Study of Ke4 decays at NA48 and χPT tests

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Outline

- Introduction to Ke4 decays ($K^{\pm}\to\pi^{+}\pi^{-}e^{\pm}\nu$, $K^{\pm}\to\pi^{0}\pi^{0}e^{\pm}\nu$)
  - Interest of the decays in the χPT framework
- The NA48 Experiment
  - The kaon beam
  - The detector
  - The new Branching Ratio measurement of $K^{\pm}\to\pi^{+}\pi^{-}e^{\pm}\nu$
  - The new Branching Ratio measurement of $K^{\pm}\to\pi^{0}\pi^{0}e^{\pm}\nu$
- Form Factors measurements
  - Method
  - Summary of Form Factors measurement for $K^{\pm}\to\pi^{+}\pi^{-}e^{\pm}\nu$
  - First look to $K^{\pm}\to\pi^{0}\pi^{0}e^{\pm}\nu$ Form Factor
- Conclusions

Chiral Perturbative Theory and Kl4 decays

At low energy (<~1 GeV) , perturbative QCD does not apply anymore but an effective theory (χPT) can be used to describe the physical observables in terms of external momenta and light quarks masses (Weinberg 1979).

Isospin symmetry translates into relations between decay modes ($m_u = m_d$, $\alpha_{QED} = 0$)

Rates : $\Gamma(Kl4(+-)) = \frac{1}{2}\Gamma(Kl4(0-)) + 2\Gamma(Kl4(00))$ (valid for both e, μ leptons)

BRs: BR(Kl4(+-))=0.121BR((Kl4 0-))+2BR(Kl4(00) $\tau(K^+) = 1.238 \cdot 10^{-8}$s, $\tau(K^0_L) = 5.116 \cdot 10^{-8}$s

Codes	Decays	PDG BR	Rel. Prec.	#evts
Ke4(+-)	$K^+ \rightarrow e \nu \pi^+ \pi^-$	$(4.09 \pm 0.10) \cdot 10^{-5}$	2.4%	418000
Ke4(00)	$K^+ \rightarrow e \nu \pi^0 \pi^0$	$(2.20 \pm 0.40) \cdot 10^{-5}$	18.2%	37
Ke4(0-)	$K^0 \rightarrow e \nu \pi^0 \pi^-$	$(5.20 \pm 0.11) \cdot 10^{-5}$	2.1%	6131

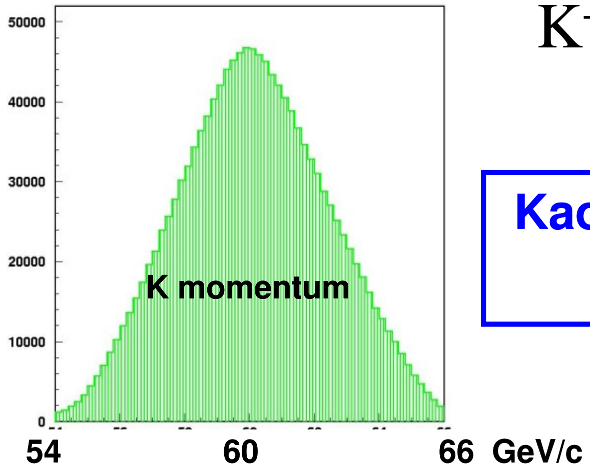
Direct Predictions using Form Factor calculations by χPT at O(p2,p4,p6…)

Bijnens,Colangelo,Gasser (Nucl Phys B427 1994):			predicted Br	rel. prec.
using as input	Ke4(+-)	= (3160 ± 140) s-1	$(3.91 \pm 0.17) \cdot 10^{-5}$	~ 5%
prediction	Ke4(00)	= (1625 ± 90) s-1	$(2.01 \pm 0.11) \cdot 10^{-5}$	~ 5%
prediction	Ke4(0-)	= (917 ± 170) s-1	$(4.69 \pm 0.87) \cdot 10^{-5}$	~ 18%

BR relation and direct BR predictions verified within the above experimental errors

there is room for improved χPT tests from better experimental measurements !

The simultaneus K^+/K^- beams

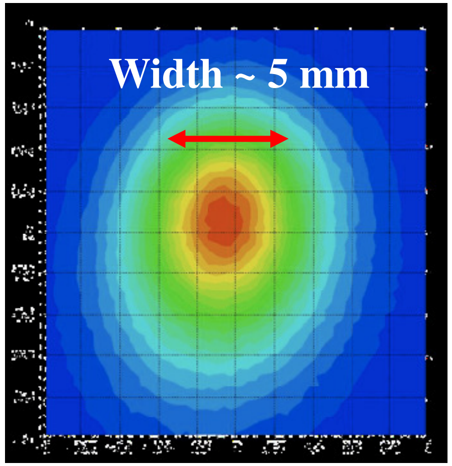


K^+ and K^- superimposed in space

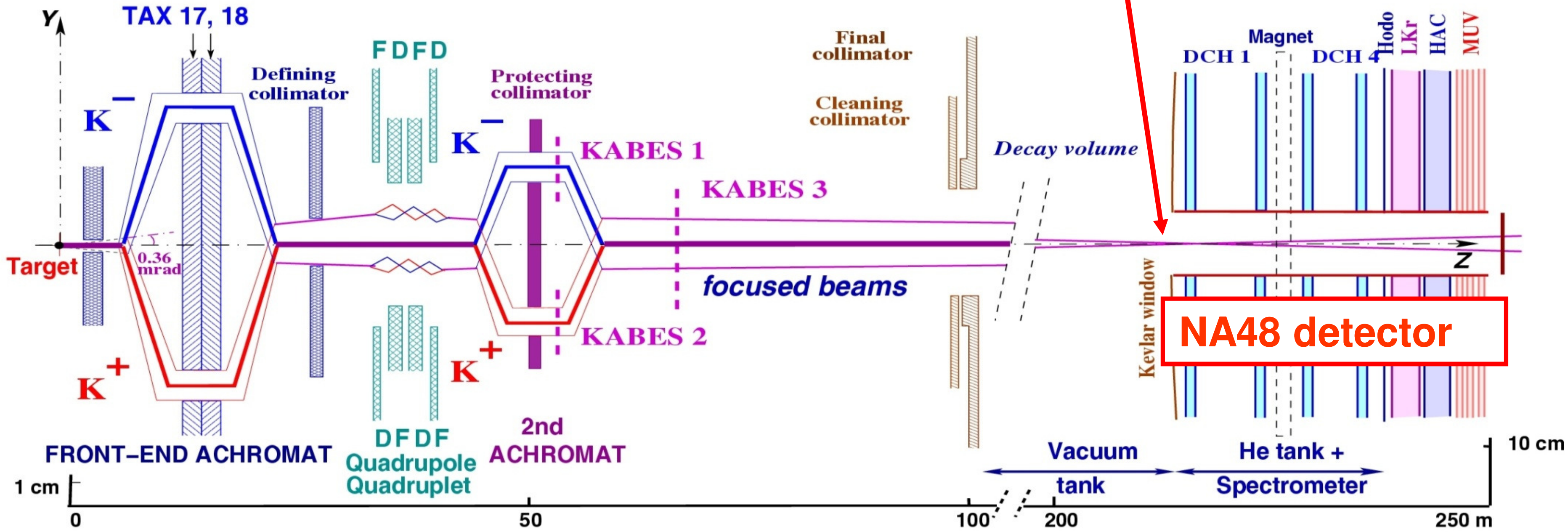
Flux ratio: K^+/K^- ~1.8

Kaon momentum:
60±3 GeV/c

Data taking:
2003 – 50 days
2004 – 60 days



Beams **coincide within 1 mm**



The NA48 detector

Magnetic spectrometer(4 DCHs):

4 views: redundancy ⇒ efficiency

$\sigma(p)/p = 1.0\% + 0.044\%\ p$ [GeV/c]

Charged hodoscope (scintillators):

Fast trigger and precise time measurement (~250 ps on single track)

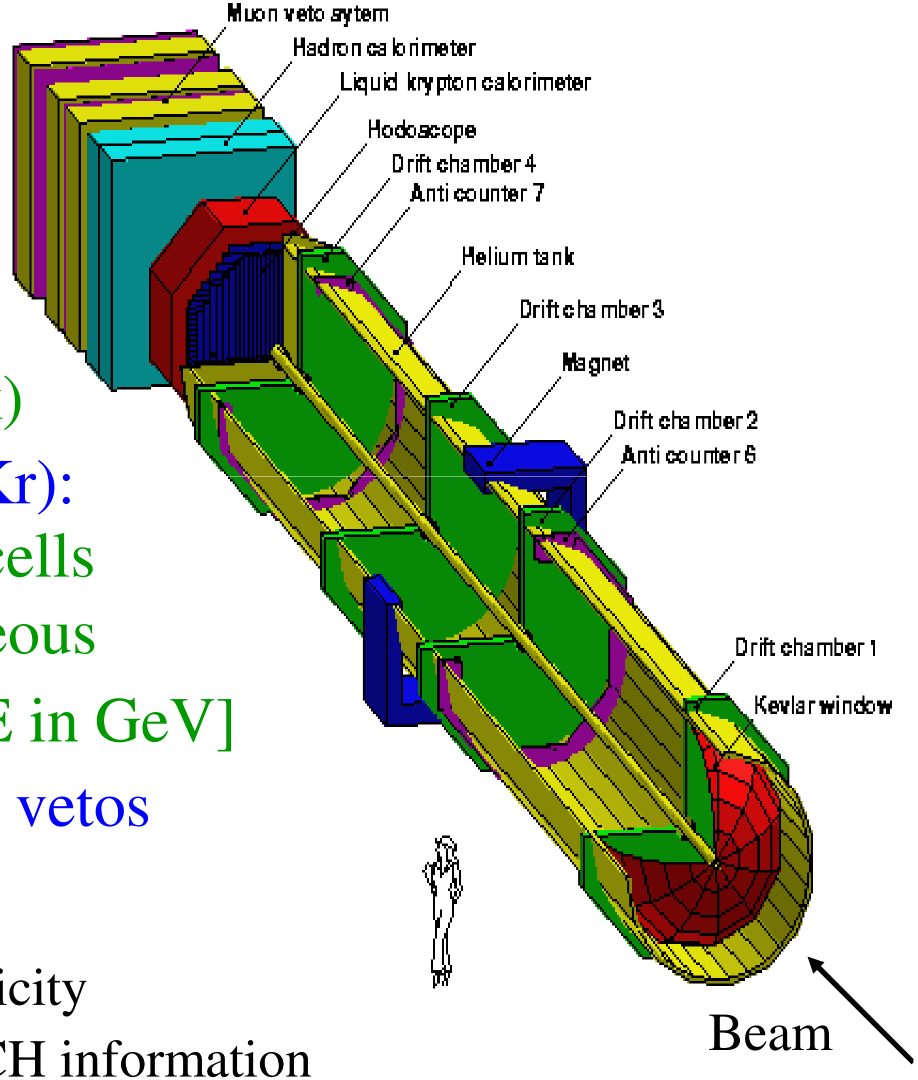
Liquid Krypton E.M. Calorimeter (LKr):

10 m^3 (~22 t), 1.25 m (27 X_0), 13212 cells

granularity: 2x2 cm^2, quasi-homogeneous

$\sigma(E)/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [E in GeV]

Then hadronic calorimeter, large angle vetos and muon counter (scintillators)



Trigger:

L1: Hodoscope, DCH multiplicity

L2: ON-line processing of DCH information

Ke4(+-) branching fraction measurement

$K^{\pm} \rightarrow e^{\pm} \nu \pi^{+} \pi^{-}$ extensively studied for the form factors measurement

Decay normalized to the abundant and similar topology mode $K^{\pm} \rightarrow \pi^{\pm} \pi^{+} \pi^{-}$ (K3π)

$$BR(Ke4) = [N(Ke4) - Nbkg]/N(K3\pi) \cdot A(K3\pi)/A(Ke4) \cdot \varepsilon(K3\pi)/\varepsilon(Ke4) \cdot BR(K3\pi)$$

Candidates for both decay extracted from the same trigger (~2.5 10^{10} total recorded triggers) at the same time:

N(Ke4) candidates = 1.11×10^{6} (7.12×10^{5} K^{+} and 3.97×10^{5} K^{-})

Nbkg (relative to Ke4) = 0.95%

N(K3π) candidates = 1.9×10^{9}

Acceptances (Geant3 based simulation used):

A(ke4) = 18.22% A(K3π) = 24.18%

Trigger efficiencies (measured using minimum bias control triggers):

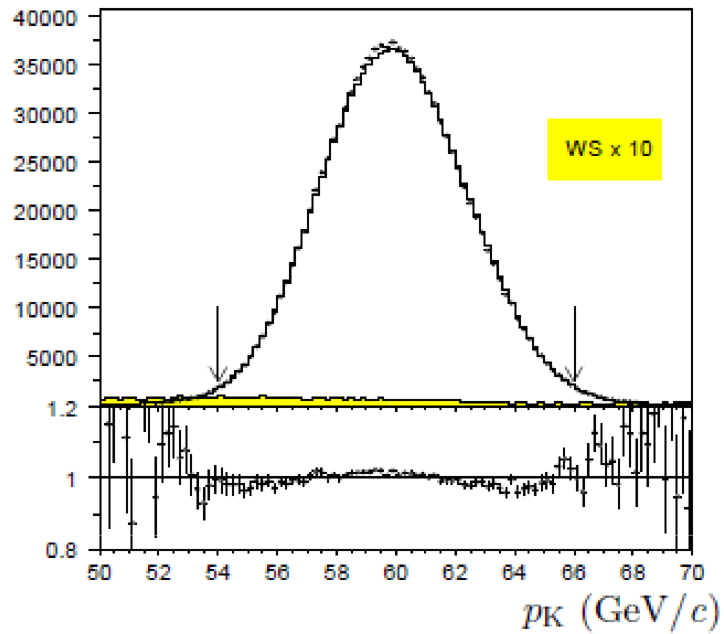
High efficiency, similar for signal and normalization mode

ε (Ke4) = 98.3% ε(K3π) = 97.5%

Branching ratio of K3π=(5.59 ±0.04)% 0.72% external error on BR(Ke4)

Result for Ke4(+-) Branching Fraction

Systematic Uncertainty	[%]
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



BR(K^+e4) = $(4.277 \pm 0.009_{\,stat+trig}) \cdot 10^{-5}$

BR(K^-e4) = $(4.283 \pm 0.012_{\,stat+trig}) \cdot 10^{-5}$ ⟵ never measured before

combined (common systematic error) to:

BR($K^\pm$e4) = $(4.279 \pm 0.004_{stat} \pm 0.005_{trig(stat)} \pm 0.015_{syst} \pm 0.031_{ext}) \cdot 10^{-5}$

= $(4.279 \pm 0.035_{tot}) \cdot 10^{-5}$ (0.8% rel.) external error dominated

To compare to PDG2010 $(4.09 \pm 0.10) \cdot 10^{-5}$ (2.4% rel.) systematic dominated

Ke4(00) Branching Fraction

Normalized to $K^{\pm} \rightarrow \pi^{\pm} \pi^{0} \pi^{0}$ extensively studied by NA48

(CP violating Asymmetry in the Dalitz plot Eur. Phys. J. C52 (2007) 875)

($\pi\pi$ scattering lengths measurement EPJ C64(2009)589)

BR (K3π) = (1.761 ± 0.022)% → external relative error 1.25% (PDG2010)

Common Event reconstruction for ($\pi^0\pi^0$ + charged track) system:

Find γ clusters (ab) and (cd) satisfying:

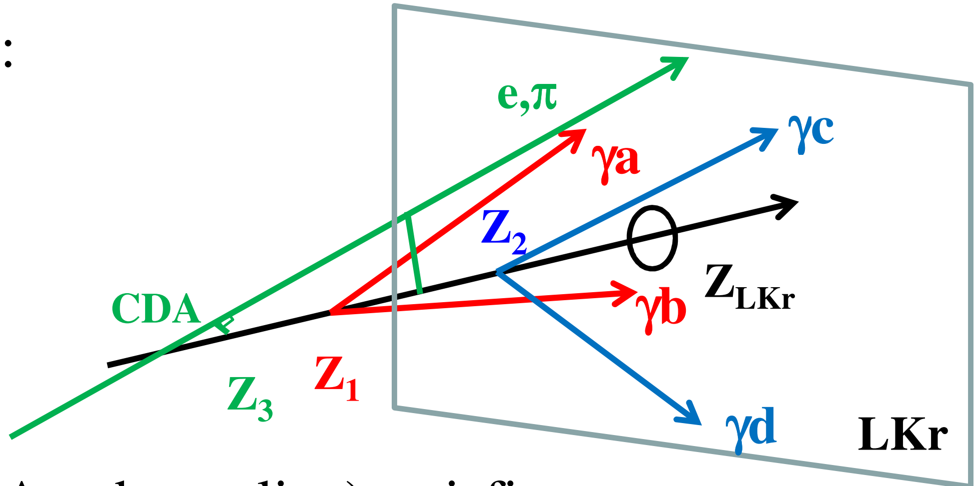
π^0 mass constraint:

$$Z_1 = Z_{LKr} - D_{ab} \sqrt{(E_a E_b)} / m(\pi^0)$$

$$Z_2 = Z_{LKr} - D_{cd} \sqrt{(E_c E_d)} / m(\pi^0)$$

$D_{ZN} = |Z_1 - Z_2| < 500$ cm

$Z_N = 0.5 \cdot (Z_1 + Z_2)$ within decay volume range [-16,+90]m



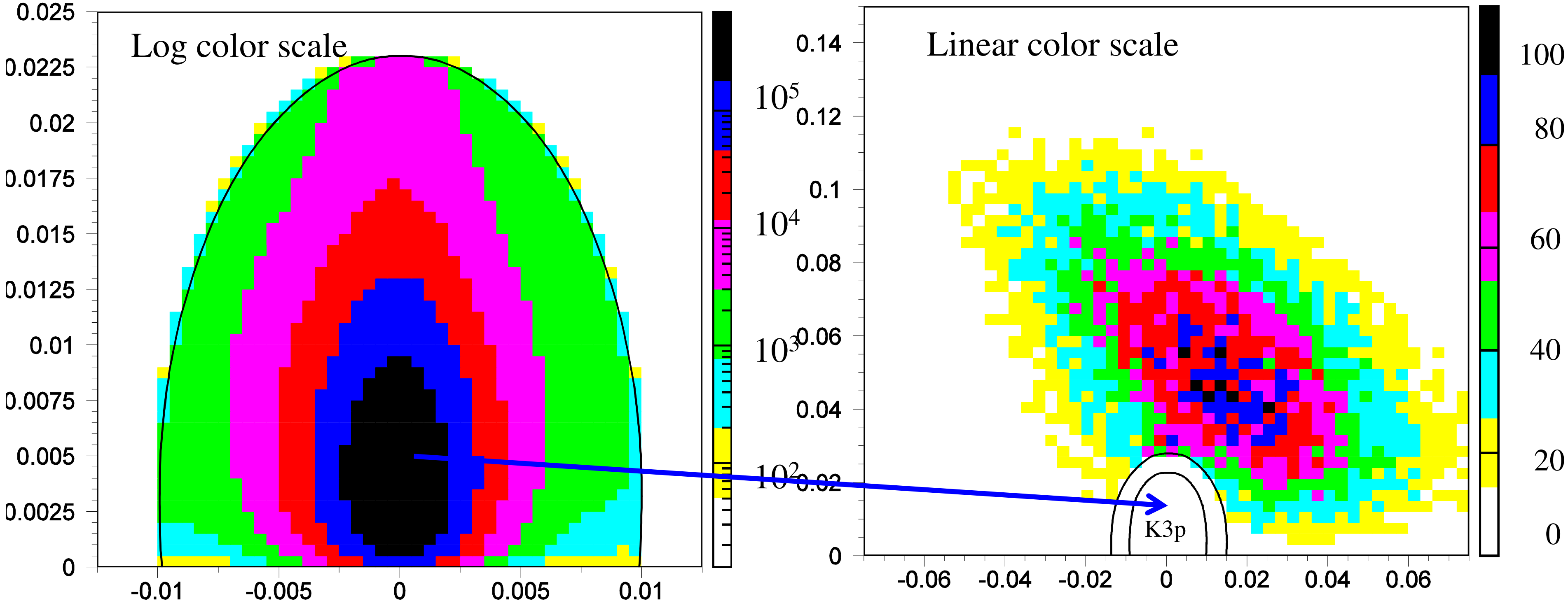
Combine with charged track if Z_3 (CDA to beam line) satisfies:

$D_z = |Z_3 - Z_N| < 800$ cm

No P-ID at this point: 2 π^0's + 1 charged track

Ke4(00): signal selection

Assign m_π to the charge track and compute invariant mass,
plot m_I vs p_t to the beam line: K3π events cluster at low p_t and around M_k
Ke4 events have larger p_t and a large spread of mass values (missing ν)



p_t (GeV/c) vs $M_I - M_k$ (GeV/c^2)

Elliptic cut separates 70 M K3π candidates from 45K Ke4 candidates

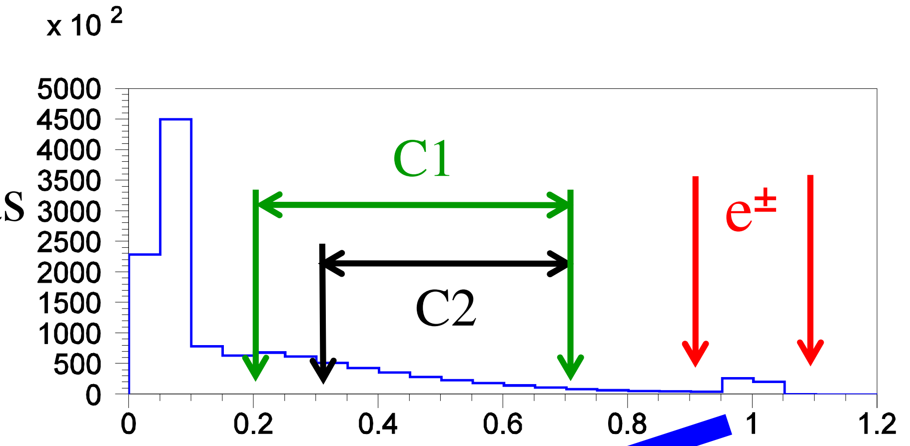
Ke4(00) : electron identification

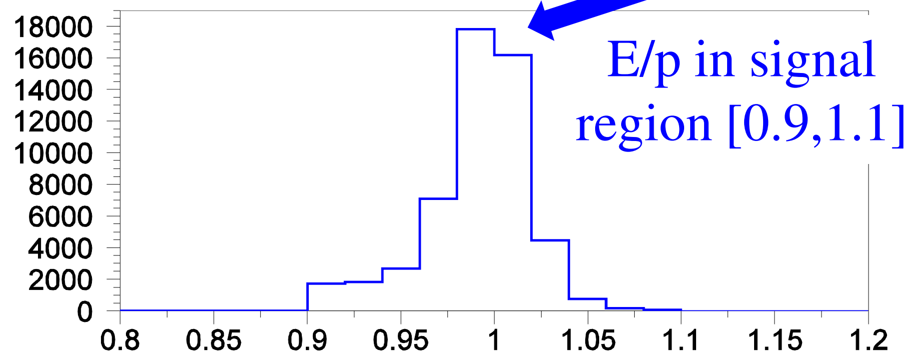
E_{LKr}/p_{DCH} ~1 for electrons

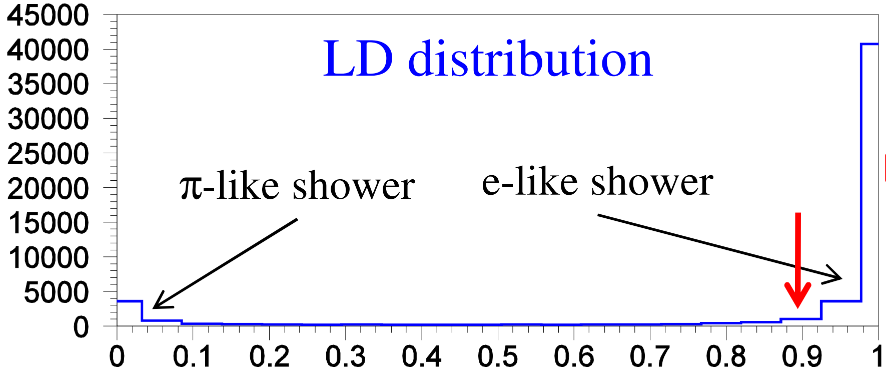
E/p cut → Pion contamination

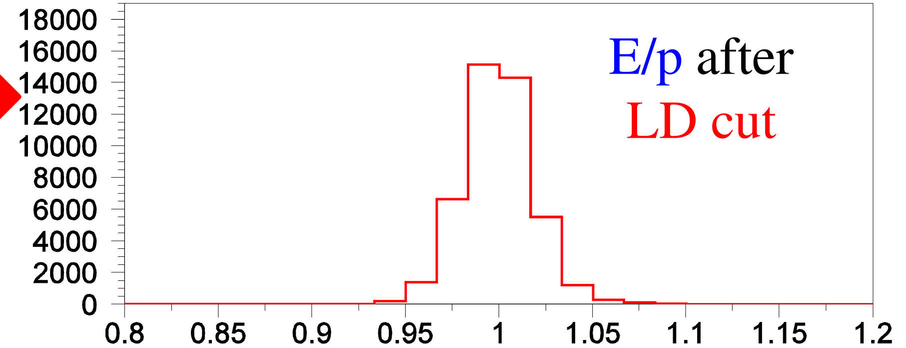
Defined 2 control regions C1(C2) as [0.2(0.3),0.7] with pions only.

Fake-electron rejection using a dedicated variable (Linear Discr.) based on shower properties and trained on real and fake electrons from data.



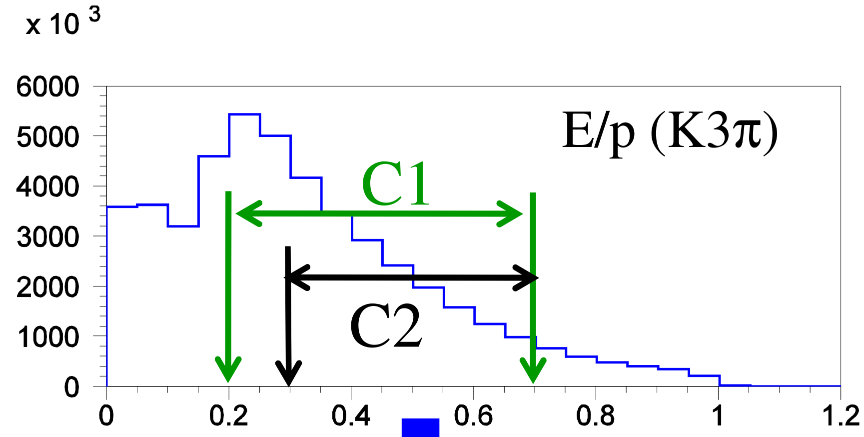


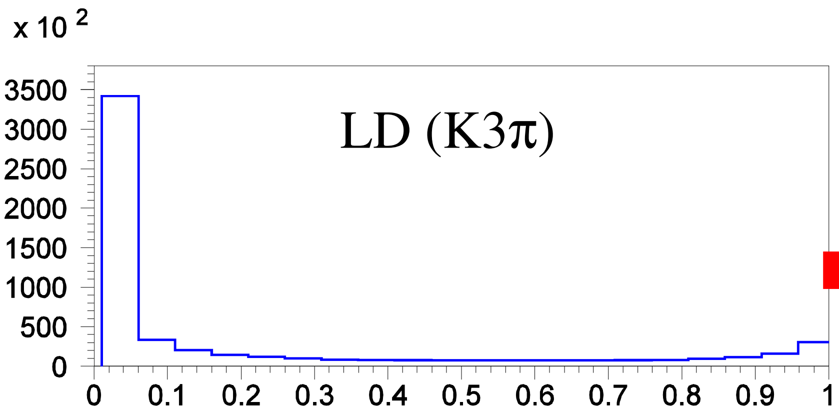




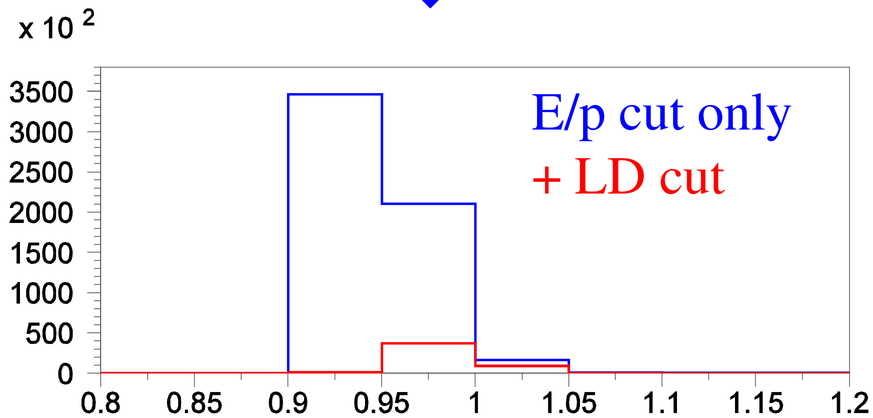
Ke4(00): background estimation

Residual fake-electrons background estimated directly from data looking to E/p control regions (C1 and C2) for K3π reconstructed candidates:





After E/p and LD cuts:

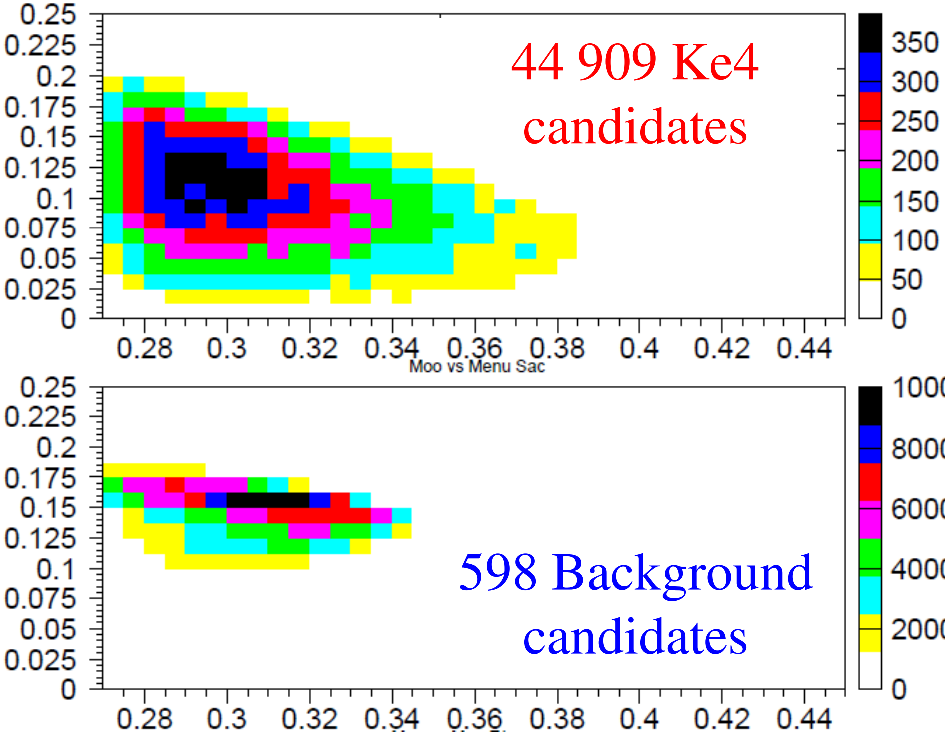


1.3% residual background relative to Ke4 signal

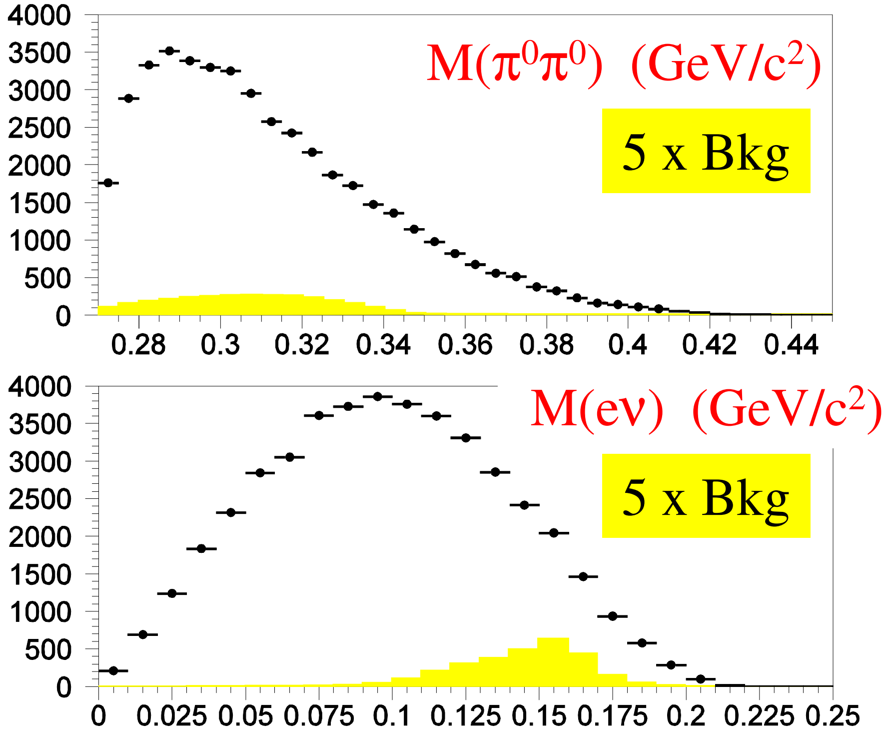
Ke4 (00): Dalitz plot

Background events cluster at low $M(\pi^0\pi^0)$ mass and $M(e\nu) = m(\pi^+)$ as expected if $K^\pm \rightarrow \pi^\pm \pi^0\pi^0$ is the dominant source.

$M(e\nu)$ (GeV/c^2) vs $M(\pi^0\pi^0)$ (GeV/c^2)



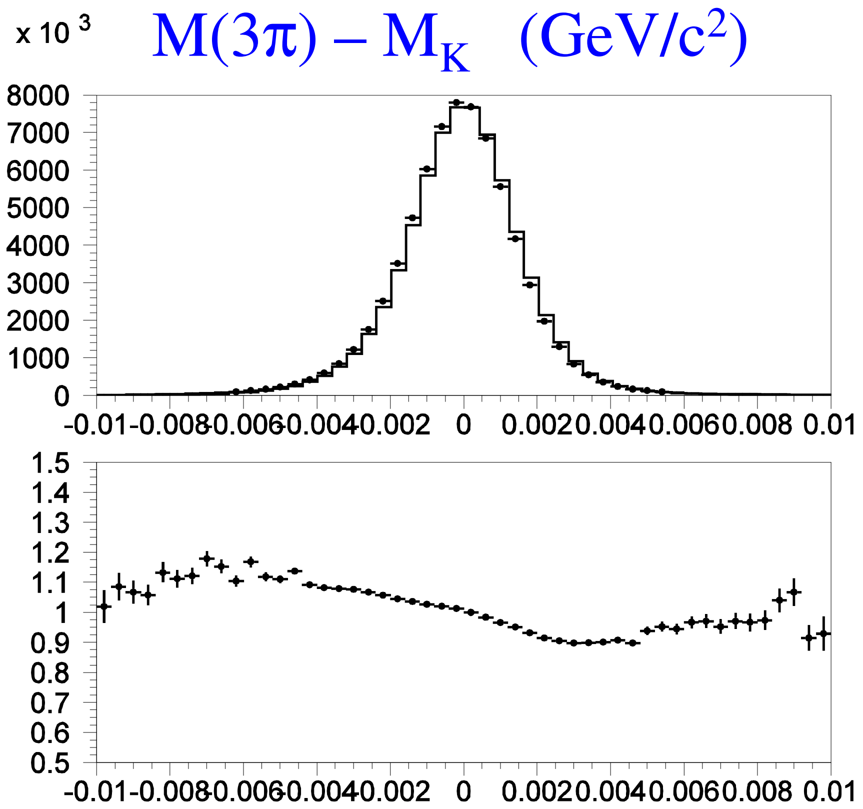
Projections

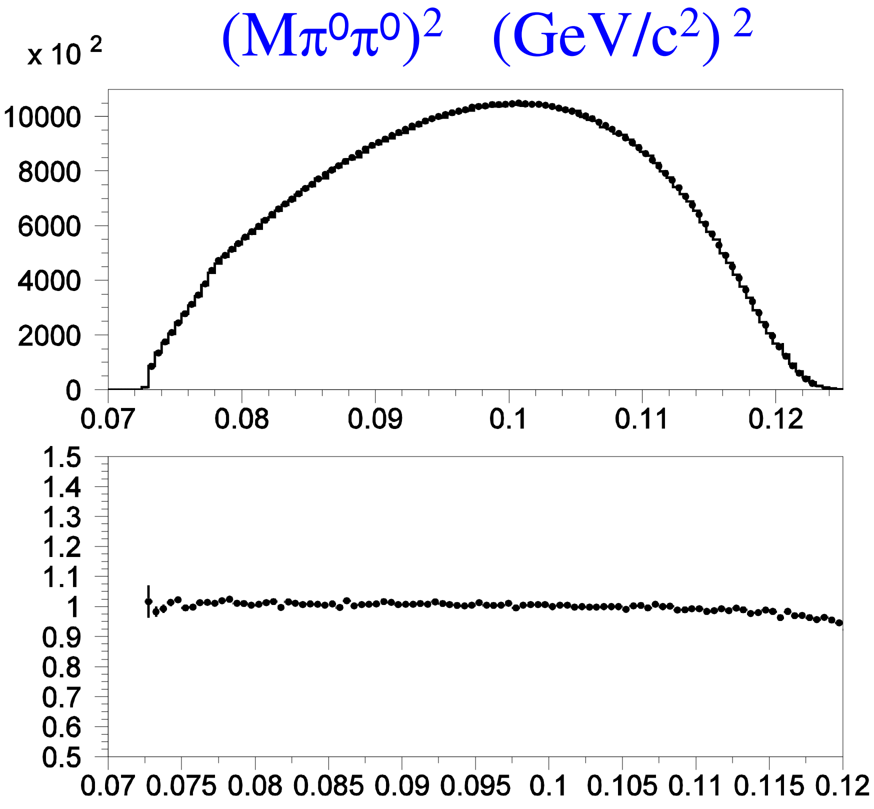


$K \rightarrow \pi^+\pi^0\pi^0$: energy scale/calibration control

Reconstructed Kaon mass with expected 1.5 MeV/c^2 resolution; small shift data vs MC (80 KeV/c^2) consistent with beam geometry modeling and non-linearities corrections

$(M\pi^0\pi^0)^2$: well modeled (including cusp), as described by an empirical parameterization to our Data (Phys Lett B 686 (2010) 101)



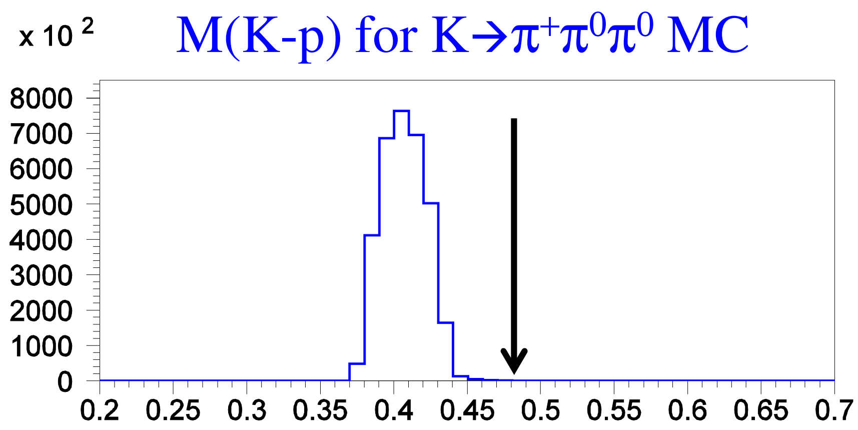


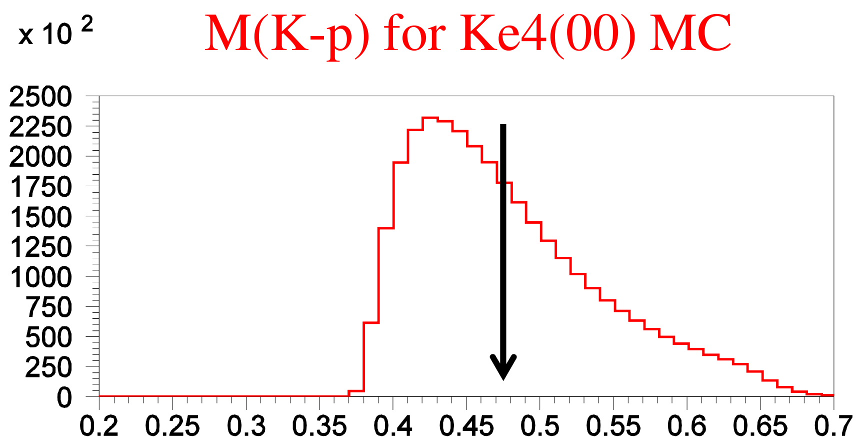
Ke4 (00) : Trigger efficiency

Level 1 : > 2 Neutral energy deposits in LKr in both transverse views

Level 2 : [Q1 (1 Hodoscope coincidence)] X [Software trigger from fast DCH Track reconstruction]

Level 2 Trigger cut rejects $K^+ \rightarrow \pi^+\pi^0$: $M(K\text{-}p) < 0.475$ GeV/c^2





Efficiency measured directly from data with minimum bias triggers, large systematic error (dominated by limited statistics on control samples)

Ke4 (00) : BR measurement

Because of data taking conditions variations with time, Br is measured in successive subsamples and then combined

N(Ke4) candidates	=	44909
N(bkg)	=	598
N(K3π) candidates	=	70 984 882
Acceptance K3π	=	4.11%
Acceptance Ke4	=	1.77%
ε(Ke4)		from 92% to 98%

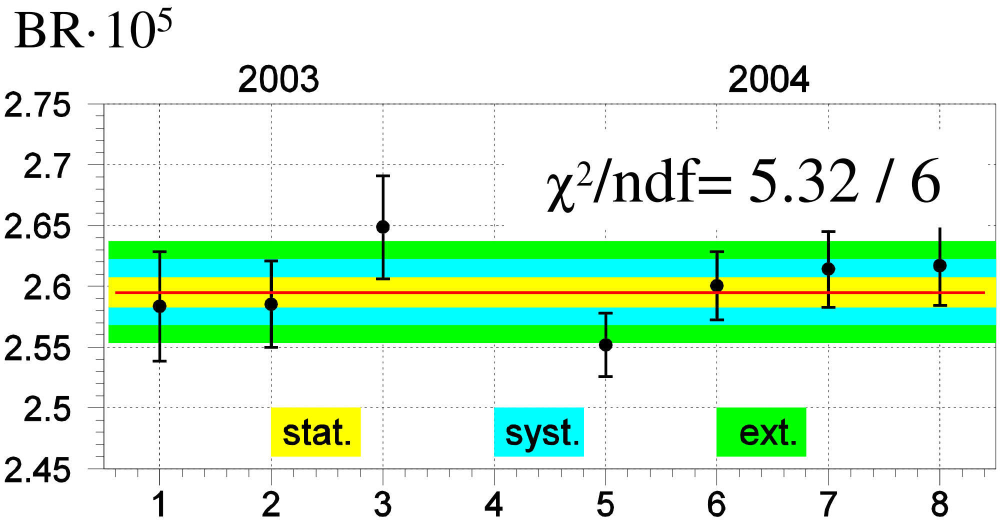
Systematic Uncertainties [%]
(preliminary thus conservative)

Background	0.35
Simulation stat	0.12
FF dependence	0.20
Rad. Corr.	0.23
Trigger	0.80
e-ident.	0.10
Beam geometry	0.10
Total	1.00

Normalization : BR = (1.761 ± 0.022) % (1.25% external error)

$$BR\ (Ke4(00)) = (2.595 \pm 0.012_{stat} \pm 0.024_{syst} \pm 0.032_{ext}) \cdot 10^{-5}$$

Ke4(00) and Ke4(+-): BR summary

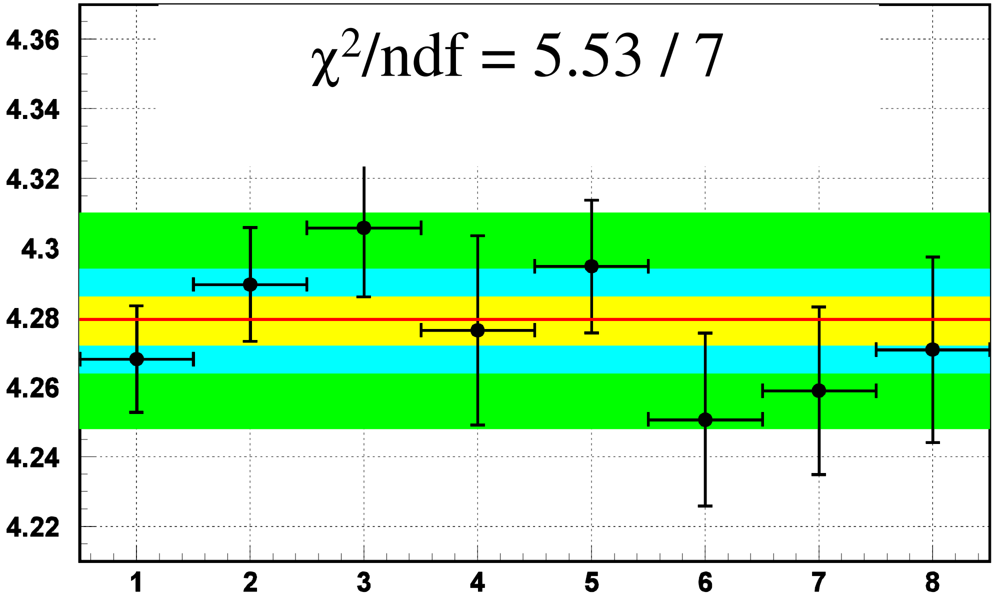


Ke4(00) normalized to $K\pi^{\pm}\pi^{0}\pi^{0}$

$(2.595 \pm 0.012 \pm 0.024 \pm 0.032) \cdot 10^{-5}$

stat syst ext

$(2.595 \pm 0.042) \cdot 10^{-5}$ 1.6% rel.



Preliminary results

(B. Bloch @ Moriond QCD 2011)

Ke4(+-) normalized to $K\pi^{\pm}\pi^{+}\pi^{-}$

$(4.279 \pm 0.007 \pm 0.015 \pm 0.031) \cdot 10^{-5}$

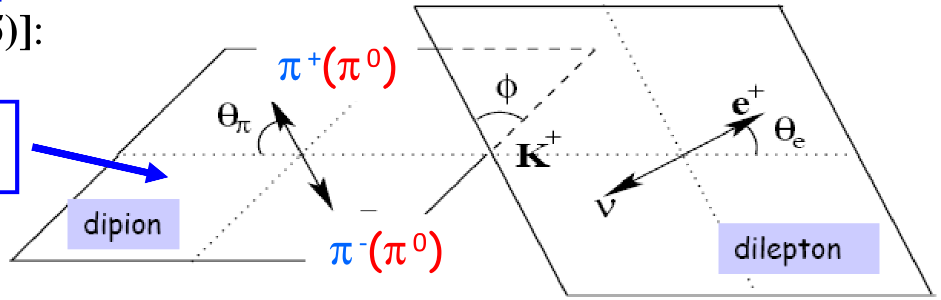
stat syst ext

$(4.279 \pm 0.035) \cdot 10^{-5}$ 0.8% rel.

Form factors: analysis procedure

5 kinematic variables **[Phys.Rev. 137, B438 (1965)]**:

$S_\pi(M^2_{\pi\pi})$ | $S_e(M^2_{e\nu})$ | $\cos\theta_e$ | $\cos\theta_\pi$ | ϕ



Reduce to 3 variables in the ke4(00) case

3 form factors (F,G,H) – partial waves expansion
[Pais-Treiman1968]

axial

$$F = F_s e^{i\delta_s} + F_p e^{i\delta_p} \cos\theta_\pi$$

$$G = G_p e^{i\delta_g}$$

vector

$$H = H_p e^{i\delta_h}$$

+ *d-wave…*

Expanding also in terms of $q^2=(S_\pi/4m_\pi-1)$ and S_e
[Amoros-Bijnens1999]

In the ke4(+-) decay F_s, F_p, G_p , H_p and $\delta = \delta_s - \delta_p$ are evaluated in q^2 bins and the slopes are extracted from these q^2 dependence

Extract a_0 from $\delta(q^2)$ dependence

Without the overall normalization from Branching Fraction, only relative form factors are measured:

$$(F_p, G_p, H_p)/F_s$$

Ke4(00): Dalitz plot density proportional to $(F_s)^2$

The measurement reduces to the Fs extraction only

Ke4(+-): Form Factors

Extensively studied with 1.1 million decays and published as
Eur. Phys. C70 (2010) 635

Precise determination of the S-wave ππ scattering lengths in I=0 and I=2 states

$$F_s^2 = f_s^2(1+f_s'/f_s \cdot q^2 + f_s''/f_s \cdot q^4 + f_e'/f_s \cdot S_e/4m_p^2)^2$$

Correlation	f_s''/f_s	f_e'/f_s
f_s'/f_s	-0.95	0.08
f_s''/f_s		0.02

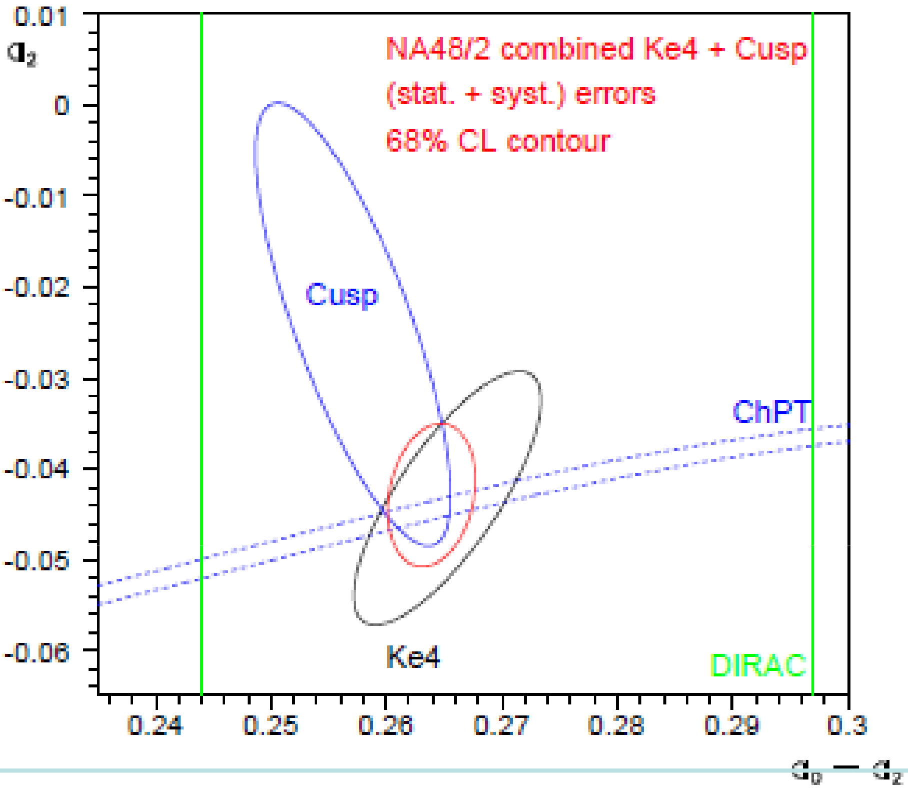
$$G_p/f_s = g_p/f_s + g_p'/f_s \cdot q^2$$

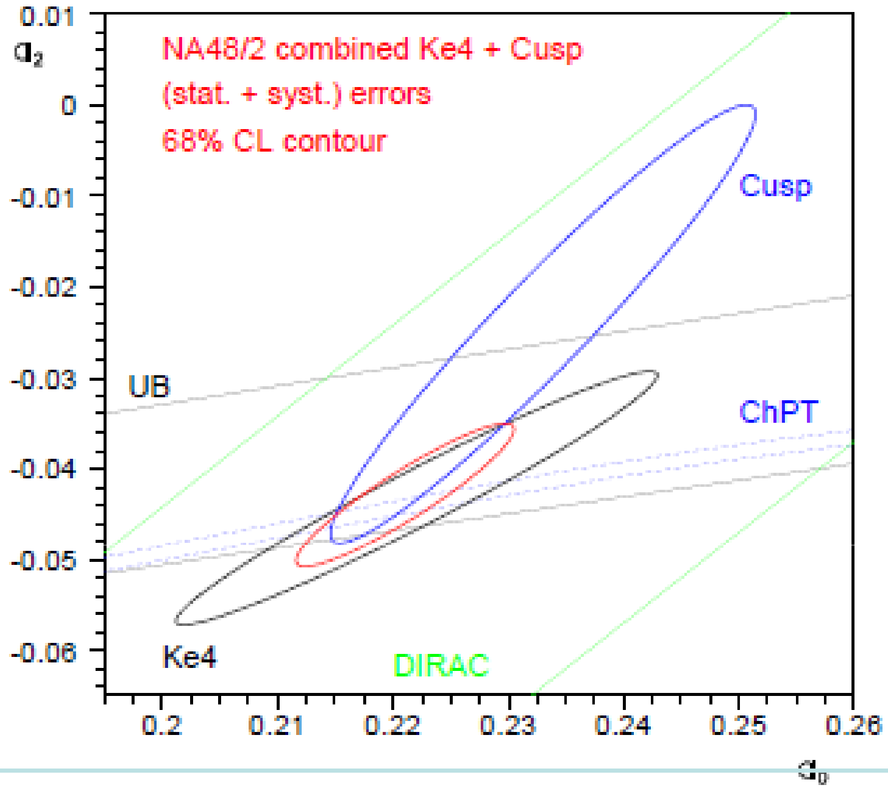
Correlation (g_p/f_s, g_p'/f_s): -0.91

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

Branching ratio measurement will fix f_s and the form factor absolute values

Scattering lengths from cusp and Ke4





Including the χPT constraint: stat syst (theo)

$a_2 = -0.0444 \pm 0.0007 \pm 0.0005 \quad (\pm 0.0008)$

$a_0 = 0.2196 \pm 0.0028 \pm 0.0020$

$a_0 - a_2 = 0.2640 \pm 0.0021 \pm 0.0015$

Published as:
Eur. Phys. C70 (2010) 635

Total error $\Delta a_2 = \pm 0.0009$ $\Delta a_0 = \pm 0.0034$ $\Delta(a_0 - a_2) = \pm 0.0026$

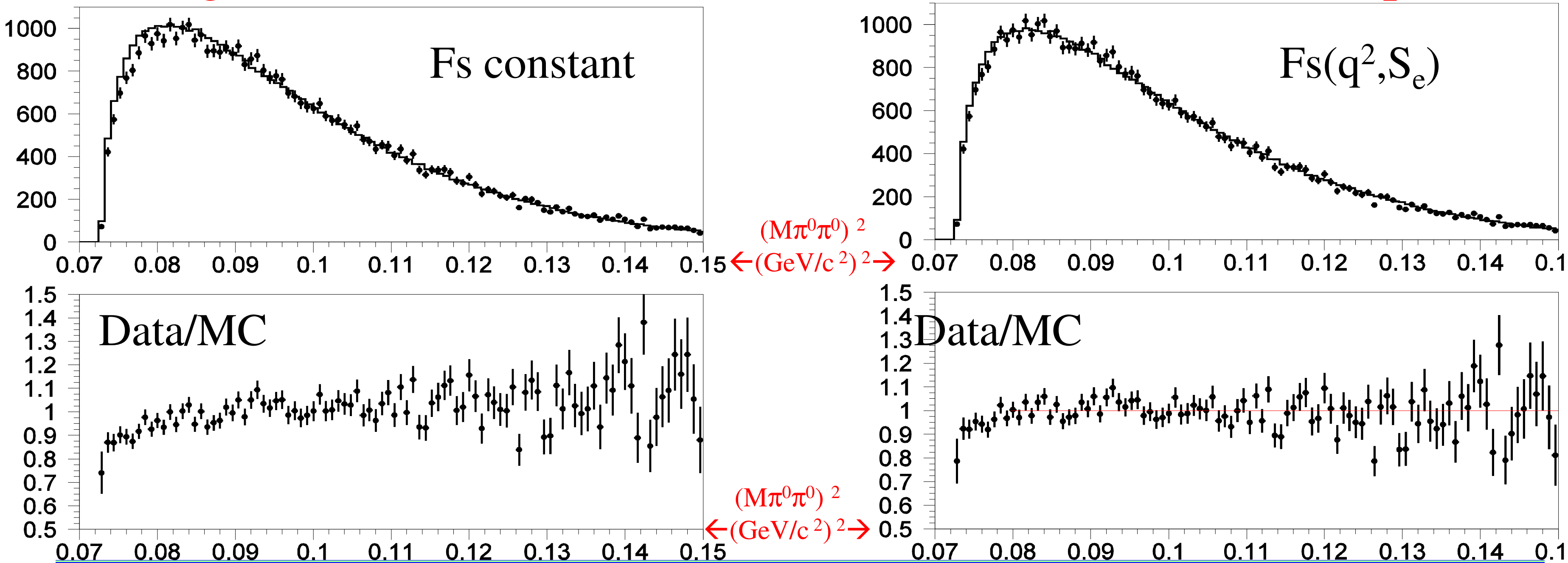
Ke4(00): First look at Form Factor

Given the limited statistics (~45k events), the same precision as the Ke4(+-) cannot be reached

Here the $(M\pi^0\pi^0)^2$ distribution is compared with the distribution obtained with:

- simulation of a constant Form Factor F_s
- simulation of the F_s Form Factor measured from Ke4(+-)

Better agreement in the second case… …cusp effect?



Summary

~1.11 M Ke4(+-) and 44000 Ke4(00) events analyzed by NA48

Data recorded among $2.5 \cdot 10^{10}$ triggers in years (2003+2004)

Improved measurements for the Branching fractions have been obtained:

BR Ke4 (+-) = $(4.279 \pm 0.035)\ 10^{-5}$ 0.8% rel. (factor 3 improvement /PDG)

BR Ke4 (00) = $(2.595 \pm 0.042)\ 10^{-5}$ 1.6% rel. (factor >10 improvement/PDG)

Errors in both modes are now dominated by the external error (normalization)

When finalized, this will allow to give precise absolute values for all Form Factors of the decays

First approach to the Ke4(00) Form factor measurement shows consistency with f_s measured from Ke4(+-)

SPARES

From phase space to scattering lengths

ππ phases at threshold can be predicted from data above 0.8 GeV using Roy Equation (unitarity, analycity , crossing symmetries) .

The S-wave scattering lengths a_0 and a_2 can be extracted from the variation of $\delta=\delta_0^0-\delta_1^1$

Numerical solutions have been developed (ACGL, DFGS) valid in the Isospin symmetry limit (Universal Band in the $[a_0,a_2]$ plane), but broken in the experimental world

Factorization of electromagnetic and mass effects:

Gamow factor x PHOTS generator x Isospin corrections

Radiative effects: included in the simulation

Gamow factor: " classial" Coulumb attraction between the 2 charged pions

PHOTOS generator: real photon(s) are emitted and tracked in the simulation

→Effect on event selection + possible bias on reconstructed quantities

Mass effects:

- Recently computed as a correction to the measurements
- Even larger than current experimental precision!

Full statistics

Uniform conditions for selection and Data/MC statistics, so the 2003 and 2004 data were merged for a joint analysis

2003+2004

60.31 millions events

Fit region is choosen to reach a minimum total error (systematical contribution grows with upper M_{00})