Studies of the K_{e4} decay at NA48/2

Michal Zamkovský on behalf of NA48/2 collaboration

Charles University in Prague

June 29, 2015

Outline

1. NA48 detectors
2. Physics motivation
3. Current experimental & theoretical situation
4. Event selection
5. Form factor measurement
6. Branching ratio measurement
7. Summary

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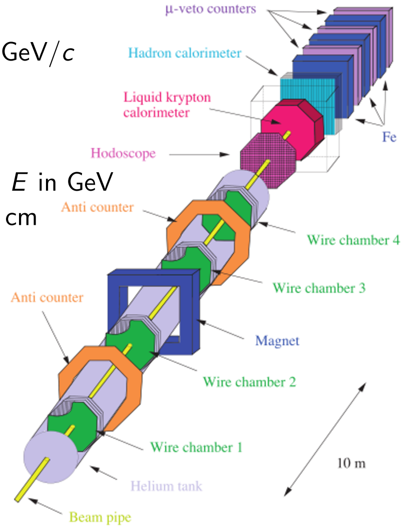
Experimental setup

1. Detector performances and resolutions:

DCH	$\sigma_x = \sigma_y = 90\mu\text{m}$ $\sigma_p/p = (1.02 \oplus 0.044 \cdot p)\%$ p in GeV/c
HOD	$\sigma_t \sim 150$ ps
LKr	$\sigma_E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ E in GeV $\sigma_x = \sigma_y = (0.42/\sqrt{E} \oplus 0.06)$ cm

2. Beam: simultaneous K^+ and K^- with a central momentum 60 GeV/$c \pm 3.8\%$ (rms)
   - Focused at DCH1 with ~ 10 mm transverse size
   - Superimposed beam axes within 1 mm



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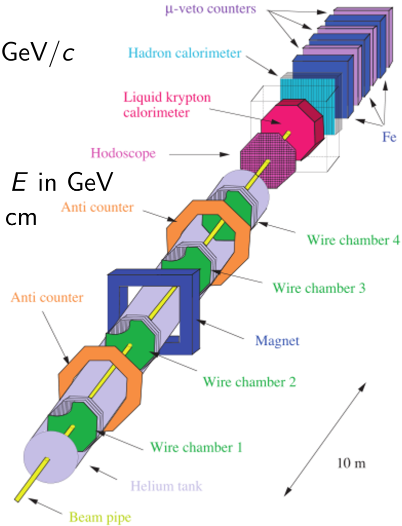

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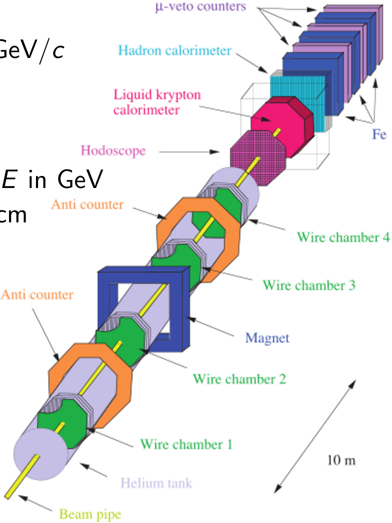

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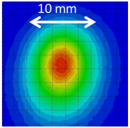

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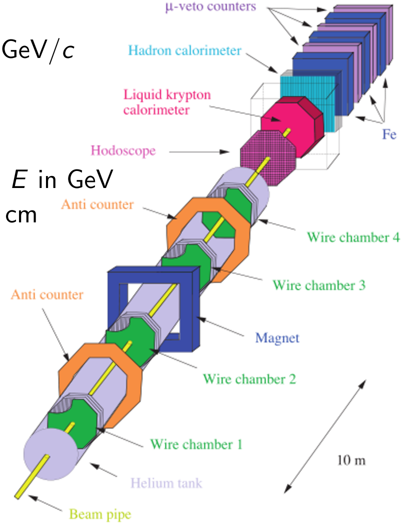

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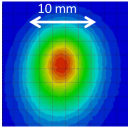

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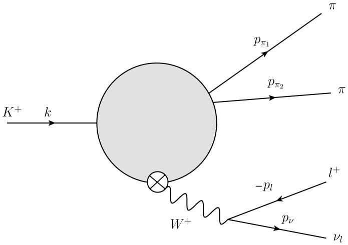
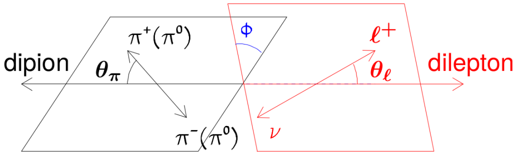
Kinematics

1. Mandelstam variables:

$$s = (p_{\pi_1} + p_{\pi_2})^2 = (k - L)^2 ,$$
$$t = (p_{\pi_2} + L)^2 = (k - p_{\pi_1})^2 , \quad u = (p_{\pi_1} + L)^2 = (k - p_{\pi_2})^2$$
$$L = p_l + p_\nu , \quad P = p_{\pi_1} + p_{\pi_2} , \quad Q = p_{\pi_1} - p_{\pi_2}$$

2. Kinematic constrain: $s + t + u = m_K^2 + 2m_\pi^2 + L^2$
3. Cabibbo-Maksymowicz formulation: $S_\pi = M_{\pi\pi}^2$, $S_e = M_{e\nu}^2$, and three angles: θ_π, θ_e, ϕ





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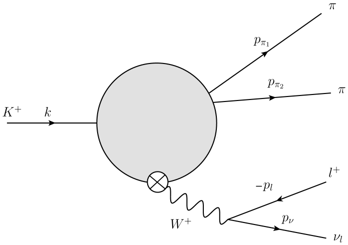

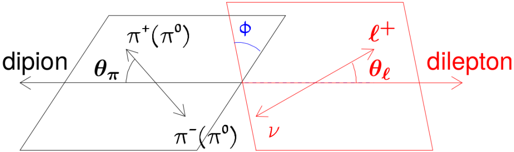

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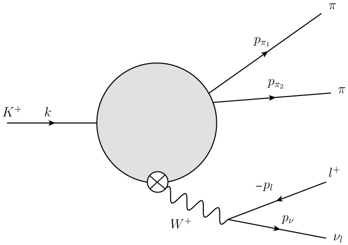

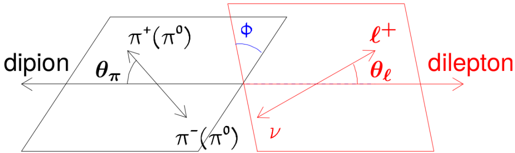

Cabibbo-Maksymowicz approach

1. Differential decay rate summed over lepton spins in Cabibbo-Maksymowicz formulation:

$$d^5\Gamma = \frac{G_F^2|V_{us}|^2}{2(4\pi)^6 m_K^5}\rho(S_\pi, S_e)J_5(S_\pi, S_e, \cos\theta_\pi, \cos\theta_e, \phi)$$
$$\times dS_\pi dS_e d\cos\theta_\pi d\cos\theta_e d\phi,$$

2. Function J_5 depends on complex hadronic form factors:

$$F_1 = \frac{1}{2}\lambda^{1/2}(m_K^2, S_\pi, S_e)\cdot F + \sigma(S_\pi)(PL)\cos\theta_\pi \cdot G,$$
$$F_2 = \sigma(S_\pi)\,(S_\pi S_l)^{1/2}\,G,$$
$$F_3 = \sigma(S_\pi)\,(S_\pi S_l)^{1/2}\,\frac{H}{m_K^2},$$
$$F_4 = -(PL)F - S_l R - \sigma(S_\pi)\frac{1}{2}\lambda^{1/2}(m_K^2, S_\pi, S_e)\cos\theta_\pi \cdot G$$

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$$\frac{F_1}{m_K^2} = \sum_{l=0}^{\infty} P_l(\cos\theta_\pi)\ F_{1,l} e^{i\delta_l}, \quad \frac{F_{2(3)}}{m_K^2} = \sum_{l=0}^{\infty} P_l'(\cos\theta_\pi)\ F_{2(3),l} e^{i\delta_l}$$

2. Expression for F, G, H form factors:

$$F = F_s e^{i\delta_{fs}} + (F_p e^{i\delta_{fp}} \cos\theta_\pi + F_d e^{i\delta_{fd}} \cos^2\theta_\pi + \dots),$$

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$$F_s = \left(f_s + f_s' q^2 + f_s'' q^4 + f_e \left(\frac{S_e}{4m_{\pi^+}^2} \right) \right) e^{i\delta_0^0}, \quad q = \sqrt{\frac{S_\pi - 4m_{\pi^+}^2}{4m_{\pi^+}^2}}$$

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Current experimental status of K_{e4}^{00}

1. Measurements done by other experiments
   - 37 events from three different experiments: $\mathrm{BR} = (2.2 \pm 0.4) \cdot 10^{-5}$
   - 214 events from KEK E470: $\mathrm{BR} = (2.29 \pm 0.34) \cdot 10^{-5}$
     error dominated by systematics
   - No form factor determination so far, just a relation between partial rate and a constant form factor value : $\Gamma = 0.8|V_{us} \cdot F|^2 \cdot 10^3 \mathrm{s}^{-1}$
2. Theoretical predictions for BR
   - Isospin symmetry relates more precisely measured modes and predicts:
     $\Gamma(\mathrm{K}_{l4}^{+-}) = 1/2\Gamma(\mathrm{K}_{l4}^{0\pm}) + 2\Gamma(\mathrm{K}_{l4}^{00})$
     Considering the different mean lifetimes τ_{K^+}, $\tau_{K_L^0}$, this results in:
     $$\mathrm{BR}(\mathrm{K}_{e4}^{+-}) - 2\mathrm{BR}(\mathrm{K}_{e4}^{00}) - \frac{1}{2}\mathrm{BR}(\mathrm{K}_{e4}^{0\pm})\frac{\tau_{K^\pm}}{\tau_{K_L^0}} = (-0.772 \pm 0.801) \cdot 10^{-2},$$
     where the error is dominated by K_{e4}^{00}
   - χPT calculations $O(p^2, p^4, p^6)$ from Bijnens Colangelo Gasser (1994) using K_{e4}^{+-} form factors from 1977 predicts:
     $BR\left(\mathrm{K}_{e4}^{00}\right) = (2.01 \pm 0.11) \cdot 10^{-5}$

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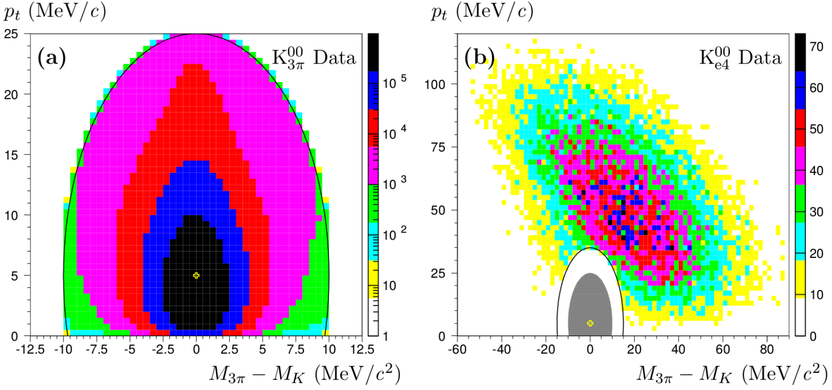

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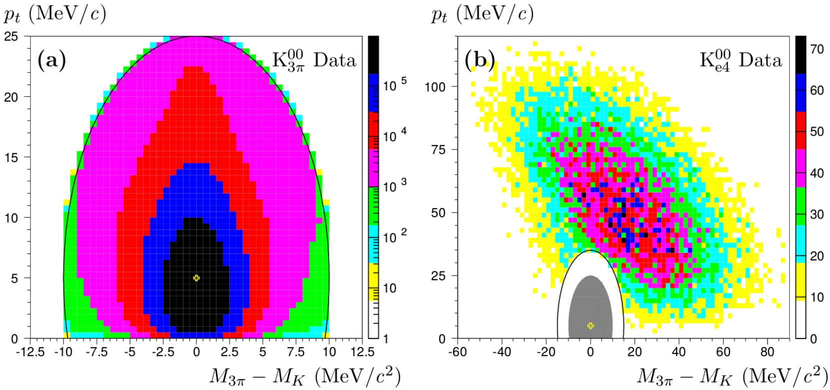

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1. Fit performed in 2D plane (S_π, S_e) after background subtraction
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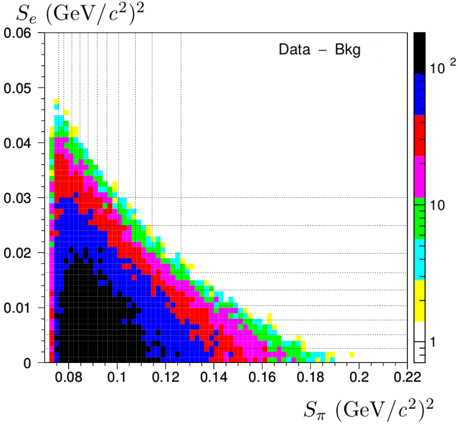
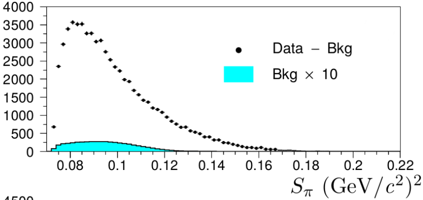
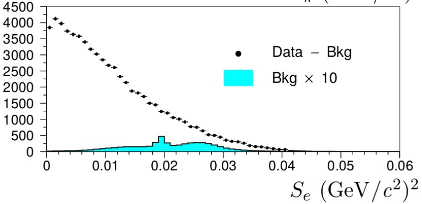
3. Fitting ten equal population bins for S_π above $4m^2_{\pi^+}$ and two bins below







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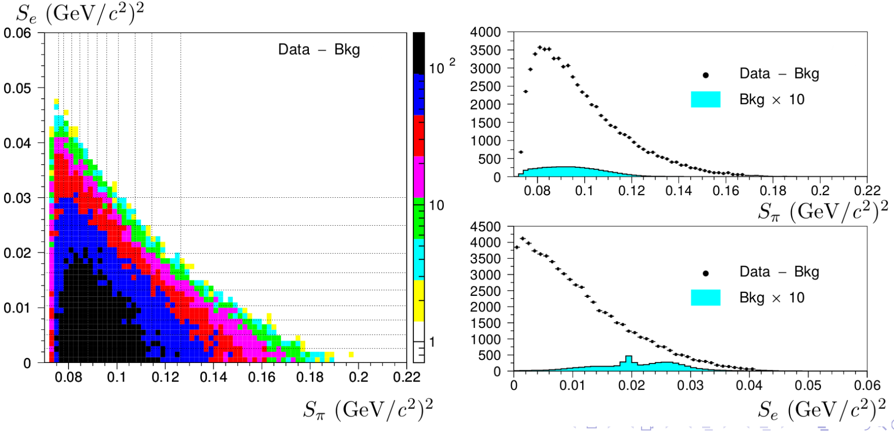

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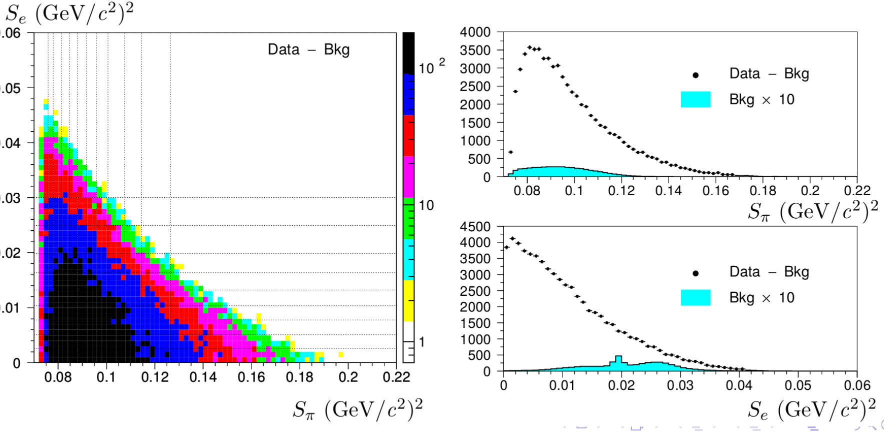

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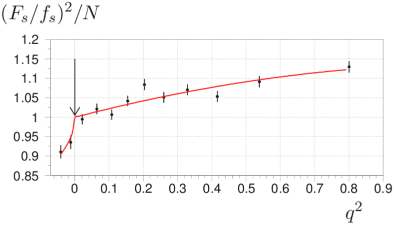

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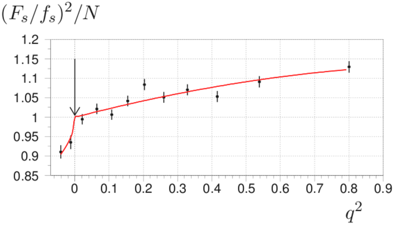

Fit results for K_{e4}^{00}

- $a = 0.149 \pm 0.033$
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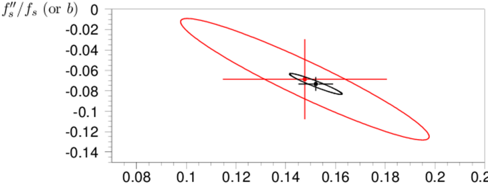

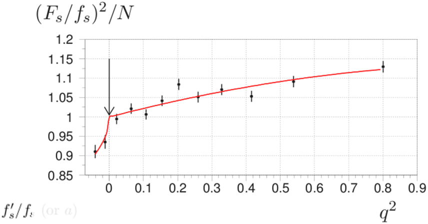

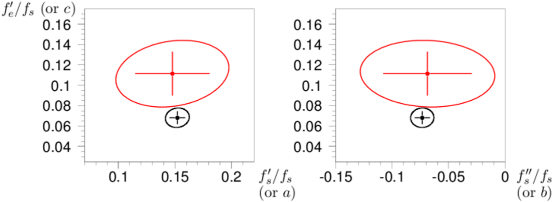

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$\pi - \pi$ *re-scattering*

1. $\left(\mathrm{K}^+ \to \pi^0\pi^0 l^\pm \nu\right)$ decay amplitude: $\mathcal{M} = \mathcal{M}_0 + \mathcal{M}_1$
2. The unperturbed amplitude $\mathcal{M}_0$ corresponds to the tree level:

$$\mathcal{M}_0 = f_{s0}\left(1 + aq^2 + bq^4 + c\frac{S_e}{4m_{\pi^+}^2}\right)$$

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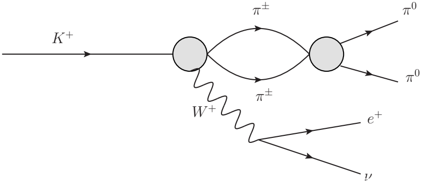

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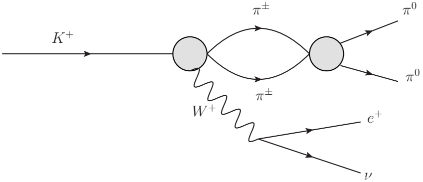

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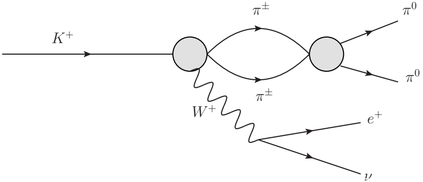
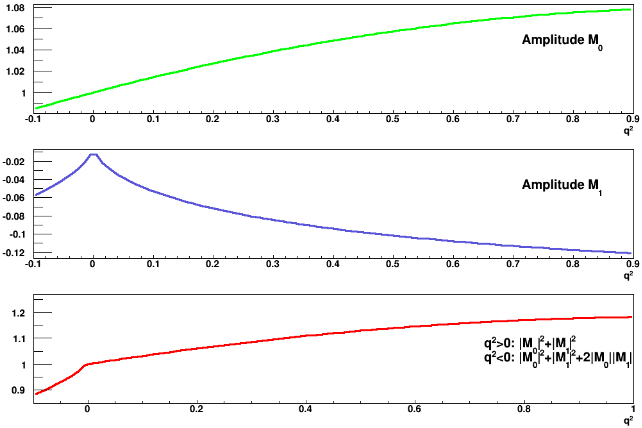


The amplitude $\mathscr{M}_1$ changes from real to imaginary at $2m_{\pi^+}$ with the consequence that $\mathscr{M}_1$ interferes destructively with $\mathscr{M}_0$ in the region below $2m_{\pi^+}$ threshold, while it adds quadratically above it:

$$|\mathscr{M}|^2 = |\mathscr{M}_0 + i\mathscr{M}_1|^2 = |\mathscr{M}_0|^2 + |\mathscr{M}_1|^2, \quad \text{above threshold}$$
$$|\mathscr{M}|^2 = |\mathscr{M}_0 + \mathscr{M}_1|^2 = |\mathscr{M}_0|^2 + |\mathscr{M}_1|^2 + 2|\mathscr{M}_0||\mathscr{M}_1|, \quad \text{below threshold}$$



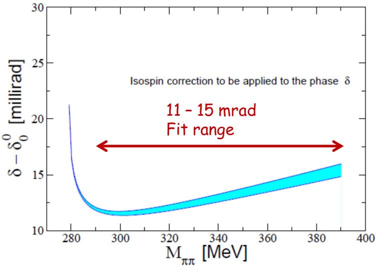
Related measurements on NA48 experiment

Isospin correction - χPT approach
Colangelo Gasser Rusetsky
EPJ C59,777(2009)

$$\delta = \frac{1}{32\pi F^2}\left\{(4\Delta_\pi + s)\sigma + (s - M_{\pi^0}^2)\left(1 + \frac{3}{2R}\right)\sigma_0\right\} - \delta_1^1 + O(p^4)$$

where

$$\Delta_\pi = M_{\pi^+}^2 - M_{\pi^0}^2,\ \sigma = \sqrt{1 - \frac{4M_\pi}{s}},\ R = \frac{m_s - \hat{m}}{m_d - m_u}$$



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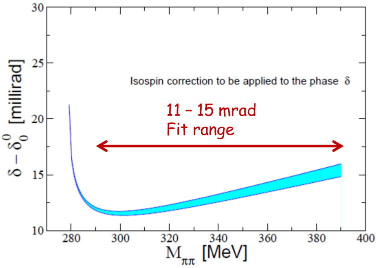

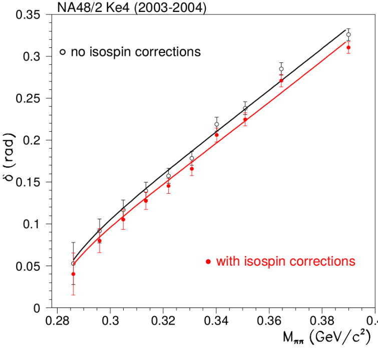

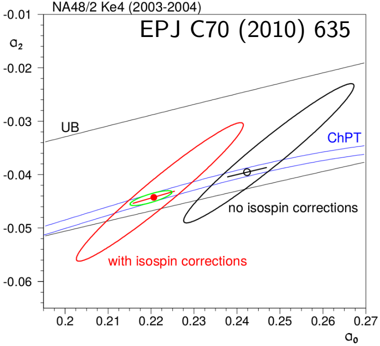

Branching ratio measurement

1. Branching ratio measurement:

$$\mathrm{BR}\left(\mathrm{K}_{e4}^{00}\right) = \frac{N\left(\mathrm{K}_{e4}^{00}\right)}{N\left(\mathrm{K}_{3\pi}^{00}\right)} \cdot \frac{A\left(\mathrm{K}_{3\pi}^{00}\right)}{A\left(\mathrm{K}_{e4}^{00}\right)} \cdot \frac{\epsilon\left(\mathrm{K}_{3\pi}^{00}\right)}{\epsilon\left(\mathrm{K}_{e4}^{00}\right)} \cdot \mathrm{BR}\left(\mathrm{K}_{3\pi}^{00}\right)$$

$$\mathrm{BR}(\mathrm{K}_{3\pi}^{00}) = (1.761 \pm 0.022) \times 10^{-2}$$

2. Result

$$\mathrm{BR}(\mathrm{K}_{e4}^{00}) = (2.552 \pm 0.010_{stat} \pm 0.010_{syst} \pm 0.032_{ext}) \times 10^{-5}$$

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Branching ratio measurement

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$$\mathrm{BR}\left(\mathrm{K}_{e4}^{00}\right) = \frac{N\left(\mathrm{K}_{e4}^{00}\right)}{N\left(\mathrm{K}_{3\pi}^{00}\right)} \cdot \frac{A\left(\mathrm{K}_{3\pi}^{00}\right)}{A\left(\mathrm{K}_{e4}^{00}\right)} \cdot \frac{\epsilon\left(\mathrm{K}_{3\pi}^{00}\right)}{\epsilon\left(\mathrm{K}_{e4}^{00}\right)} \cdot \mathrm{BR}\left(\mathrm{K}_{3\pi}^{00}\right)$$

2. Result

$$\mathrm{BR}(\mathrm{K}_{3\pi}^{00}) = (1.761 \pm 0.022) \times 10^{-2}$$

$$\mathrm{BR}(\mathrm{K}_{e4}^{00}) = (2.552 \pm 0.010_{stat} \pm 0.010_{syst} \pm 0.032_{ext}) \times 10^{-5}$$

Source	δBR/BR $\times 10^2$
Background and electron-ID	0.25
Radiative events modeling	0.19
Form factor uncertainty	0.17
Acceptance stability	0.16
Level 2 Trigger cut	0.04
Simulation statistics	0.07
Trigger efficiency	0.03
Total systematics	0.40
External error from BR($\mathrm{K}_{3\pi}^{00}$)	1.25
Statistical error	0.39

Summary and outlook

1. Sample of 65000 K_{e4}^{00} reconstructed events has been studied (JHEP 08 (2014) 159)
    - First measurement of form factor F_s parametrized by described a, b, c, d constants obtained from the fit in (S_π, S_e) plane
    - Significantly improved precision of BR measurement
    - Observation of the cusp singularity which can be related to $\pi - \pi$ scattering - consistent with a_0^0, a_2^0 values measured in K_{e4}^{+-} mode
2. Prospects
    - NA62 is starting data taking (see Augusto Ceccucci talk in plenary session)
    - Lots of kaon decays expected in the next years (2015-2018)
    - Suggestions of deeper studies welcome

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Thank you for the attention!