Probing non perturbative QCD with K_{e4} and $K^{\pm}\rightarrow\pi^{\pm}\gamma\gamma$ decays from the NA48/2 and NA62 experiments

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on behalf of the **NA48/2** and **NA62** collaborations

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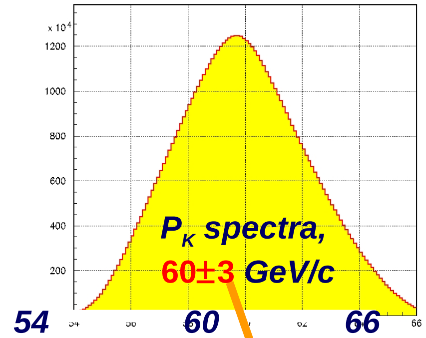
Outline

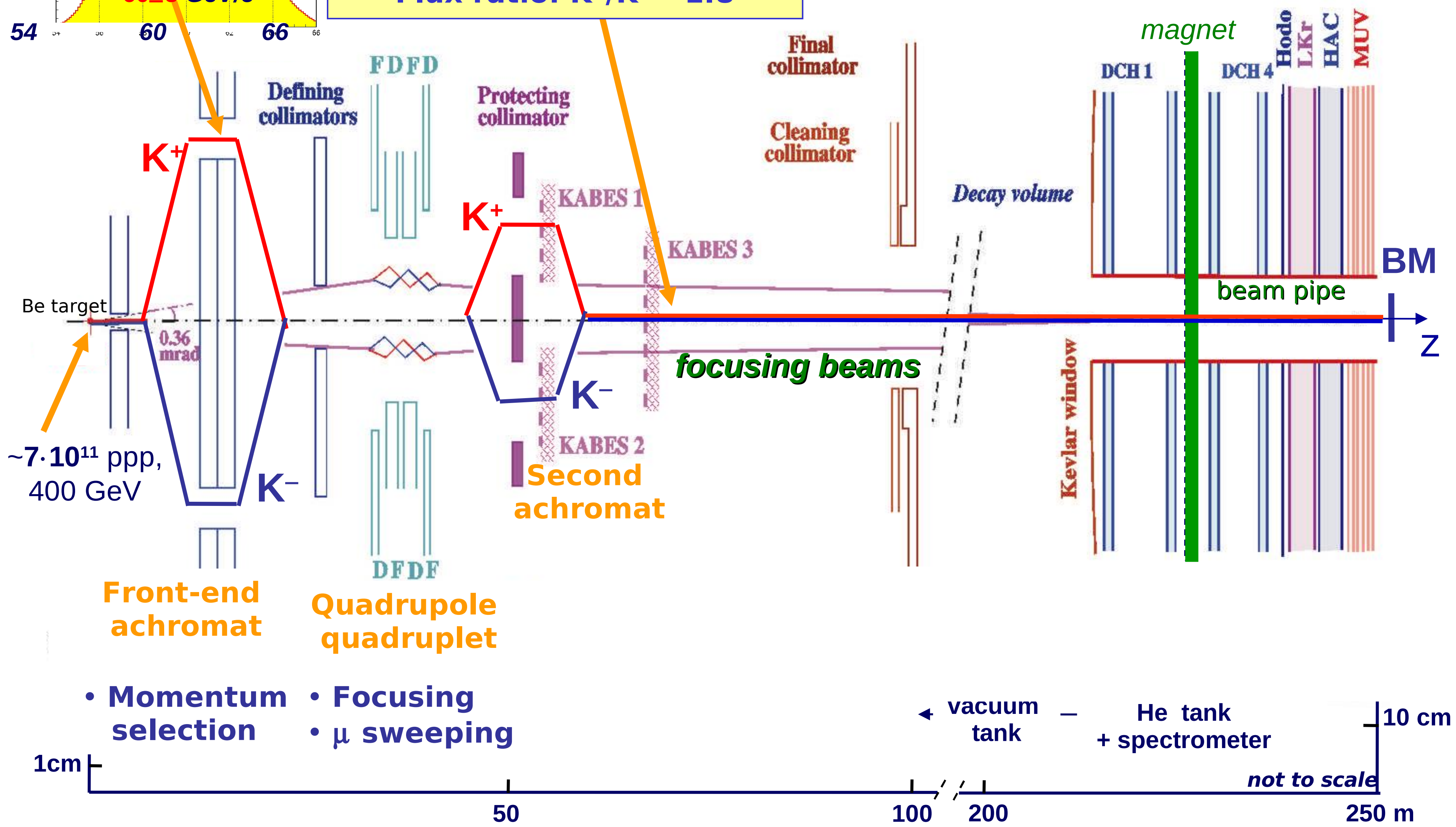
- Introduction to NA48/2 experiment
- Ke4 : theory
- NA48/2: $K^{\pm} \rightarrow \pi^{+}\pi^{-}e^{\pm}\nu$ Form Factors and Branching fraction
- NA48/2: $K^{\pm} \rightarrow \pi^{0}\pi^{0}e^{\pm}\nu$ Branching fraction
- NA48/2 and NA62 (Phase I): $K^{\pm} \rightarrow \pi^{+}\gamma\gamma$ study
- Summary and prospects

NA48/2 beam line



2-3M K/spill (π/K~10),
π decay products stay in pipe.
Flux ratio: K⁺/K⁻ ≈ 1.8

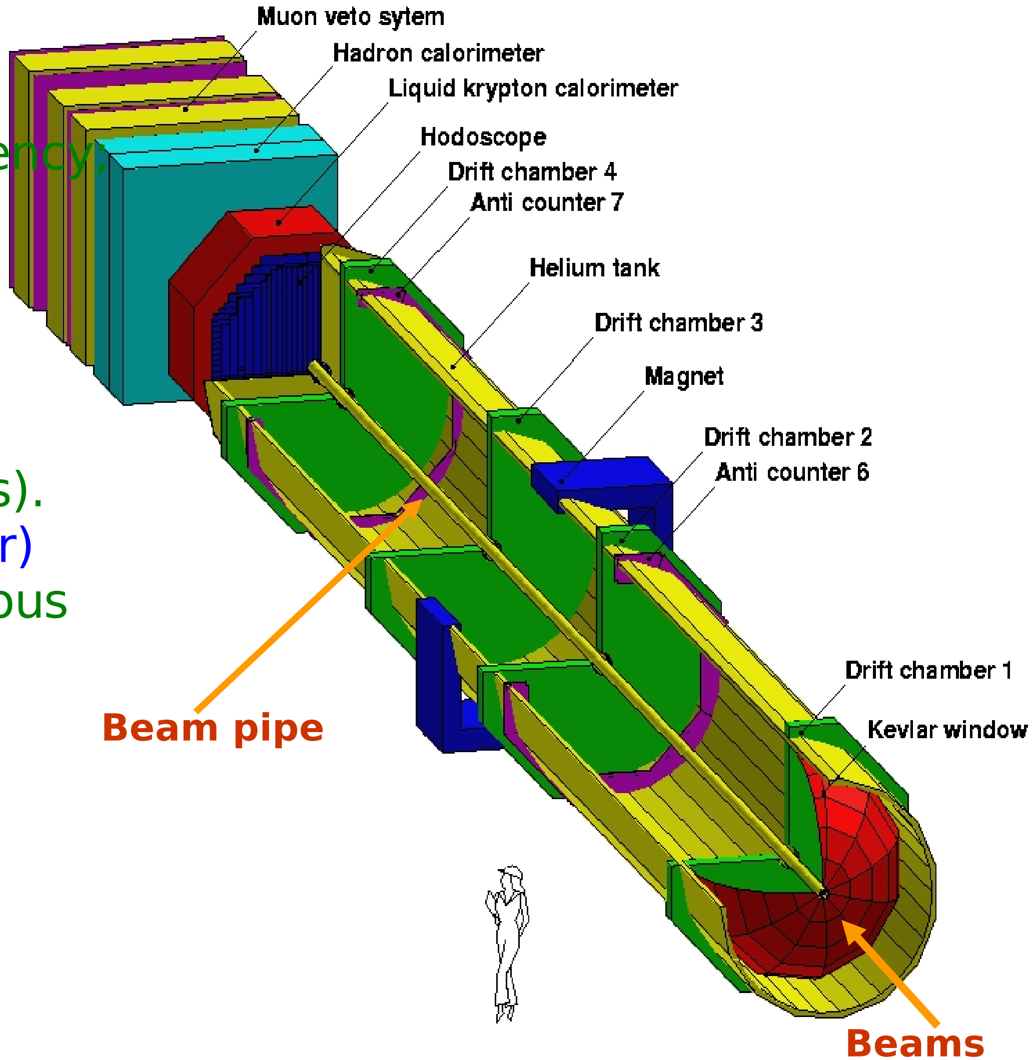
Simultaneous K⁺ and K⁻ beams:
large charge symmetrization of experimental conditions



The NA48 detector

Main detector components:

- Magnetic spectrometer (4 DCHs):
  4 views/DCH: redundancy ⇒efficiency;
  used in trigger logic;
  $\Delta p/p = 1.0\% \oplus 0.044\%{*}p$
  [p in GeV/c].
- Hodoscope
  fast trigger;
  precise time measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogenious
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$
  $\sigma_x=\sigma_y=0.42/E^{1/2} \oplus 0.06\text{cm}$
  [E in GeV].
  (0.15cm@10GeV).
- Hadron calorimeter, muon veto counters,
  photon vetoes.



Introduction: K_{e4} amplitude

$K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu$ amplitude
is a product of weak leptonic current and (V-A) hadronic current:

$$\frac{G_w}{\sqrt{2}} V^*_{us} \bar{u}_\nu \gamma_\lambda (1-\gamma_5) v_e \, \langle \pi^+\pi^- | V^\lambda - A^\lambda | \mathrm{K}^+ \rangle, \quad \text{where}$$

$$\langle \pi^+\pi^- | A^\lambda | \mathrm{K}^+ \rangle = \frac{-i}{m_K} \big(F(\mathbf{p}_{\pi^+} + \mathbf{p}_{\pi^-})^\lambda + G(\mathbf{p}_{\pi^+} - \mathbf{p}_{\pi^-})^\lambda + R(\mathbf{p}_e + \mathbf{p}_\nu)^\lambda \big)$$

R enters in the decay rate multiplied by lepton mass squared => this term is negligible for K_{e4}

and

$$\langle \pi^+\pi^- | V^\lambda | \mathrm{K}^+ \rangle = \frac{-H}{m_K^3} \epsilon^{\lambda\mu\rho\sigma} (\mathbf{p}_{\pi^+} + \mathbf{p}_{\pi^-} + \mathbf{p}_e + \mathbf{p}_\nu)_\mu \times (\mathbf{p}_{\pi^+} + \mathbf{p}_{\pi^-})_\rho (\mathbf{p}_{\pi^+} - \mathbf{p}_{\pi^-})_\sigma .$$

In the above expressions, $\mathbf{p}$ is the four-momentum of each particle, F, G, R are three axial-vector and H one vector complex form factors with the convention $\epsilon^{0123} = 1$.

F,G,R,H form factors (FF) depend on decay Lorentz invariants, so their parameterisation (or some tabulation) is needed to describe data.

Ke4 decays : formalism of $(\pi^+\pi^-)$ and $(\pi^0\pi^0)$ modes

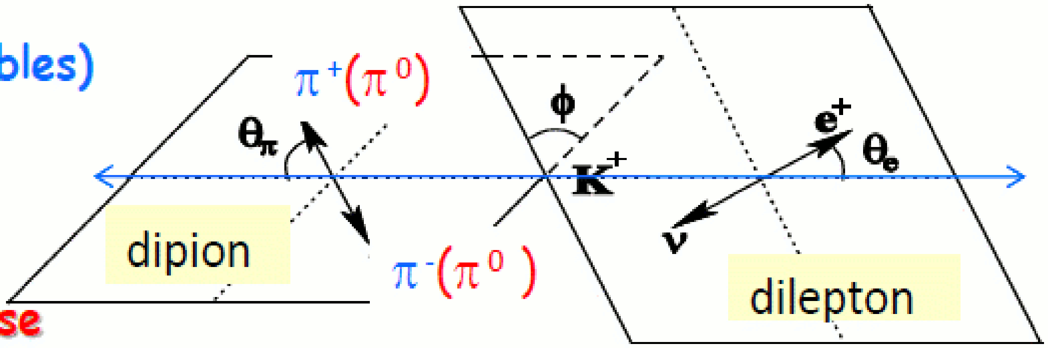
Five kinematic variables (Ca.Ma. variables)

(Cabibbo-Maksymowicz 1965)

S_π ($M^2_{\pi\pi}$), S_e ($M^2_{e\nu}$), $\cos\theta_\pi$, $\cos\theta_e$ and ϕ

Reduce to 3 variables in the $(\pi^0\pi^0)$ case

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)

+ Watson theorem (T-invariance) for δ_l^I

$\delta_0^0 \equiv \delta_s$ and $\delta_1^1 \equiv \delta_p$

F, G = 2 complex Axial Form Factors

$F = F_s\, e^{i\delta s} + F_p\, e^{id\delta p} \cos(\theta_\pi)$

$G = G_p\, e^{i\delta g}$

H = 1 complex Vector Form Factor

$H = H_p\, e^{i\delta h}$

Reduces to the single Fs Form Factor

Map the distributions of the Ca.Ma. variables in the **five-dimensional space** with **4 real Form factors** and only **one phase shift**, assuming identical phases for the p-wave Form Factors F_p, G_p, H_p

Dalitz plot density proportional to Fs^2

The fit parameters (real) are :

F_s F_p G_p H_p and $\delta = \delta_s - \delta_p$

reduce to the only Fs

Ke4(+-) : $K^{\pm}\to\pi^+\pi^-e^{\pm}\nu$

Signal ($\pi^+ \pi^- e^{\pm} \nu$) topology:

- 3 charged tracks, good vertex
- Opposite sign 2π («Right Sign»)
- 1 electron ($E_{LKr} / P_{DCH} \sim 1$)

Main background sources: $K\to3\pi$

Case of K^+ :

a $K^+ \to [\pi^+$ misident. as $e^+]\pi^+\pi^-$

$K^+ \to [\pi^+ \to e^+\nu]\pi^+\pi^-$

contributes twice more to «Right Sign» events:

(RS = $e^+\pi^+\pi^-$, 2 π^+ can decay)

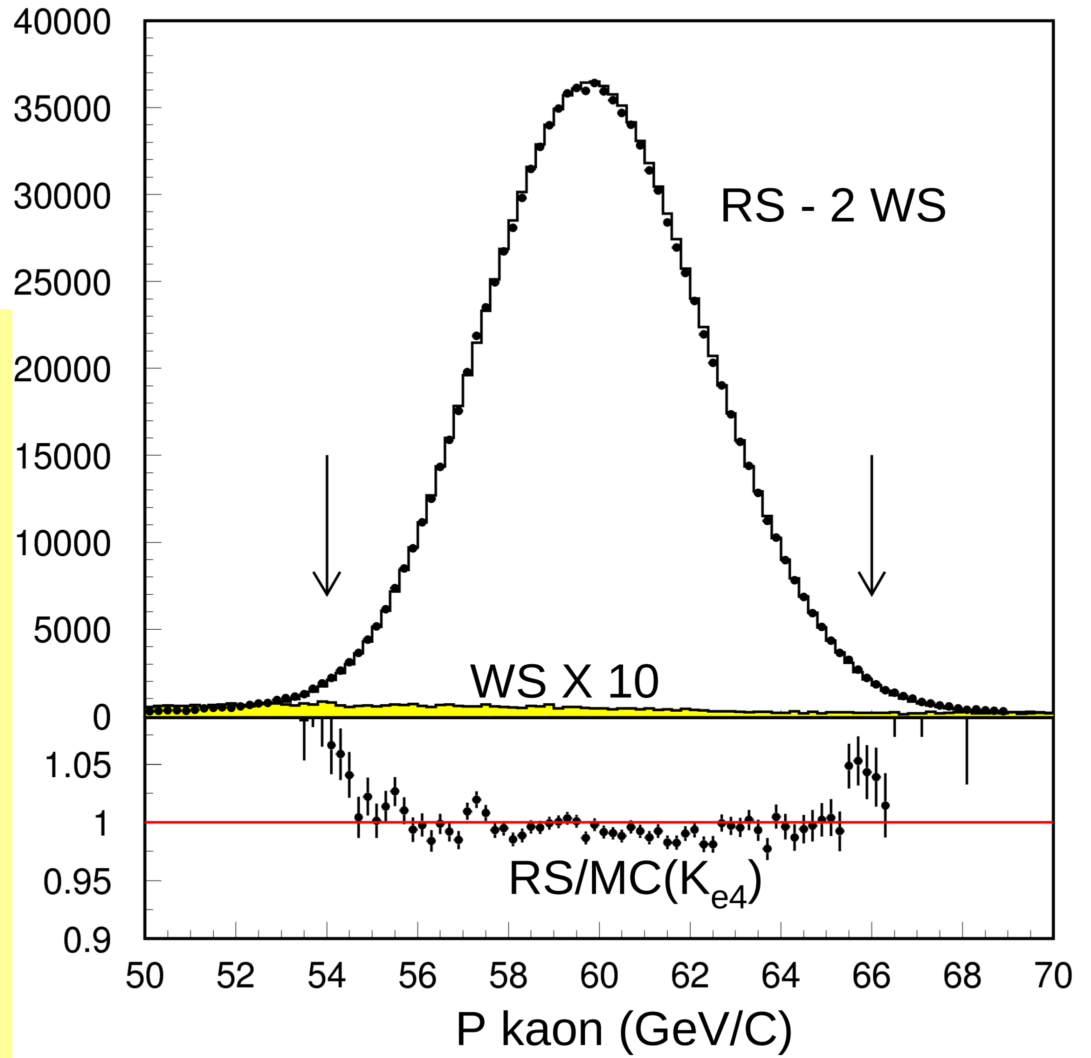
than to «Wrong Sign» ones:

(WS = $e^-\pi^+\pi^+$, 1 π^- can decay).

misident. lost

b $K^+ \to [\pi^0 \to e^+e^- \gamma]\ \pi^0\ \pi^+$

almost negligible



Total background is below 1% ,

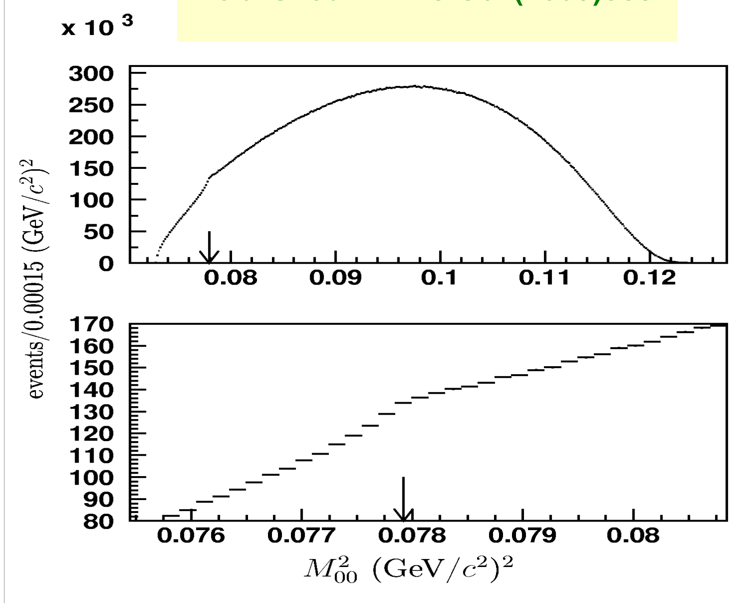
*estimated from WS events (contribution **a** is dominant) and checked by MC*

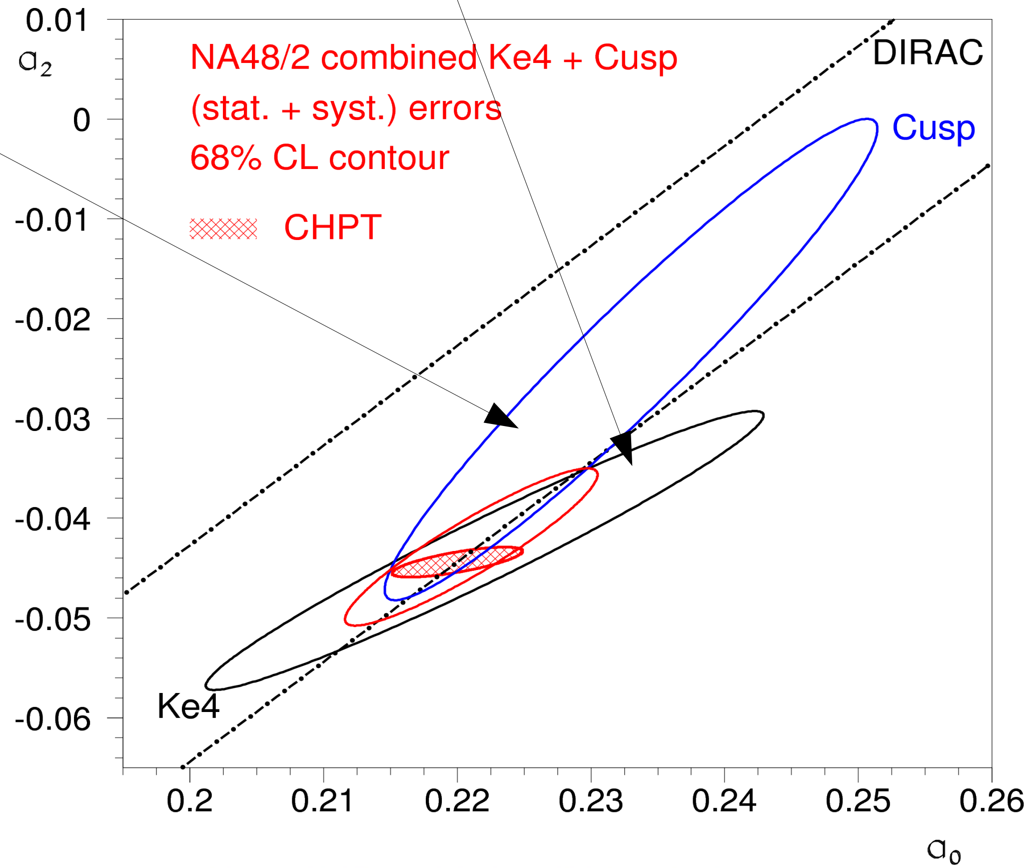
ππ scattering lengths measurement from phase shift $\delta (M_{\pi\pi}) = \delta_s - \delta_p$

[Eur.Phys. C70 (2010) 635]

Cusp in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$

Published in EPJ C64(2009)589





combined ππ scattering lengths result:

$$a_0^0 = 0.2210 \pm 0.0047_{\text{stat}} \pm 0.0040_{\text{syst}},$$

$$a_0^2 = -0.0429 \pm 0.0044_{\text{stat}} \pm 0.0028_{\text{syst}},$$

$$a_0^0 - a_0^2 = 0.2639 \pm 0.0020_{\text{stat}} \pm 0.0015_{\text{syst}}.$$

Form factors (normalized to f_s)

[Eur.Phys. C70 (2010) 635]

Series expansion with:

- $q^2 = S_\pi/(4m_\pi^2) - 1$
- $S_e/(4m_\pi^2)$

K_{e4} formfactors: fit results

	value	stat	syst
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 (const)	$= -0.048$	$\pm 0.003_{stat}$	$\pm 0.004_{syst}$
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 (const)	$= -0.398$	$\pm 0.015_{stat}$	$\pm 0.008_{syst}$

	correlations			
	f''_s/f_s	f'_e/f_s		g_p/f_s
f'_s/f_s	-0.954	0.080	g'_p/f_s	-0.914
f''_s/f_s		0.019		

$$F_s^2 = f_s^2(1+f'_s/f_s q^2+f''_s/f_s q^4+f'_e/f_s S_e/4m_\pi^2)^2$$

$$G_p/f_s=g'_p/f_s + g'_p/f_s q^2$$

$K_{e4}(+-)$ branching fraction measurement

[Phys.Lett.B715 (2012) 105]

$$K^{\pm}\rightarrow\pi^{+}\pi^{-}\nu e^{\pm} \; / \; K^{\pm}\rightarrow\pi^{+}\pi^{-}\pi^{\pm}$$

$$Br(K_{e4})=Br(K_{3\pi})\,(N(K_{e4}) - N(Bkg))/N(K_{3\pi})\;A(K_{3\pi})/A(K_{e4})\;\varepsilon(K_{3\pi})/\varepsilon(K_{e4})$$

Candidates:

$N(K_{e4})$ = 1 108 941 (K^{+} : 712 288 , K^{-} : 396 653)

N(bkg) = 2 x N(WS events) = 2 x 5 276

$N(K_{3\pi})$ = 18 818 920 (with negligible background)

Acceptance - GEANT3 based simulation:

$A(K_{3\pi}) = (23.967 \pm 0.010)\%$

$A(K_{e4}) = (18.193 \pm 0.004)\ \%$

Trigger efficiencies (measured using control triggers):

$\varepsilon(K_{3\pi}) = (97.65 \pm 0.03)\%$

$\varepsilon(K_{e4}) = (98.52 \pm 0.11)\%$

$Br(K_{3\pi}) = (5.59 \pm 0.04)\%$ (source of 0.72% external error for $Br(K_{e4})$)

$K_{e4}(+-)$ branching fraction measurement

Source	Correction (%) to BR value	Contribution (%) to BR uncertainty
Common to all subsamples		
Acceptance stability	–	0.18
Muon vetoing efficiency	–	0.16
Accidental activity	–0.12	0.21
Particle identification	–	0.09
Background estimate	–	0.07
Radiative events modeling	–	0.08
Subsample-dependent quoted as a global equivalent		
Trigger efficiency	–	0.11
Simulation statistics	–	0.05
Total systematics	–0.12	0.37
External error	–	0.72

Relative corrections and contributions to uncertainty

$\Gamma(K_{e4}(+-))/\Gamma(K_{3\pi}) = (7.615 \pm 0.008_{stat} \pm 0.028_{syst}) \times 10^{-4}$

$Br(K_{e4}(+-)) = (4.257 \pm 0.004_{stat} \pm 0.016_{syst} \pm 0.031_{ext}) \times 10^{-5}$
$= (4.257 \pm 0.035_{tot}) \times 10^{-5}$ *(external error is dominating)*

PDG 2012: $(4.09 \pm 0.10_{tot}) \times 10^{-5}$

Absolute form factor value (for $|V_{us}| = 0.2252 \pm 0.0009$ from PDG 2012) :

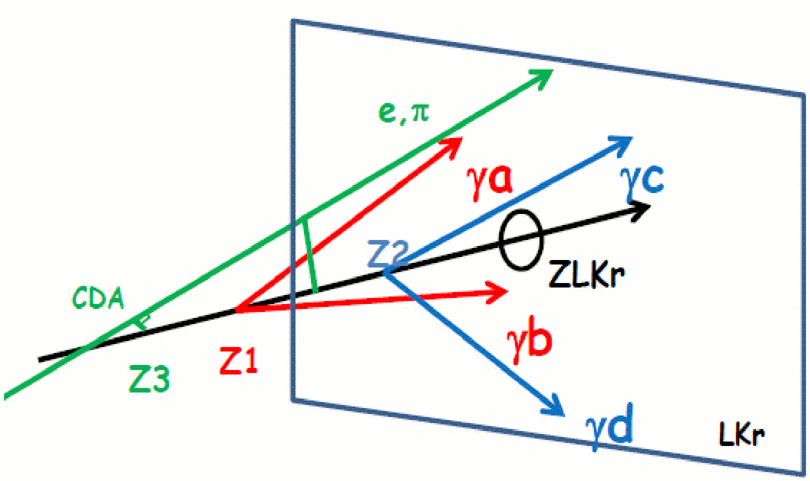
$F_s(q2=0,Se=0) = 5.705 \pm 0.003_{stat} \pm 0.017_{syst} \pm 0.031_{ext}$

Ke4(00) : $K^{\pm}\rightarrow\pi^0\pi^0\nu e^{\pm}$

Preliminary

$K^{\pm}\rightarrow\pi^0\pi^0\nu e^{\pm}$ relative to $K^{\pm}\rightarrow\pi^0\pi^0\pi^{\pm}$ with Br=(1.761±0.022)%

Common part of event reconstruction:



Find LKr γ-cluster pairs (ab) and (cd)
in-time (±2.5 ns), E>3GeV

- Decay positions Z_1 and Z_2 assuming $\pi^0 \rightarrow \gamma\gamma$.
- $Zn = (Z_1+Z_2)/2$ within (-16,+90) m
- $D_{Zn} = |Z_1-Z_2| < 500$ cm

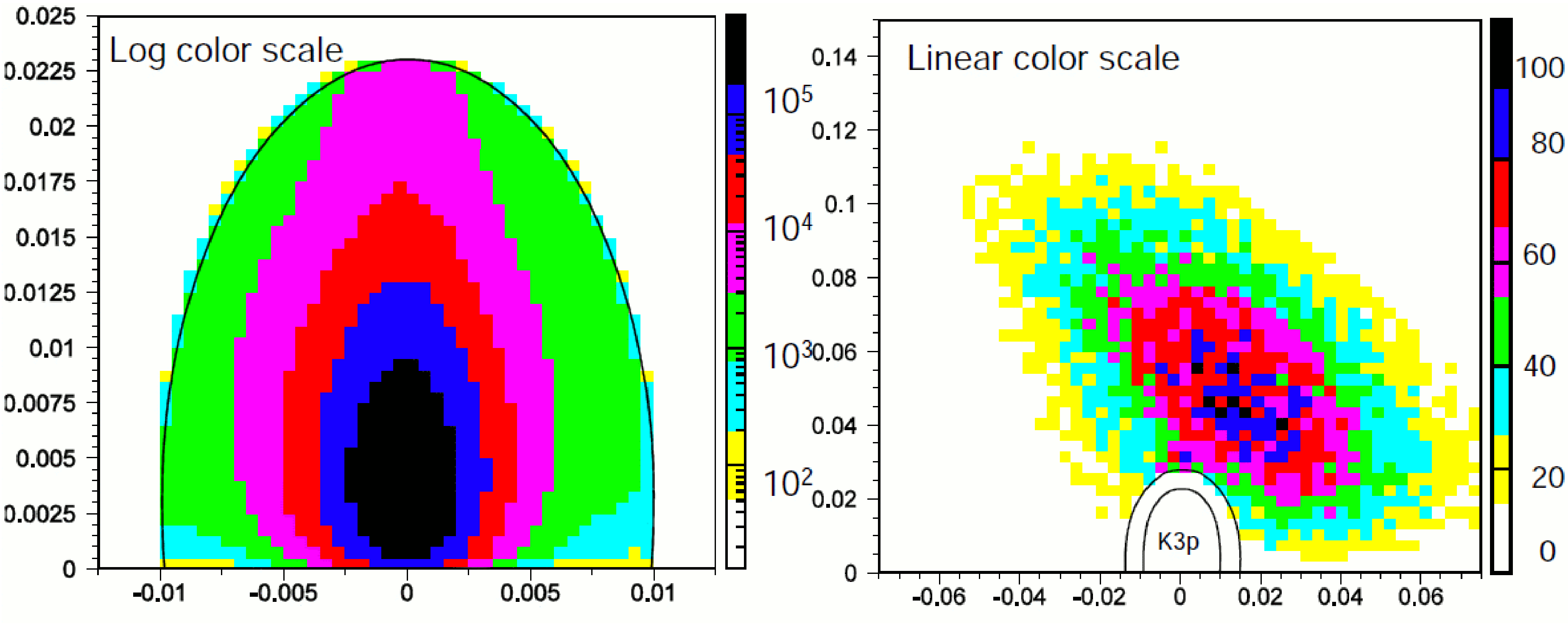
Combined with charged track (Z_3 at CDA to beam line) if:

- $D_Z = |Z_3-Z_n| < 800$ cm

$K_{e4}(00)$ signal selection

- Assign m_π to the charged track, plot P_t (to beam) vs invariant mass
- Cut $K_{3\pi}$ events with a small P_t and ~ kaon PDG mass

Elliptic cut separates ~70 x 10^6 $K_{3\pi}$ from ~45000 K_{e4} candidates



P_t(GeV/c) vs ($M_{3\pi}$ — M_K) (GeV/c²)

$K_{e4}(00)$ background rejection

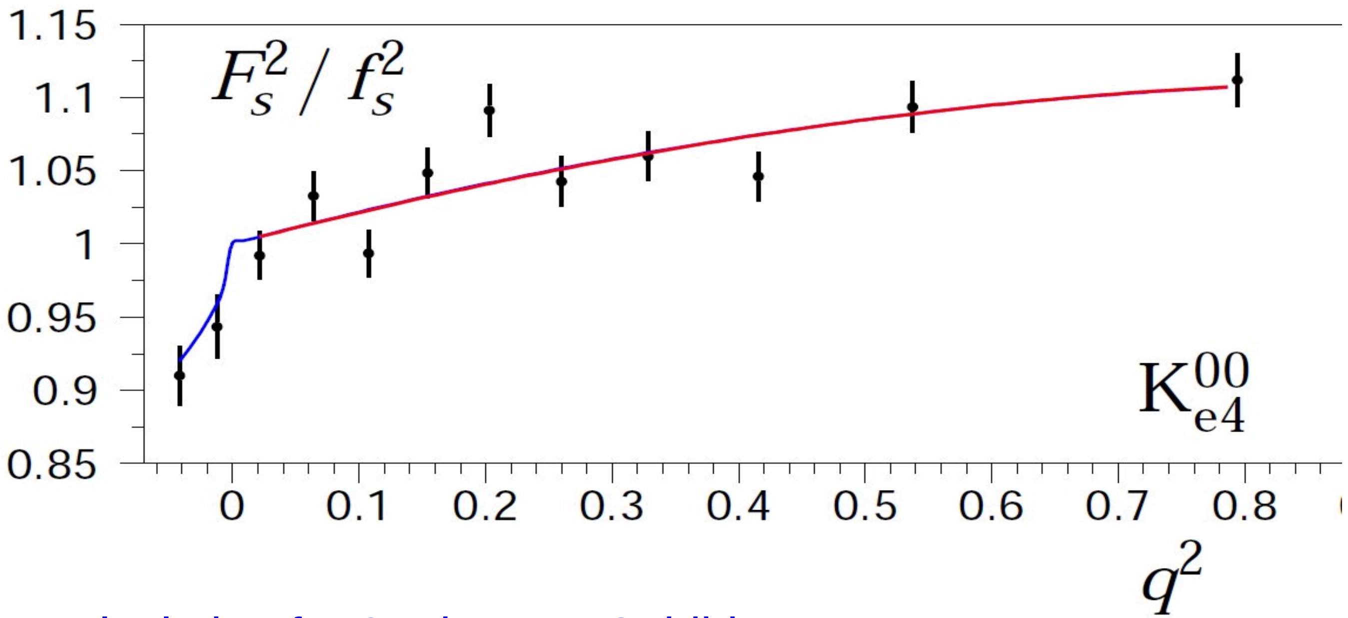
Electron identification:

- LKr cluster associated to track is in-time (10 ns) with track and $2\pi^0$
- E(LKr)/P(DCH) ~ 1 [0.9-1.1]
- Extra rejection using a dedicated discriminant variable. It is a linear combination of variables related to shower properties and trained on real and fake electrons from data.

- Fake-electron background ($K\rightarrow\pi^0\pi^0\pi^+$) 1.3%
- Real electron background ($K\rightarrow\pi^0\pi^0\pi^+$; $\pi\rightarrow e\nu$) 0.1%

Kaon momentum reconstruction imposing energy-momentum conservation and zero neutrino mass.

K_{e4}(00) Form Factor



1-loop calculation for 3π decays: Cabibbo, PRL 93(2004)121801

Above threshold: $|M|^2 = |M0 + i\ M1|^2 = M0^2 + M1^2$

Below threshold : $|M|^2 = |M0 + M1|^2 = M0^2 + M1^2 + 2\ M0\ M1$

$q2 = S\pi/4m\pi+^2 - 1 \quad \sigma\pi = \sqrt{(4m\pi+^2/S\pi - 1)} = \sqrt{(|q2|/(1+q2))}$

M0 = unperturbed amplitude: $Fs = fs\ (1 + a\ q2 + b\ q4 + c\ Se/4m\pi+^2)$

M1 = scattering amplitude: $-2/3\ (a0-a2)\ fs \sqrt{(|q2|/(1+q2))}$

$K_{e4}(00)$: Br measurement

Br is measured in independent subsamples and then combined.

N(K_{e4} candidates) = 44909 N(bkg) = 598

N($K_{3\pi}$ candidates) = 70.98 M

Acceptances: A(K_{e4}) = 1.77% A($K_{3\pi}$) = 4.11%

Trigger efficiency ε(K_{e4}) = 92-98% (ratio to $K_{\pi 3}$ ~ 1)

Normalization: Br ($K_{3\pi}$) = (1.761 ± 0.022)% - source of external error

Systematic Uncertainty (%)

Background	0.35
Simulation stat	0.12
FF dependence	0.20
Rad. Corr.	0.23
Trigger	0.80
Ident. of e	0.10
Beam geometry	0.10
Total	**0.94**

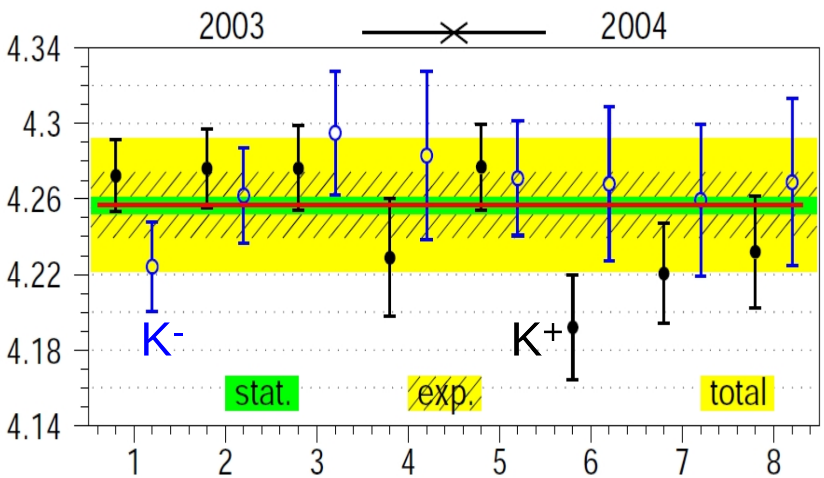
$Br(K_{e4}^{00})$ =

$(2.595 \pm 0.012_{stat} \pm 0.024_{syst} \pm 0.032_{ext})10^{-5}$

PDG 2012 : $(2.2 \pm 0.4)\ 10^{-5}$

Ke4 Br measurement in statistically independent subsamples

all in units of 10^{-5}

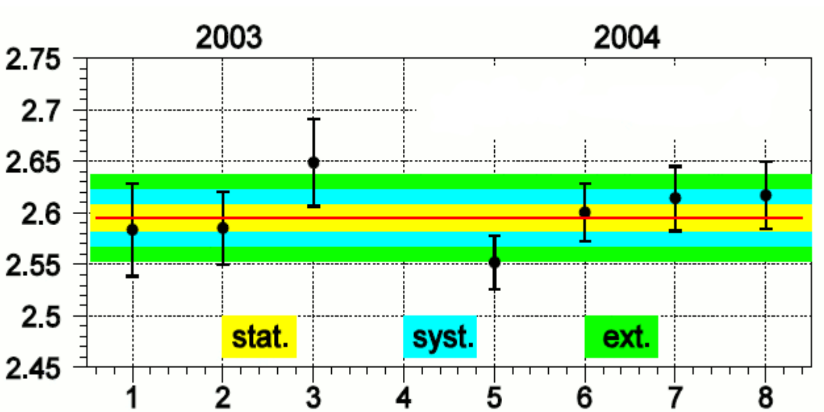


Phys.Lett. B715 (2012) 105:

K_{e4}(+-) normalized to $K_{3\pi}$(+-)

$(4.257 \pm 0.004 \pm 0.016 \pm 0.031) =$
Stat Syst Ext

(4.257 ± 0.035) 0.8% rel.err.



Preliminary:

K_{e4}(00) normalized to $K_{3\pi}$(00)

$(2.595 \pm 0.012 \pm 0.024 \pm 0.032) =$
Stat Syst Ext

(2.595 ± 0.042) 1.6% rel.err.

$K^{\pm} \to \pi^{\pm}\gamma\gamma$

- Dependence on a single parameter **ĉ** at $O(p^4)$ and $O(p^6)$

$$\frac{\partial\Gamma}{\partial y \partial z}(\hat{c}, y, z) = \frac{m_K}{2^9\pi^3}\left[z^2\left(|A(\hat{c}, z, y^2) + B(z)|^2 + |C(z)|^2\right) + \left(y^2 - \frac{1}{4}\lambda(1, r_\pi^2, z)\right)^2 |B(z)|^2\right]$$

loop contribution — **pole contribution** — **loop $O(p^6)$**

where $z = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2$, $y = \frac{p(q_1 - q_2)}{m_K^2}$

p, q_1, q_2 : $K^{\pm}, \gamma, \gamma$ momenta

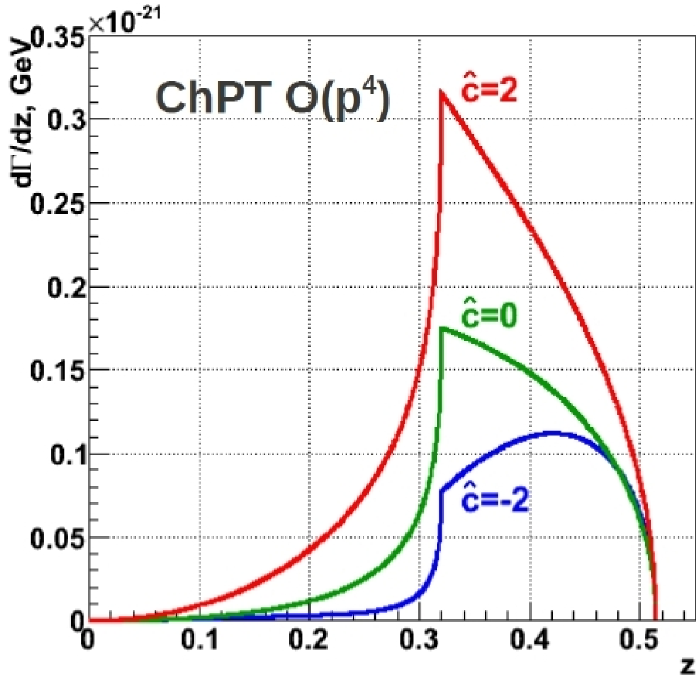
Experimental status:

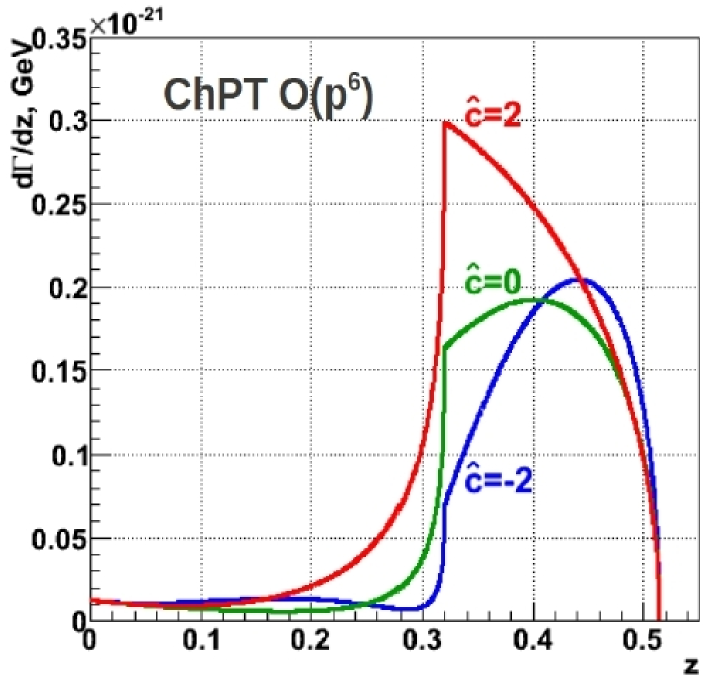
E787
[PRL 79 (1997) 4079]:

$Br = (1.1 \pm 0.3) 10^{-6}$

31 cand. , 5 est. bkg.

$\hat{C} = 1.1 \pm 0.6$ for $O(P^4)$
$\hat{C} = 1.8 \pm 0.6$ for $O(P^6)$

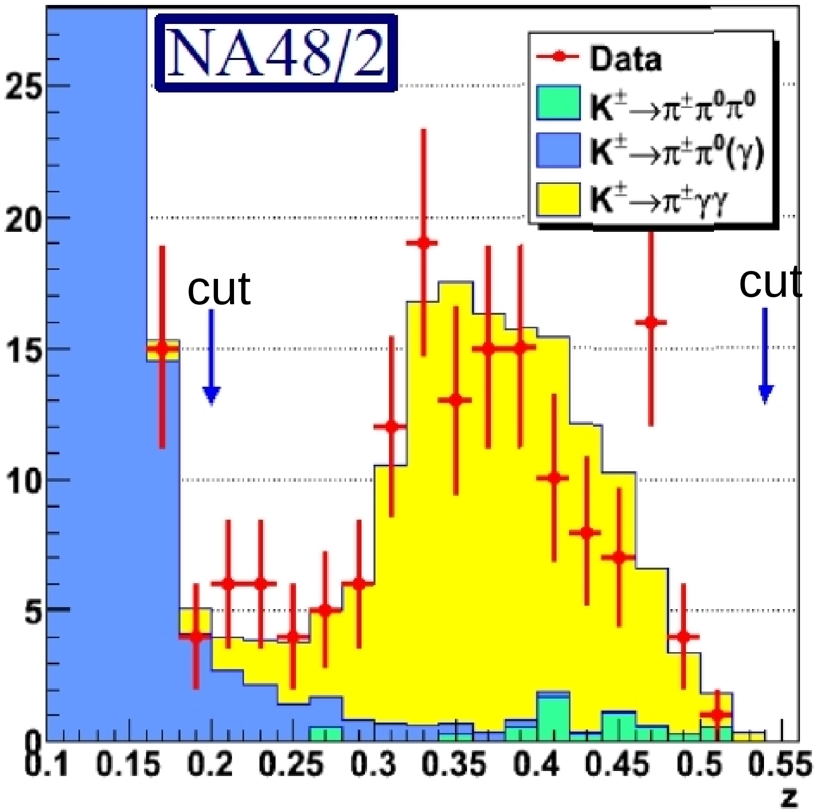


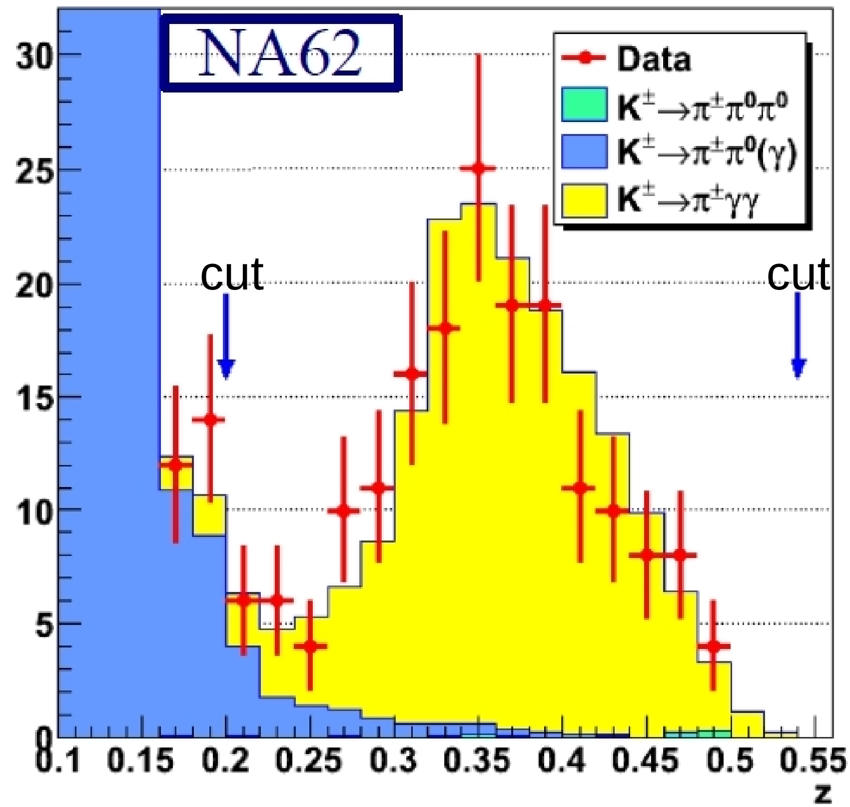


Cusp at $m_{\gamma\gamma} = 2m_{\pi^+}$ threshold

$K^\pm \to \pi^\pm \gamma\gamma$

- NA48/2 2004 data (3 days special minimum bias run)
- NA62 (phase I) 2007 data (3 month control min. bias trigger downscaled by 20)



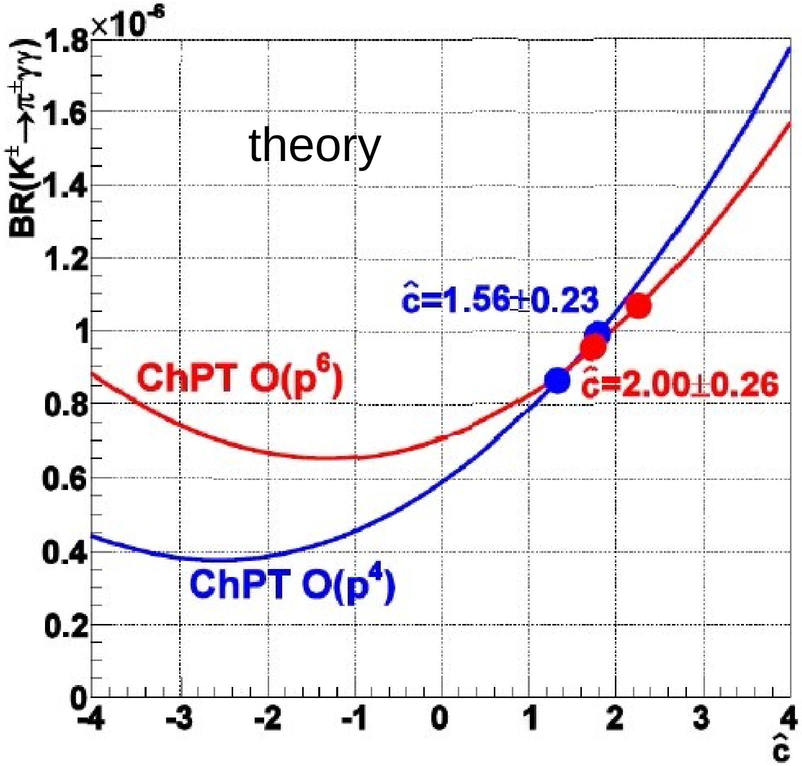


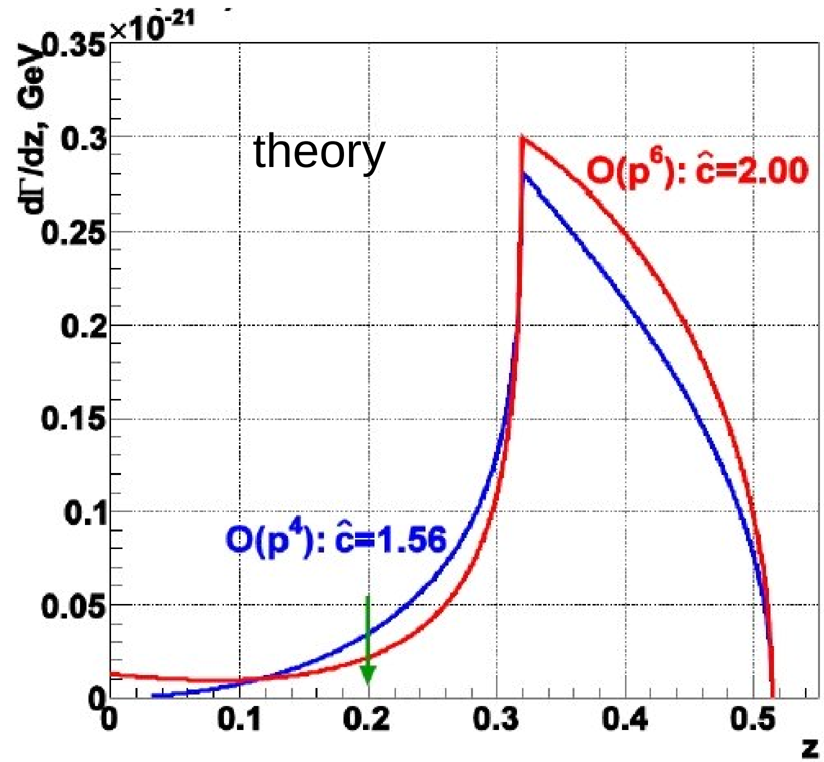
	NA48/2	NA62
$\pi^\pm\gamma\gamma$ cand.	147	175
$\pi^\pm\pi^0\gamma$	11.0±0.8	11.1±1.0
$\pi^\pm\pi^0\pi^0$	5.9±0.7	1.3±0.3
Signal $\pi^\pm\gamma\gamma$	130±12	163±13

$K^{\pm}\to\pi^{\pm}\gamma\gamma$

Combined NA48/2 and NA62 preliminary result, based on almost 300 events (10 times the present world sample):

Ĉ for $O(p^4)$ = (1.56±0.22stat±0.07syst) = 1.56±0.23
Ĉ for $O(p^6)$ = (2.00±0.24stat±0.09syst) = 2.00±0.26





Both approximations for this Z spectrum predict very similar Br values.

Measured Br for $O(p^6)$ = $(1.01\pm0.06)\cdot10^{-6}$: Preliminary!

Summary and future prospects

- **1.11 millons of reconstructed $K^{\pm}\to\pi^{+}\pi^{-}\nu e^{\pm}$ ($K_{e4}(+-)$) and ~45000 of $K^{\pm}\to\pi^{0}\pi^{0}\nu e^{\pm}$ ($K_{e4}(00)$) decays (2003+2004 data).**
- **Improved branching fractions:**

  Br $K_{e4}(+-)$ = (4.257 ± 0.035) 10^{-5} [Phys.Lett. B715 (2012) 105] (3 times better/PDG)

  Br $K_{e4}(00)$ = (2.595 ± 0.042) 10^{-5} [preliminary] (10 times better/PDG)
- **$K_{e4}(00)$ F_s form factor variation with q^2 looks similar to $K_{e4}(+-)$ one above $2m_{\pi+}$ threshold. Deficit below can be due to pions rescattering.**
- **Prospects: the observation of several 1000 decays in similar $K_{\mu 4}(00)$ (never observed) and $K_{\mu 4}(+-)$ (7 events observed).**
- **Preliminary result for $\pi^{\pm}\gamma\gamma$**

  $\hat{C}$ for $O(p^4)$=1.56±0.23; $\hat{C}$ for $O(p^6)$=2.00±0.26;

  Br($\pi^{\pm}\gamma\gamma$) for $O(p^6)$ = (1.01±0.06) $\cdot 10^{-6}$