Measurements of the Branching ratios for $K^{\pm} \rightarrow \pi^{\pm} \mu^{+} \mu^{-}$

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FNAL Wine and Cheese
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Outline

1. Introduction to $K^+ \rightarrow \pi^+ l^+ l^-$ decay
2. Overview of HyperCP (E871) Experiment
3. Data Summary of 1997 and 1999 runs
4. Measurements of B($K^{\pm} \rightarrow \pi^{\pm}\mu^+\mu^-$)
5. Summary

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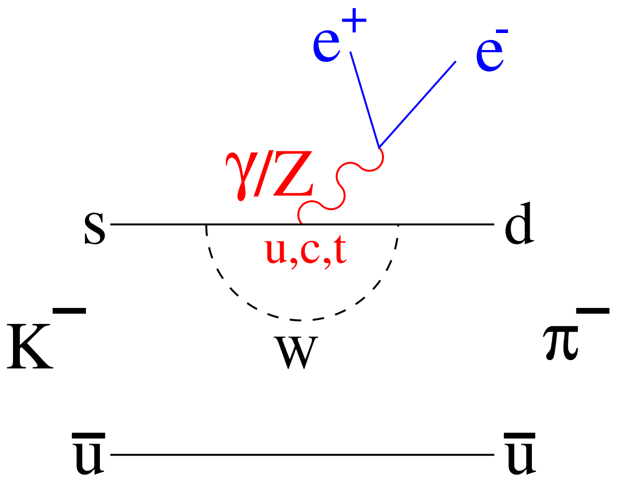
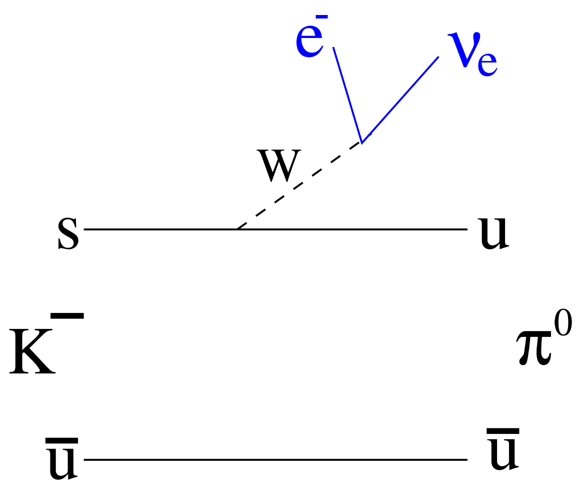
Introduction to $K^{\pm} \to \pi^{\pm} l^{+} l^{-}$ decay

- This decay mode involves FCNC. In SM, there is no FCNC at tree level.
  $\longrightarrow$ Provide a test of SM at one-loop level

Flavor Changing Neutral Current



Charged Current



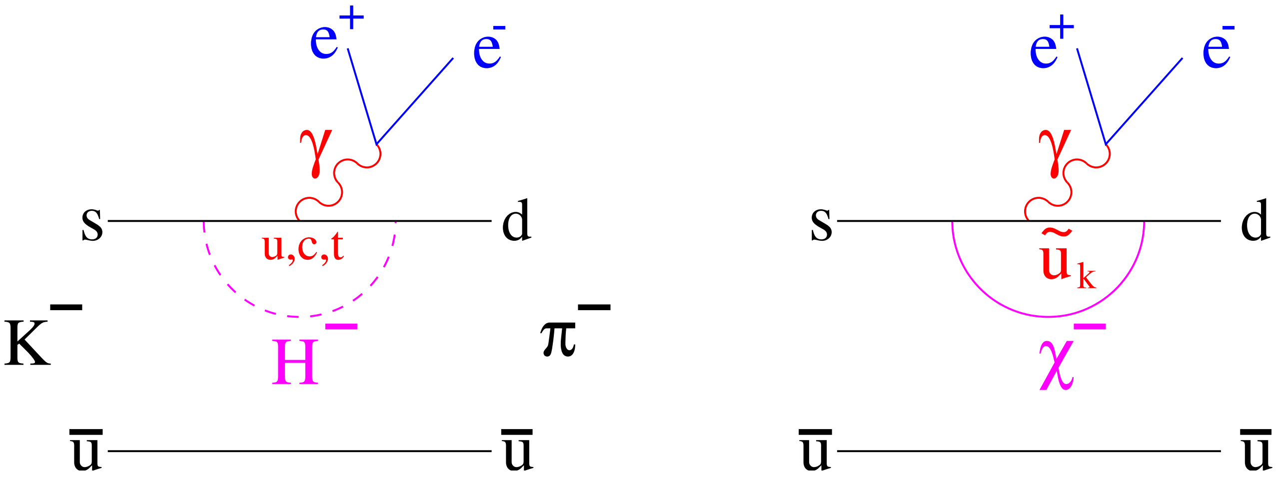
$$V_{us}V_{ud}^{*} + V_{cs}V_{cd}^{*} + V_{ts}V_{td}^{*} = 0$$

$\Longrightarrow$ GIM Cancellation if $m_u = m_c = m_t$

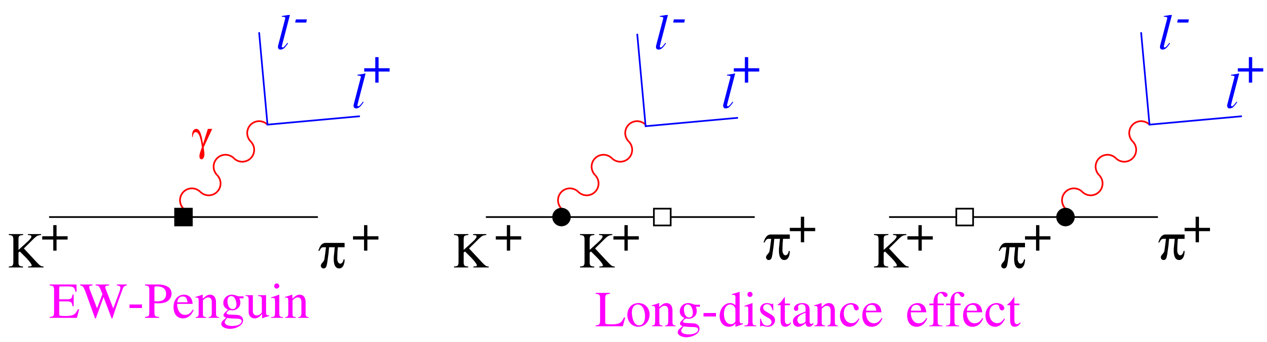
$$\frac{\Gamma(K^{+} \to \pi^{+} e^{+} e^{-})}{\Gamma(K^{+} \to \pi^{0} e^{+} \nu_e)} \approx 5.6 \times 10^{-6} \quad (G_F^2 \alpha^2 / G_F^2 \approx 10^{-4})$$

$\longrightarrow$ Highly Suppressed

- Possibly new physics contributes to loop diagram

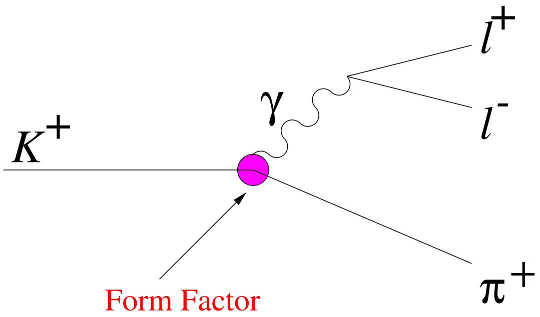


- This decay is dominated by long-distance hadronic effects through one-photon exchange.



- Chiral Perturbation theory used for systematic calculations of long-distance hadronic effects.

- Chiral Perturbation theory describes the form factor and branching ratio of $K^+ \to \pi^+ l^+ l^-$ with two parameters, a_+ and b_+.



$$\phi(q^2) = a_+ + b_+ q^2 + W^{\pi\pi}(q^2)$$

$$B(K^+ \to \pi^+ e^+ e^-) = (0.14 - 3.23 a_+ - 0.88 b_+ + ...) \times 10^{-8}$$
$$B(K^+ \to \pi^+ \mu^+ \mu^-) = (1.13 - 19.2 a_+ - 6.32 b_+ + ...) \times 10^{-9}$$

The rare decay $K^+ \to \pi^+ l^+ l^-$ gives a test of Chiral Perturbation theory

Chiral Perturbation theory predictions:

$$R = \frac{B(K^+ \to \pi^+ \mu^+ \mu^-)}{B(K^+ \to \pi^+ e^+ e^-)} > 0.23$$

- A CP asymmetry between $K^+ \to \pi^+ l^+ l^-$ and $K^- \to \pi^- l^+ l^-$ decays:

$$\Delta_{K^+ \to \pi^+ l^+ l^-} = \frac{\Gamma(K^+ \to \pi^+ l^+ l^-) - \Gamma(K^- \to \pi^- l^+ l^-)}{\Gamma(K^+ \to \pi^+ l^+ l^-) + \Gamma(K^- \to \pi^- l^+ l^-)} \sim 10^{-5}$$

Experimental Results

- $B(K^+ \to \pi^+ e^+ e^-)$ is well measured:

$(2.6 \pm 0.5) \times 10^{-7}$	(CERN)
$(2.75 \pm 0.23 \pm 0.13) \times 10^{-7}$	(BNL-E777)
$(2.94 \pm 0.05 \pm 0.13 \pm 0.05) \times 10^{-7}$	(BNL-E865)
$(2.88 \pm 0.13) \times 10^{-7}$	(PDG)

- $B(K^+ \to \pi^+ \mu^+ \mu^-)$:

$(5.0 \pm 0.4 \pm 0.7 \pm 0.6) \times 10^{-8}$	(BNL-E787)
$(9.22 \pm 0.60 \pm 0.49) \times 10^{-8}$	(BNL-E865)

$\to$ 3.3σ discrepancy !

- From the experimental inputs on $B(K^+ \to \pi^+ e^+ e^-)$ and $B(K^+ \to \pi^+ \mu^+ \mu^-)$, the value of R:

$R = 0.17 \pm 0.03$	(BNL-E787)
$R = 0.32 \pm 0.03$	(BNL-E865)

If the BNL-E787 result is correct, it's not easy to explain it within SM.

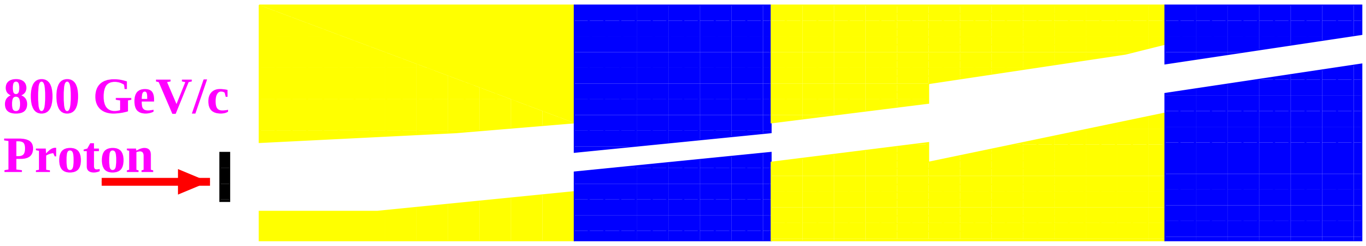
Need another measurement to resolve this discrepancy

HyperCP VS. BNL Experiments

Experiment	Kaon Beam	No. of Events	Normalization
BNL-E787	800 MeV/c stopped K^+	10.6 ± 4.7 (3-trk) 196.0 ± 16.7 (2-trk)	$K^+ \to \mu^+\nu$
BNL-E865	6 GeV/c K^+	430 ± 28	$K^+ \to \pi^+\pi^+\pi^-$
HyperCP	120 GeV/c - 250 GeV/c of K^+ and K^-	will see	$K^\pm \to \pi^\pm\pi^\pm\pi^\mp$

HyperCP can study both K^+ and K^- decays.

Production of Secondary Beams



- p(800 GeV/c) + Cu $\longrightarrow$ Secondary Particles

- Collimator (6.096 m) with 1.667 T of Dipole Magnetic Field
  - Bend charged particles upward or downward. $\rightarrow$ Select only + or - charged particles.
  - Central-Orbit Momentum = 170 GeV/c
  - Bending Angle = 19.5 mrad

- Only long lived charged particles exit from the Collimator:

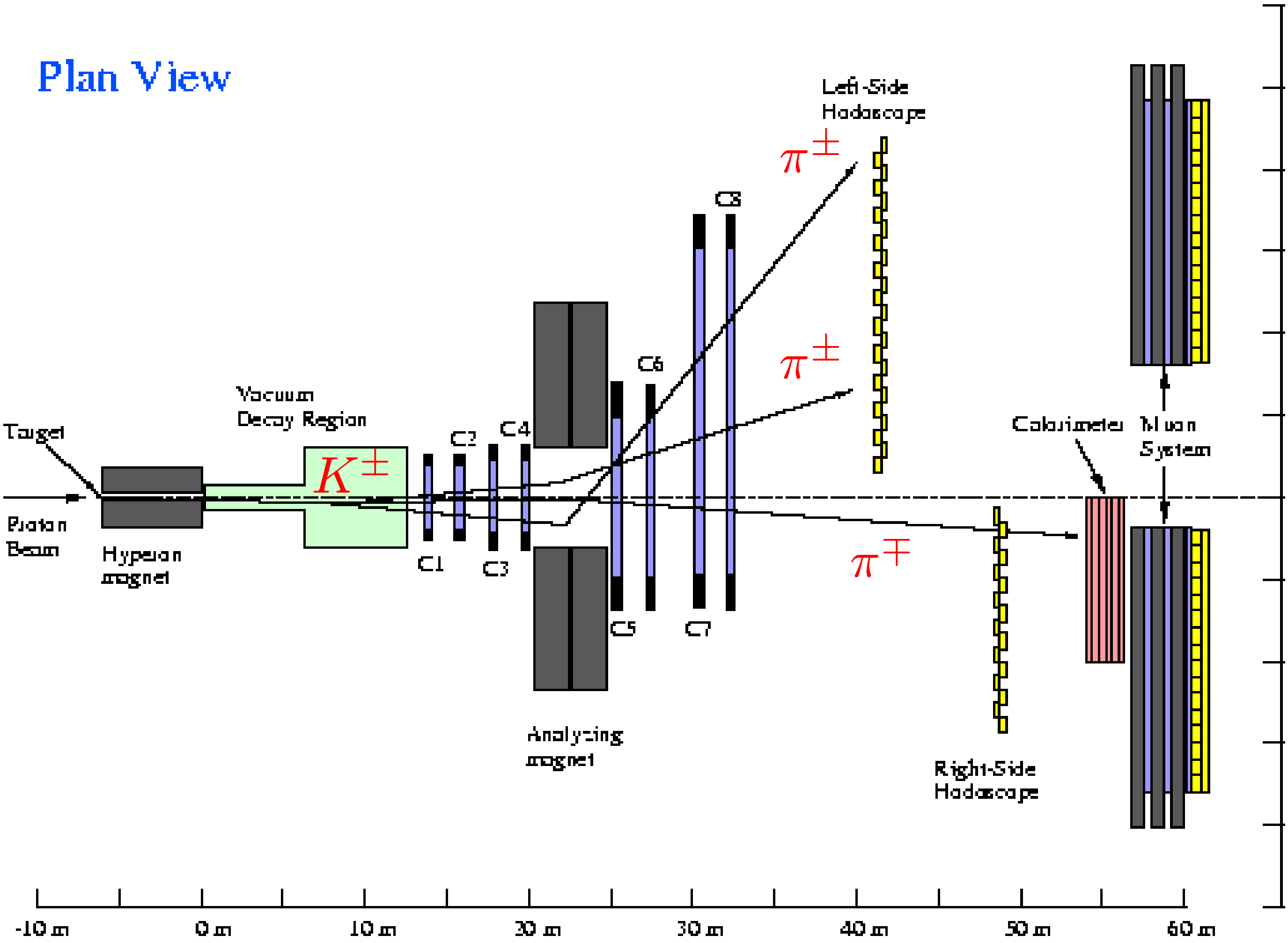
  Mainly $\pi^{\pm}$, p, $\overline{p}$, $K^{\pm}$, $\Sigma^{\pm}$, $\Xi^{\pm}$, $\Omega^{\pm}$

Spectrometer

- 13 m vacuum decay region
- 8 fast narrow-pitch multiwire proportional chambers (32 planes)
- Analysis Magnet :
  Bend charged particles in horizontal direction.
- High-rate DAQ :
  1997 : $\sim$63,000 events/s
  1999 : $\sim$100,000 events/s
- Simple trigger using hodoscopes
  Left-Right trigger: Coincidence of the left- and right-side hodoscope hits
- Muon System
  - Two stations on left and right side
  - Three layers of 80 cm thick steel
  - Three layers of Proportional wire tubes
  - Hodoscopes at the end of the station for muon trigger

  $\mu^+\mu^-$ trigger: Coincidence of hodoscope hits in each muon station with Left-Right trigger

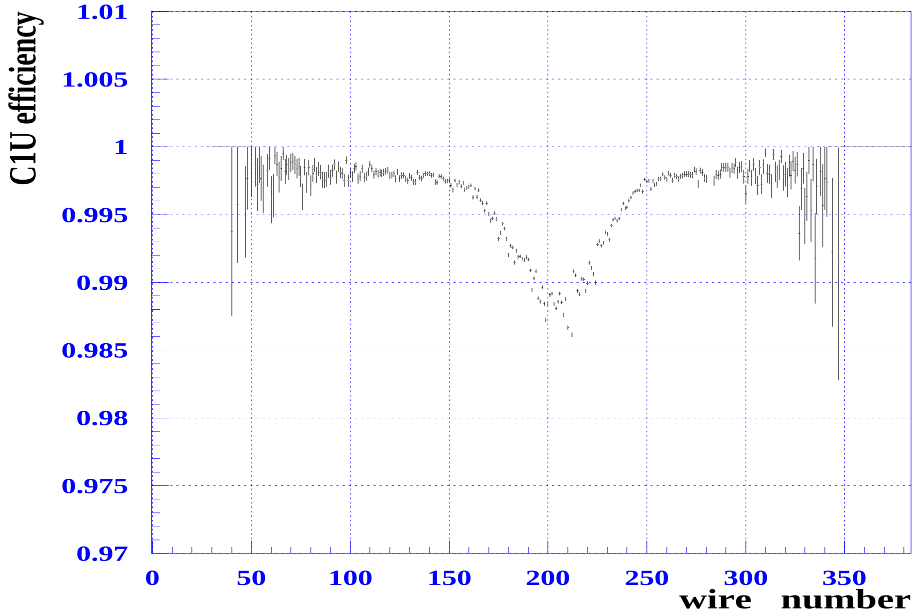
HyperCP Spectrometer

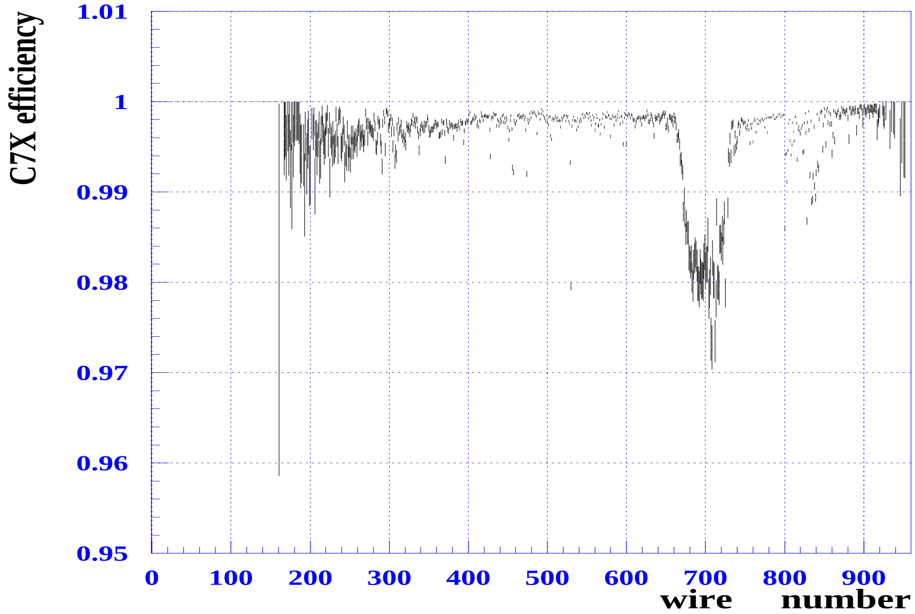


- Protons on target ≈ 7 GHz
- The secondary beam rate ≈ 13 MHz
- The typical run cycle: + + - + + -...

Performance of Spectrometer

- Chamber Efficiency for upstream and downstream MWPC

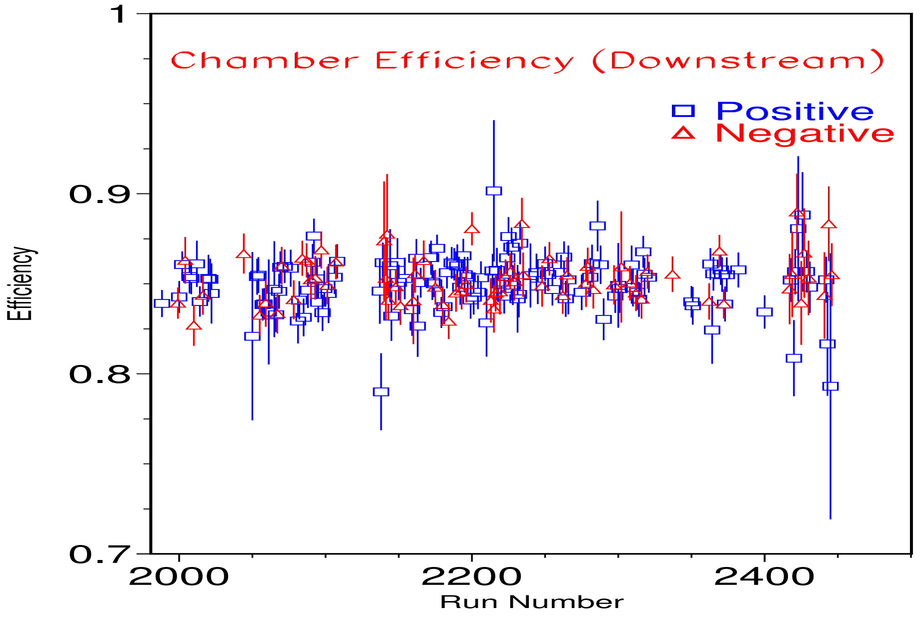


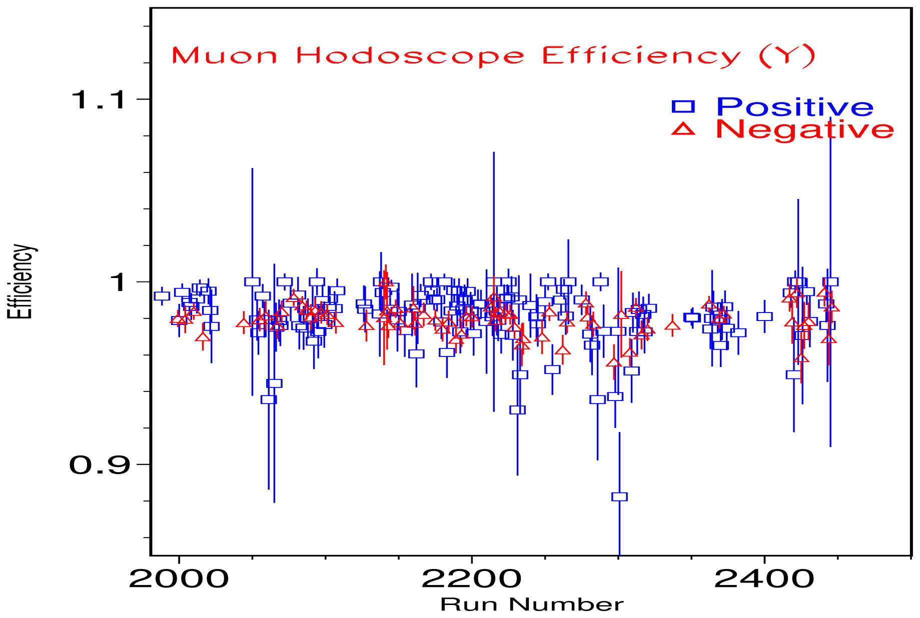


Average Chamber efficiency was $> 99\ \%$

Performance of Muon System

- Efficiency for Muon Chamber and Hodoscope during 1997 run





Muon chamber and hodoscope efficiency were about 86% and 98%, respectively

Summary of the 1997 and 1999 runs

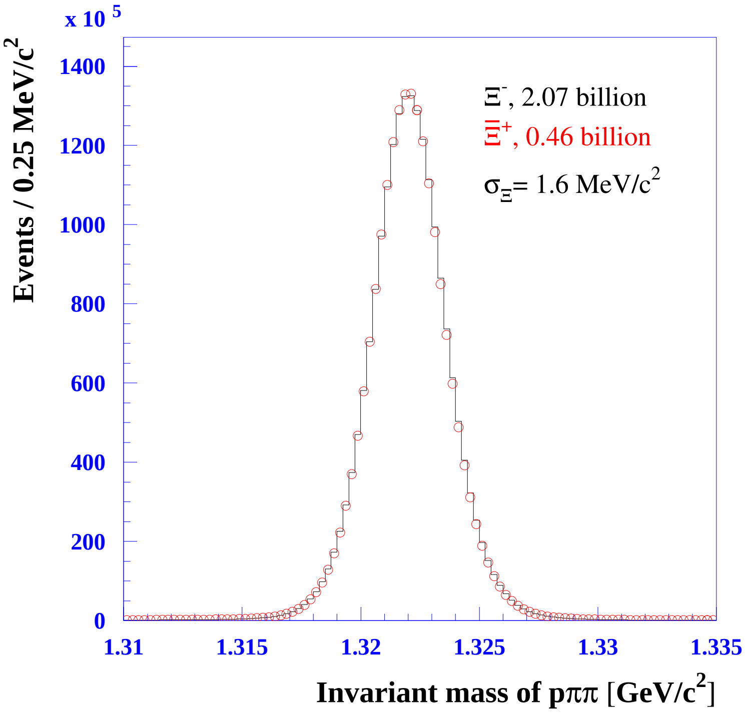
	1997 Run	1999 Run
Number of tapes	8,980	20,421
Data Volume	38 TB	82 TB

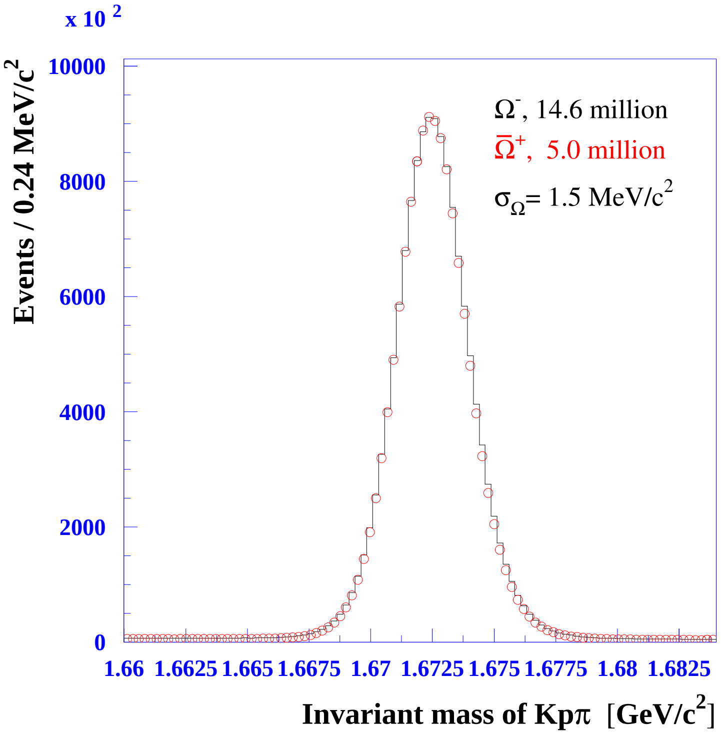
Number of reconstructed events

	Beam Polarity	
Decay	$-$	$+$
$\Xi \to \Lambda\pi$	2×10^9	0.5×10^9
$K \to 3\pi$	0.16×10^9	0.39×10^9
$\Omega \to \Lambda K$	15×10^6	5.0×10^6

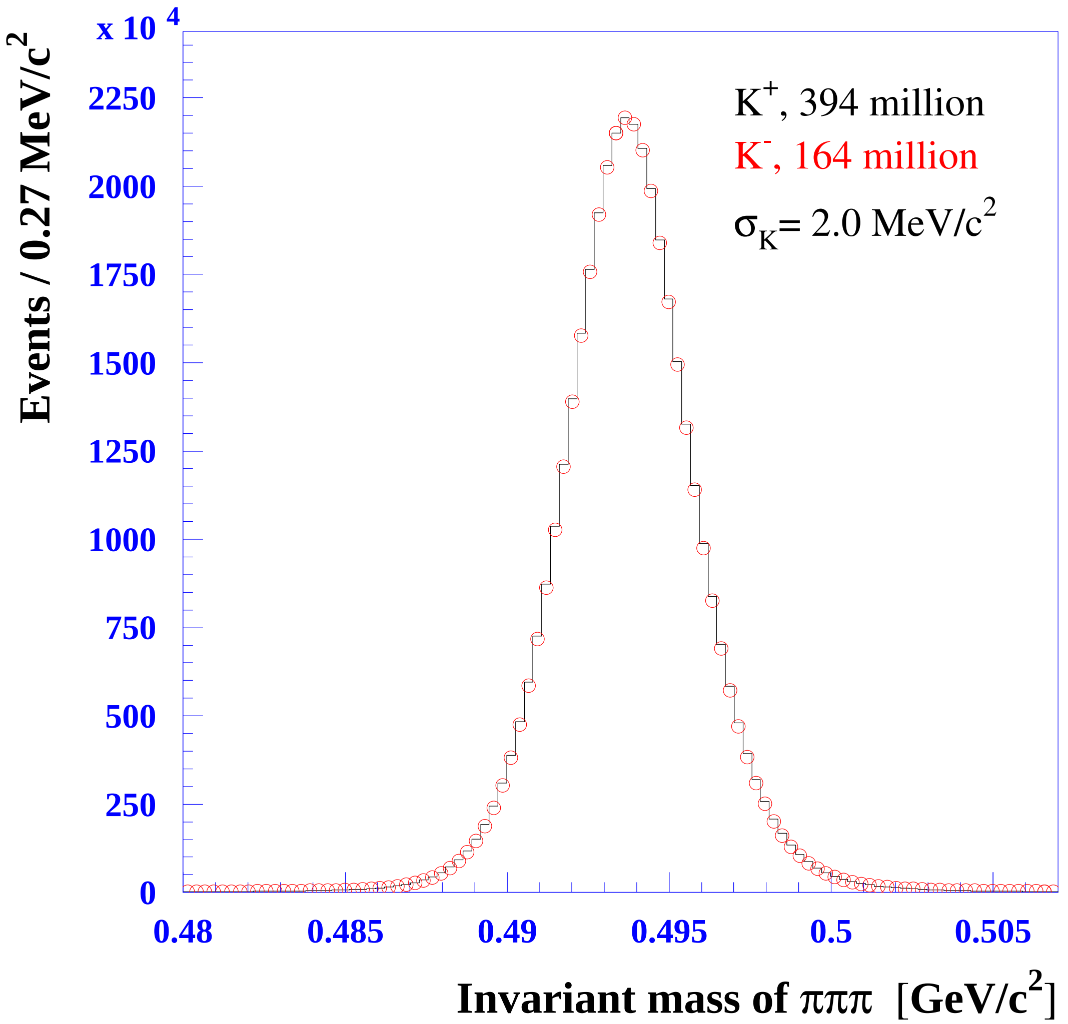
$\Longrightarrow$ The largest sample of totally reconstructed $\Xi^{\pm} \to \Lambda\pi^{\pm}$, $\Omega^{\pm} \to \Lambda K^{\pm}$ and $K^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}$

$\Xi^- \to \Lambda\pi^-$ and $\Omega^- \to \Lambda K^-$





$$\boxed{K^{\pm} \rightarrow \pi^{\pm}\pi^{\pm}\pi^{\mp}}$$



No difference in the reconstructed masses for Ξ^- vs. $\overline{\Xi}^+$, Ω^- vs. $\overline{\Omega^+}$ and K^- vs. K^+ with very good mass resolution.

Measuring $B(K^\pm \to \pi^\pm\mu^\pm\mu^\mp)$ in HyperCP

- Use $K^\pm \to \pi^\pm\pi^\pm\pi^\mp$ for normalization
- Measure $B(K^\pm \to \pi^\pm\mu^\pm\mu^\mp)$ according to the equation:

$$B(K^\pm \to \pi^\pm\mu^\pm\mu^\mp) = \frac{N^{obs}_{\pi\mu\mu}}{200 \cdot N^{obs}_{3\pi}} \frac{A_{3\pi}}{A_{\pi\mu\mu}} \frac{\epsilon^{trig}_{3\pi}}{\epsilon^{trig}_{\pi\mu\mu}} \frac{\epsilon^{cut}_{3\pi}}{\epsilon^{cut}_{\pi\mu\mu}} \frac{B(K \to 3\pi)}{\epsilon_{\mu^+\mu^-}}$$

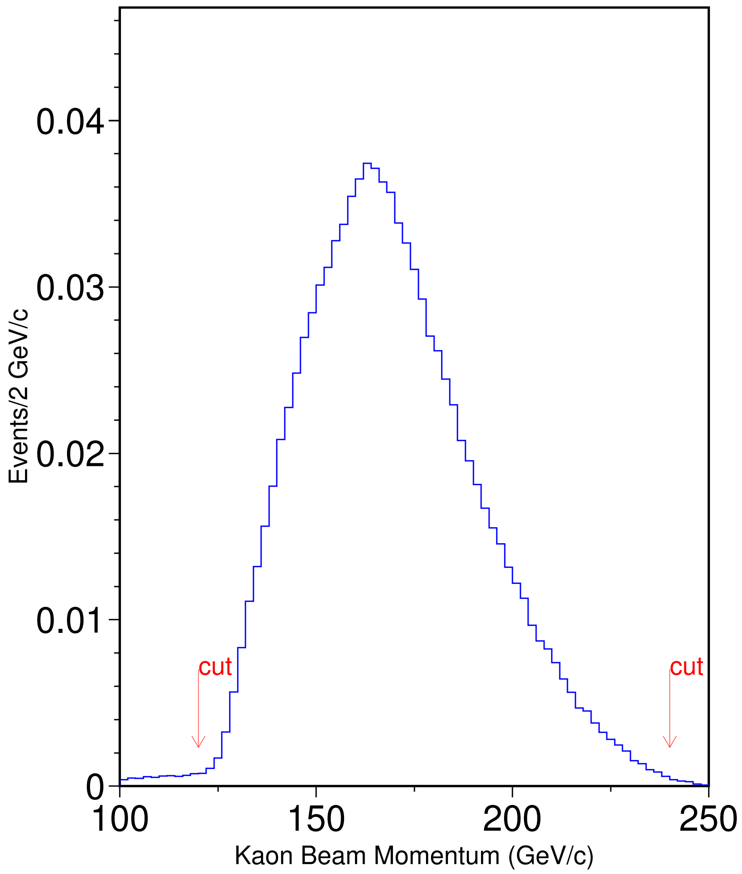
where

200 =	Prescale factor for $K \to 3\pi$
N^{obs} =	number of observed events
A =	geometric acceptance
ϵ^{trig} =	trigger efficiency
ϵ^{cut} =	event selection efficiency
$\epsilon_{\mu^+\mu^-}$ =	efficiency of identifying $\mu^+\mu^-$
$B(K^+ \to 3\pi)$ =	(5.59 ± 0.05)% in PDG

Basic Event Selection

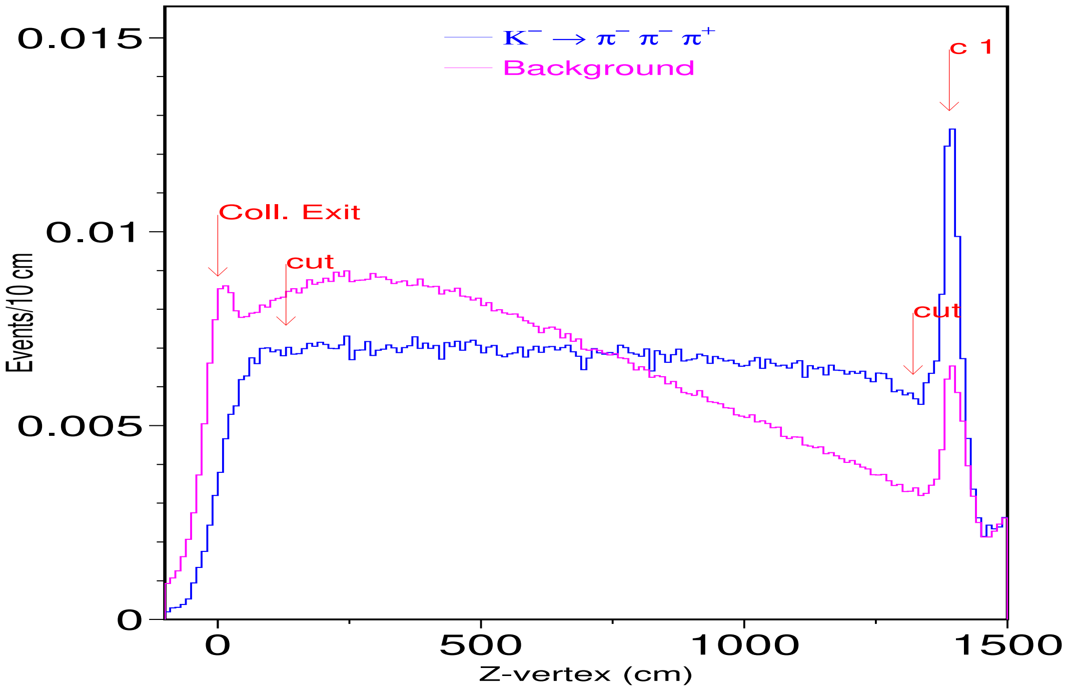
Required for selecting
$K^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}$ and $K^{\pm} \to \pi^{\pm}\mu^{\pm}\mu^{\mp}$ events

- 2 tracks in Left side and 1 track in Right side
- Fiducial Cut at muon station for each track
- Total Momentum of event



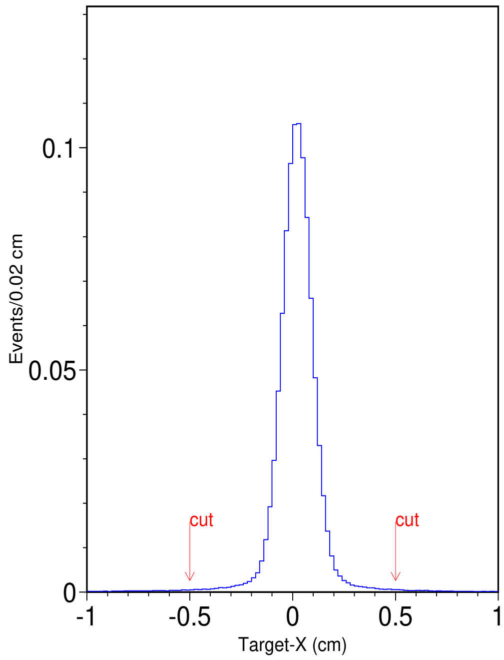
Basic Event Selection (cont.)

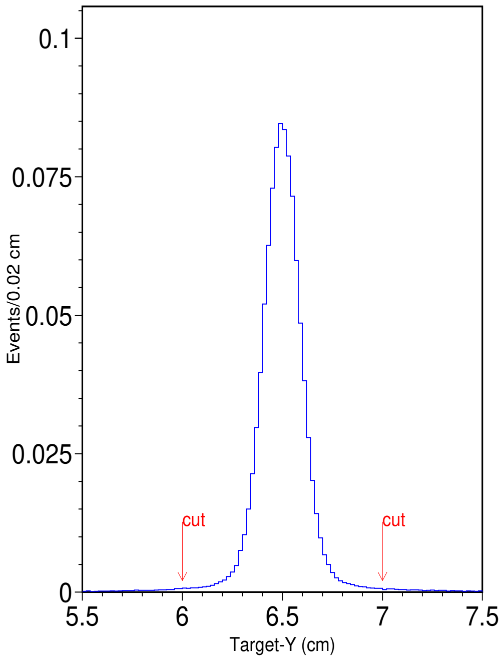
- Location of decay vertex:



- X and Y position at the target:

  (Transverse target size = 2.0 mm × 2.0 mm)

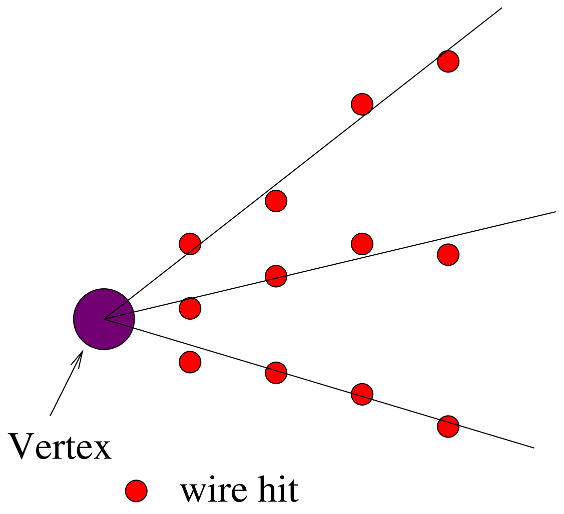




Basic Event Selection (cont.)

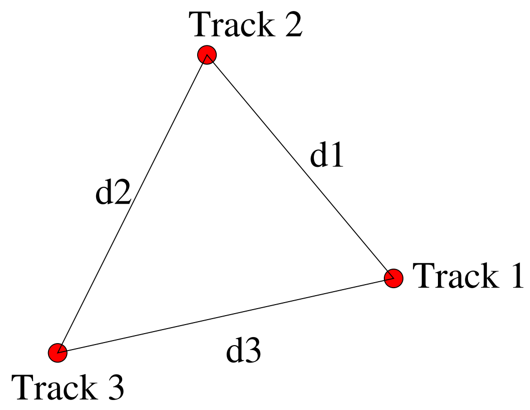
- Single-Vertex tagging:

$\chi^2/n.d.f.$

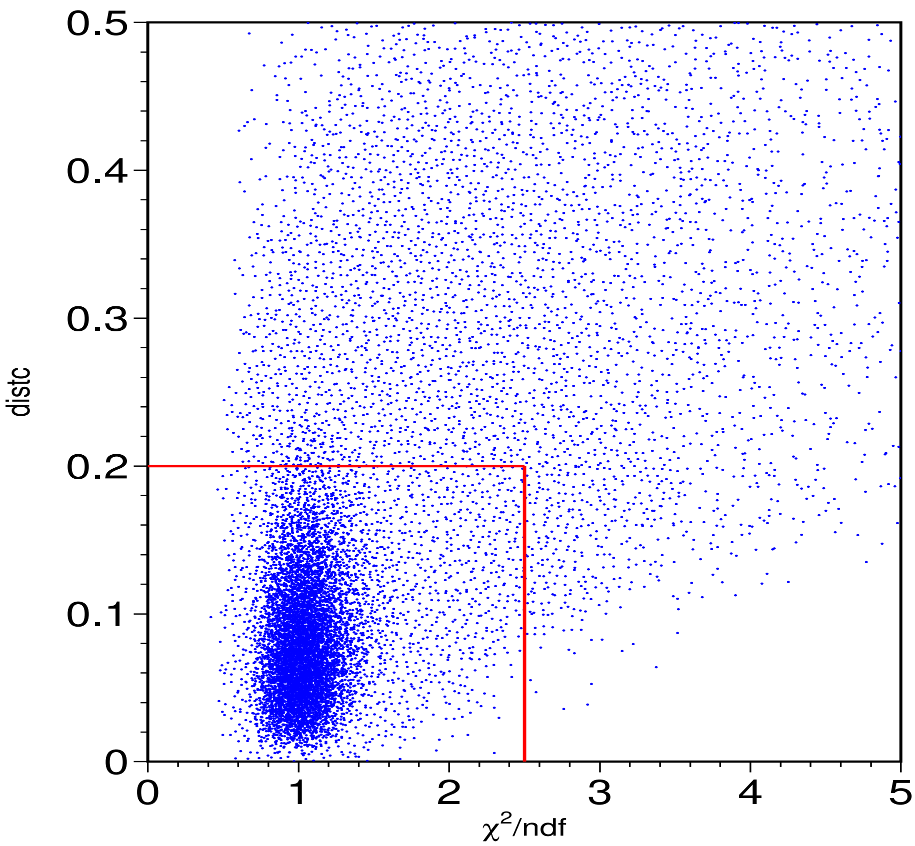


$distc$

on x-y plane



distc= (d1 + d2 + d3)/3



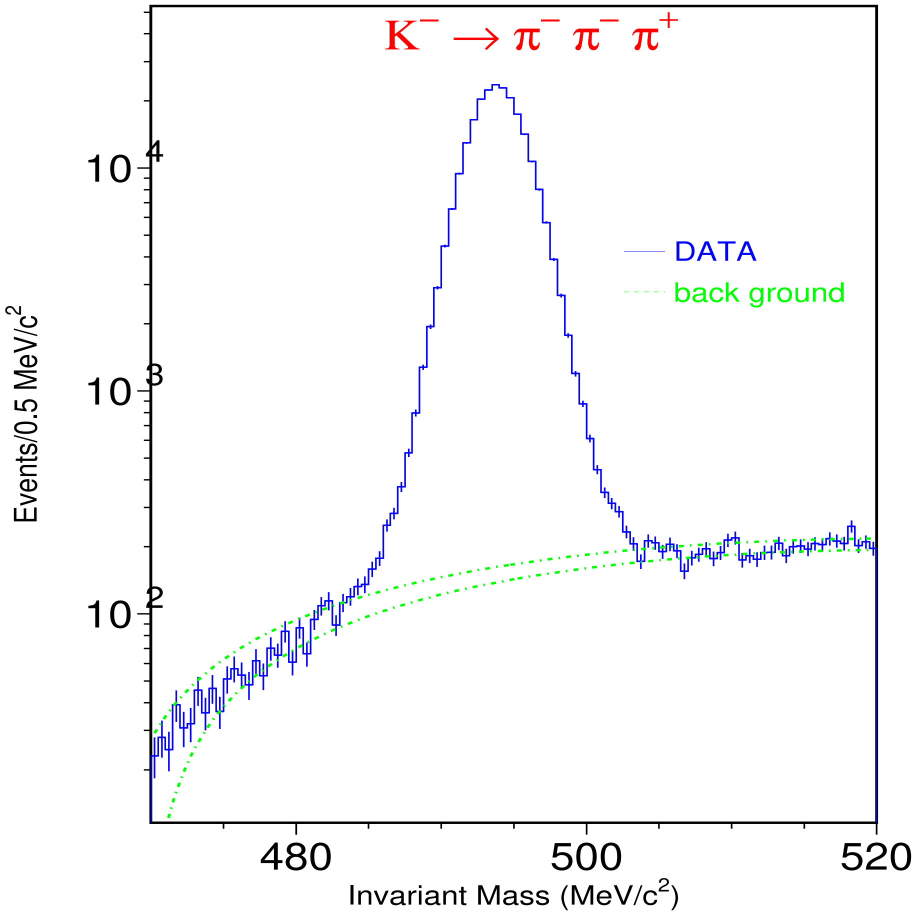
Summary of the event selection

- 2 tracks in left and 1 track in right
- Fiducial cut:
  -174.9 cm $< \ x_{proj} \ <$ +235.2 cm

  where x_{proj} is x-position of projected track at z=muon hodoscope
- Total Momentum:
  120 GeV/c $< \ P_{tot} \ <$ 250 GeV/c
- z-decay Vertex:
  100 cm $< \ v_z \ <$ 1300 cm (K^+)
  130 cm $< \ v_z \ <$ 1320 cm (K^-)
- Beam X and Y Position at the Target :
  $|X_{target}| \ <$ 0.5 cm, $|Y_{target} - 6.5| \ <$ 0.5 cm
- Single-Vertex tagging:
  $\chi^2/n.d.f. \ < \ 2.5, \ \ distc \ <$ 0.2 cm

No. of $K^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}$

- Apply the basic event selection cut with Left-Right trigger prescaled by 200
- Fit side band of mass peak with the following background function: $b(x) = c_0 + c_1 x + c_2 x^2$



Estimated No. of prescaled $K^{\pm} \to 3\pi$ events in 1997 run:

$$N_{K^+ \to 3\pi} = (4.446 \pm 0.010) \times 10^5$$
$$N_{K^- \to 3\pi} = (2.318 \pm 0.008) \times 10^5$$

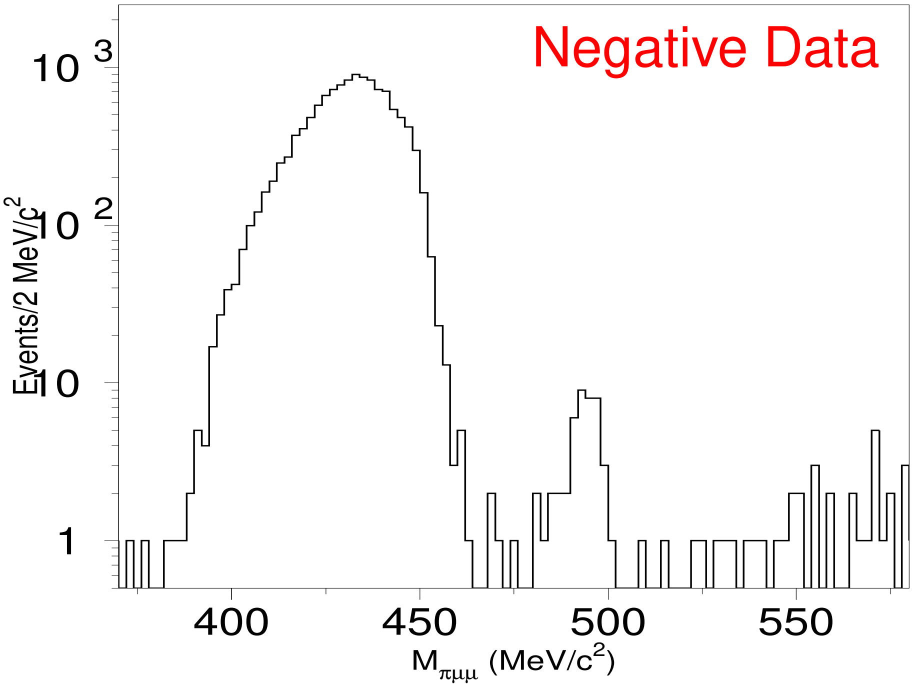
Finding $K^{\pm} \to \pi^{\pm}\mu^{\pm}\mu^{\mp}$ events

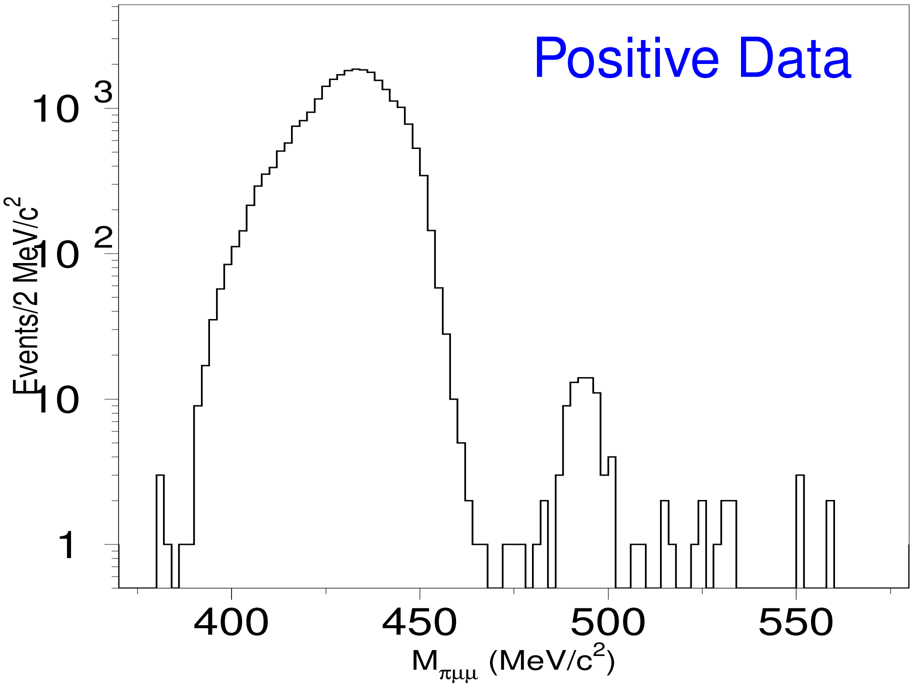
- Apply the basic event selection cut
- Unlike-sign dimuon trigger
- Muon track selection:
  - At least 2 of 3 muon chamber hits associated with downstream track
  - Muon hodoscope hits in x and y view
- Require a muon track in each muon station
  Muon momentum $P_{\mu} > 20$ GeV/c

Reconstruct dimuon events under $\pi\mu^{+}\mu^{-}$ hypothesis

Finding $K^\pm \to \pi^\pm\mu^\pm\mu^\mp$ event (cont.)

First observation of $K^- \to \pi^-\mu^+\mu^-$





Estimating No. of $K^\pm \to \pi^\pm \mu^\pm \mu^\mp$ Events

- Estimate the number of $K^\pm \to \pi^\pm \mu^\pm \mu^\mp$ using unbinned maximum likelihood fits:

$$\mathcal{L} = e^{-(N_S+N_B)} \prod_{i=1}^{N} (N_S f_s(x_i) + N_B f_b(x_i))$$

where

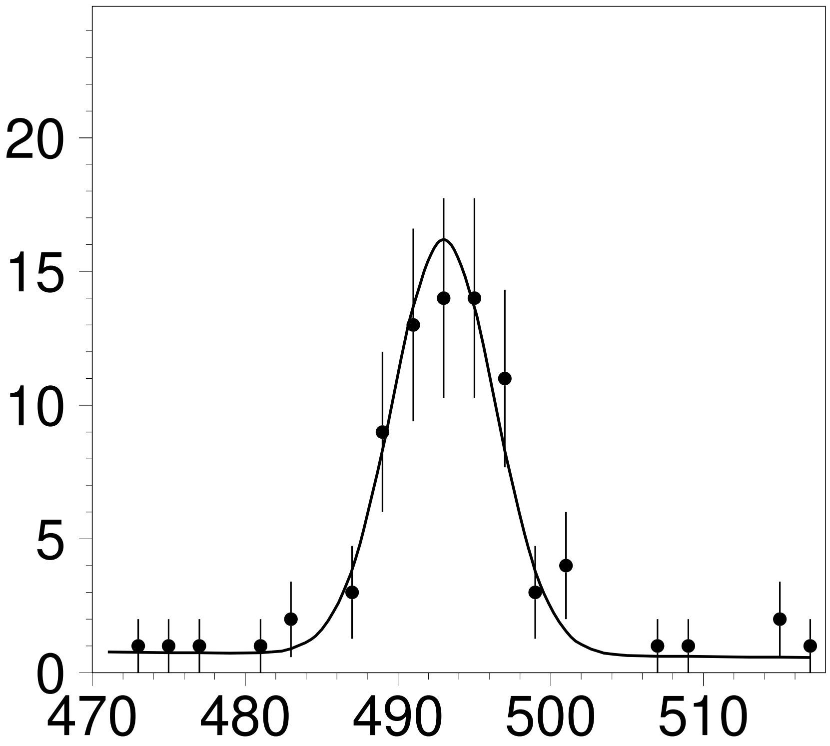
$$\begin{aligned} N &= \text{ number of data events} \\ N_S &= \text{ number of signal events} \\ N_B &= \text{ number of background events} \\ x_i &= \text{ invariant mass of event } i \end{aligned}$$

$$f_s(x_i) = \frac{1}{p_1\sqrt{2\pi}} e^{-\frac{(M_{K^+} - x_i)^2}{2p_1^2}}$$

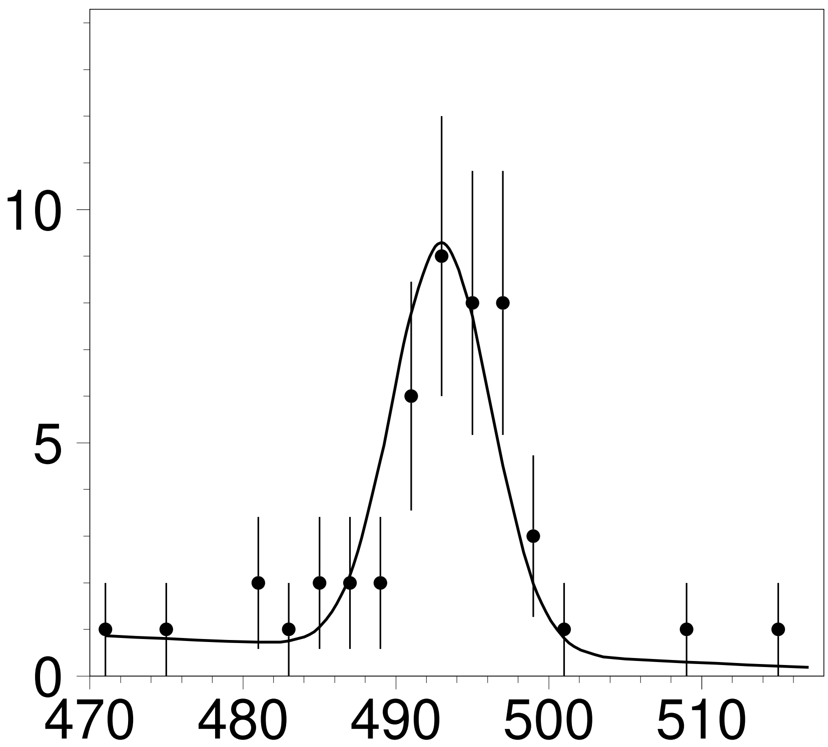
$$f_b(x) = (p_2 + p_3 x_i)$$

N_S, N_B, p_1, p_2 and p_3 are determined from the fit.

No. of $K^{\pm} \to \pi^{\pm}\mu^{\pm}\mu^{\mp}$ events for '97 run



No. of $K^{+} \to \pi^{+}\mu^{+}\mu^{-}$
65.3 ± 8.2



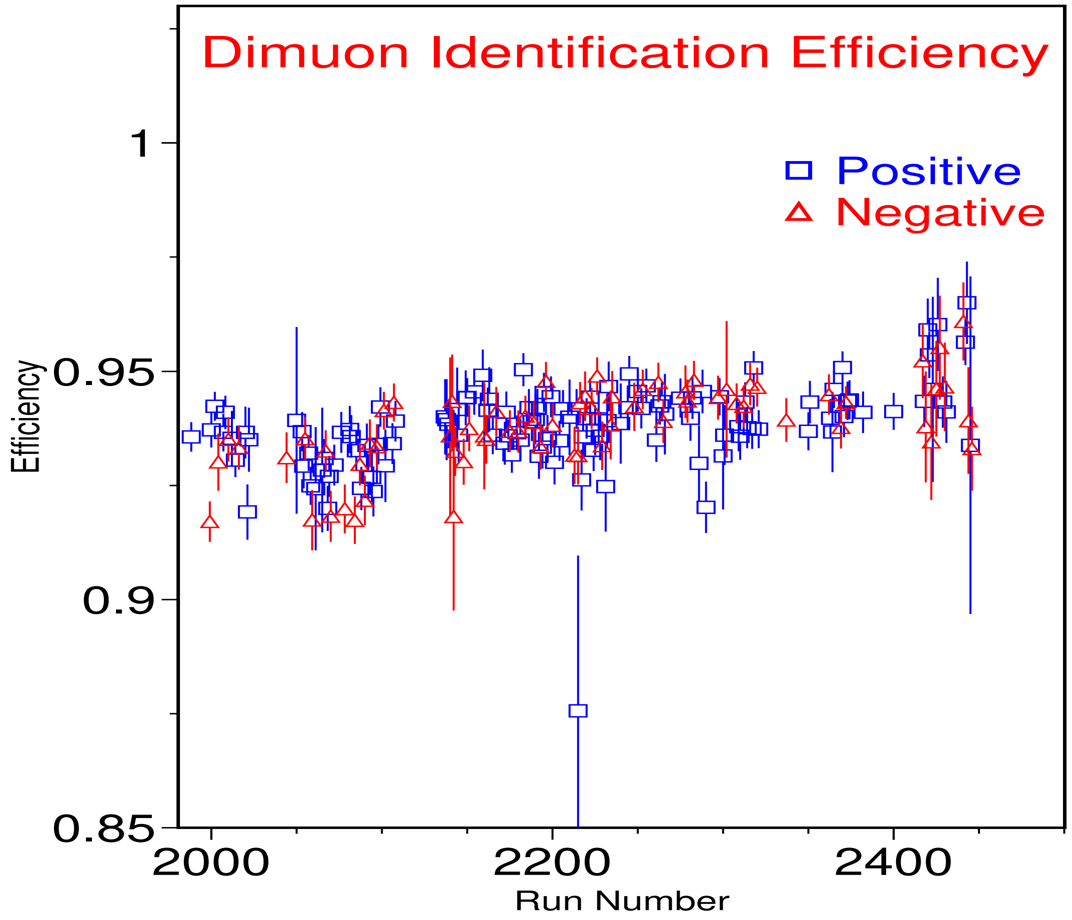
No. of $K^{-} \to \pi^{-}\mu^{+}\mu^{-}$
35.2 ± 6.6

Efficiencies of Dimuon Trigger and Identification

- Use the full '97 data sample

- Estimate the dimuon trigger efficiency with respect to $K_{3\pi}$ trigger: $(86.6 \pm 2.7)\%$

- Muon identification efficiency is: $(93.8 \pm 0.3)\%$



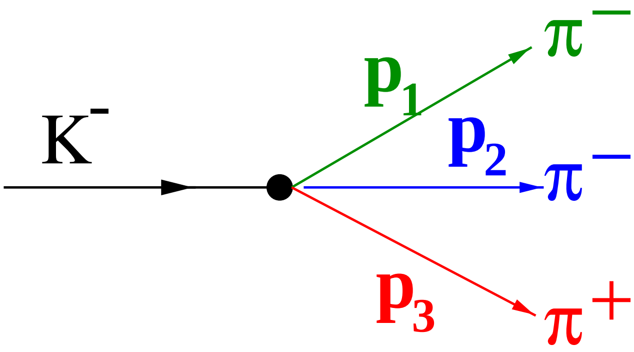
MC Simulation

- Tune the MC inputs to fit the observed $K^\pm$ spectra.

Generation of $K^\pm \to \pi^\pm\pi^\pm\pi^\mp$

- The Dalitz distribution for $K^\pm \to \pi^\pm\pi^\pm\pi^\mp$ depends only on two kinematic variables:

$$X = \frac{s_2 - s_1}{m_\pi^2}$$
$$Y = \frac{s_3 - s_0}{m_\pi^2}$$



where

$$\begin{aligned} s_i &= (\mathbf{p}_K - \mathbf{p}_i)^2 = (m_K - m_i)^2 - 2m_K T_i \ , i = 1,2,3 \\ s_0 &= \frac{1}{3}\sum_i s_i = \frac{1}{3}(m_K^2 + m_1^2 + m_2^2 + m_3^2) \end{aligned}$$

- The Dalitz plot for $K \to 3\pi$ can be parameterized by series expansion:

$$|M(K \to 3\pi)|^2 \propto 1 + gY + hY^2 + kX^2 + \ldots$$

MC Simulation (cont.)

Generation of $K^{\pm} \to \pi^{\pm}\mu^{\pm}\mu^{\mp}$

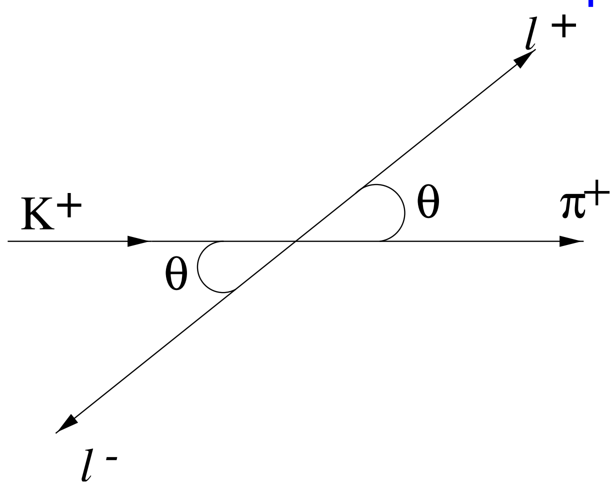
- Previous experimental results showed that $K^+ \to \pi^+ e^+ e^-$ and $K^+ \to \pi^+\mu^+\mu^-$ decays are consistent with one photon exchange.
- The dilepton mass and angular distribution are expressed by

$$\frac{d\Gamma}{dq^2\, d\cos\theta} \sim \lambda^{3/2}(1, q^2/M_K^2, m_\pi^2/M_K^2)(1-4m_l^2/q^2)^{1/2} \times \frac{(m_l^2 + p_l^2 \sin^2\theta)}{q^2} |\phi(q^2/M_K^2)|^2$$

where

q^2 = invariant mass square of dilepton

θ = opening angle between pion and l^+ in the rest frame of virtual photon



$\phi(q^2/M_K^2)$ = Form factor function

MC Simulation (cont.)

Generation of $K^\pm \to \pi^\pm \mu^\pm \mu^\mp$ (cont.)

- The form factor $\phi(q^2/M_K^2)$ is parameterized by

  $\phi(q^2/M_K^2) = c(1 + \delta \frac{q^2}{M_{K^+}^2})$

  where δ = slope parameter

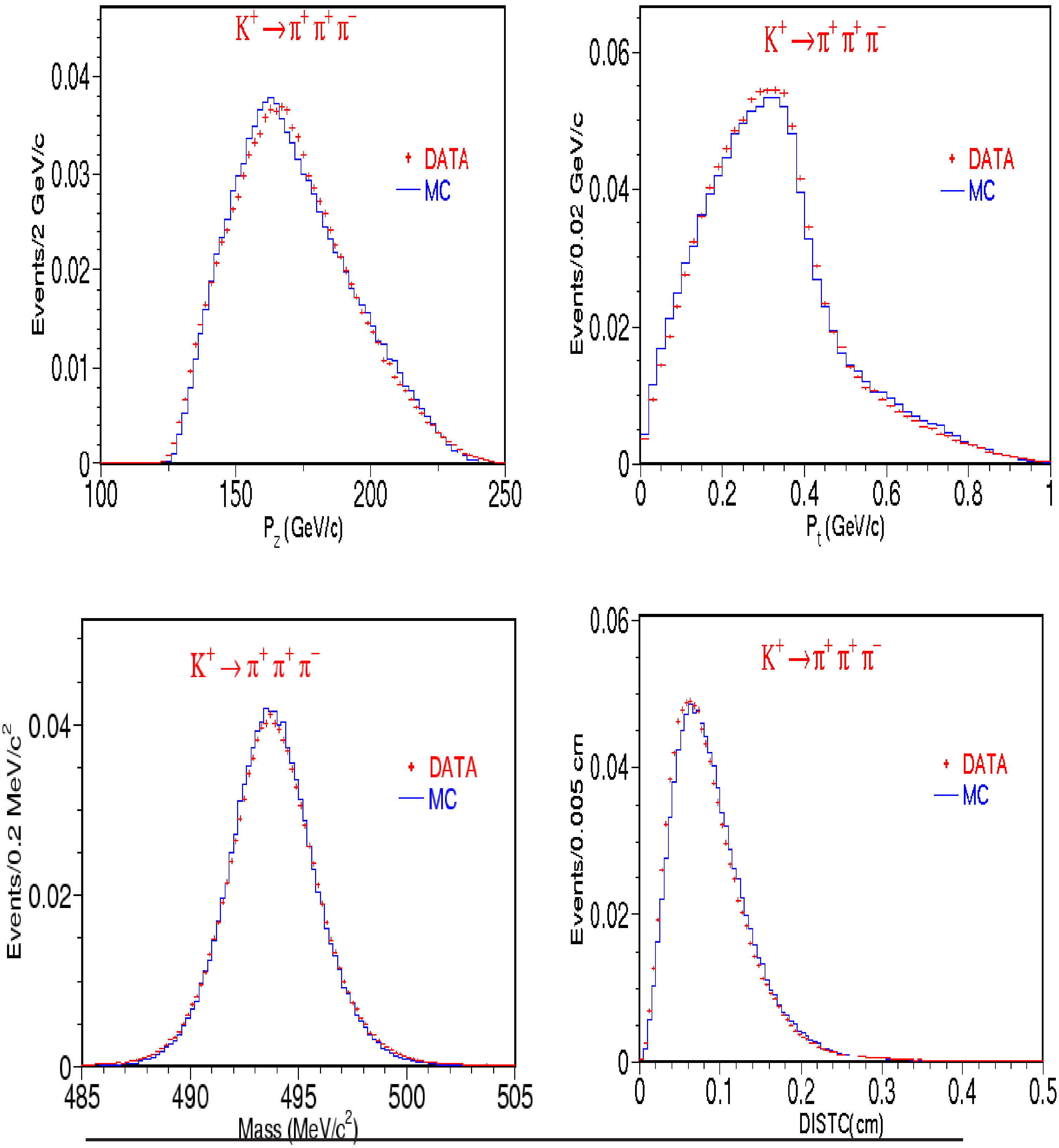
BNL E-787:	$1.31 \pm 0.44 \pm 0.19$	$(K^+ \to \pi^+ e^+ e^-)$
BNL E-865:	$2.14 \pm 0.13 \pm 0.15$	$(K^+ \to \pi^+ e^+ e^-)$
BNL E-865:	$2.45^{+1.30}_{-0.05}$	$(K^+ \to \pi^+ \mu^+ \mu^-)$

Average : $\delta = 2.08 \pm 0.12$

Simulate pion decay in flight and pion punch-through to the muon station for $K^\pm \to \pi^\pm \pi^\pm \pi^\mp$ and $K^\pm \to \pi^\pm \mu^\pm \mu^\mp$

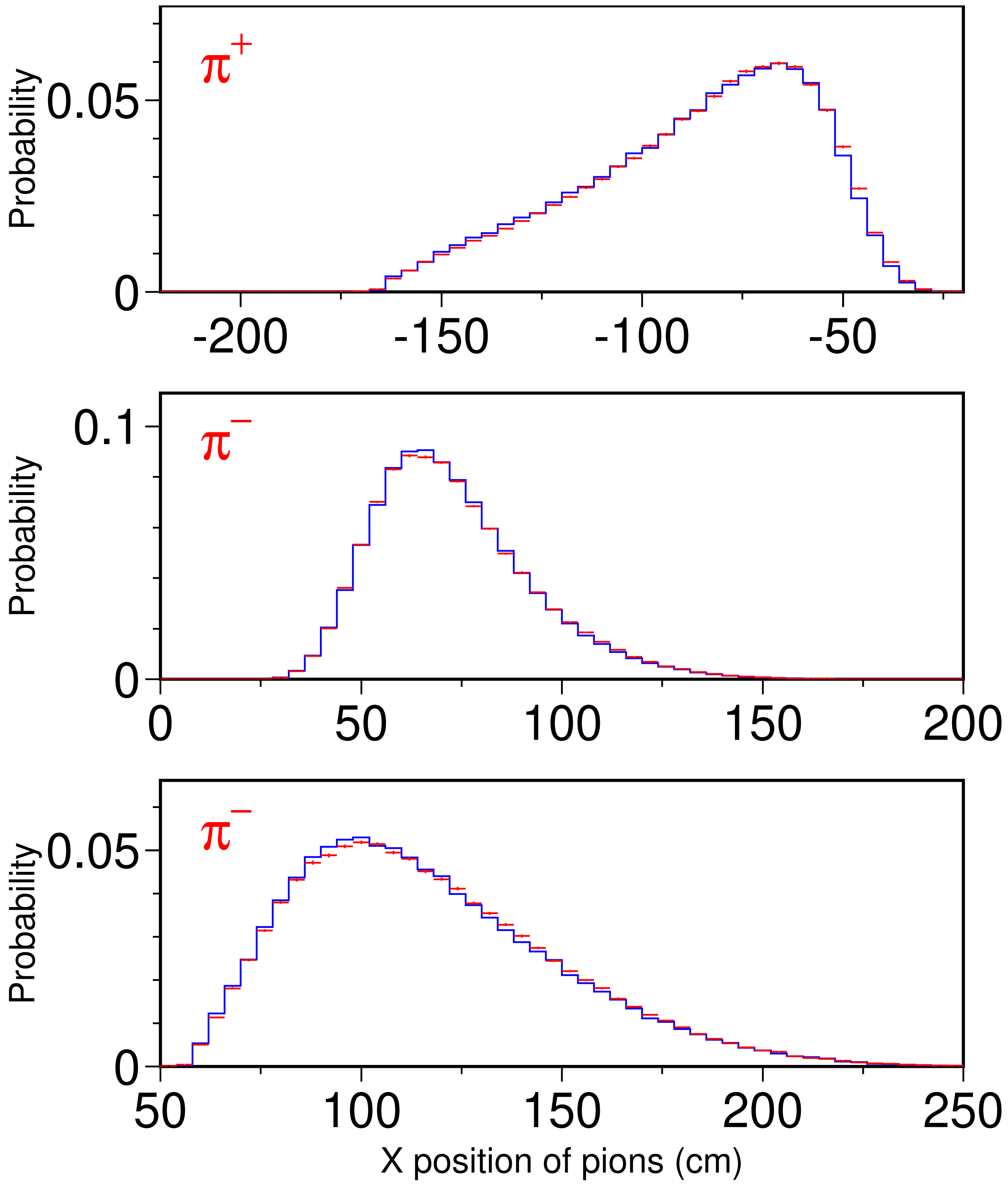
The probability for pion decay in flight : $\sim$ 1%
The probability for pion punch-through : $< 1\%$

Data and MC Comparison



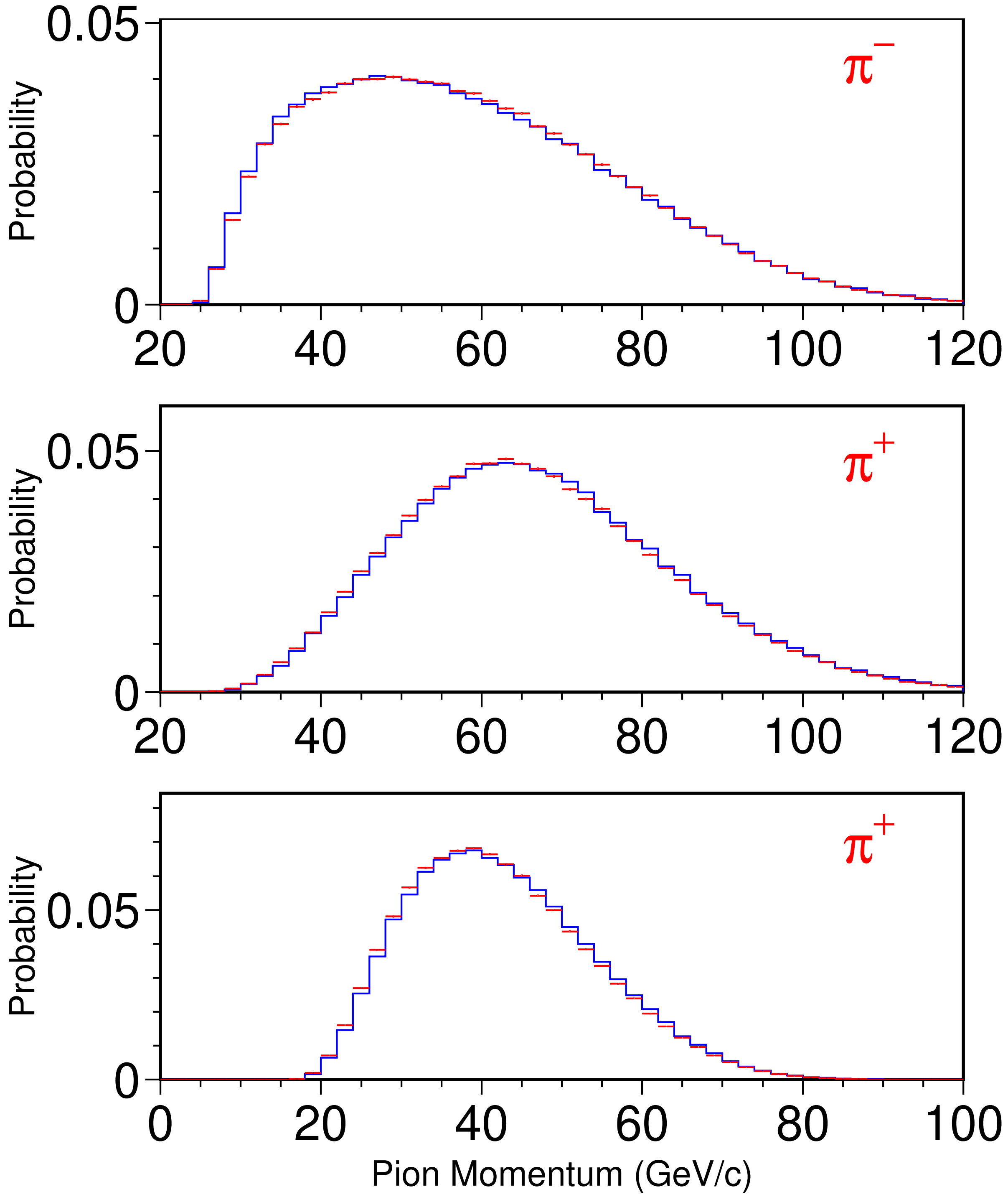
Data and MC Comparison (cont.)

- X-positions for pions at $z = 5431$ cm from $K^- \to \pi^- \pi^- \pi^+$



Data and MC Comparison (cont.)

- Momentum for pions from $K^+ \to \pi^+\pi^+\pi^-$



Summary of Acceptance and Efficiency

acceptance or efficiency	Positive	Negative
$A_{3\pi}$	0.944	0.942
$A_{\pi\mu\mu}$	0.475	0.477
$\epsilon_{3\pi}^{cut}$	0.779	0.760
$\epsilon_{\pi\mu\mu}^{cut}$	0.803	0.783
$\epsilon_{\pi\mu\mu}^{trig}$	0.866	0.866
$\epsilon_{\mu^+\mu^-}$	0.938	0.938

- $A_{3\pi}$ and $A_{\pi\mu\mu}$ are estimated by requiring Left-Right and $\mu^+\mu^-$ trigger, respectively.

The uncertainties for acceptance and efficiency are less than 0.1%

The different efficiencies for K^+ and K^- are due to the different momentum spectra for $K^\pm$ production.

Systematics

- Run by run variation:
  - Beam targeting X and Y position: $\pm$ 0.5 mm
  - Vertical and Horizontal beam targeting angle: $\pm$ 0.5 mrad
  - B-field in collimator and analysis magnet: $\pm$ 0.1%

- Background estimation for Signal mode:
  470 MeV/c^2 $< M_{\pi\mu\mu} <$ 520 MeV/c^2
  475 MeV/c^2 $< M_{\pi\mu\mu} <$ 515 MeV/c^2
  465 MeV/c^2 $< M_{\pi\mu\mu} <$ 525 MeV/c^2

  Background functions: constant and quadratic function

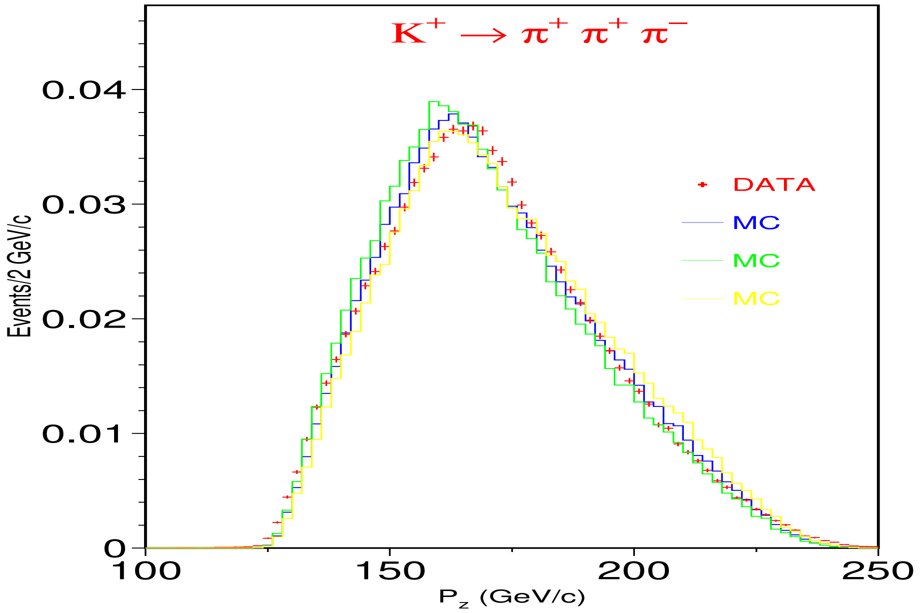
- Background estimation for Normalization mode:
  Vary the uncertainties for background function

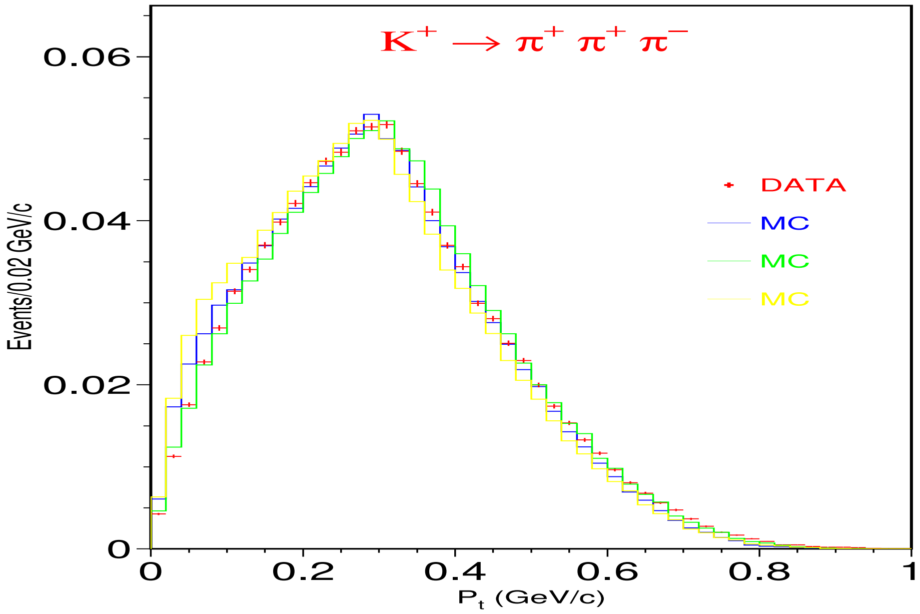
Systematics (cont.)

- Geometric Acceptance:

$$\frac{d^2\sigma}{dx_F dp_t^2} \sim (1 - x_F)^{p_1 + p_2 P_t^2} \exp\left(p_3 p_t^2 + p_4 p_t^4\right)$$

Vary MC input parameters more than 1 σ





Systematics (cont.)

- $B(K^+ \to \pi^+\pi^+\pi^-)$ = (5.59 $\pm$ 0.05)%

- Dalitz decay parameters for $K^\pm \to \pi^\pm\pi^\pm\pi^\mp$ decay:

Decay Parameters	$K^+ \to 3\pi$	$K^- \to 3\pi$
g	-0.2154 $\pm$ 0.0035	-0.217 $\pm$ 0.007
h	0.012 $\pm$ 0.008	0.010 $\pm$ 0.006
k	-0.0101 $\pm$ 0.0034	-0.0084 $\pm$ 0.0019

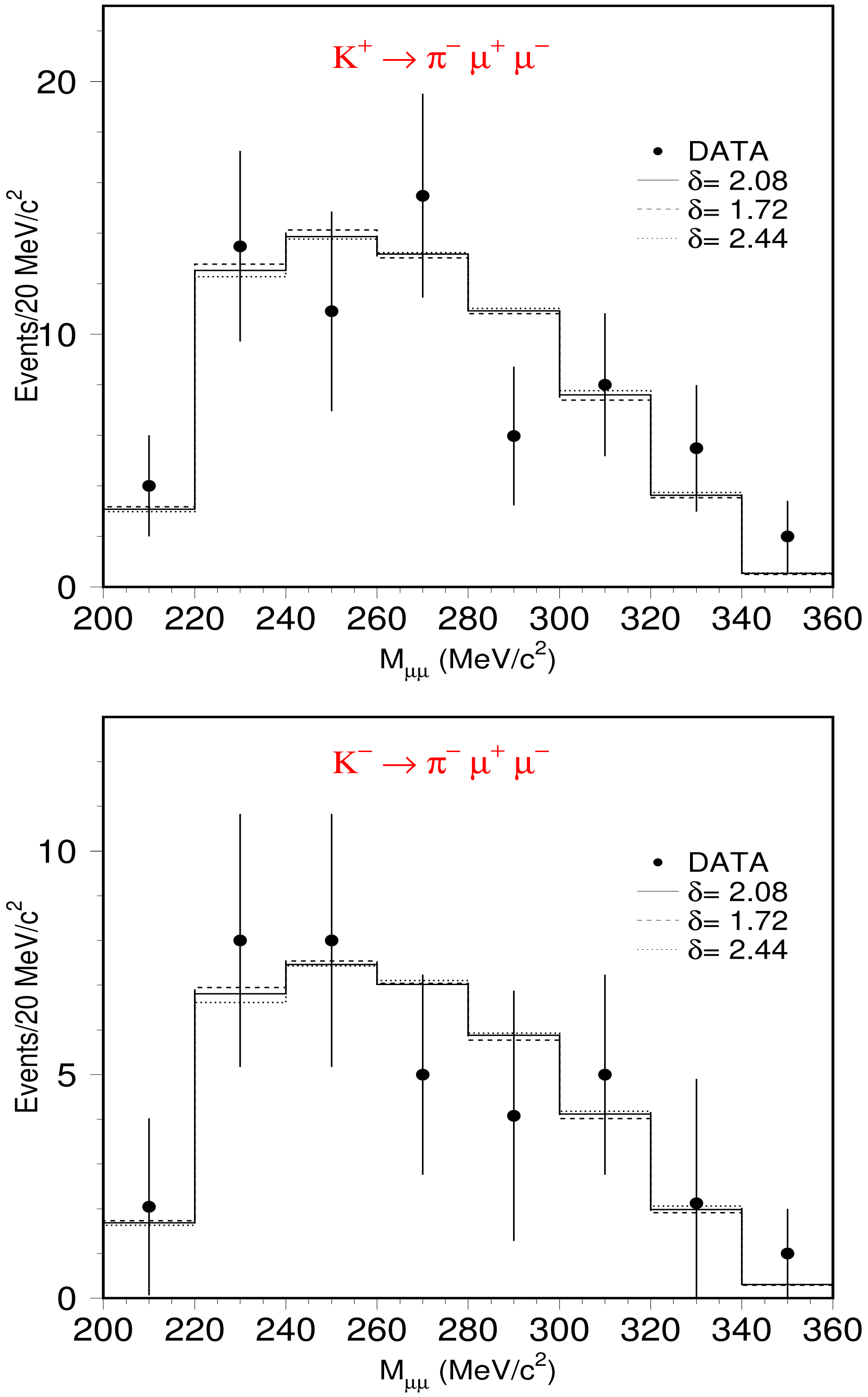
- Slope parameter δ in form factor for $K^+ \to \pi^+\mu^+\mu^-$ decay:

$$\delta = 2.08 \pm 0.12$$

Vary the slope parameter δ by 3 σ

Systematics (cont.)

- Dimuon invariant mass distribution



No evidence for $K^\pm \to \pi^\pm X, \quad X \to \mu^+\mu^-$

Summary of Systematics

Source	σ_B/B (%,+)	σ_B/B (%,−)	Combined (%)
Beam targeting	1.1	0.9	1.0
Magnetic field	0.5	0.4	0.5
Trigger efficiency	3.1	3.1	3.1
Muon identification	0.3	0.3	0.3
Background Est. ($K^{\pm}_{\pi 3}$)	0.2	0.3	0.2
Background Est. ($K^{\pm}_{\pi\mu\mu}$)	2.4	6.4	3.6
Acceptance	0.4	0.4	0.4
Dalitz parameter	0.3	0.3	0.3
Slope parameter (δ)	0.2	0.3	0.2
$B(K^+ \to \pi^+\pi^+\pi^-)$	0.9	0.9	0.9
Total	4.2	7.3	5.0

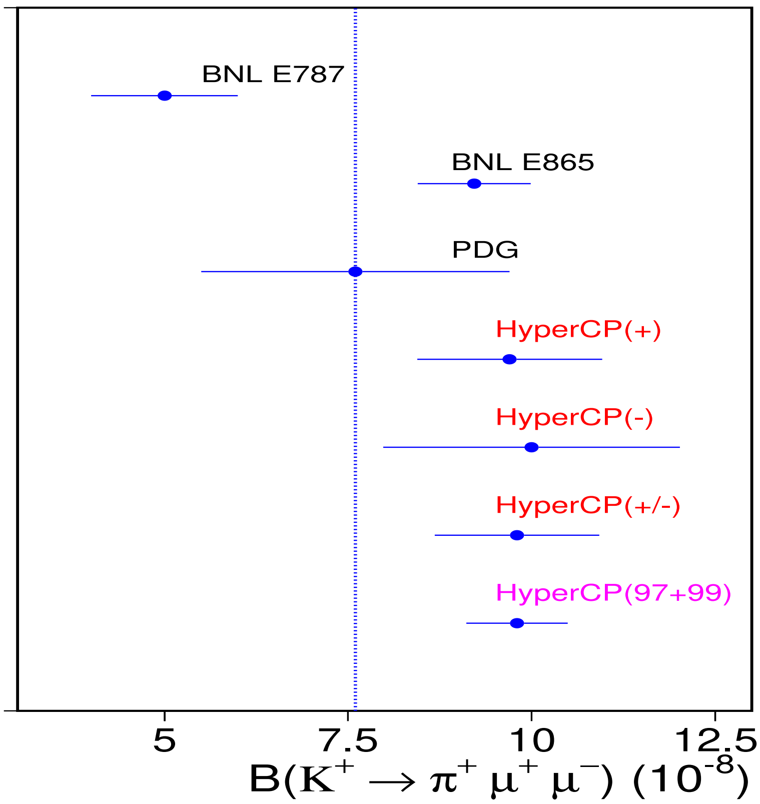
Results

- Based on the 1997 data, we obtained

$$B(K^+ \to \pi^+\mu^+\mu^-) = (9.7 \pm 1.2 \pm 0.4) \times 10^{-8}$$
$$B(K^- \to \pi^-\mu^+\mu^-) = (10.0 \pm 1.9 \pm 0.7) \times 10^{-8}$$

Combined result:

$$B(K^\pm \to \pi^\pm\mu^\pm\mu^\mp) = (9.8 \pm 1.0 \pm 0.5) \times 10^{-8}$$

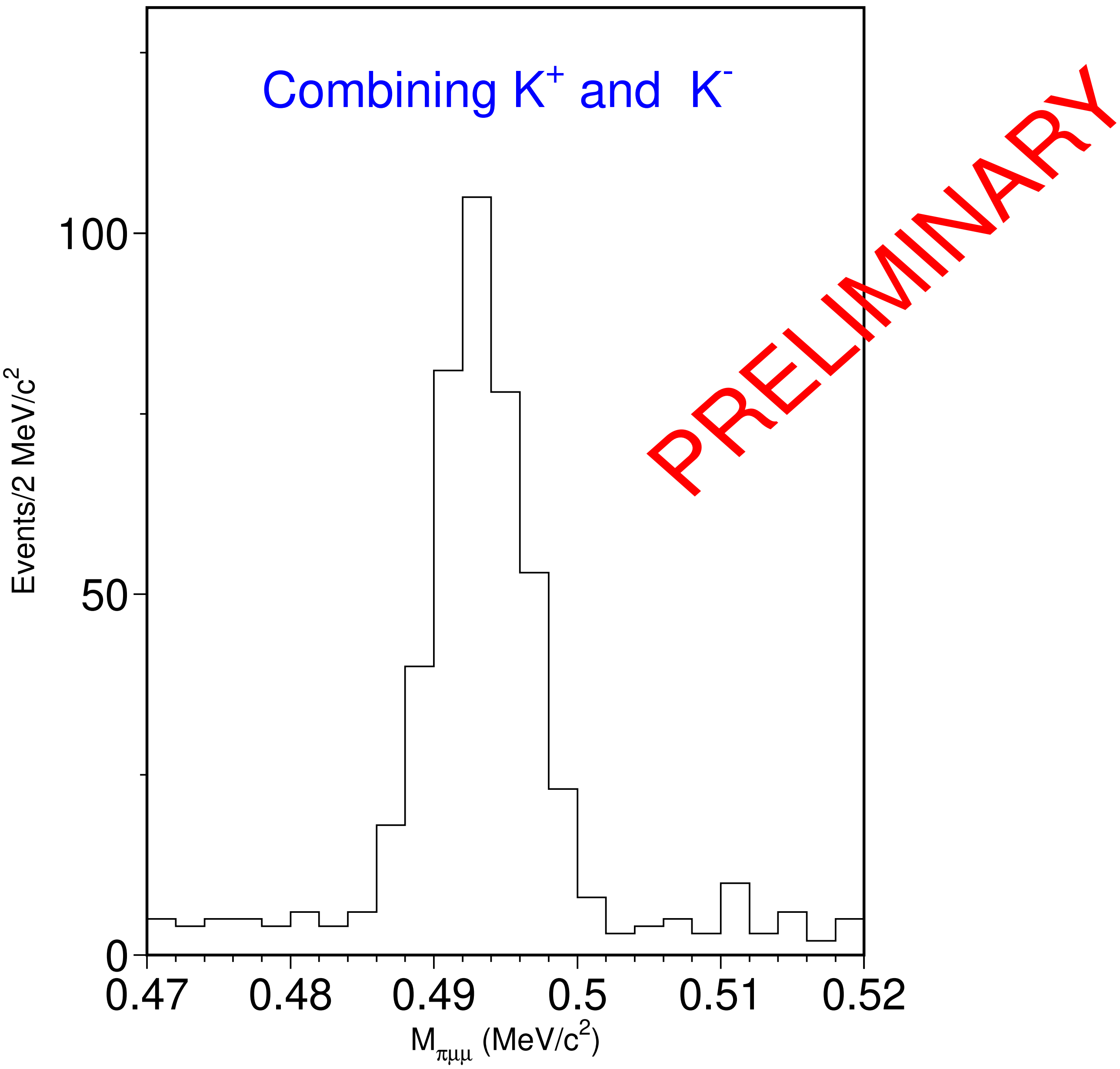


- Measured CP asymmetry:

$$\Delta = \frac{B(K^+ \to \pi^+\mu^+\mu^-) - B(K^- \to \pi^-\mu^+\mu^-)}{B(K^+ \to \pi^+\mu^+\mu^-) + B(K^- \to \pi^-\mu^+\mu^-)}$$
$$= -0.02 \pm 0.11 \pm 0.04$$

Prospect for ’99 data

- Based on the full ’99 data



- Statistical error for ’99 run expect to be reduced by a factor of two.
- ’99 and ’97 run have different systematics.

Summary

- HyperCP had successful 1997 and 1999 runs and has collected the largest sample of fully-reconstructed hyperon and charged kaon decays in the world.

- We observed $K^- \to \pi^- \mu^+ \mu^-$ decays for the first time.

- Based on 1997 data, the measured $B(K^\pm \to \pi^\pm \mu^\pm \mu^\mp)$ is in good agreement with the result of BNL E865.

- The measured CP asymmetry for $K^\pm \to \pi^\pm \mu^\pm \mu^\mp$ is consistent with no CP violation for this mode.

- A rich program of hyperon and charged kaon physics is in progress.