Measurement of $K^+ \to \pi^+ \nu \nu$ at CKM

by Sasha Kushnirenko

July 13, 2001

Snowmass 2001

CKM experiment

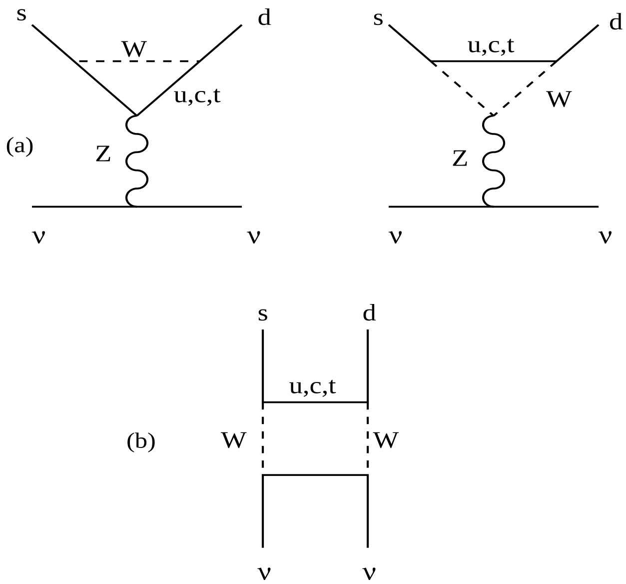
CKM is a proposed K^+ decay-in-flight experiment at Fermilab. The GOAL of CKM experiment is to observe a sample of 100 $K^+ \to \pi^+ \nu \overline{\nu}$ events with small background.

- Precise measurement of $|V_{td}|$
- Constrain $\rho - \eta$ plane
- Rare K^+ decays

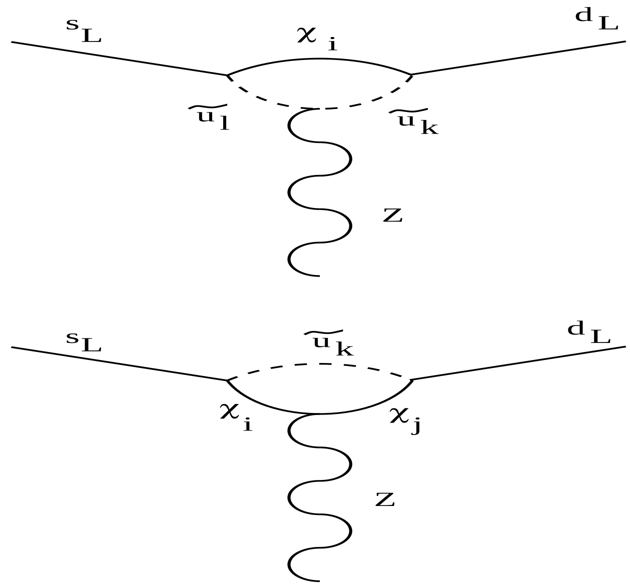
Experimental Feautures

- Decay in flight experiment
- Narrow band search
- Redundancy (BNL experience)
- High resolution
- Control non-gaussian tails

Physics motivation



SM diagrams



SUSY diagrams

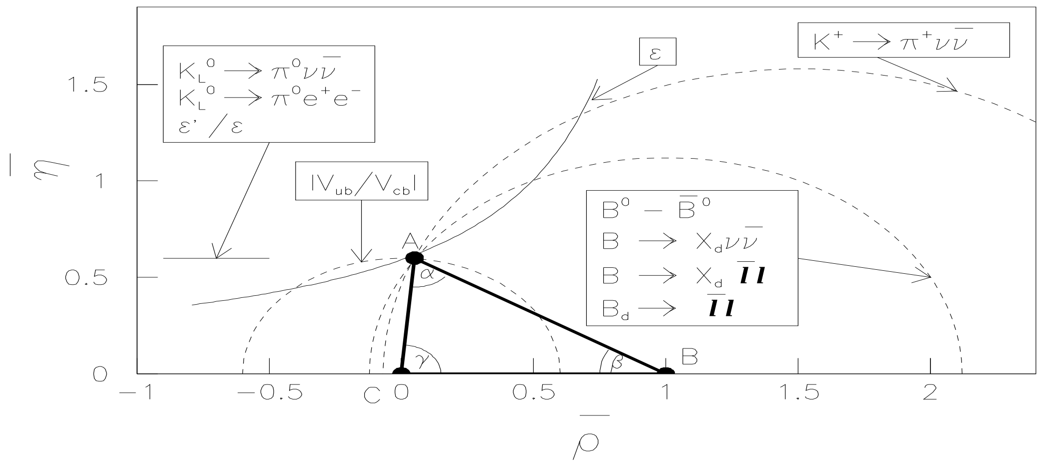
100 $K^+ \to \pi^+ \nu\overline{\nu}$ events provides 10% theoretically clean measurement of $|V_{td}|$

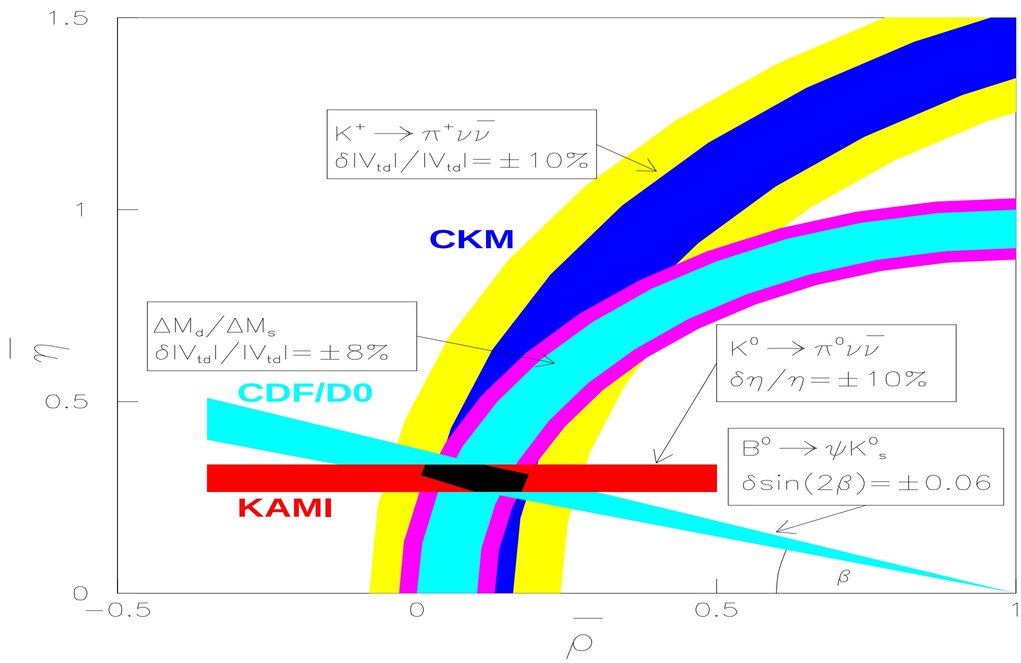
$$BR(K^+ \to \pi^+ \nu\overline{\nu}) \sim |V_{cb}|^4 \cdot ((\overline{\rho} - \rho_0)^2 + \overline{\eta}^2)$$

$$BR(K^0 \to \pi^0 \nu\overline{\nu}) \sim |V_{cb}|^4 \cdot \overline{\eta}^2$$

Simultaneous measurement of $K^+ \to \pi^+ \nu\overline{\nu}$
and $K^0 \to \pi^0 \nu\overline{\nu}$ is extremely important

Physics motivation





- In ideal SM world all $\rho - \eta$ measurements should agree
- CKM triangle can be overconstrained within Kaon system only.
- Comparison with B physics can reveal New Physics
- Comparison with B requires knowledge of $|V_{cb}|$

Charged Kaons at the Main Injector

April 2, 2001

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

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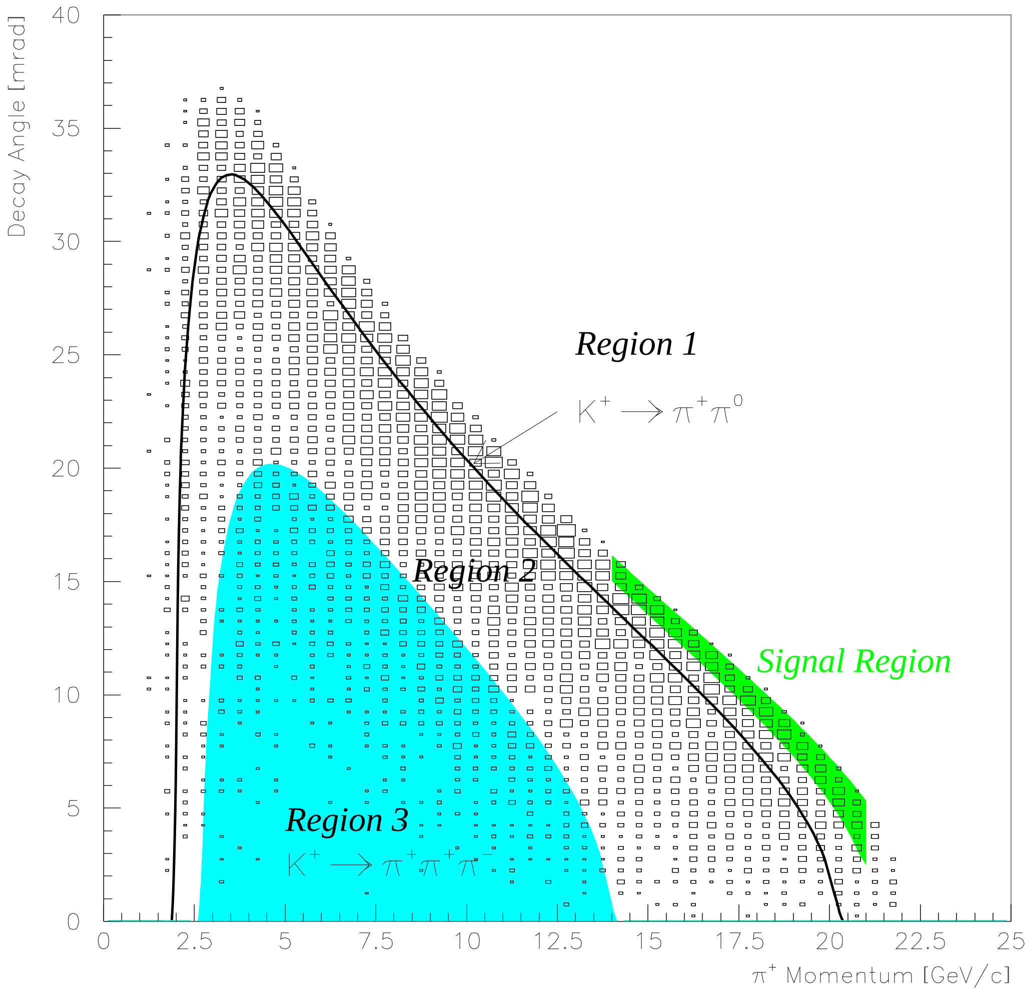
Decay kinematics



- Region 1 - Goal to get 100 events
- Region 2 - Did not invest in that yet, but will definetly try
- Region 3 - Hopeless

$K^+ \to \pi^+\pi^0$ is the main background source

Basic orders of magnitude

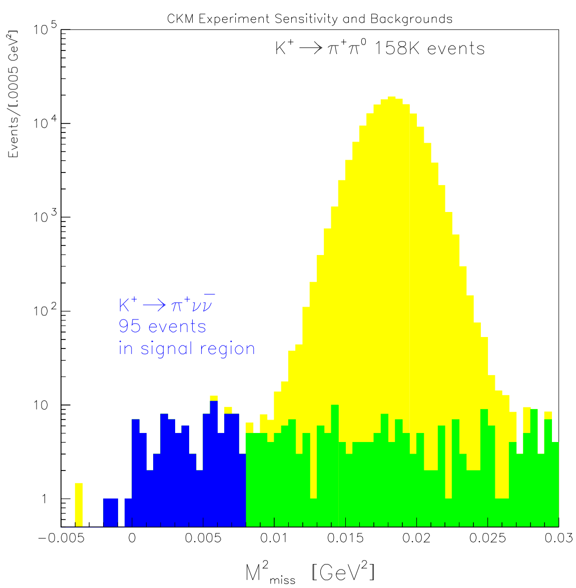
$$Br(K^+ \to \pi^+ \nu \overline{\nu}) \simeq 10^{-10}$$

100 events	$\to$	10^{12} K^+ decays
$\epsilon \sim 1\%$	$\to$	10^{14} K^+ decays
$\gamma c\tau = 165\text{m}, \epsilon = 10\%$	$\to$	10^{15} K^+ decays

$$10^{15}\ K^+/10^7\ \text{s} = 100\,\text{MHz beam}$$

Resoulution to fight $K^+ \to \pi^+\pi^0$ background:

near $K^+ \to \pi^+\nu\overline{\nu}$	$\to$	$\sim 10^{13}$ $K^+ \to \pi^+\pi^0$ decays
$\epsilon_{\gamma\gamma} \sim 10^{-7}$	$\to$	$\sim 10^{6}$ $K^+ \to \pi^+\pi^0$ decays
$\epsilon_{\text{kinem}} \sim 10^{-5}$	$\to$	~ 1 $K^+ \to \pi^+\pi^0$ decays



- Divide in half available M^2_{miss}
- $\epsilon_{\text{kinem}} \sim 10^{-5}$
  $5\sigma_{M^2} = M^2_{\pi^0}/2$
- $\sigma_{M^2} \sim 0.002\,\text{GeV}^2$

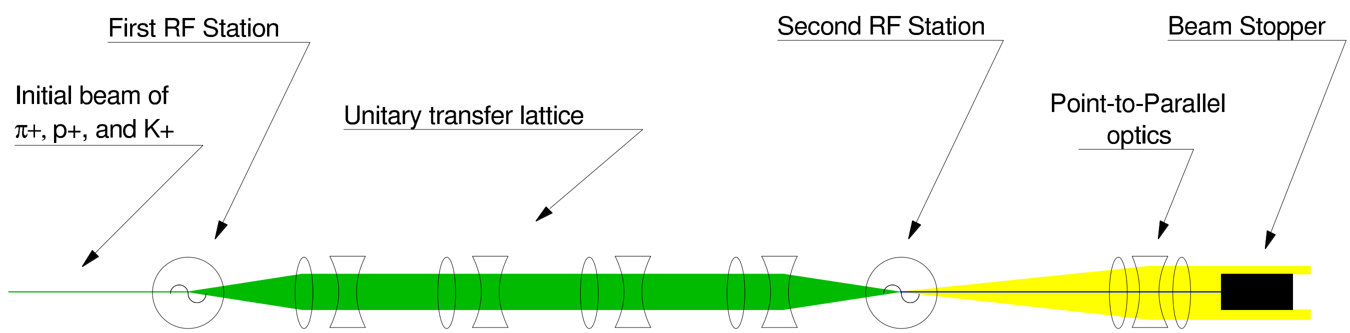
$$M^2_{miss} = M^2_K(1 - \frac{p_\pi}{p_K}) + m^2_\pi(1 - \frac{p_K}{p_\pi}) - p_\pi p_K \theta^2$$

$$\sigma_p/p \sim 1\% \qquad \sigma_\Theta \sim 0.1\,\text{mrad}$$

RF separated K^+ beam

Requirements

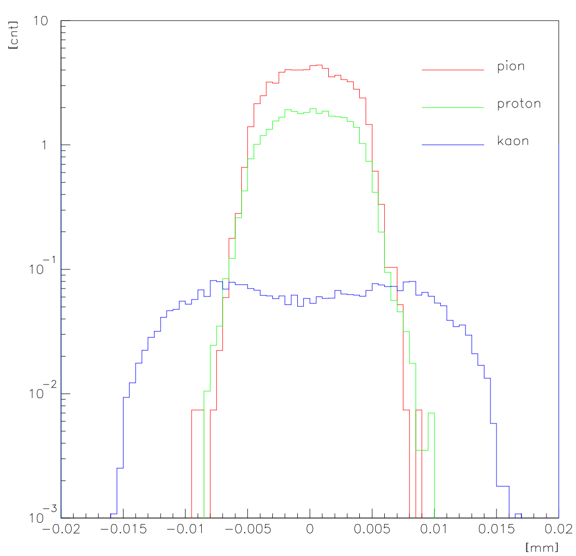
- $30\,\text{MHz}$ K^+ rate @ $22 \pm 0.4\,\text{GeV}$
- $< 50\,\text{MHz}$ total charged particle rate.
- Debunched beam



Due to their differing velocities, π+, p+ and K+ "slip" in phase by different amount.

π+ and **p+** arrive 180 degrees out of phase with respect to first RF station and receive **no net deflection.**

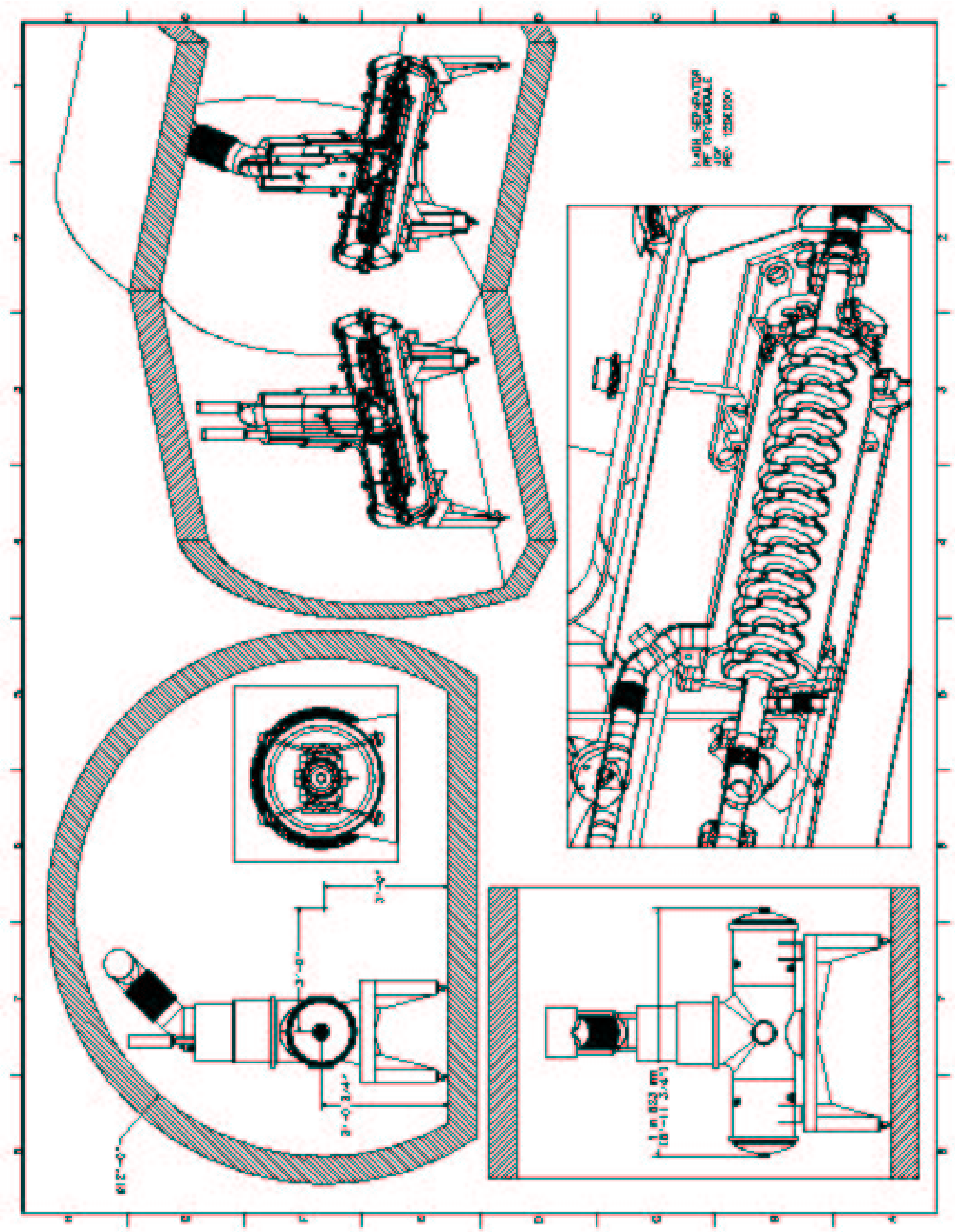
K+ arrive ~93 degrees out of phase with respect to first RF station and receive **time-varying deflection.**



L=86m, f=3.9GHz

π^+	$0\,\text{ps}$	$\phi = 0^o$
p^+	$257\,\text{ps}$	$\phi = 360^o$
K^+	$67\,\text{ps}$	$\phi = 94^o$

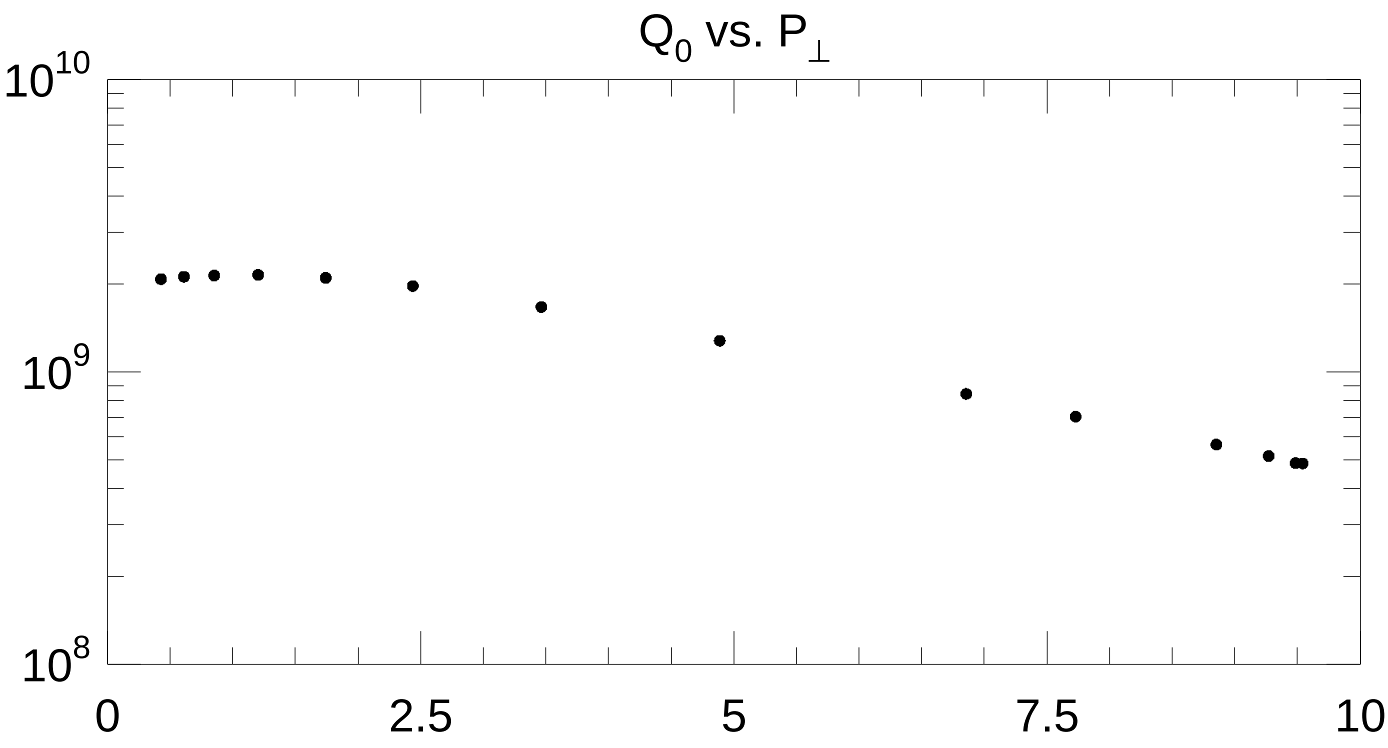
RF separated K^+ beam



RF separated K^+ beam

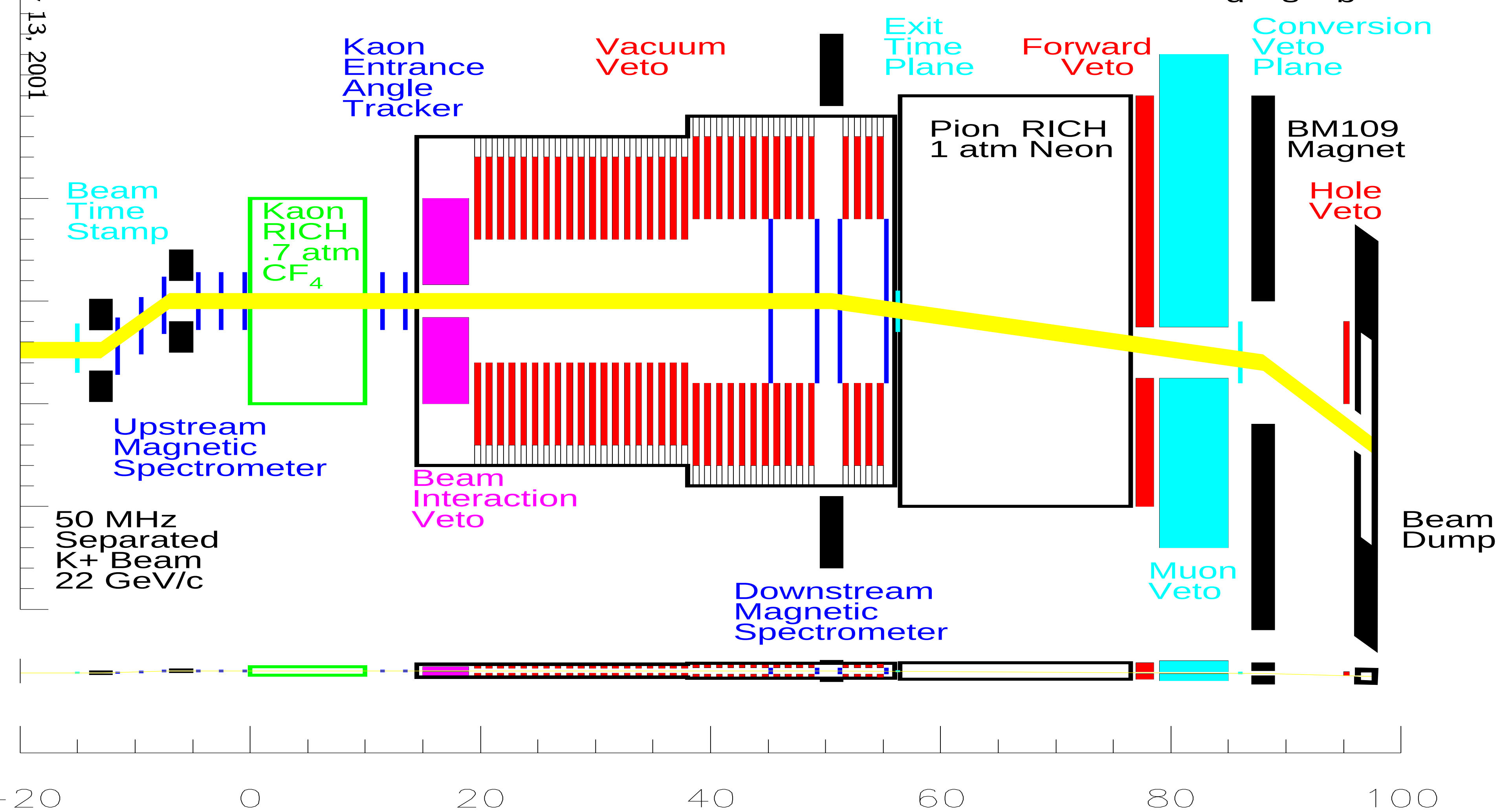
- 2 station with 13-cell superconductiong RF
- p_T=5MeV/m
- GEANT/TURTLE simulation
- The design exceeds the requirement
- R&D under extensive study
- Collaboration with TESLA on SCRF design

Our most recent 1-cell test result

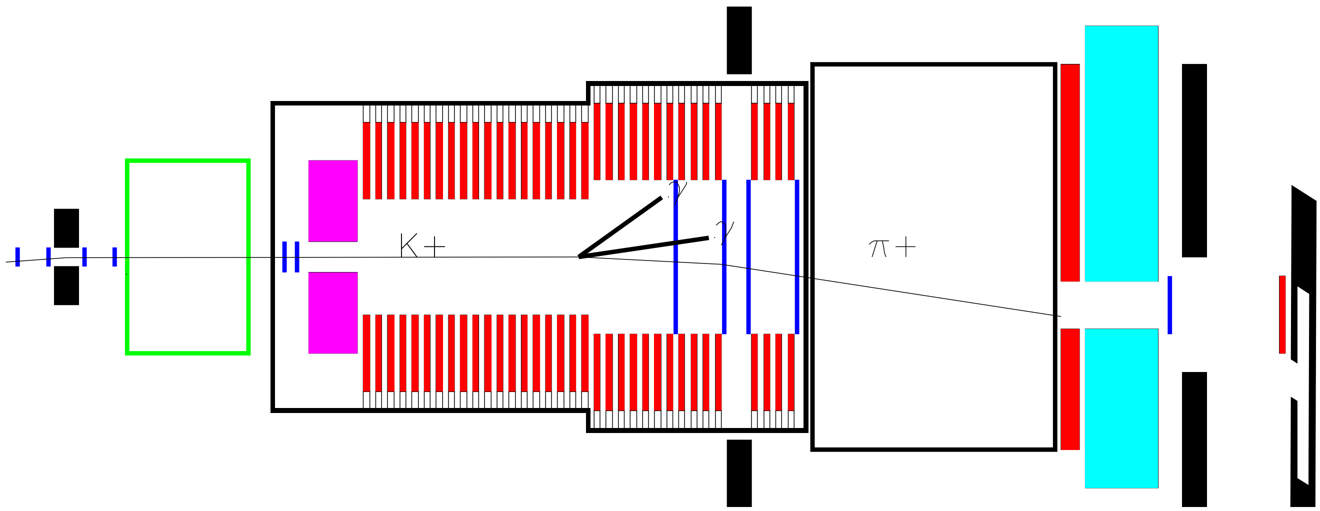


Goal is to test a complete cryomodule in 2002
and test it in a beam during 2003

CKM Apparatus



Photon Veto System

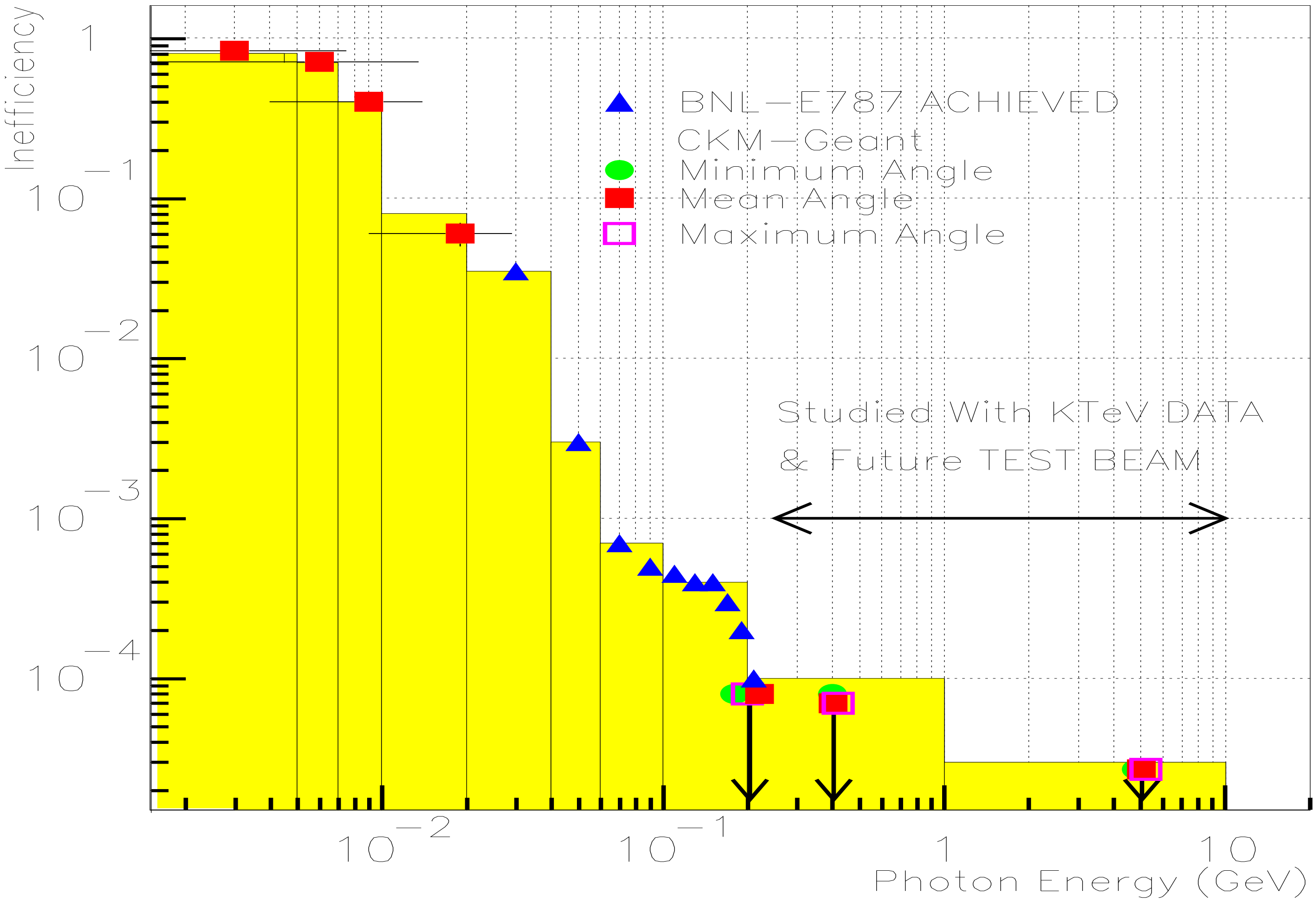


Total π^0 inefficiency $= 1.6 \cdot 10^{-7}$

- $0.3 \cdot 10^{-7}$ low energy γ escapes in the gap.
- $0.5 \cdot 10^{-7}$ when γ lands within $10\,\mathrm{cm}$ from π^+ in FVS.
- $0.8 \cdot 10^{-7}$ low energy/high energy photon pair is lost. Mostly in VVS.

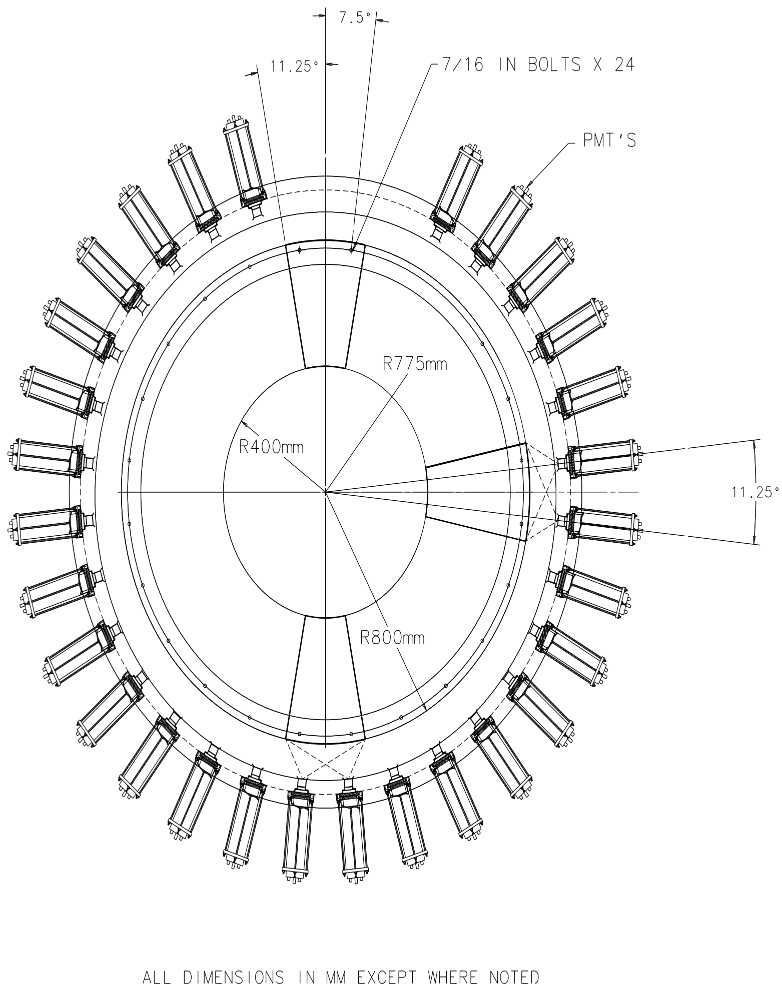
- VVS - most stringent inefficiency requirements up to $3 \cdot 10^{-5}$
- FVS - only 10% of photons hit it.
  Inefficiency requirement $\sim 1 \cdot 10^{-4}$
  Fine segmentation to separate π^+ and γ.
  Simulated with MC and checked on KTeV data.
- HVS - even more relaxed requirement $2 \cdot 10^{-3}$

Vacuum Veto System



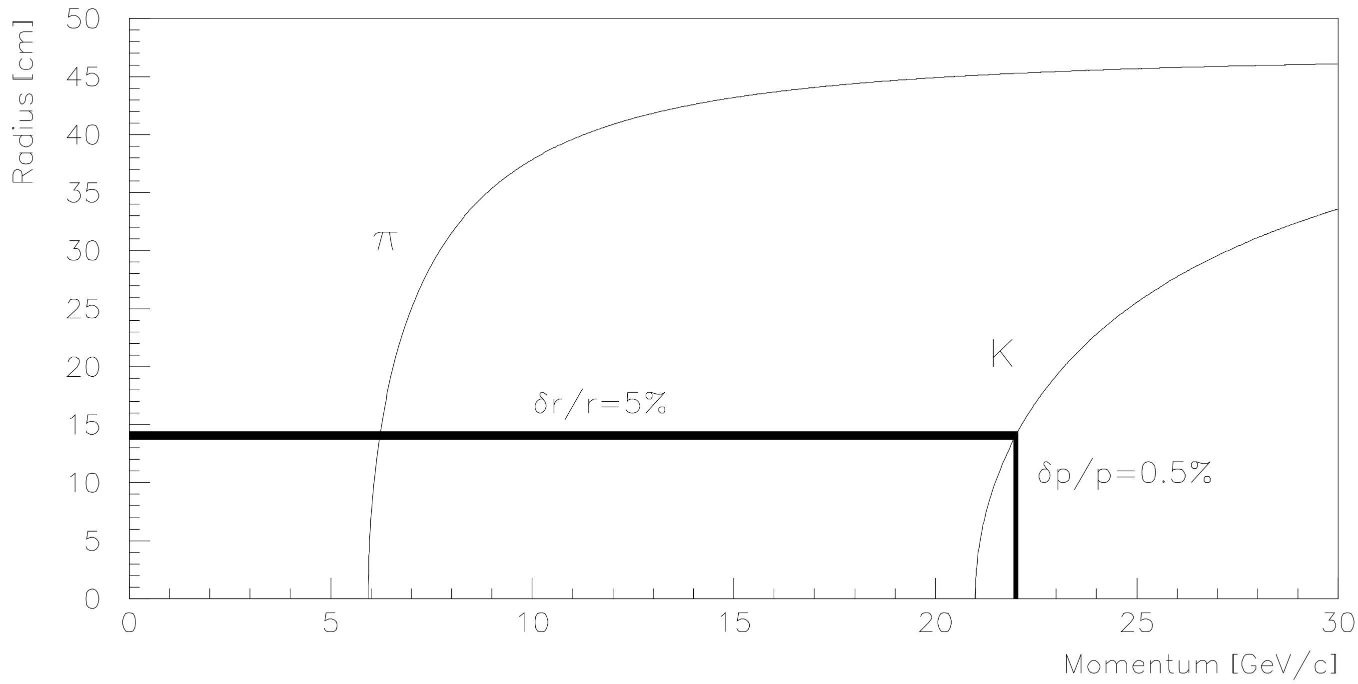
- Low energy inefficiencies due to sampling. Studied with GEANT.
- Middle energy inefficiencies: data exist for the similar Photon Veto system in BNL-E787
- High energy inefficiencies: very important. Background almost proportional to inefficiency.
  - Shower escaping in vacuum - GEANT
  - Photo-Nuclear interactions: Estimates from data
  - Tagged e sample in KTeV data. $1 - \epsilon < 3 \cdot 10^{-5}$.

Vacuum Veto System



- 34 annular stations which fill 50%
- $15\,X_0$: 81 layer $1\,\mathrm{mmPb}/5\,\mathrm{mm}$ scinitillator
- Light collegtion with WLS fibers
- $10\,\mathrm{p.e./MeV}$ (better values achieved in studies)
- Modeled after KTeV and BNL-E787
- Odd/Even layer are mapped to 2 PMT
- Monitioring with LED, muons

Measurement of momenta with RICH

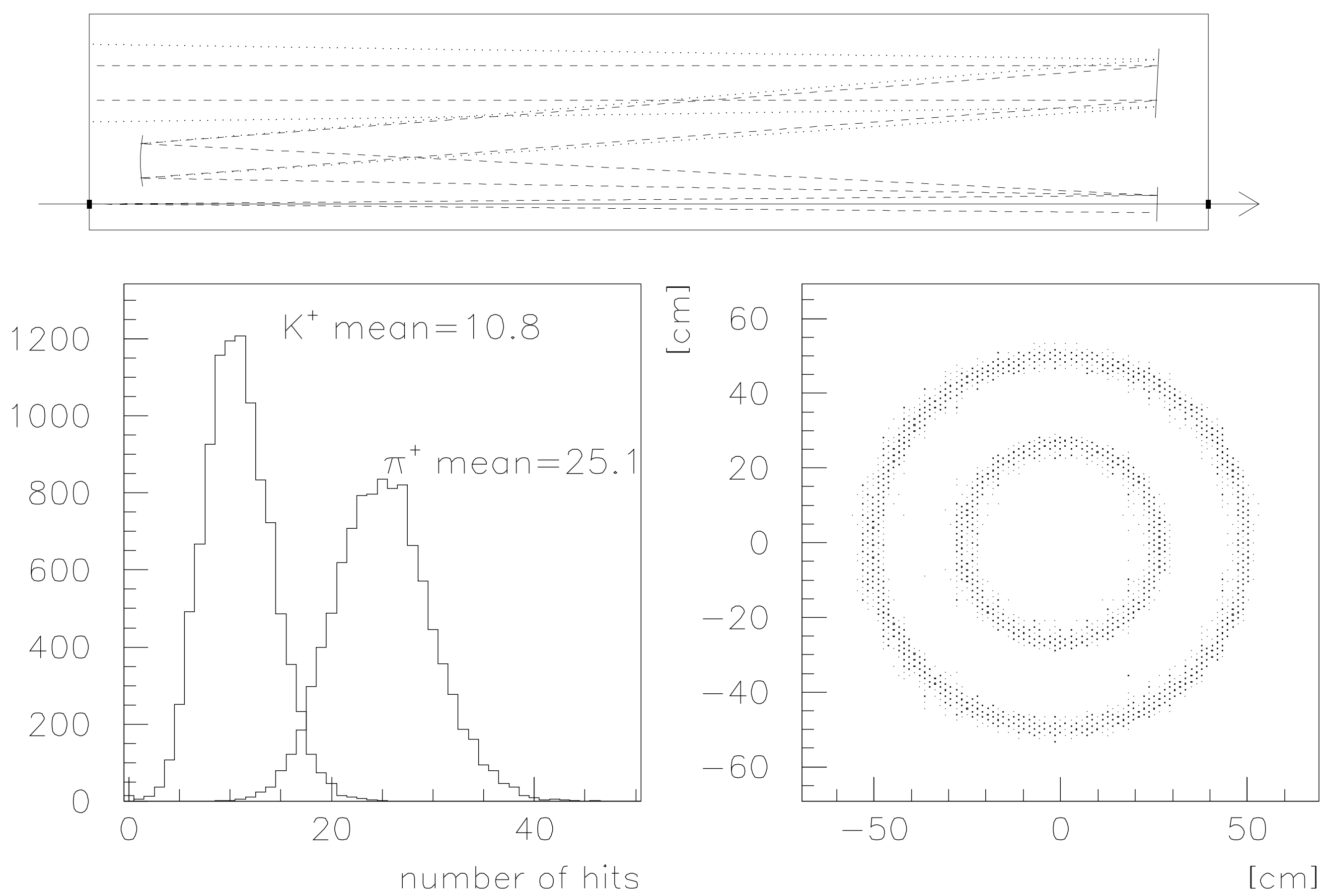


- 5% measurement of radius gives 0.5% momentum resolution
- K^+ is well separated from π^+
- Modeled after successfull SELEX RICH

2 RICHs can measure K and π track directions and momenta. So they can give an independent measure of $M^2_{\rm miss}$. Comparision of Tracking and RICH measurements is a critical element of the experiment.

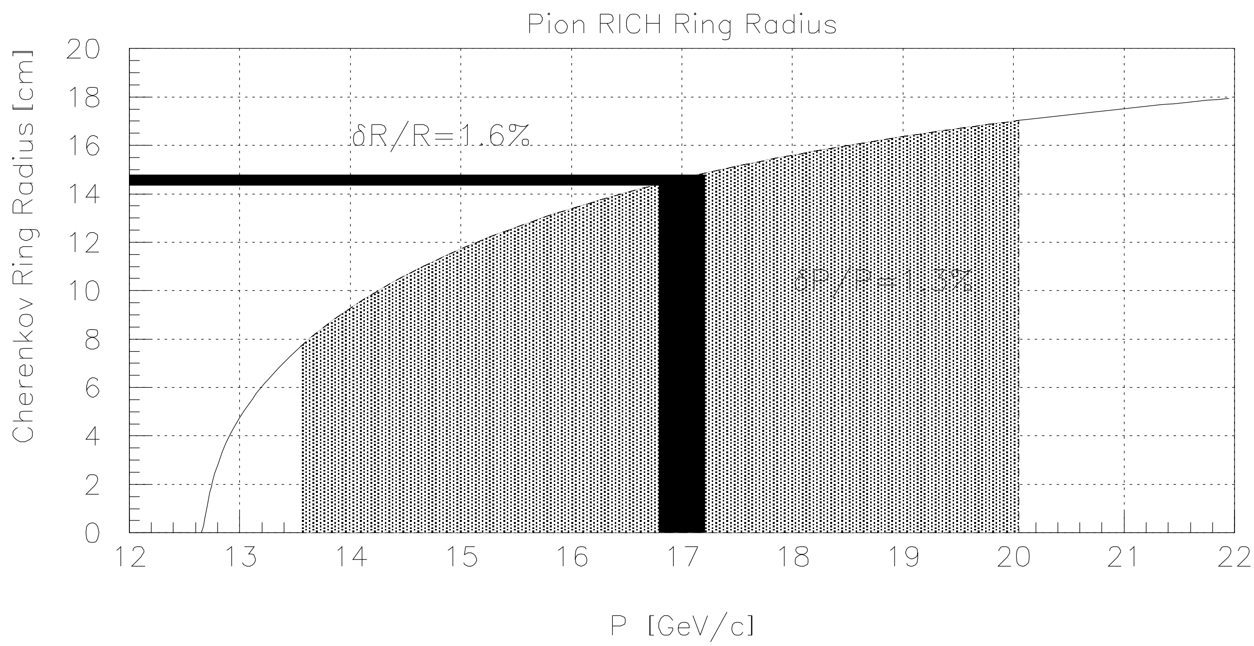
Running RICH in "momentum-measuring" mode limits accessible momentum range.

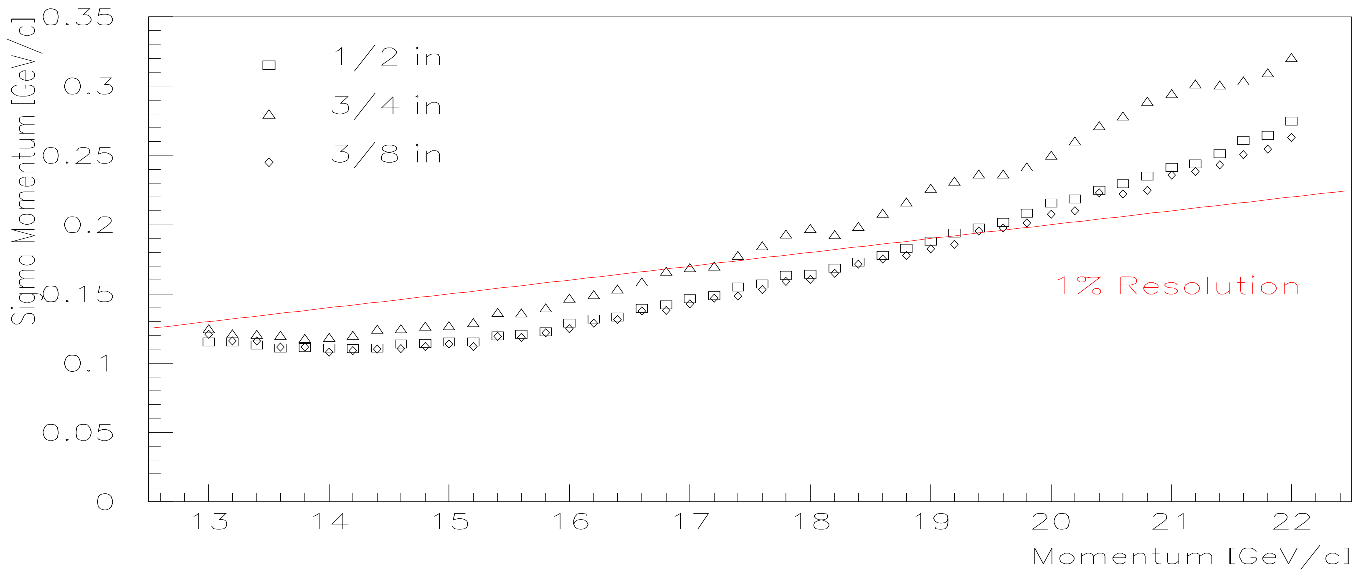
Kaon RICH



- $11\,\mathrm{m}$ long vessel
- CF_4 @ $0.7\,\mathrm{atm}$ or N_2 @ $1.2\,\mathrm{atm}$
- 600 $1/2'$-PMT
- Excellent π/K separation $\sim 50\sigma$
- Rate per tube $< 1.4\,\mathrm{MHz}$
- $n_{hit} = 10.8$, $\sigma_\Theta = 0.1\,\mathrm{mrad}$, $\sigma_p/p \simeq 0.5\%$
- Resolution limited by chromatic dispersion $dn/d\lambda$

Pion RICH

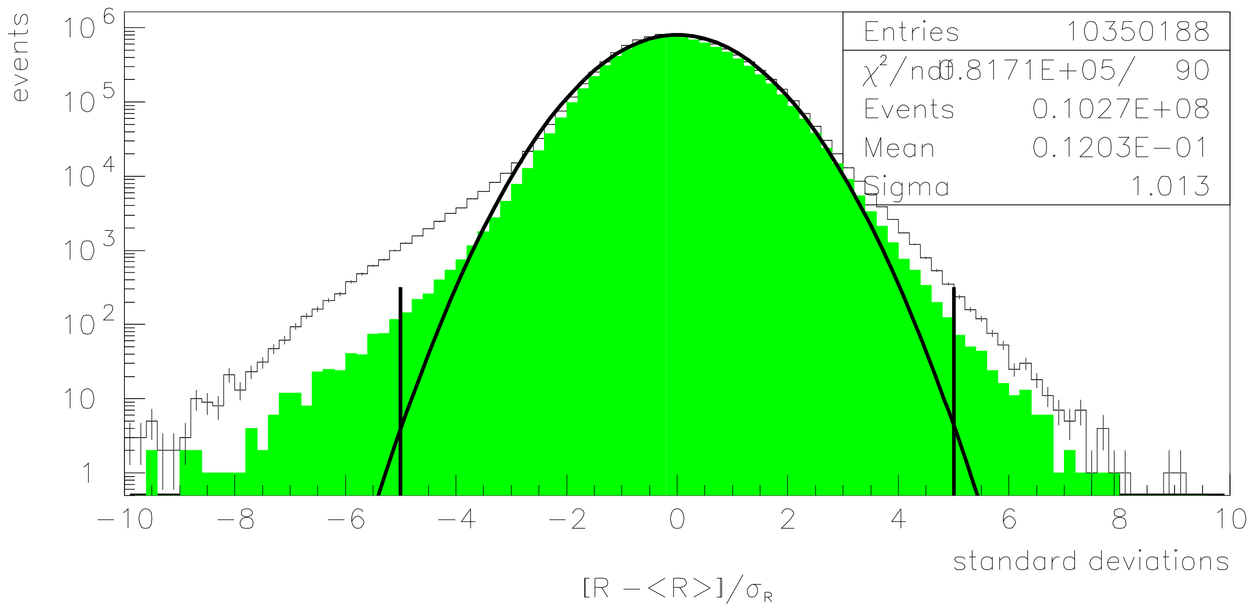


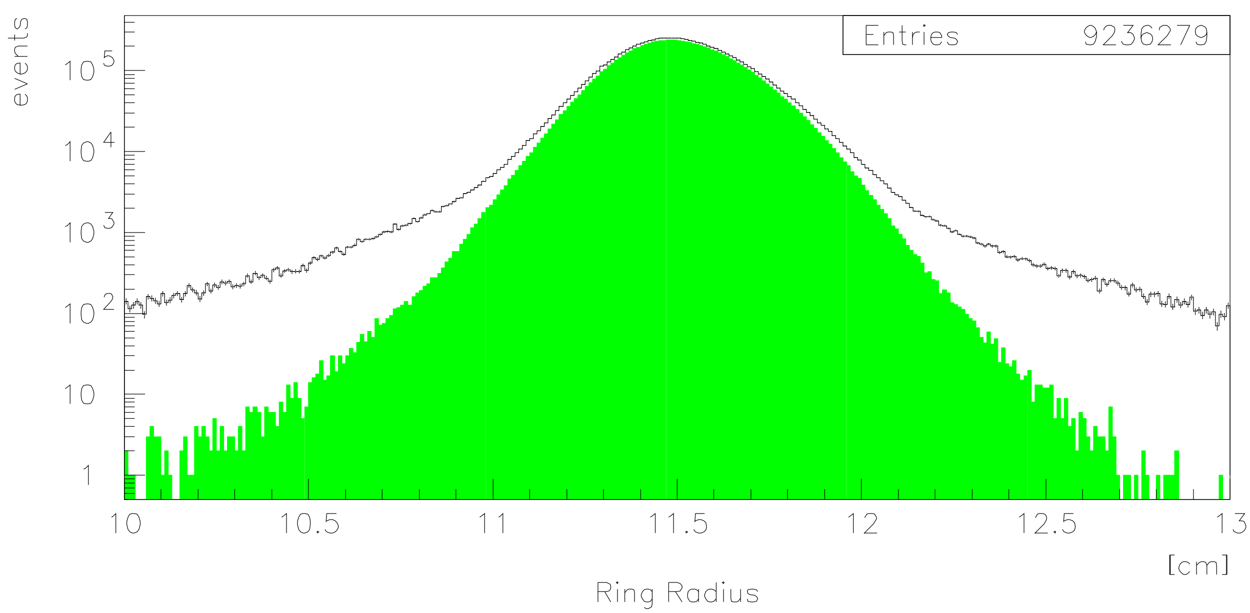


- $20\,\mathrm{m}$ long vessel, $d = 2\,\mathrm{m}$
- Ne @ $1\,\mathrm{atm}$
- 3000 $1/2'$-PMT
- Good π/μ separation $\sim 10 - 15\sigma$
- Rate per tube $f_\pi < 90\,\mathrm{kHz}$, $f_K < 400\,\mathrm{kHz}$
- $n_{hit} \simeq 20$, $\sigma_\Theta \simeq 0.1\,\mathrm{mrad}$, $\sigma_p \simeq 0.17\,\mathrm{GeV}$, $\sigma_p/p \simeq 1\%$
- Resolution not limited by one factor.

SELEX RICH performance

Non-gaussian tails in RICH detectors?

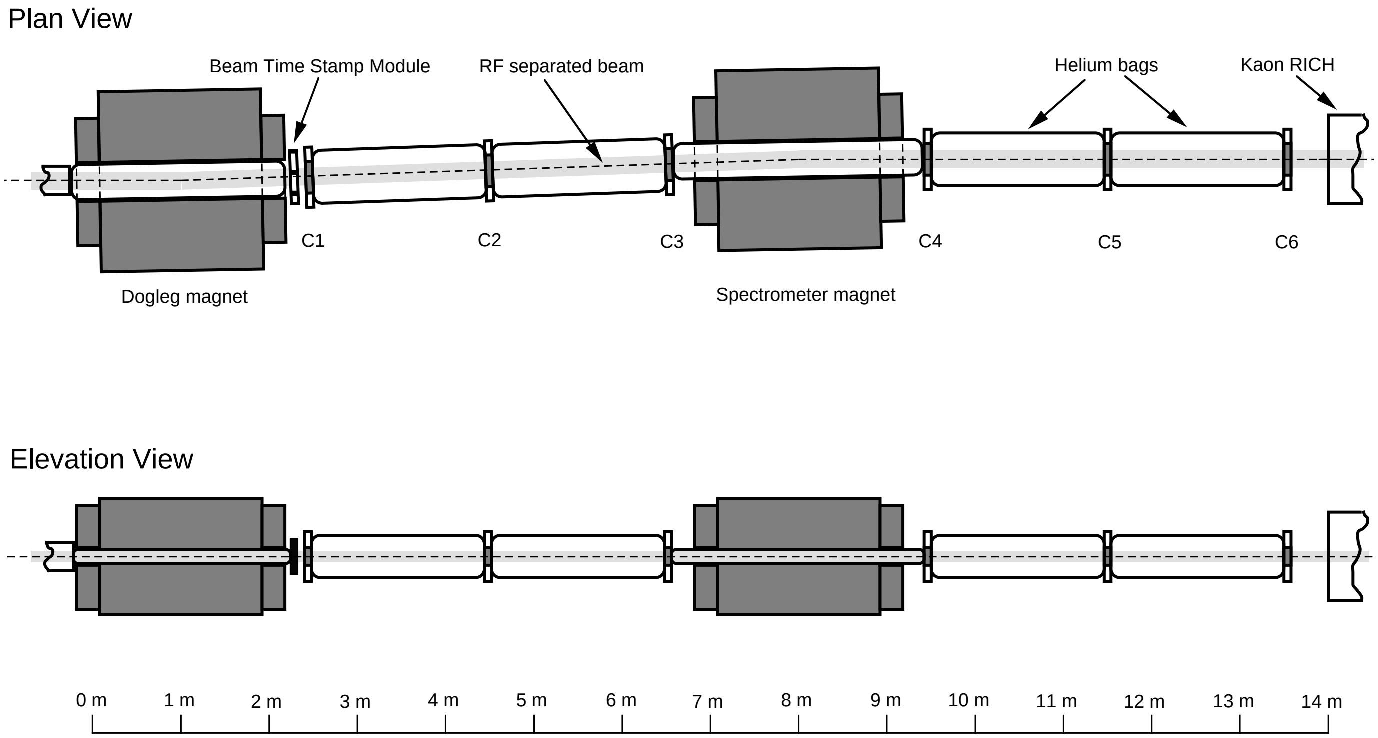




Solid histogrma already gives acceptable performance

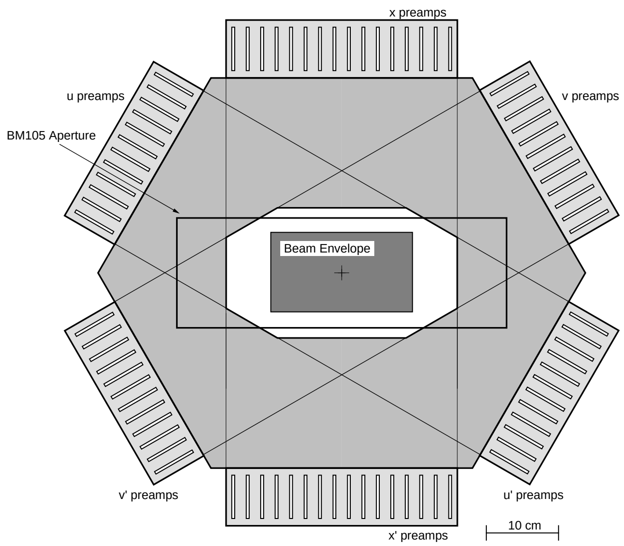
We think we can do better.

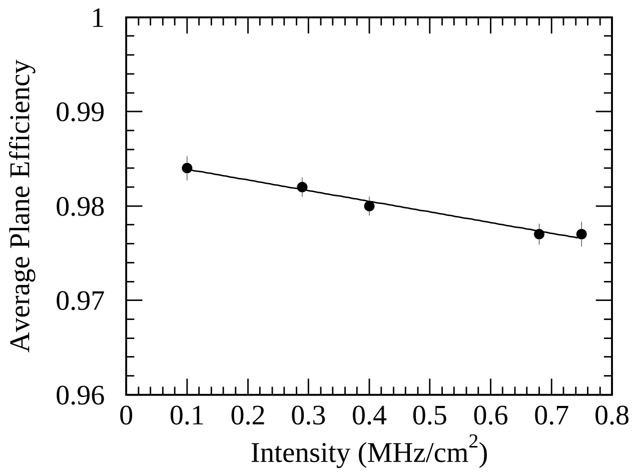
Upstream Magnetic Spectrometer

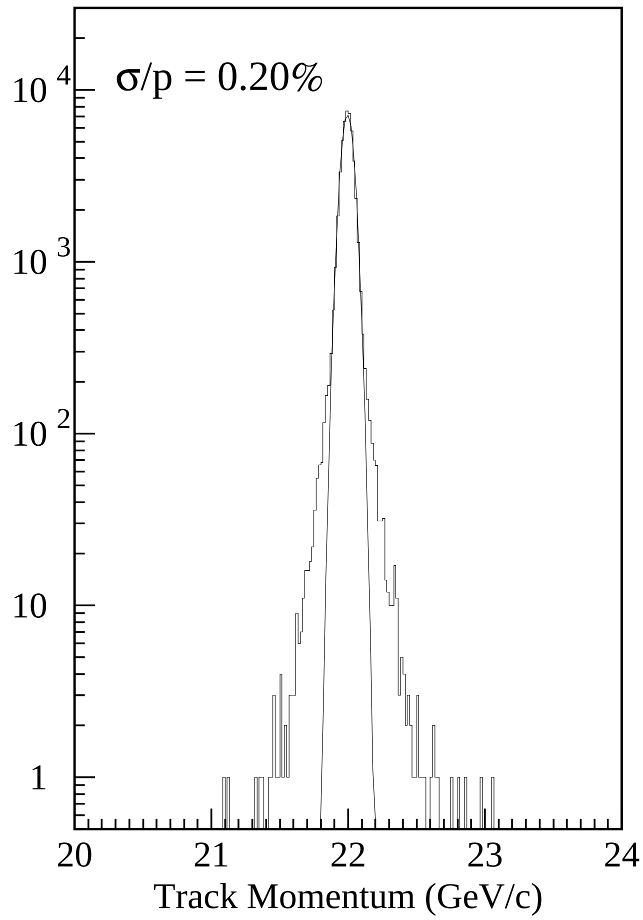


- 6 stations, each has 6 views (x, x', u, u', v, v')
- Inter length = 1.7%, Rad length = 2.1%
- UMS have to provide excellent resolution in high-intensity beam
- Modeled after HyperCP chambers

Upstream Magnetic Spectrometer





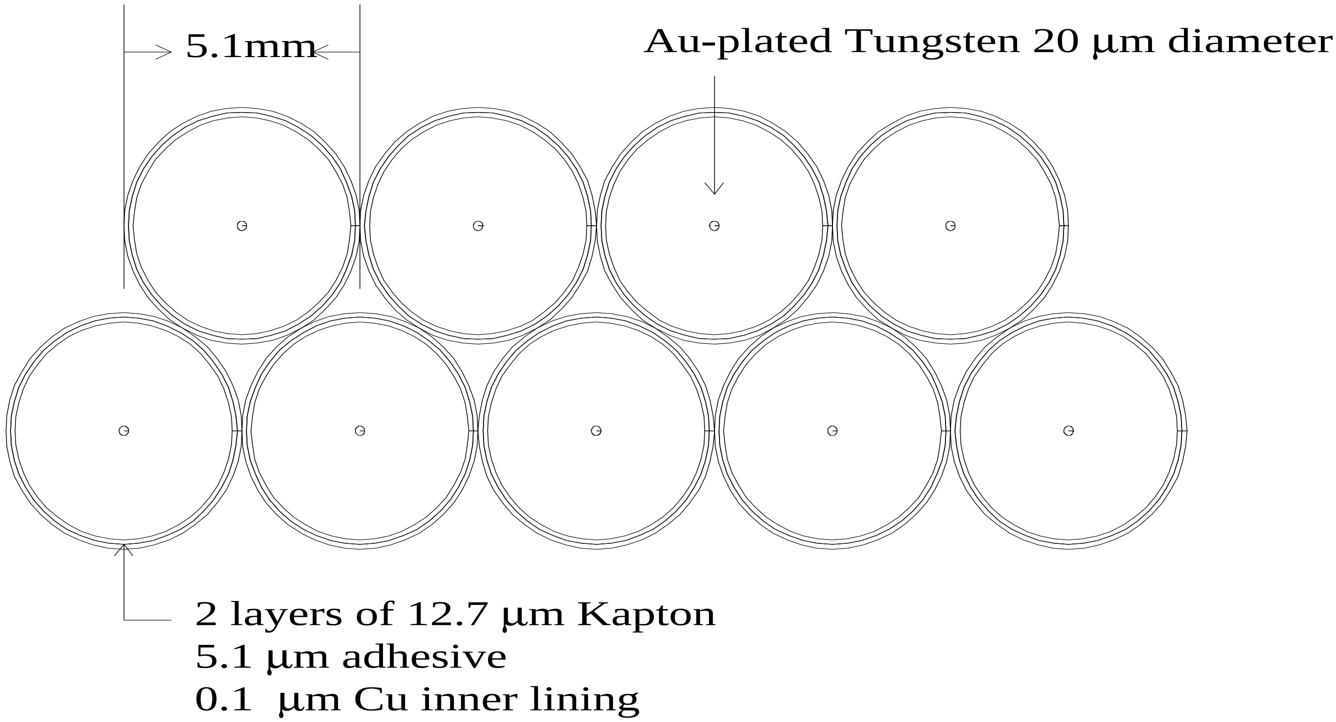


- HiperCP $= 1\,\mathrm{mm}$ wire pitch @ $270\,\mathrm{kHz/cm^2}$ max rate)
  CKM $= 0.8\,\mathrm{mm}$ wire pitch @ $750\,\mathrm{kHz/cm^2}$ max rate)
- Maximum rate per wire $610\,\mathrm{kHz}$,
  HyperCP tested $640\,\mathrm{kHz}$ rate rate per wire
- $\sigma_p/p \simeq 0.2\%$, $\sigma_\Theta \simeq 0.06\,\mathrm{mrad}$

Kaon Entrance Angle Tracker

- Kaon RICH introduces 10% of the rad length
- 2 UMS chambers separated by $2.6\,\mathrm{m}$. $\sigma_\Theta \simeq 0.08\,\mathrm{mrad}$
- Another option: Silicon in Vacuum

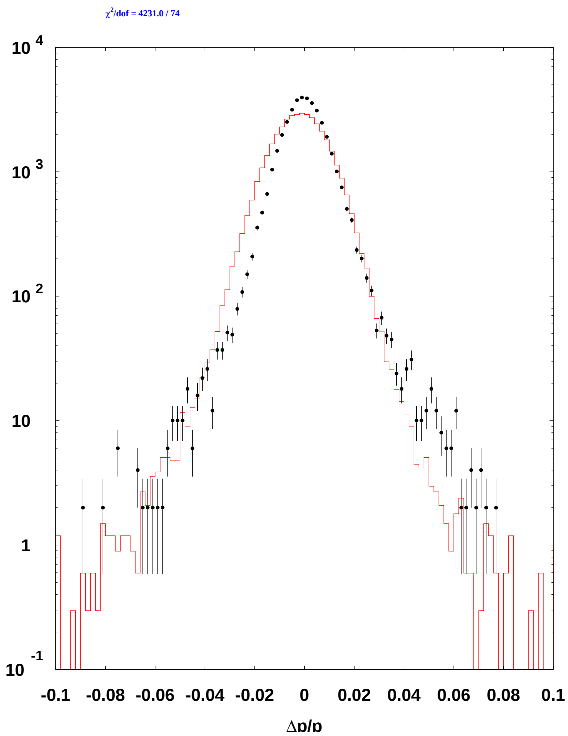
Downstream Magnetic Spectrometer



- 4 straw chambers in Vacuum
- 5/8/8/8, 4 views $(0°, 90°, \pm 45°)$
- As thin as possible:
  $5\,\mathrm{layers} = 0.21\,X_0$, $8\,\mathrm{layers} = 0.34\,X_0$
- Active area $80 \times 80\,\mathrm{cm}^2$, drift time$=25\,\mathrm{ns}$
- Maximum rate per straw $120\,\mathrm{kHz}$
- Deadened in the beam
- Gas leackage in vacuum is tiny compared to scintillator.
- Similar system worked in BNL-871
- MECO also plan to use straws in vacuum

Downstream Magnetic Spectrometer

Non-gaussian tails in DMS? Comparison with BNL-871



BNL-871:	CKM:
3-4GeV	14-20GeV
4 chambers	4 chambers
5 straw layers	8 straw layers
$100\,\mathrm{kHz}$	$< 110\,\mathrm{kHz}$

- GEANT simulation: $\sigma_p/p \simeq 1.1\%$, $\sigma_\Theta \simeq 0.04\,\mathrm{mrad}$
- Data from BNL-871 shows higher tails
- Resoultion tails: we understand some differences with BNL-871

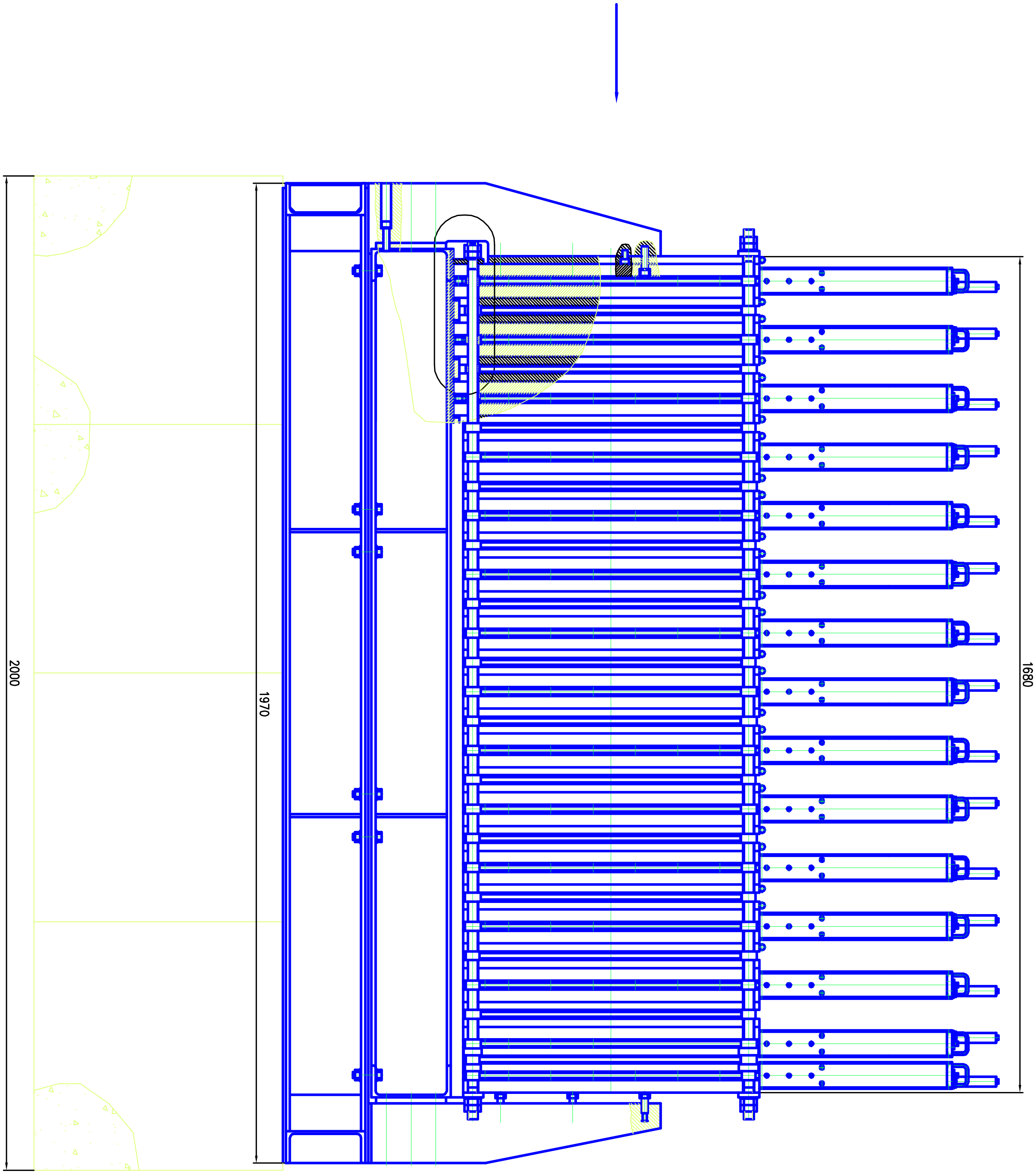
Muon Veto

To control $K^+ \to \mu^+ \nu_\mu$ background.

- Veto μ, identify π
- Prototype test on $25\,\mathrm{GeV}$ beam in Protvino (Russia)
- 26 layers: $4.1\,\mathrm{cm}$ Fe / $1\,\mathrm{cm}$ scintillator
- Alternating X, Y projections
- Requirement: $< 1 \times 10^{-5}$ at 95% π efficiency
- Test Beam: $< 3 \times 10^{-6}$ at 75% π efficiency

Possible improvements:

- Increase length (83%)
- Better plastic and light collection
- Relaxing cuts
- Better alghoritms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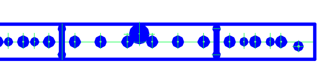
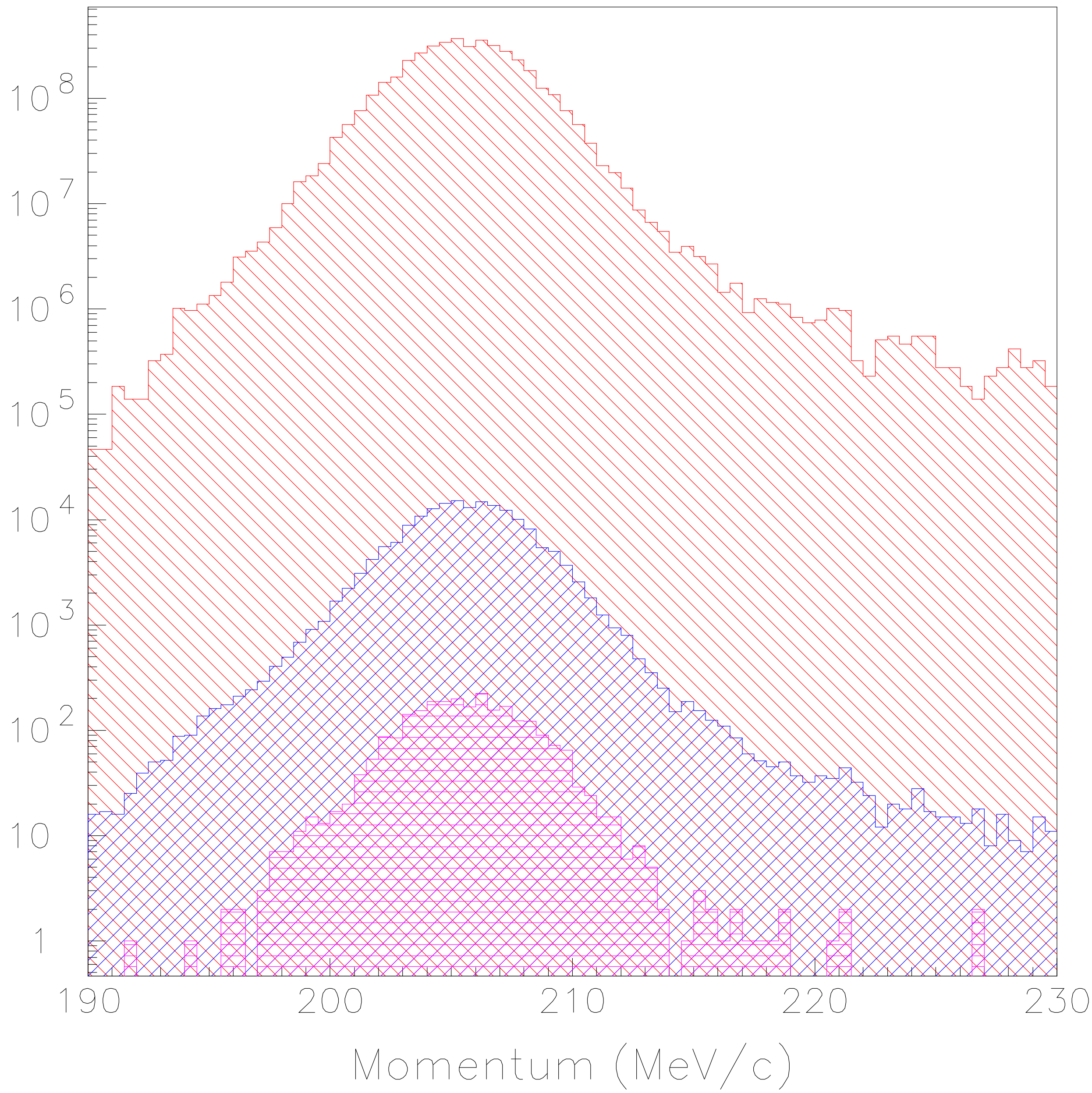


Summary of CKM backgrounds

Background source	Effective BR $(\times 10^{-12})$
$K^+ \to \mu^+\nu_\mu$	< 0.04
$K^+ \to \pi^+\pi^0$	3.7
$K^+ \to \mu^+\nu_m u\gamma$	< 0.09
$K^+A \to K_L X, K_L \to \pi^+ e^- \overline{\nu}_e$	< 0.14
$K^+A \to \pi^+ X$ in trackers	< 4.0
$K^+A \to \pi^+ X$ in residual gas	< 2.1
Accidentals (2 K^+ decays	0.51
Total	< 10.6

E787 and Background Factorization

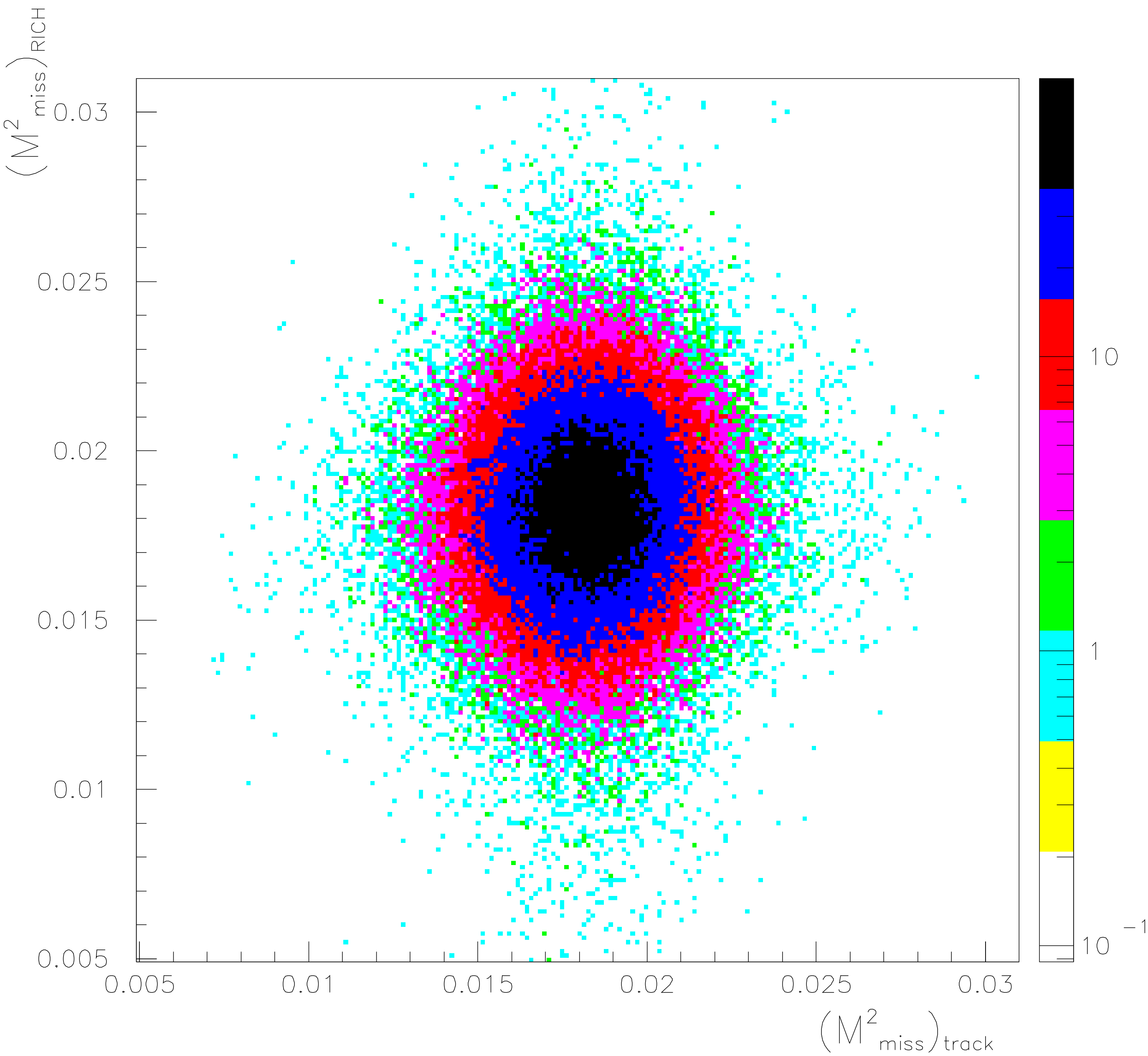


- No photon veto cuts
- Online photon veto cuts
- Full offline photon veto cuts

Shape does not change.

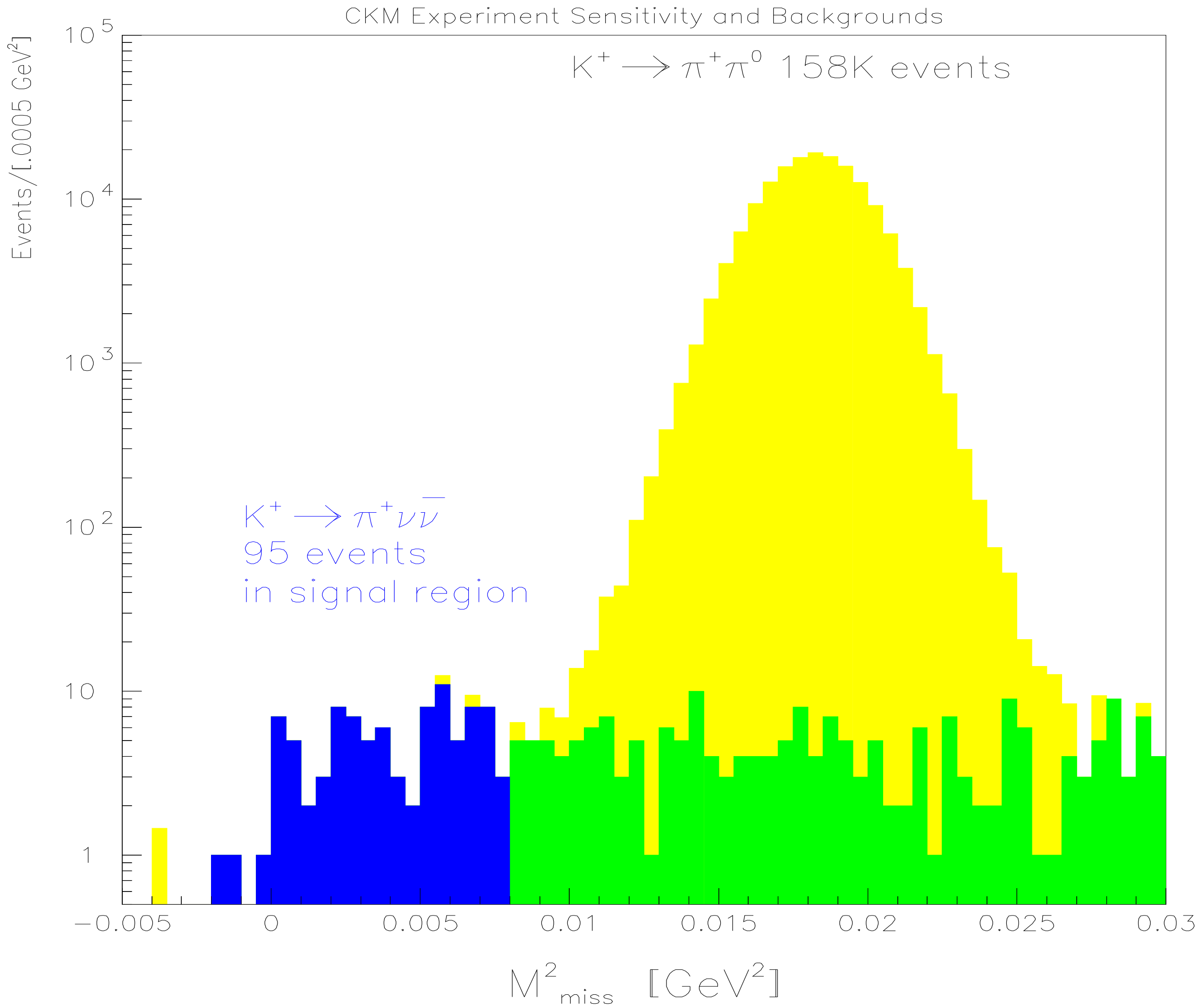
Does not prove that it will work for CKM, but gives us hope.

Comparison of Momentum (Tracking) and Velocity (RICH) Spectrometers



Based on GEANT simulation of $K^+ \to \pi^+\pi^0$.

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



Selection cuts:

- Clean event, reasonable number of hits
- Decay angle $\Theta_{K\pi} > 2.5\,\mathrm{mrad}$ - good vertex
- x, y on the beam, z inside vacuum veto
- Distance between K and π tracks $< 1\,\mathrm{cm}$
- $14 < p_\pi < p_K - 1$ (GeV)
- $|M^2_{\nu\nu}(\mathrm{RICH}) - M^2_{\nu\nu}(\mathrm{tracking})| < 0.01$
- $-0.005 < |M^2_{\nu\nu}| < 0.008$

Summary

- Rare K decay program has a solid physics case.
- CKM has a potential of robust measurement on $\rho - \eta$ plane.
- CKM got a scientific approval on June 28, 2001