FCNC Kaon Decays from *HyperCP*: $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$

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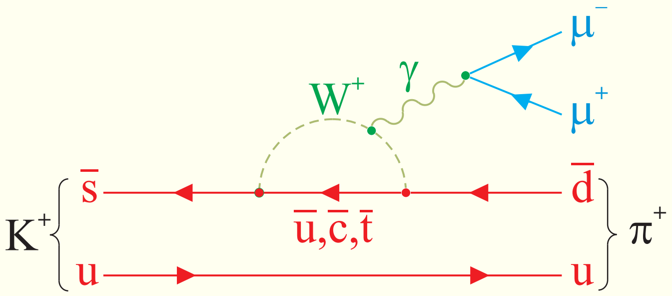
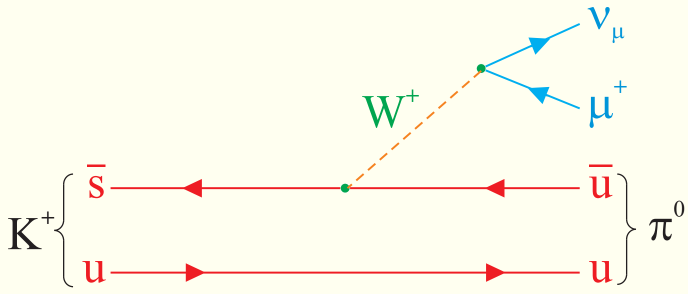
Why Study $K^{\pm} \rightarrow \pi^{\pm} l^{+} l^{-}$ Decays?

- FCNC Decay: no tree-level diagrams.



$K^+ \rightarrow \pi^+ \mu^+ \mu^-$

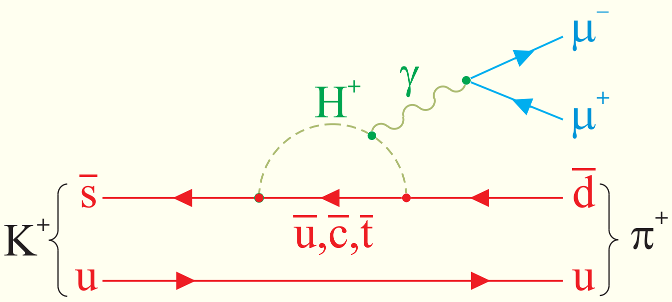


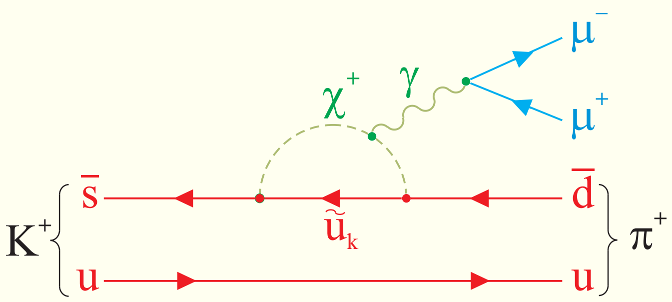
$K^+ \rightarrow \pi^\circ \mu^+ \nu_\mu$

- Highly suppressed by GIM mechanism:

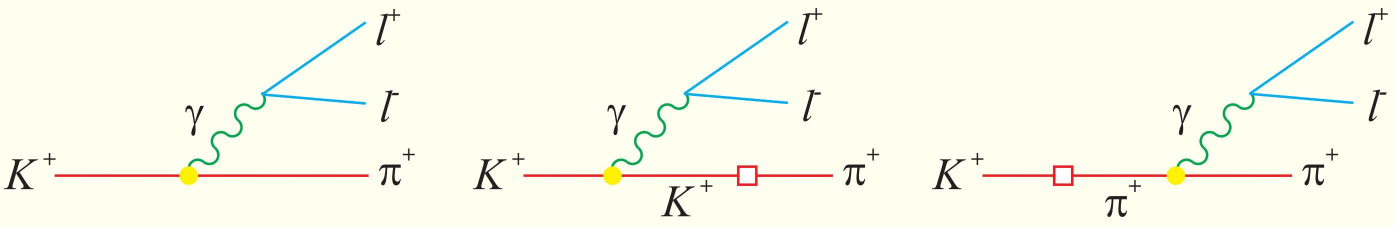
$$\frac{\Gamma(K^+ \rightarrow \pi^+ \mu^+ \mu^-)}{\Gamma(K^+ \rightarrow \pi^\circ \mu^+ \nu_\mu)} \approx 2.4 \times 10^{-6} \qquad (G_F^2 \alpha^2 / G_F^2 \approx 10^{-4})$$

$\Rightarrow$ Hence sensitive to New Physics





Decay is Dominated by Long-Distance Effects



EW Penguin Long Distance Terms

- Chiral Perturbation Theory used for systematic calcuations of long-distance hadronic effects.
- The rate and di-lepton invariant mass spectra of $K^+ \rightarrow \pi^+ l^+ l^-$ are described in terms of two parameters: a_+ and b_+ in a recent $\mathcal{O}(p^6)$ ChPT calculation (D'Ambrosio, Ecker, Isidori, Portolés).
- A "model independent" calculation of the ratio of rates gives:

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

Experimental Problems

- $\mathrm{BR}(K^+ \to \pi^+ e^+ e^-)$ well measured:

$$
\begin{array}{ll}
(2.6 \pm 0.5) & \times 10^{-7}\ \text{(CERN)} \\
(2.75 \pm 0.23 \pm 0.13) & \times 10^{-7}\ \text{(BNL-777)} \\
(2.94 \pm 0.05 \pm 0.13 \pm 0.05) & \times 10^{-7}\ \text{(BNL-865)} \\
(2.88 \pm 0.13) & \times 10^{-7}\ \text{(PDG)}
\end{array}
$$

- $\mathrm{BR}(K^+ \to \pi^+ \mu^+ \mu^-)$ not so well measured!

$$
\begin{array}{lll}
(5.0 \pm 0.4 \pm 0.7 \pm 0.6) & \times 10^{-8} & \text{BNL-787} \\
(9.22 \pm 0.60 \pm 0.49) & \times 10^{-8} & \text{BNL-865}
\end{array}
$$

$\Rightarrow 3.3\sigma$ discrepancy!

- The BNL-E787 result on R is too low:

$$
\begin{array}{ll}
R = 0.17 \pm 0.03 & \text{BNL-787} \\
R = 0.32 \pm 0.03 & \text{BNL-865}
\end{array}
$$

- Another measurement is needed to resolve these discrepancies.

HyperCP vs BNL Experiments

Experiment	Kaon Beam	Events	Normalization
BNL-E787	800 MeV/c stoppped K^+	10.6 ± 4.7 (3-trk) 196.0 ± 16.7 (2-trk)	$K^+ \to \mu^+\nu$
BNL-865	6 GeV/c K^+	430 ± 28	$K^+ \to \pi^+\pi^+\pi^-$
HyperCP	120–250 GeV/c K^+,K^-	stay tuned	$K^\pm \to \pi^\pm\pi^+\pi^-$

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

The *HyperCP* Collaboration

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HyperCP Physics Goals

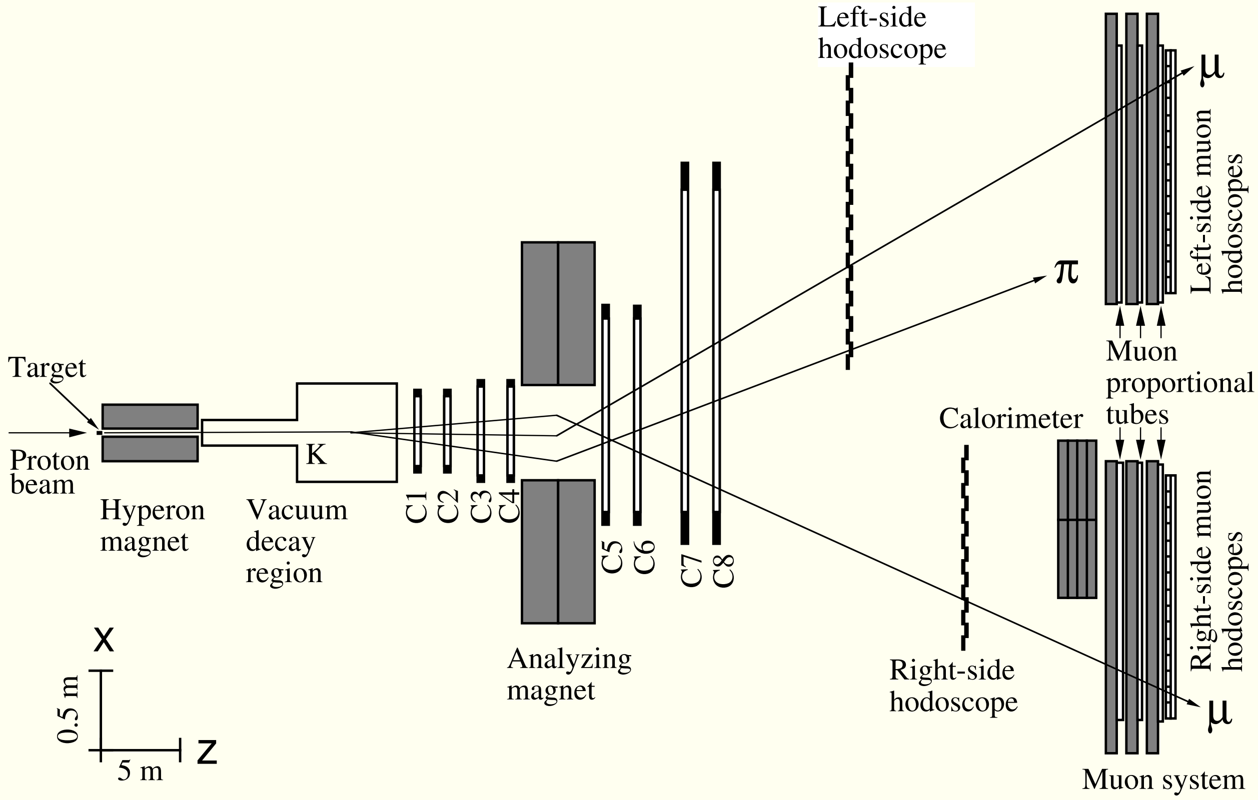
Primary Goal:

- A search for direct CP violation in $\Xi^- \to \Lambda\pi^-$, $\Lambda \to \mathrm{p}\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+$, $\overline{\Lambda} \to \overline{p}\pi^+$ decays.

Secondary Goals:

- Search for CP violation in $\mathrm{K}^\pm \to 3\pi$ decays.
- Search for rare and forbidden hyperon and charged kaon decays:
  - Lepton number nonconservation in kaon and hyperon decays: $\Xi^- \to p\mu^-\mu^-$, $\Sigma^- \to p\mu^-\mu^-$, $K^+ \to \pi^-\mu^+\mu^+$.
  - Flavor changing neutral currents in hyperon and charged kaon decays: $\Sigma^+ \to p\mu^+\mu^-$, $K^\pm \to \pi^\pm\mu^+\mu^-$.
  - $\Delta S = 2$ decays: $\Xi^- \to p\pi^-\pi^-$, $\Omega^- \to \Lambda\pi^-$, $\Omega^- \to pK^-\pi^-$.
- Measure various hyperon production and decay properties:
  - $\Xi^-(\overline{\Xi}^+)$ and $\Omega^-(\overline{\Omega}^+)$ polarization.
  - β decay parameter in Ξ^- decays.
  - α decay parameter in $\Omega^\pm \to \Lambda K^\pm$ decays.
  - Hyperon production cross sections.

The *HyperCP* Spectrometer



- 800-GeV/c proton beam on $2{\times}2$ mm^2 target: 13 MHz channeled beam.
- High-rate magnetic spectrometer: 8 fast, narrow-pitch wire chambers.
- Very high-rate DAQ: 50-80 KHz evts/spill-s to tape.
- Muon system for rare and forbidden hyperon and kaon decays:
  - Two stations on left and right side.
  - Three layers of 80-cm thick steel.
  - Three layers of xy measuring proportional tubes.
  - Hodoscopes at rear for triggering.
  - $\mu^+\mu^-$ trigger: coincidence of muon hodoscopes with Left-Right trigger.

HyperCP Data Set Enormous!

- In a year of data taking we recorded the largest data sample ever by a particle physics experiment: 231 billion events, 29,401 tapes, and 120 TB data.
- Data volume compared to other, much larger experiments: [1]

Parameters	Aleph	Babar	*HyperCP*	CDF	CMS
Event Size (KB)	250	50	0.5	250	1000
Events/yr (10^9)	0.004	2	240	2	2
Data/yr (TB)	1	100	120	450	2000
Manpower	300	500	42	600	2000

- Note:
  - One copy of the Encyclopaedia Britannica: 1 GB.
  - The World Wide Web as of September 11, 2001: 5 TB.
  - A video store (5,000 videos): 8 TB.
  - The Library of Congress (not counting pictures): 20 TB.
  - The Internet Archive (from 1996 to October 2001): 100 TB.
  - It would take 576 years to download all this data at 56 kbaud.

[1] E. Augé, EPS HEP 2001.

HyperCP Yields

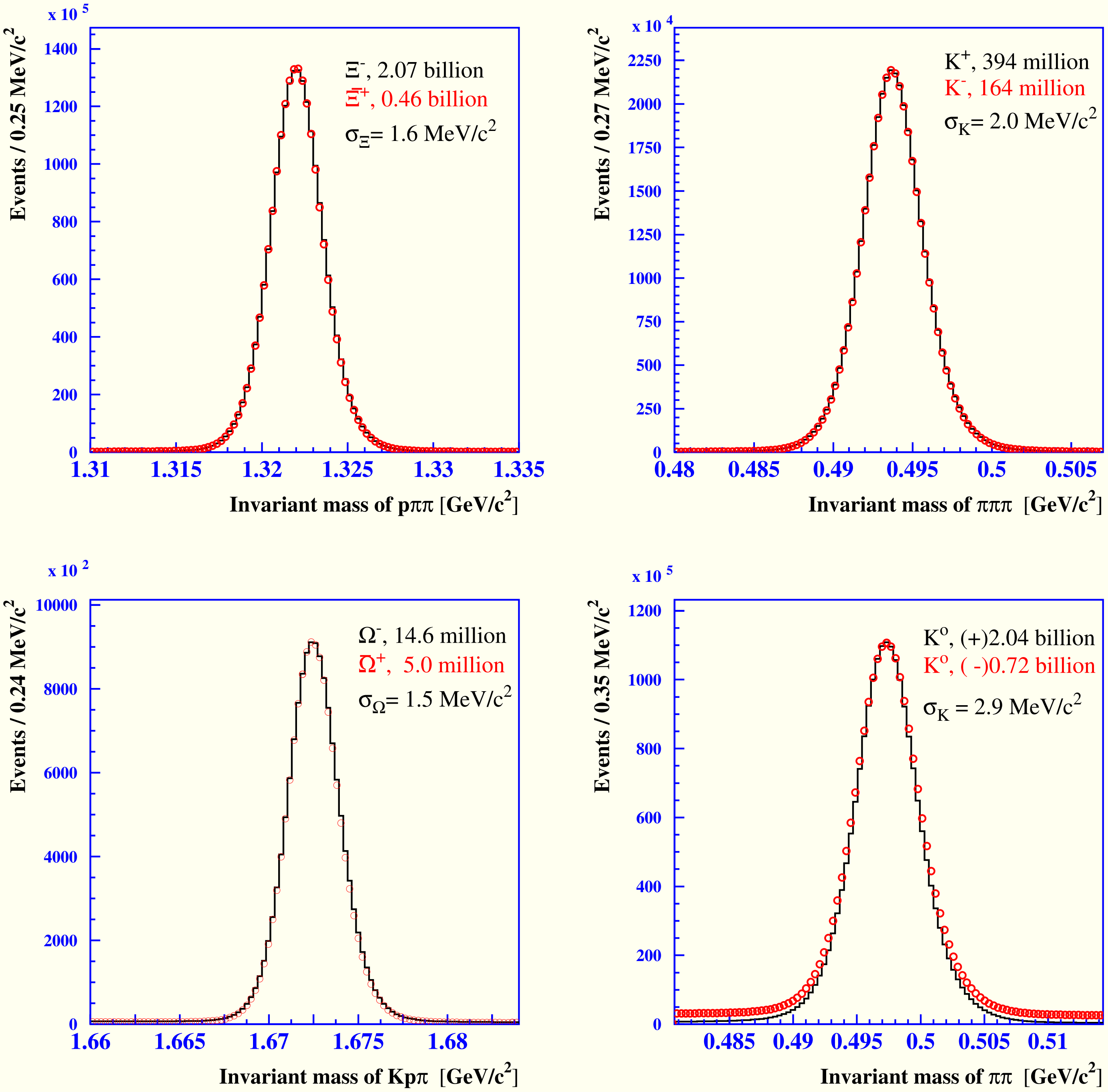
- In a year of data taking we recorded the largest data sample ever by a particle physics experiment: 231 billion events, 29,401 tapes, and 119.5 TB data.

Events			
Trigger	Year 1997	Year 1999	Total
Cascade	39×10^9	81×10^9	120×10^9
All	58×10^9	173×10^9	231×10^9

Number of Reconstructed Events			
Type	Channeled beam polarity $+$	Channeled beam polarity $-$	Total
$\Xi \to \Lambda\pi$	458×10^6	$2\,032 \times 10^6$	$2\,490 \times 10^6$
$K \to \pi\pi\pi$	391×10^6	164×10^6	555×10^6
$\Omega \to \Lambda K$	4.9×10^6	14.1×10^6	19.0×10^6

- Largest sample of fully reconstructed $\Xi^\pm$, $K^\pm$, and $\Omega^\pm$ decays.

Masses from the Farm Analysis



Measuring the $K^\pm \to \pi^\pm\mu^+\mu^-$ Branching Ratio

- Use $K^\pm \to \pi^\pm\pi^+\pi^-$ for normalization.
- Simply a counting experiment with a few acceptances and efficiencies thrown in:

$$B(K \to \pi\mu^+\mu^-) = \frac{1}{200}\frac{N^{obs}_{\pi\mu\mu}}{N^{obs}_{3\pi}}\frac{A_{3\pi}}{A_{\pi\mu\mu}}\frac{\epsilon^{trig}_{3\pi}}{\epsilon^{trig}_{\pi\mu\mu}}\frac{\epsilon^{cut}_{3\pi}}{\epsilon^{cut}_{\pi\mu\mu}}\frac{B(K \to 3\pi)}{\epsilon^{\mu^+\mu^-}}$$

where:

$$\begin{aligned}
N^{obs} &= \text{number of observed events}\\
A &= \text{geometric acceptance}\\
\epsilon^{trig} &= \text{trigger efficiency}\\
\epsilon^{cut} &= \text{event selection efficiency}\\
\epsilon^{\mu^+\mu^-} &= \text{efficiency in identifying } \mu^+\mu^-\\
B(K^\pm_{\pi 3}) &= \mathrm{B}(K^\pm \to \pi^\pm\pi^+\pi^-) = (5.59 \pm 0.05)\%
\end{aligned}$$

- Note: acceptances and efficiencies all high!

Acceptances and Efficiencies

	Positive	Negative
$A_{3\pi}$	0.944	0.942
$A_{\pi\mu\mu}$	0.475	0.477
$\epsilon^{cut}_{3\pi}$	0.779	0.760
$\epsilon^{cut}_{\pi\mu\mu}$	0.803	0.783
$\epsilon^{trig}_{\pi\mu\mu}/\epsilon^{trig}_{3\pi}$	0.866	0.866
$\epsilon^{\mu^+\mu^-}$	0.938	0.938

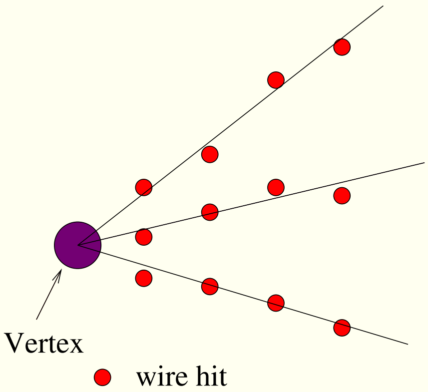
Note:

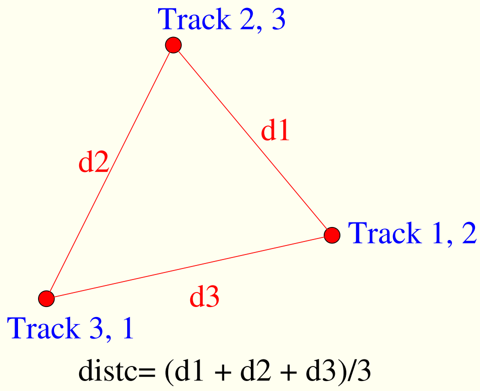
- Acceptances and efficiencies all large!
- The different acceptances and efficiencies for K^+ and K^- are due to the different momentum spectra for $K^\pm$ production.

Event Selection Cuts

Cuts common to signal and normalization samples:

- Three-track topology: two SS and one OS tracks.
- Target pointing: $\pm 5\,\mathrm{mm}$ in x and y.
- Decay vertex: within vacuum decay region.
- Decay consistent with single vertex:
  1) Good fit: $\chi^2/ndf \;<\; 2.5$.
  2) Small lateral separation at z_{vertex}: $distc \;<\; 2\,\mathrm{mm}$.

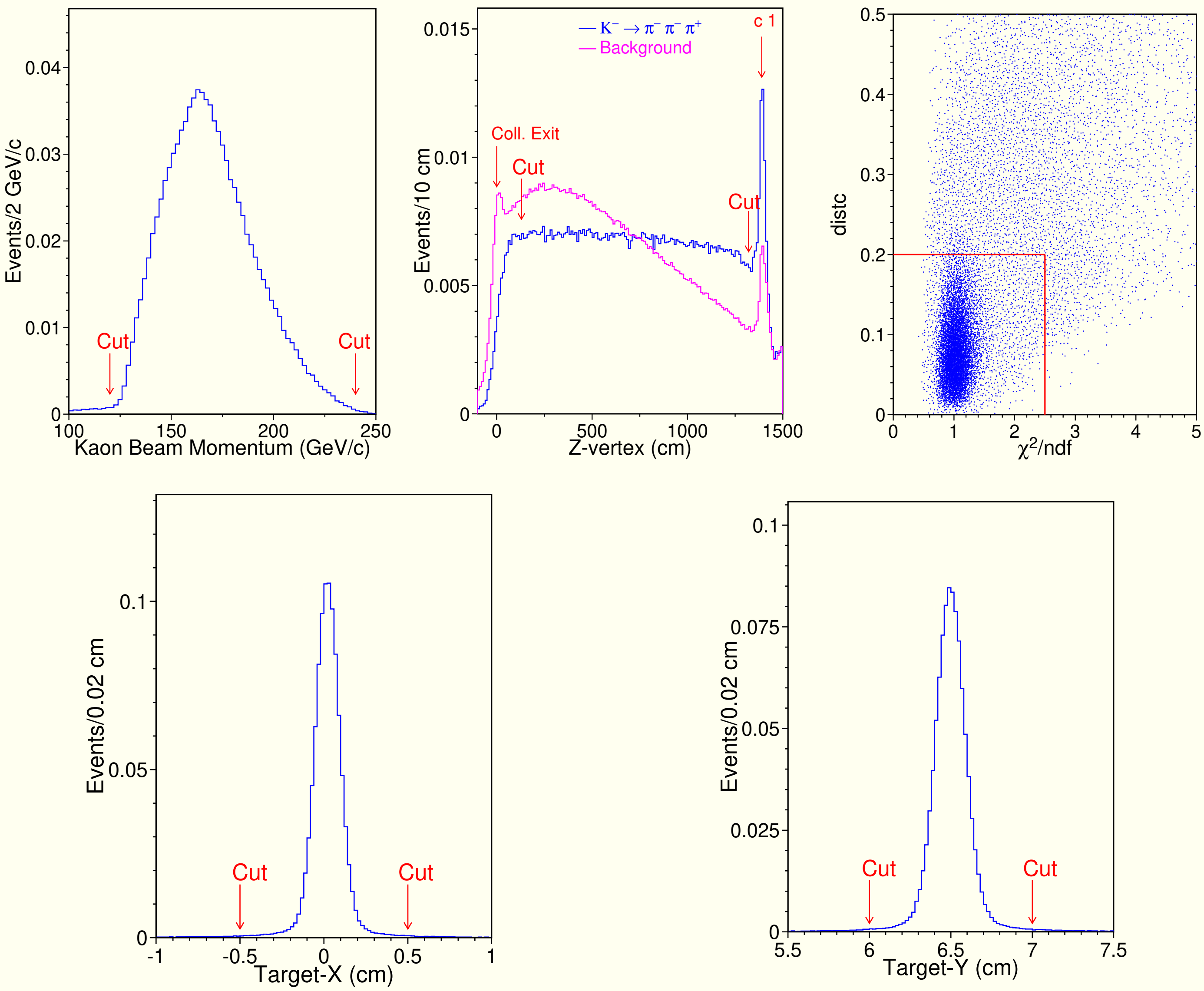




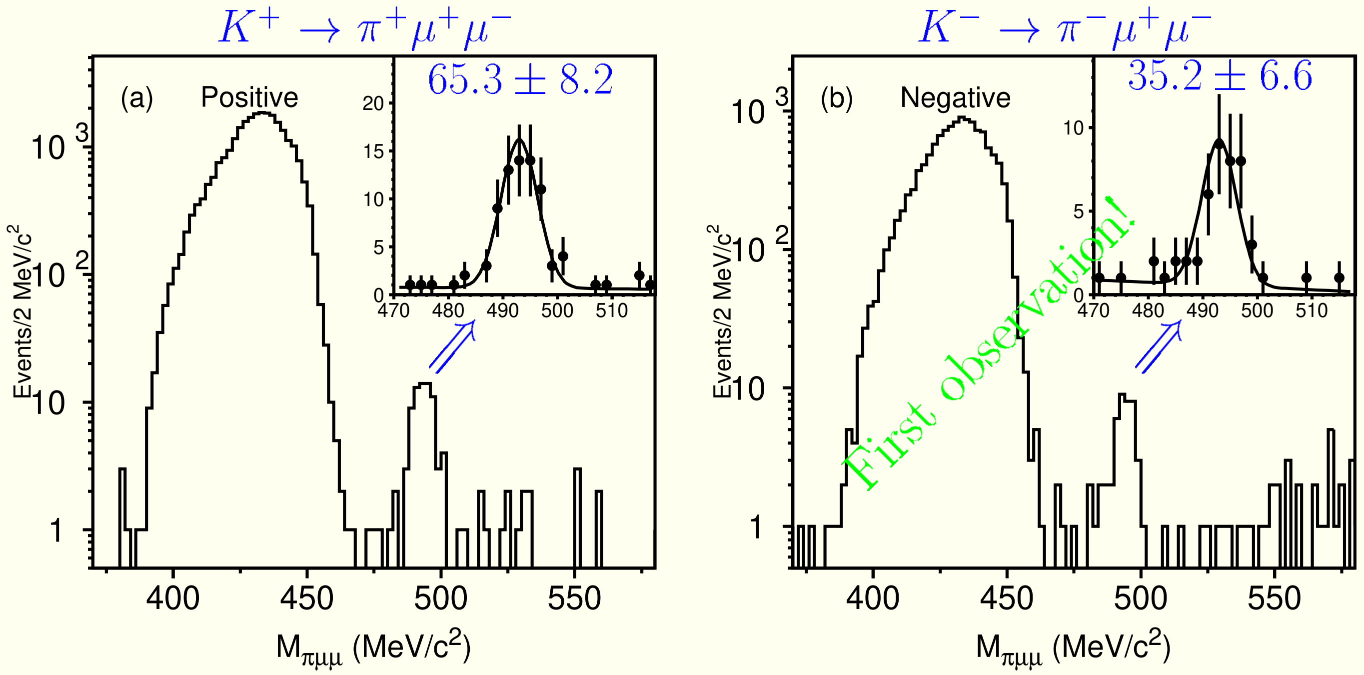
Cuts applied to just signal events — muon identification:

- Hits in 2/3 muon chambers in both x and y.
- Correlated in-time hits in muon hodoscopes.

Event Selection Cuts

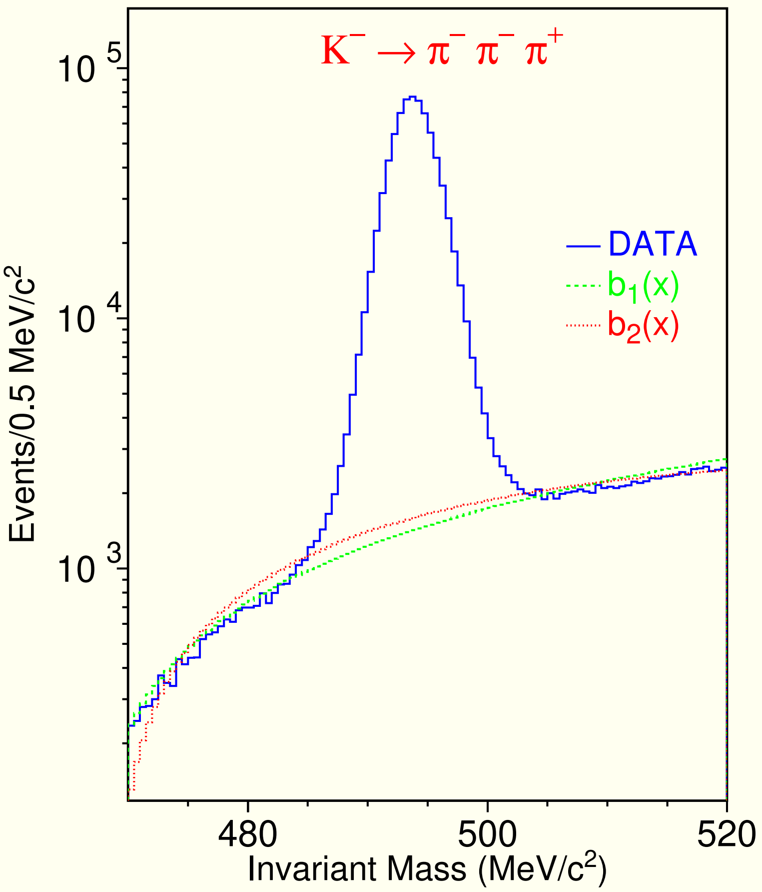


Estimating the Number of $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ Events



- Signal is clean with minimum of cuts.
- Large peak to the left of the signal is from $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays reconstructed with the $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ hypothesis.
- First observation of $K^{-} \to \pi^{-}\mu^{+}\mu^{-}$!

Estimating the Number of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ Events



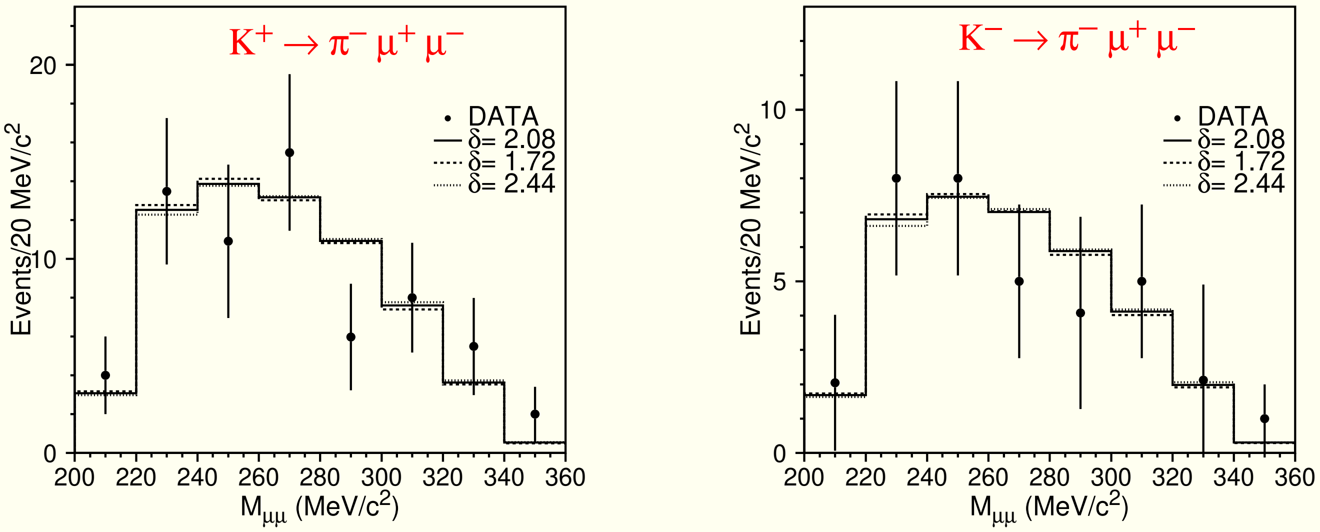
- Try linear and quadratic fits to the background in the side-bands:

$$b_1(m) = c_1 + c_2 m$$
$$b_2(m) = c_1 + c_2 m + c_3 m^2$$

- Estimated number of events in the 1997 run:

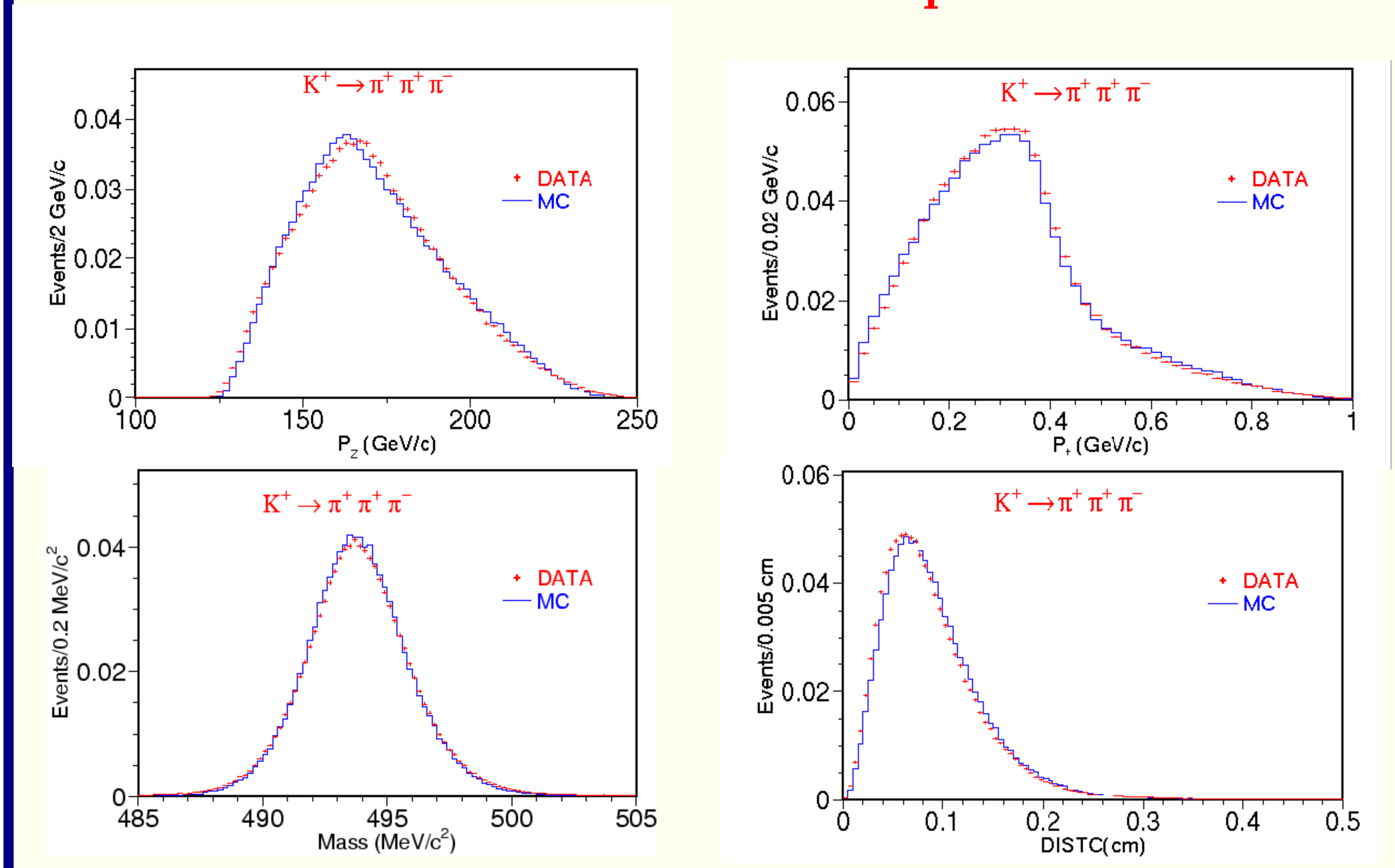
$$N(K^{+} \to \pi^{+}\pi^{+}\pi^{-}) = (4.446 \pm 0.010)\times 10^5$$
$$N(K^{-} \to \pi^{-}\pi^{+}\pi^{-}) = (2.318 \pm 0.008)\times 10^5$$

$K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ Monte Carlo



- Assume a vector interaction, based on BNL-865 $K^+ \to \pi^+ e^+ e^-$ results.
- Use the well-measured $K^+ \to \pi^+ e^+ e^-$ form factor slope parameter in Monte Carlo: $\phi(q^2/M_K^2) = c(1 + \delta\frac{q^2}{M_K^2})$.
- Acceptance is quite uniform: BR not sensitive to value of slope parameter.

Monte Carlo Data Comparison



Summary of Systematic Errors

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 Estimation ($K^{\pm}_{\pi 3}$)	0.2	0.3	0.2
Background Estimation ($K^{\pm}_{\pi\mu\mu}$)	2.4	6.4	3.6
Data and MC disagreement	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

The systematic error is less than the statistical error and is dominated by:

1. Uncertainty in the relative trigger efficiency.
2. Background to the $K^{\pm} \to \pi^{\mp}\mu^+\mu^-$ peak.

HyperCP $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ **Results**

- Separate branching ratios:

$$B(K^{+} \to \pi^{+}\mu^{+}\mu^{-}) = [9.7 \pm 1.2(\mathrm{stat}) \pm 0.4(\mathrm{syst})] \times 10^{-8}$$

$$B(K^{-} \to \pi^{-}\mu^{+}\mu^{-}) = [10.0 \pm 1.9(\mathrm{stat}) \pm 0.7(\mathrm{syst})] \times 10^{-8}$$

- Combined result:

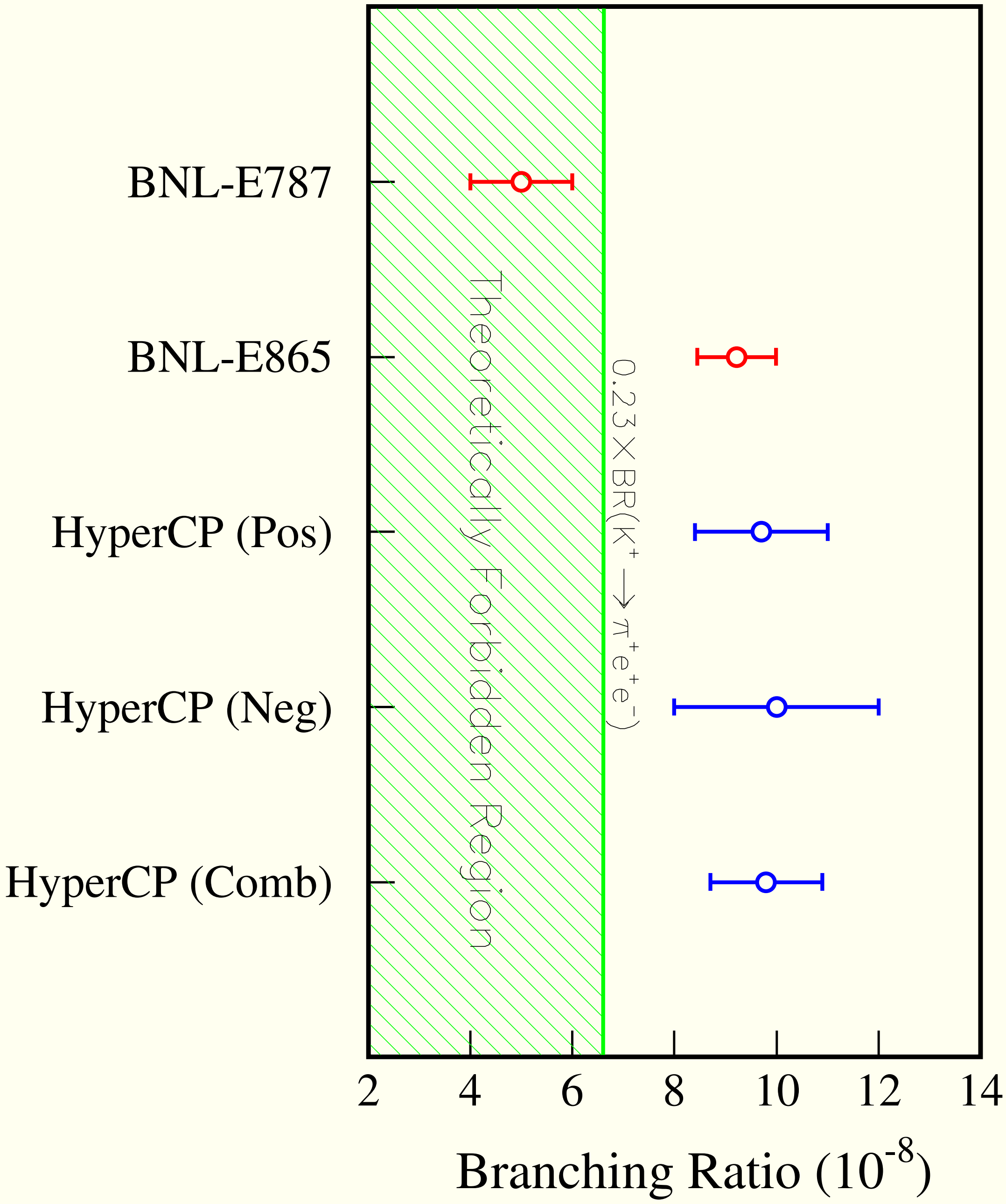
$$\boxed{B(K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}) = (9.8 \pm 1.0 \pm 0.5) \times 10^{-8}}$$

- CP asymmetry:

$$\begin{aligned} \Delta(K^{\pm}_{\pi\mu\mu}) &= \frac{\Gamma(K^{+}_{\pi\mu\mu}) - \Gamma(K^{-}_{\pi\mu\mu})}{\Gamma(K^{+}_{\pi\mu\mu}) + \Gamma(K^{-}_{\pi\mu\mu})} \\ &= -0.02 \pm 0.11(\mathrm{stat}) \pm 0.04(\mathrm{syst}) \end{aligned}$$

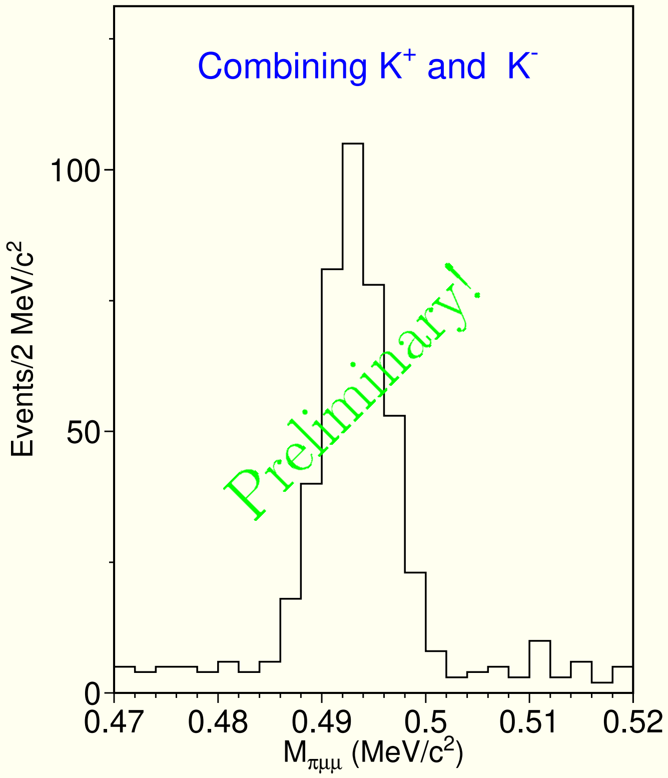
- Our result is consistent with the Chiral Perturbation theory calculation of $R = (K^{+} \to \pi^{+}\mu^{+}\mu^{-})/(K^{+} \to \pi^{+}e^{+}e^{-})$.
- Reference: Phys. Rev. Lett **88** (2002) 111801.

Summary of Experimental Results on $\mathbf{BR}(K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-})$



There is More to Come!

- The 1999 data set has four times the statistics.
- Systematics are different from 1997 run: different MC, analysis code, trigger, tracking program, people.



- CKM at Fermilab will accumulate about 100,000 $K^+ \to \pi^+ e^+ e^-$ and 100,000 $K^+ \to \pi^+ \mu^+ \mu^-$ decays by the end of the decade, allowing R to be measured to 2–3% precision and hence testing ChPT predictions to the 10% level.

Main Goal of CKM is $K^+ \to \pi^+ \nu \overline{\nu}$

- Goal: Measure the CKM matrix element $|V_{\rm td}|$ with an overall precision of 10% through a measurement of the branching ratio: $K^+ \to \pi^- \nu \overline{\nu}$.
- Goal: Overconstrain the CKM matrix; only four accessible measurements have sufficient theoretical robustness that a contradiction could call the Standard Model into question:

$K^+ \to \pi^+ \nu \overline{\nu}$	:	BNL787/949, CKM
$K^\circ \to \pi^\circ \nu \overline{\nu}$	:	KOPIO, JHF
$B_d \to {\rm J}/\psi K_{\rm S}$	:	Babar, Belle, CDF, D0, LHCb, Atlas, CMS, BTeV
$\Delta M_d / \Delta M_s$	:	CDF, D0, LHCb, Atlas, CMS, BTeV