Seeking New Physics with Rare Kaon Decays

(with a little help from a friend)

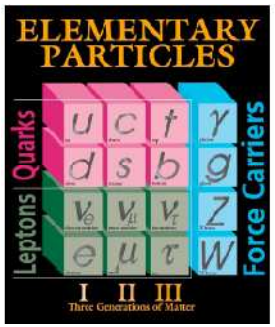
"Excellent!" [Watson] cried.

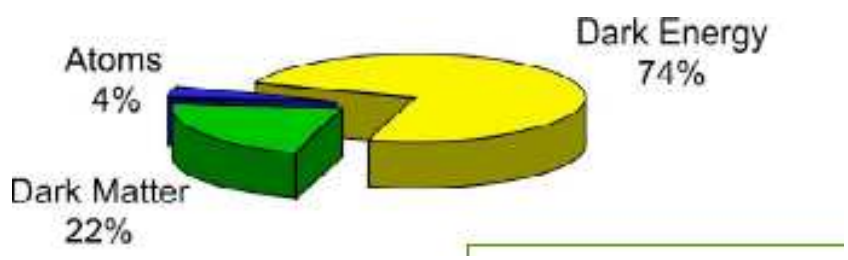
"Elementary," said [Holmes].

Douglas Bryman
University of British Columbia

Standard Model : *A great story … but not likely the whole story…*

- ***Cosmological issues***: inflation, dark matter, dark energy, **matter anti-matter asymmetry…**
- ***Theoretical issues***: gravity, neutrino mass, ***flavor problem***, hierarchy problem, divergences ….





•Energy Frontier

Tevatron → LHC; TeV Energy Scale

New Physics

•Precision Frontier

•DARK Matter Frontier

High Mass Scales?

•Flavor Physics

COSMOLOGICAL EVOLUTION, BBN

Rare Decays and CP violation

Symmetry Violation

LEPTOGENESIS?

NEUTRINO PHYSICS

The Flavor Puzzle

Quarks

u	c	t
d	**s**	b

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

- Fermion weak states $\not\Leftrightarrow$ mass states
- Quark, lepton flavors not conserved
- Three flavors $\Rightarrow$ **CP violation**, …BAU,…

Unexplained observations (no theory of flavor):

- Huge mass differences between and within the generations
- Universality of interactions
- Symmetry, relationship between lepton and quark sectors
- Tiny neutrino mass

BNL Nobel Prize discoveries (2 neutrinos, J, CPV) are all closely related to the flavor puzzle.

Light Particle Rare Decay Experiments

Big BNL Impact

Probe new physics at the 1-1000 TeV Scales!

State of the art: single event sensitivity, 10^{-12}

Exotic Searches ***New physics if seen; SM effects are negligible.***	$K_L^0 \to \mu\, e, K \to \pi\mu\, e$ LFV	**<4.7 10^{-12}**
	$\mu \to e\gamma$ *LFV*	**<1.2 10^{-11}**
	$\mu^- N \to e^- N$ *LFV*	**<7.8 10^{-13}**
	$K^+ \to \pi^+ f$ "Axions"	
	$K_L^0 \to \pi^- \bar{\mu}^+ \nu$ T-violation	
BSM Physics ***New physics if deviations from well-calculated SM predictions occur.***	$K_L^0 \to \mu^+ \mu^-$	**10^{-8}: 6200 events**
	$K^+ \to \pi^+ \nu \bar{\nu}$	**10^{-10}: 3events**
	$K_L^0 \to \pi^0 \nu \bar{\nu}$ *CP* violation	
	$\frac{\pi^+(K^+) \to e^+ \nu}{\pi^+(K^+) \to \mu^+ \nu}$ Lepton Universality	**10^{-4}: 4×10^5 events**

Selected Rare Kaon Decay Experiments c.1980s-2000s

BNL AGS

Search for T-violation in $K \to \pi\mu\nu$

R. Adair *et al.*

$$\left\{\begin{array}{l}\text{Search for } K_L^0 \to \mu e \\ \text{Measurements of } K_L^0 \to \mu\mu \text{ and } K_L^0 \to ee, \ldots\end{array}\right\}$$

S. Wojckiki, R. Cousins, W. Molzon, J. Ritchie *et al.*

$$\left\{\begin{array}{l}\text{Search for } K^+ \to \pi^+\mu e \\ \text{Measurements of } K_{e3}(\mathrm{V_{us}}), K_{e4}, \ldots\end{array}\right\}$$

M. Zeller *et al.*

$$\left\{\begin{array}{l}\text{Measurement of } K^+ \to \pi^+\nu\bar{\nu} \\ \text{Measurements of } K^+ \to \pi^+\gamma\gamma, K^+ \to \pi^+\mu\mu, \\ K^+ \to \mu\nu\gamma(SD),\ K^+ \to \pi^+\pi^0\gamma(DE), \ldots\end{array}\right\}$$

A. J. S. Smith, T. Kycia, L. Littenberg, D.B;
S. Kettell, S. Sugimoto, *et al.*

CERN, Fermilab

$$\left\{\begin{array}{l}\text{Measurement of } \varepsilon'/\varepsilon \text{ in } K_L^0 \to \pi^0\pi^0 \\ \text{Measurements of } K_L^0 \to \pi^0 ll, K_{e3}(V_{us}), K_{\mu 3} \\ \text{Searches for } K_L^0 \to \pi^0\mu e, \ldots\end{array}\right\}$$

B. Winstein,... Blucher, Nguyen *et al.* (Fermilab)
H. Wahl, ... A. Ceccucci *et al.* (CERN)

KEK

Search for $K_L^0 \to \pi^0 ee$, ...

N. Sasao *et al.*

Search for $K_L^0 \to \mu e$

T. Inagaki *et al.*

Search for T-violation in $K \to \pi\mu\nu$

J. Imazato *et al.*

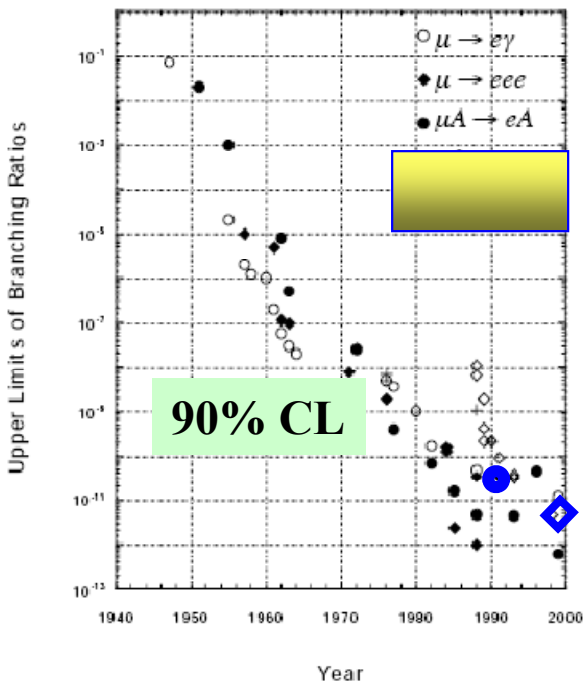
KIOE Frascati

P. Franzini *et al.*

AGS Rare K Experiments

Lepton Flavor Violation

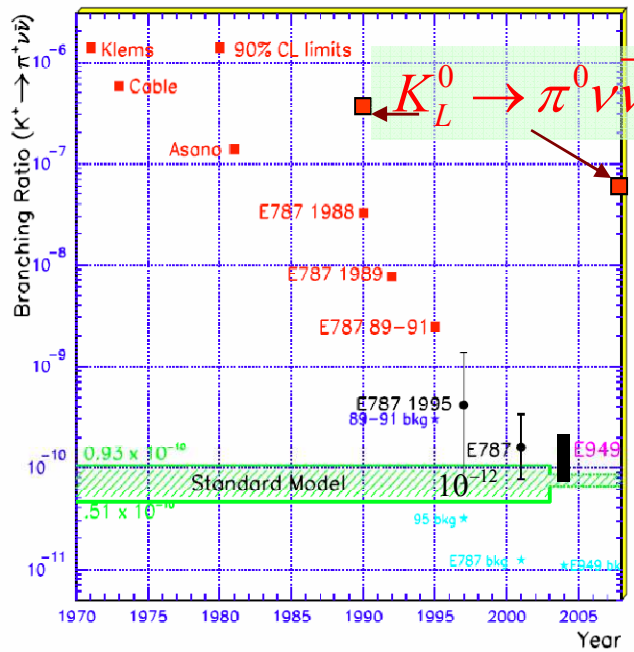
- $B(K_L^0 \to \mu e) < 4.7x10^{-12}$
- $B(K^+ \to \pi^+ \mu e) < 1.3x10^{-11}$



}AGS{

Flavor-changing neutral current

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

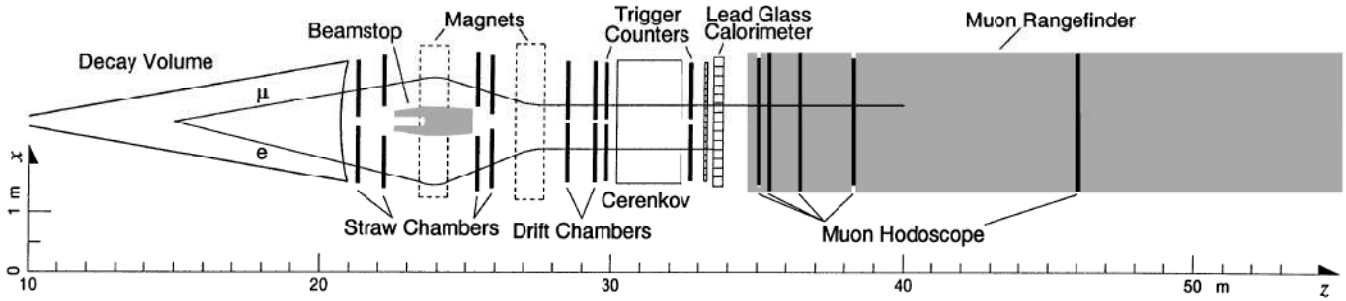


7 **E787/E949**

100 Future?

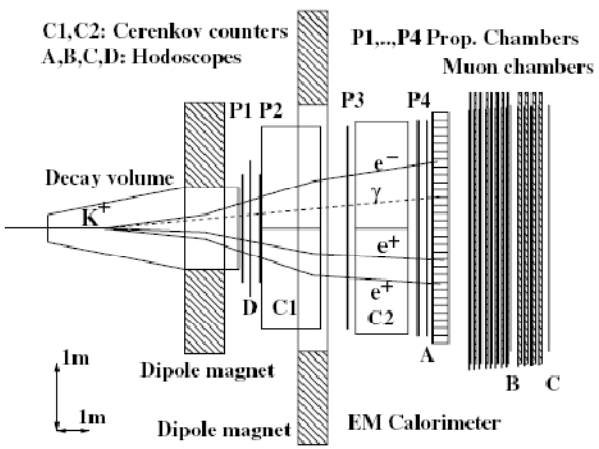
1000

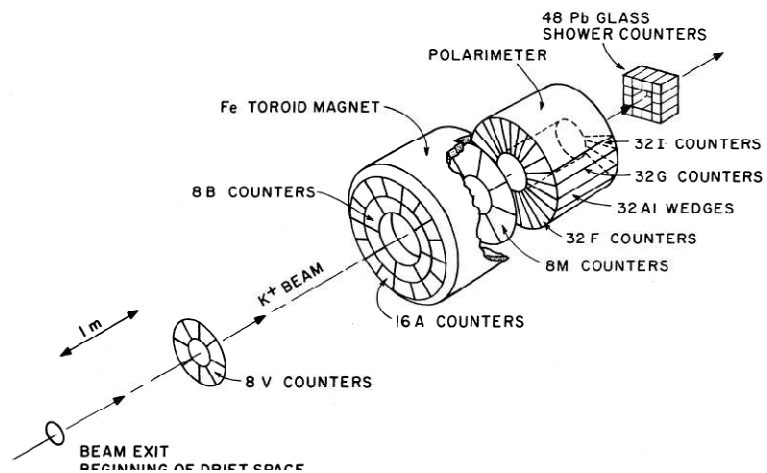
BNL/AGS Rare Kaon Decay Experiments 1980s-2000s



Measurement of $K_L^0 \to ee \quad R = 8.7^{+5.3}_{-4.8} x10^{-12}$ *Rarest particle decay observed!*

D. Ambrose et al. PRL 20, 4309 (1998).





$70000\ K^+ \to \pi^0 e^+ \bar{\nu}$: $\mathrm{R}(K_{e3}) = (5.13 \pm .02_{stat} \pm 0.09_{ys} \pm 0.04_{norm})\%$

$V_{us} \to 2.3\sigma$ *higher; solved the unitarity problem!*

A. Sher et al Phys.Rev.Lett.91:261802,2003

Observed $2x10^7$ $K^+_{\bar{\mu}3}$ decays:

Stringent limit *on new source of T Violation*

S. R. Blatt et al. PRD 27 1056 (1983)

Rare Decays in the LHC Era

New Physics found at LHC

New particles with unknown flavor- and CP-violating couplings

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

Quark Gen.	Processes to Study NP
1	μ-e Conversion, $\pi \to e\nu$
2	$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L^0 \to \pi^0 \nu\bar{\nu}$
3	$b \to s\gamma$, other rare decays

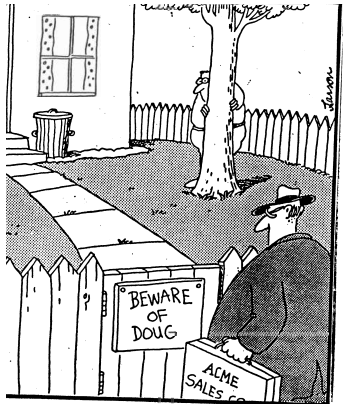
New Physics NOT found at LHC

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

These reactions have special status because of their small SM uncertainties and large NP reach.

Thanks to Jack Ritchie

$$K \to \pi \nu \bar{\nu}$$

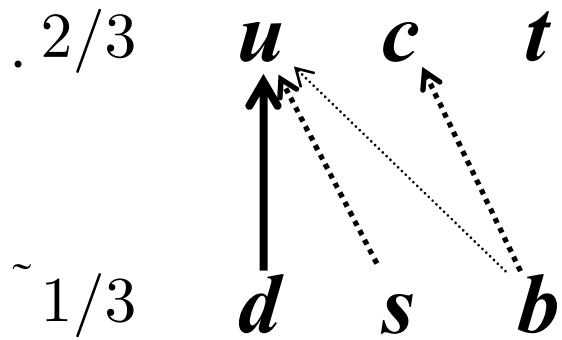


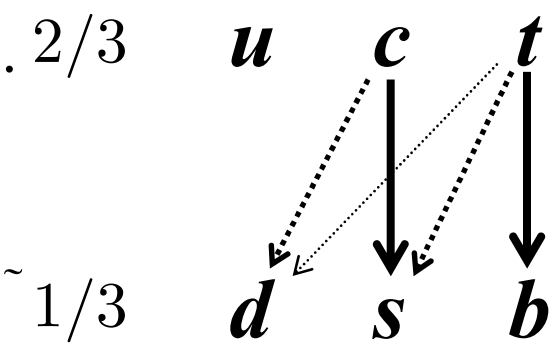
..the curious incident of the dog in the night-time...

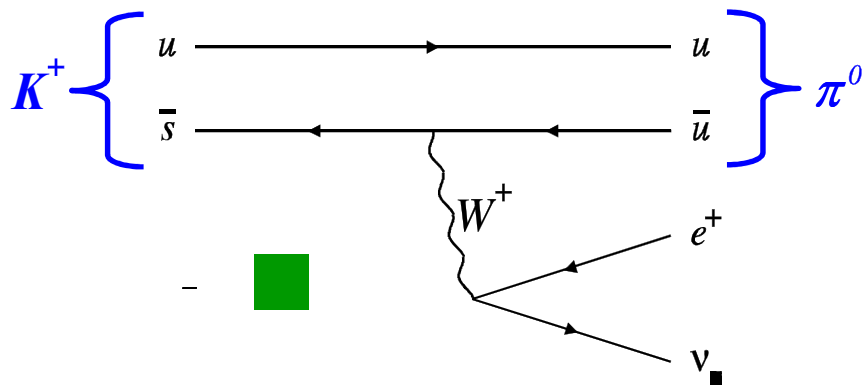
"The dog did nothing in the night-time."
"That was the curious incident,"
remarked Sherlock Holmes.

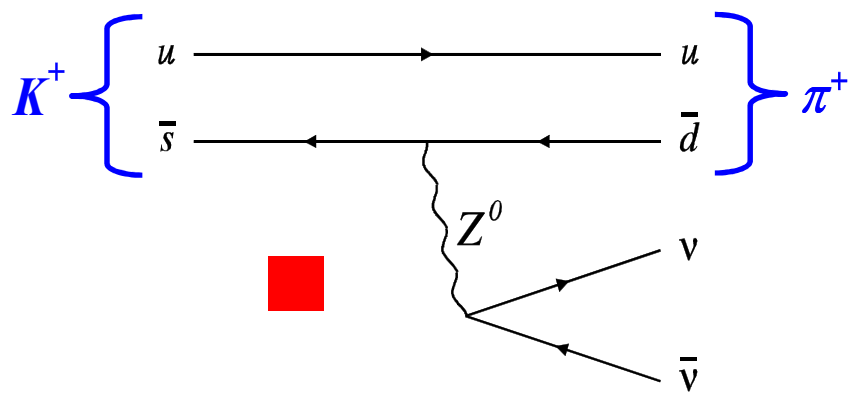
Sherlock Holmes in "Silver Blaze"

Flavor-changing neutral currents (e.g. s → d) are absent in the Standard Model:



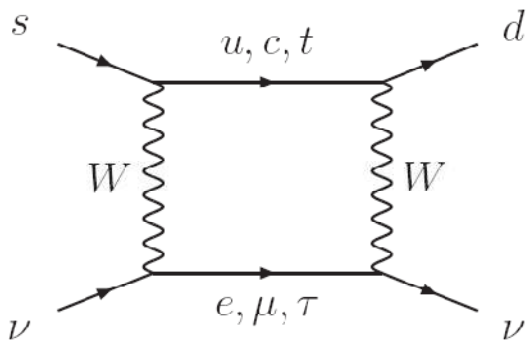


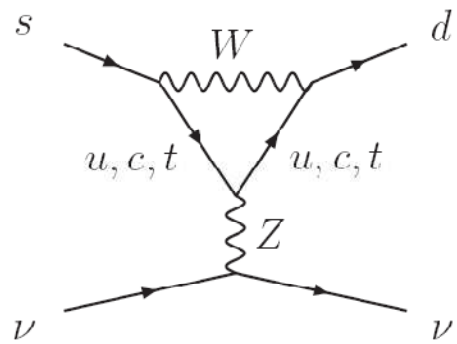


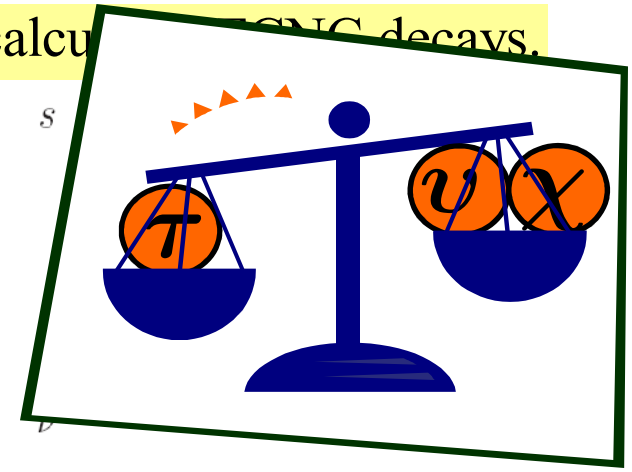


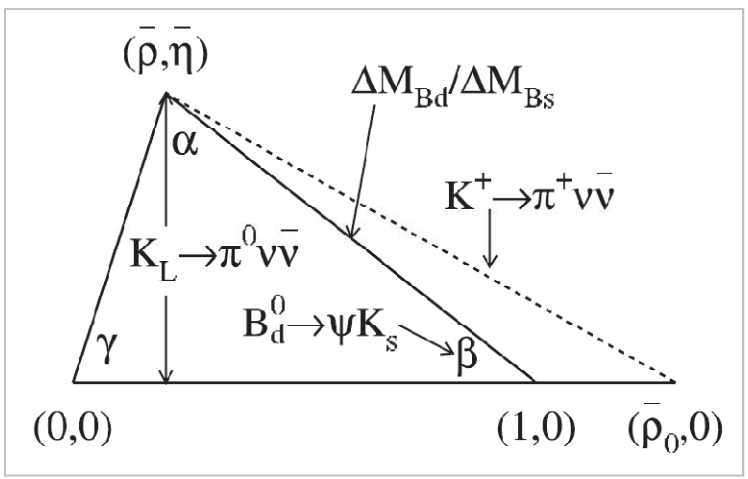
$K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

The $K \to \pi\nu\bar{\nu}$ decays are the most precisely calcu[illegible] FCNC decays.









- 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 New Physics models** *(unlike many other observables)*

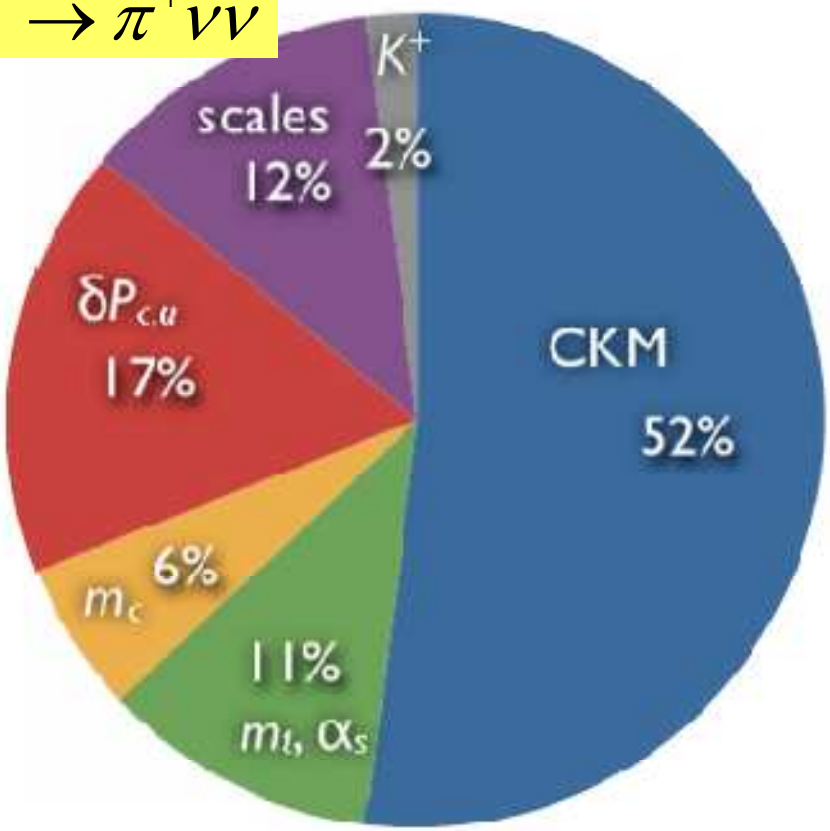
$$B_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.5 \pm 0.7) \text{ x } 10^{-11}$$

Brod and Gorbahn, PRD 78, 034006(2008)

Summary of SM Theory Uncertainties

CKM parameter uncertainties dominate the error budget today.

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



With foreseeable improvements, expect total SM theory error ≤6%.

A. Kronfeld (FNAL)

Unmatched by any other FCNC process (K or B).

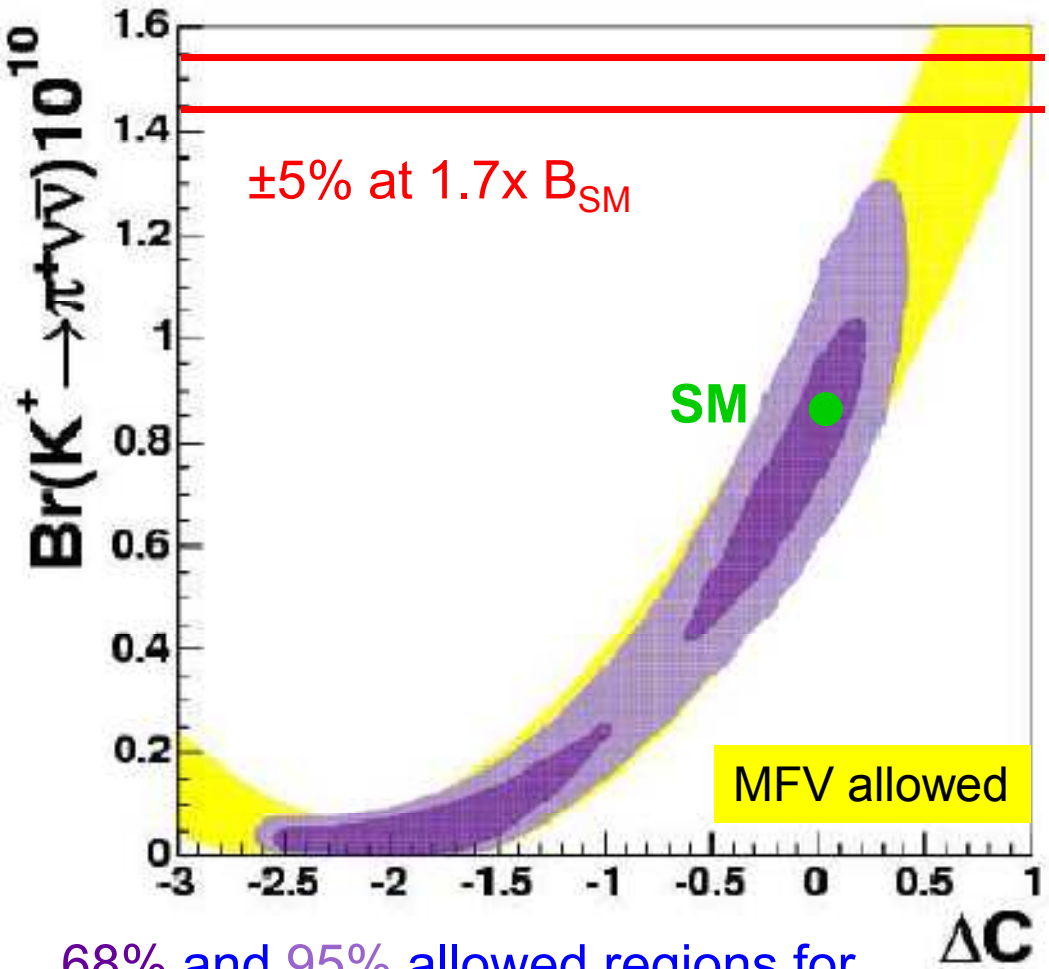
30% deviation from the SM would be a 5σ signal of NP

SM theory error for $K_L^0 \to \pi^0 \nu\bar{\nu}$ mode exceeds that for $K^+ \to \pi^+ \nu\bar{\nu}$.

U. Haisch, arXiv:0707.3098

Minimal Flavor Violation (*a highly pessimistic hypothesis*)

Bobeth et al, Nucl Phys B726, 252(2005)



68% and 95% allowed regions for NP, based on $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$

The MFV hypothesis assumes that all flavor- and CP-violating effects in New Physics are governed by the SM Yukawa couplings (CKM mixing and phase).

±5% measurement of $B(K^+ \to \pi^+\nu\bar{\nu})$ will provide strong constraints on New Physics within MFV, or demonstrate failure of the MFV hypothesis.

$C = C - C_{SM}$,
where C characterizes the Z-penguin in b→s

General MSSM with R-parity

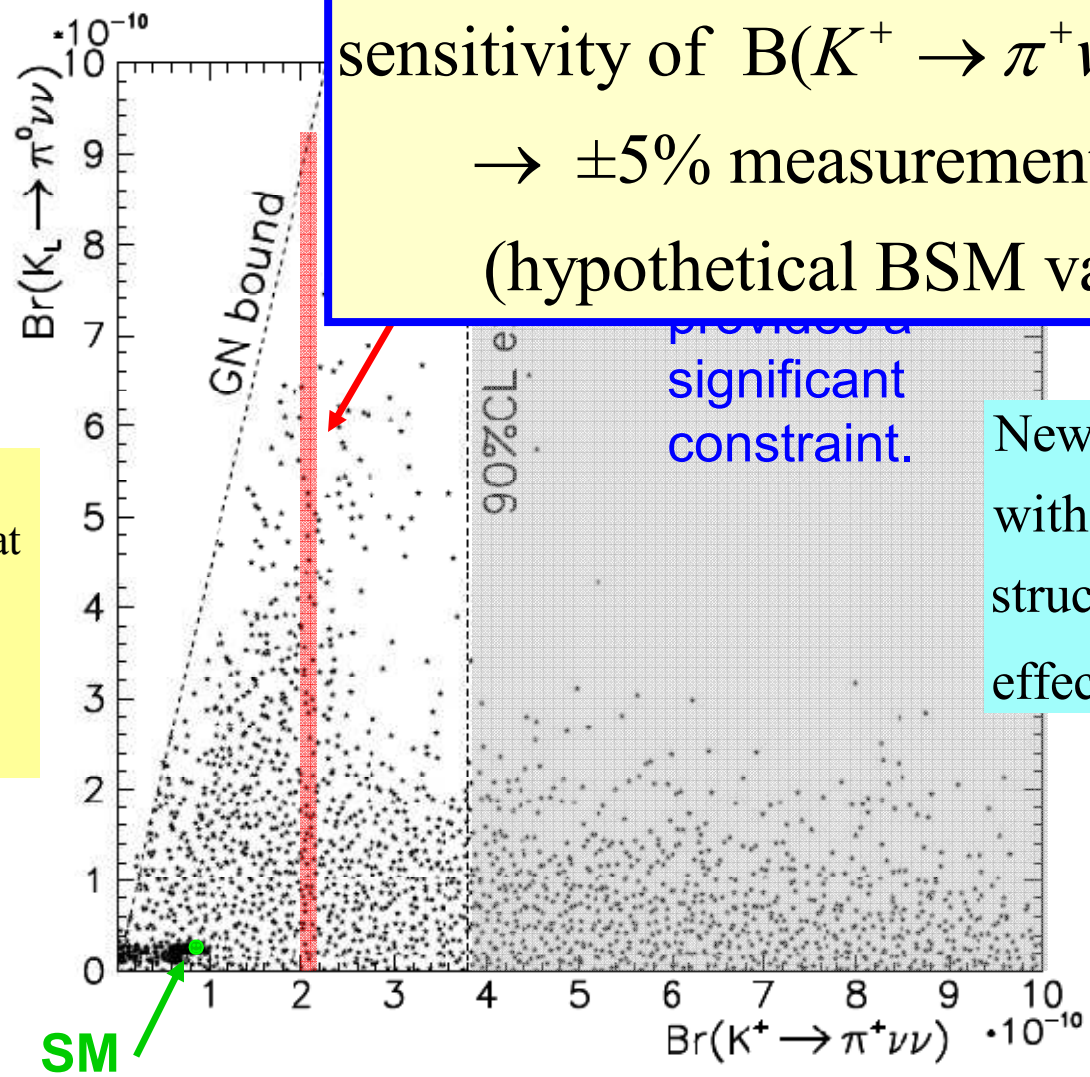
Fermilab proposal P996: improve the sensitivity of $B(K^+ \to \pi^+ \nu\bar{\nu})$ by >100 !

$\to$ ±5% measurement

(hypothetical BSM value)

Buras et al, NP B714,103(2005)

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



provides a significant constraint.

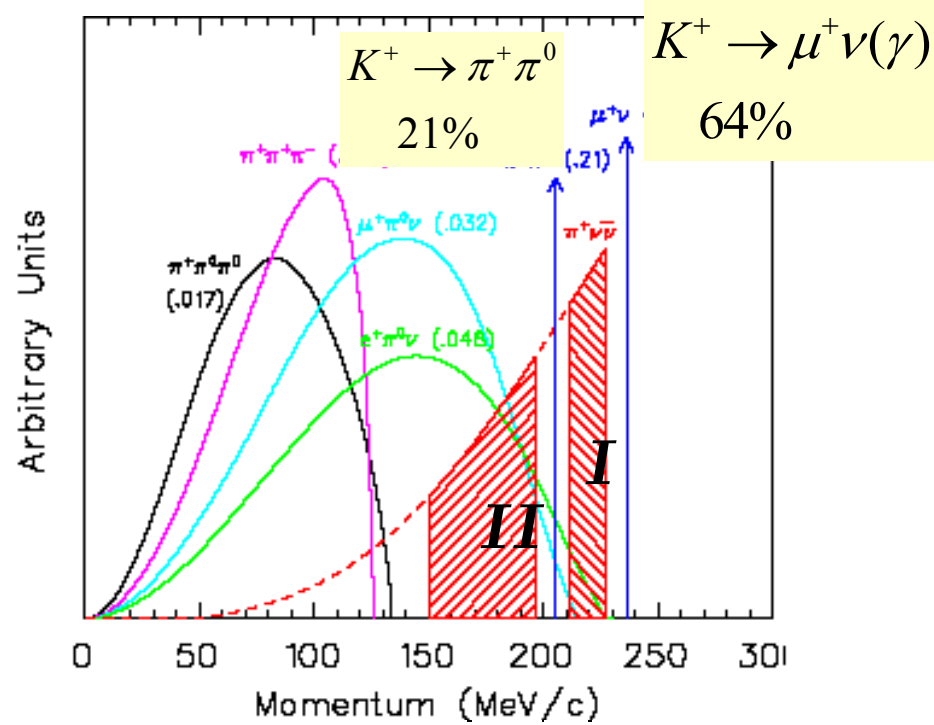
New Physics models with generic flavor structure induce large effects in $K^+ \to \pi^+ \nu\bar{\nu}$.

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

Special Features of Measuring

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

Experimentally weak signature with background processes exceeding signal by >10^{10}

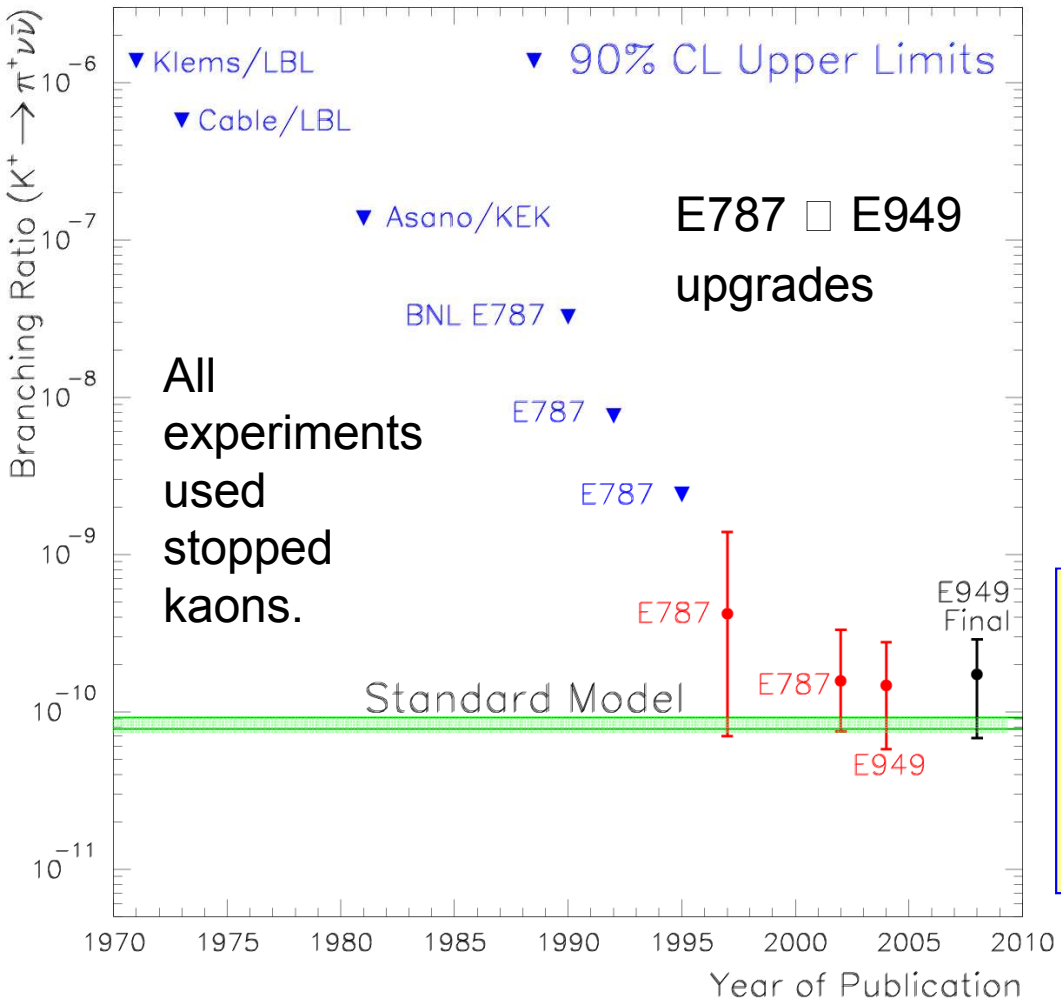


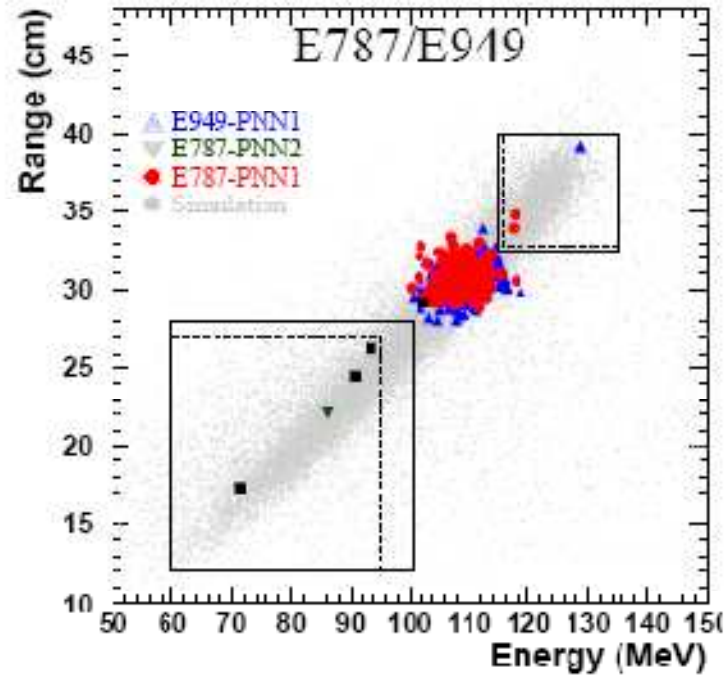
- Determine everything possible about the K^+ and π^+
  - * π^+/μ^+ particle ID better than 10^6 ($\pi^+ \to \mu^+ \to e^+$)
- Eliminate events with extra charged particles or ***photons***
  - * π^0 inefficiency < 10^{-6}
- Suppress backgrounds well below the expected signal (S/N~10)
  - * Predict backgrounds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

"…when you have eliminated the impossible, whatever remains, *however improbable*, must be the truth? "

Sherlock Holmes in The Sign of the Four (1890)

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





E787/E949 Final: 7 events observed

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$$

Standard Model:

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (0.85 \pm 0.07) x10^{-10}$$

Intensity Frontier: Rare K, π, μ Experiments

- Fermilab (K, μ)
- J-PARC (K, μ)
- CERN (K)
- PSI and TRIUMF (π, μ)

Intensity Frontier: Fermilab Now and in the Future

Now:

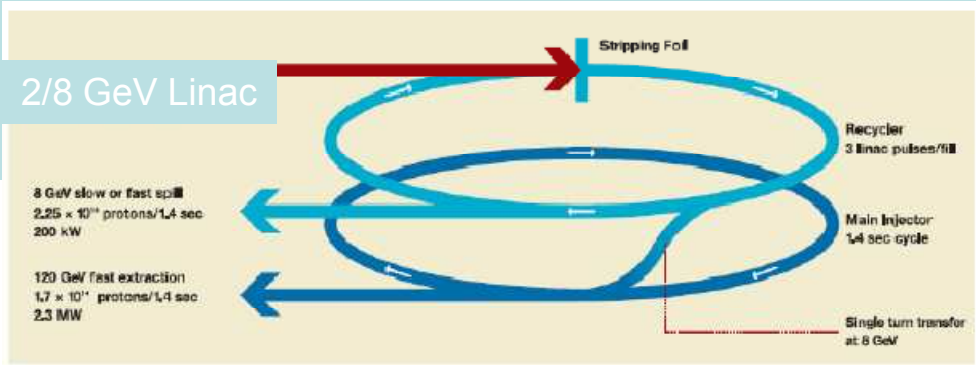
Main Injector Neutrino Program (MINOS,Miniboone,Minerva,NOVA)

8 GeV Booster Proposals: Mu2E (10^{-16}), g-2 (4x), ...

Tevatron Stretcher Proposal: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Future:

Project X



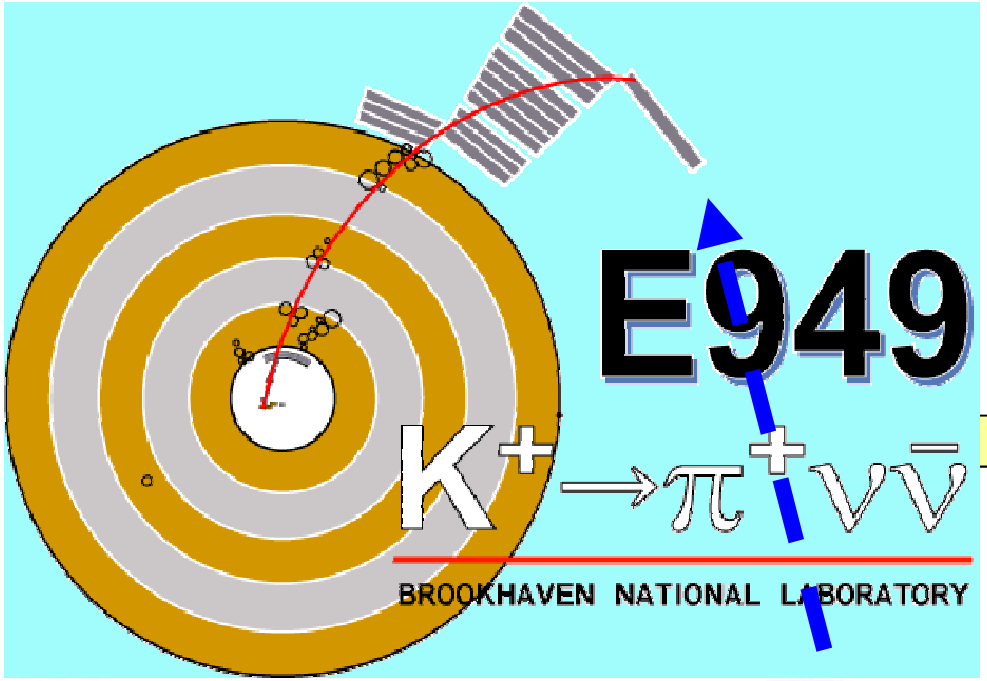
Future $K \to \pi \nu \bar{\nu}$ Experiments

Fermilab: $K^+ \to \pi^+ \nu \bar{\nu}$ (P996 and Project X)

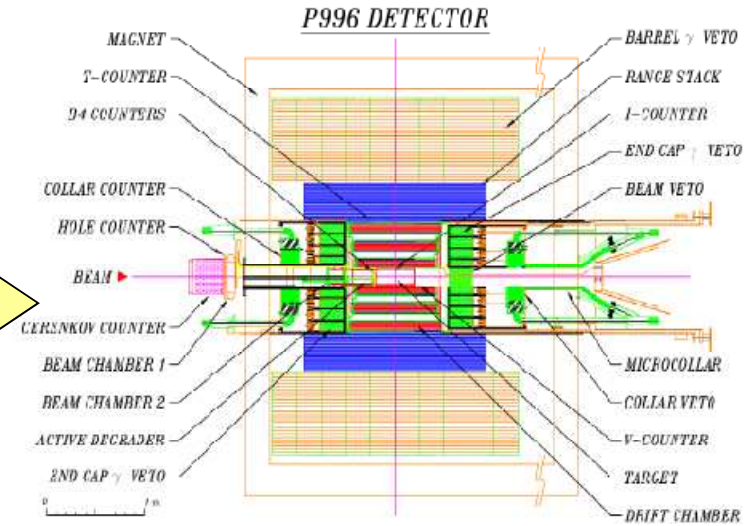
$K_L^0 \to \pi^0 \nu \bar{\nu}$ (Project X)

CERN: $K^+ \to \pi^+ \nu \bar{\nu}$ (NA62)

J-PARC: $K_L^0 \to \pi^0 \nu \bar{\nu}$ (KOTO, "KOTOII")

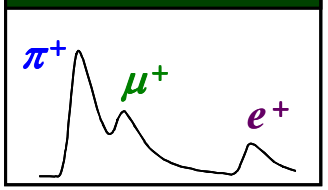


4th generation: P996 proposed at FNAL



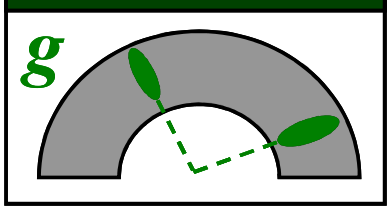
- **Measure everything possible**
- 710 MeV/c K^+ beam
- Stop K^+ in scintillating fiber target
- Wait at least 2 ns for K^+ decay (delayed coincidence)
- Measure π^+ momentum in drift chamber
- Measure π^+ range and energy in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in range stack
- Veto photons, charged tracks

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



500 MHz digitizers

4p Photon Veto



Incremental Improvements

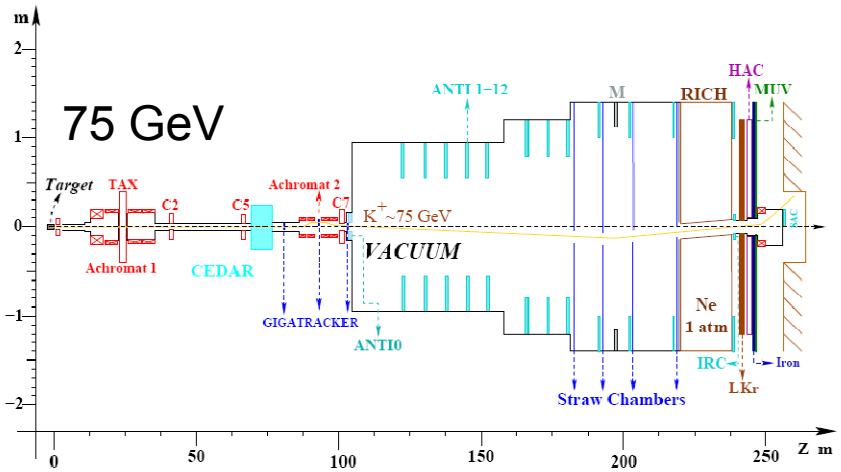
- 550 MeV/c K stopping rate **x5** with comparable instantaneous rate
- Larger solid angle – Acceptance **x 10**
- Finer segmentation, improved resolutions -

Reduced backgrounds

- Overall **100 x** sensitivity

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

CERN NA-62 first generation decay-in-flight experiment.



- Builds on NA-31/NA-48
- Un-separated GHz beam
- Aim: 50 events/yr at SM
- Under construction; start >2012

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

KOTO: 2nd try with ~same setup as KEK ($B(K_L^0 \to \pi^0 \nu\bar{\nu}) < 2.6 x 10^{-8}$)

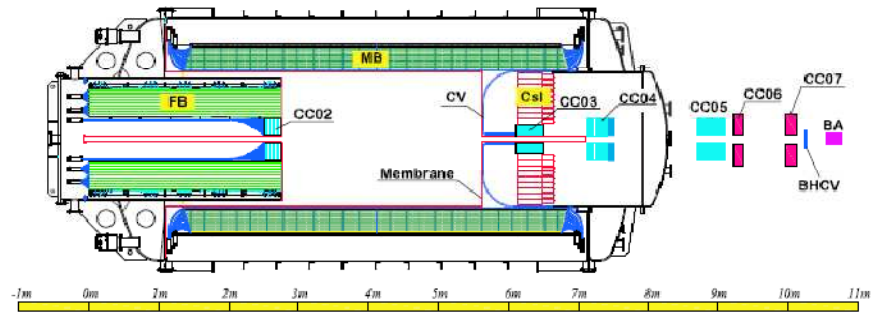
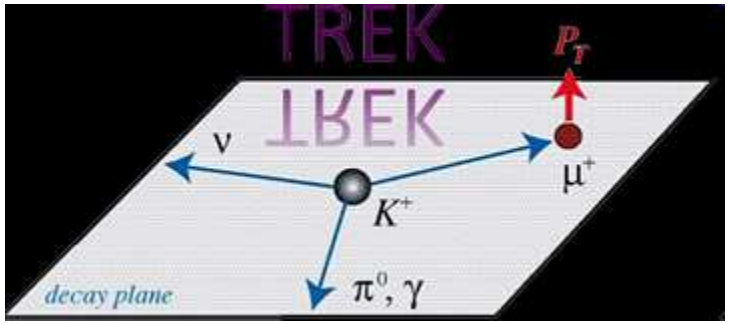


FIG. 1: Cross section of the E391a detector. K_L^0's enter from the left side.

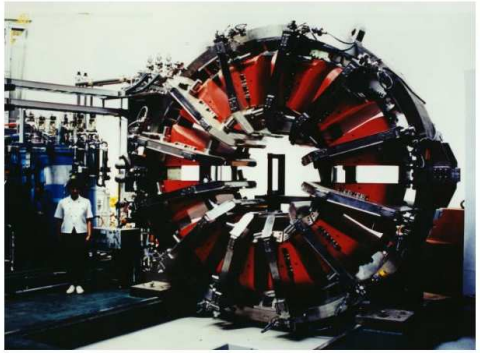
- Improved J-PARC Beam line
- (Eventually) higher power
- Aim: 2.8 events (S/B~1) at SM
- Under construction; start >2011

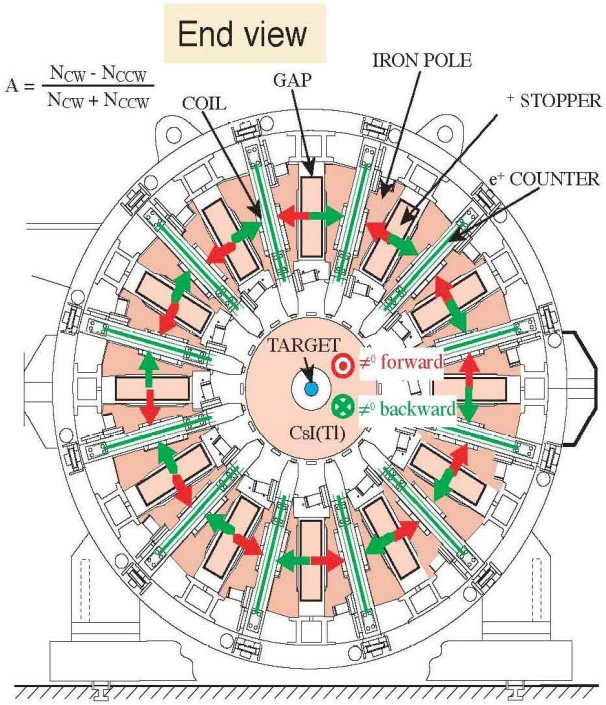
Search for T-violation in $K \rightarrow \pi\mu\nu$ TREK at J-PARC

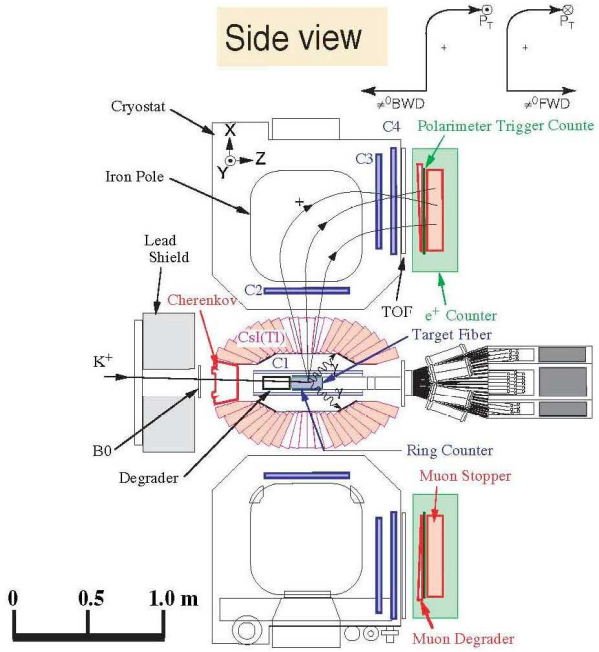


Goal:
$\Delta P_T = 10^{-4}$

Superconducting toroidal magnet

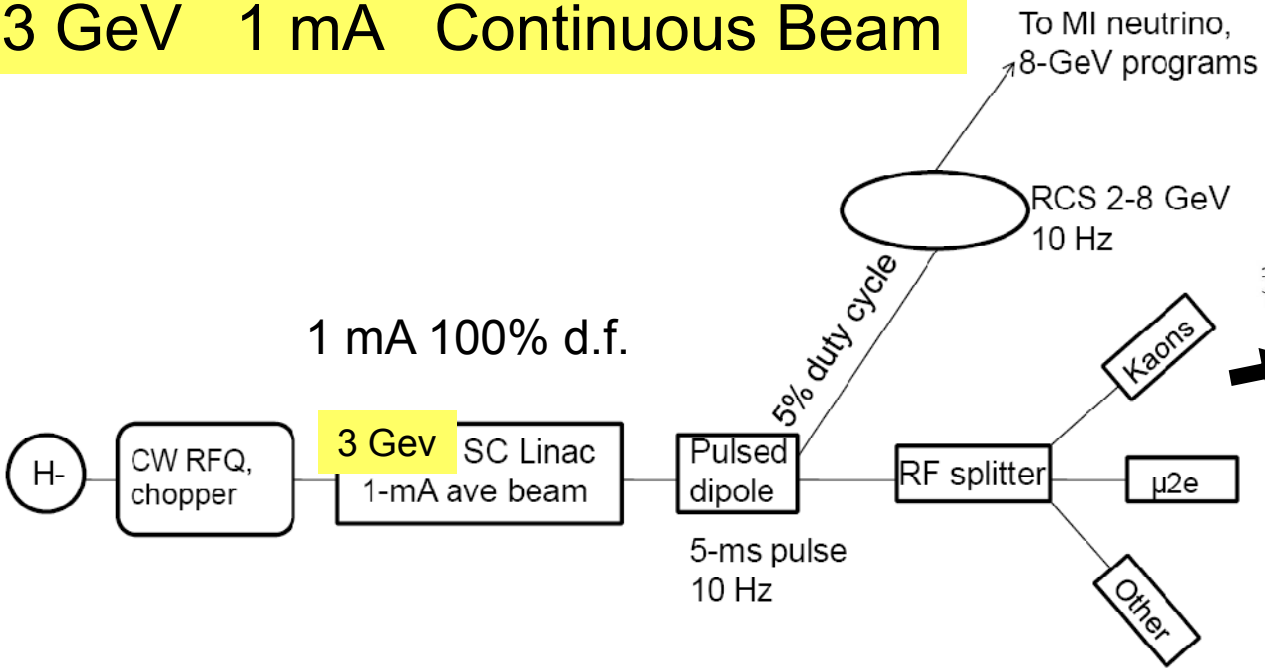




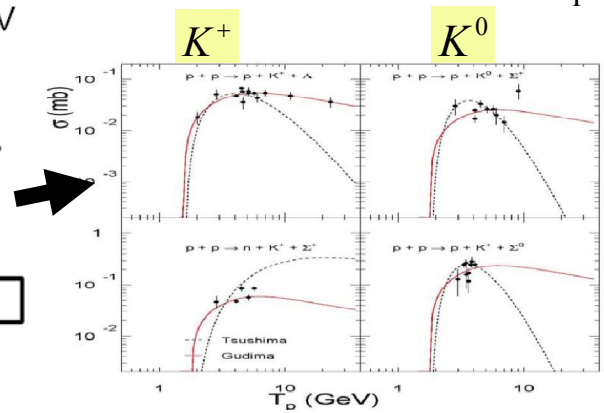


Fermilab Project X (ICD-2)

3 GeV 1 mA Continuous Beam



Kaon Production *vs*. T_P



K production (<1 GeV): $\dfrac{\sigma_K^{3\ \mathrm{GeV}}}{\sigma_K^{24\ \mathrm{GeV}}} \sim \dfrac{1}{10}$

p beam intensity: $\dfrac{\text{Proj. X}}{\text{AGS}} \sim 300$

K flux: $\dfrac{\text{Proj. X}}{\text{AGS}} \sim 30$

The Challenge: $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

- $B(K_L \rightarrow \pi^0 \nu\nu) \sim 2.5 \times 10^{-11}$

  Need huge flux of K's -> high rates
- Weak *neutral particle* kinematic signature

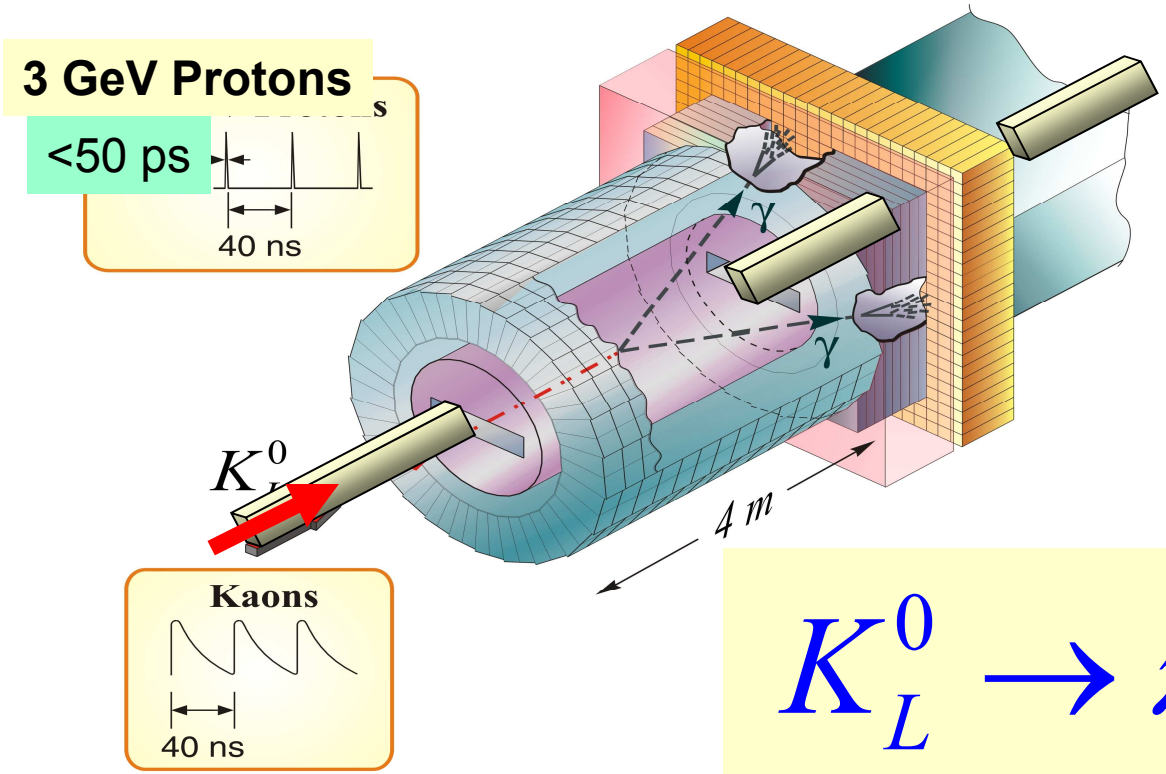
  2 particles missing
- Backgrounds with π^0 up to 10^9 times larger
- Veto inefficiency on extra particles must be $\leq 10^{-4}$
- Neutrons dominate the beam
  - make π^0 off residual gas – requires high vacuum
  - halo must be very small
  - hermeticity requires photon veto in the beam
- Need convincing measurement of background

Sherlock Holmes in "The Crooked Man"

- "**You know my methods, Watson.** … **And it ended by my discovering traces,** but very different ones from those which I had expected.

Project X : $K_L^0 \to \pi^0 \nu \bar{\nu}$ Experiment Concept

a la KOPIO



$$K_L^0 \to \pi^0 \nu \bar{\nu}$$

- Use TOF to work in the K_L^0 c.m. system
- Identify main 2-body background $K_L^0 \to \pi^0 \pi^0$
- Reconstruct $\pi^0 \to \gamma\gamma$ decays with pointing calorimeter
- 4π solid angle photon and charged particle vetos

$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ *At Project X :*

Ideal time structure for TOF-based experiment.

- High intensity allows small beam dimensions (like KOTO):
  "Difficult" flat beam and vacuum vessel unnecessary
- Symmetrical beam, detector; geometric acceptance maximized
- 2-D beam kinematic constraint increases S/B
- Upstream backgrounds, backgrounds in the fiducial volume reduced
- Same micro-bunch event spoilage reduced
- Random vetos reduced due to high duty factor
- Beam veto may be unnecessary
- *Neutron rates higher – could be problematic*

(See 2008 Project X workshop talks by L. Littenberg, S. Kettell)

$K \to \pi\nu\bar{\nu}$ Prospects

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

Now: $B(K^+ \to \pi^+\nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$

(7 events)

Future: Sensitivity at SM $(0.85 \pm 0.07)x10^{-10}$

Goals	NA62 CERN	P996 FNAL	Proj.X FNAL
Events/ yr	40	200	500
S/N	5	5	5
Precision	10%	5%	3%

$K_L^0 \to \pi^0\nu\bar{\nu}$

Now: $B(K_L^0 \to \pi^0\nu\bar{\nu}) < 2.6\, x\, 10^{-8}$

Future: Sensitivity at SM $3\, x\, 10^{-11}$

Goals	KOTO J-PARC	Proj.X FNAL
Events/yr	~1	"200"
S/N	~1	5-10
Precision		5%

* J-PARC plans a phase II to reach higher sensitivity.

Summary: Rare Kaon Decays

* The AGS played a major role in the study and discovery of K decays

* New experiments have exceptional sensitivity to Flavor Physics:

CERN NA62$\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$, *JPARC* KOTO $\left(K_L^0 \to \pi^0 \nu\bar{\nu}\right)$ & TREK($K_{\vec{\mu}3}$)

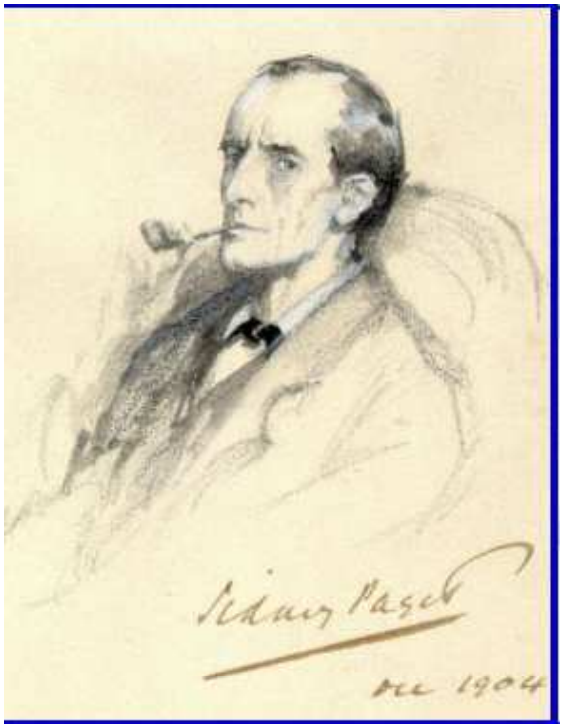
* Future experiments possible at *Fermilab* :

Great potential for advancing the intensity frontier

"Ultimate" high precision experiments possible

MI+Tevatron Strecher: $K^+ \to \pi^+ \nu\bar{\nu}$

Project X : $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L^0 \to \pi^0 \nu\bar{\nu}$, many others



"... the lowest and vilest alleys in London do not present a more dreadful record of sin than does the smiling and beautiful countryside."

Sherlock Holmes in the Copper Beeches

i.e. We really don't know where the new physics will turn up!