Study of the Ke4 ($\pi^0\pi^0e^\pm\nu$) decay with NA48/2 @ CERN

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on behalf of the NA48/2 Collaboration

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Outline

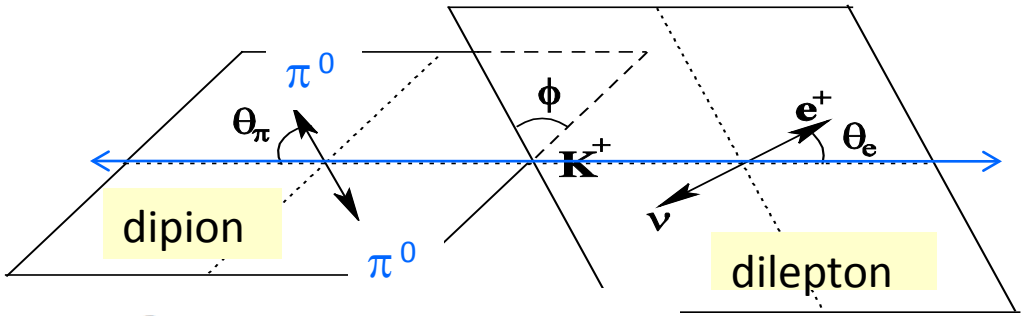
- No need to repeat NA48/2 description of experimental setup & detector performances…
- The Ke4 decay mode ($\pi^0 \pi^0 e^\pm \nu$)
- Selection and backgrounds
- Branching Ratio
- Form factor
- Summary

Preliminary !

Ke4 (00) decays : a simpler formalism than Ke4(+-)

Four-body final state with two identical particles , described by 3 kinematic variables :

S_π ($M^2_{\pi\pi}$), S_e (M^2_{ev}), $\cos\theta_e$



$$d^3\Gamma = \frac{G_F^2|V_{us}|^2}{2(4\pi)^6 m_K^5}\,\rho(S_\pi, S_e)\;2|XF_s|^2\sin^2\theta_e \times dS_\pi\, dS_e\, d\cos\theta_e.$$

Complex hadronic form factors F1,F2,F3 (F4) reduce to **F1**

Partial Wave expansion of F1 reduces to S-wave (no P-wave in the $\pi^0\,\pi^0$ system) if neglecting D-wave

Only 1 complex Form Factor

$F = F_s\, e^{i\delta s}$

$\cos\theta_e$ distribution does not carry information

Map the distributions of the Sπ, Se variables in the **two-dimensional space** with **1 real Form Factor** (may be energy dependent)

The fit parameter (real number) is only **F_s** determined in a grid of statistically independent (equi-populated) boxes in the **(Mππ, Mev) plane**

Ke4 (00) BR and form factor: experiments and theory

Previous experiments had very low statistics (PDG 2012)

37 events from 3 experiments: BR = (2.2 ± 0.4)10^{-5} (18% rel. error)
214 events from KEK E470 (not considered): BR = (2.29 ± 0.34)10^{-5} (large syst.)

No form factor determination so far, just a relation between partial rate and a constant form factor value :

$$\Gamma = 0.8|V_{us} \cdot F|^2 10^3 \mathrm{s}^{-1}$$

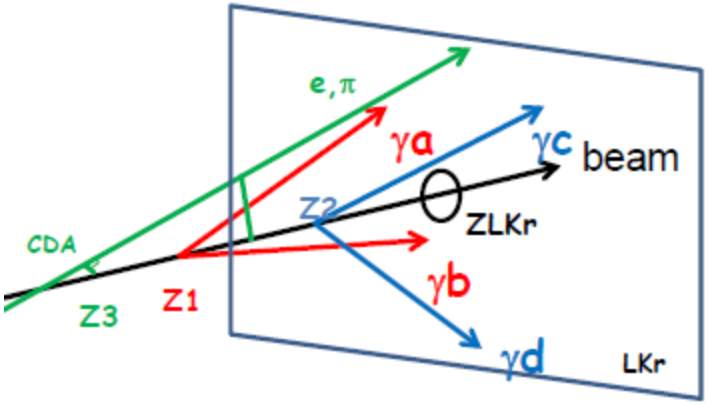
Using the kaon mean life time (1.2380 ± 0.00021) 10^{-8} s, it translates to
|Vus| . F = 1.49 ± 0.13 or F = 6.61 ± 0.58 for |Vus| = 0.2252 ± 0.0009

Theoretical predictions :

Isospin symmetry (mu=md= 0, αQED = 0) predicts a relation between rates
Γ(Kl4 +-) = ½ Γ (Kl4 0±) + 2 Γ (Kl4 00) (valid for lepton = e,μ)
$K^{\pm}$ (2.4% now 0.8%) K^0 (2.1%) $K^{\pm}$ (18%)
ChPT calculations O(p2,p4,p6) from Bijnens Colangelo Gasser (*NPB 427 (1994) 427*) using available 1977 Ke4(+-) form factors predict :
BR(Ke400) = (2.01 ± 0.11) 10^{-5} (~5% precision)

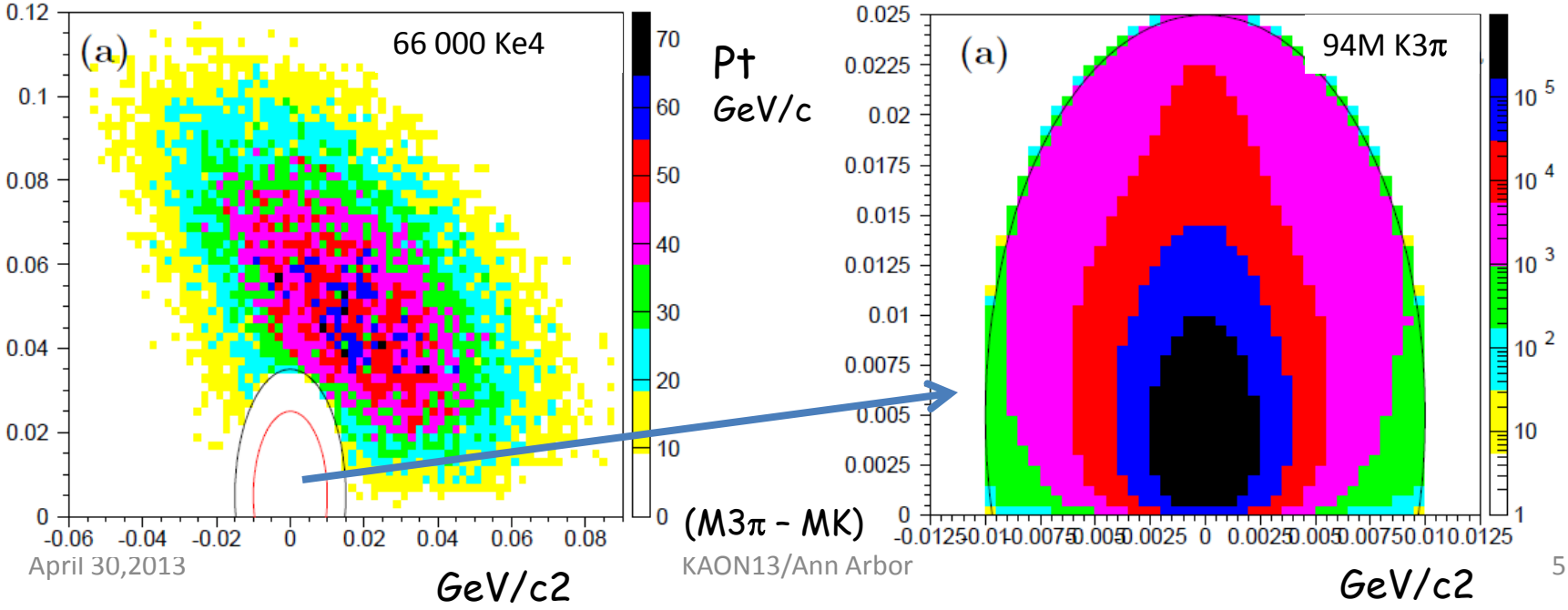
Event selection

Final state reconstructed from 1 charged track and 4 photons forming two π^0 s pointing to the same decay vertex



Reconstruct the $\pi^{\pm}$ π^0 π^0 invariant mass assuming the charged track to be a pion.

In the plane (M3π - MPDG, pt), Ke4 candidates (missing neutrino) are well separated from K3π fully reconstructed events.



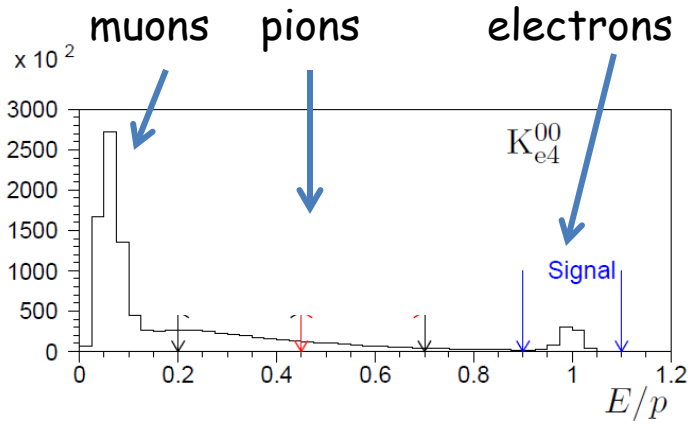
Particle-ID and background contamination

Normalization: requires pion-ID
- pion momentum > 5 GeV/c
- no requirement of an associated cluster

94 M candidates

Signal: requires electron-ID
- electron momentum > 5 GeV/c
- LKr Calorimeter cluster associated to track
- E(LKr)/p within [0.9,1.1] + shower properties

66K candidates

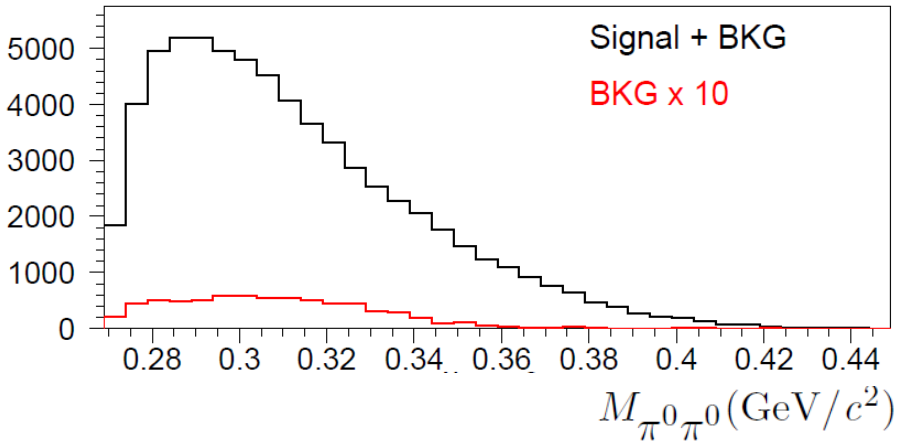


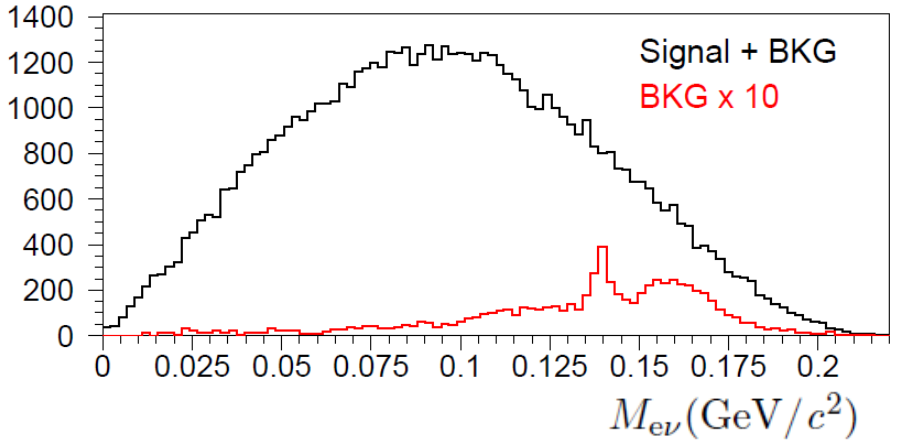
:Background in Signal region
- fake-electron (π^0 π^0 $\pi^\pm$) measured with a data driven procedure
- real electron (π^0 π^0 $\pi^\pm$ & $\pi^\pm$ decay to $e^\pm$ ν, BR = 1.23 10^{-4}) estimated from a dedicated modified simulation
- accidentals (photons or tracks) measured from data with relaxed timing cuts and using side bands

B/S+B
0.71 %
0.12 %
0.24 %
1.07 %

Form factor measurement : principle

- Differential rate in the (Sπ,Se) plane is proportional to $|Fs|^2$
- Subtract background in the 2d-plane



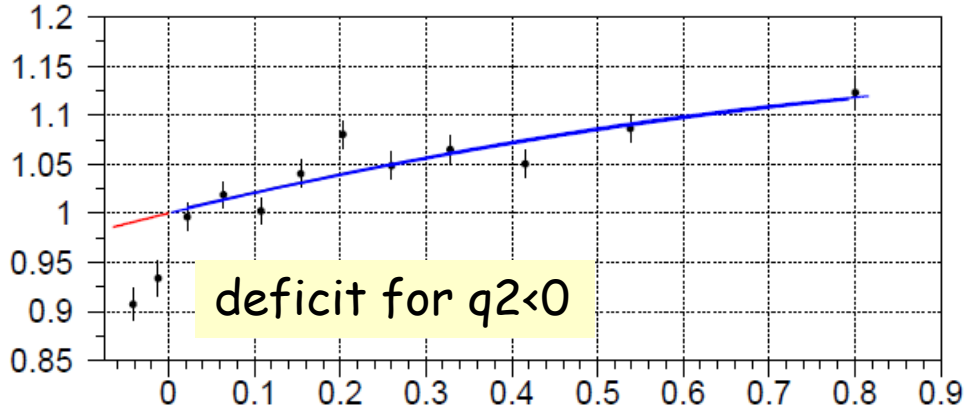


- Compare to the same distribution obtained from simulation including acceptance, resolution, trigger efficiency, radiative corrections (real photon emission at decay vertex) and kinematic factors but using a constant form factor
- switch to dimensionless variables: $q2 = S\pi/4m^2_{\pi+} - 1$, $Se/4m^2_{\pi+}$
- Define a grid of 10 equal population bins in q2 above q2=0 ($2m_{\pi+}$ threshold) and two equal population bins below (10 bins with 6000 events each, 2 bins with 3000 events each), 10 bins in Se (300 or 600 events in 2d-bins)

$M_{e\nu}(\mathrm{GeV}/c)$

Form factor measurement : energy dependence

$(F_s/f_s)^2$



Ratio (Data / MC) ~ |Fs| ^{2}

focus on q2 dependence above q2=0

Normalization is adjusted in the fit to have a value 1 for q2 = 0, Se = 0

q^2

$$(1 + f'_s/f_s\ q^2 + f''_s/f_s\ q^4)^2$$

Step 1: q2 dependence only

$$(1 + f'_s/f_s\ q^2 + f''_s/f_s\ q^4 + f'_e/f_s\ S_e/4m^2_{\pi^+})^2$$

Step 2 : include Se dependence

Fit q2 1d-projection

$f'_s/f_s = 0.102 \pm 0.031$

$f''_s/f_s = -0.040 \pm 0.037$

$\rho = -0.949.$

chi2/ndf = 2.06 (5%)

Fit q2 in 2d-plane

$f'_s/f_s = 0.110 \pm 0.032$

$f''_s/f_s = -0.051 \pm 0.039$

$\rho = -0.954$

chi2/ndf = 1.22 (8%)

Fit 2d-plane

$f'_s/f_s = 0.136 \pm 0.033$

$f''_s/f_s = -0.060 \pm 0.039$

$f'_e/f_s = 0.110 \pm 0.024$

$C = \begin{matrix} -0.946 & 0.189 \\ & -0.063 \end{matrix}$

chi2/ndf = 0.97 (54%)

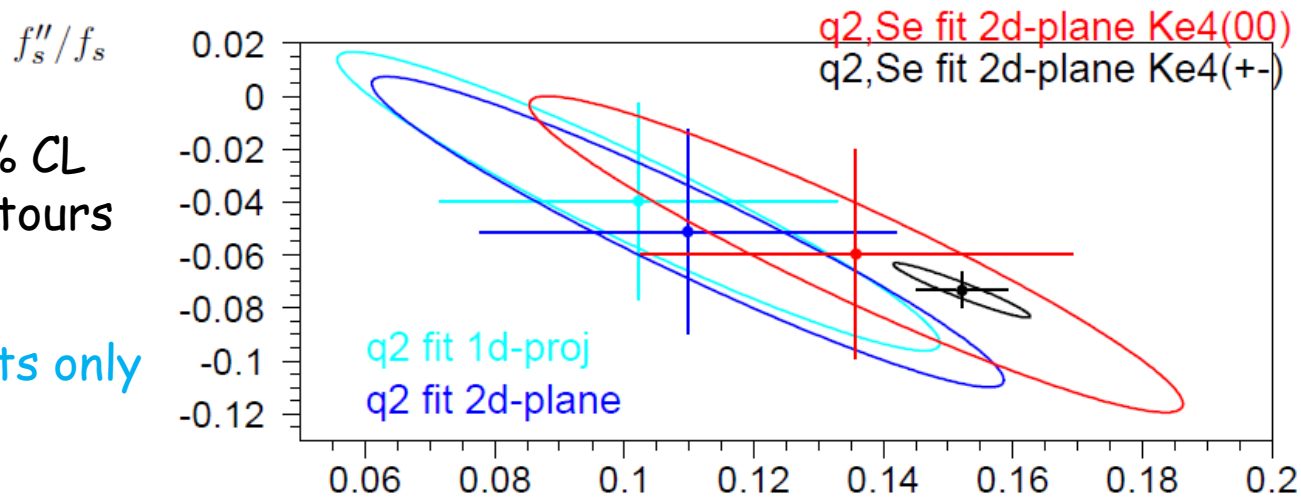
The improved chi2 supports the extra fit parameter ➡

Form factor energy dependence

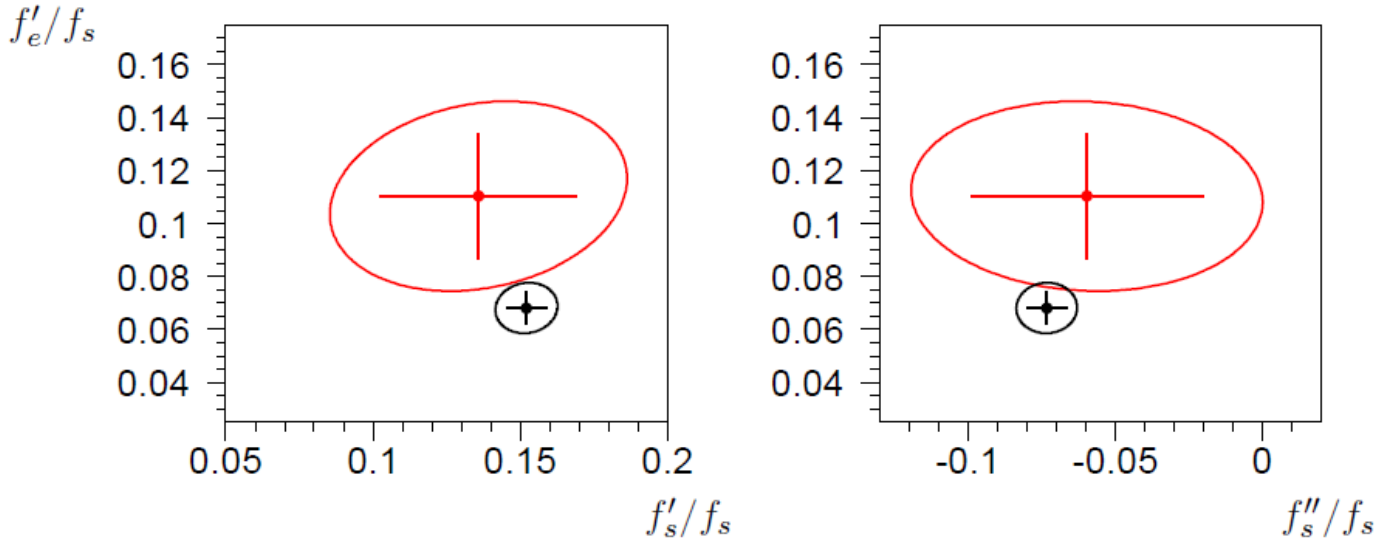
Are the various results statistically consistent ? YES ,also with the charged Ke4 mode

68% CL contours

q2 fits only



Ke4 (00)
60K events
Ke4 (+-)
1M events



Ke4 (00)

Ke4(+-)

Form factor systematics and results

Source	f'_s/f_s	f''_s/f_s	f'_e/f_s
fit procedure	–	–	–
reconstruction	–	–	–
trigger corrections	–	–	–
acceptance control	0.002	0.002	0.001
background control	0.012	0.013	0.022
electron-id	0.008	0.007	0.002
total systematics	0.015	0.015	0.022
statistical error	0.033	0.040	0.024

Preliminary !

$$f'_s/f_s = 0.136 \pm 0.033_{stat} \pm 0.015_{syst}$$
$$f''_s/f_s = -0.060 \pm 0.039_{stat} \pm 0.015_{syst}$$
$$f'_e/f_s = 0.110 \pm 0.024_{stat} \pm 0.022_{syst}$$

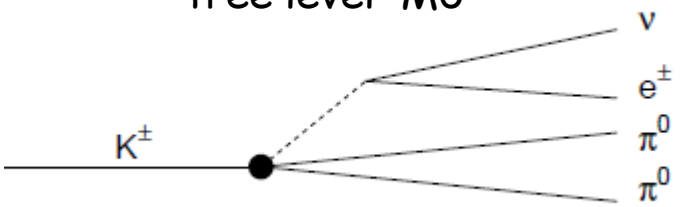
Chi2/ndf = 0.97 (54% prob)

	f''_s/f_s	f'_e/f_s
f'_s/f_s	−0.946	0.189
f''_s/f_s		−0.063

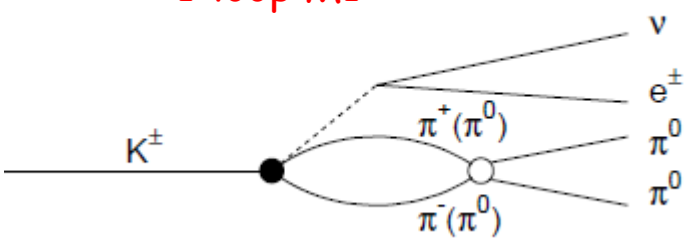
Form factor below q2 = 0

The 10% drop (cusp-like) for q2<0 can be interpreted as final state charge exchange scattering in the Ke4(+-) mode :

tree level M0



1-loop M1



Follow papers by Cabibbo (PRL 93 (2004)) and Cabibbo-Isidori (JHEP 03 (2005)) to write the amplitudes :

$$M_0 = f_s(1 + a\ q^2 + b\ q^4 + c\ S_e/4m_{\pi+}^2),$$

$$M_1 = -2/3\ (a_0^0 - a_0^2)\ f_s\ \sigma_\pi,$$

$$q^2 = S_\pi/4m_{\pi+}^2 - 1 \text{ and } \sigma_\pi = \sqrt{1 - 4m_{\pi+}^2/S_\pi} = \sqrt{|q^2/(1+q^2)|}$$

above threshold (q^2 >0): $|M|^2 = |M0 + iM1|^2 = M0^2 + M1^2$

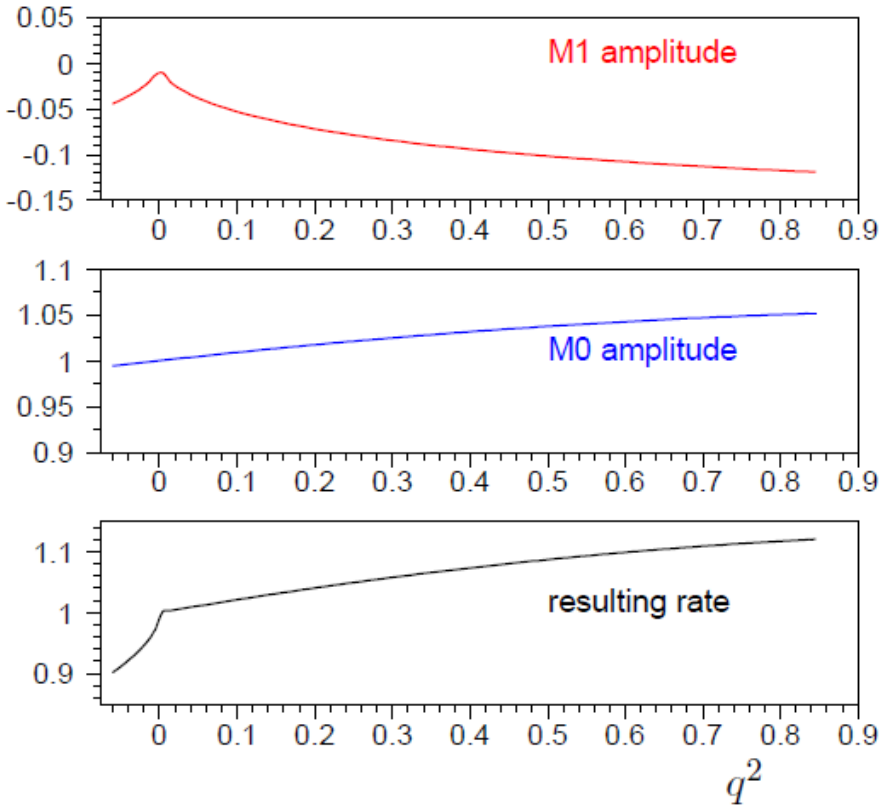
below threshold (q^2 <0): $|M|^2 = |M0 + M1|^2 = M0^2 + M1^2 + 2M0\ M1$

M is reduced as M1 < 0

Playing with amplitudes

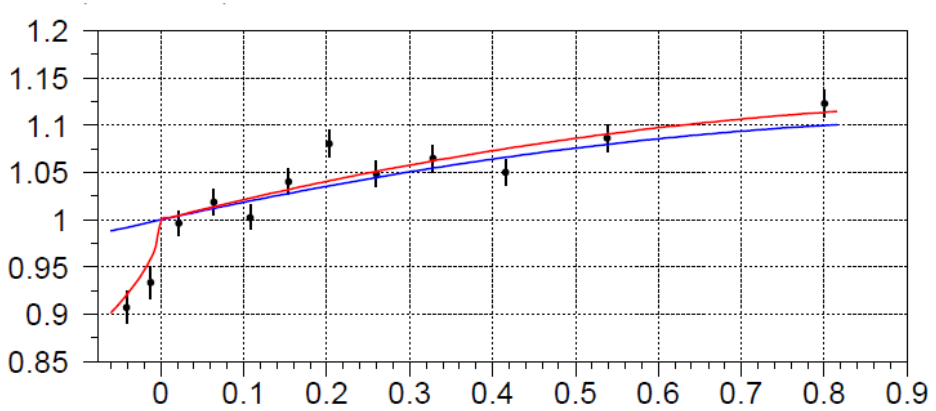
Preliminary !

Simple exercise :
- M1 and M0 add up to $|M|^2$
- reproduce qualitatively the deficit below q2 =0



Replaying the fit to the (q2,Se) plane, including the known M1 contribution for q2> 0, one gets different parameter values with same errors and correlations

$$f_s'/f_s = 0.123 \pm 0.034_{stat}$$
$$f_s''/f_s = -0.054 \pm 0.040_{stat}$$
$$f_e'/f_s = 0.111 \pm 0.024_{stat}$$



Extending the fitted function to q2<0, reproduces the observed distribution (not a fit to the q2<0 distribution !)

Branching ratio measurement and uncertainties

BR (Ke4) = (N4 –Nbkg)/ N3 x A3/A4 x ε(K3π) /ε(Ke4) x BR (K3π)

N4 Signal events	66000	(1.761 ± 0.022) %
Nbkg background events	708 (~1% relative)	
N3 normalization events K3π ($\pi^{\pm}\ \pi^0\ \pi^0$)	94×10^6	
A3 normalization Acceptance	4.05%	
A4 signal Acceptance	1.92%	
ε(K3π) normalization trigger eff	97.4%	
ε(Ke4) signal trigger eff	96.1%	

Preliminary !

Systematic error 0.38%

External error 1.25%

Statistical error 0.39%

Source	Contribution (%) to BR uncertainty
Acceptance stability with cuts	0.15 (not final)
Form factor uncertainty	0.13
Background evaluation	0.02
Accidental activity	0.02
Trigger cut	0.08
Particle identification	0.25
Radiative events modeling	0.17
Simulation statistics	0.09
Trigger efficiency	0.03
Total systematics	0.38 (not final)
External error	1.25
Statistical error	0.39

Branching ratio result

combination of 10 statistically independent samples
(each with stable data taking conditions)

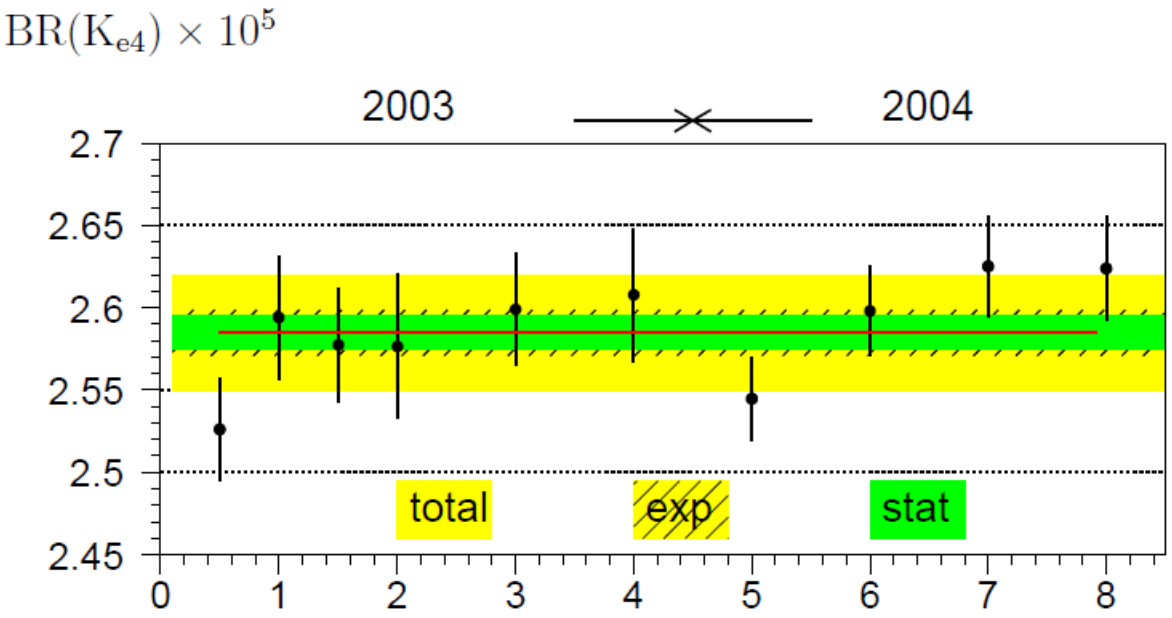
Preliminary !

$\Gamma(Ke400)/\Gamma(K3\pi) = (1.468 \pm 0.008_{exp})\ 10^{-3}$
0.6% relative uncertainty

BR (Ke400) = $(2.585 \pm 0.010\ stat \pm 0.010\ syst \pm 0.032\ ext) \times 10^{-5}$
= $(2.585 \pm 0.035\ ) \times 10^{-5}$

1.3% relative

PDG 2012 $(2.2 \pm 0.4) \times 10^{-5}$ 18% relative



Error bars = sample dependent errors

from BR to absolute form factor

Integrating $d^3\Gamma = \frac{G_F^2 |V_{us}|^2}{2(4\pi)^6 m_K^5} \rho(S_\pi, S_e)\ J_3(S_\pi, S_e, \cos\theta_e) \times\ dS_\pi\ dS_e\ d\cos\theta_e.$

One gets : $\mathrm{BR}(\mathrm{K}^{00}_{e4}) = \tau_{K^\pm} \cdot |V_{us}|^2 \cdot f_s^2 \cdot \int d\Gamma_3/(|V_{us}| \cdot f_s)^2$

and using the kaon mean life time $(1.2380 \pm 0.0021) \times 10^{-8}$ s

$$|V_{us}| \cdot f_s = \quad 1.372 \pm 0.003_{stat} \pm 0.004_{syst} \pm 0.008_{ext}$$
$$\text{corresponding to } f_s = \quad 6.092 \pm 0.012_{\mathrm{stat}} \pm 0.017_{\mathrm{syst}} \pm 0.045_{\mathrm{ext}}$$

for $|V_{us}| = 0.2252 \pm 0.0009$

Preliminary !

To be compared with fs in the Ke4(+-) mode :

$$f_s = \quad 5.705 \pm 0.003_{\mathrm{stat}} \pm 0.017_{\mathrm{syst}} \pm 0.031_{\mathrm{ext}}$$

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both values not really consistent within their errors: is there a missing ingredient ?

Summary

Preliminary !

NA48/2 has collected a large sample of Ke4(00) events which leads to

- most precise BR value (1.3% relative precision) improving the world average value by more than one order of magnitude

- first form factor determination including significant dependence with q2 and Se + evidence for rescattering effect in the final state

- absolute form factor value significantly away from the Ke4(+-) corresponding form factor value

- results are PRELIMINARY but should be finalized by Summer 2013 and go for publication

- discussion with theory groups is most important for a correct and precise formulation of the processes under study.

- Prospects : both Kμ4 modes should be also accessible with $O(10^3)$ events, Kμ4 (+-) known so far from 9 events, Kμ4 (00) never observed …

Thank you !

Spares

Fs(0,0) = fs measurement systematic uncertainties

Preliminary !

$$f_s = 6.092 \pm 0.012_{\text{stat}} \pm 0.017_{\text{syst}} \pm 0.045_{\text{ext}}$$

Source	relative contribution (%)
BR(K_{e4}) statistical error	0.19
BR(K_{e4}) systematic error	0.19
Form factor energy dependence (systematic error)	0.10
Form factor cusp effect (systematic error)	0.13
Integration method (systematic error)	0.02
Radiative effects in integration (systematic error)	0.03
Total experimental error	0.32
BR(K_{e4}) external error	0.62
Kaon lifetime (external error)	0.08
$\|V_{us}\|$ (external error)	0.40
Total error (including external errors)	0.81