

Study of K_{e4} decays at NA48 and χ PT tests

Mauro Piccini
(INFN - sezione di Perugia)

On behalf of the NA48/2 collaboration

HADRON 2011

Munich

June 17, 2011

Outline

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

Chiral Perturbative Theory and Kl4 decays

At low energy ($< \sim 1$ GeV), perturbative QCD does not apply anymore but an effective theory (χ PT) 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 ($m_u = m_d$, $\alpha_{\text{QED}} = 0$)

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

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

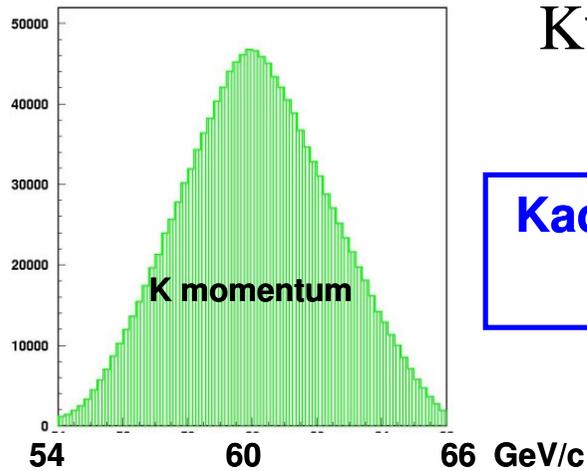
Codes	Decays	PDG BR	Rel. Prec.	#evts
Ke4(+)	$\text{K}^+ \rightarrow e \nu \pi^+ \pi^-$	$(4.09 \pm 0.10) \cdot 10^{-5}$	2.4%	418000
Ke4(00)	$\text{K}^+ \rightarrow e \nu \pi^0 \pi^0$	$(2.20 \pm 0.40) \cdot 10^{-5}$	18.2%	37
Ke4(0-)	$\text{K}^0 \rightarrow e \nu \pi^0 \pi^-$	$(5.20 \pm 0.11) \cdot 10^{-5}$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

Direct Predictions using Form Factor calculations by χ PT at $\mathcal{O}(p^2, p^4, p^6 \dots)$

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

BR relation and direct BR predictions verified within the above experimental errors
there is room for improved χ PT tests from better experimental measurements !

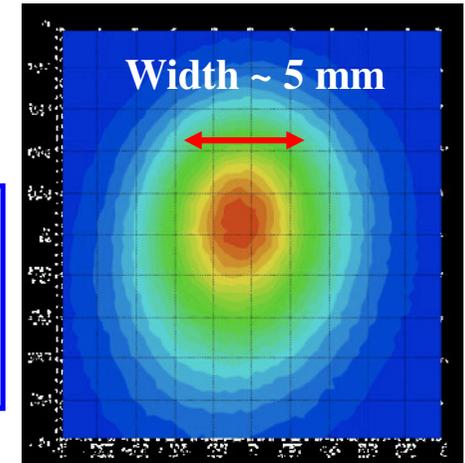
The simultaneous K^+/K^- beams



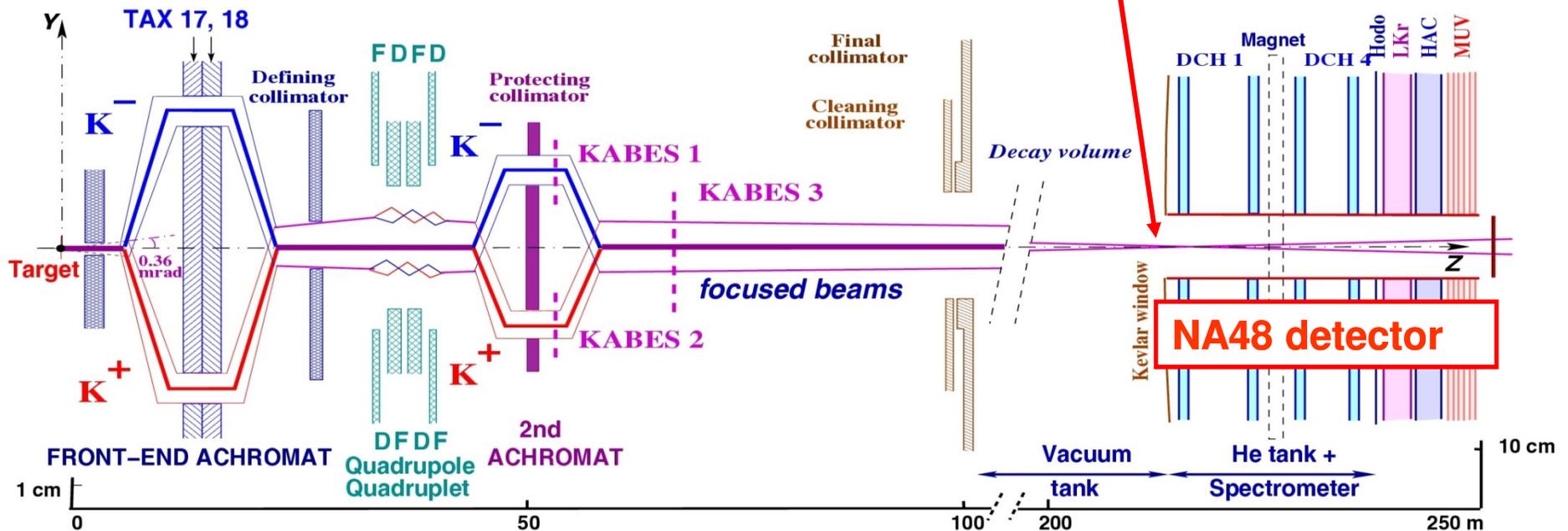
K^+ and K^- superimposed in space
 Flux ratio: $K^+/K^- \sim 1.8$

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 \Rightarrow 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):

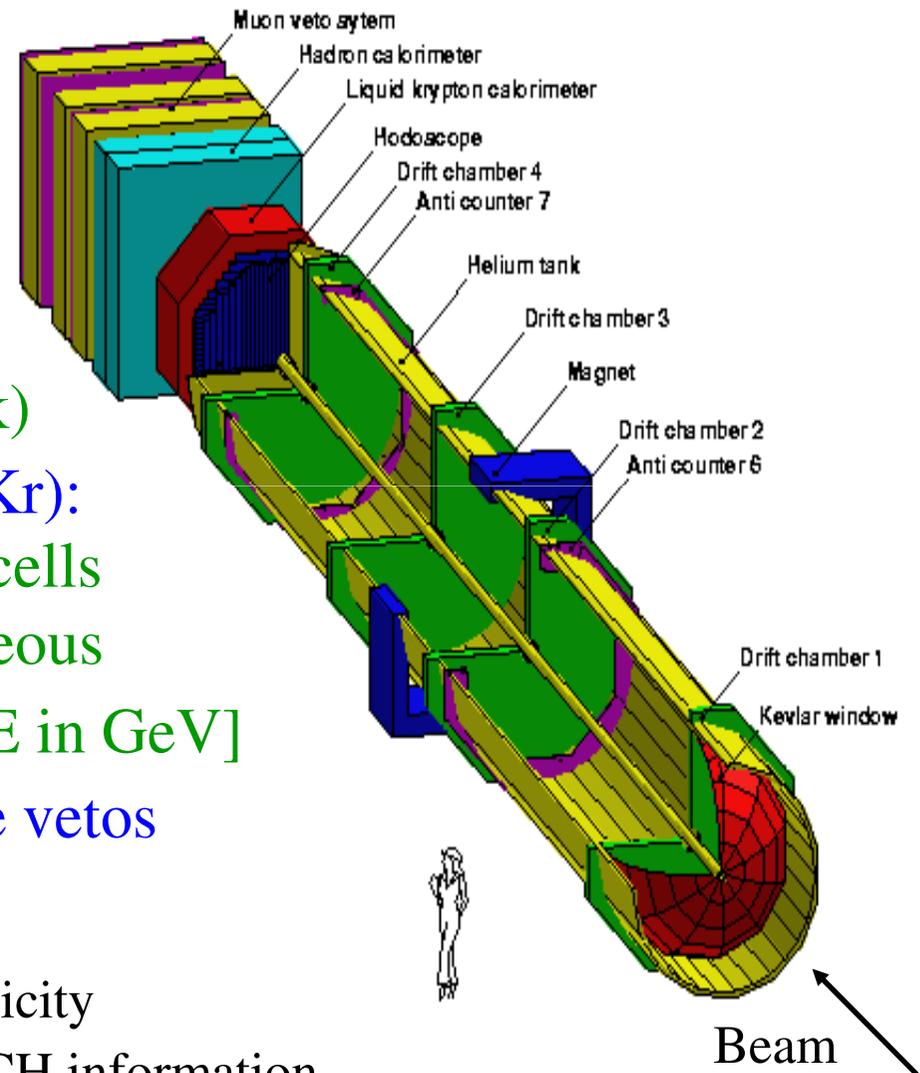
10 m³ (~22 t), 1.25 m (27 X₀), 13212 cells

granularity: 2x2 cm², 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 $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ (K3 π)

$$\text{BR}(K_{e4}) = \frac{N(K_{e4}) - N_{\text{bkg}}}{N(K3\pi)} \cdot \frac{A(K3\pi)}{A(K_{e4})} \cdot \frac{\epsilon(K3\pi)}{\epsilon(K_{e4})} \cdot \text{BR}(K3\pi)$$

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

$$N(K_{e4}) \text{ candidates} = 1.11 \times 10^6 \quad (7.12 \times 10^5 K^+ \text{ and } 3.97 \times 10^5 K^-)$$

$$N_{\text{bkg}} \text{ (relative to } K_{e4}) = 0.95\%$$

$$N(K3\pi) \text{ candidates} = 1.9 \times 10^9$$

Acceptances (Geant3 based simulation used):

$$A(K_{e4}) = 18.22\%$$

$$A(K3\pi) = 24.18\%$$

Trigger efficiencies (measured using minimum bias control triggers):

High efficiency, similar for signal and normalization mode

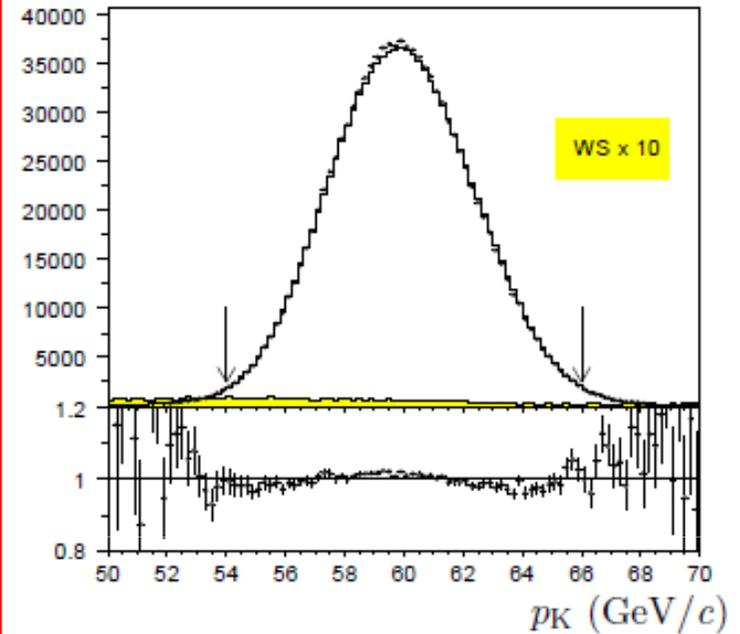
$$\epsilon(K_{e4}) = 98.3\%$$

$$\epsilon(K3\pi) = 97.5\%$$

Branching ratio of K3 π = $(5.59 \pm 0.04)\%$ 0.72% external error on BR(K $_{e4}$)

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



$$\text{BR}(\text{K}^+\text{e}4) = (4.277 \pm 0.009_{\text{stat+trig}}) \cdot 10^{-5}$$

$$\text{BR}(\text{K}^-\text{e}4) = (4.283 \pm 0.012_{\text{stat+trig}}) \cdot 10^{-5} \quad \leftarrow \text{never measured before}$$

combined (common systematic error) to:

$$\begin{aligned} \text{BR}(\text{K}^\pm\text{e}4) &= (4.279 \pm 0.004_{\text{stat}} \pm 0.005_{\text{trig(stat)}} \pm 0.015_{\text{syst}} \pm 0.031_{\text{ext}}) \cdot 10^{-5} \\ &= (4.279 \pm 0.035_{\text{tot}}) \cdot 10^{-5} \quad (0.8\% \text{ rel.}) \text{ external error dominated} \end{aligned}$$

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 ($K3\pi$) = $(1.761 \pm 0.022)\%$ \rightarrow 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:

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

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

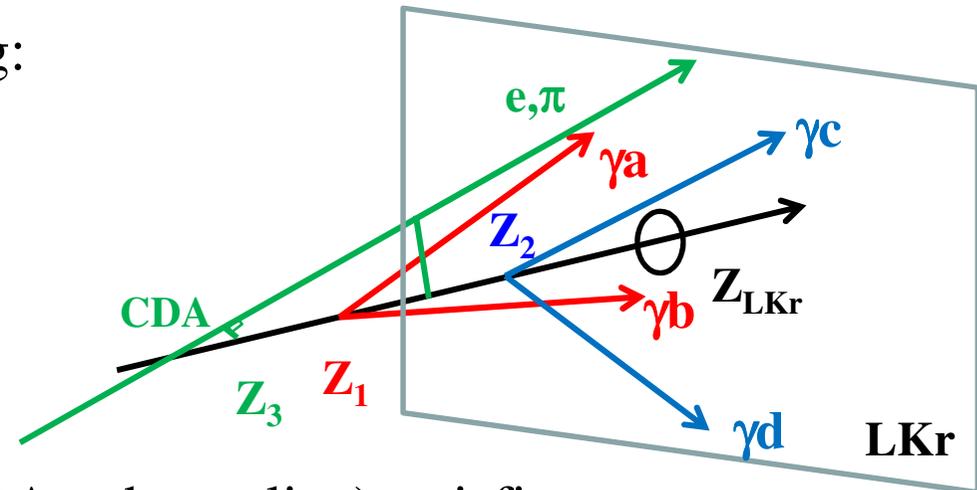
$$D_{ZN} = |Z_1 - Z_2| < 500 \text{ cm}$$

$$Z_N = 0.5 \cdot (Z_1 + Z_2) \text{ within decay}$$

volume range [-16,+90]m

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

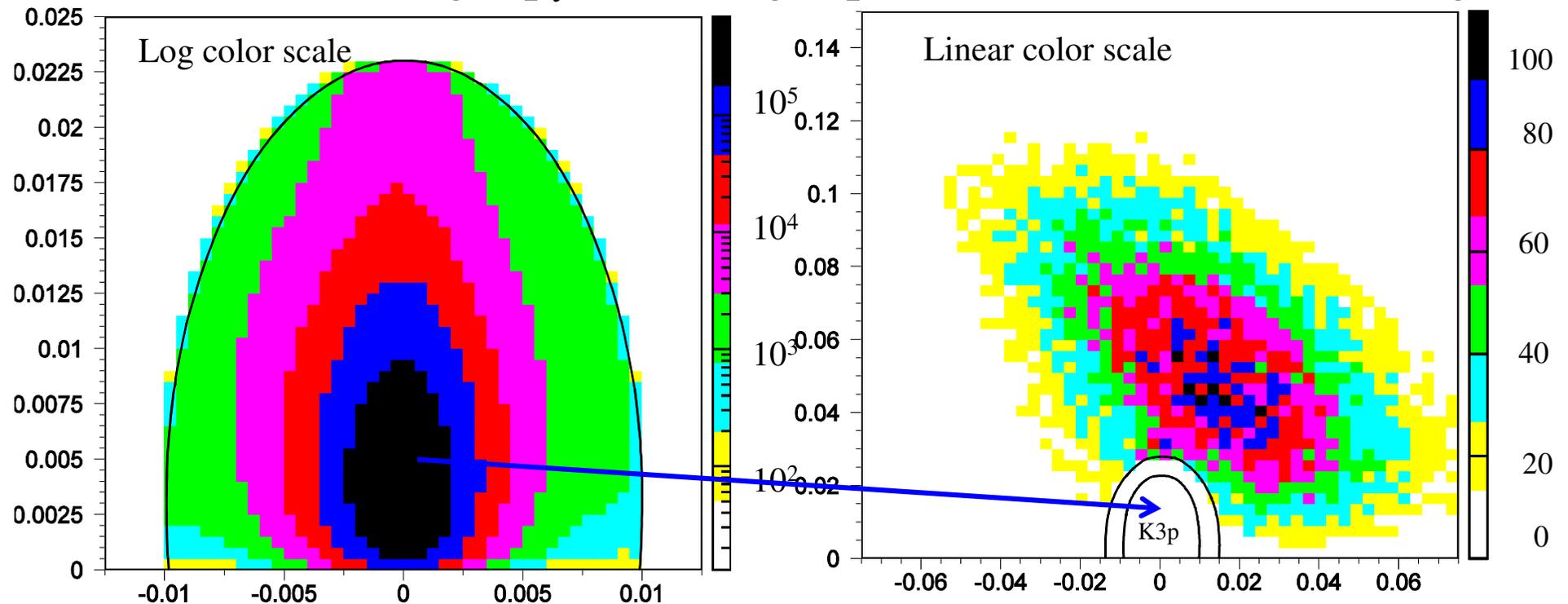
$$D_z = |Z_3 - Z_N| < 800 \text{ cm}$$



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: $K3\pi$ 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/c²)

Elliptic cut separates 70 M $K3\pi$ candidates from 45K Ke4 candidates

Ke4(00) : electron identification

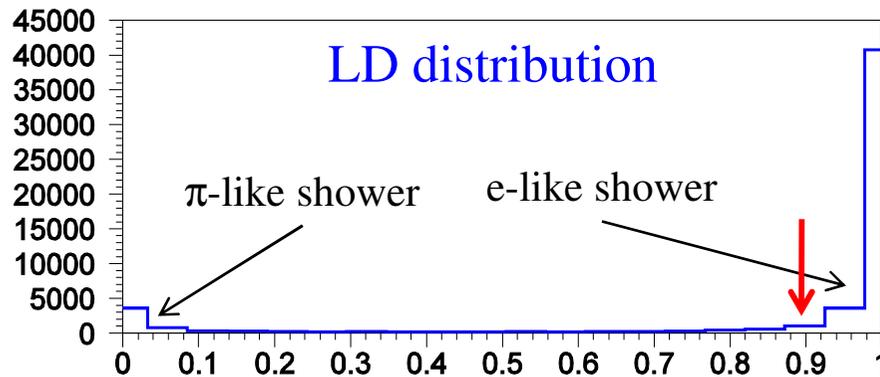
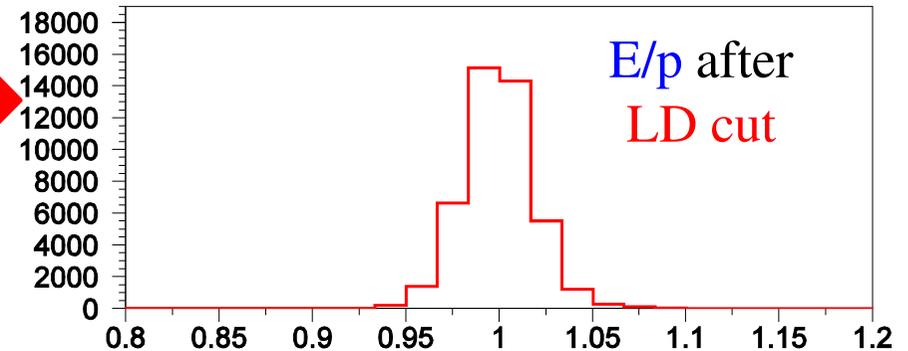
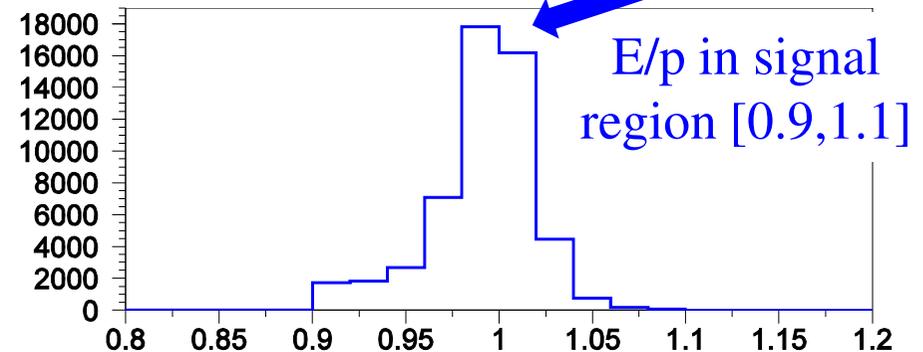
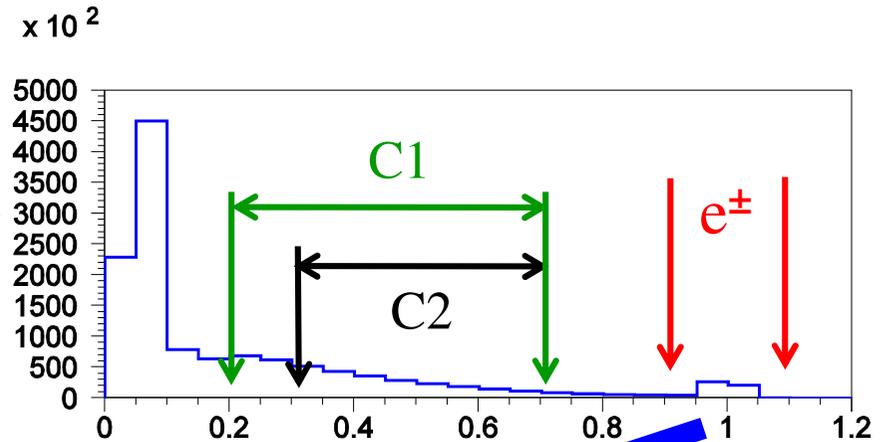
$E_{LKr}/p_{DCH} \sim 1$ for electrons

E/p cut \rightarrow Pion contamination

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

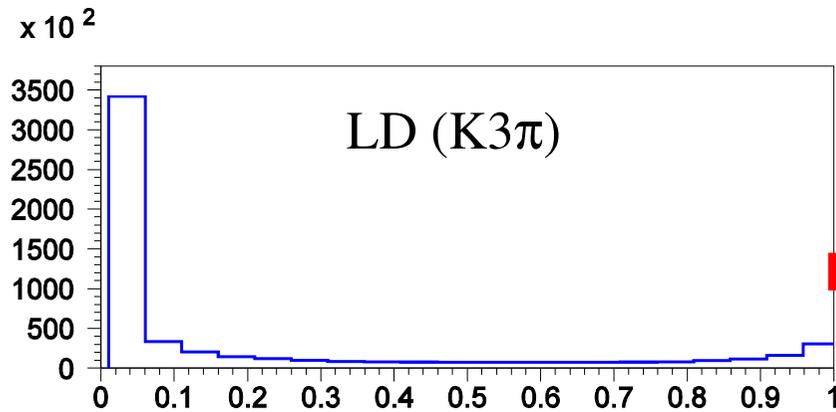
Fake-electron rejection using a
dedicated variable (**Linear Discr.**)

based on shower properties and
trained on real and fake electrons
from data.

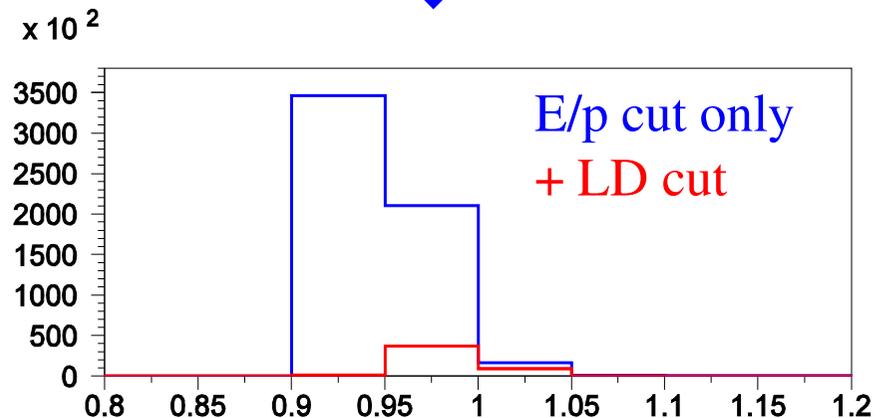
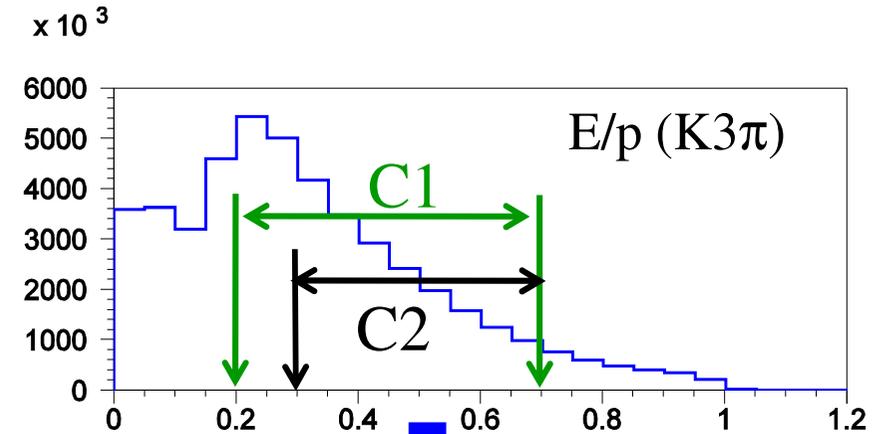


Ke4(00): background estimation

Residual fake-electrons background estimated directly from data looking to E/p control regions (C1 and C2) for $K3\pi$ reconstructed candidates:



After E/p and LD cuts:

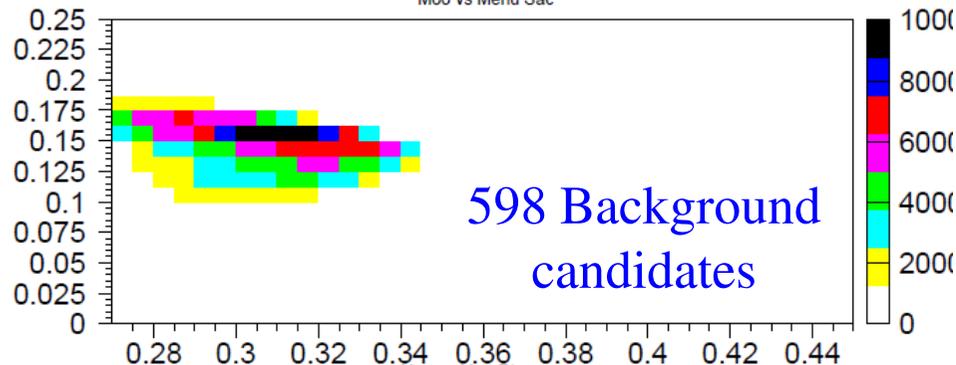
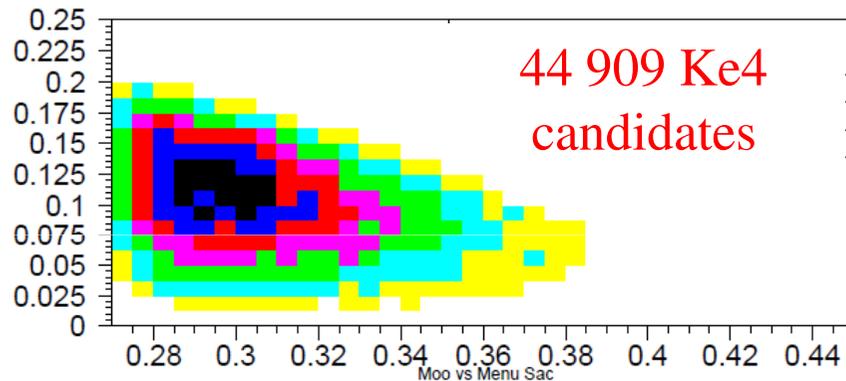


1.3% residual background relative to Ke4 signal

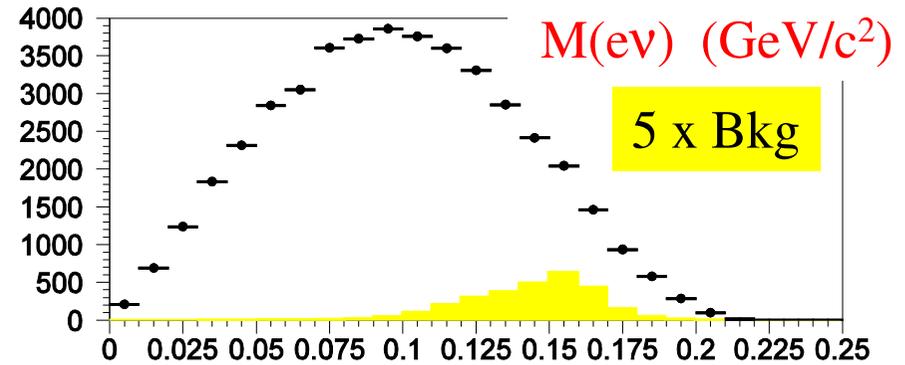
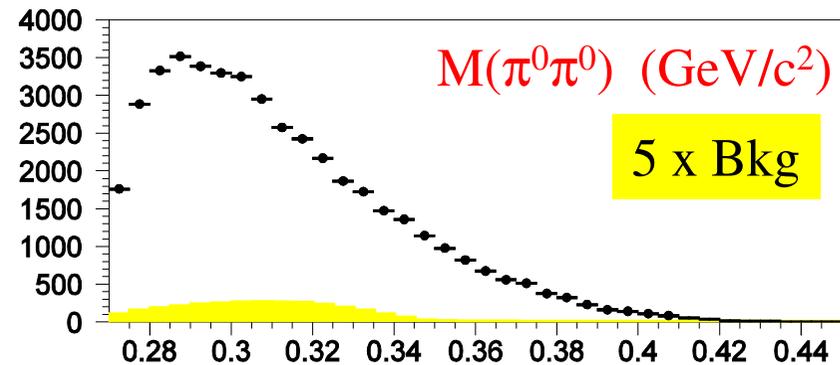
Ke4 (00): Dalitz plot

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/c²) vs $M(\pi^0\pi^0)$ (GeV/c²)

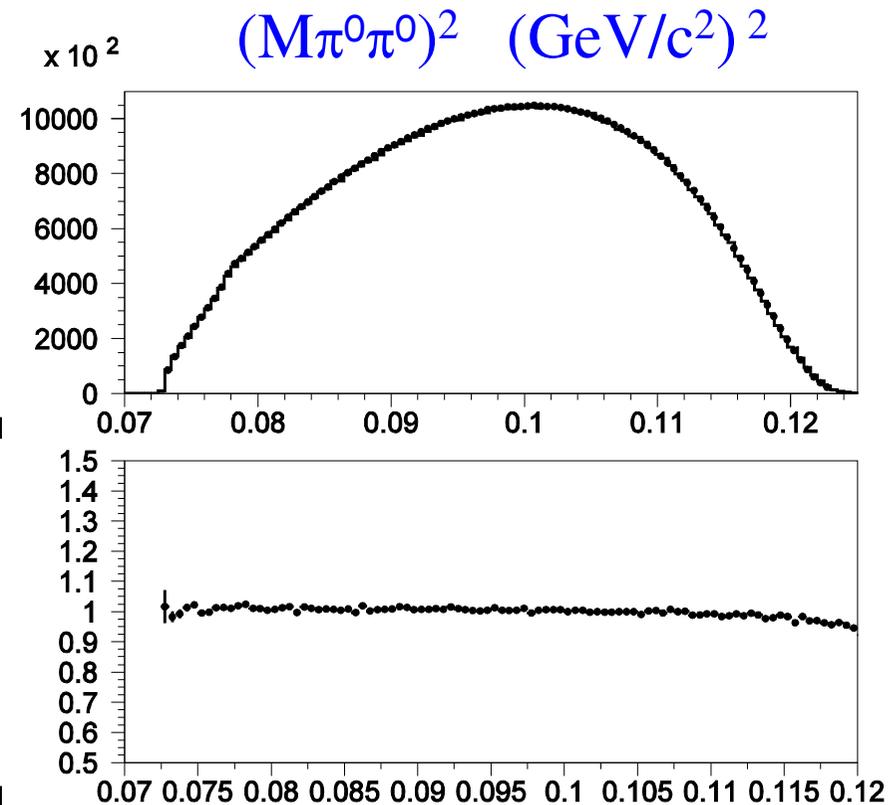
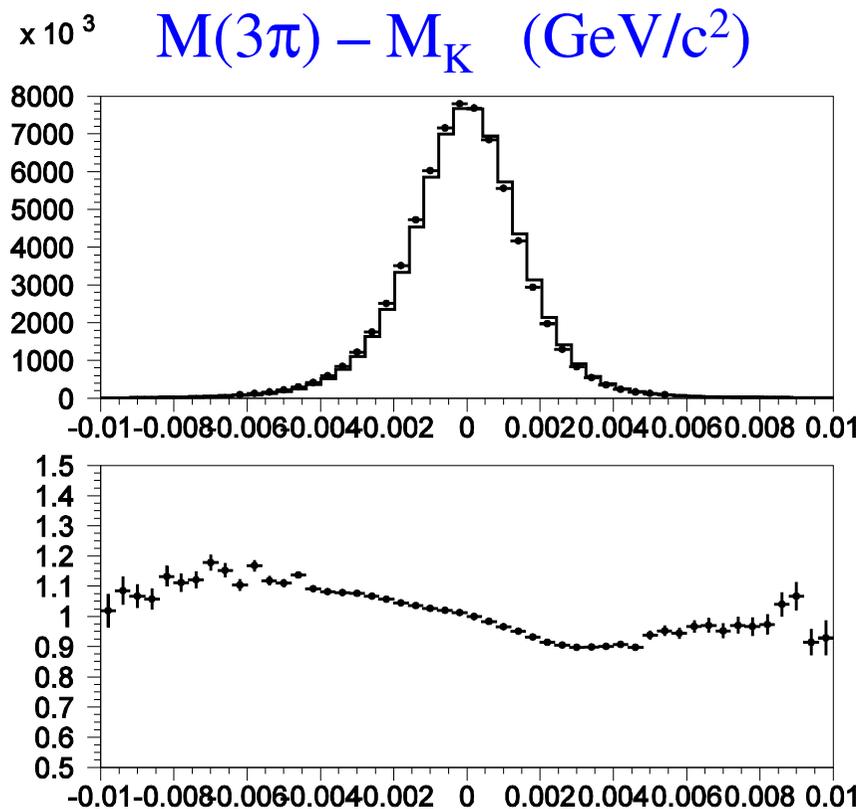


Projections



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

Reconstructed Kaon mass with expected $1.5 \text{ MeV}/c^2$ resolution; small shift data vs MC ($80 \text{ KeV}/c^2$) 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)

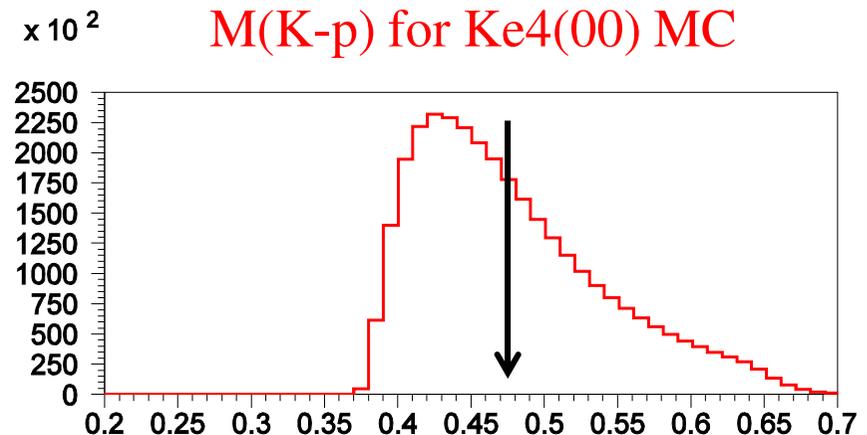
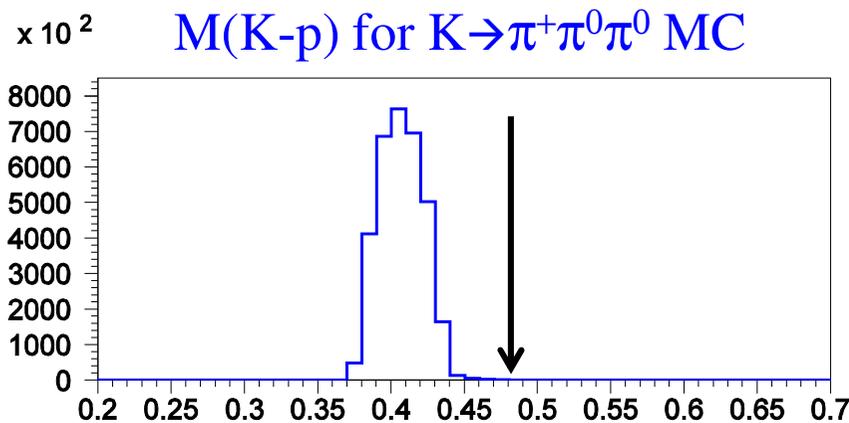


Ke4 (00) : Trigger efficiency

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



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

Ke4 (00) : BR measurement

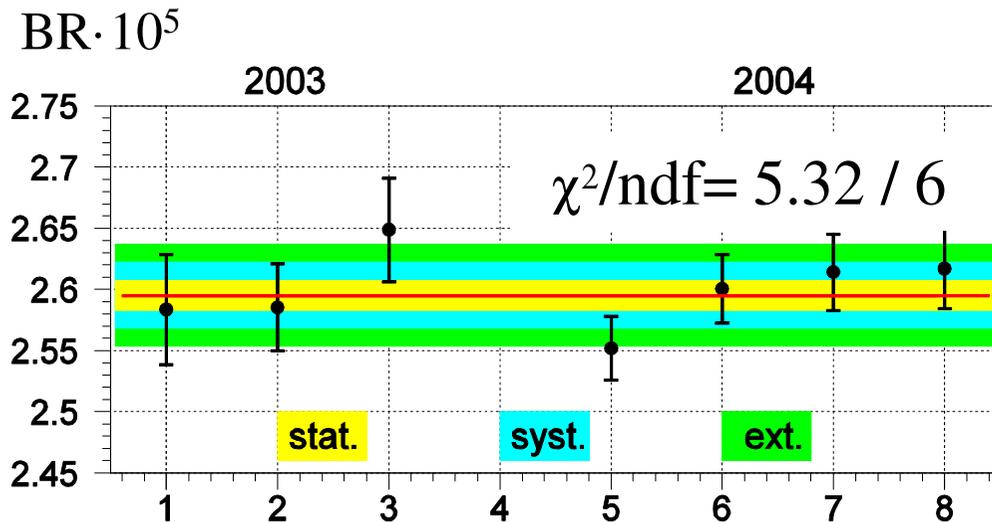
Because of data taking conditions variations with time, Br is measured in successive subsamples and then combined

N(Ke4) candidates	=	44909	Systematic Uncertainties [%] (preliminary thus conservative)		
N(bkg)	=	598			
N(K3 π) candidates	=	70 984 882		Background	0.35
Acceptance K3 π	=	4.11%		Simulation stat	0.12
Acceptance Ke4	=	1.77%		FF dependence	0.20
ϵ (Ke4)		from 92% to 98%	Rad. Corr.	0.23	
			Trigger	0.80	
			e-ident.	0.10	
			Beam geometry	0.10	
			<hr/>		
			Total	1.00	

Normalization : BR = $(1.761 \pm 0.022) \%$ (1.25% external error)

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

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

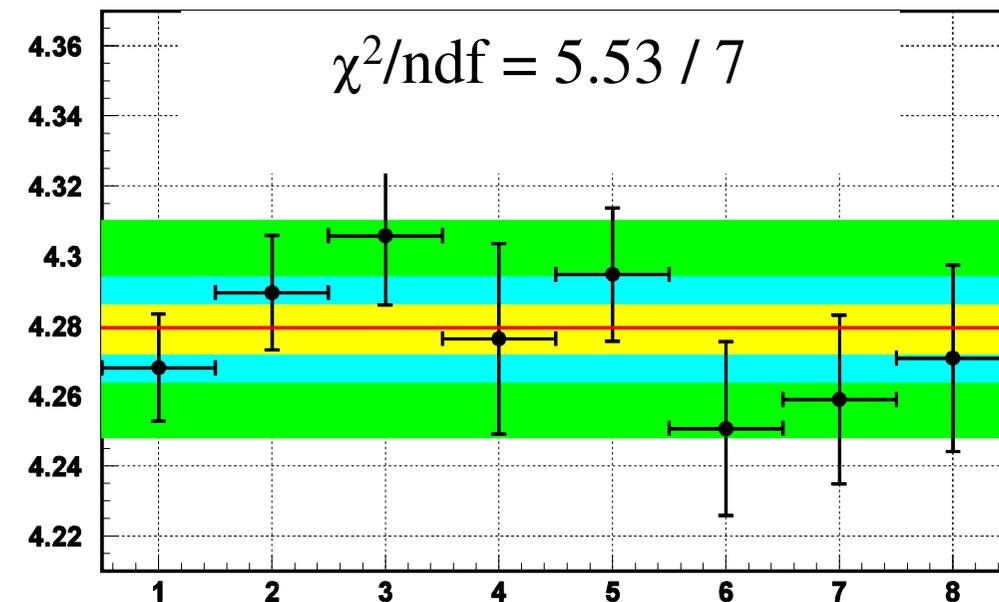


Ke4(00) normalized to $K \pi^\pm \pi^0 \pi^0$
 $(2.595 \pm 0.012 \pm 0.024 \pm 0.032) \cdot 10^{-5}$
 stat syst ext

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

Preliminary results

(B. Bloch @ Moriond QCD 2011)



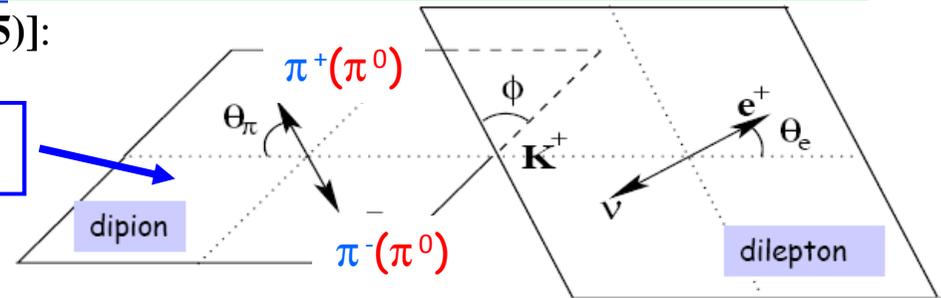
Ke4(+-.) normalized to $K \pi^\pm \pi^+ \pi^-$
 $(4.279 \pm 0.007 \pm 0.015 \pm 0.031) \cdot 10^{-5}$
 stat syst ext

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

Form factors: analysis procedure

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

$$\boxed{S_\pi(M_{\pi\pi}^2)} \quad \boxed{S_e(M_{e\nu}^2)} \quad \boxed{\cos\theta_e} \quad \boxed{\cos\theta_\pi} \quad \boxed{\phi}$$



Reduce to 3 variables in the $ke4(00)$ case

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

$$\left. \begin{array}{l} \text{axial} \\ \text{vector} \end{array} \right\} \begin{cases} F = F_s e^{i\delta_s} + F_p e^{i\delta_p} \cos\theta_\pi \\ G = G_p e^{i\delta_g} \\ H = H_p e^{i\delta_h} \quad + d\text{-wave...} \end{cases}$$

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 F_s 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 $\pi\pi$ 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

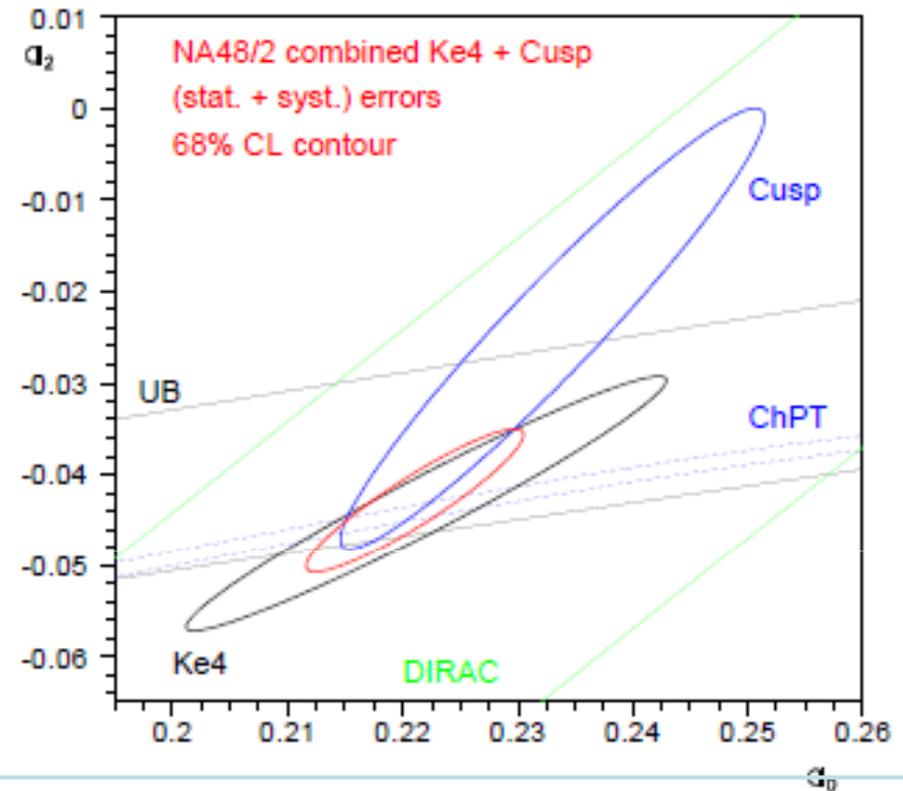
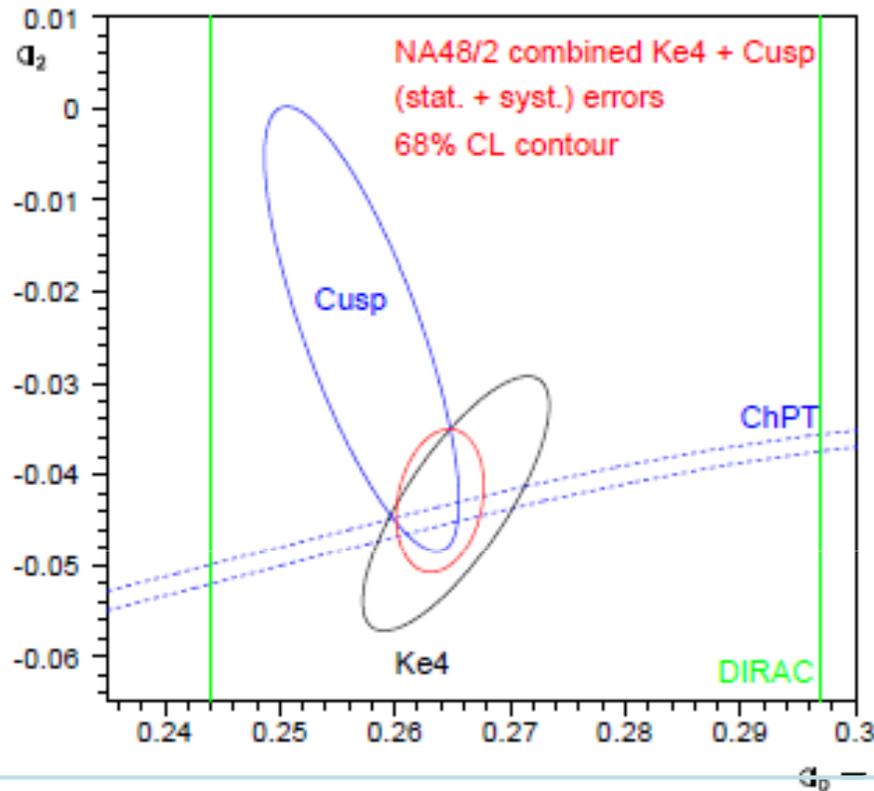
$$G_p/f_s = g_p/f_s + g_p'/f_s \cdot q^2$$

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

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

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

Scattering lengths from cusp and Ke4



Including the χ PT constraint:

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

	stat	syst	(theo)
$a_2 =$	-0.0444 ± 0.0007	± 0.0005	(± 0.0008)
$a_0 =$	0.2196 ± 0.0028	± 0.0020	
$a_0 - a_2 =$	0.2640 ± 0.0021	± 0.0015	

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

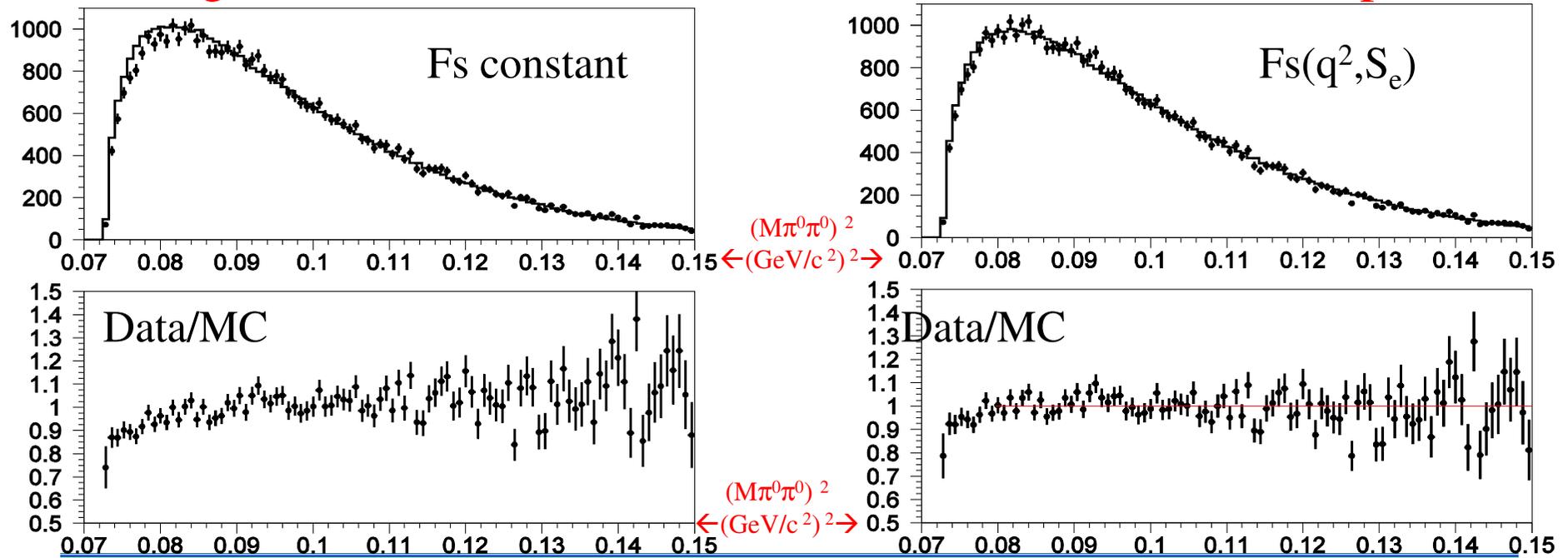
Given the limited statistics ($\sim 45k$ events), the same precision as the Ke4(+/-) cannot be reached

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

BR Ke4 (00) = $(2.595 \pm 0.042) \cdot 10^{-5}$ 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

$\pi\pi$ phases at threshold can be predicted from data above 0.8 GeV using Roy Equation (unitarity, analyticity, 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 PHOTOS generator

x

Isospin corrections

Radiative effects: included in the simulation

Gamow factor: “classical” Coulomb 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 chosen to
reach a minimum total
error (systematical
contribution grows
with upper M_{00})

