

Study of the decay $K^+ \rightarrow p^+ \pi^-$

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Pushkinskie gory, 25 May 2004

Outline

- $K_L \rightarrow p^0 \bar{m} m$ and $K^+ \rightarrow p^+ \bar{m} m$ in and beyond the SM
- measurement of $K^+ \rightarrow p^+ \bar{m} m$
- new $K^+ \rightarrow p^+ \bar{m} m$ result
- conclusion

CKM matrix

K and B decays as a test of the SM and CP-violation in the SM

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_1 & +s_1c_3 & +s_1s_3 \\ -s_1c_2 & c_1c_2c_3 - s_2s_3e^{i\delta} & c_1c_2s_3 + s_2c_3e^{i\delta} \\ -s_1s_2 & c_1s_2c_3 + c_2s_3e^{i\delta} & c_1s_2s_3 - c_2c_3e^{i\delta} \end{pmatrix}$$

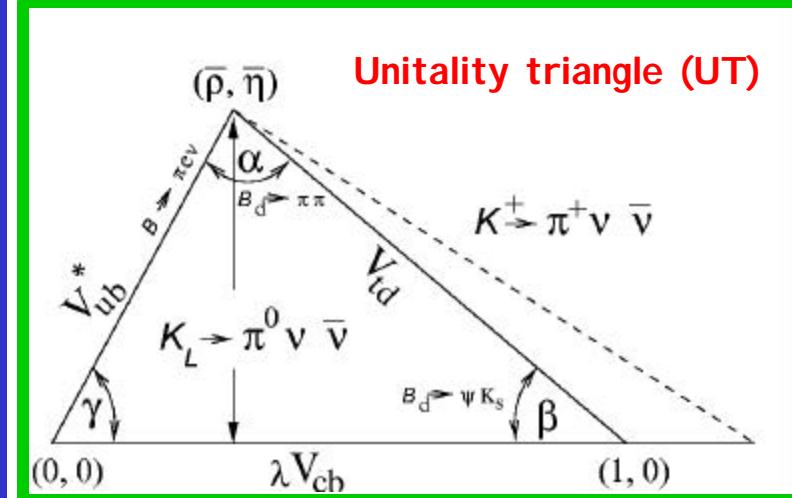
$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \equiv \bar{\rho} + i\bar{\eta}$$

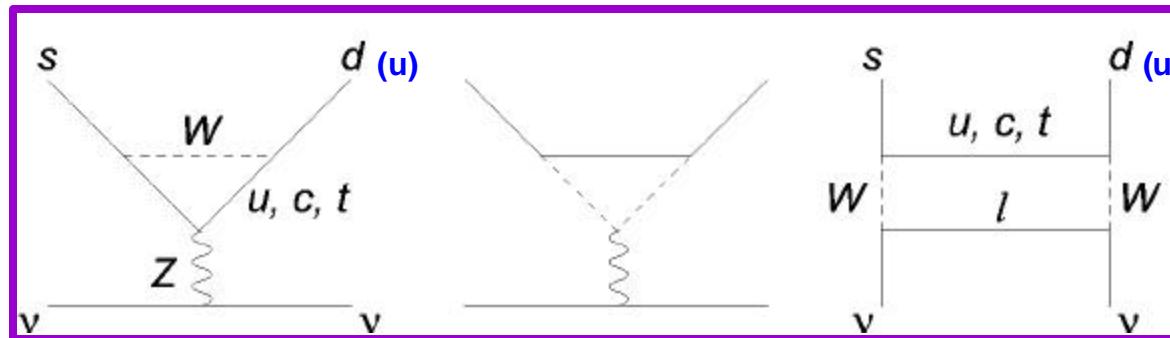
$$\bar{\rho} \simeq \rho(1 - \lambda^2/2) \text{ and } \bar{\eta} \simeq \eta(1 - \lambda^2/2)$$

b - CP violating parameter



K_L ® p⁰nn and K⁺ ® p⁺nn in SM

Flavor – changing neutral current decays



● $\text{Br}(K_L \rightarrow p^0 nn) \sim \text{Im}(V_{td} V_{ts}^*)^2 @ 1.8 \cdot 10^{-10} h^2 A^4 X^2(x_t) \mu h^2$

$\text{Br}(K^+ \rightarrow p^+ nn) \sim S_{e, mu} |V_{cd} V_{cs}^* X_{NL}^l + V_{td} V_{ts}^* X^2(x_t)|^2 \mu [(r_0 - r)^2 + h^2]$

From isospin symmetry

$\text{Br}(K_L \rightarrow p^0 nn) \approx 4.4 \text{Br}(K^+ \rightarrow p^+ nn) \approx 2 \times 10^{-9}$

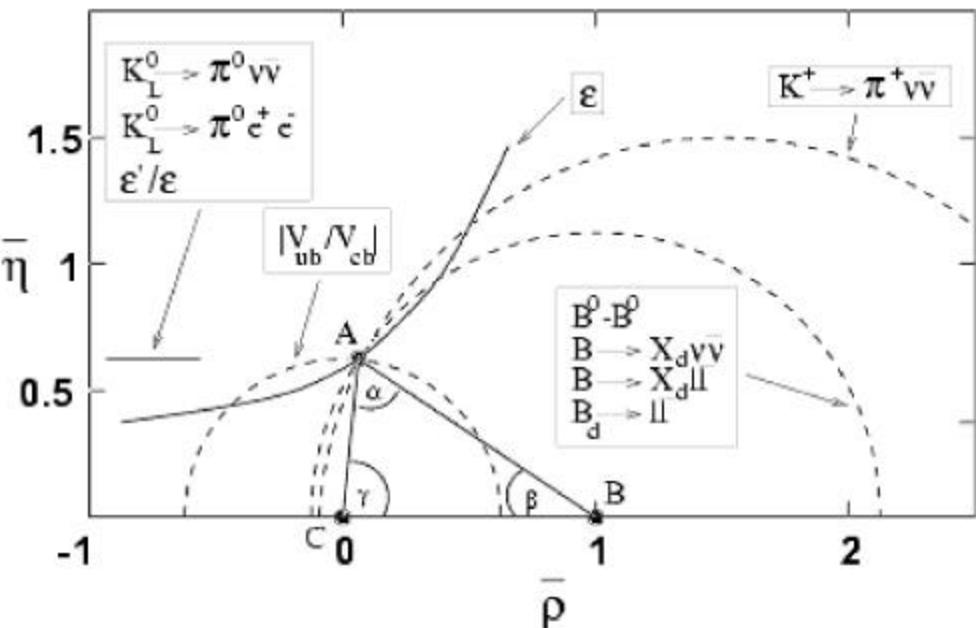
Theory SM

$\text{Br}(K_L \rightarrow p^0 nn) = (3.0 \pm 0.6) \times 10^{-11}$

$\text{Br}(K^+ \rightarrow p^+ nn) = (7.8 \pm 1.2) \times 10^{-11}$

Recent update:
A. Buras et al hep-ph/0405132

UT from B and K decays



- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ $\Rightarrow |V_{ts}^* V_{td}|$
- $K_L \rightarrow \pi^0 \nu \bar{\nu}$ $\Rightarrow \text{Im}(V_{ts}^* V_{td})$
- $B \rightarrow \psi K_s$ $\Rightarrow \beta$
- $\Delta M_d / \Delta M_s$ $\Rightarrow |V_{td}| / |V_{ts}|$

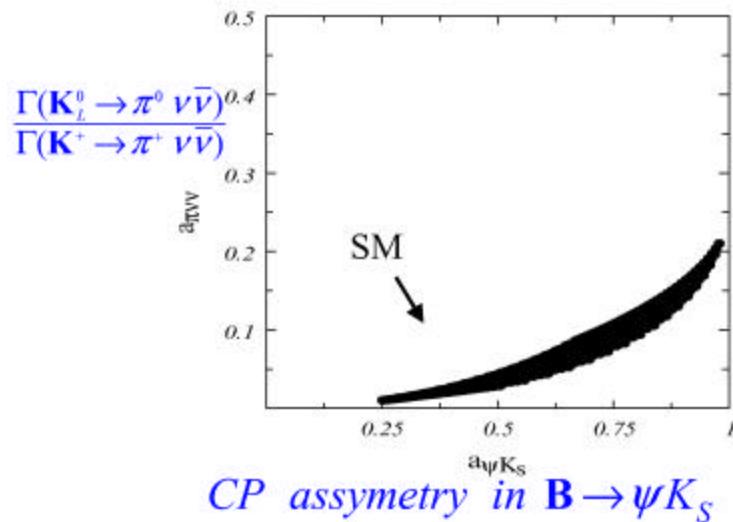
Tests of SM:

Comparison of $|V_{td}|$ from $K^+ \otimes p^+ \bar{p}^-$ and $\Delta M_s / \Delta M_d$

Comparison of $\sin 2\beta$ from $\text{Br}(K_L \otimes p^0 \bar{p}^-) / \text{Br}(K^+ \otimes p^+ \bar{p}^-)$ and $A(B \otimes J/\psi K_s)$

$$\text{SM} \rightarrow (\sin 2\beta)_{\pi \nu \bar{\nu}} = (\sin 2\beta)_{\psi K_s}$$

K \otimes p_{miss} beyond the SM



(Nir and Worrah, Phys. Lett. B319, 1998)
Low energy SUSY, Minimal Flavor Violation,
Multiple Higgs

- A.Buras, hep-ph/0109197
- G.Isidori, hep-ph/0101121
- T.Yanir, hep-ph/0205073
- M.S.Chanowitz, hep-ph/9905478
- C.-H.Chen, hep-ph/0202188
- A.Buras et al., hep-ph/0402112
- H.G.He, G.Valencia, hep-ph/0404229

Model
review
SUSY
4th generation of fermions
$SU(2)_L \times SU(2)_R$ Higgs
SUSY gluino exchange
non-SM
right-handed Z'

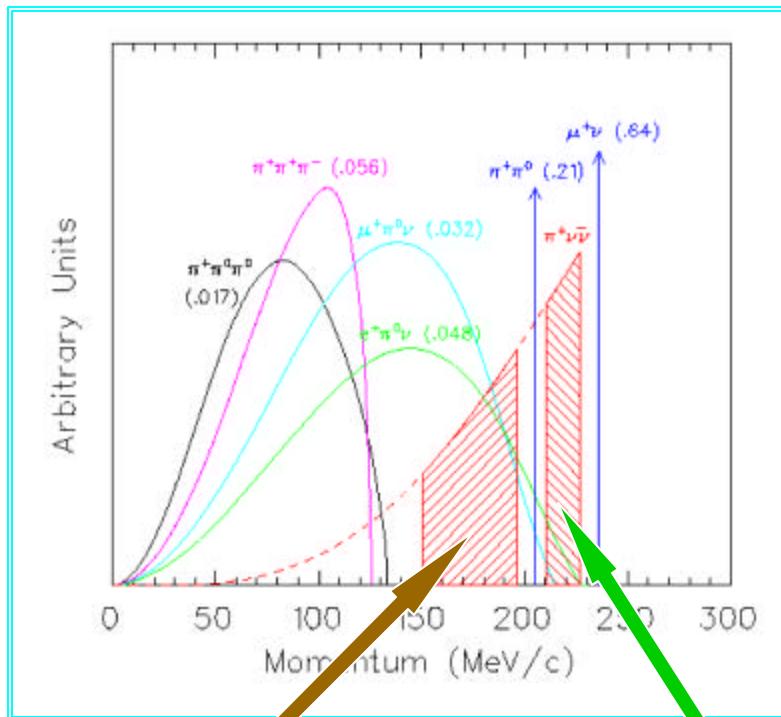
$Br(K \otimes p_{miss}^0) \times 10^{11}$
SM and beyond
$\leq 27 (K^+), \leq 40 (K^0)$
$\leq 60 (K^+), \leq 400 (K^0)$
2.8 – 10.6
15 (K^+)
30(K^0)/7.7(K^+)
14(K^0)/15(K^+)

Experiment

$$Br(K_L \otimes p_{miss}^0) < 5.9 \times 10^{-7} \text{ (90% c.l.) kTeV}$$

Measurement of $K^+ \rightarrow p^+ \bar{m} m$

Observation of π^+ in the momentum region
 $211 < p_\mu < 229$ MeV/c + no other detector activity



Region 2

Region 1

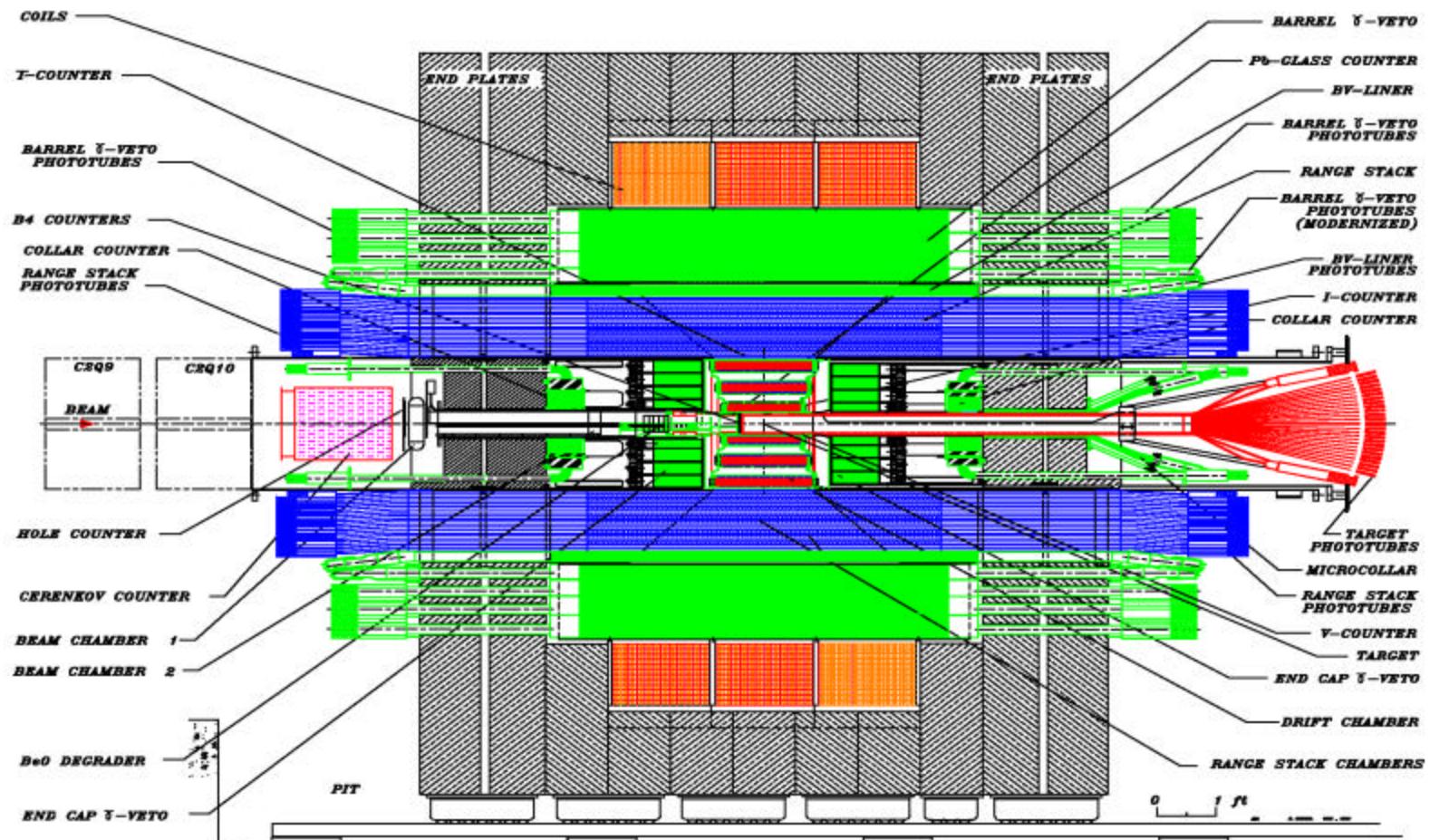
Physics backgrounds

Decay	BR	PID	g-veto	kinematics
$K^+ \rightarrow p^+ p^0$	0.21	-	++	+
$K^+ \rightarrow m^+ m^-$	0.63	+	-	+
$K^+ \rightarrow m^+ n\bar{g}$	0.005	+	+	-
$K^+ \rightarrow m^+ p^0 n$	0.032	+	++	-
$K^+ \rightarrow e^+ p^0 n$	0.048	+	++	-
$K^+ \rightarrow p^+ p^- p^+$	0.056	-	+	++
$K^+ \rightarrow p^+ \bar{m} m$	$\sim 8 \cdot 10^{-11}$ (SM)			

Only $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ produces pions with momentum ≥ 205 MeV/c

E787/E949 detector

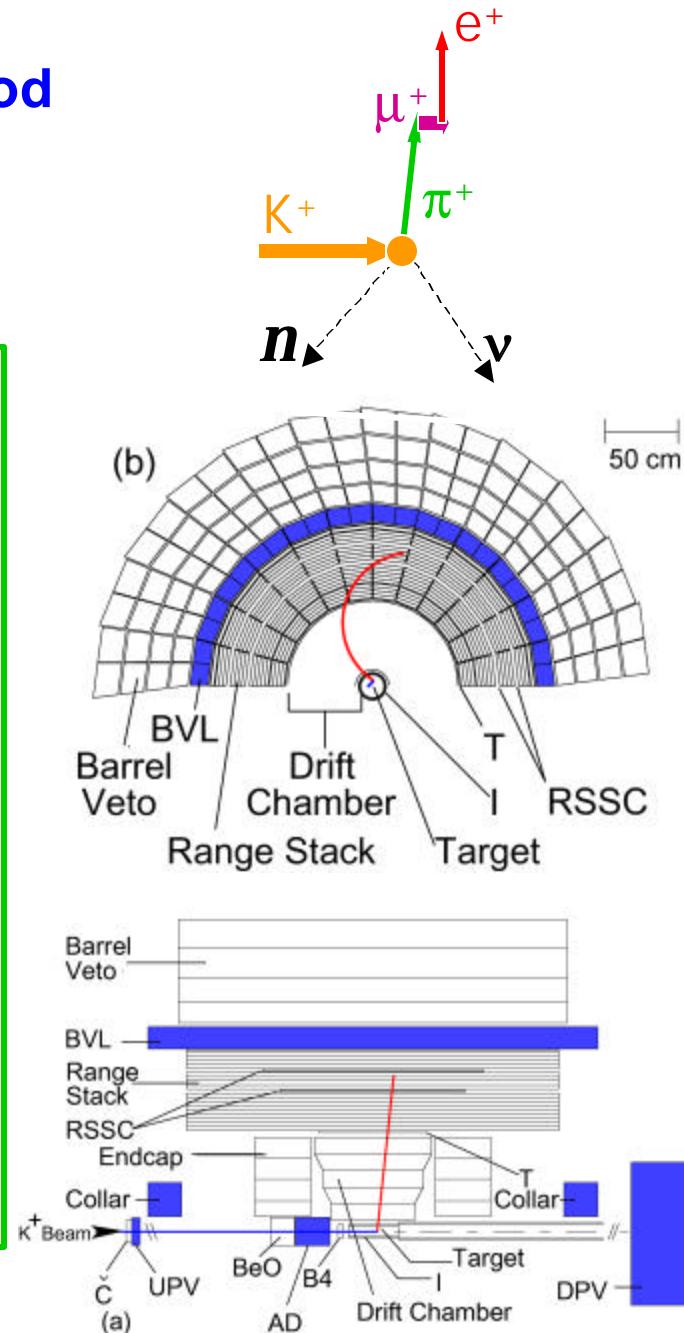
Alberta/BNL/FNAL/Fukui/IHEP/INR/KEK/Kyoto/UNM/Osaka/TRIUMF



Method

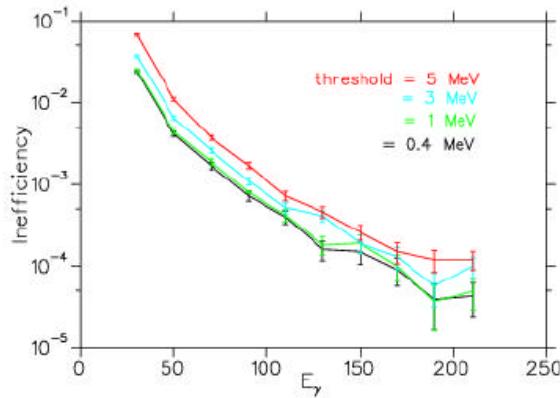
Experimental method

- 700 MeV/c K^+ beam $p/K \sim 1/3$
- stop K^+ in active target
- delay 2 ns for K^+ decay
- momentum measurement in drift chamber
 $\Delta p/p \sim 2.5\%$
- measurement of range R and energy E
in target and range stack RS
- stop p^+ in range stack (RS)
- detection $p^+ \rightarrow \mu^+ \rightarrow e^+$ chain in RS
- veto photons and charge particles

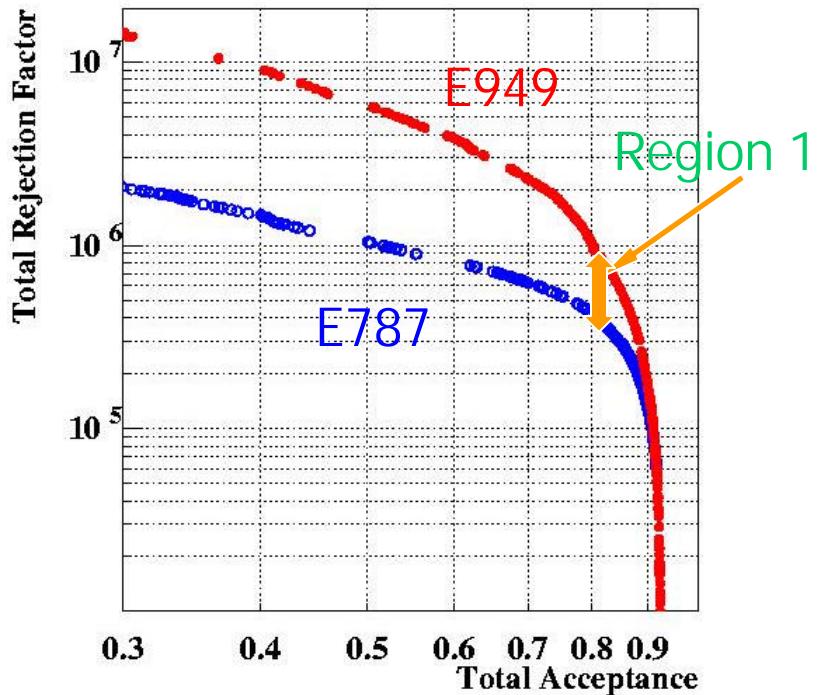


Suppression of neutrals

Photon inefficiency



Average photon inefficiency $\sim 10^{-3} - 10^{-4}$



Suppression of $K_{\pi 2}$ $K_{\mu 3}$ $K_{e 3}$ $K_{\mu 2 \gamma}$

π^0 detection inefficiency $\sim 10^{-6}$ for
photon threshold = 1 MeV

Suppression: $1\gamma \sim 10^{-3}$
 $\pi^0 \sim 10^{-6}$

Analysis

- Search region (**signal box**) in multi-dimentional cut space

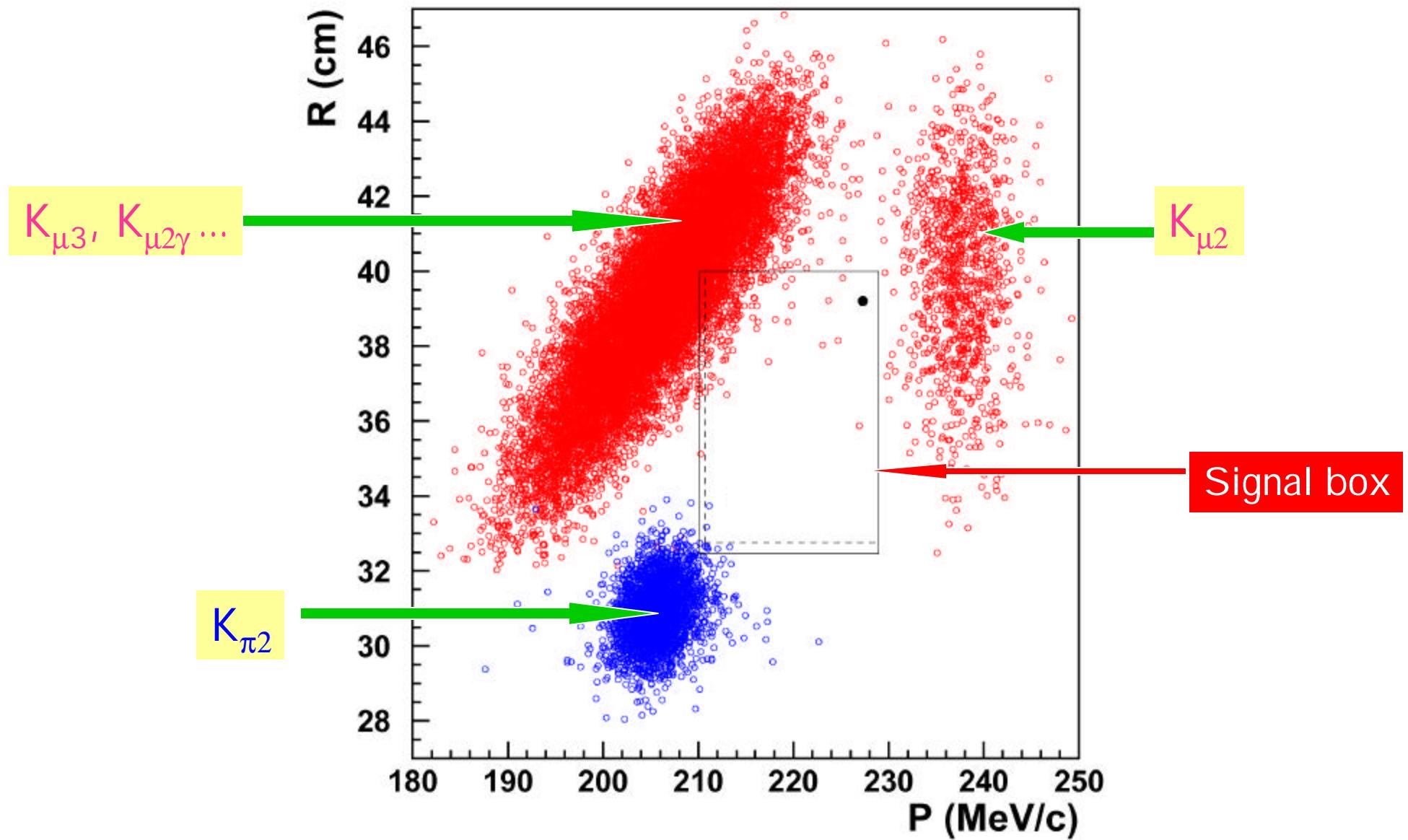
- Background study

$K_{\pi 2}$	0.216 ± 0.023
$K_{\mu 2}$	0.044 ± 0.005
$K_{\mu m}$	0.024 ± 0.010
beam	0.009 ± 0.003
K^+ charge exchange	0.005 ± 0.001
Total background	0.298 ± 0.026

- Acceptance and sensitivity in **box** region

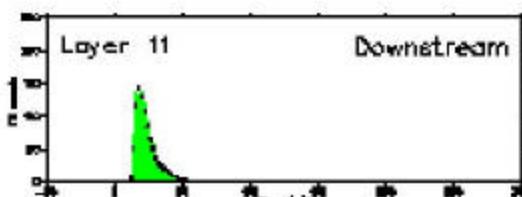
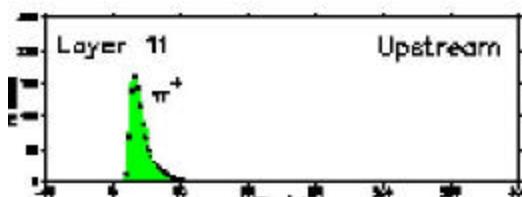
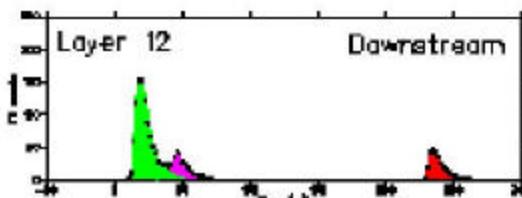
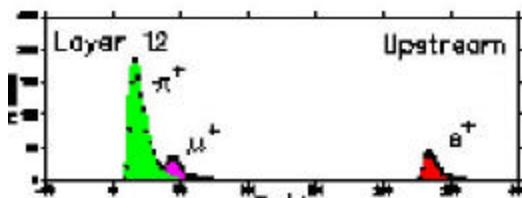
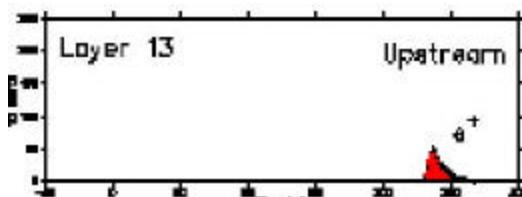
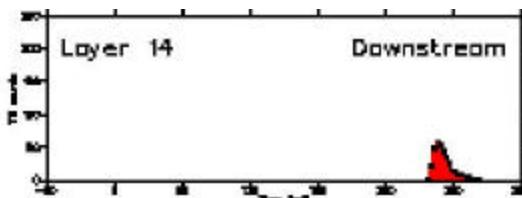
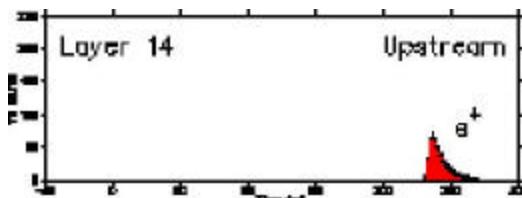
total acceptance $0.22 \pm 0.02\%$
single event sensitivity 2.6×10^{-10}

Backgrounds



p ® m® e chain

Signals from RS recorded by 500 MHz TD



Suppression factor 10^{-5}

Sample pulse height
every 2 ns

p^+ stops in RS (2cm/layer)

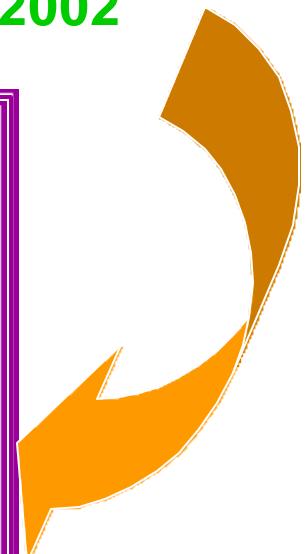
$p^+ \circledR m \circledR n$ $E_m = 4.1$ MeV
 $R_m \sim 1$ mm $t_p = 26$ ns

$m \circledR e^+ m$ $E_e \approx 53$ MeV
 $t_m = 2.2$ ms

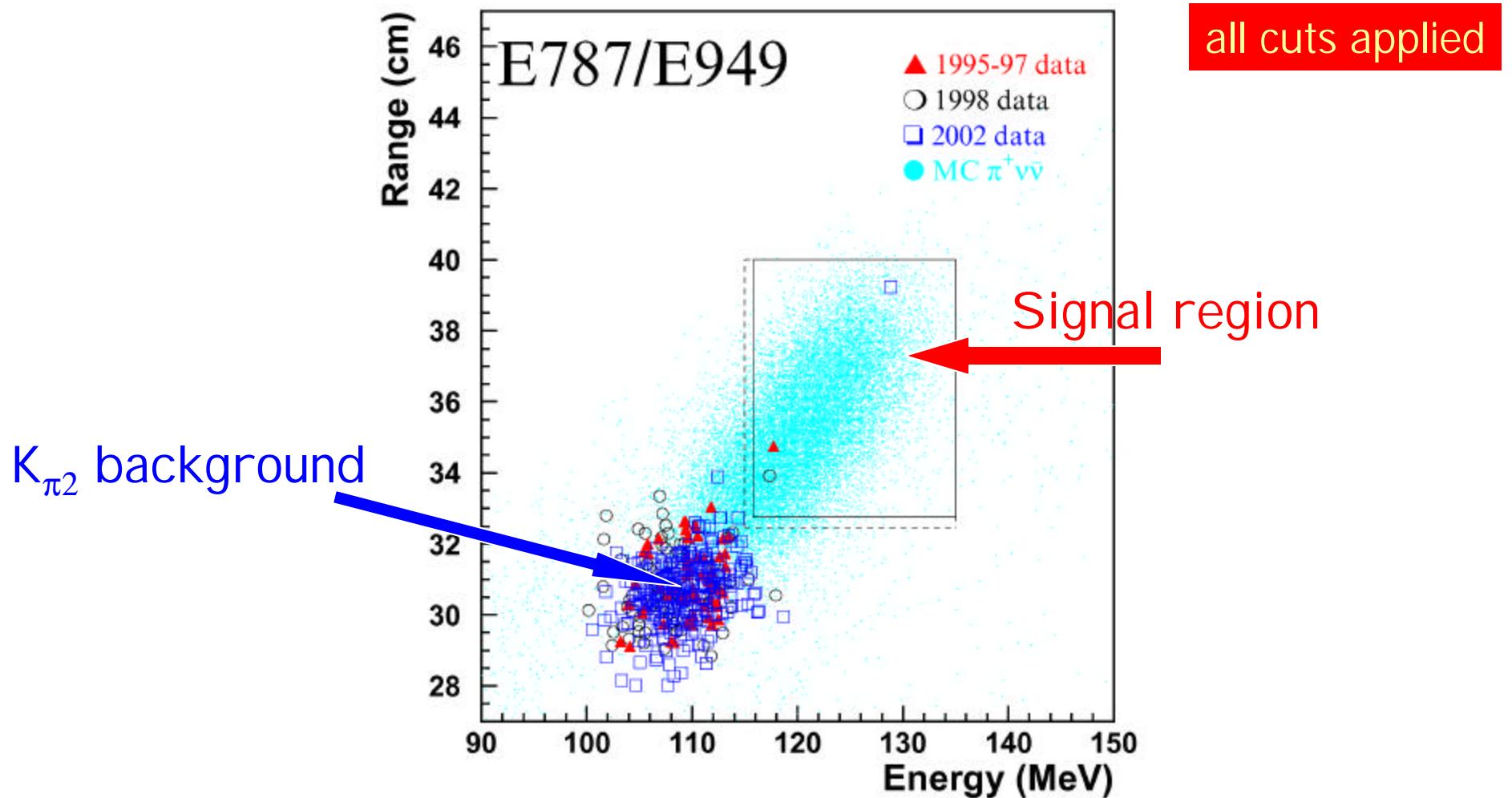
K⁺ ® p⁺ m acceptance

Category	E787	E949 2002
1995-97	1998	
K^+ stop efficiency	0.704	0.702
K^+ decay after 2 ns	0.850	0.851
$\pi^+ \nu \bar{\nu}$ phase space	0.155	0.136
Solid angle acceptance	0.407	0.409
π^+ nucl. interaction	0.513	0.527
Reconstruction efficiency	0.959	0.969
Other kinematic constraints	0.665	0.554
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay acc.	0.306	0.392
Beam and target analysis	0.699	0.706
Accidental loss	0.785	0.751
Total acceptance	0.0021	0.0020
Total K^+ triggers ($\times 10^{12}$)	3.2	2.7
		0.0022
		1.8

E949 acceptance = 0.0022±0.0002



Signal



Result

E949

Stopped kaons	1.8×10^{12}
Total acceptance	$0.22 \pm 0.02 \%$
Signal	1
Background	0.30 ± 0.03

$$\rightarrow Br = (0.96 + 4.09 - 0.47) \times 10^{-10}$$

E949 + E787

$$K^+ \circledast p^+ \bar{m} m \quad 1 + 2 \text{ (from E787)} = 3$$

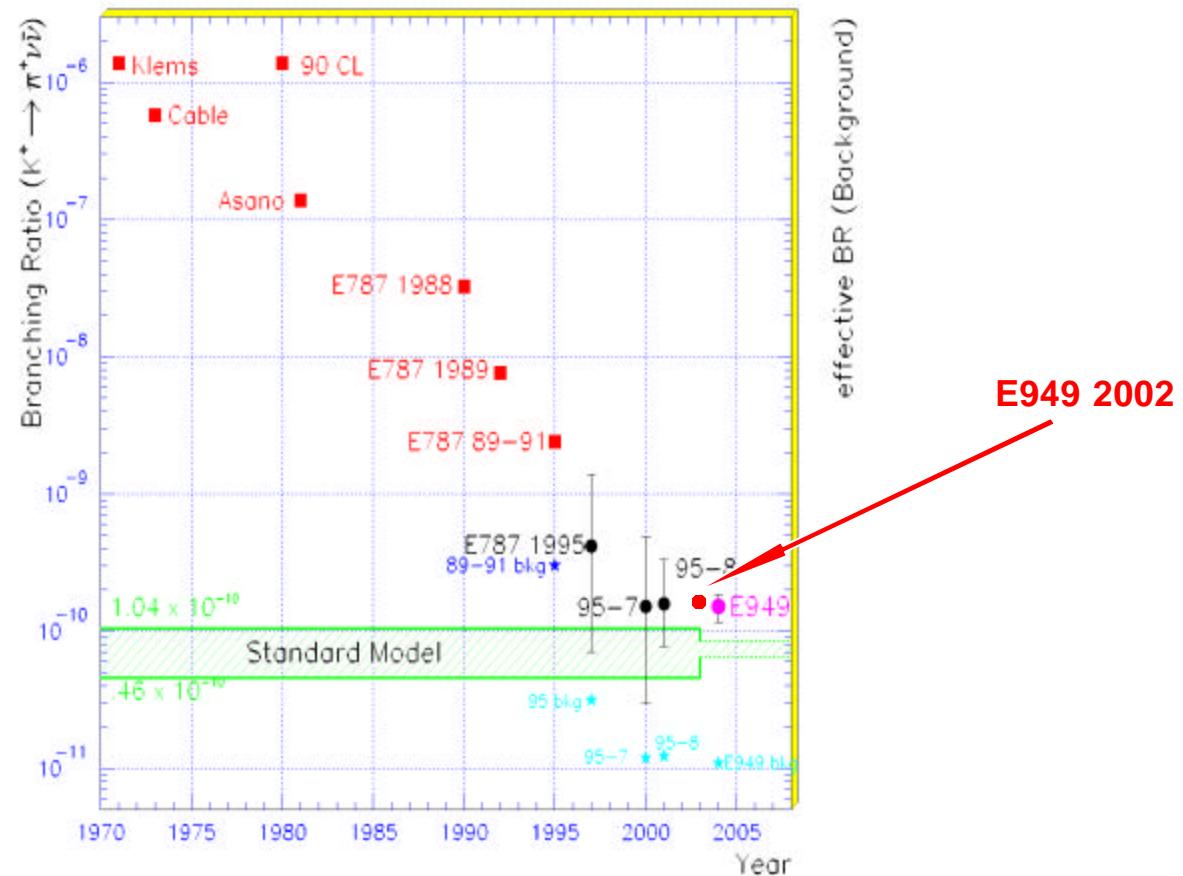
$$Br(K^+ \circledast p^+ \bar{m} m) = (1.47 + 1.30 - 0.89) \times 10^{-10} \quad (hep-ex/0403036)$$

consistent with the SM predictions

$$0.006 < |V_{td}| < 0.027 \quad \lambda_t = V_{ts}^* \bullet V_{td} = A^2 \lambda^5 (1 - \rho - i\eta) \quad 0.24 \times 10^{-3} < |\lambda_t| < 1.08 \times 10^{-3}$$

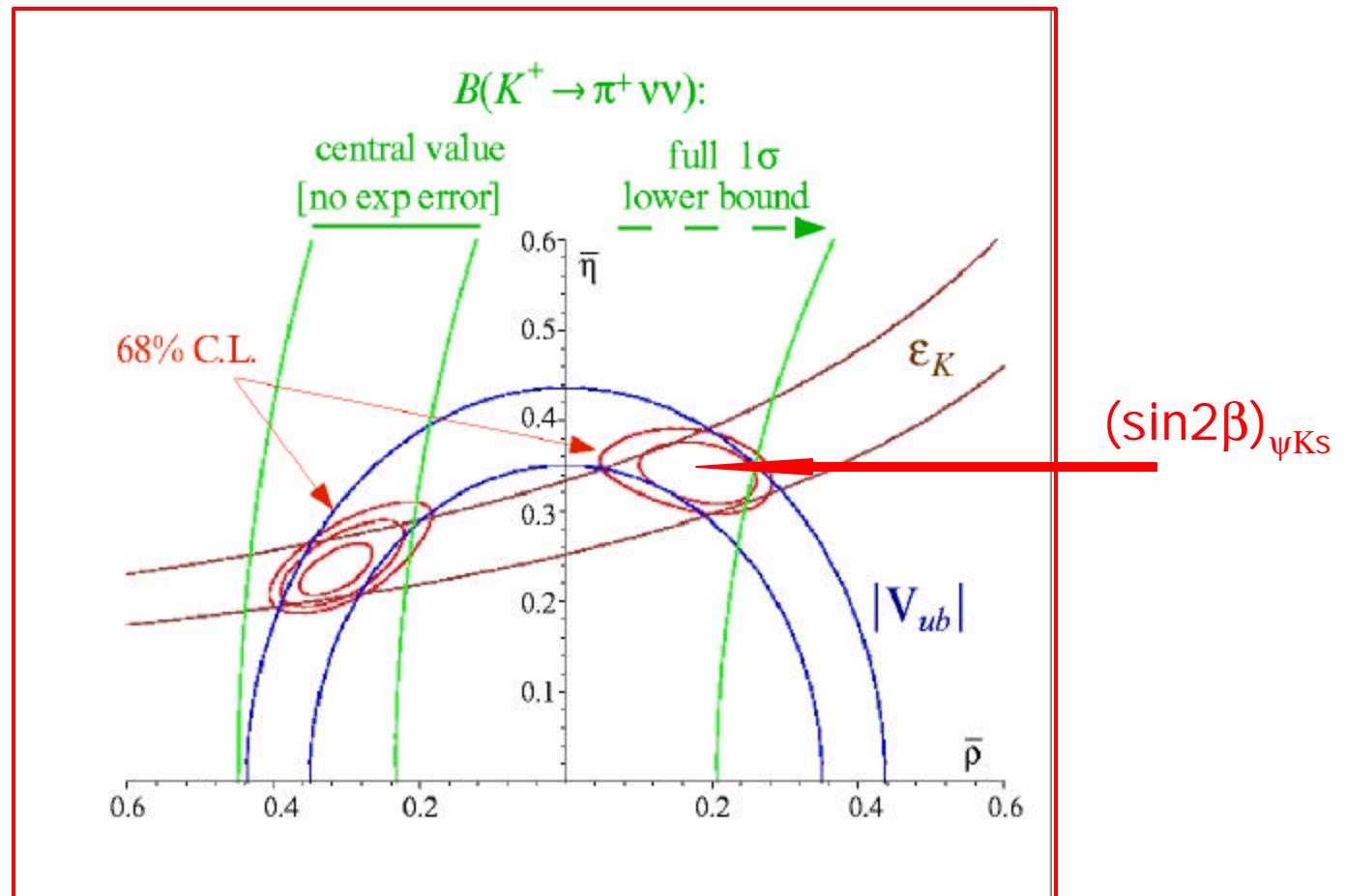
K^+ ® p^{+mn} history

History of the Search for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$



r - h plane and $K^+ \otimes p^{+nn}$

G.Isidori
hep-ph/0307014



Conclusion and perspectives

K[®] p[±] - useful probe of new physics

	Theory	Experiment
K⁺ ® p⁺	(7.8 ± 1.2) × 10 ⁻¹¹	(14.7 + 13.0 – 8.9) × 10 ⁻¹¹

Perspectives: E949 - analysis below K_{π2} peak is under way
 - doubles sensitivity next year
 - final result - 10 events expected

CKM at FNAL
CERN
J-PARC