

# Charged Kaons at the Main Injector.

R. Tschirhart, Fermilab

Representing the CKM Collaboration.

February 16th, 2001

- The Physics.
- Overview of the Technique.
- Backgrounds, Backgrounds, Backgrounds...
- Weapons we have to fight the backgrounds.
- Future plans.



## Charged Kaons at the Main Injector

November 21, 2000

**A Proposal for a Precision Measurement of the Decay  
 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  and Other Rare  $K^+$  Processes at Fermilab  
Using the Main Injector**

J. Frank, S. Kettell, R. Strand  
Brookhaven National Laboratory, Upton, NY, USA

L. Bellantoni, R. Coleman, P.S. Cooper\*, M. Crisler, T. R. Kobilarcik, C. Milstene, H. Nguyen,  
E. Ramberg, R. S. Tschirhart, H. B. White, J. Y. Wu  
Fermi National Accelerator Laboratory, Batavia, IL, USA

A. Kohzevnikov, V. Kubarovsky, V. Kurshetsov, L. Landsberg, V. Molchanov, V. Obraztsov, V. Polyakov,  
D. Vavilov, O. Yushchenko  
Institute of High Energy Physics, Serpukhov, Russia

J. Engelfried, A. Morelos  
Instituto de Fisica, Universidad Autonoma de San Luis Potosi, Mexico

M. Campbell, R. Gustafson, M. Longo, H. Park  
University of Michigan, Ann Arbor, Michigan 48109

K. Lang  
University of Texas at Austin, Austin, Texas 78712

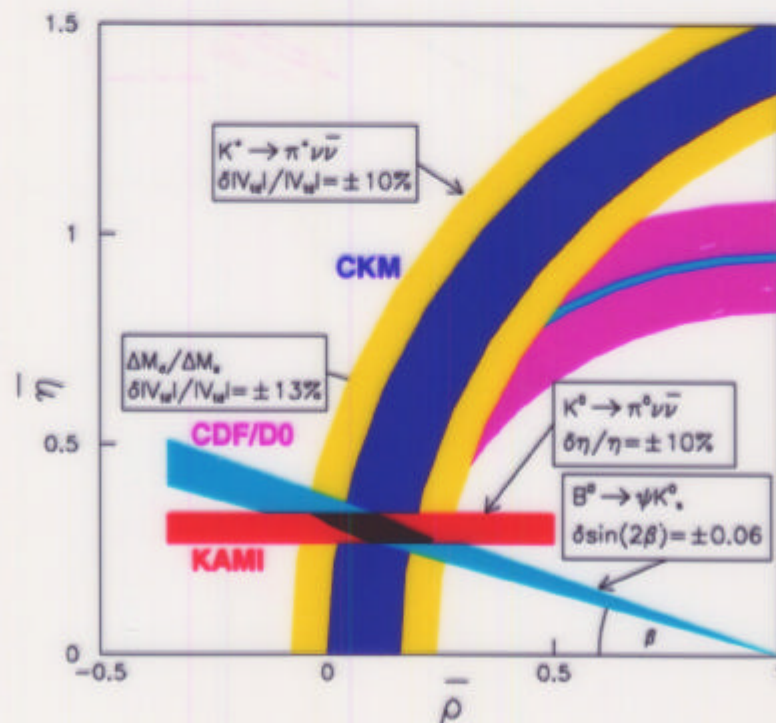
C. Dukes, R. Godang, K. Nelson  
University of Virginia, Charlottesville, VA 22901

\* Spokesman: P.S. Cooper, pcooper@fnal.gov, (630) 840-2629

Web Address: [www.fnal.gov/projects/ckm/Welcome.html](http://www.fnal.gov/projects/ckm/Welcome.html)

## The Physics...

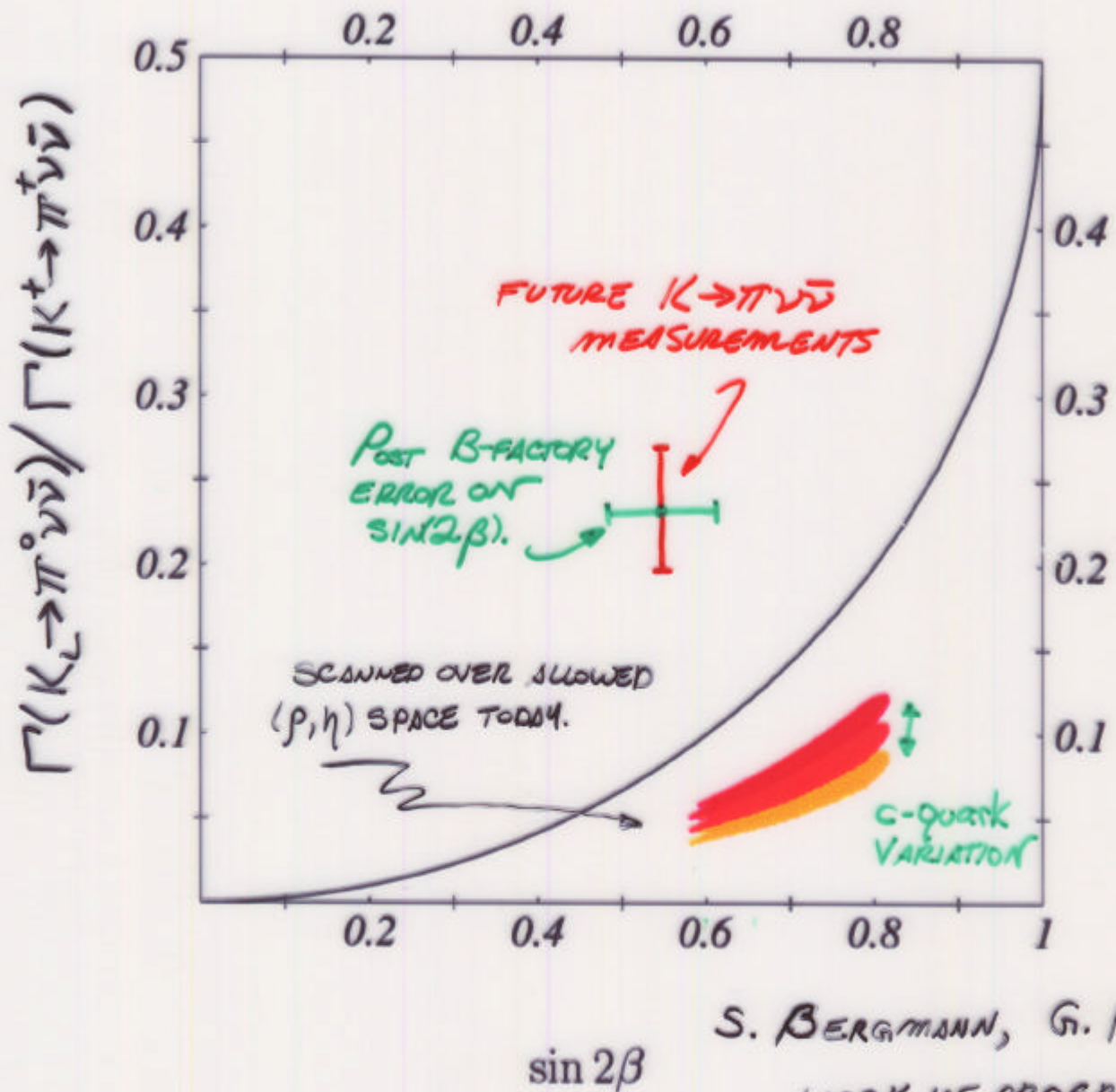
- Measurement of the ultra-rare process  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  provides clean access to the CP-violating parameters of the Standard Model.
- This process is expected to occur with a branching fraction of  $(8 \pm 3 \times 10^{-11})$ , and one clear candidate event has been observed by BNL-E787 with a branching fraction of  $(15^{+34}_{-12} \times 10^{-11})$ .
- The **CKM** experiment proposes to measure this process with a sensitivity of  $1 \times 10^{-12}$ .



## Quantitative Access to CKM parameters.

- Goal is to test the Standard Model hypothesis that a single phase in the CKM matrix is the sole source of CP violation.
- This means *over – constraining* the prediction, and testing for consistency. Paraphrasing Wolfenstein: “...I invented the parameters  $\rho$  and  $\eta$ , and I don't care what the values are so why should you?? The substance here is to *over – constrain* the model and test for *consistency...*”
- To falsify the Standard Model hypothesis the only foreseeable results with controlled errors are:
  - B physics:  $B_d^0 \rightarrow \Psi K_s$ , and perhaps  $x_s/x_d$  mixing.
  - K physics:  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  and  $K^0 \rightarrow \pi^0 \nu \bar{\nu}$ .

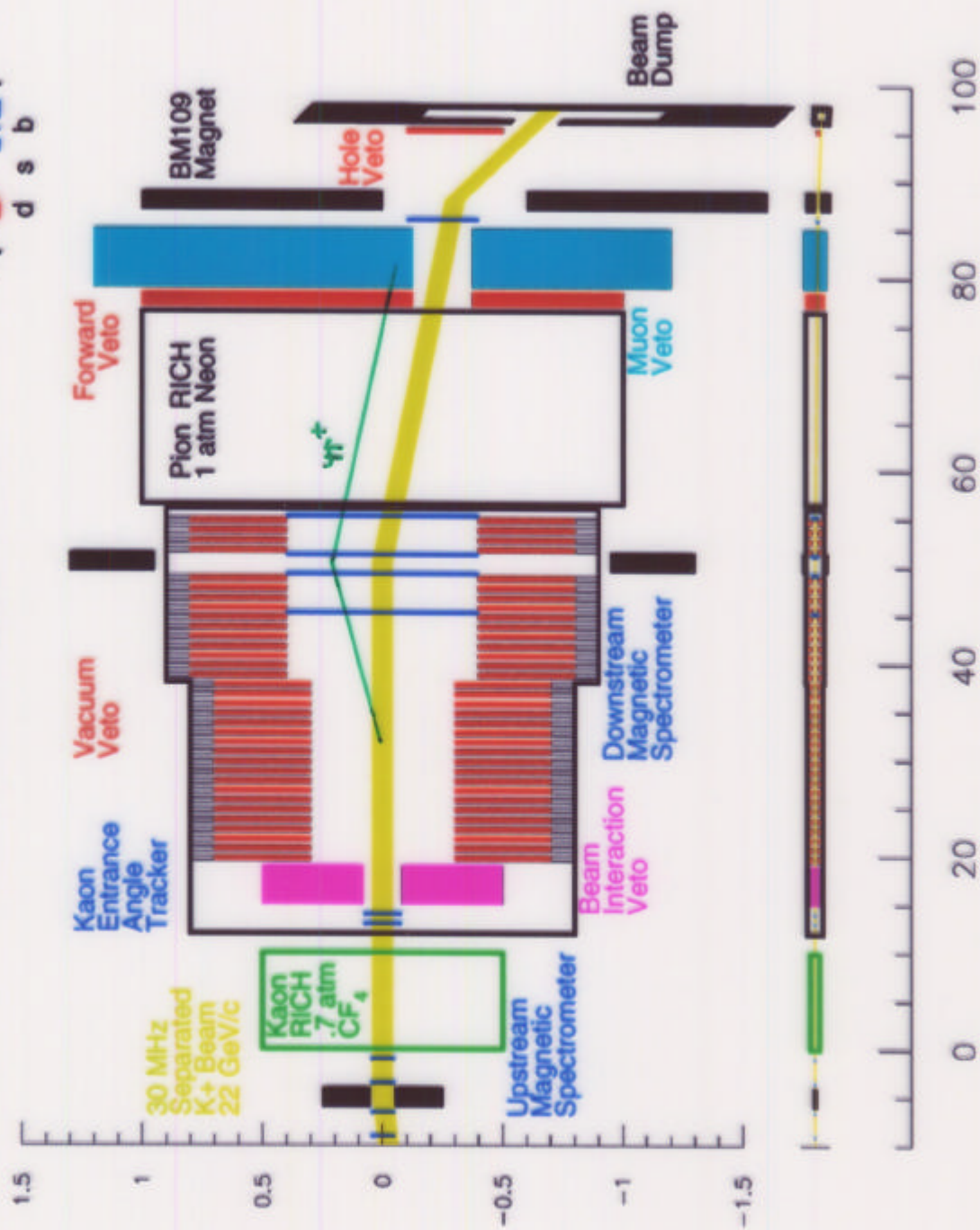
# $a_{\pi\nu\bar{\nu}}$ CHALLENGING THE STANDARD MODEL



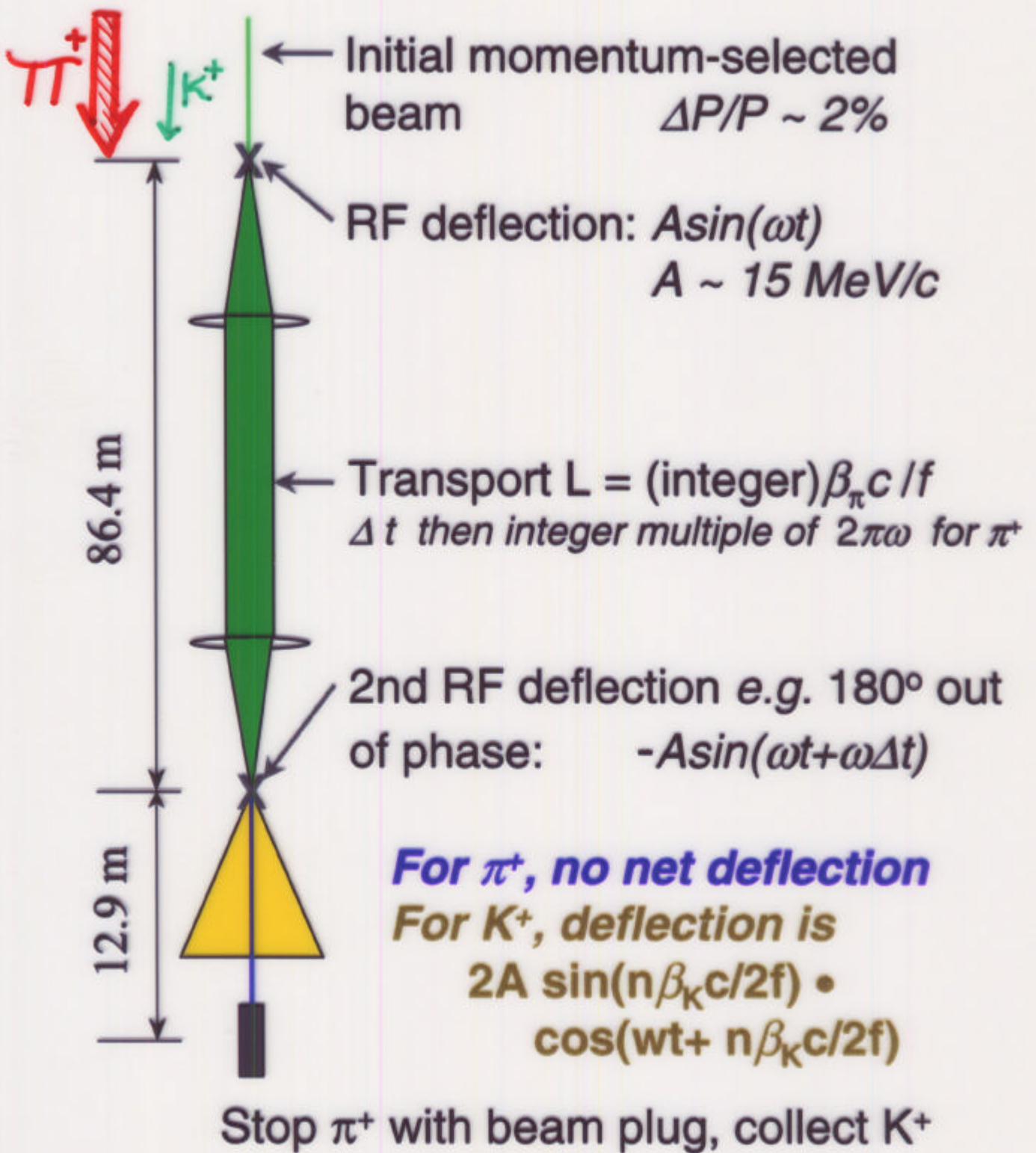
S. BERGMANN, G. PEREZ,  
WORK IN PROGRESS.

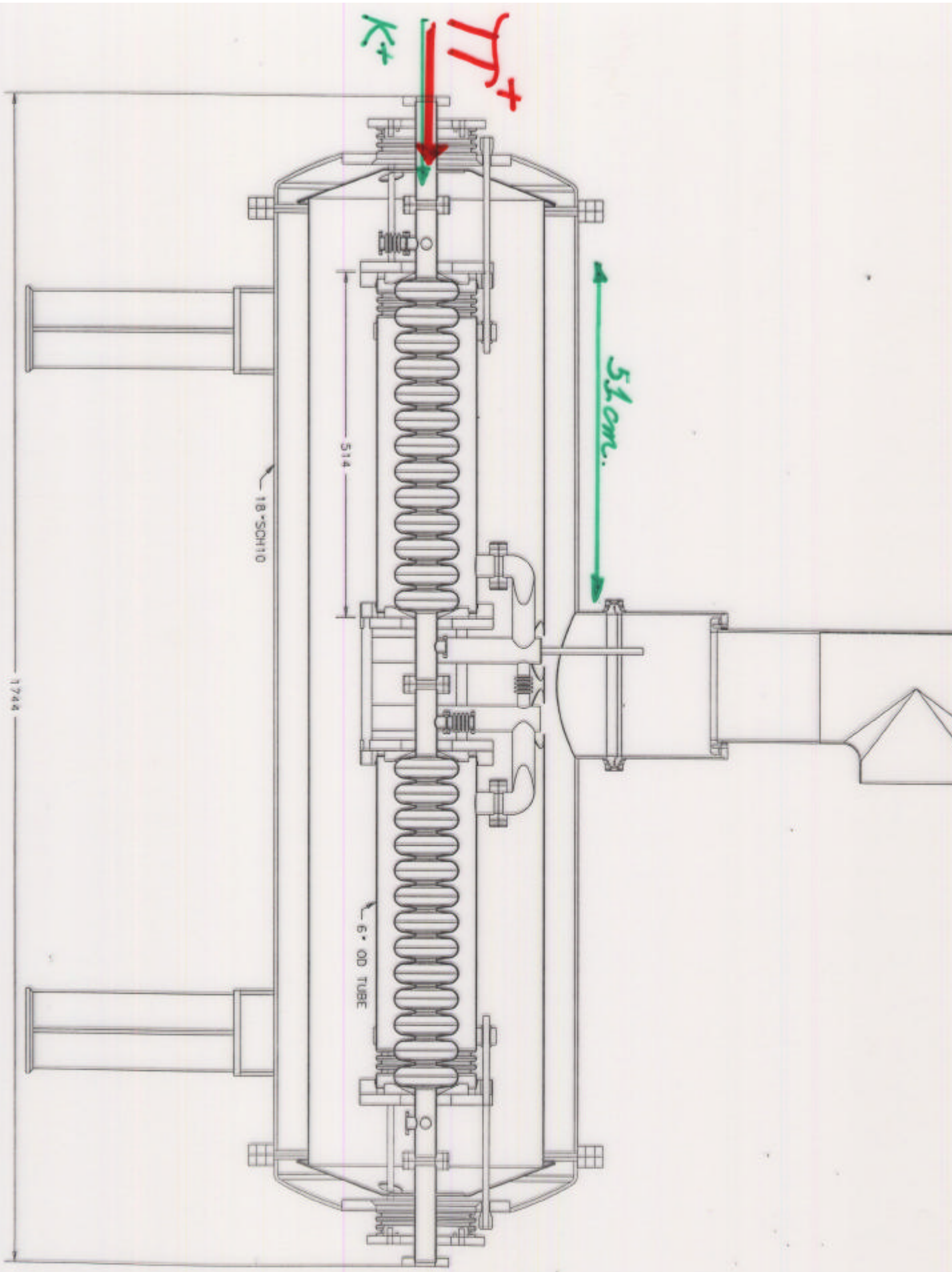
FIG. 3. Relation between  $a_{\pi\nu\bar{\nu}}$  and  $\sin 2\beta$ : The solid curves displays  $a_{\pi\nu\bar{\nu}}(\sin 2\beta)$  for  $\Delta = 0$ . Only in this case there is a one-to-one correspondence between  $a_{\pi\nu\bar{\nu}}$  and  $\sin 2\beta$ . A scan over the presently allowed region for  $(\bar{\rho}, \bar{\eta})$  (c.f. Fig. 1) with  $\Delta = 0.41$  ( $\Delta_{\max} = 0.56$ ,  $\Delta_{\min} = 0.29c$ ) yields the orange (yellow, red) region in the  $\sin 2\beta - a_{\pi\nu\bar{\nu}}$  plane.

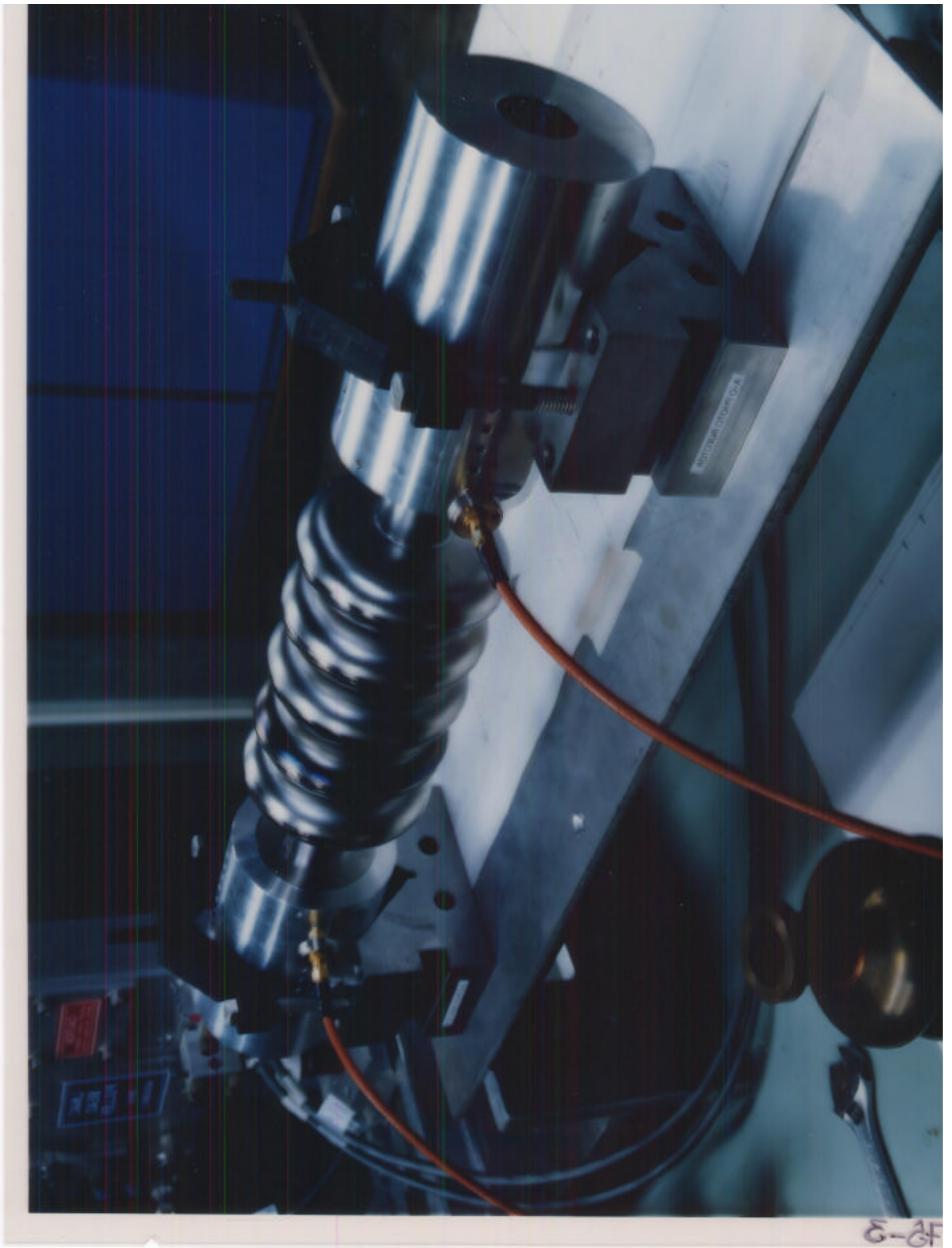
# CKM Apparatus



# 30:1 *RF separated K<sup>+</sup> beams*

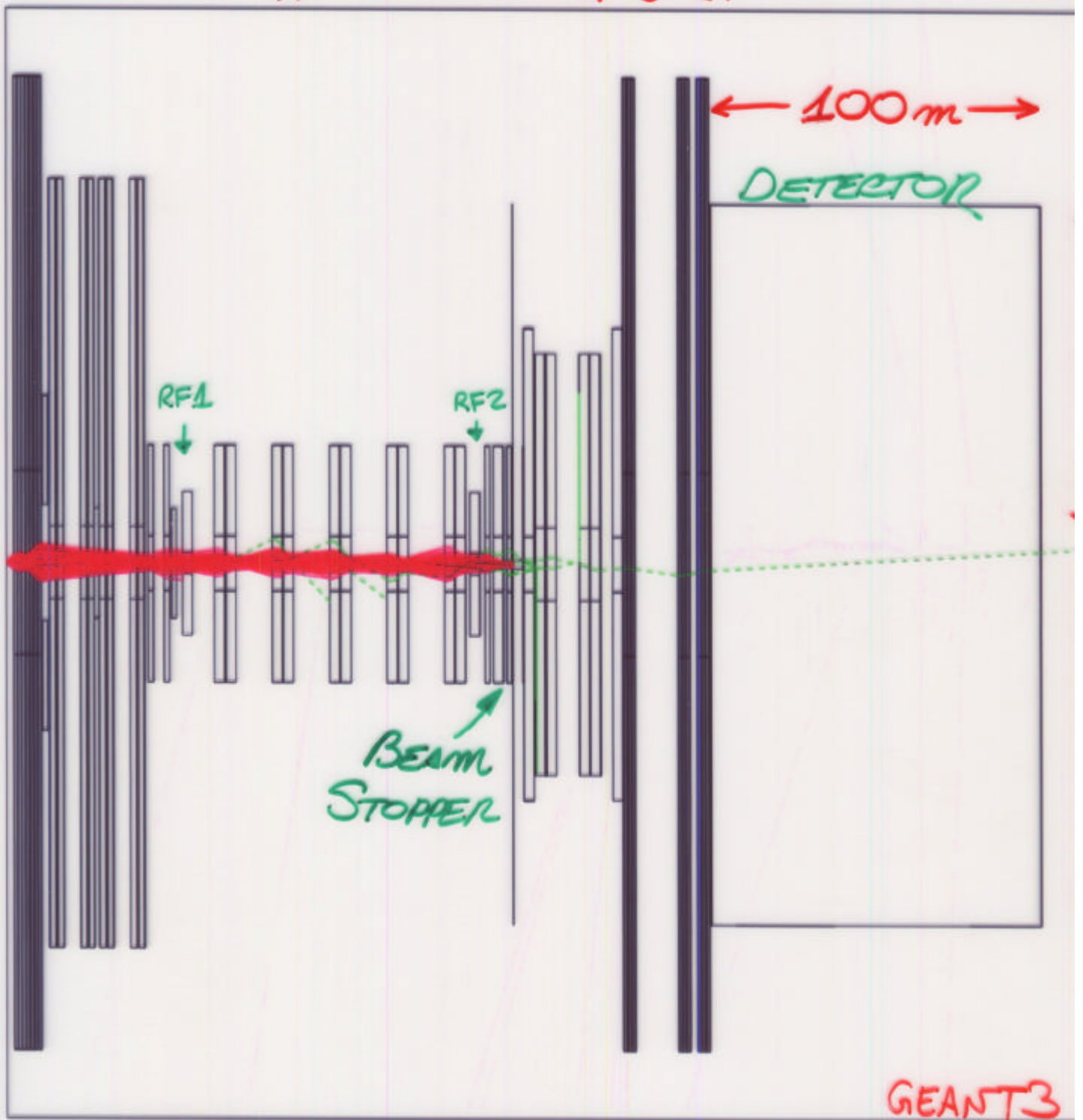






E-2F

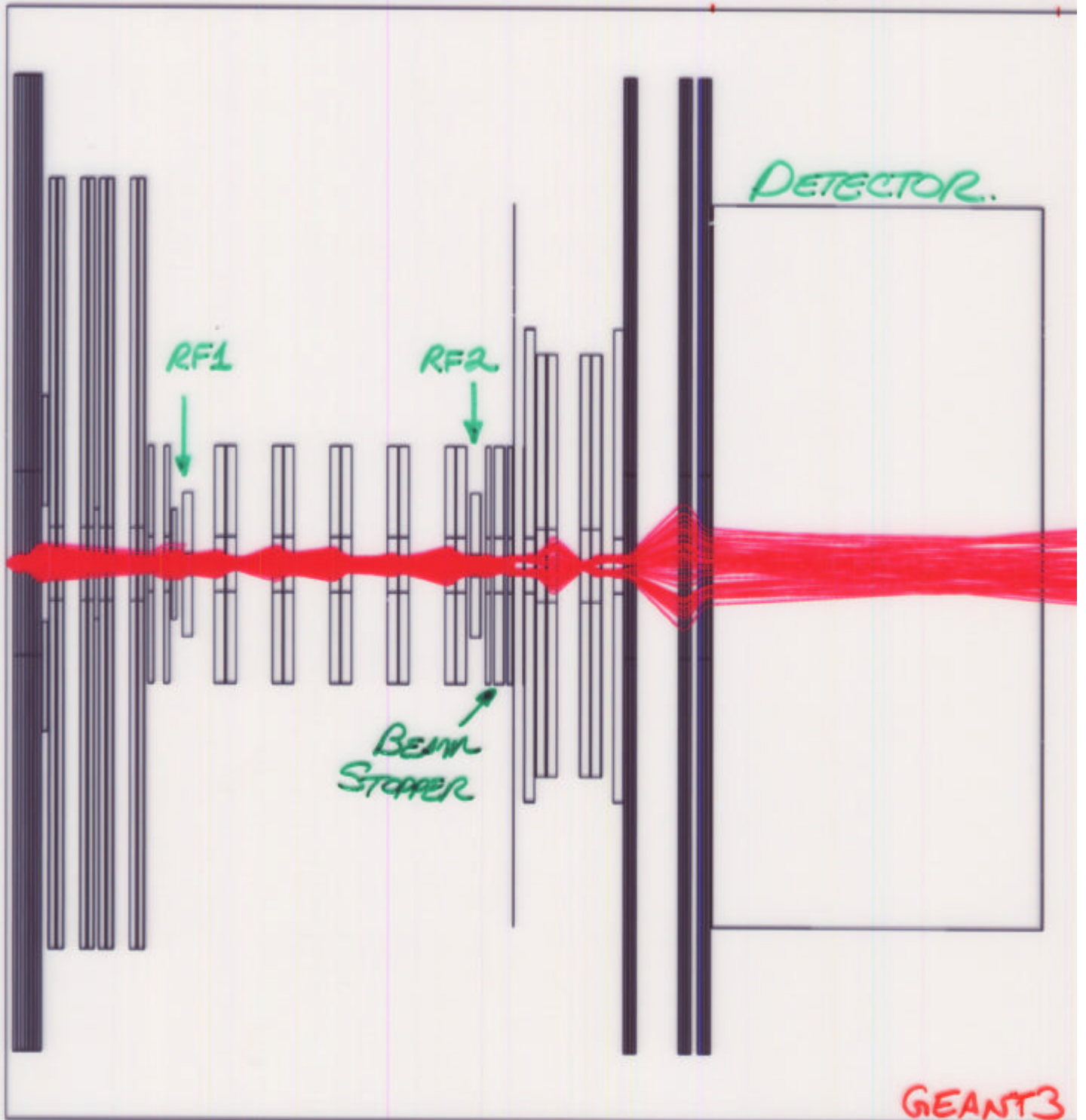
# $\pi^+$ TRANSPORT



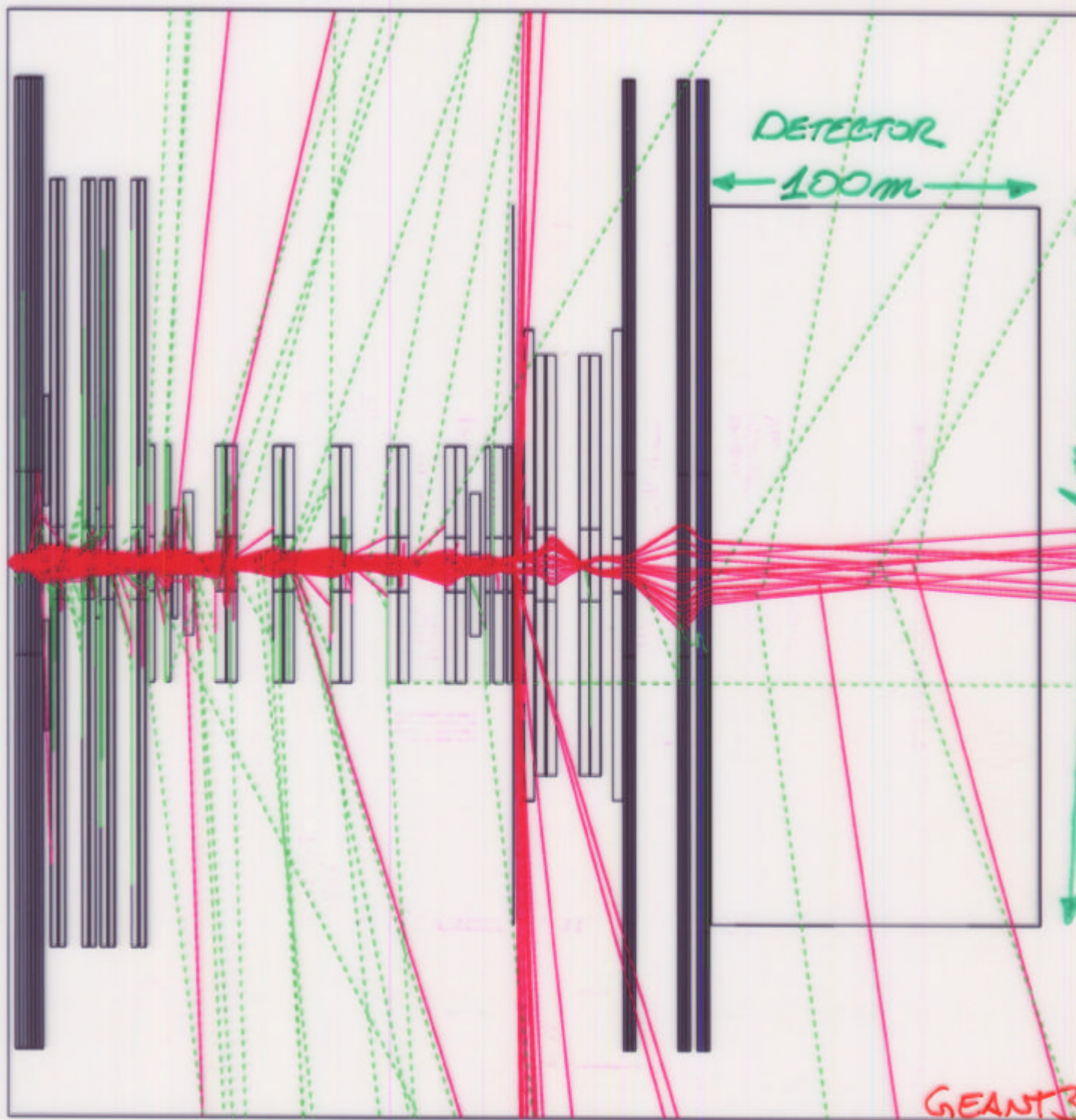
--- MUONS  
— PIONS.

# $K^+$ TRANSPORT:

100m




— KAONS, DECAYS TURNED OFF.



--- MUONS.  
— KAONS + PIONS.

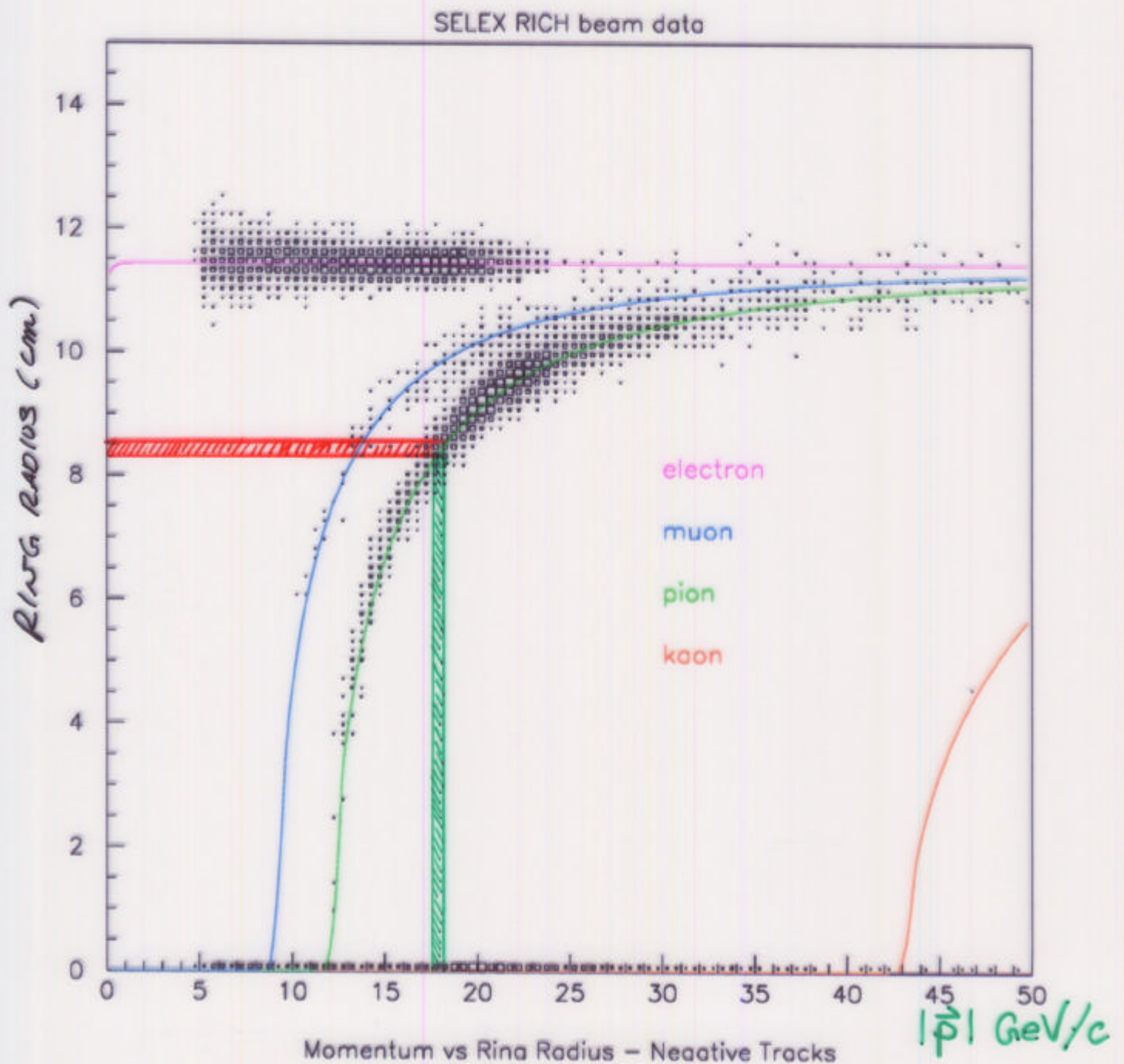
## Summary of Current Beam Results

	Required	Achieved in Simulation
K rate per  5E12 ppp	30 MHz	40 MHz
Purity (K/all hadrons)	70%	~90%
Beam Divergence	<0.5 mr	0.5 mr
dp/p	+/- 2 %	+/- 2%
RF Kick		30 MeV

# CKM "VELOCITY" SPECTROMETER

—

BASED ON THE PERFORMANCE OF  
THE SELEX PHOTO-TUBE BASED RICH



# Experimental Methods

- Control of backgrounds is the whole game
  - $K^+ \rightarrow \pi^+ \nu \nu$  ( $1 \times 10^{-10}$ ),  $K^+ \rightarrow \pi^+ \pi^0$  (21%),  $K^+ \rightarrow \mu^+ \nu$  (63%)
- Observables
  - Coordinates, vector momentum and velocity of  $K^+$  and  $\pi^+$
  - Relative time of both tracks
  - Veto everything else (photons, muons, electrons)
- REDUNDANT high resolution measurements
  - $\sigma_P \sim 1\%$ ,  $\sigma_V \sim 1\%$ ,  $\sigma_t \sim 1$  nsec require to control the dominant backgrounds.
- High rates to achieve sensitivity
  - 6 MHz  $K^+$  decays
  - $1.1 \times 10^7$  live seconds (2 years, 39 weeks/year, 120 h/week) at  $\sim 1.25\%$  acceptance to get 72 events
  - Implies 30 MHz  $K^+$  flux through CKM  $\Rightarrow$  Main Injector

BNL-E787/E949 & FNAL-CKM

REDUNDANT MEASURES

E787

$$\vec{p}_{\pi^+}$$

$\pi^+$  RANGE

$$E_{\pi^+}$$

MATERIAL  
THICK

$\sim 1$  MHz

$K^+$  STOPS

CKM

$$\vec{p}_{\pi^+}, \vec{p}_{K^+}$$

$$\vec{v}_{\pi^+}, \vec{v}_{K^+}$$

$$E_{\pi^+}$$

MATERIAL  
THIN

6 MHz

$K^+$  DECAYS.

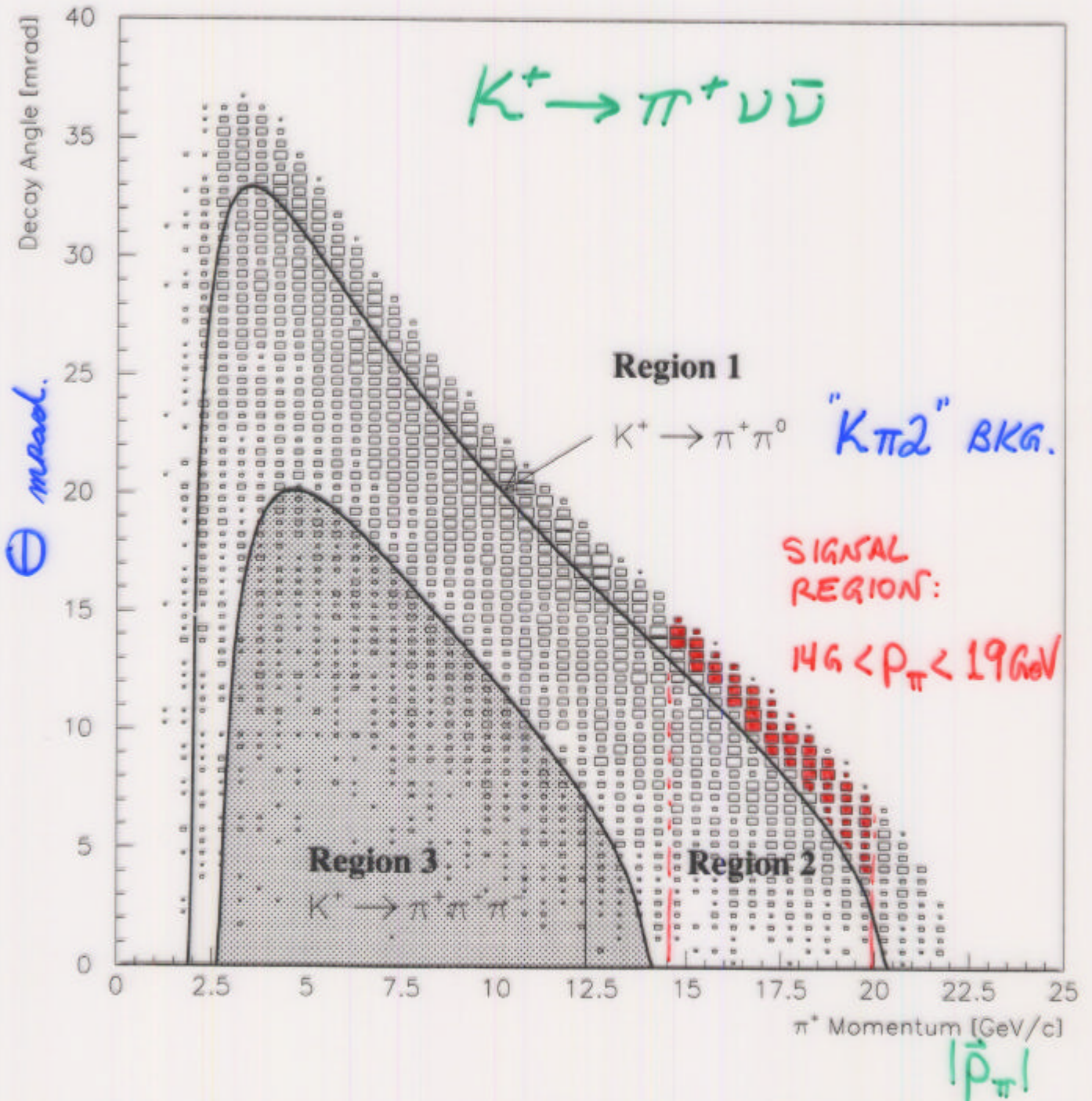
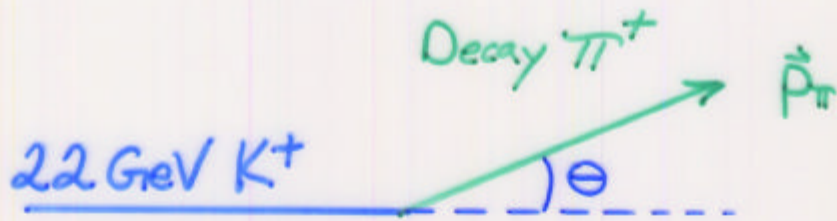


Figure 2: Decay angle versus momentum for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  events. Three distinct analysis regions are shown.

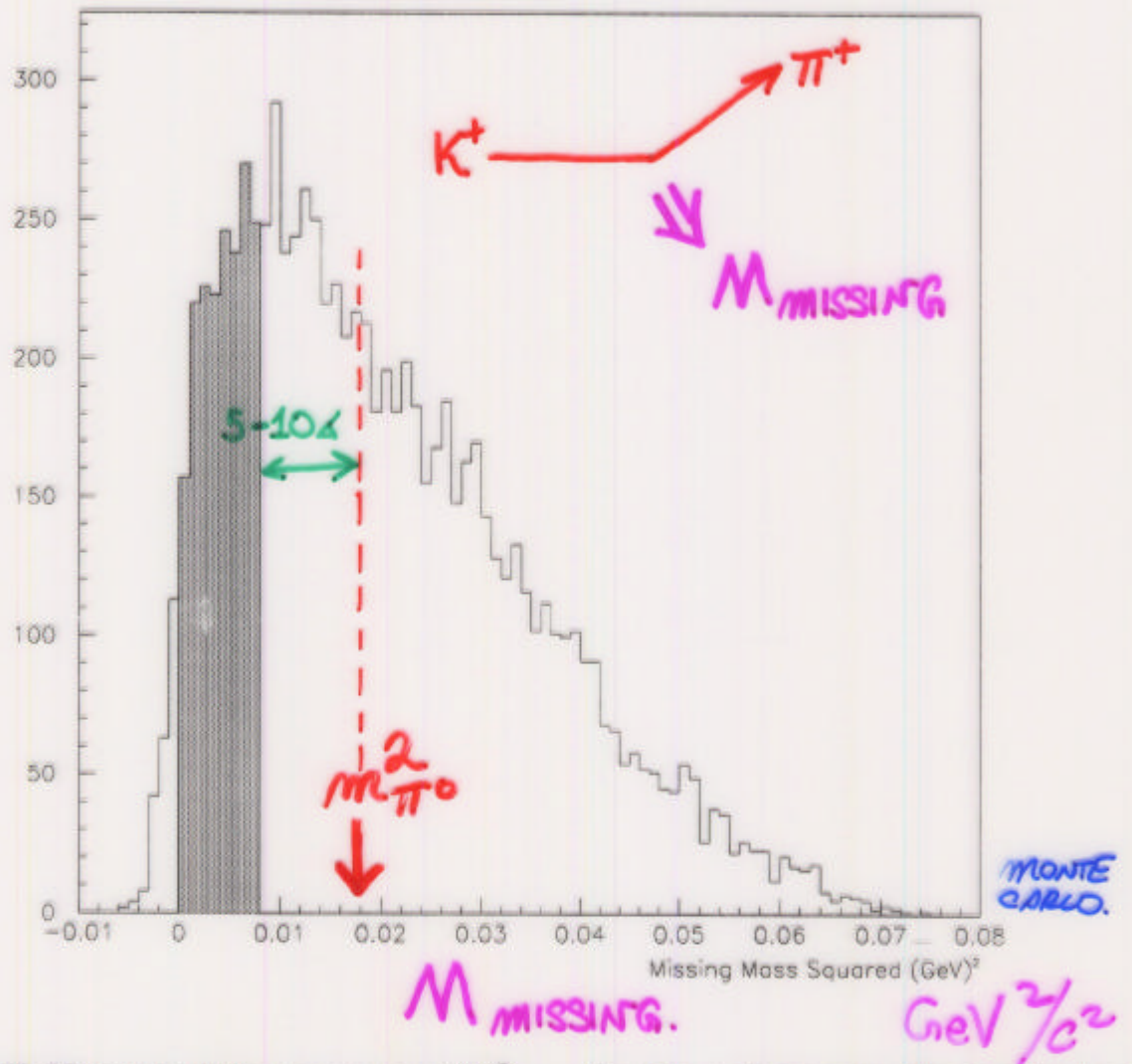
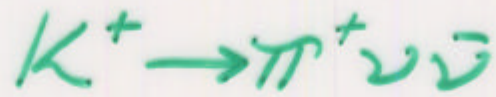
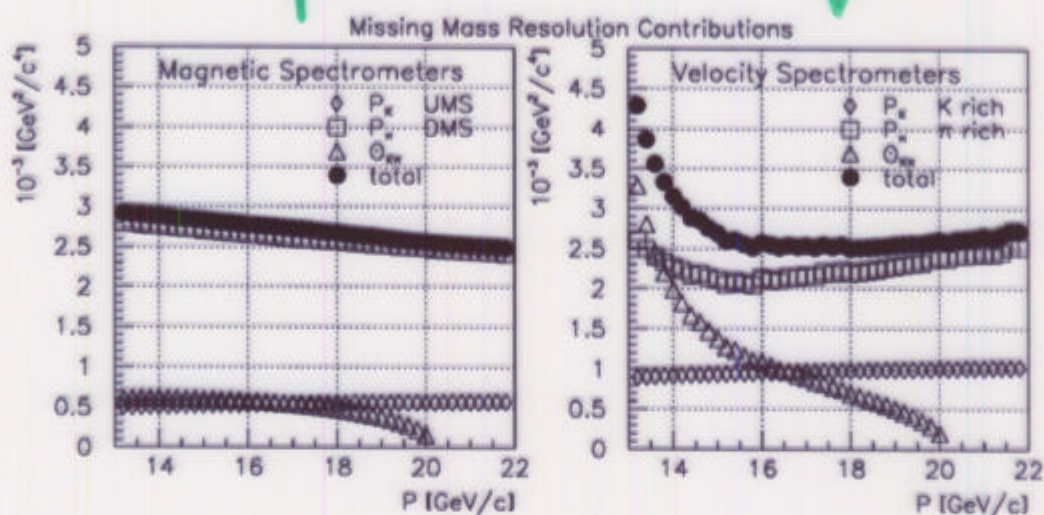


Figure 10: Measured missing mass squared ( $M_{\text{combined}}^2$ ) in  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  events. The signal region is shaded.

# $K^+ \rightarrow \pi^+ X$ Missing Mass Resolution.



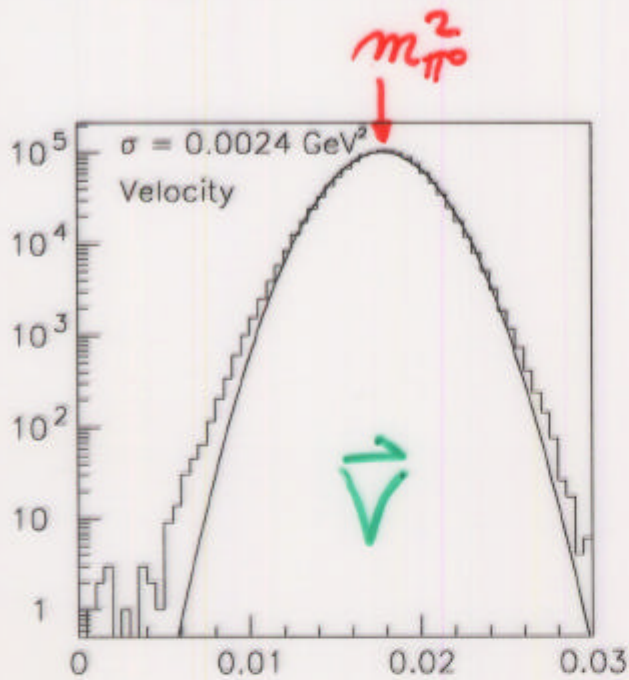
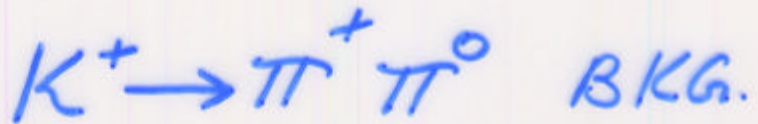
0.003

- Magnetic and Velocity mass resolutions are well matched, and flat over  $\pi^+$  momentum.
- If necessary we can improve the magnetic spectrometer missing mass resolution by simply increasing the analysis magnetic field from  $100\text{MeV}/c$  to  $200\text{MeV}/c$

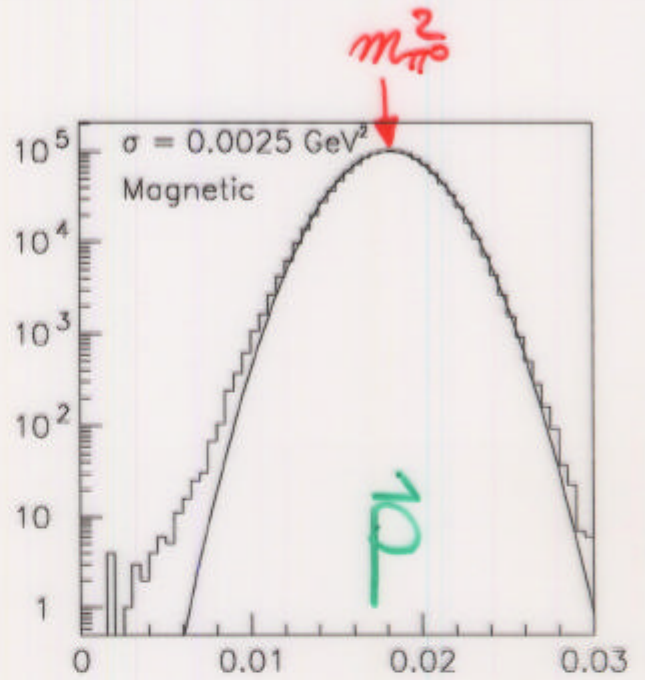
COMBINED MASS RESOLUTION:

$$0.003 \text{ GeV}^2/c^2 \oplus 0.003 \text{ GeV}^2/c^2$$

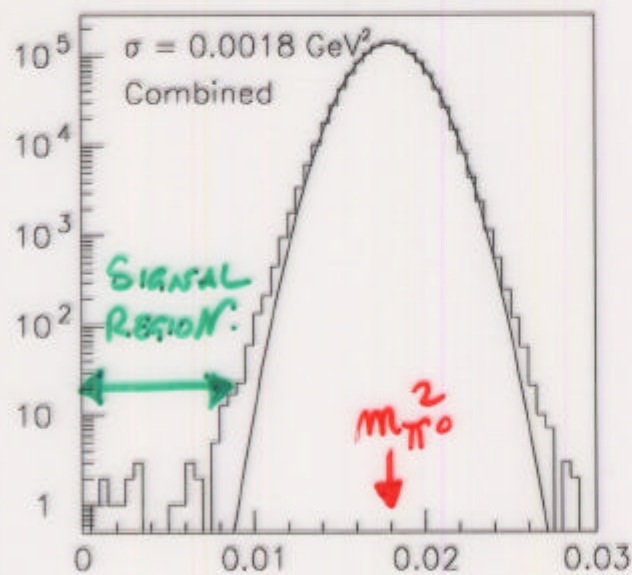
$$\rightarrow \sim 0.002 \text{ GeV}^2/c^2$$



Missing Mass Squared (GeV\*\*2)



Missing Mass Squared (GeV\*\*2)



Missing Mass Squared (GeV\*\*2)

$\vec{p} \neq \vec{v}$   
MISSING MASS  
RESOLUTIONS.

# GEANT3

## SPECTROMETER SIMULATIONS

INCLUDE THE EFFECTS

OF:

Coulumb SCATTERING.

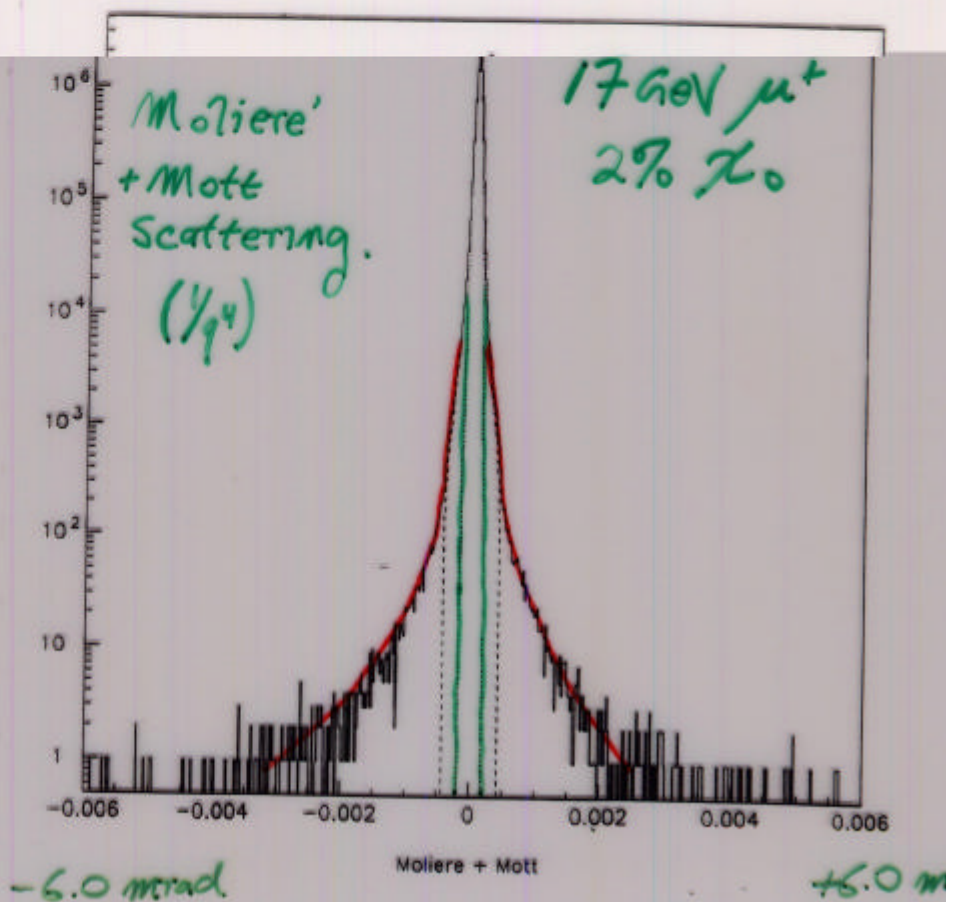
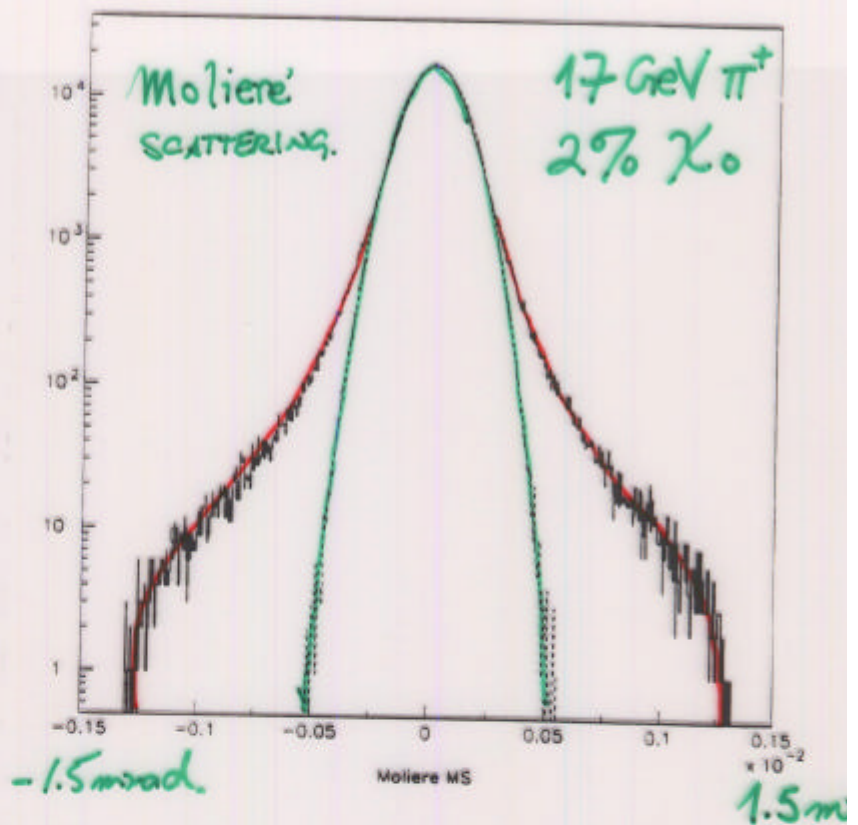
Moliere' SCATTERING.

Mott SCATTERING.

$\mu$ -BREEM.

NUCLEAR ELASTIC

NUCLEON ELASTIC



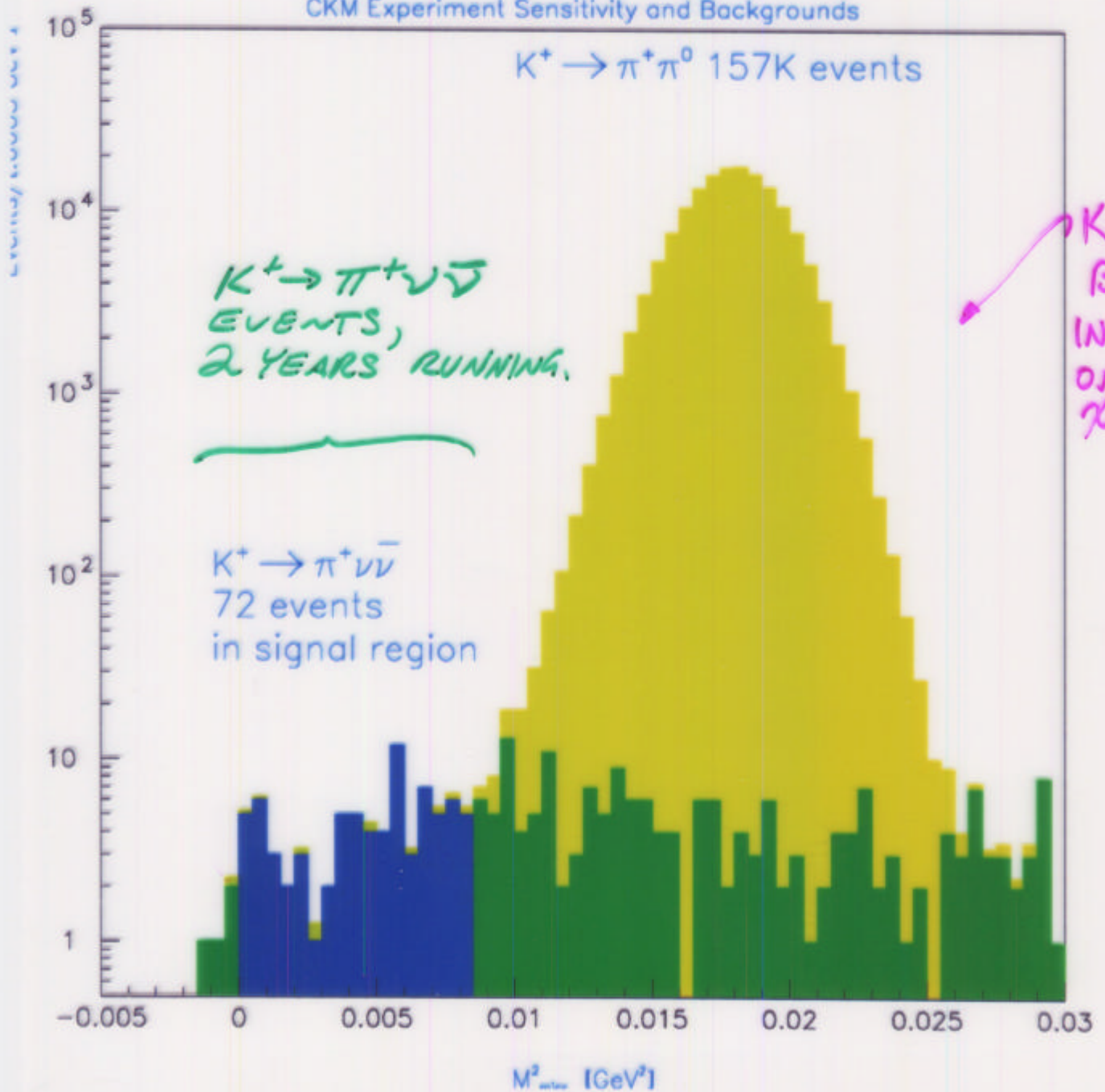
$K^+ \rightarrow \pi^+ \pi^0$  EVENTS  
THAT SURVIVE

$$\bar{\epsilon}_{\pi^0} = 2 \times 10^{-7}$$



CKM Experiment Sensitivity and Backgrounds

$K^+ \rightarrow \pi^+ \pi^0$  157K events



## CKM Background Summary.

Background Source	Effective BR ( $\times 10^{-12}$ )
$K^+ \rightarrow \mu^+ \nu_\mu$	< 0.04
$K^+ \rightarrow \pi^+ \pi^0$	* 3.7
$K^+ \rightarrow \mu^+ \nu_\mu \gamma$	< 0.09
$K^+ A \rightarrow K_L X$ followed by $K_L \rightarrow \pi^+ e^- \nu$	< 0.14
$K^+ A \rightarrow \pi^+ X$ in trackers	< 4.0
$K^+ A \rightarrow \pi^+ X$ in residual gas ( $10^{-6}$ torr)	< 2.1
Accidentals (2 $K^+$ decays)	0.51
<b>Total</b>	<b>&lt; 10.6</b>

Table 1: Background estimates in terms of effective branching ratio.

# CKM Photon Veto Design Strategy

- The design assumes the demonstrated performance of the BNL-E787 (1mm Pb/5mm Scint) system for vetoing low energy (20 MeV-200 MeV) photons.
- Benchmark the high energy performance of the design with studies of electrons (1-10 GeV) on Pb/Scint KTeV veto structures. A special KTeV data set was collected in the '99 Fixed Target run that serves as a laboratory for these studies.
- Base the engineering of the vacuum decay-volume veto system on the proven success of the KTeV vacuum veto system.

