ORKA: Seeking New Physics with the "Golden Kaon" Decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

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ORKA Briefing Agenda

• Overview	Doug Bryman	(30 min.)
• Cost estimate	Bob Tschirhart	(20 min.)
• Mission Need	Jack Ritchie	
• Discussion		

Executive Summary

The focus of the Fermilab mission for the coming decades is accelerator driven intensity frontier research. Precise measurement of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is broadly recognized to be on the short list of the most compelling accelerator-driven intensity frontier experiments.

- ORKA: 1000 Event Measurement of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at FNAL MI
- Proven technique; experienced team; leveraged resources
- "Guaranteed" high impact measurement
- Matches SM uncertainty; covers all accessible Non-SM Physics approaches $\rightarrow$ 1-1000 TeV mass scales
- Goal endorsed by HEPAP/P5 and Fermilab PAC; FNAL Stage One approval granted
- Total Project cost estimate: $53M (FY2010)
- Excels relative to competition at CERN and JPARC

Precise Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ can deeply challenge the Flavor Problem :

Why don't we see the *Terascale Physics we expect* affecting the flavor physics we study today??

Some Favorites

- Accurately measure sides + angles of Unit. Tr. (obvious)
- CPV in $B_s - \bar{B}_s$ (SM "accidentally" small)
- $K \to \pi \nu \nu$ (miniscule in SM + incredibly clean theoretically)
- $\mu \to e$, $\tau \to e, \mu$ (suggested by big ν angles)

"Flavor Physics: Pushing Beyond the LHC"

Intensity Frontier Workshop

Nima Arkani-Hamed
(Princeton, IAS)

Rare Decays in the LHC Era

Access to TeV and Higher Mass Scales

New Physics found at LHC
New particles with unknown flavor- and CP-violating couplings

New Physics NOT found at LHC

Precision flavor-physics experiments needed to help sort out the **flavor- and CP-violating couplings** of the NP.

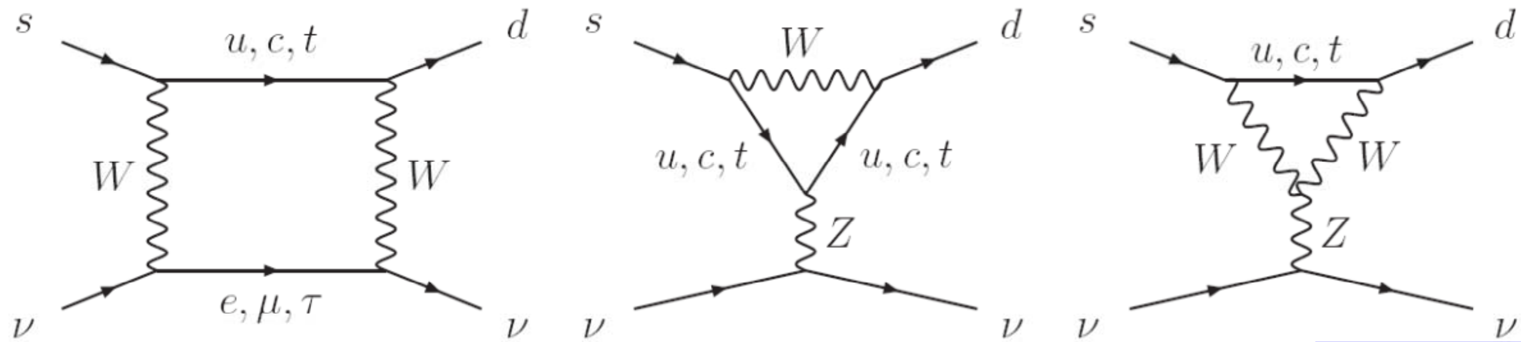
Precision flavor-physics experiments needed -> access to **mass scales beyond the reach of the LHC** (through virtual effects).

Q(L) Flavor	Special Processes to Probe NP
1(2)	$\mu \to e\gamma, \mu$-e Conversion, $\pi(K)^+ \to e^+\nu$
2	$K^+ \to \pi^+\nu\bar{\nu}, K_L^0 \to \pi^0\nu\bar{\nu}$
3(3)	$b \to s\gamma$, $\mathrm{B} \to \mu\mu, (\tau \to \mu\gamma)$...

Special status: small SM uncertainty and large NP reach.

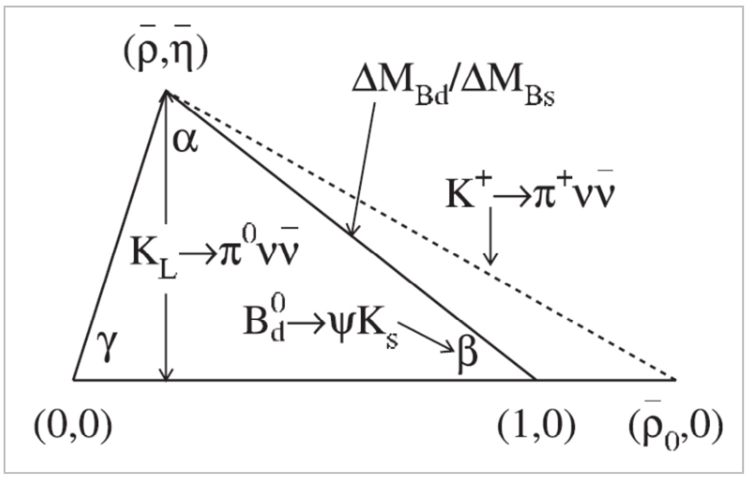
$K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

FCNC with exceptionally precise prediction



- A single effective operator $(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$
- Dominated by top quark (charm significant, but controlled)
- Hadronic matrix element shared with Ke3
- Uncertainty from CKM elements (*will improve*)
- **Remains clean in most New Physics models**

(unlike many other observables)



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

Brod, Gorbahn, Stamou PR **D83**, 034030 (2011)

Precision now 10%->5%

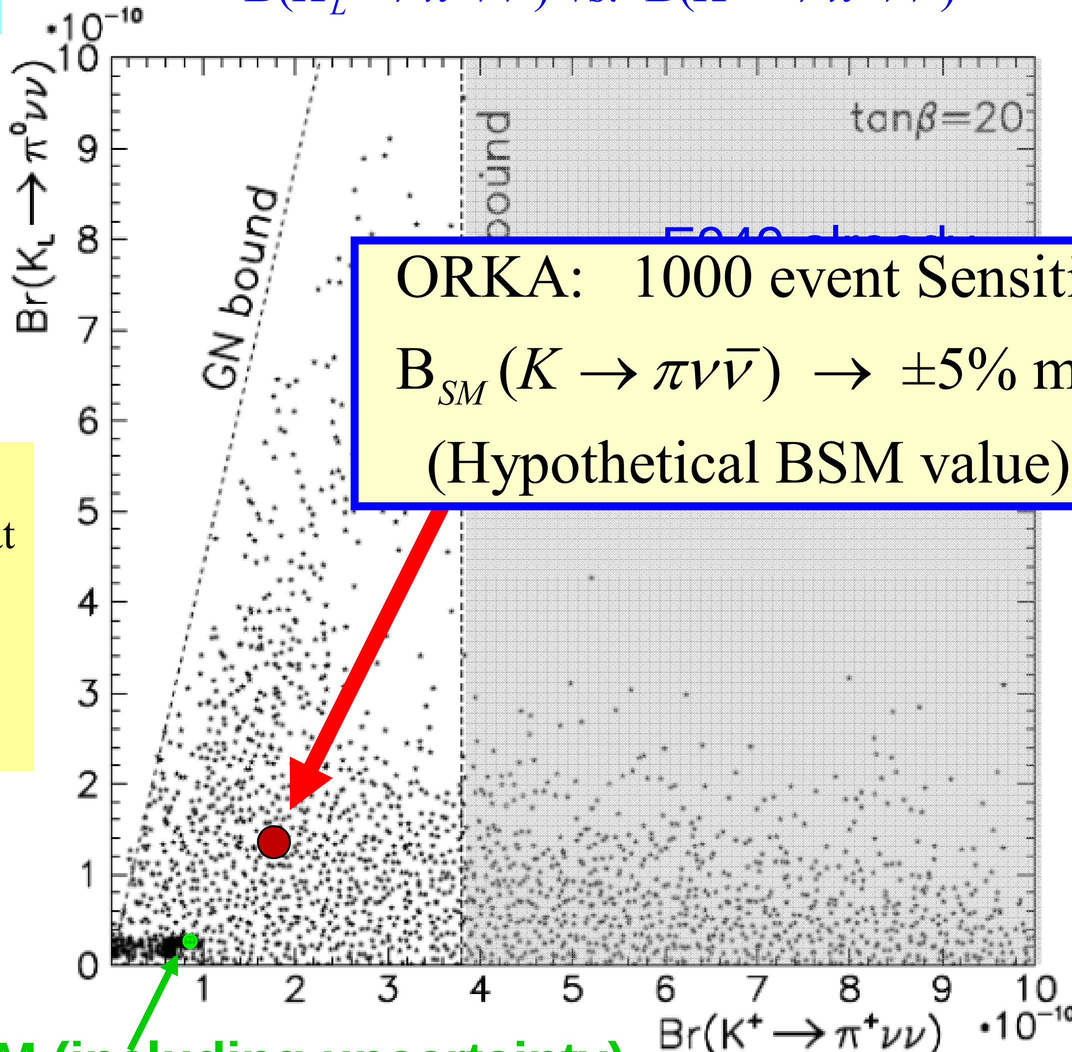
Example: MSSM with R-parity

New Physics models with generic flavor structure induce large effects in $K \to \pi\nu\bar{\nu}$.

$\mathrm{B}(K_L^0 \to \pi^0\nu\bar{\nu})$ vs. $\mathrm{B}(K^+ \to \pi^+\nu\bar{\nu})$

Buras et al, NP B714,103(2005)

Points from a scan of MSSM parameters that satisfy experimental constraints except $\mathrm{B}(K^+ \to \pi^+\nu\bar{\nu})$



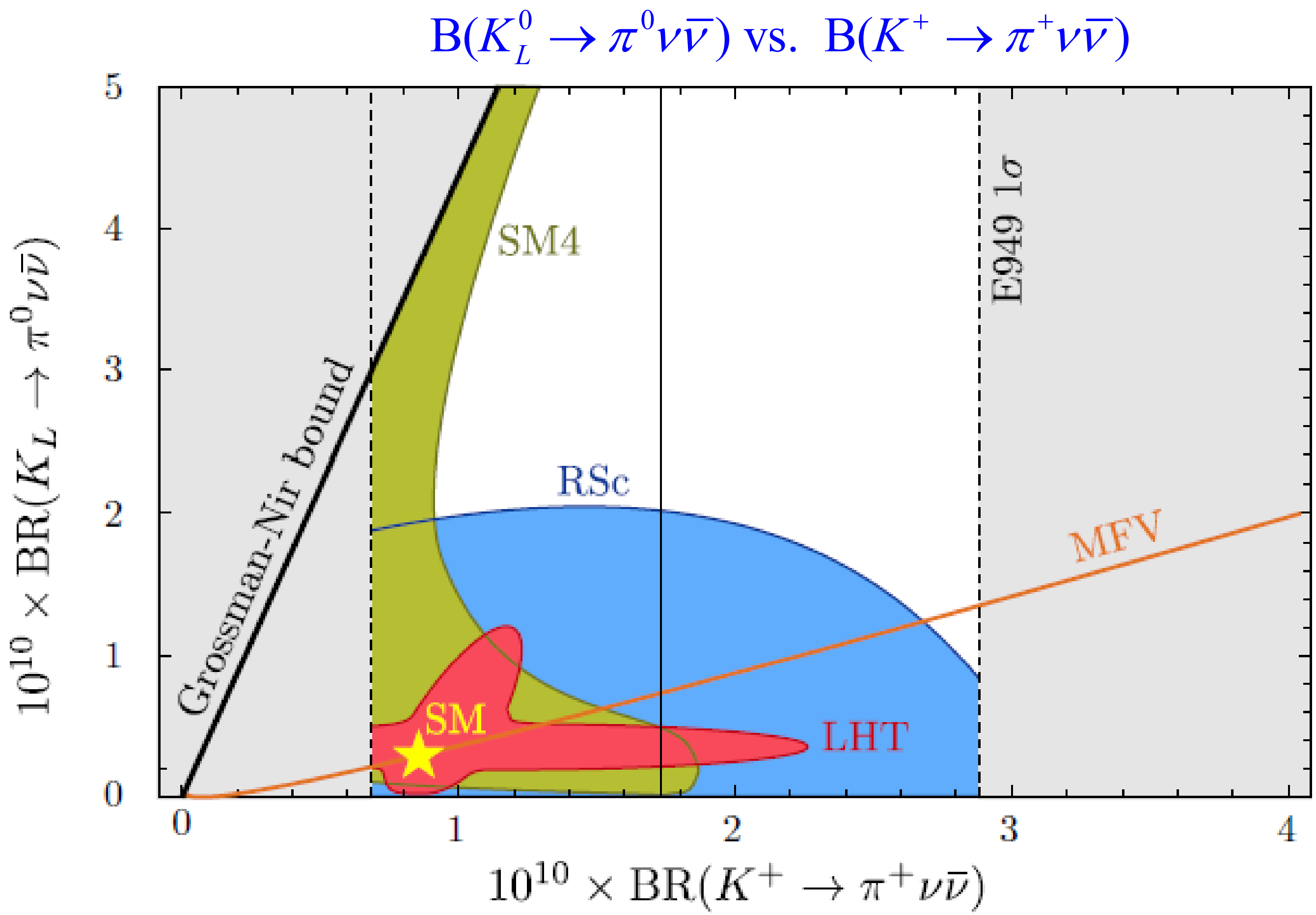
ORKA: 1000 event Sensitivity for $\mathrm{B}_{SM}(K \to \pi\nu\bar{\nu}) \to \pm 5\%$ measurement (Hypothetical BSM value)

SM (including uncertainty)

R Parity: R = (-1)$^{2j+3B+L}$.

$K^+ \to \pi^+ \nu\bar{\nu}$: Sensitive to New Physics

e.g. High mass scale effects, Warped Extra Dimensions as a Theory of Flavor, …??



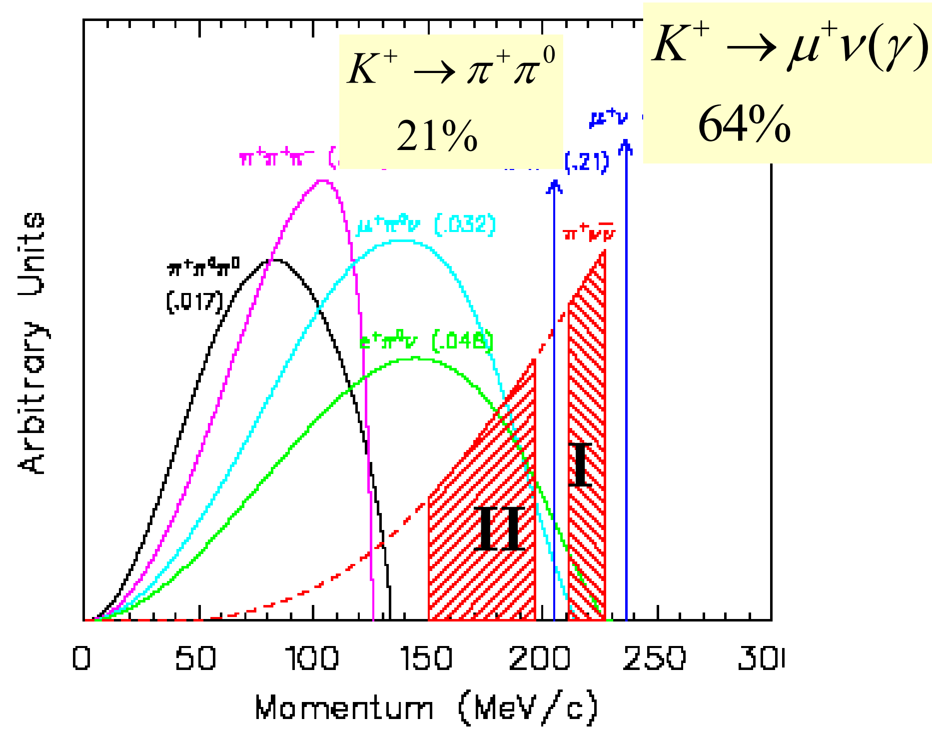
D. M. Straub, arXiv:1012.3893 [hep-ph].

Challenges for Measuring

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

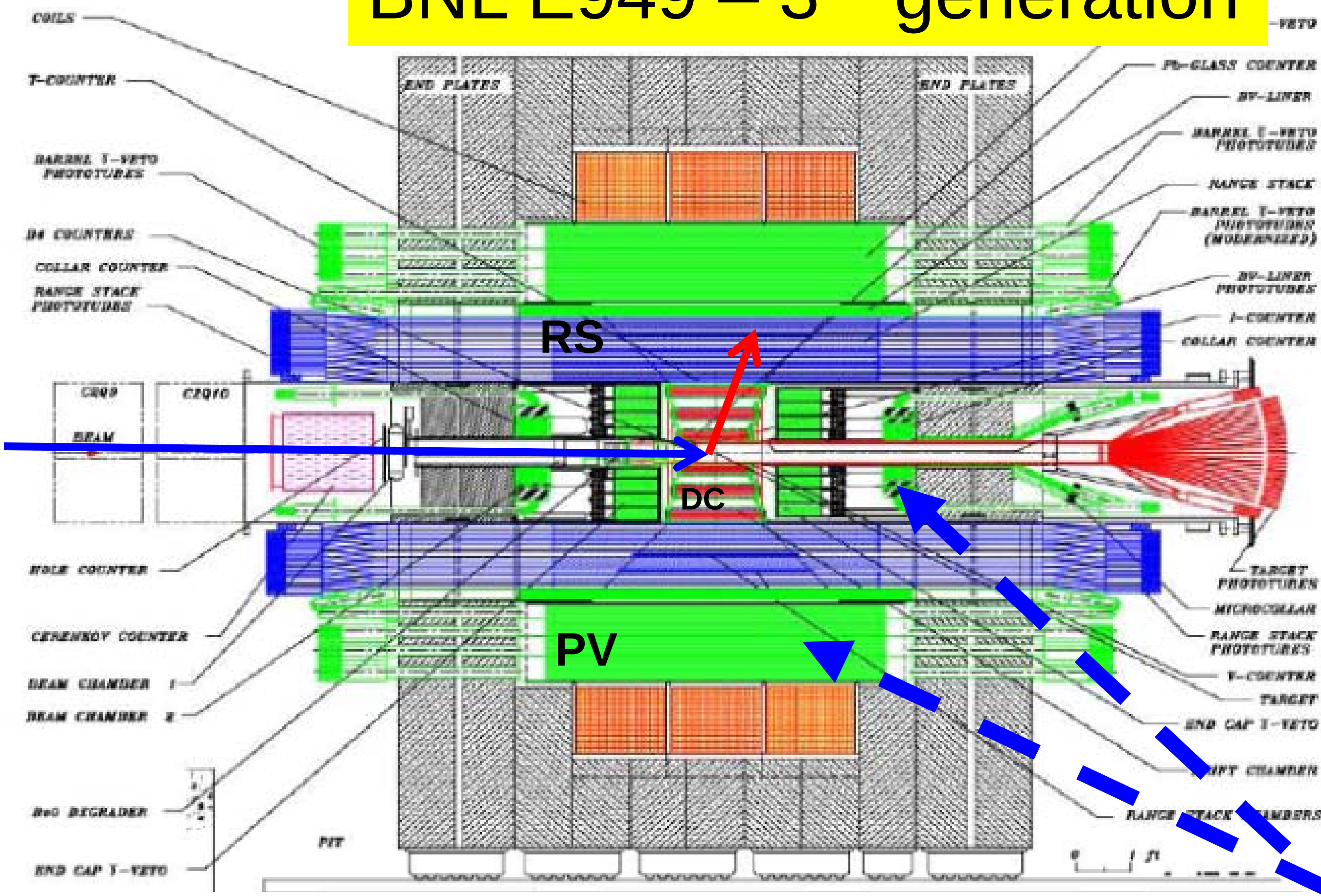
$B_{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (7.8 \pm 0.8) \text{ x } 10^{-11}$

Experimentally weak signature: backgrounds exceed signals by $>10^{10}$



- Determine everything possible about the K and π
    - π^+/μ^+ particle ID better than 10^6 ($\pi^+ \rightarrow \mu^+ \rightarrow e^+$)
    - Work in the CM system (stopped K^+)
- Eliminate events with extra charged particles or ***photons***
- * π^0 inefficiency $< 10^{-6}$
- Suppress backgrounds well below the expected signal (S/N~10)
- * Predict backgrounds *from data*: dual independent cuts
- * Use "Blind analysis" techniques
- * Test predictions with outside-the-signal-region measurements
- Evaluate candidate events with S/N function

BNL E949 – 3rd generation



Stop 700 MeV/c K^+

Scintillating fiber tgt.

π^+ Momentum in DC

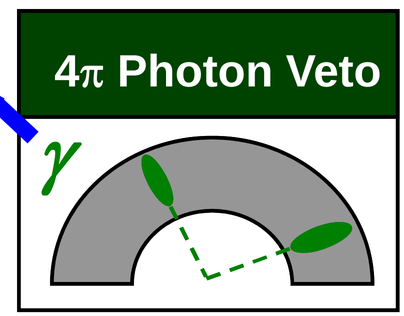
Energy, range in RS

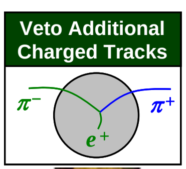
$\pi \to \mu \to e$

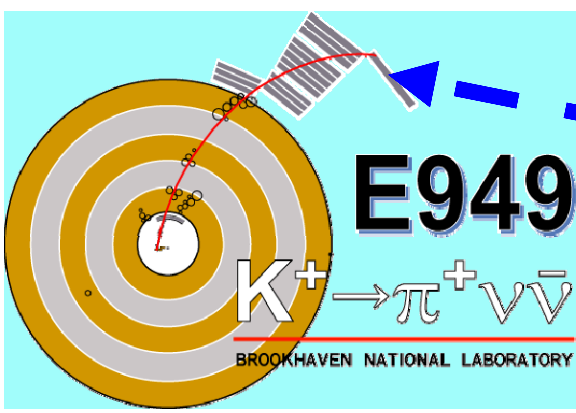
$> 10^6$ μ suppression

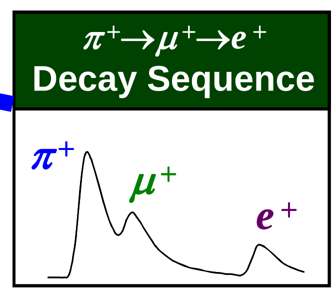
4π Photon Veto

$>10^6 \pi^0$ suppression









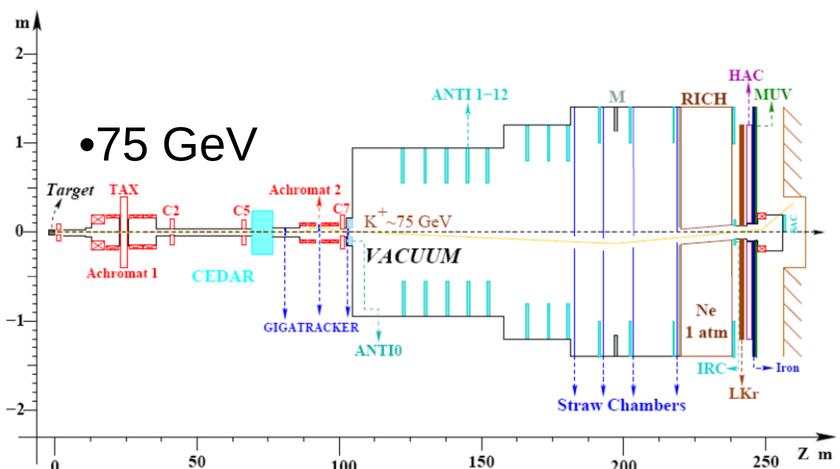
500 MHz digitizers

Future $K \rightarrow \pi\nu\bar{\nu}$ Measurements

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

CERN NA-62

Decay-in-flight experiment.



- Builds on NA-31/NA-48
- *Un-separated* GHz beam
- **Aim: 40 events/yr at SM**
- Under construction
  Start >2013

$K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ at J-PARC

KOTO: 2nd try with upgraded

KEK setup ($< 2.6x10^{-8}$)

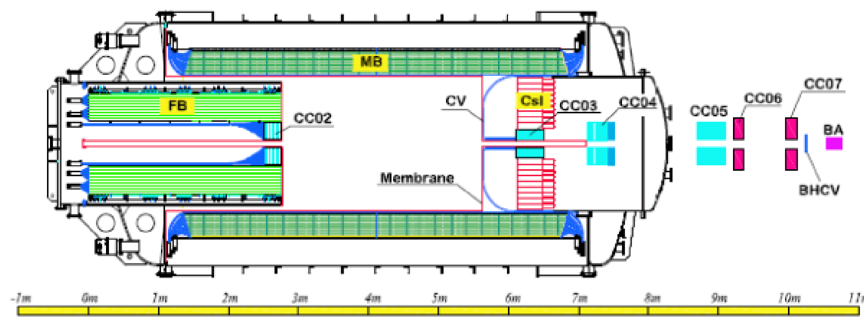


FIG. 1: Cross section of the E391a detector. K_L^0's enter from the left side.

- Improved J-PARC Beam line
- (Eventually) higher power
- **Aim: 3 events at SM**
- Under construction
  Start >2012

ORKA at Fermilab

Aim: 1000 Event Measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

OleMiss

•Napoli

•Pisa

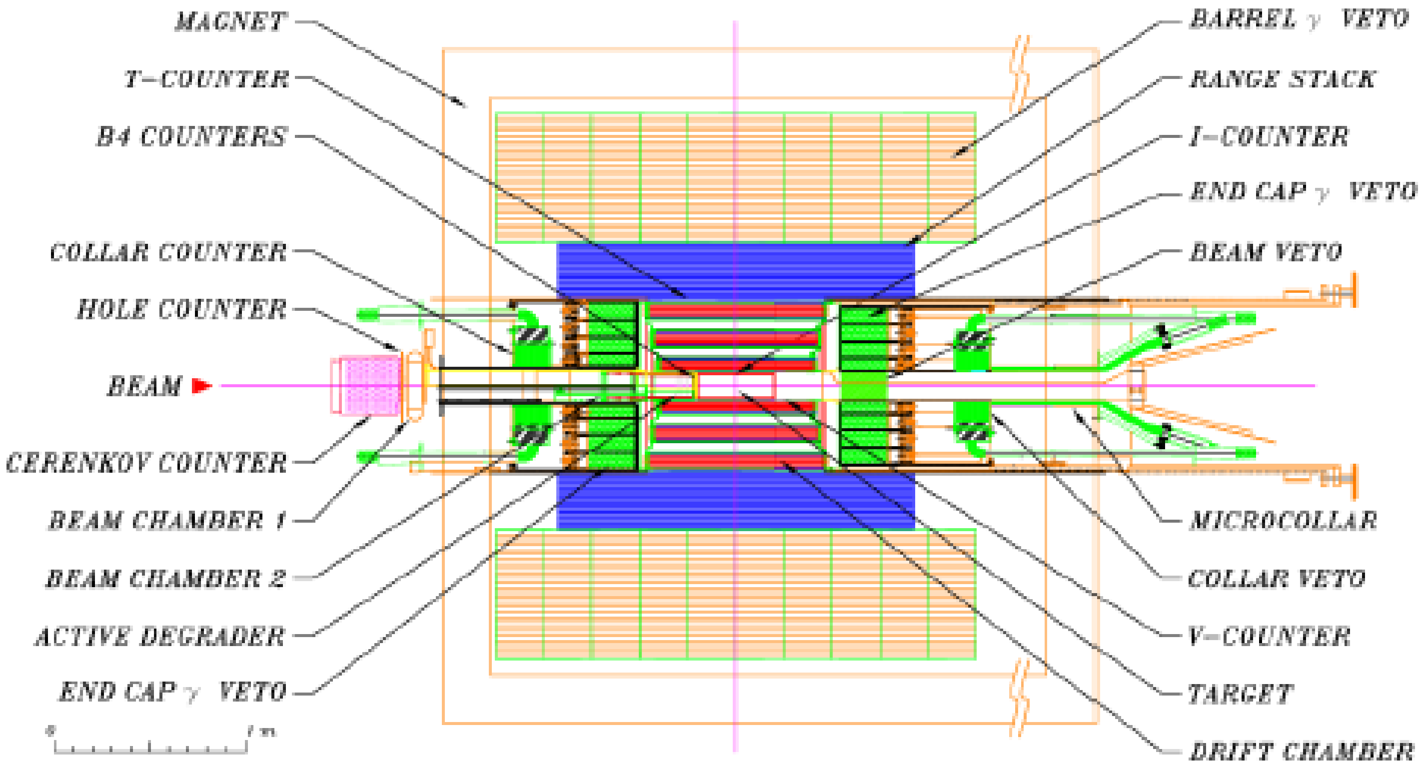
- Sixteen institutes spanning six nations:

  Canada, China, Italy, Mexico, Russia, USA

  Five US universities now; in active discussion with several others
- Two US National Laboratories
- Leadership from US rare kaon decay experiments from the past 20 years

ORKA at the FNAL Main Injector

4^{th} Generation $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Experiment



Incremental Improvements

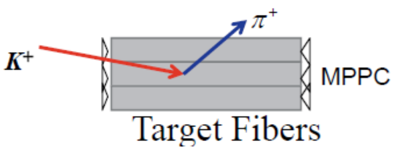
- 600 MeV/c
- K(stop) rate **x5** (Comparable accidentals)
- Acceptance **x10**
- Finer segmentation
- Improved resolutions
- Reduced background

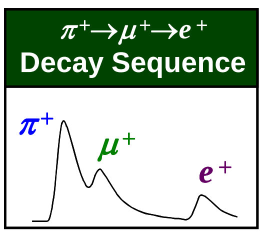
Overall, >100 x sensitivity:
>1000 Events at the SM level

5σ Discovery Potential for deviations from SM >30%

ORKA Detector improvements

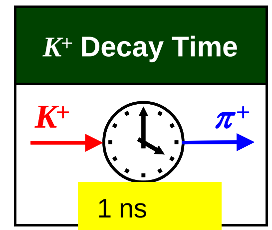
Incremental increases in signal acceptance based largely on E787/E949 measurements.

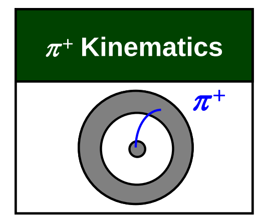





Shashlyk Calorimeter

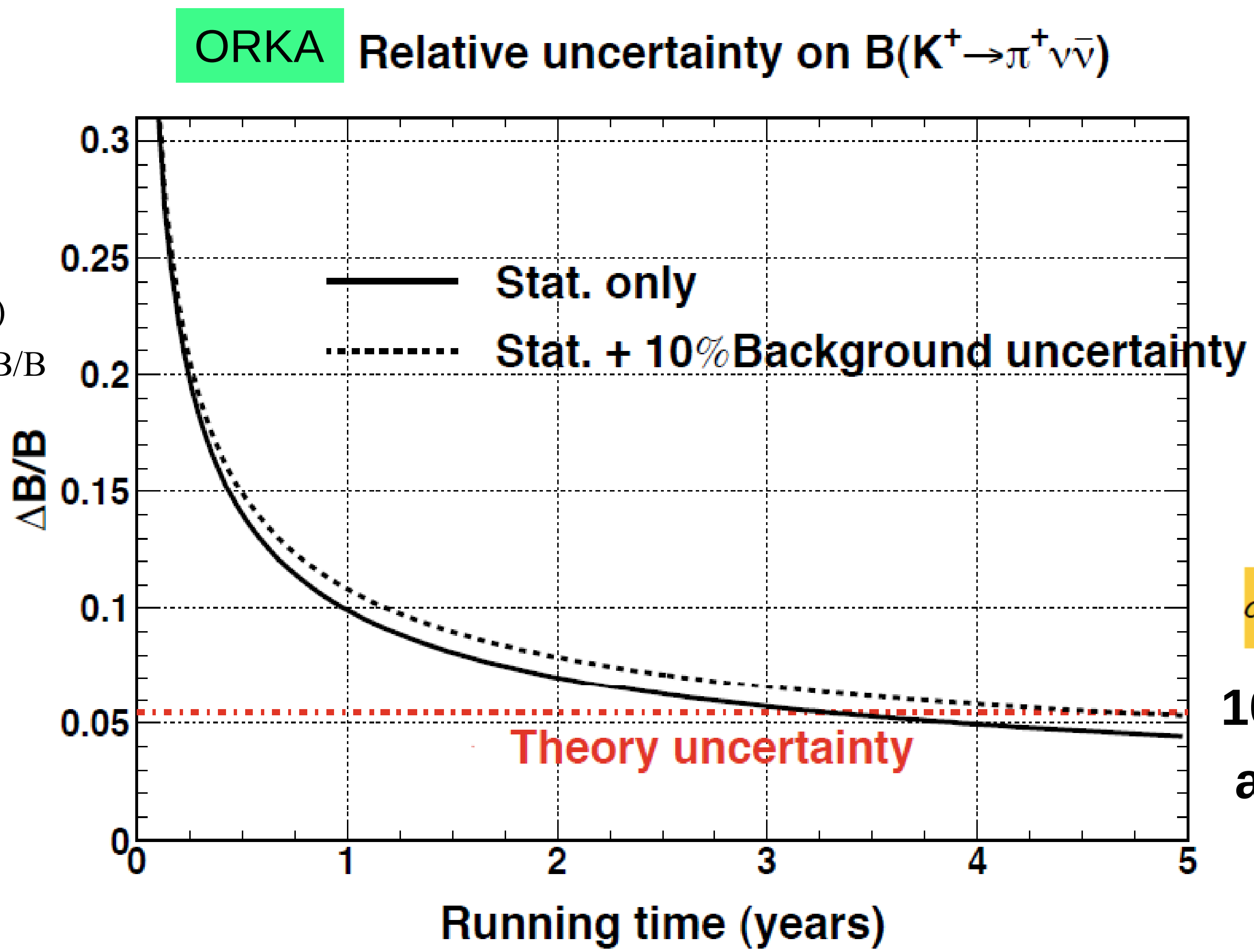
Component	Acceptance factor
$\pi \to \mu \to e$	2.24 ± 0.07
Deadtimeless DAQ	1.35
Larger solid angle	1.38
1.25-T B field	1.12 ± 0.05
Range stack segmentation	1.12 ± 0.06
Photon veto	$1.65^{+0.39}_{-0.18}$
Improved target	1.06 ± 0.06
Macro-efficiency	1.11 ± 0.07
Delayed coincidence	1.11 ± 0.05
Product (R_{acc})	$11.28^{+3.25}_{-2.22}$





Additional acceptance gains expected from trigger improvements.

ORKA Sensitivity *vs.* Time



$B(K^+ \to \pi^+ \nu \bar{\nu})$

Uncertainty ΔB/B

1050 Events at SM

Aggressive Schedule Possible

Would be competitive for discovery of non-SM effects:
3 year construction period technically feasible

Table 11.1: Our projected timescale for major milestones and activities. Dates refer to calendar year, not fiscal year.

Milestone/Activity	Time Period
Stage One Approval	Dec. 2011
DOE Approval of Mission Need (CD-0)	Fall 2012
Beam/Detector Design	2012–2013
Approve Cost Range (CD-1)	early 2013
Baseline Review/CD-2	End of 2013
Start Construction (CD-3)	Spring 2014
Begin Installation	mid-2015
First Beam/Beam Tests	End of 2015
Complete Installation	Mid-2016
First Data (Start Operations/CD-4)	End of 2016

Additional key measurements & thesis topics

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

Summary

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

A unique opportunity to search for new physics with Rare Kaon Decays using existing facilities at Fermilab.

- $K^+ \to \pi^+ \nu \bar{\nu}$ can be measured with high precision (4-5%) at the Fermilab Main Injector.

  "Ultimate" experiment can be done i.e. comparable precision to SM prediction;

  5σ Discovery potential for deviations as small as 30%.

  Complementary to LHC for studying flavor interactions at high mass scales.
- Many other rare Kaon processes can also be accessed
- ORKA a major entry for the FNAL Intensity Frontier Program:

  High impact physics and high quality training for future generations

The ORKA scope is $53M (FY10,TPC) - relatively low-risk, requiring modest accelerator improvements, and no civil construction. Construction starting in 2014 is technically plausible with data taking by 2017 and first results in 2020.