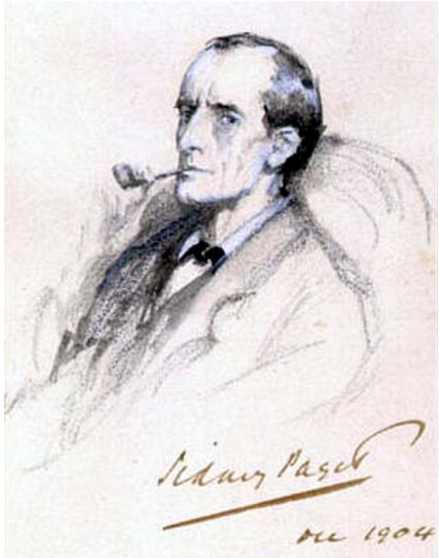
Solving Mysteries with
Rare Kaon Decays



Douglas Bryman
University of British Columbia

Energy Frontier

Tevatron → LHC; TeV Energy Scale

New Physics

Precision Frontier

DARK Matter Frontier

High Mass Scales?

Flavor Physics

Rare Decays and CP violation

Symmetry Violation

COSMOLOGICAL EVOLUTION, BBN

LEPTOGENESIS?

NEUTRINO PHYSICS

The Memoirs of Sherlock Holmes
by Sir Arthur Conan Doyle

"Excellent!" [Watson] cried.
"Elementary," said [Holmes].

"**The Crooked Man**"

Five Special Rare Decay Experiments

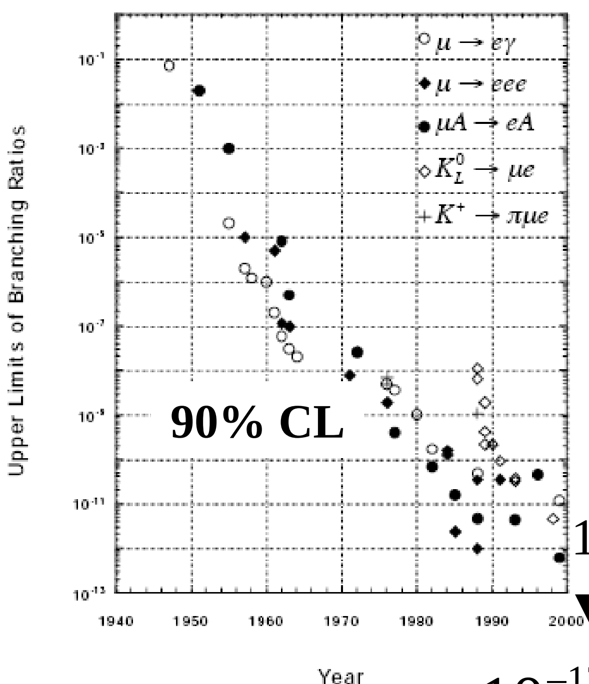
Probe new physics at the 1-1000 TeV Scales!

		State of the art: $: 10^{-12}$
Exotic Searches- *New physics if seen since SM effects are negligible.*	Lepton Flavor Violation:	
	$\mu \to e\gamma$	**$<1.2\ 10^{-11}$**
	$\mu^- N \to e^- N$	**$<7.8\ 10^{-13}$**
SM Parameters and BSM Physics *New physics if deviations from well-calculated SM predictions occur.*	$\left\{ \frac{\pi^+(K^+) \to e^+\nu}{\pi^+(K^+) \to \mu^+\nu} \right\}$	*****±0.4%**
	$\left\{ \begin{matrix} K^+ \to \pi^+ \nu \bar{\nu} \\ K_L^0 \to \pi^0 \nu \bar{\nu} \end{matrix} \right\}$	*****10^{-10}: 7events** $< 6.7\, x 10^{-8}$

Experiments

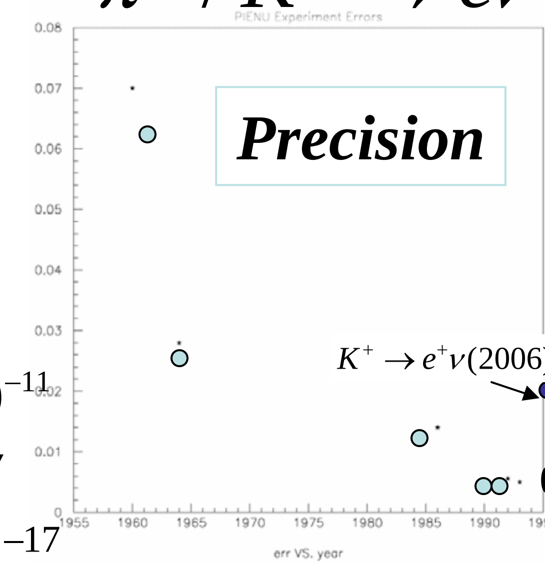
Prospects for 10-1000 x improvements.

Lepton Flavor Violation



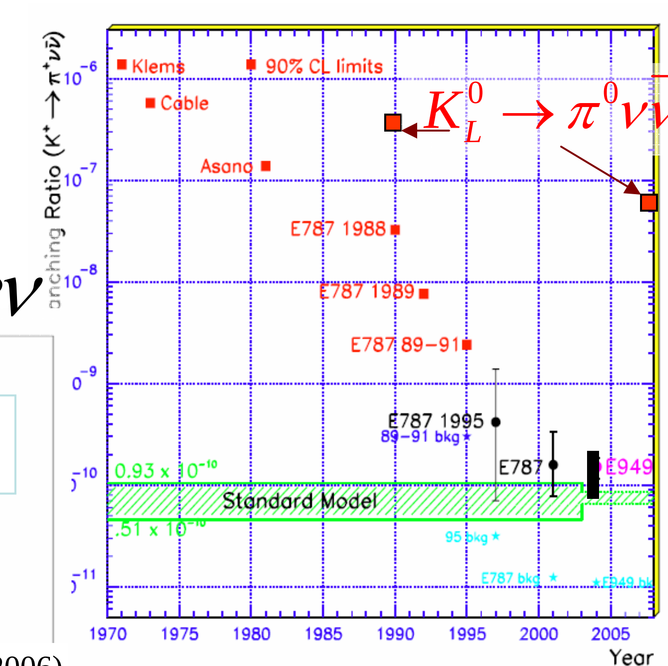
10^{-11} ↓ $10^{-13/-17}$

$\pi^+ / K^+ \to e\nu$



↓ 0.4% ↓ 0.06%

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



7 ↓ 100 ↓ 1000

Intensity Frontier at Fermilab: Now and in the Future

Now:

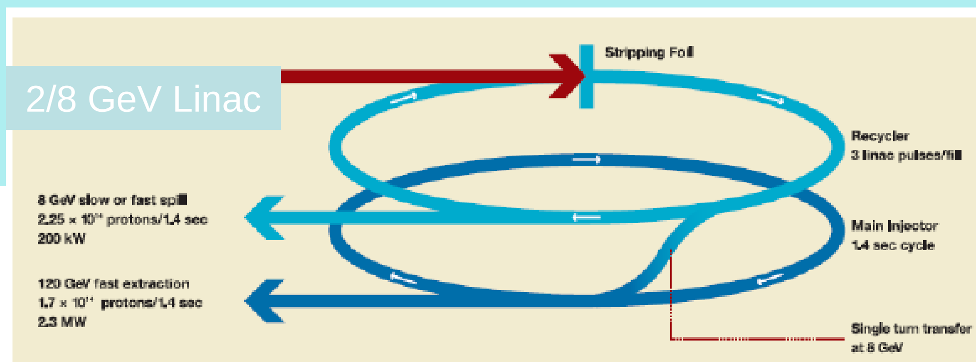
Main Injector Neutrino Program (MINOS,Miniboone,Minerva,NOVA)

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

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

Future:

Project X



Tevatron Stretcher

Mike Syphers

- Tevatron stretcher: 150 GeV beams to Fermilab switch yard.
- MI: 1.33 s cycle time, 2(of 30) pulses->Tevatron
- 100 Tp stored in Tevatron for slow, resonant extraction
- 10% of the available MI beam → 80 kW with **95% duty factor,** 27.3 s cycle time.

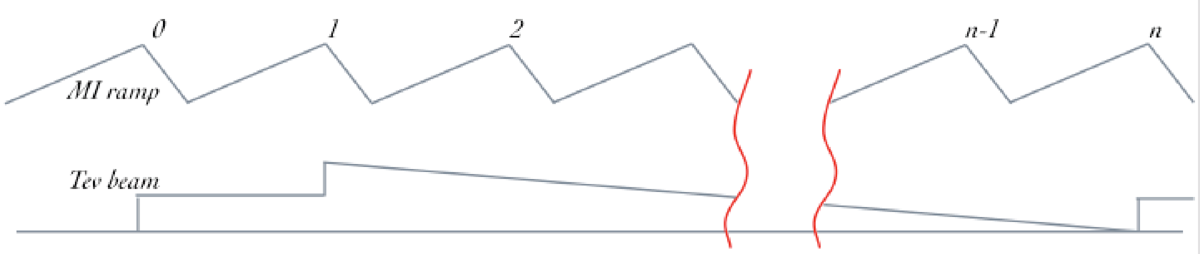
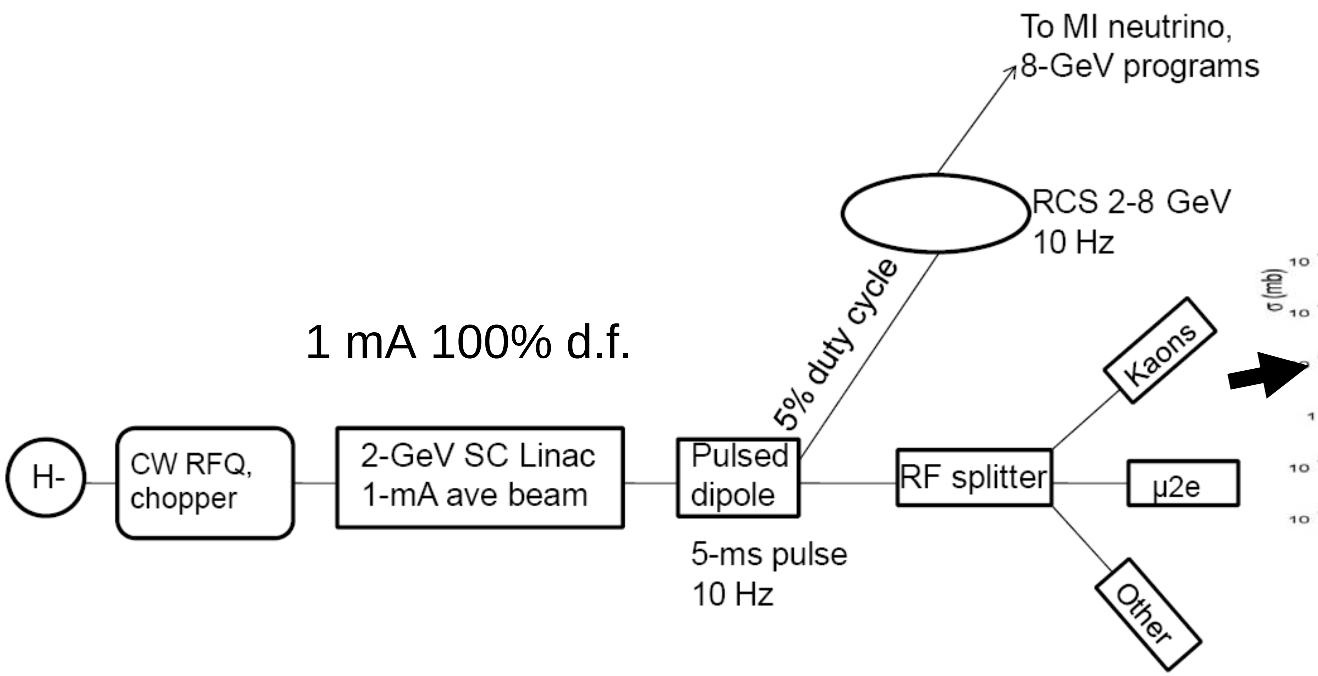


Figure 2. Main Injector energy ramps (top curve) and Tevatron beam intensity (bottom curve). Out of n, beam is injected over two cycles, and spilled for n-1.

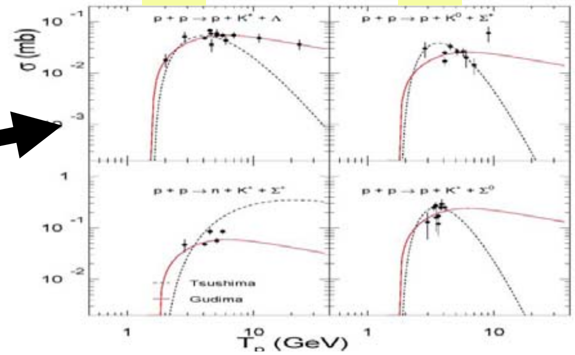
$$\text{K flux: } \frac{\text{MI+Tevatron}}{\text{AGS}} \sim 2.5$$

Project X ICD-2



Kaon Production *vs.* T_P

K^+ K^0



$$\text{K production (<1 GeV):} \quad \frac{\sigma_K^{2\text{ GeV}}}{\sigma_K^{24\text{ GeV}}} \sim \frac{1}{30}$$

$$\text{p beam intensity:} \quad \frac{\text{ICD-2}}{\text{AGS}} \sim 300$$

$$\text{K flux:} \quad \frac{\text{ICD-2}}{\text{AGS}} \sim 10$$

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

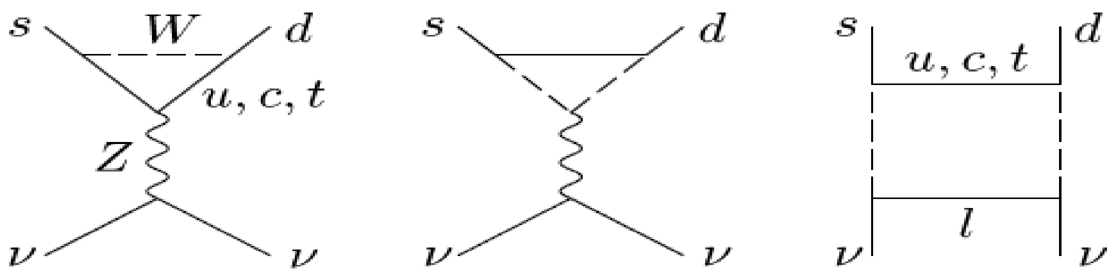
..the curious incident of the dog in the night-time...

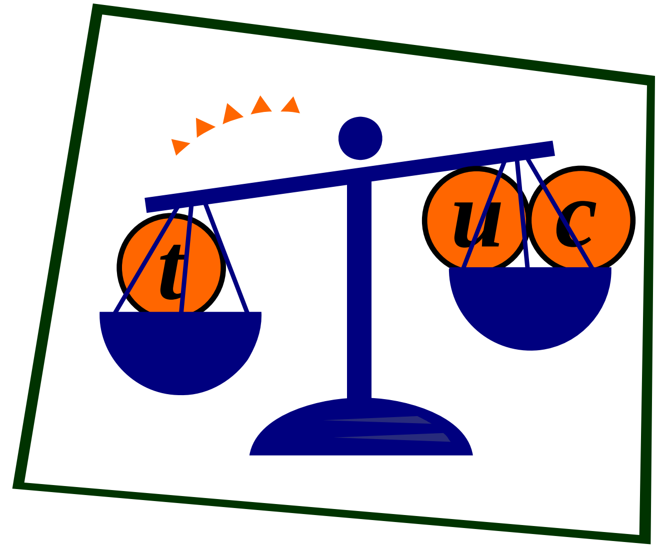
"The dog did nothing in the night-time."
"That was the curious incident,"
remarked Sherlock Holmes.

Sherlock Holmes in "Silver Blaze"

$K \to \pi \nu \bar{\nu}$ in the SM

2nd order weak: proceeds very slowly!





Standard Model (*Buras*):

$\mathrm{Im}\,\lambda_t = \mathrm{Im} V_{ts}^* V_{td} = \eta A^2 \lambda^5$

$$B(K_L^0 \to \pi^0 \nu \bar{\nu}) = 1.8\,x10^{-10} \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 = 2.5 \pm 0.40\,x10^{-11}$$

$(\pm 16\% \to \pm 12\%)$

$$B(K^+ \to \pi^+ \nu \bar{\nu}) \sim 1.0\,x10^{-10} A^4 \left[\eta^2 + (\rho_0 - \rho)^2 \right] = 8.5 \pm 0.7\,x10^{-11}$$

$(\pm 8\% \to \pm 6\%)$

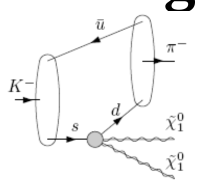
Kronfeld

$K \to \pi\nu\bar{\nu}$: Great Discovery Potential

$\pm 10\%$ measurements $K \to \pi\nu\bar{\nu} \to$ mass scale ~1000 TeV!

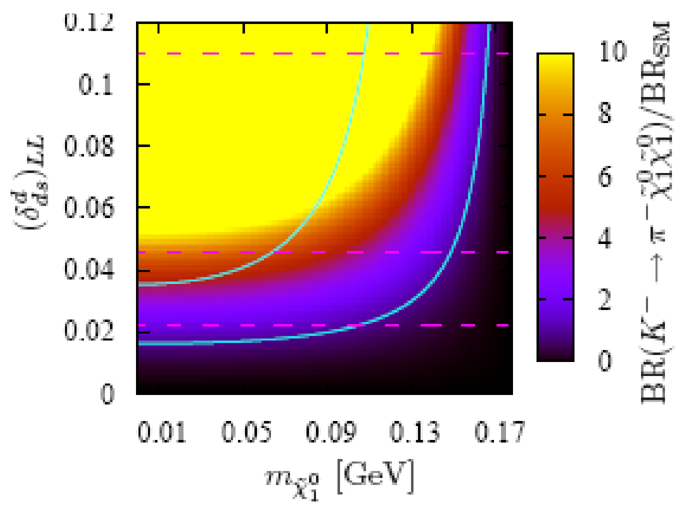
Two Examples:

SUSY: Rare meson decays into light neutralinos



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

$\to$ 5 x SM

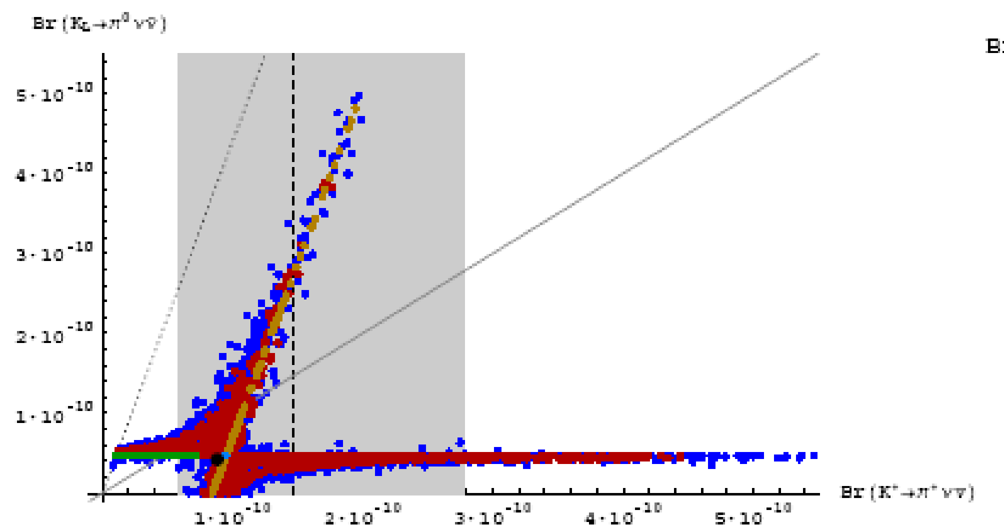


H. K. Dreiner ***et al.*** Bonn-TH-2009-04

Minimal Flavor Violation e.g.

Littlest Higgs Model with T-parity

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

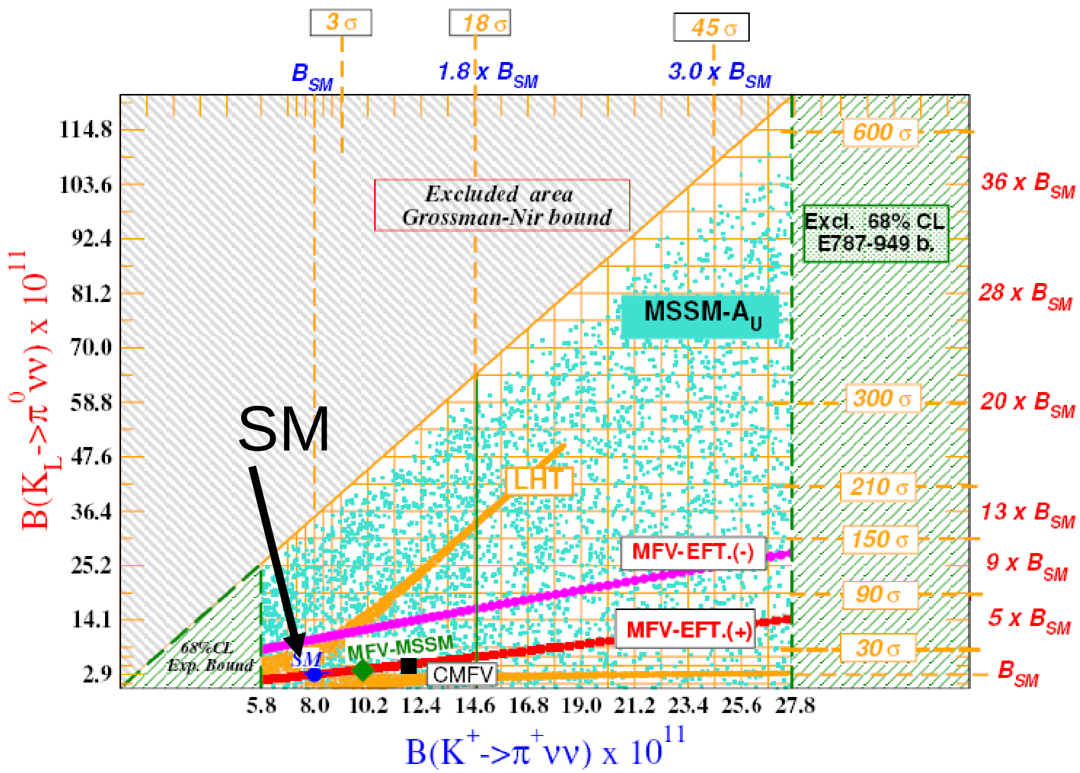


M. Blanke, *et al.*,arXiv:hep-ph/0610298.

A wide range of non-SM possibilities.... (Mescia*)

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

* From G. Isidori, PoS KAON, 064 (2008) [arXiv:0709.2438 [hep-ph]].



Deviations in $\mathrm{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ as small as 30% from SM could be observed at 5σ!

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

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

- BNL E787/949: $B(K^+ \to \pi^+\nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$
- CERN NA62; New Technique
- New proposal: Fermilab P996
- Fermilab Project X?

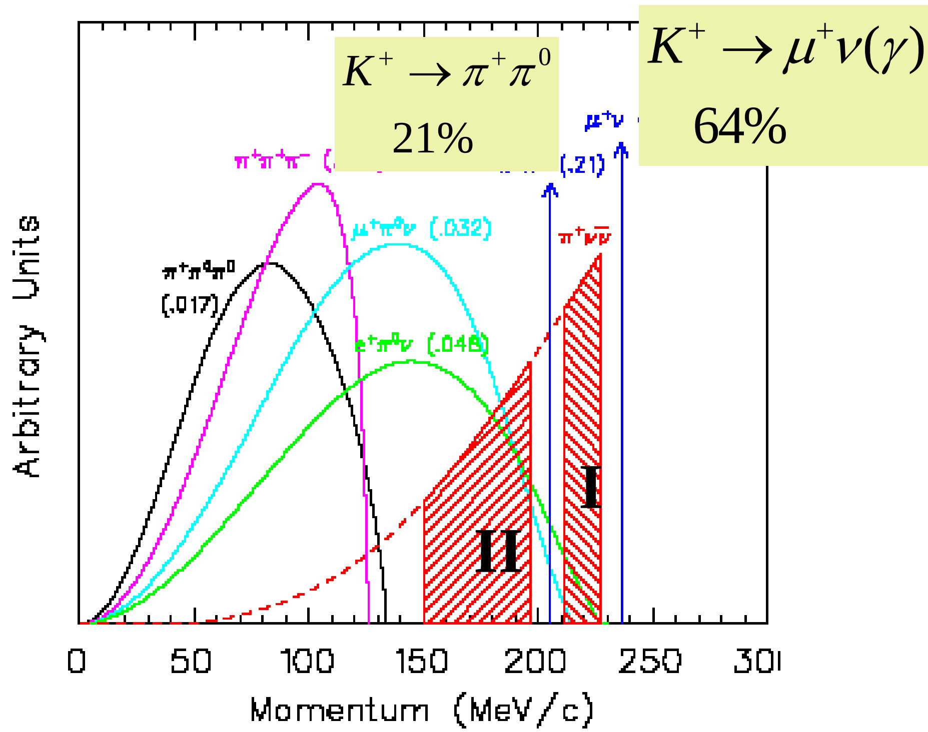
$K_L^0 \to \pi^0\nu\bar{\nu}$

- KEK E391a: $B(K_L^0 \to \pi^0\nu\bar{\nu}) < 6.7\, x10^{-8}$
- JPARC KOTO
- Fermilab Project X?

Special Features of Measuring

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

Background processes exceed signal by $>10^{10}$



- Determine everything possible about the K^+ and π^+
  - * Measure momentum, energy, range, decay sequences
  - * π^+/μ^+ particle ID better than 10^6 (π^+-μ^+-e^+)
- Eliminate events with extra charged particles or ***photons***
  - * π^0 inefficiency $< 10^{-6}$
- Suppress backgrounds well below the expected signal (S/N~5-10)
  - * Predict backgrounds *from data*: dual independent cuts
  - * Use “Blind analysis” techniques
  - * Test predictions with “outside-the-box” measurements
- Evaluate candidate events with S/N function

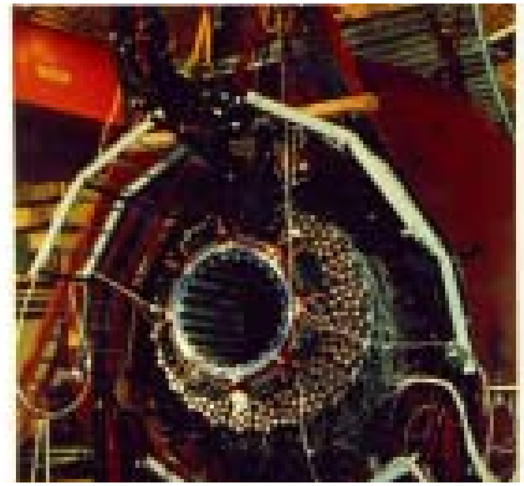
“…**when you have eliminated the impossible, whatever remains, *however improbable*, must be the truth**? ”

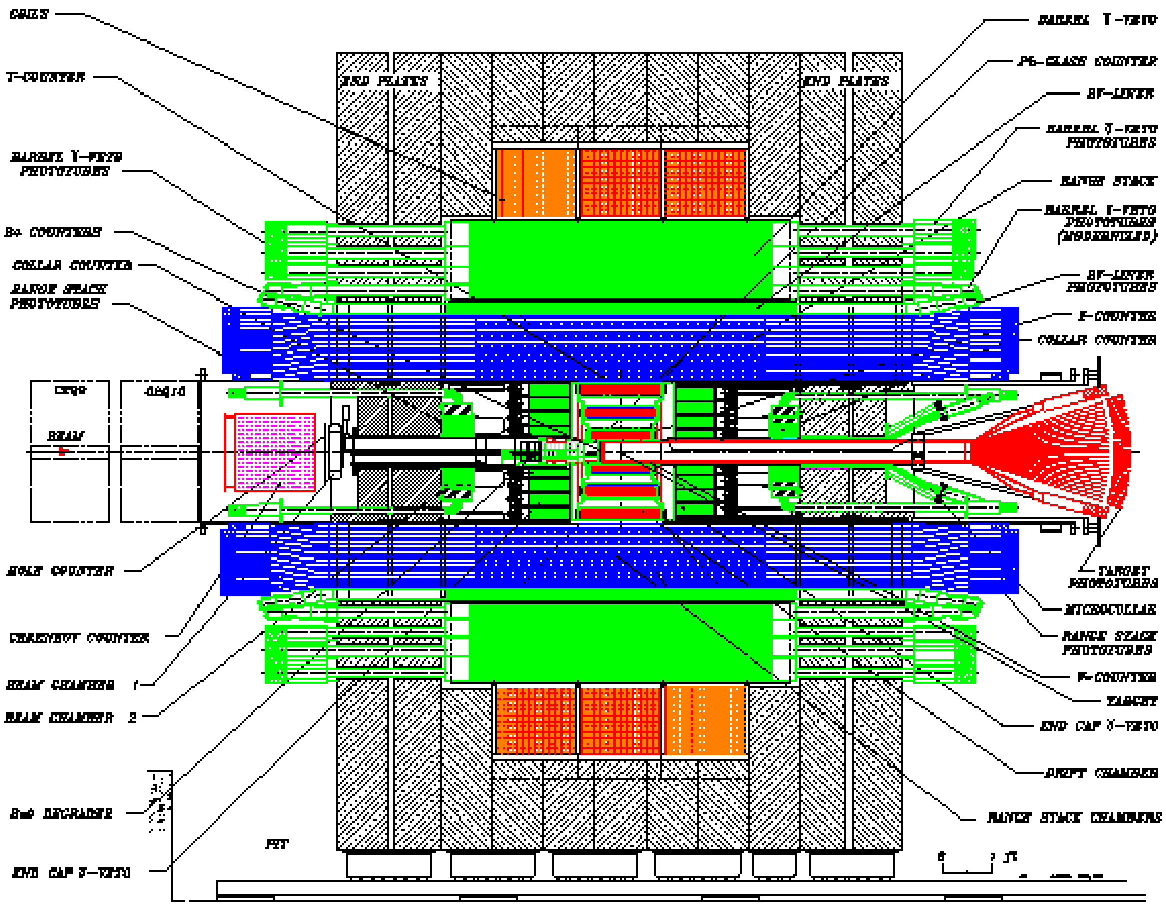
Sherlock Holmes in The Sign of the Four (1890)

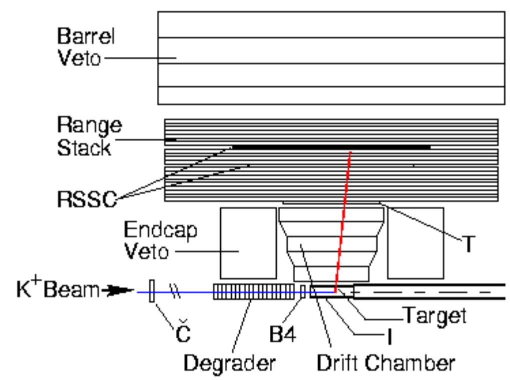
BNL E787/949

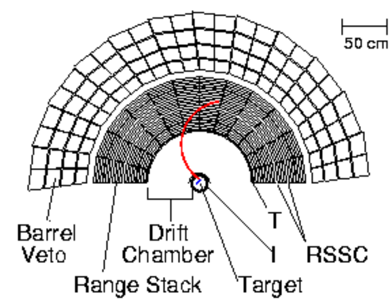
Measurement of

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





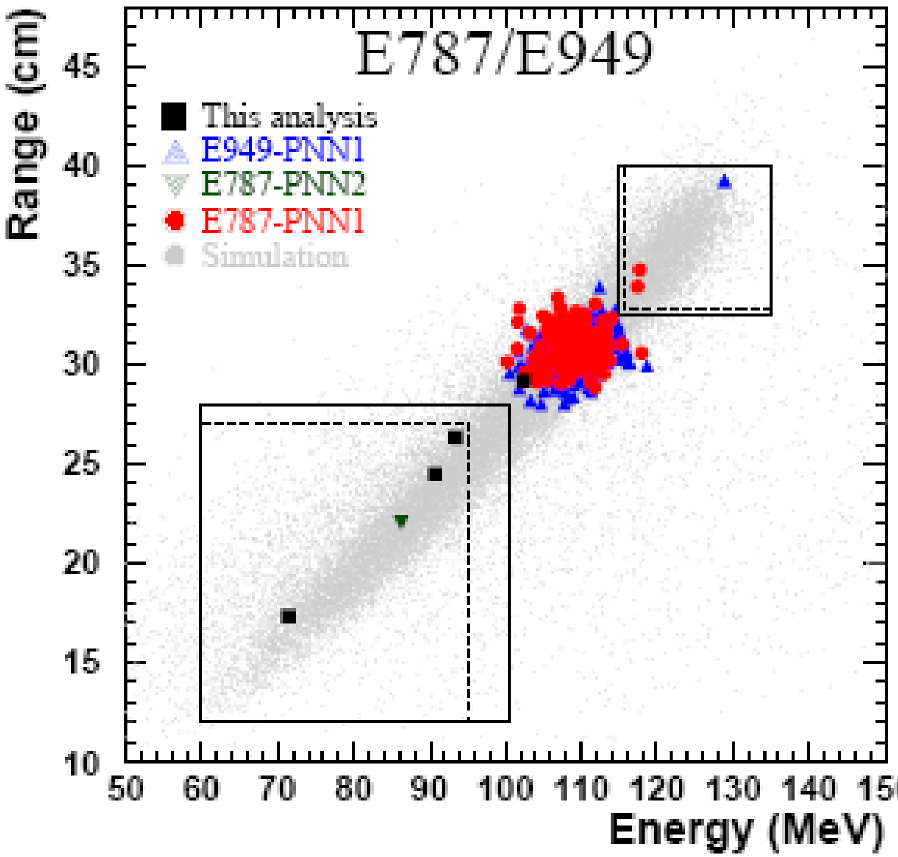




E787/E949 Final Result:

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

7 events observed



E787(dashed) and E949(solid) signal regions shown. All cuts applied.

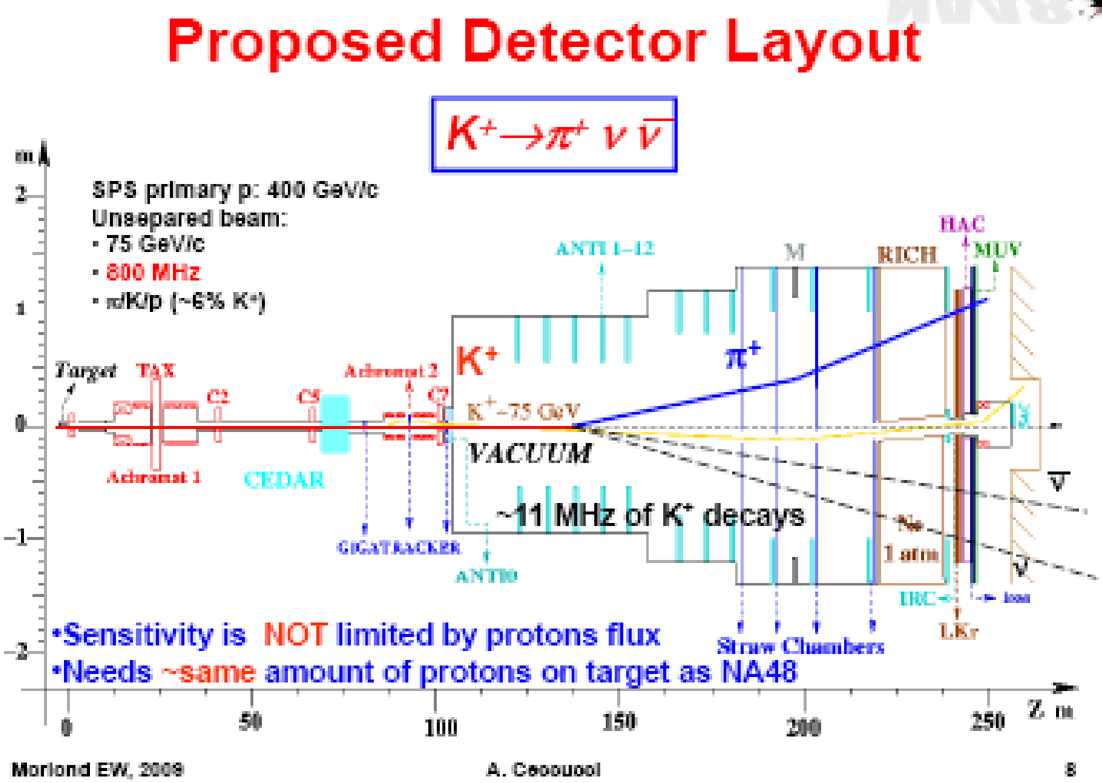
(Standard Model:

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

Probability for all 7 events to be due to background: 0.001

New Approach to $K^+ \to \pi^+ \nu\bar{\nu}$: Decay-in-flight at 75 GeV/c

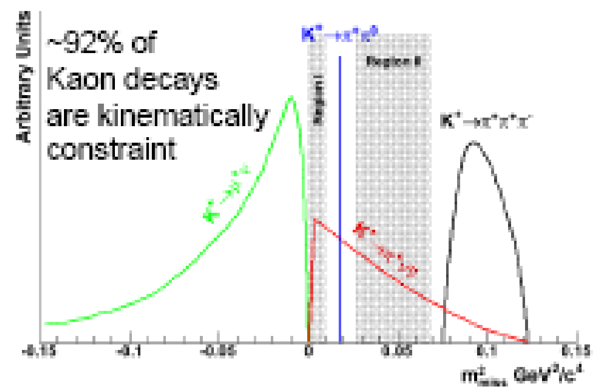
CERN Proposal NA62



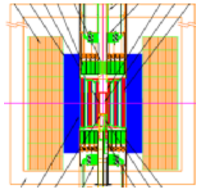
Goal: 10 x E949

50 events/yr; Bkg. 14%

New technique



New Proposal P996:



Measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Decay at Fermilab

- **150 GeV MI beam (10% of available current) + Tevatron stretcher (after Run II)→ 95% d.f.**
- **New short K^+ beam at P=550 MeV/c**:

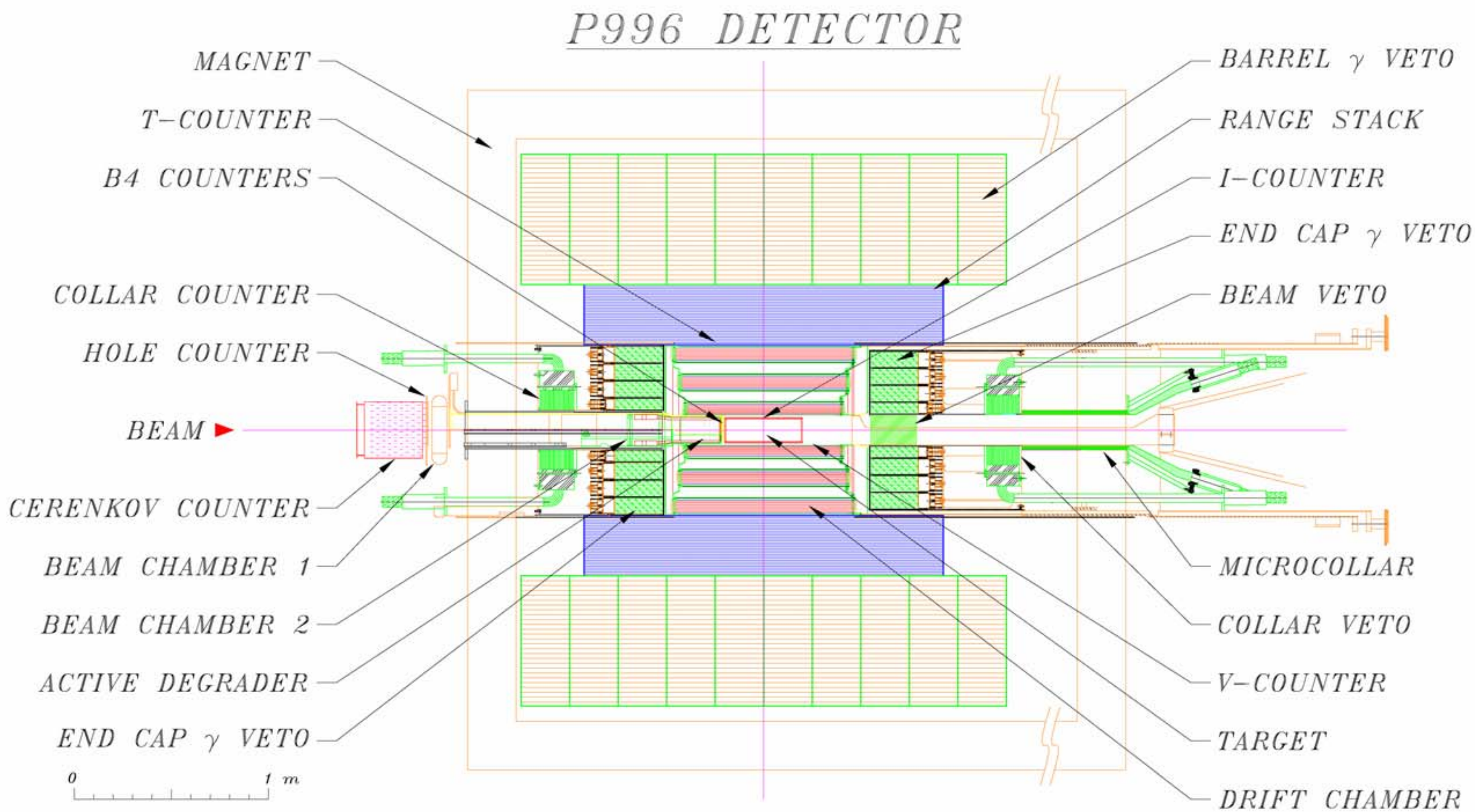
  7 x K^+ flux relative to LESB3 at the AGS

  3 x efficiency for stopping kaons

- **Detector Improvements**

  >10 x acceptance of E949**.**

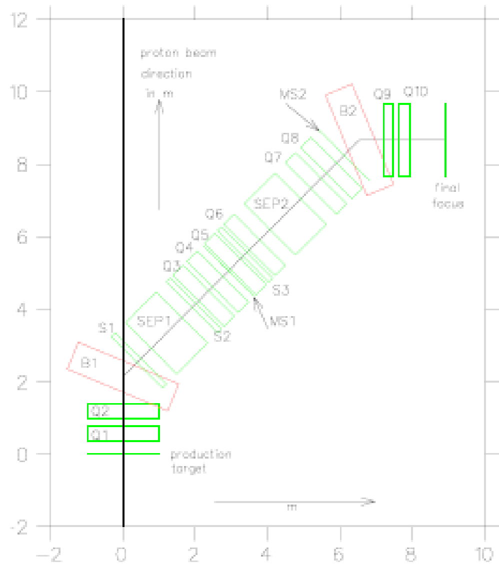
- **Goal: >100 x E949**
- ***Proven technique.***



Magnetic Field: B=1.25 T

P996: Incremental Improvements to E949 Technique

13.7 m K+ beam at 550 MeV/c



$$\left[\frac{K}{\pi} \sim 3\right]$$

Acceptance Gain Factor: $11.28^{+3.25}_{-2.22}$

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

Estimated sensitivity at the SM level: 194^{+89}_{-79} events/yr.

Can reach precision <5%, comparable to future improvements expected for SM prediction.

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

	MI+Tevatron Stretcher (P996)	Project X ICD-2 (Rough est.)
Events/yr	194^{+89}_{-79}	“500”
S/N	~4	~4
Precision attainable	5%	3%

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

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

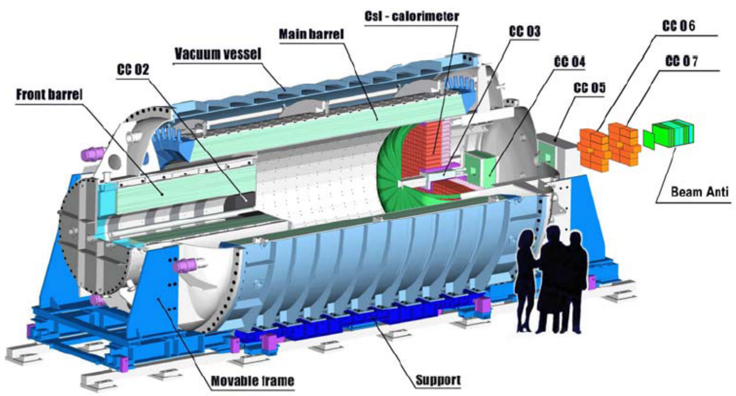
Sherlock Holmes in "The Crooked Man"

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

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

KEK PS E391a → JPARC **KOTO** with KTEV CsI

E391a Result: $B(K_L^0 \to \pi^0 \nu \bar{\nu}) < 6.7\, x 10^{-8}$ $(90\% CL)$



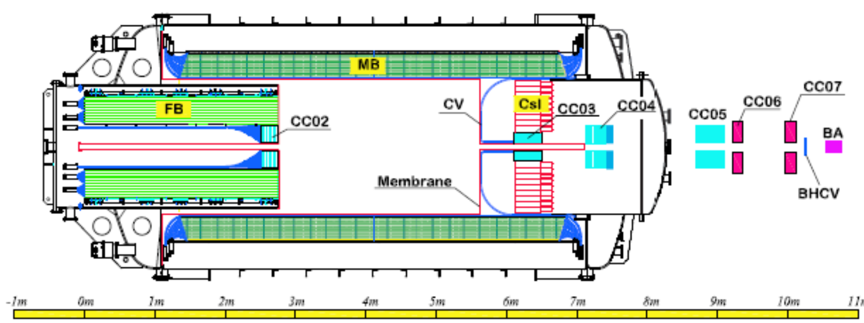


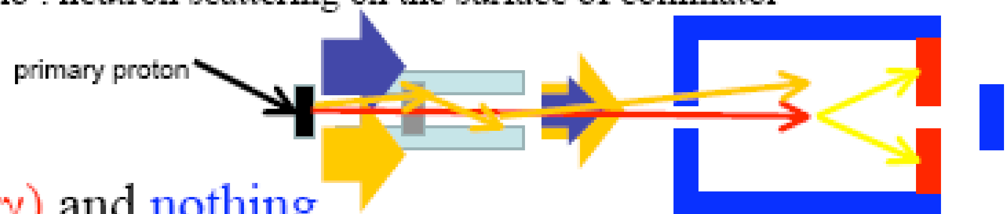
FIG. 1: Cross section of the E391a detector. K_L^0's enter from the left side.

Features:

- Pencil Beam , High P_T selection
- High acceptance
- Reliance on high photon veto efficiency
- Sensitivity goal: ~SM level: 2.8 events S/B~1

KOTO Concept of Experiment

- K_L beam (proton → target)
  - neutral beam line
    - » Long beam line → Kill particles with shorter lifetime
    - » Charged particle sweeping magnet.
    - » Pb photon absorber → reduce beam photons
    - » Collimator → shaping KL →Pencil Beam (source of beam halo)
  - Core : K_L, photon, neutron
  - Halo : neutron scattering on the surface of collimator



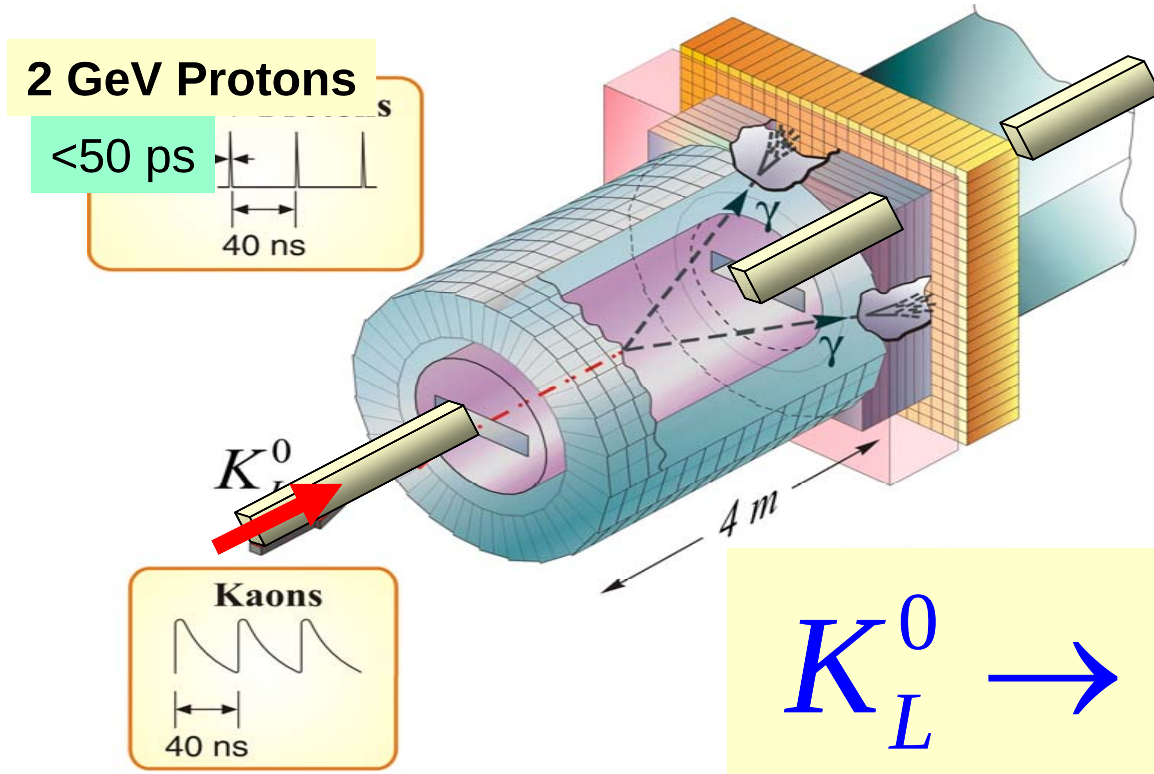
- Detector
  - π^0 ($\rightarrow\gamma\gamma$) and nothing
    - Photon calorimeter and hermetic vetos.
    - Pencil Beam Method. (small beam hole and KL rec.)

5 Kaon09

Hajime Nanjo (*Kyoto*)

Project X ICD-2: $K_L^0 \to \pi^0 \nu \bar{\nu}$ 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 ICD-2:*

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)

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

Based on KOPIO techniques, a rough estimate for a Project X ICD-2 experiment can be made. J-PARC group also plans a phase II to reach higher sensitivity.

	KOTO J-PARC	Project X ICD-2
Events/yr	~1	"200"
S/N	~1	5-10
Precision attainable		5%

Summary: Rare Kaon Decays

Exceptional sensitivity to new Flavor Physics

CERN NA62 $\left(K^{+} \rightarrow \pi^{+}\nu\bar{\nu}\right)$ and JPARC KOTO $\left(K_{L}^{0} \rightarrow \pi^{0}\nu\bar{\nu}\right)$ poised to begin soon.

* Fermilab: great potential for advancing the intensity frontier

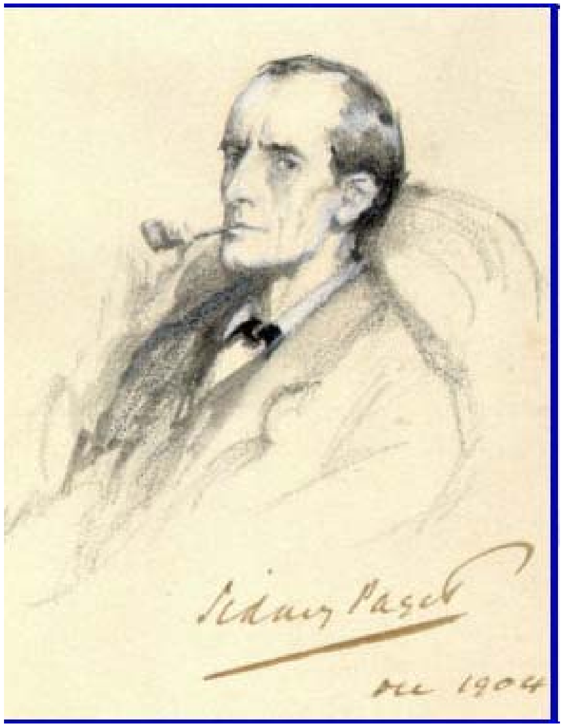
"Ultimate" high precision experiments possible

* Significant work can be done with existing facilities:

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

* Project X ICD-2 would provide extraordinary

possibilities for measuring $K_{L}^{0} \rightarrow \pi^{0}\nu\bar{\nu}$



“... 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