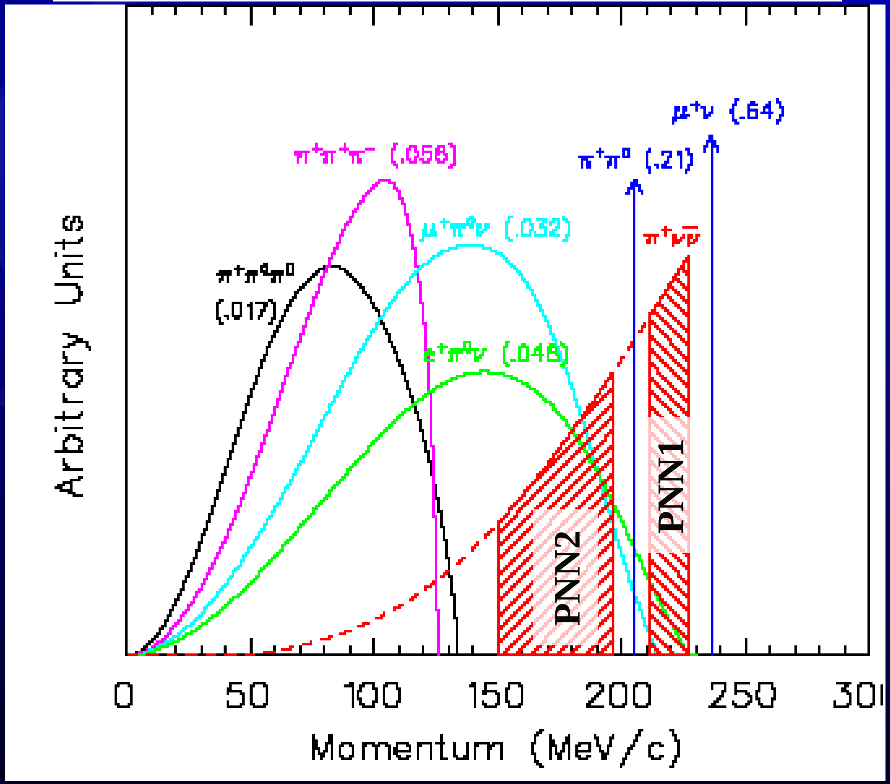
W. Altmannshofer: https://indico.fnal.gov/contribu:onDisplay.py?contribId=64&sessionId=0&confId=6248

- **Can probe up to 700 TeV with charged and neutral modes measured to 5%!**

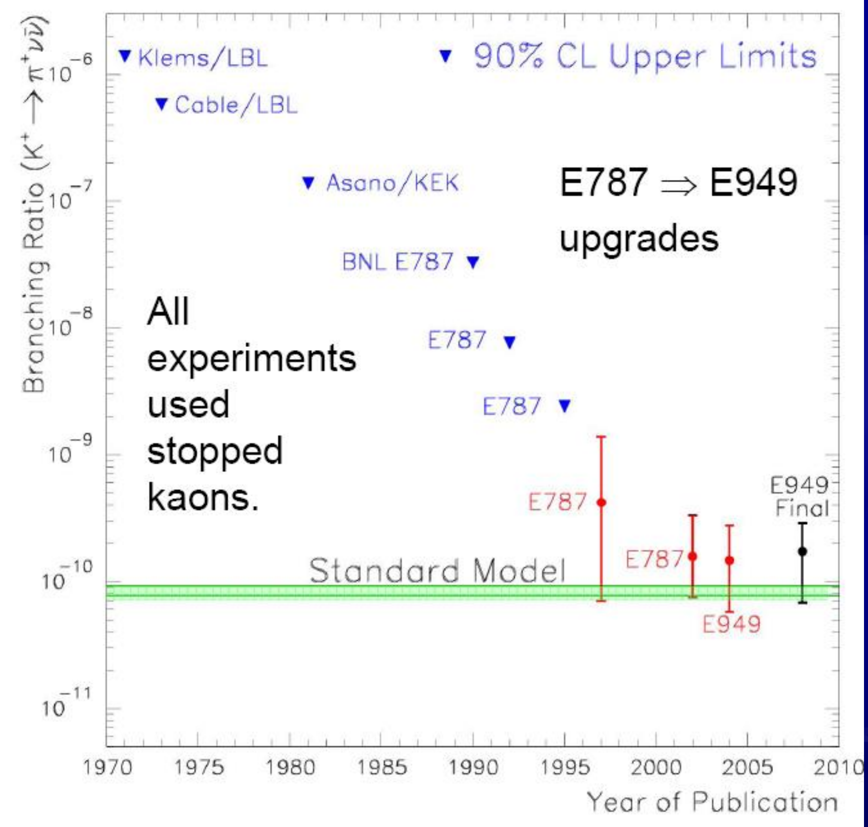
Measuring $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

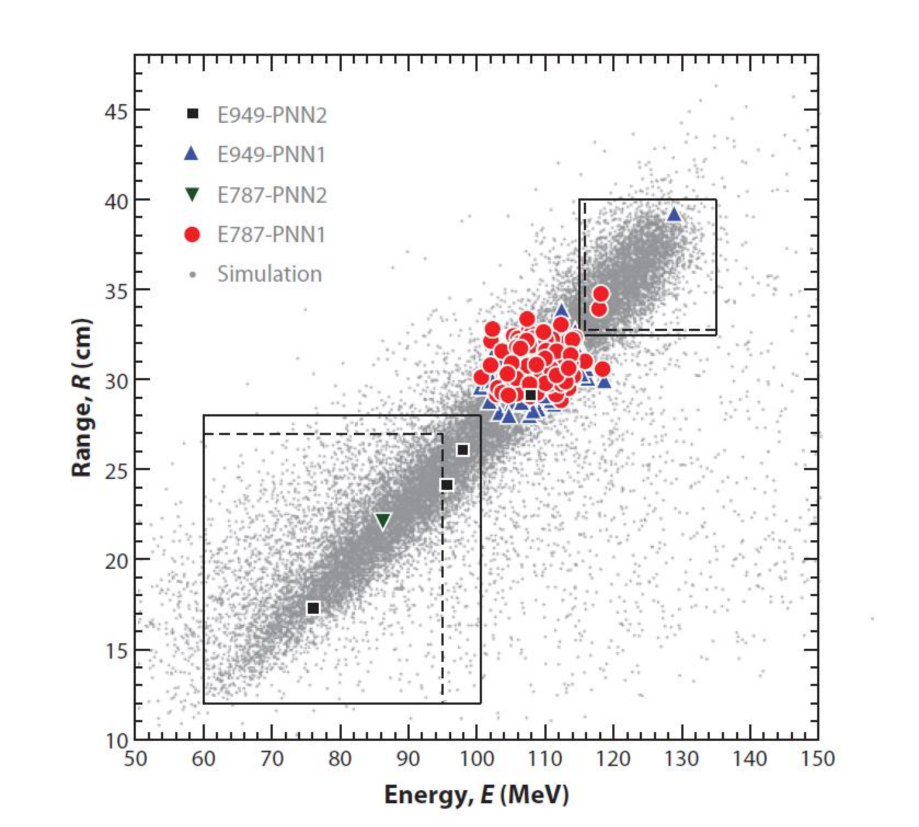
- **Observed signal is $K^+ \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$**
  - i.e. π^+ + nothing!
- **Extremely challenging problem to separate signal from background**
- **Background exceeds signal by > 10^{10}**
- **Requires background suppression to S/B ~10**
- **Requires $\pi/\mu/e$ particle ID > 10^6**
- **Requires π^0 photon veto inefficiency < 10^{-6}**
- **Requires efficient K^+ ID**

Charged Particle Momentum in K Rest Frame



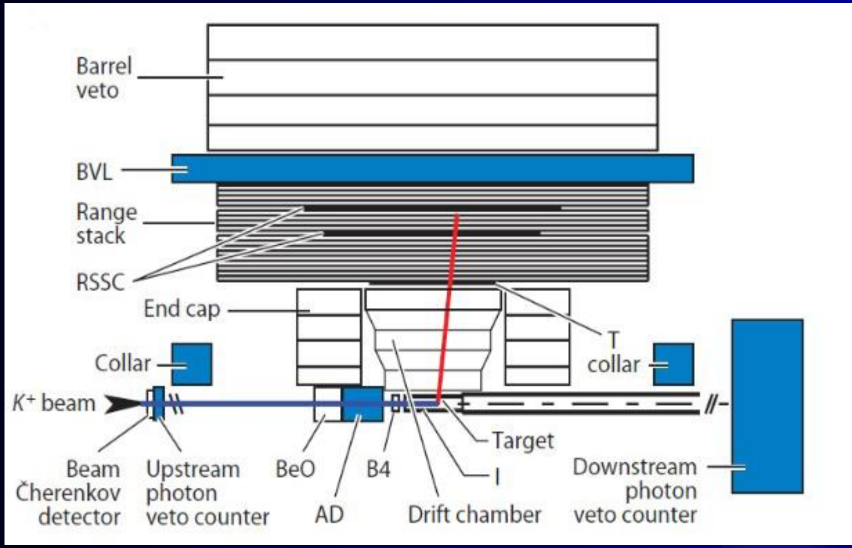
Experimental History

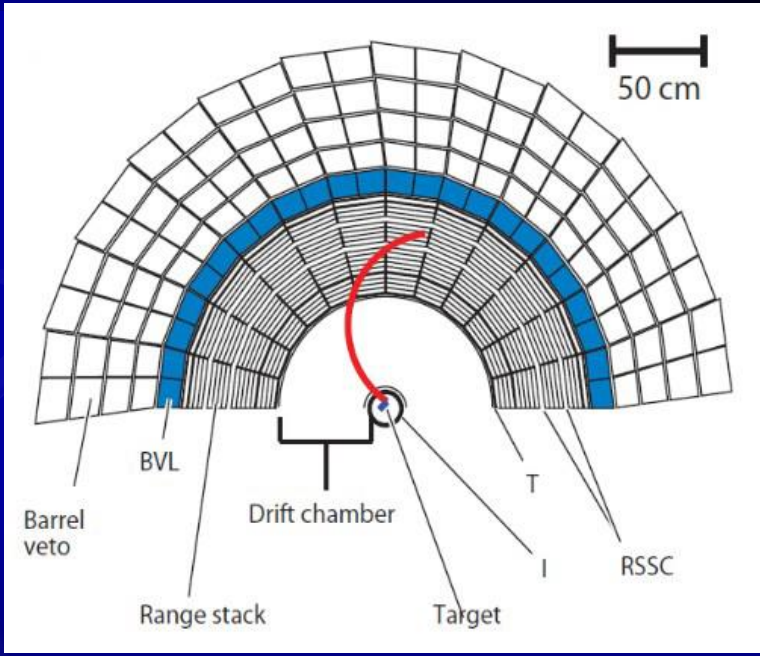




- BNL E787/E949: $BR(K^+ \to \pi^+ \nu\bar{\nu}) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$
  - 7 observed events
- Standard Model: $BR(K^+ \to \pi^+ \nu\bar{\nu}) = 7.8 \pm 0.8 \times 10^{-11}$

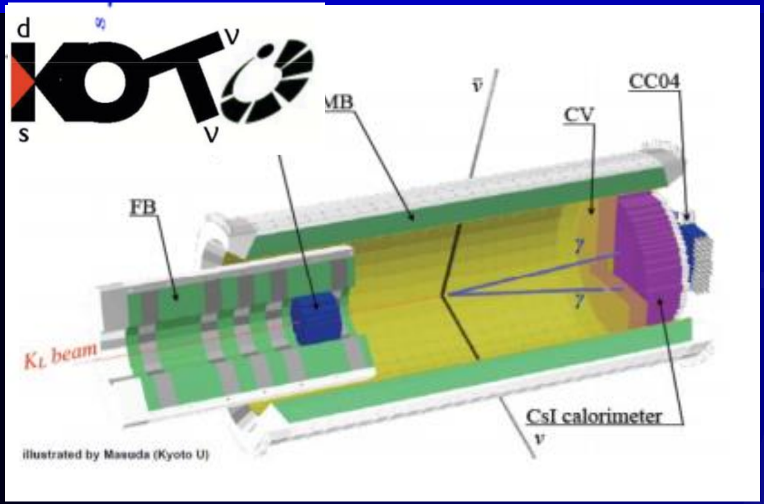
BNL Stopped K Technique

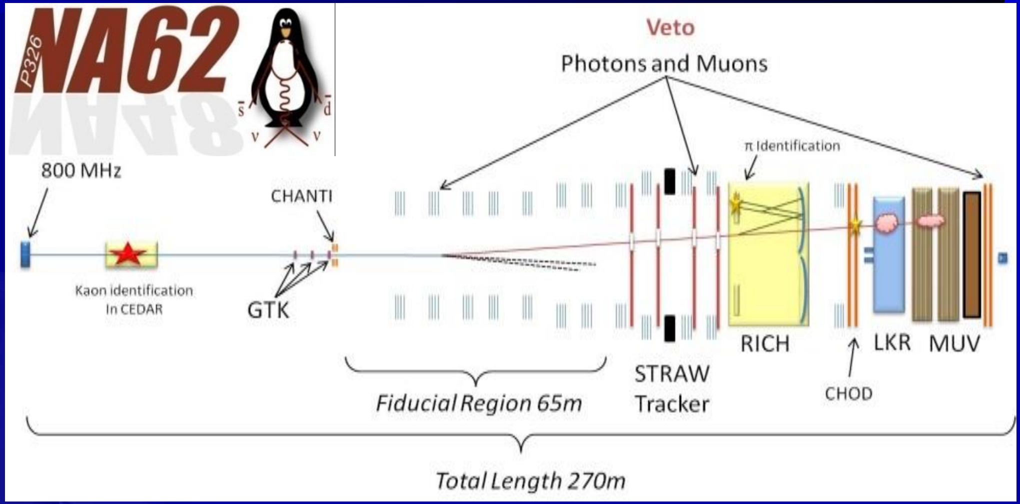




- **Stop and ID K^+ in active target**
  - Look for delayed decay to suppress prompt background
- **π^+ momentum in drift chamber**
- **π^+ energy in target and range stack (where it stops)**
  - Position in range stack straw chamber
- **$\pi^+ \rightarrow \mu^+ \rightarrow$ *(delayed)* e^+ chain in range stack**
- **4π photon veto system**

Current Worldwide Efforts





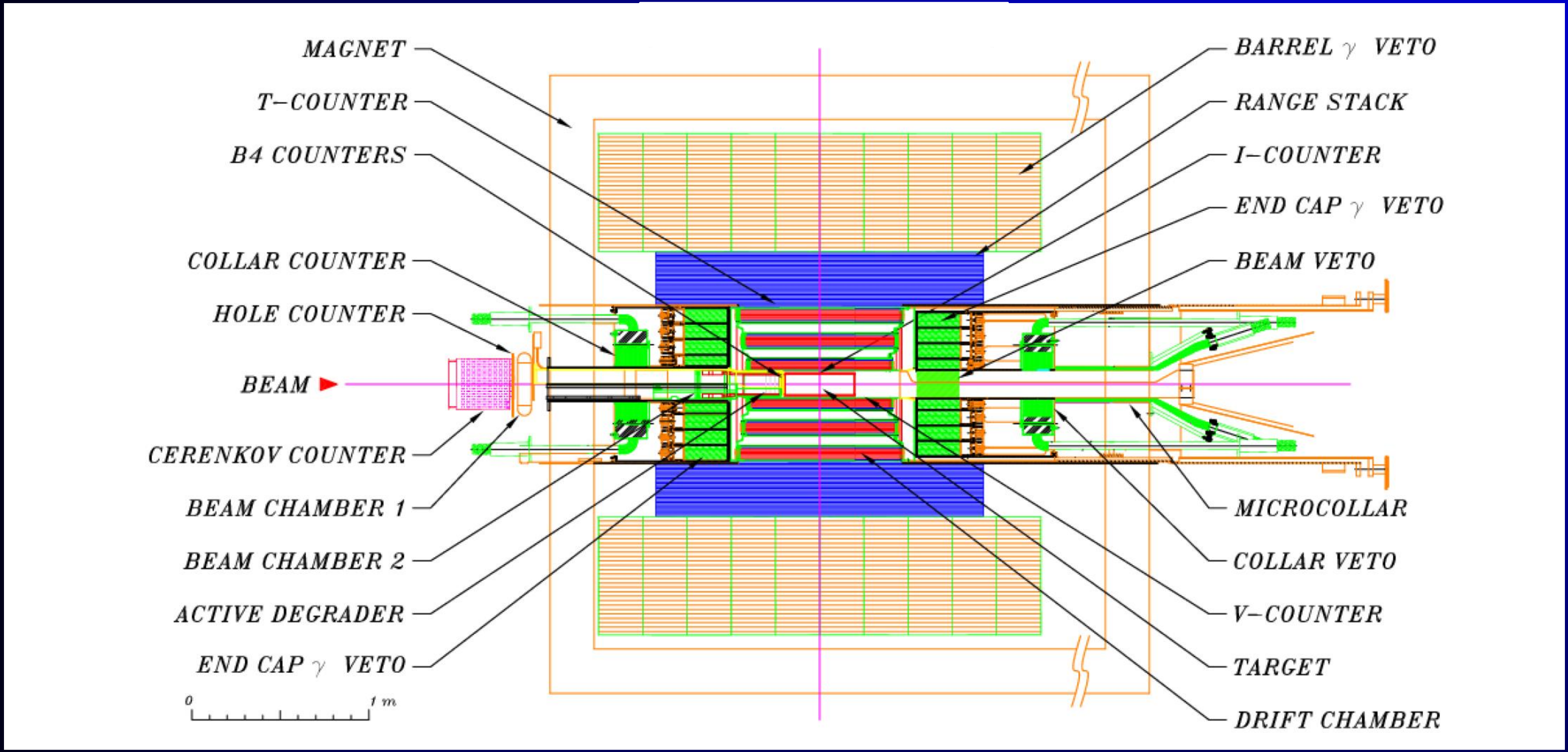
- J-PARC E14: KOTO
- $K_L \rightarrow \pi^0 \nu\overline{\nu}$
- Pencil beam decay in flight
- 2nd generation (KEK E391)
- Reuse KTeV CsI for calorimeter
- Goal: ~3 events (SM), S/B ~ 1
- 2013 commissioning

- CERN NA-62
- $K^+ \rightarrow \pi^+ \nu\overline{\nu}$
- Decay in flight
- 3rd generation (NA-31/NA-48)
- Goal: ~100 events (SM), S/B ~ 10
- Data taking 2015-2018

ORKA at Fermilab

- **Goal: ~1000 $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events over 5 year run (5% unc.)**
  - 10^{13} K^+: studies of other rare processes at 10^{-12} sensitivity
- **Stopped K^+ technique - builds on BNL E787/E949**
  - Complementary to NA-62
- **17 institutions in 6 countries (Canada, China, Italy, Mexico, Russia, USA)**
  - 6 US universities, 2 US national labs
  - Leadership from previous BNL and FNAL US rare K decay experiments

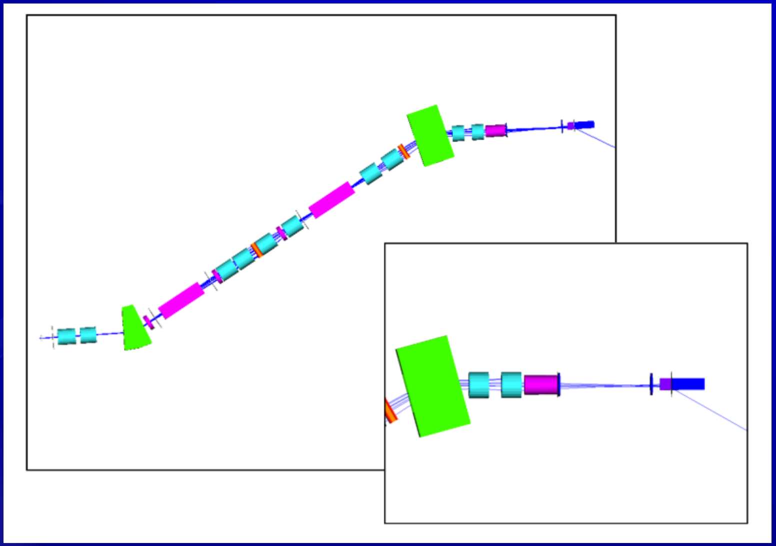
ORKA Detector



- **4th generation detector**
- **Expect ×100 sensitivity relative to BNL E949**
  - ×10 from beam, ×10 from detector

Beam Sensitivity Improvement

- **Primary Beam from Main Injector**
  - 95 GeV/c protons
  - 50-75 kW slow-extraction
  - 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)**

Overall ×10 improvement relative to E949

Detector Acceptance Improvement

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})	$11.28^{+3.25}_{-2.22}$

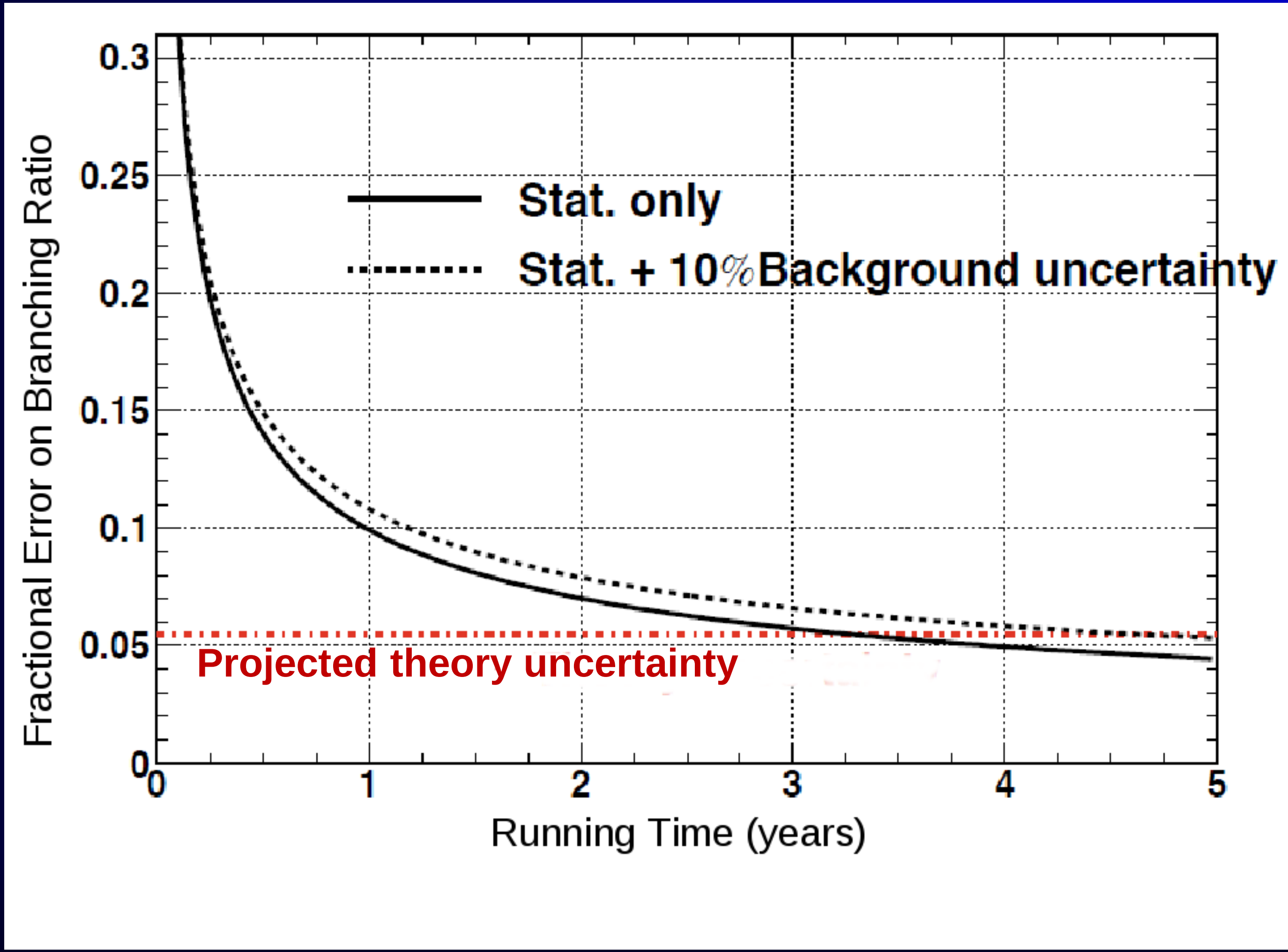
Better hermiticity, granularity, light yield

Investigate different technology

Overall ×11 improvement relative to E949

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

- **210 events/year (SM)**



Other ORKA Physics Topics

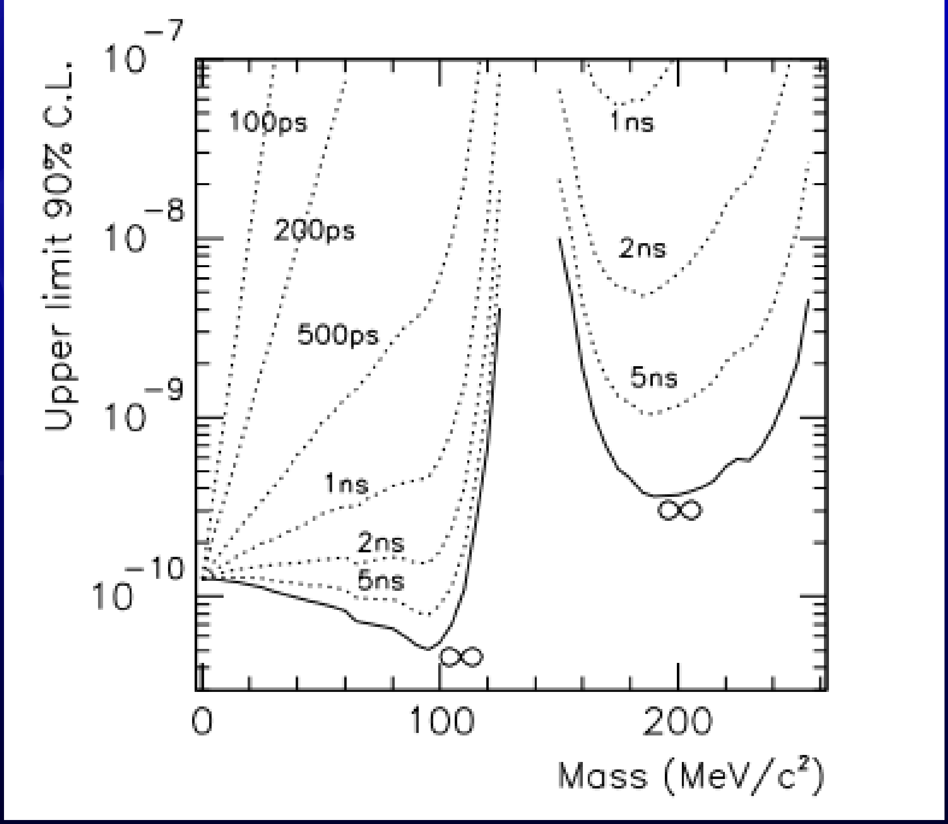
- $K^+ \to \pi^+ +$ missing energy
  - $K^+ \to \pi^+ \nu\bar{\nu}(1)$ ^{T,P}
  - $K^+ \to \pi^+ \nu\bar{\nu}(2)$ ^{T,P}
  - $K^+ \to \pi^+ \nu\bar{\nu}\gamma$
  - $K^+ \to \pi^+ X$ ^{P}
  - $K^+ \to \pi^+ \tilde{\chi}_0\tilde{\chi}_0(\mathrm{FF})$ ^{P}
- $K^+ \to \pi^+\pi^0 +$ missing energy
  - $K^+ \to \pi^+\pi^0\nu\bar{\nu}$ ^{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/E949 Thesis ; ^{P}E787/E949 Publication; DP≡Dark Photon

- **E787/E949: 42 publications, 26 theses**
- **KTeV: 50 publications, 32 theses**

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

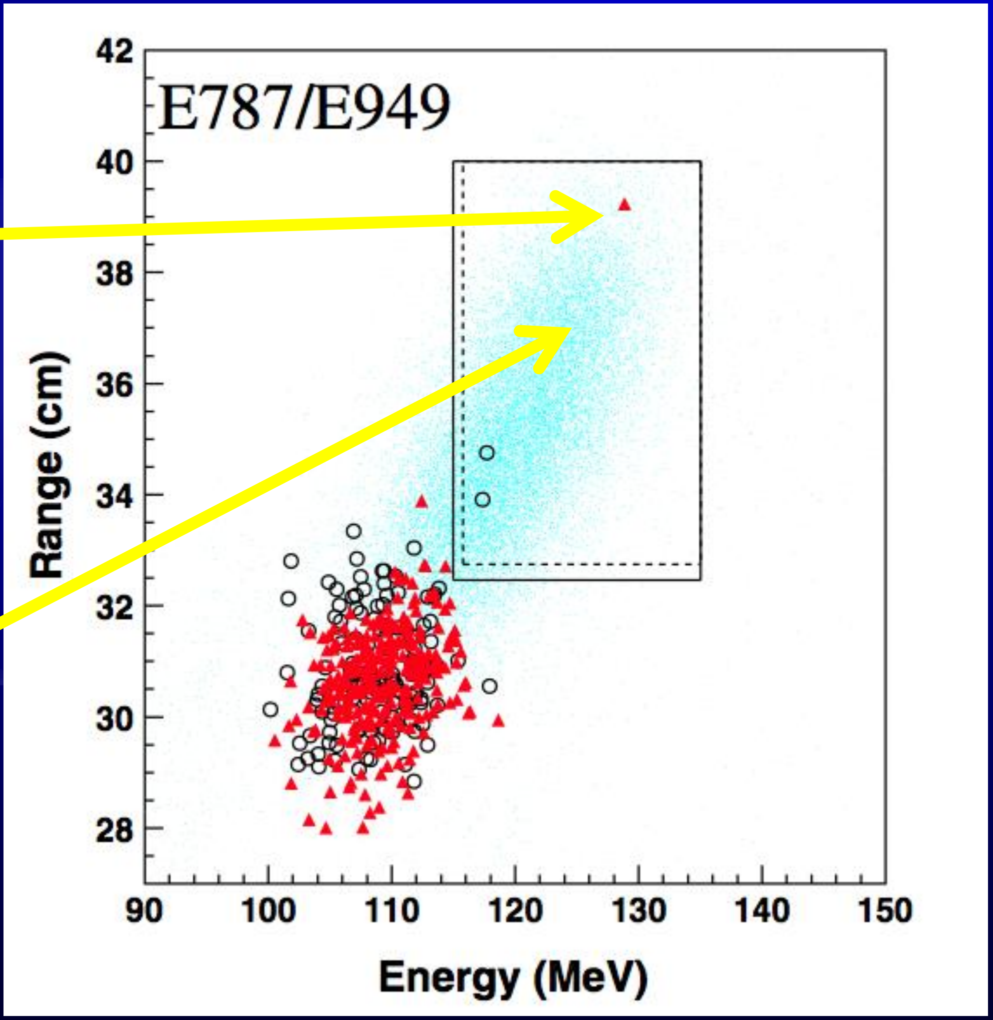
- **Many models for X^0**
  - familon, axion, light scalar pseudo-NG boson, sgoldstino, gauge boson corresponding to new U(1) symmetry, light dark matter…
- **$K^+ \to \pi^+ \nu\bar{\nu}$ is background**



- E787/E949
- Curves represent upper limits for specified X^0 lifetimes

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

- **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…**



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

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

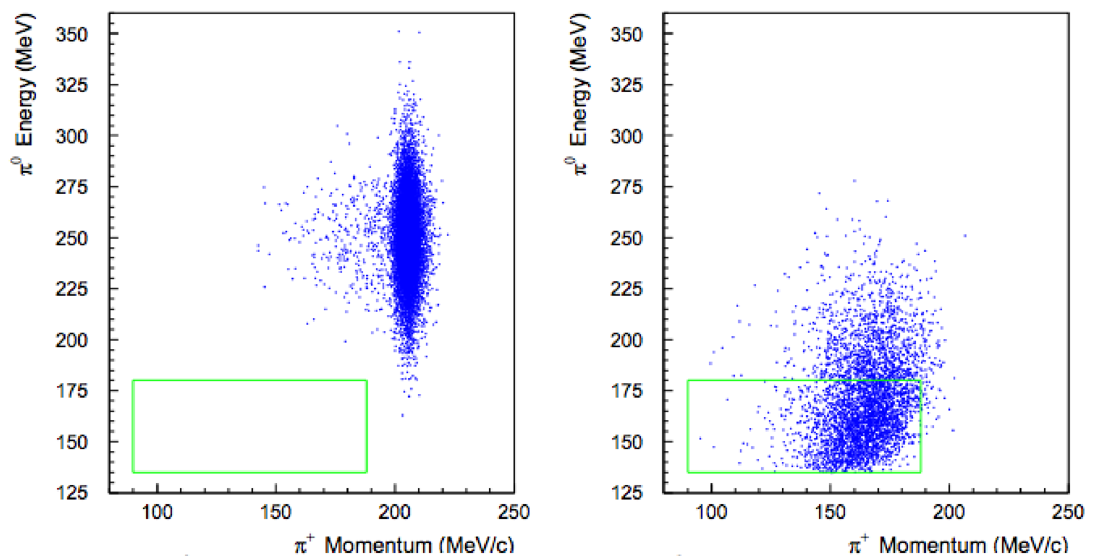


FIG. 4. π^0 energy versus π^+ momentum for $K^+ \rightarrow \pi^+\pi^0\nu\bar{\nu}$ candidates (left) and for Monte Carlo signal events (right). Box indicates the signal acceptance region. $K_{\pi 2}$ events cluster at the upper right in the top plot.

  - BNL E787 arXiv:hep-ex/0009055v1

ORKA Physics Sensitivity

Process	Current	ORKA
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \pi^0 X^0$	$<\sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$
$K^+ \to \mu^+ \nu_{heavy}$	$< 2 \times 10^{-8} - 1 \times 10^{-7}$	$< 1 \times 10^{-10}$
$K^+ \to \mu^+ \nu_\mu \nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$
$K^+ \to \pi^+ \gamma\gamma$	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 $< 4 \times 10^{-9}$
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$

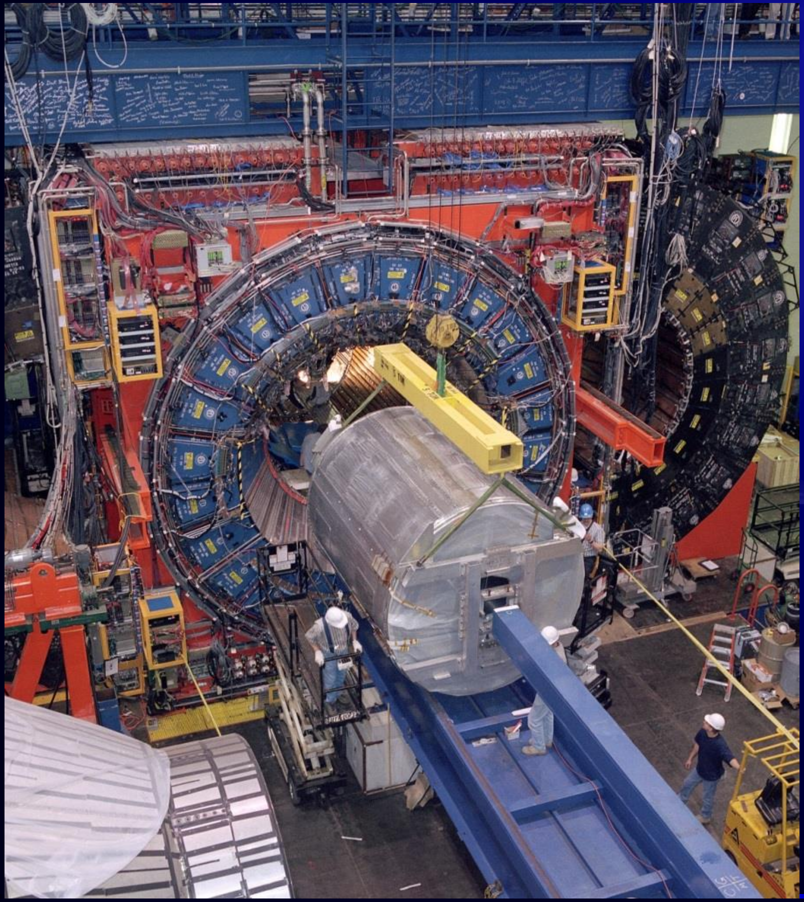
- **Optimized for $K^+ \to \pi^+ \nu\bar{\nu}$, but capable of precision measurements of many rare processes**
- **Broad discovery potential**
- **Rich training ground for next generation of students**

Experimental Facility at Fermilab

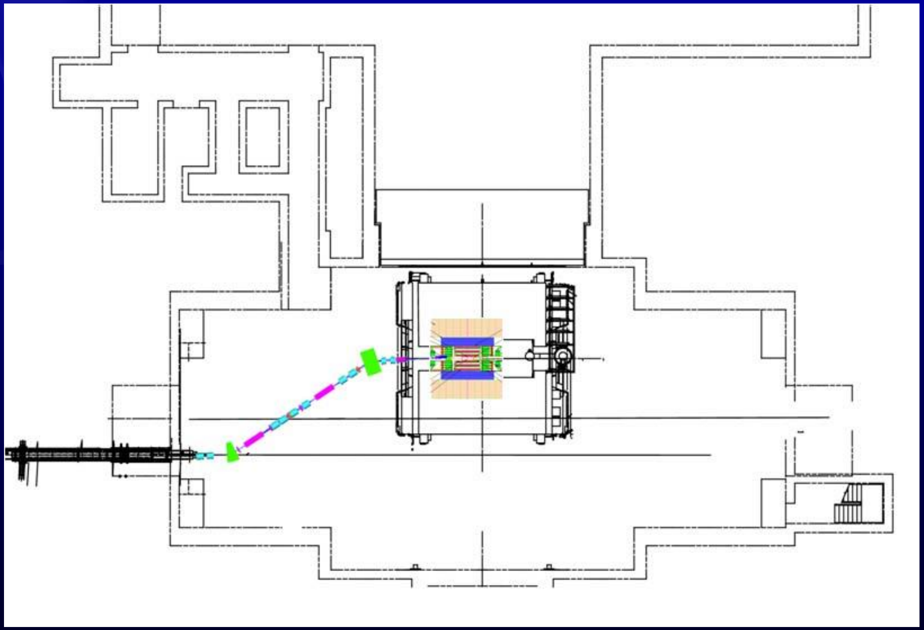
- **Main Injector**
  - 75 KW required (of 700 KW)
  - 95 GeV/c
  - 44% duty factor
    - (10 s cycle, 4.4 s spill)
- **Tevatron tunnel, A0-B0**
  - New beamline with recycled magnets
- **CDF Collision Hall**
  - ORKA fits inside CDF solenoid
  - Reuse solenoid, cryogenics, infrastructure
- **No civil construction!**

ORKA in CDF

- ORKA detector payload replaces the CDF tracker volume

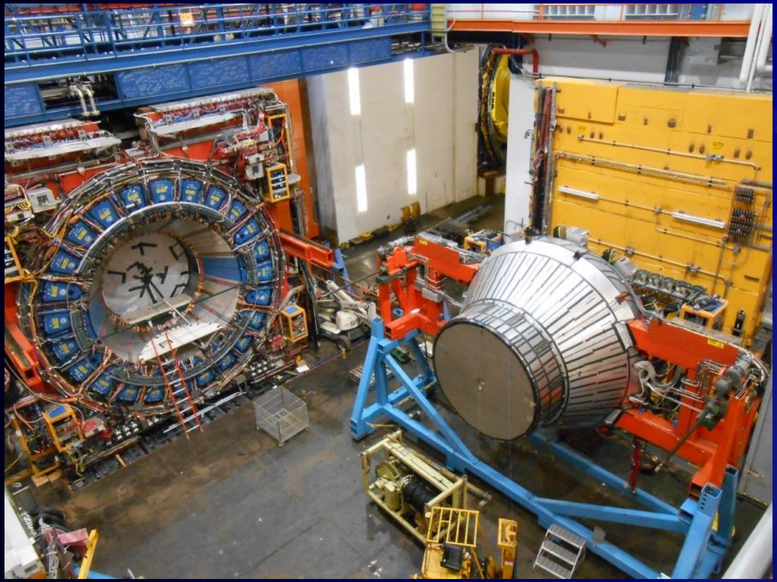


- Primary beam line moved 6 feet south
- Dog-leg kaon beam line
- Spectrometer moved 10 feet north



CDF Hall Prep

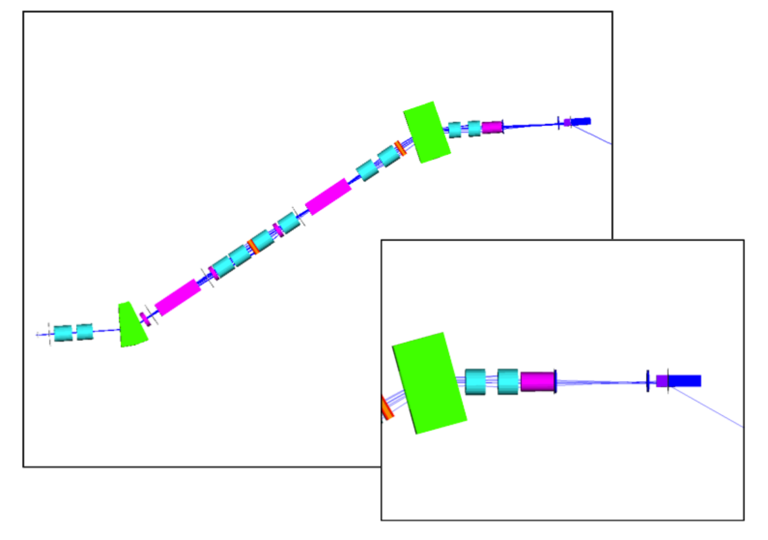
- CDF decommissioning and demolition



- Central detector removal
- Removal of cables, electronics, PMTs
- Muon system demolition
- ….

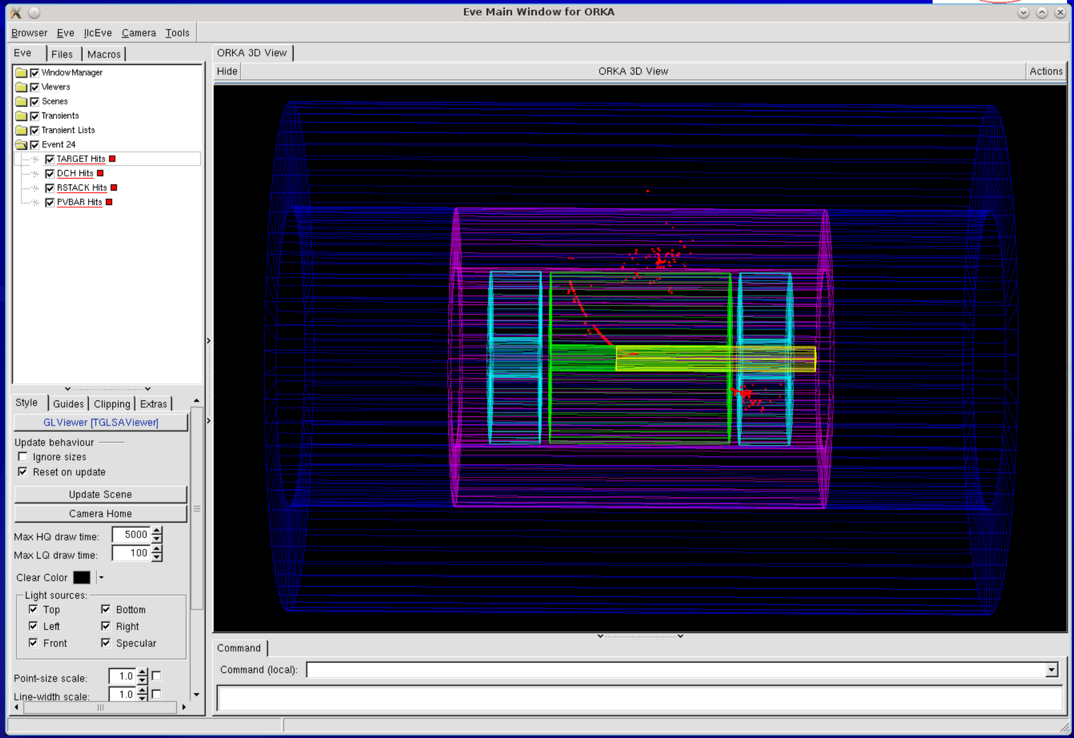
Beamline Simulations

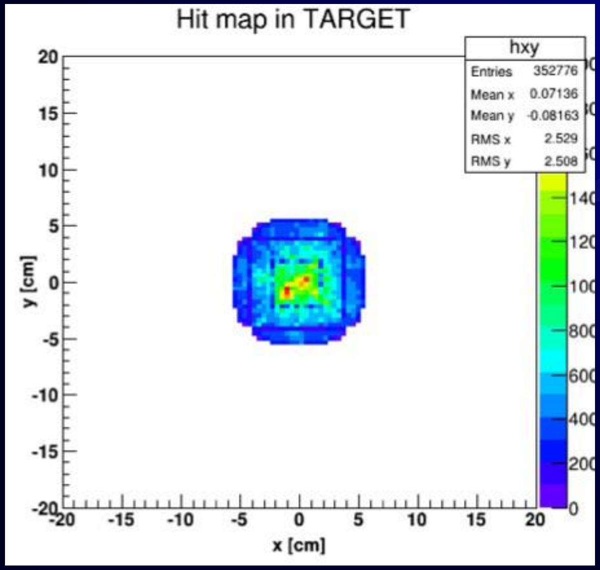
- **Detailed simulation work of beam from production target to stopping target**
  - G4Beamline, Transport, Turtle
  - Redesigned from BNL-style 90-degree bend to dog-leg configuration
- **Studies show encouraging K/π ratio**
- **MARS target studies show acceptable backgrounds**



Physics & Detector Simulations

- **Full simulation and digitization implemented in ILCRoot framework**
- **Verify improvements relative to BNL E949**





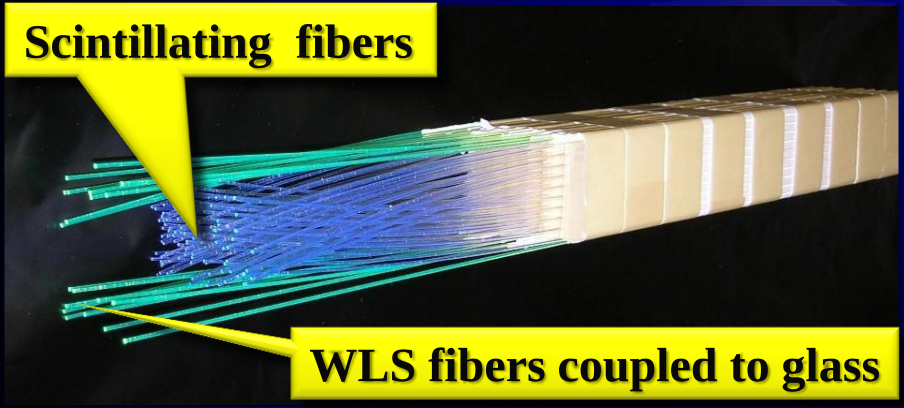
- **Detector optimization studies**
  - Length, depth and segmentation
  - Technology options
    - Shashlyk vs. Adriano calorimeter
    - Scintillator vs. high-pressure gas stopping target

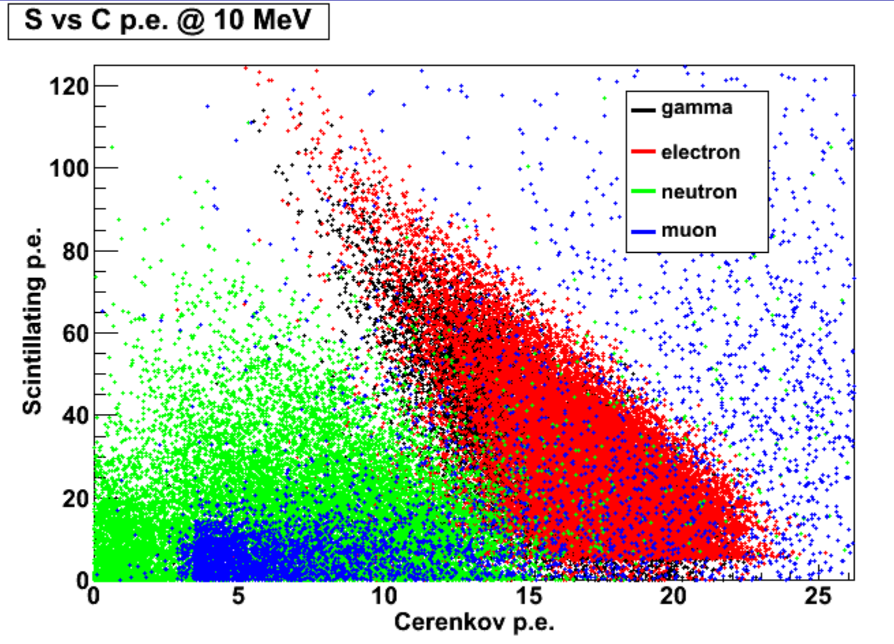
ORKA R&D Program

- **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 and target design**

R&D: Fully Active Calorimeter

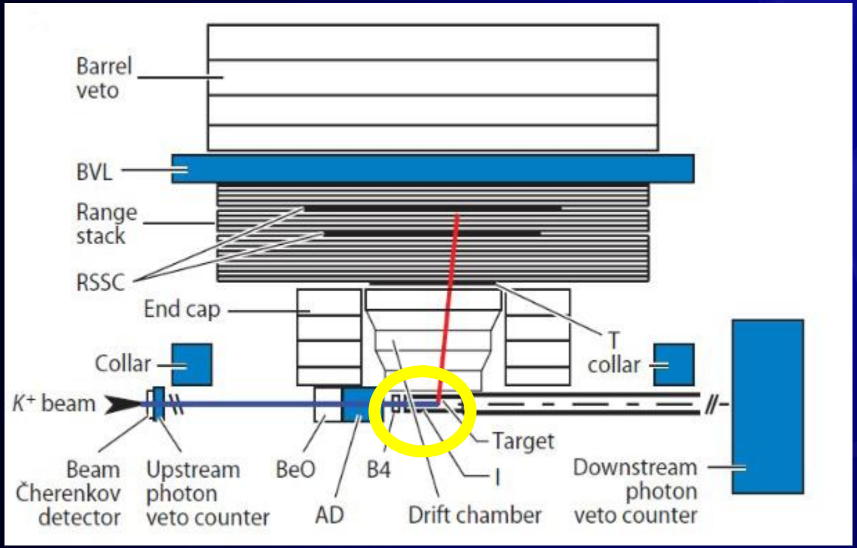
- **E949 barrel-veto detector was Shashlik detector (lead- scintillator sandwich)**
- **ADRIANO *A D*ual-*R*eadout *I*ntegrally *A*ctive *N*on-segmented *O*ption**
  - Cerenkov light from layers of lead glass coupled to WLS fibers
  - Scintillation light from layers of plastic scintillator
  - Potential to improve photon-veto efficiency
  - Potential for particle identification S vs. C light
  - T-1015 collaboration (FNAL-INFN)

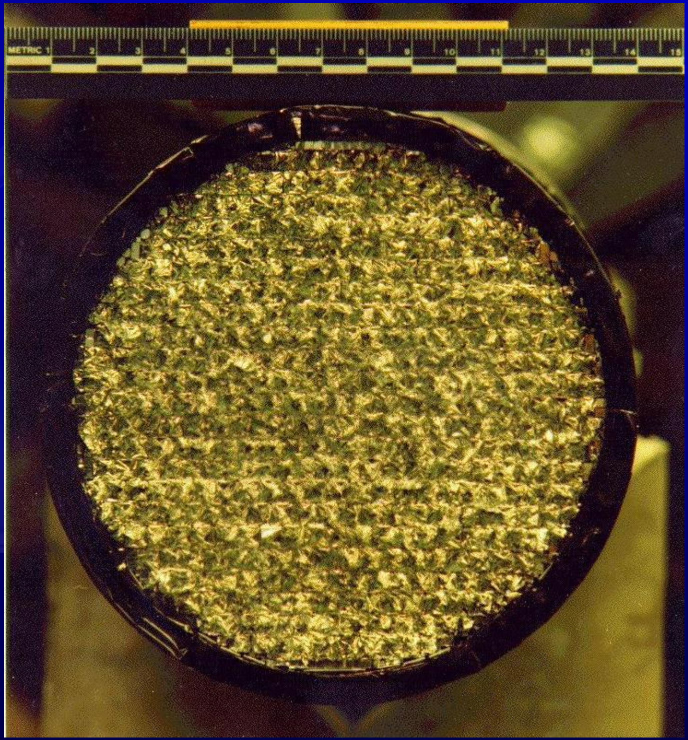




R&D: Active Stopping Target

- **E949 target:**
  - 413 5 mm^2, 310 cm long scintillating fibers
  - 1” PMT readout

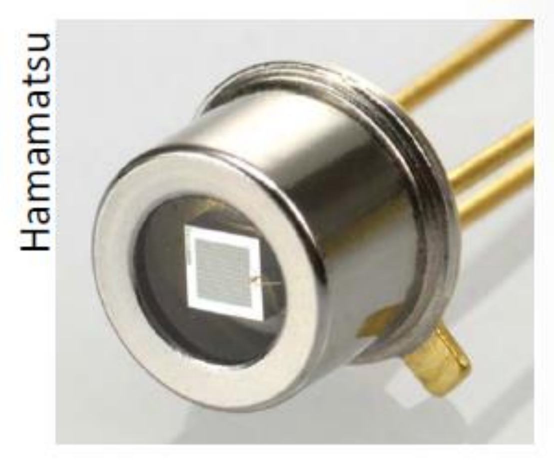


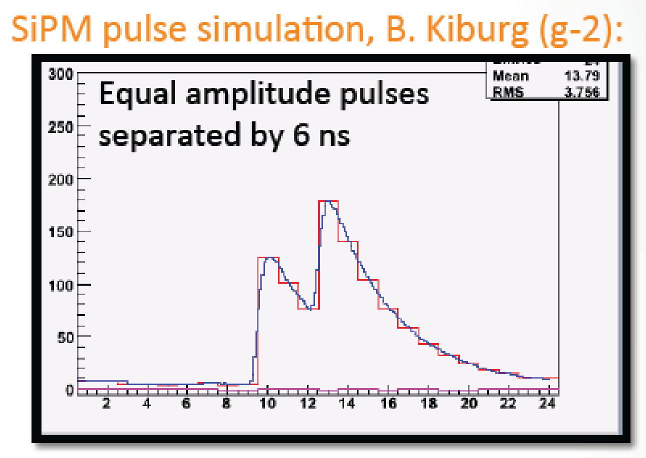


- **ORKA target**
  - Similar design with shorter fibers (100-200 cm), finer segmentation
  - SiPM readout (single/double ended?)

R&D: SiPM

- **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
- **Ongoing studies**
  - Radiation damage
  - Double pulse resolution





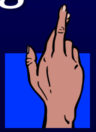
ORKA Cost & Schedule Estimates

- **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 total cost: ~$23M***
  - Covered by FNAL Accelerator Improvement Projects (AIPs)
  - Similar strategy to muon campus

*** Including 50% contingency**

Schedule

- **2011: FNAL Director Stage 1 approval**
- **2014: P5 endorsement**
- **2017-2020: Construction**
- **2020-2025: Operation**



ORKA & US Program Planning

- 2008, P5: "[experiments such as ORKA] would be a major component of a future high-sensitivity physics program at Fermilab, and their implementation should be pursued."
- 2011: Fermilab Director Stage 1 approval
- 2011, PAC: The PAC "encouraged the Laboratory and the Collaboration to explore how ORKA could proceed, even in a severely constrained budget environment."
- 2012, PAC: "The PAC again strongly encourages the Laboratory and the Collaboration to move forward with the remaining studies necessary to assess how this important experiment can be done."

- **ORKA is a golden opportunity for physics discovery and for international leadership at Fermilab.**
- **Clear time frame for ORKA Data taking:**
  2020-2025 between NOvA, Muon g-2, etc. and LBNE.

Conclusions

- **High precision measurement of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at FNAL MI**
  - Expect ~1000 events and BR precision of 5%, allowing 5σ discovery of 35% deviations from the Standard Model
  - Unique discovery potential for new physics at and above the LHC mass scale, complementary to B and lepton flavor experiments
- **Cost-effective, high-quality science**
  - $50M total project cost
  - Modest accelerator improvement and no civil construction
- **Guaranteed physics output with known technique and experienced team**
  - 4^{th} generation detector, leadership from previous US kaon experiments
- **Great opportunities for collaborators – come join us!**
  - University-scale detector R&D and construction
  - Dozens of thesis topics for students in an otherwise sparse period
- **Enthusiastic encouragement from FNAL, US funding agencies, international partners – next step, P5!**

ORKA proposal