TEST OF CHIRAL PERTURBATION THEORY WITH K^{+-}_{e4} AND K^{00}_{e4} DECAYS AT NA48/2

Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Florence, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Turin, Vienna

TIMELINE OF NA48/NA62 EXPERIMENTS

2013 2012 2011 2010 2009 2008 2007 2006 2005 2004 2003 2002 2001 2000 1999 1998 1997

NA62
Beam: K^+
Primary goal: $K^+\to\pi^+\nu\bar\nu$
2006-2012: R & D
2012: First data taking

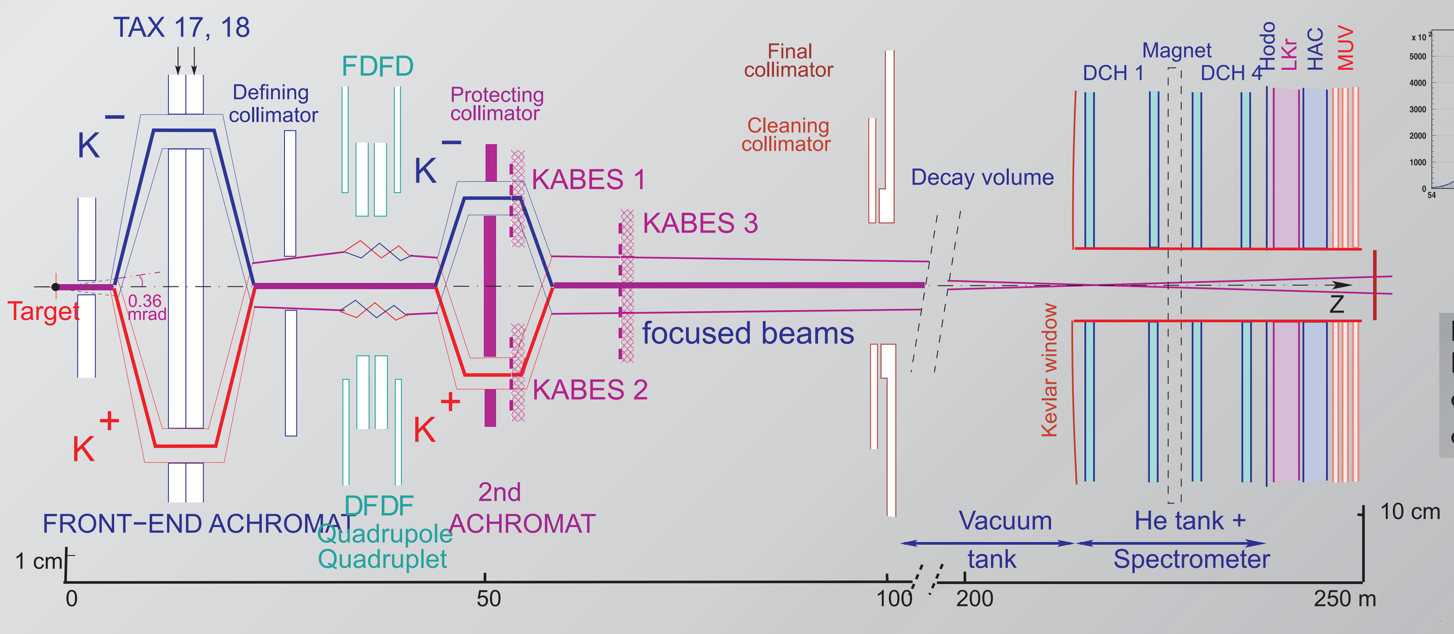
NA48/2
Beams: K^+ and K^-
Primary goals: Direct CP, $K_{\pi 3}$ studies,
Rare K decays

NA48
Beams: K_L and K_S
Primary goal: ε'/ε

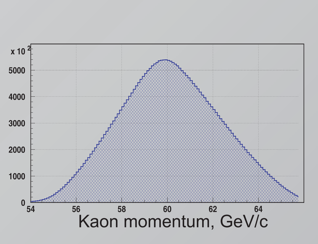
NA62 (R_K)
Beam: K^+ and K^-
Primary goal: LFV test
$R_K = BR(K_{e2})/BR(K_{\mu 2})$
Tests for NA62

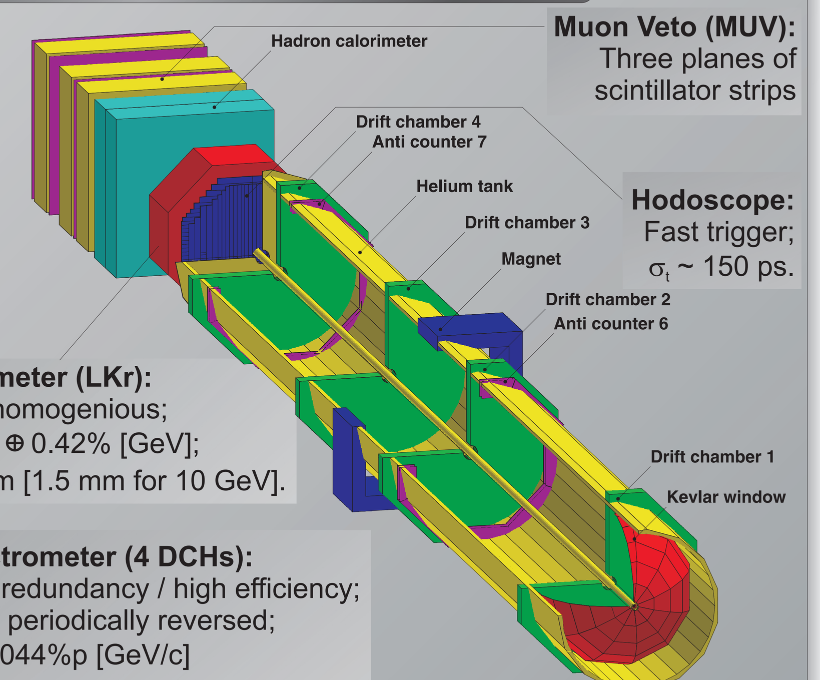
NA48/1
Beams: K_S
Primary goal: Rare K_S and Hyperon decays

NA48/2 BEAM LINE SCHEMATICS



NA48/2 DETECTOR SETUP





Muon Veto (MUV): Three planes of scintillator strips

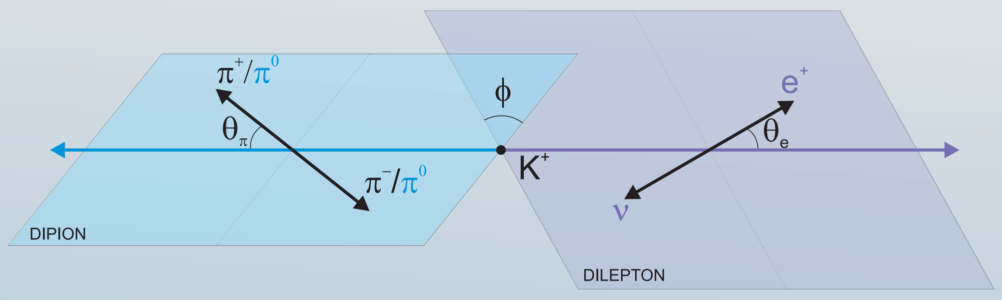
Hodoscope: Fast trigger; $\sigma_t \sim 150$ ps.

Liquid Krypton Calorimeter (LKr): High granularity, quasi-homogenious; $\sigma_E/E = 3.2\%E^{-1/2} \oplus 9\%E^{-1} \oplus 0.42\%$ [GeV]; $\sigma_x = \sigma_y = 4.2E^{-1/2} \oplus 0.6$ mm [1.5 mm for 10 GeV].

Magnetic spectrometer (4 DCHs): 4 views / DCH: redundancy / high efficiency; magnet polarity periodically reversed; $\sigma_p = 1.02\% \oplus 0.044\%p$ [GeV/c]

FORMALISM OF K_{e4} AND K^{00}_{e4} DECAYS

Four body final state, described by five kinematic variables: S_π ($M^2_{\pi\pi}$), S_e ($M^2_{e\nu}$), $\cos\theta_\pi$, $\cos\theta_e$, ϕ (Cabibbo-Maksymowicz 1965)
In K^{00}_{e4} case reduced to 3 variables: S_π ($M^2_{\pi\pi}$), S_e ($M^2_{e\nu}$), $\cos\theta_e$



Partial wave expansion of the amplitude into s- and p- waves (Pais-Treiman 1968):

2 complex axial form factors: $F = F_s e^{i\delta_s} + F_p e^{i\delta_p}\cos\theta_\pi$ and $G = G_p e^{i\delta_g}$
1 complex vector form factor: $H = H_p e^{i\delta_h}$

Expansion in q^2 and S_e: $q^2 = \frac{S_\pi}{4m^2_\pi} - 1$

$F_S = f_s + f_s' q^2 + f_s'' q^4 + f_e (S_e/4m^2_\pi) + \ldots$
$F_P = f_p + f_p' q^2 + \ldots$
$G_P = g_p + g_p' q^2 + \ldots$
$H_P = h_p + h_p' q^2 + \ldots$

In K^{00}_{e4} case: single form factor F_S. Dalitz plot density proportional to F_S^2.

Map the distributions of the Cabibbo-Maksymowicz variables in the five-dimensional space with 4 real FF and only one phase shift, $\delta = \delta_s - \delta_p$ assuming identical phases for the p-wave FF: F_p, G_p, H_p.

10 independent fits (1 fit per q^2 bin) for F_s, F_p, H_p, G_p and δ. Extract the slopes of polynomial expansion (normalized to f_s) and $\pi\pi$-scattering lengths from $\delta(q^2)$. f_s accessible from branching ratio.

χPT AND K_{e4} BRANCHING RATIOS

Isospin symmetry translates in relations between decay modes:
$\Gamma(K^\pm_{\ell 4}) = 0.5 \times \Gamma(K^{00}_{\ell 4}) + 2 \times \Gamma(K^{0\pm}_{\ell 4})$ (for ℓ=e,μ)

Experimental status (PDG 2010):
$BR(K^{+-}_{e4}) = (4.09 \pm 0.10) \times 10^{-5}$ (2.4%)
$BR(K^{00}_{e4}) = (2.20 \pm 0.40) \times 10^{-5}$ (18.2%)
$BR(K^{0\pm}_{e4}) = (5.20 \pm 0.11) \times 10^{-5}$ (2.1%)

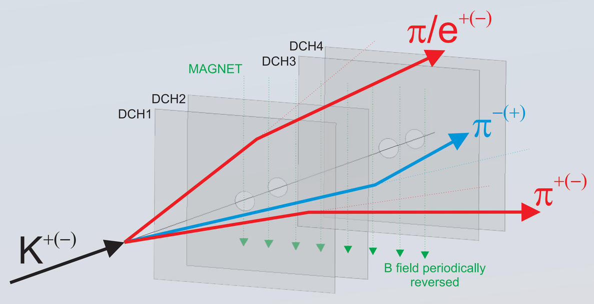
Predictions using FF by χPT at $O(p^2, p^4, p^6)$:
$BR(K^{+-}_{e4}) = (3.91 \pm 0.17) \times 10^{-5}$
$BR(K^{00}_{e4}) = (2.01 \pm 0.11) \times 10^{-5}$
$BR(K^{0\pm}_{e4}) = (4.69 \pm 0.87) \times 10^{-5}$

Using experimental input with 5% precision

Bijnens et al. NP B427 (1994) 427

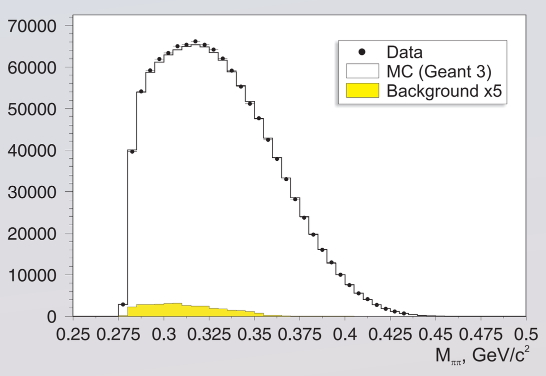
Improved measurements will provide tests of χPT predictions.

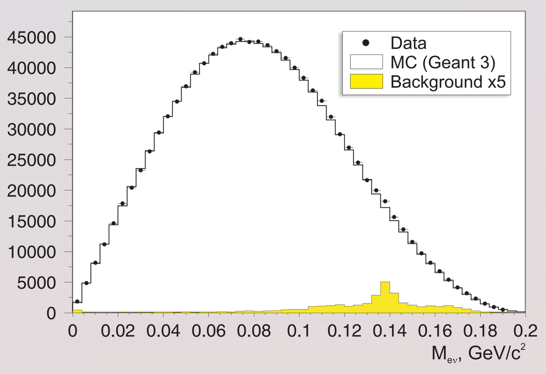
K^{+-}_{e4} SELECTION AND RECONSTRUCTION



Decay mode for normalization: $K^\pm\to\pi^\pm\pi^+\pi^-$
Reconstruction and selection as close as possible:
Require 3 tracks, reconstructed by the magnetic spectrometer, forming a vertex within the decay volume. No MUV hit associated with tracks.

Background suppression cuts:
1) Against $\pi^\pm\pi^+\pi^-$: compute the 3-track invariant mass in three-pion hypothesis ($m_{3\pi}$); make ellipse cut in ($m_{3\pi}$, p_t) space.
2) Against Dalitz decays: assign m_e to other sign pion and calculate e^+e^- invariant mass; cut at $m_{ee} > 0.03$ GeV/c^2.
3) Cut on missing mass of the same sign pion against $\pi^\pm\pi^0\pi^0$ and $\pi^\pm\pi^0$.





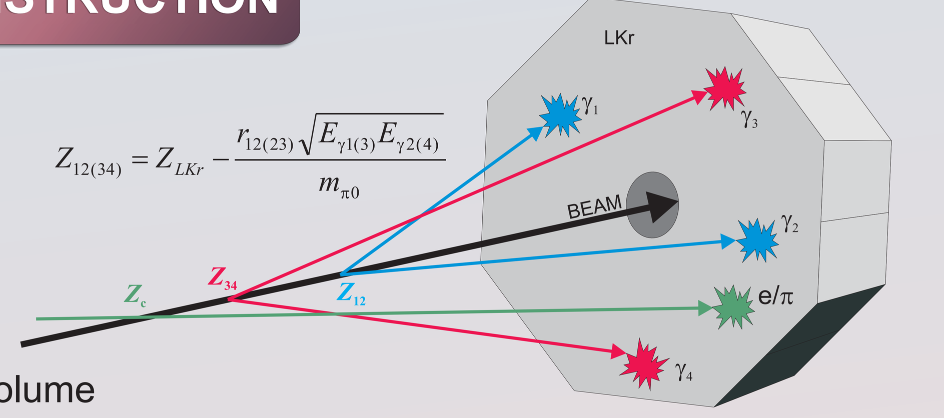
Reconstruction of K_{e4}:
Impose m_K and m_ν=0 and find the two solutions for Kaon momentum. Pick the closest to the nominal beam momentum (60 GeV/c).

Background estimation:
Count "wrong sign" events: $e^\mp\pi^\pm\pi^\pm$ (suppressed due to ΔS=ΔQ to 10^{-8}).
Background = 2 x WS

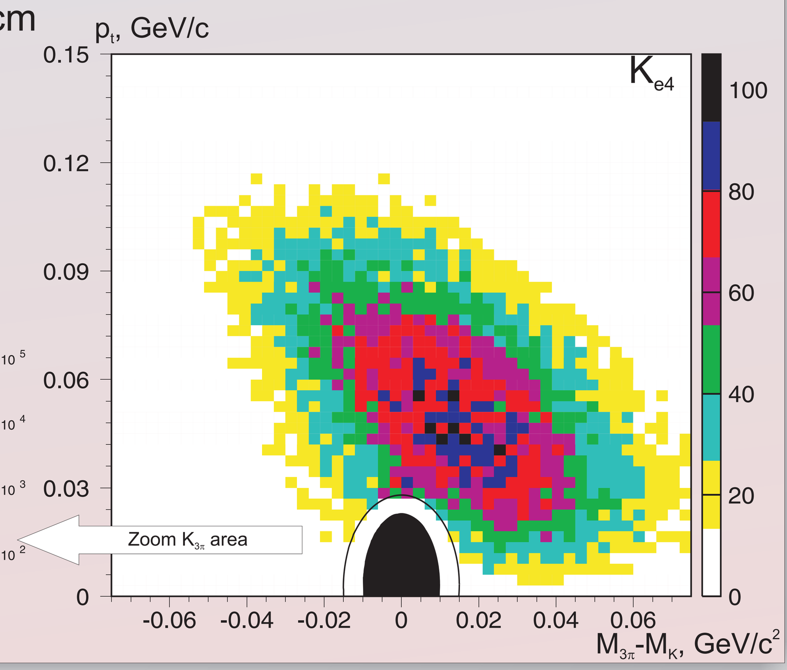
K^{00}_{e4} SELECTION AND RECONSTRUCTION

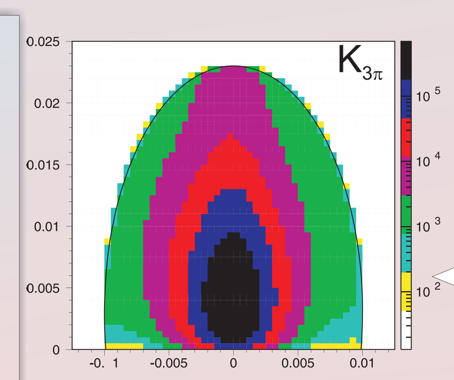
Decay mode for normalization: $K^\pm\to\pi^\pm\pi^0\pi^0$
Reconstruction and selection as close as possible for both modes.

Find 2 clusters pairs ($\gamma_1\gamma_2$) and ($\gamma_3\gamma_4$) satisfying π^0 mass constraint and the following conditions:
$|Z_{12} - Z_{34}| < 500$ cm; $Z_n = (Z_{12} + Z_{34})/2$ within decay volume
Z_c - at CDA of charged track to beam line with $|Z_c - Z_n| < 800$ cm



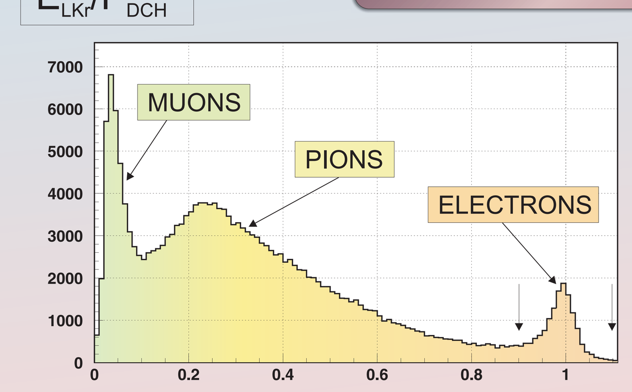
Signal / Background separation:
Compute the invariant mass and p_t (to the beam line) in pion hypothesis. Elliptic cut separates 70 millions $K_{3\pi}$ candidates from 45000 K_{e4} candidates.



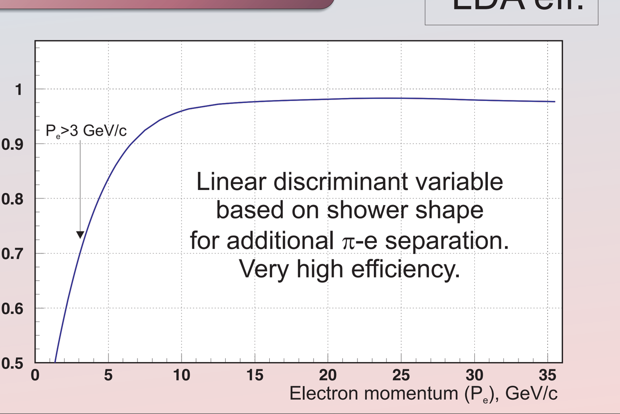


PARTICLE IDENTIFICATION

E_{LKr}/P_{DCH}

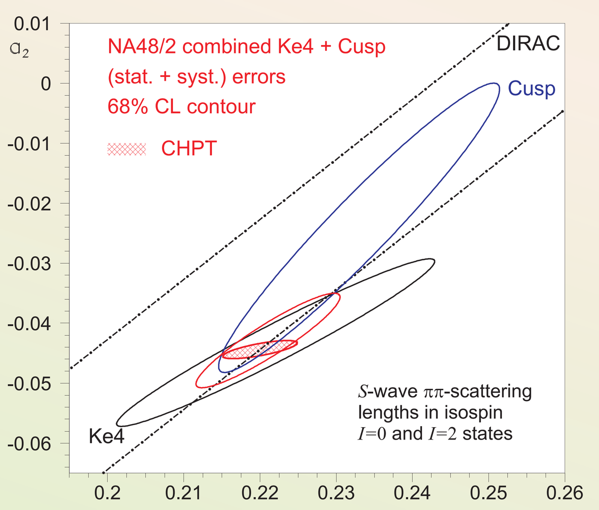


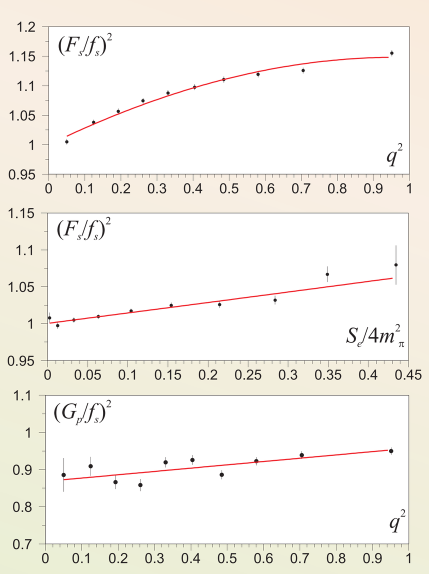
LDA eff.



K^{+-}_{e4} FORM FACTORS / FINAL

f_s'/f_s	$= 0.152$	$\pm 0.007_{stat}$	$\pm 0.005_{syst}$
f_s''/f_s	$= -0.073$	$\pm 0.007_{stat}$	$\pm 0.006_{syst}$
f_e'/f_s	$= 0.068$	$\pm 0.006_{stat}$	$\pm 0.007_{syst}$
f_p/f_s	$= -0.048$	$\pm 0.003_{stat}$	$\pm 0.004_{syst}$
g_p/f_s	$= 0.868$	$\pm 0.010_{stat}$	$\pm 0.010_{syst}$
g_p'/f_s	$= 0.089$	$\pm 0.017_{stat}$	$\pm 0.013_{syst}$
h_p/f_s	$= -0.398$	$\pm 0.015_{stat}$	$\pm 0.008_{syst}$





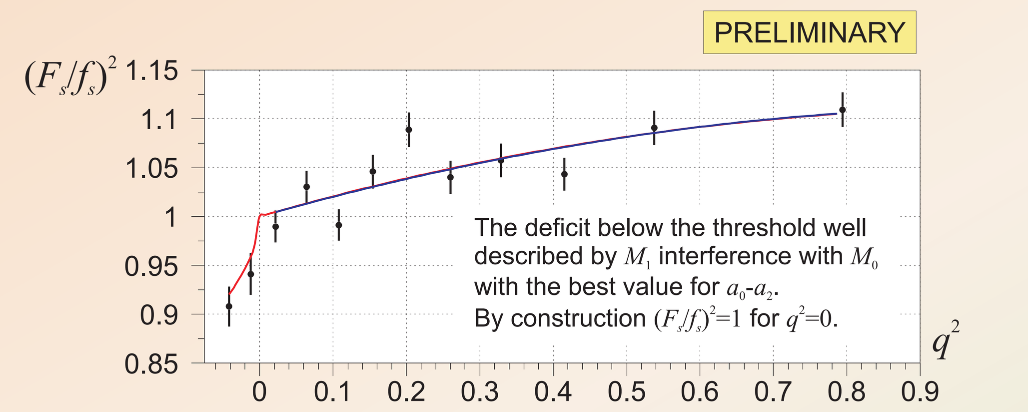
χPT prediction: Colangelo et al. PLB 488 (2000) 639
NA48/2 K_{e4} form factors: EPJ C70 (2010) 635
DIRAC Pionium: CERN-PH-EP-2011-028
NA48/2 $\pi\pi$-scattering lengths from $K^\pm\to\pi^\pm\pi^0\pi^0$: EPJ C64 (2009) 589

$$BR(K_{e4}) = \frac{N_4 - N_{BG}}{N_3} \times \frac{A_3}{A_4} \times \frac{\varepsilon_3}{\varepsilon_4} \times BR(K_{3\pi})$$

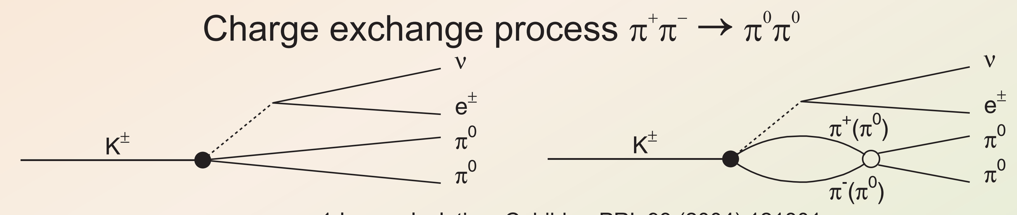
$BR(K^{+-}_{e4})$	QUANTITY	$BR(K^{00}_{e4})$
1.11×10^6	$N_4 = K_{e4}$ candidates	44 909
0.95% of K_{e4}	N_{BG} = Background to K_{e4}	1.3% of K_{e4}
1.9×10^9 ($\pi^\pm\pi^+\pi^-$)	$N_3 = K_{3\pi}$ candidates	($\pi^\pm\pi^0\pi^0$) 70.9×10^6
18.22%	A_4 = Acceptance for K_{e4}	1.77%
24.18%	A_3 = Acceptance for $K_{3\pi}$	4.11%
98.3%	ε_4 = Trigger efficiency for K_{e4}	92% - 98%
97.5%	ε_3 = Trigger efficiency for $K_{3\pi}$	92% - 98%
(5.59 ± 0.04)%	$BR(K_{3\pi})$ = Branching ratio for $K_{3\pi}$	(1.761 ± 0.022)%

K^{00}_{e4} FORM FACTOR AND CUSP

PRELIMINARY



Charge exchange process $\pi^+\pi^- \to \pi^0\pi^0$



1-loop calculation: Cabibbo, PRL 93 (2004) 121801

Unperturbed amplitude: $M_0 = F_s(q^2)$
One loop charge exchange contribution: $M_1 \approx -\frac{2}{3}(a_0 - a_2)\sqrt{\frac{|q^2|}{1+q^2}} f_s$

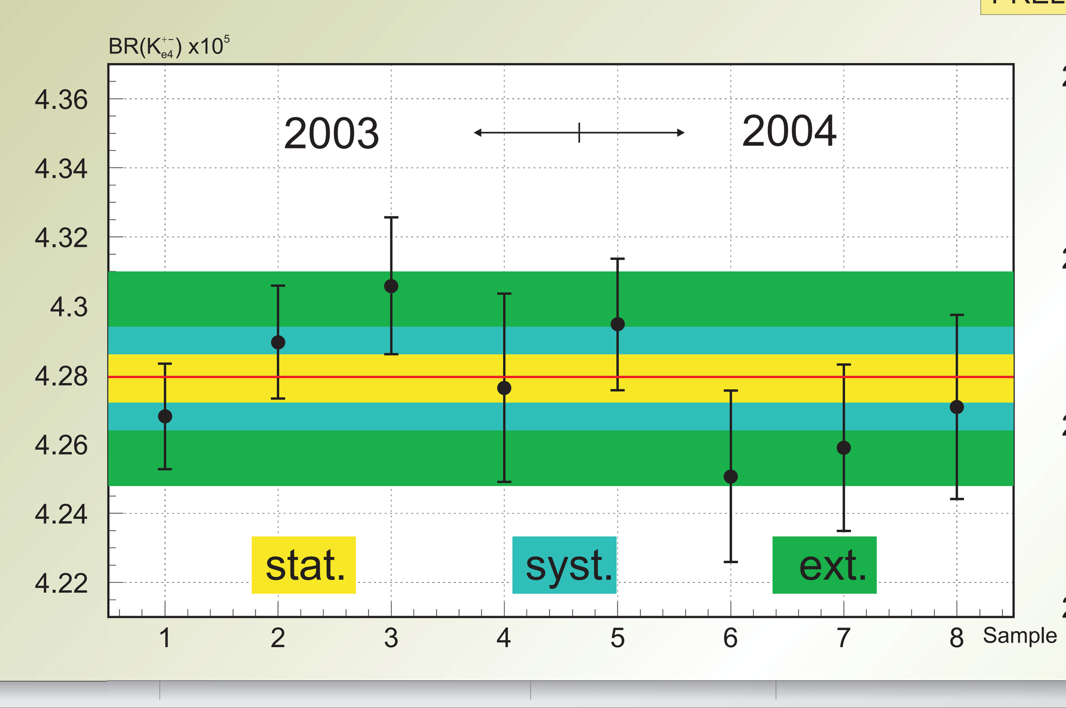
Above $2m_{\pi^+}$ threshold: $|M_0 + iM_1|^2 = M_0^2 + M_1^2$
Below $2m_{\pi^+}$ threshold: $|M_0 + M_1|^2 = M_0^2 + M_1^2 + 2M_0M_1$ with destructive interference.

Form factor measurement in progress.

$BR(K^{+-}_{e4}) = (4.279 \pm 0.035)\times 10^{-5}$ (0.8%)

$BR(K^{+-}_{e4}) = (4.279 \pm 0.007_{stat} \pm 0.015_{syst} \pm 0.031_{ext})\times 10^{-5}$

Source of systematic uncertainty	Error [%]
Acceptance and beam geometry	0.18
Muon vetoing	0.16
Accidental activity	0.15
Background	0.14
Particle ID	0.09
Radiative effects	0.08
Independent analysis	0.10

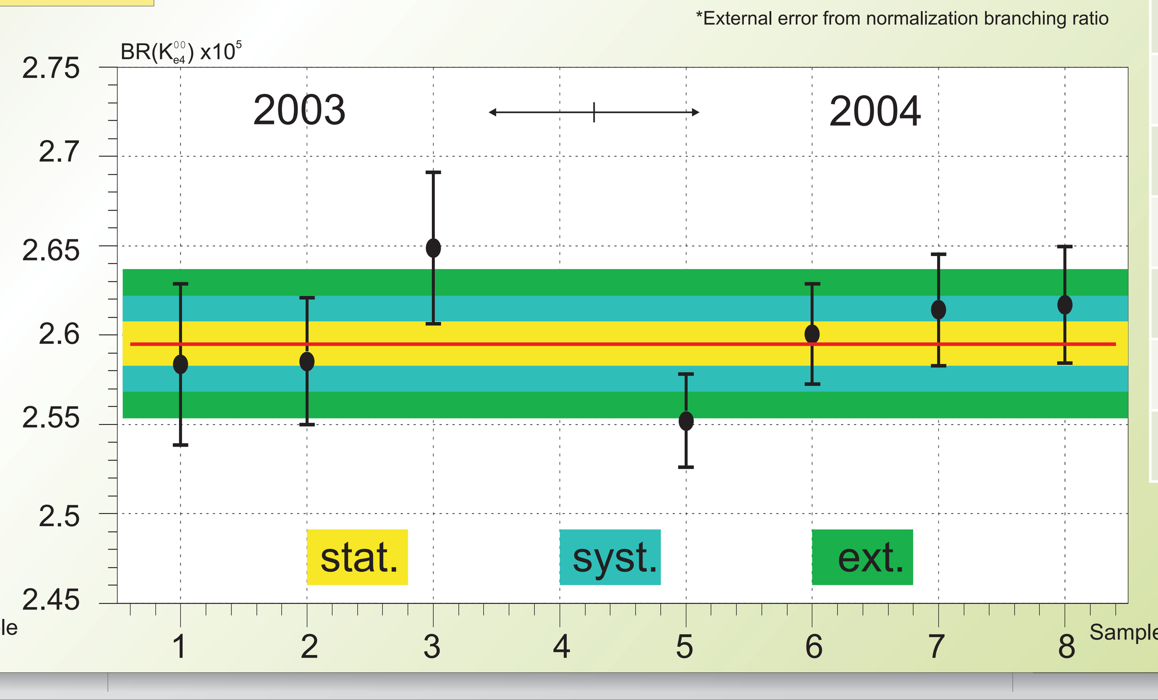


PRELIMINARY

$BR(K^{00}_{e4}) = (2.595 \pm 0.042)\times 10^{-5}$ (1.6%)

$BR(K^{00}_{e4}) = (2.595 \pm 0.012_{stat} \pm 0.024_{syst} \pm 0.032_{ext})\times 10^{-5}$

*External error from normalization branching ratio



Source of systematic uncertainty	Error [%]
Background	0.35
Simulation statistics	0.12
Form factors dependence	0.20
Radiative effects	0.23
Trigger efficiency	0.80
Particle ID	0.10
Beam Geometry	0.10

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