Study of Ke4 decays in the NA48/2 experiment at CERN

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On behalf of the NA48/2 collaboration:

Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Wien

outline

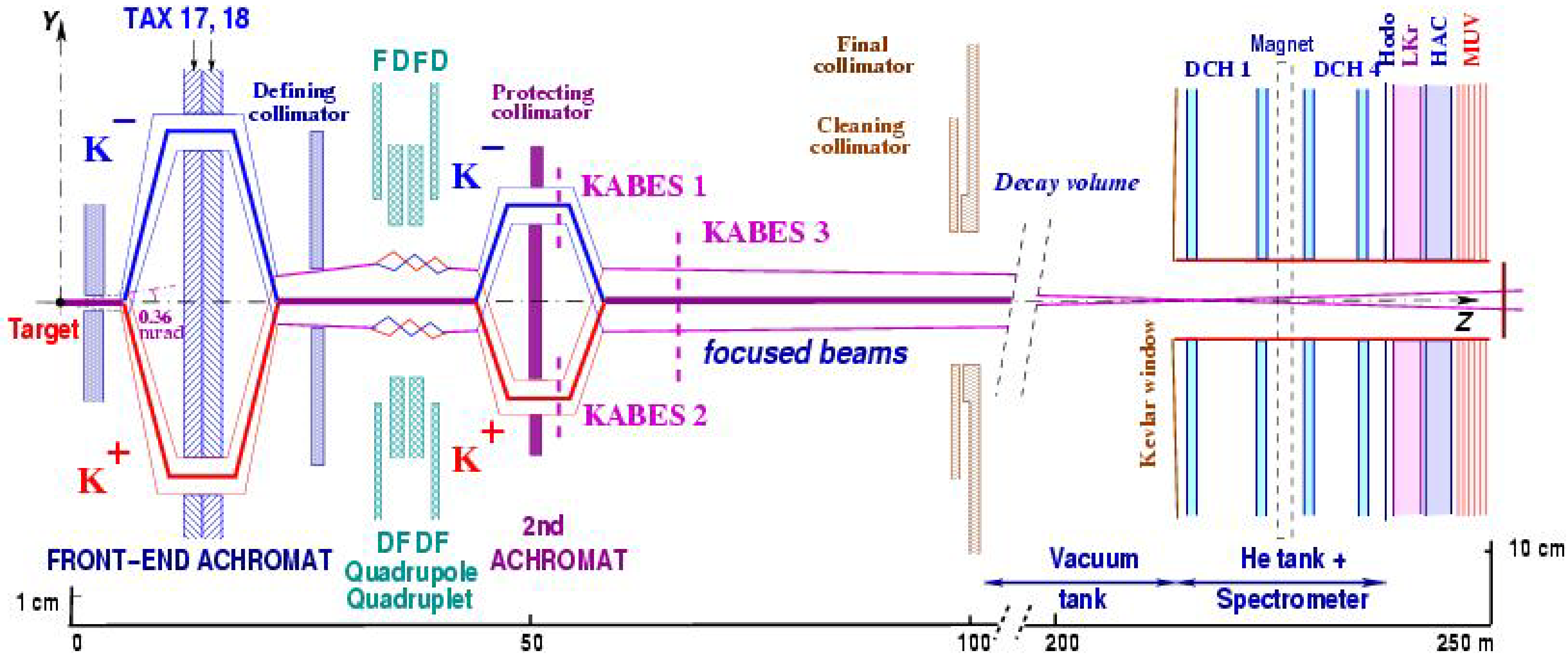
- Brief introduction to NA48/2 experiment
- Ke4 decays : Theoretical introduction
- Ke4 decays : Experimental situation
- NA48 measurements

  $K^{\pm} \rightarrow \pi^{+}\pi^{-} e^{\pm} \nu$ Form Factors + Branching fraction

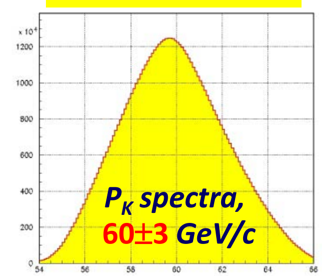
  $K^{\pm} \rightarrow \pi^{0}\pi^{0} e^{\pm} \nu$ Branching fraction
- Summary and prospects

The NA48/2 experiment at the CERN-SPS: primarily designed for CP violating charge asymmetries studies in K3π decays

2003 run: ~ 50 days + 2004 run: ~ 60 days and >200TB Data on tape



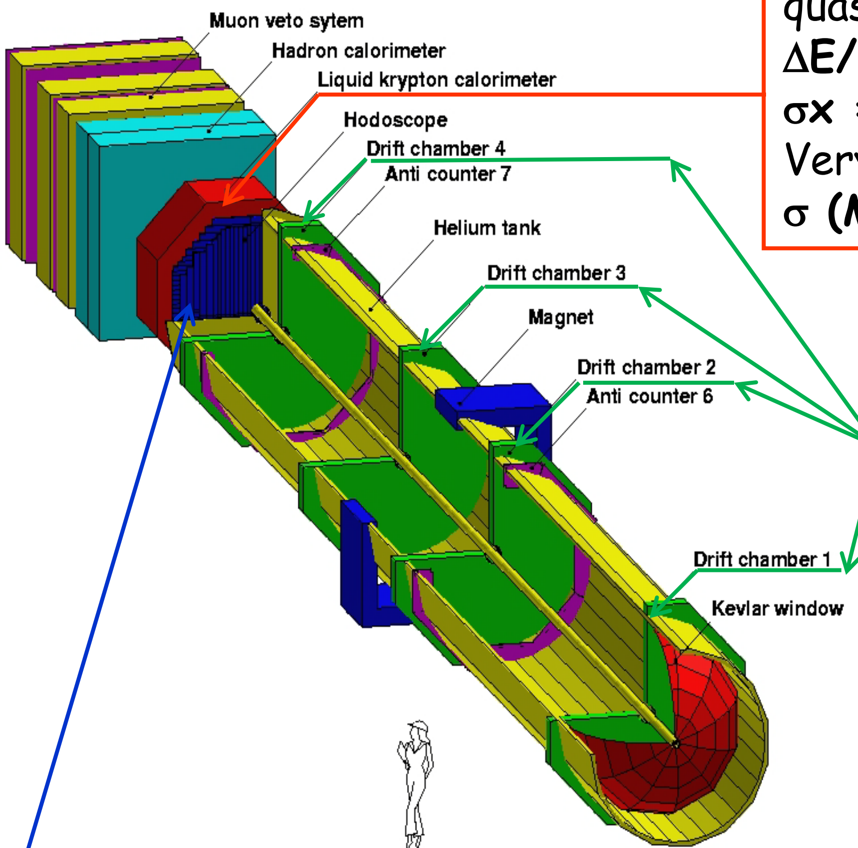
2-3M K/spill



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

Beams coincide within ~1mm all along the 114m decay volume flux ratio K⁺/K⁻ ~1.8

The NA48/2 experiment: detector and performances



LKr electromagnetic calorimeter :
quasi-homogenous and high granularity
$\Delta E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV)
$\sigma x = \sigma y \sim 1.5$ mm for E=10 GeV
Very good resolution for neutrals ($\pi^0 \rightarrow \gamma\gamma$)
$\sigma (M\pi\pi^0\pi^0) = 1.5$ MeV/c^2

+

Magnetic spectrometer :
4 high-resolution DCH's + dipole magnet
$\Delta p/p = (1.0 \oplus 0.044\ p)\%$ (p in GeV/c)
Very good resolution for charged invariant masses: $\sigma (M3\pi^{\pm}) = 1.7$ MeV/c^2

E/p ratio used for e / π discrimination

Hodoscope for charged fast trigger

$\sigma t = 150$ ps

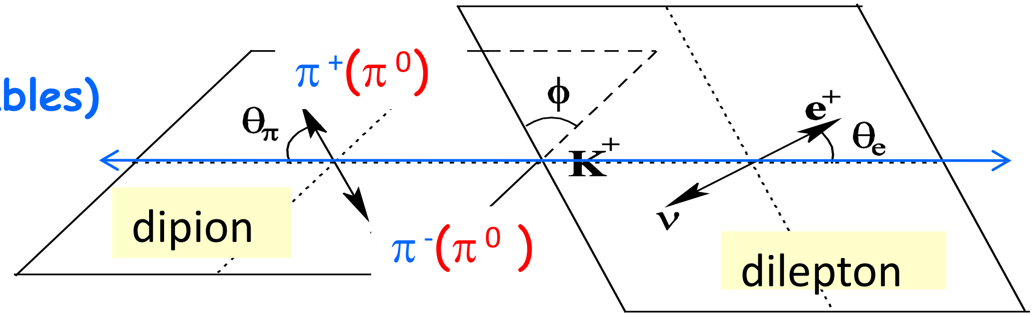
Ke4 decays : formalism of ($\pi^+\pi^- e\,\nu$) and ($\pi^0\pi^0 e\,\nu$) modes

Four-body final state described by

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

$F = F_s\, e^{i\delta s} + F_p\, e^{id\delta p} \cos\theta_p$

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

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

(00): Dalitz plot density proportional to Fs^2

The fit parameters (real) are :

(+-): F_s F_p G_p H_p and $\delta = \delta_s - \delta_p$

(00): reduce to the only Fs

Chiral Perturbative Theory and Kl4 decays

At low energy (<~1 GeV) , perturbative QCD does not apply anymore but an effective theory (ChPT) 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 (mu=md=0, αQED=0)

Rates : Γ(Kl4 +-) = ½ Γ (Kl4 0-) + 2 Γ (Kl4 00) (valid for lepton = e,μ)

			rel. prec.	#evts
Ke4 +-	$K^+ \to e\ \nu\ \pi^+ \pi^-$	PDG (4.09 ± 0.10) 10^{-5} / 1.238 10^{-8} s	2.4%	418000
Ke4 00	$K^+ \to e\ \nu\ \pi^0 \pi^0$	PDG (2.20 ± 0.40) 10^{-5} / 1.238 10^{-8} s	18.2%	37
Ke4 0-	$K^0 \to e\ \nu\ \pi^0 \pi^-$	PDG (5.20 ± 0.11) 10^{-5} / 5.116 10^{-8} s	2.1%	6131

Branching ratios : BR(Kl4 +-) = 0.121 BR(Kl4 0-) + 2 BR(Kl4 00)

~verified within the above experimental errors

there is room for improvement from better experimental measurements !

Predictions using Form Factor calculations by ChPT at O(p2,p4,p6..) (Bijnens,Colangelo,Gasser Nucl Phys B427 1994):

			predicted Br	rel. prec.
using S118 value as input	Ke4 +-	= (3160 ± 140) s-1	(3.91 ± 0.17) 10^{-5}	~ 5%
prediction	Ke4 00	= (1625 ± 90) s-1	(2.01 ± 0.11) 10^{-5}	~ 5%
prediction	Ke4 0-	= (917 ± 170) s-1	(4.69 ± 0.87) 10^{-5}	~ 18%

improved experimental measurements will provide tests of ChPT predictions

Contributions to Ke4 decays from NA48 : Form Factors

Ke4 decays in the $(\pi^+\pi^-)$ mode have been extensively studied with 1.1 million decays and published as Eur. Phys. C70 (2010) 635

- precise determination of all Form Factors and their energy variation ($q^2 = S\pi/4m\pi^2 - 1$, $Se/4m\pi^2$)
- precise determination of the S-wave $\pi\pi$ scattering lengths in I=0 and I=2 states

$$F_s^2 = f_s^2(1 + f_s'/f_s\, q^2 + f_s''/f_s\, q^4 + f_e'/f_s\, S_e/4m_\pi^2)^2$$

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

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

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 fs and the form factor absolute values

Ke4 (+-) branching fraction measurement

$K^{\pm} \to e^{\pm} \nu \pi^{+} \pi^{-}$ relative to the abundant and similar topology mode $K^{\pm} \to \pi^{\pm} \pi^{+} \pi^{-}$

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

Candidates : extracted from ~2.5 10^{10} total recorded triggers

N4 Ke4 candidates: **1.11×10^6** (7.12×10^5 K^+ and 3.97×10^5 K^-)

Nbkg (relative to Ke4) : **0.95%**

N3 K3π candidates: **1.9×10^9**

Acceptances (Geant3 based simulation used):

Large and similar values for signal and normalization modes

A4 acceptance of Ke4: 18.22% A3 acceptance of 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 $K^{\pm}$ 3π :(5.59 ±0.04)% **0.72% external error on BR(Ke4)**

Ke4 (+-) branching fraction measurement

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 ± 0.009 stat+trig) x 10^{-5}
BR(K^-e4) = (4.283 ± 0.012 stat+trig) x 10^{-5} ⇐ **never measured before**

combined (common systematic error) to

BR($K^\pm$e4) = (4.279 ±0.004stat ±0.005trig(stat) ±0.015syst ±0.031ext)x10^{-5}
= (4.279 ± 0.035tot) x 10^{-5} (0.8% rel.) external error dominated

PDG 2010 (4.09 ±0.10)x10^{-5} (2.4% rel.) systematic dominated

Ke4 (00) branching fraction measurement : event reconstruction

$K^{\pm} \rightarrow e^{\pm} \nu \pi^0 \pi^0$ relative to the more abundant and similar topology mode $K^{\pm} \rightarrow \pi^{\pm} \pi^0 \pi^0$ 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

1- π^0 mass constraint

$$Z1 = ZLKr - Dab \sqrt{(Ea\ Eb)} / m\pi^0$$

$$Z2 = ZLKr - Dcd \sqrt{(Ec\ Ed)} / m\pi^0$$

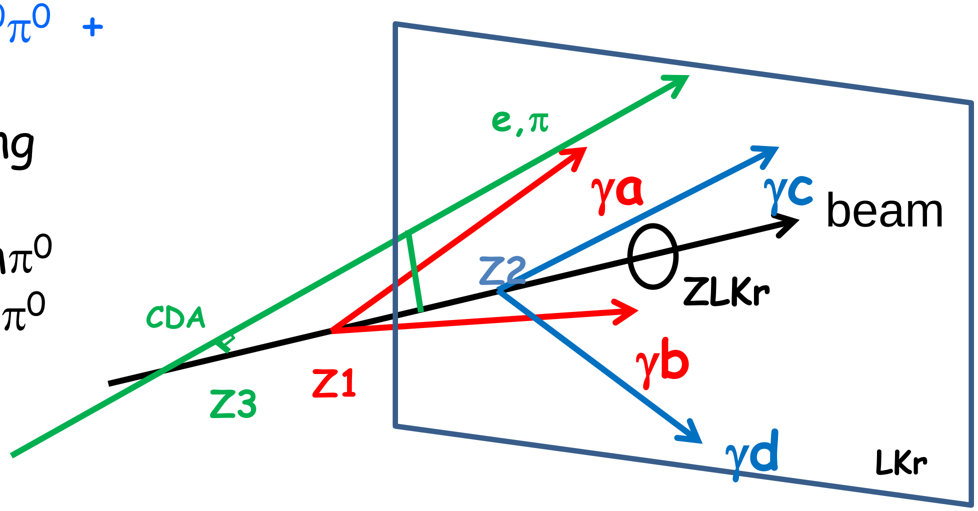
2- Dzn = |Z1 – Z2| < 500 cm

3- Zn = 0.5*(Z1+Z2) within decay volume range [-16,+90]m

4- combine with charged track if Z3 (CDA to beam line) satisfies

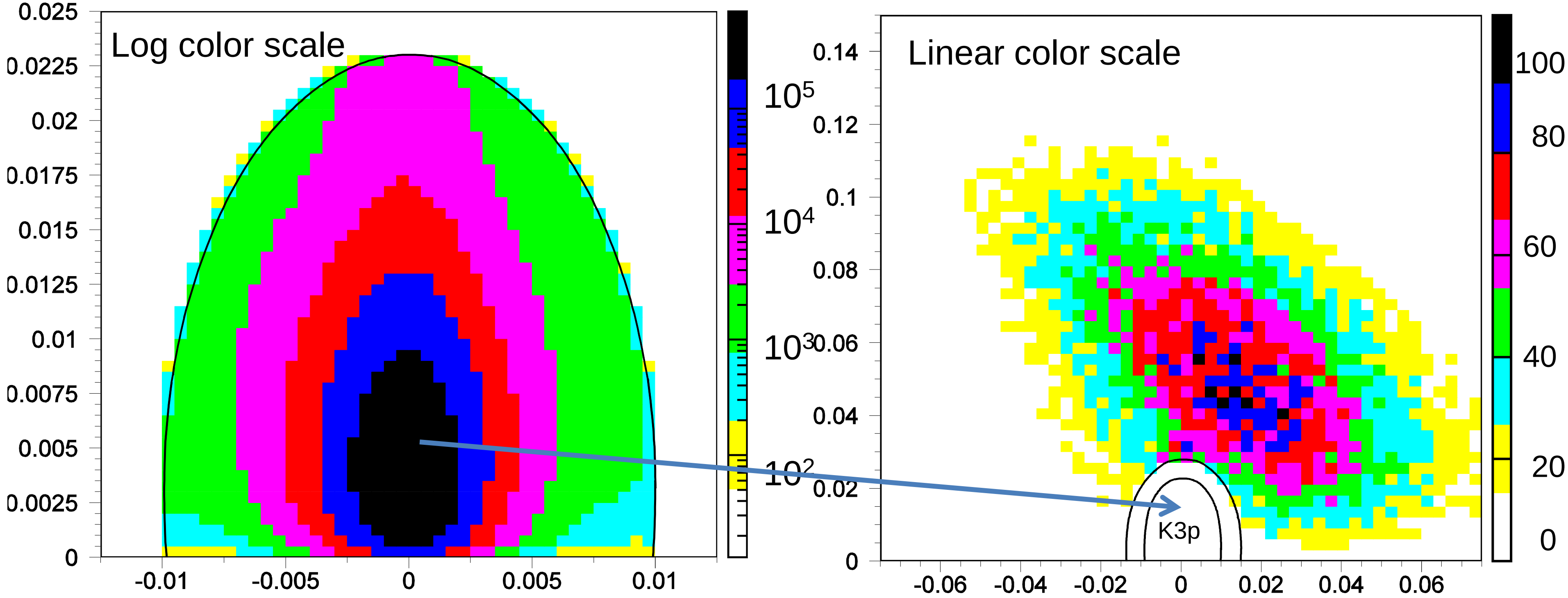
Dz = |Z3 – Zn| < 800 cm

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



Ke4 (00) branching fraction measurement : signal selection

Assign mπ to the charge track and compute invariant mass,
plot vs Pt to the beam line: K3π events cluster at low pt and Mk
Ke4 events have larger pt and a large spread of mass values (missing ν)
Elliptic cut separates 70 M K3π candidates from 45K Ke4 candidates

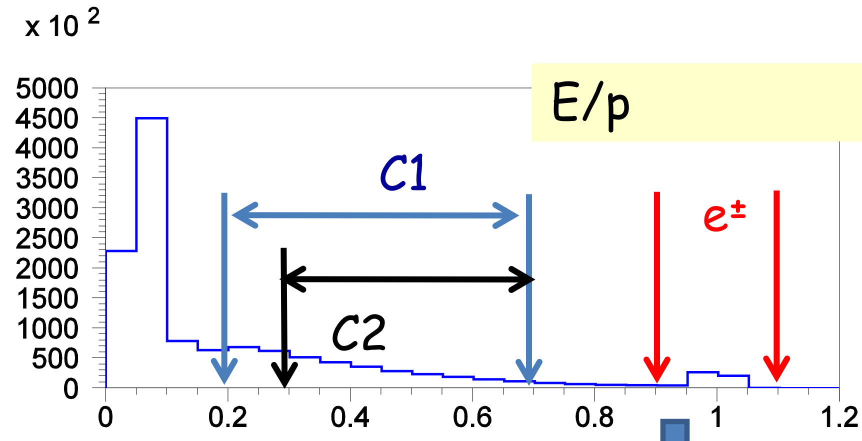


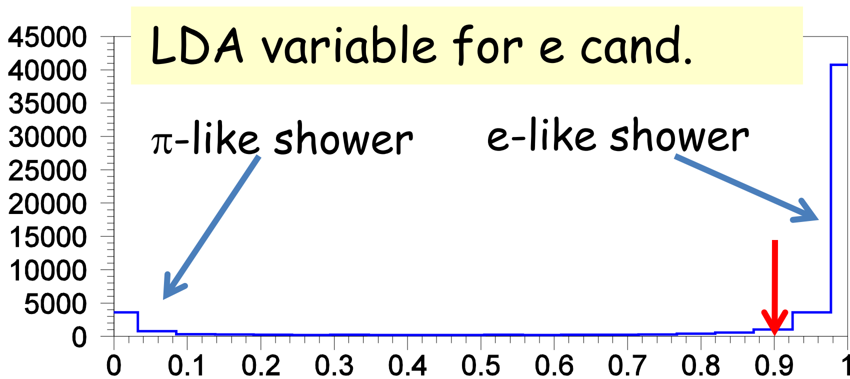
Pt (GeV/c)   vs   M3π -Mk   (GeV/c²)

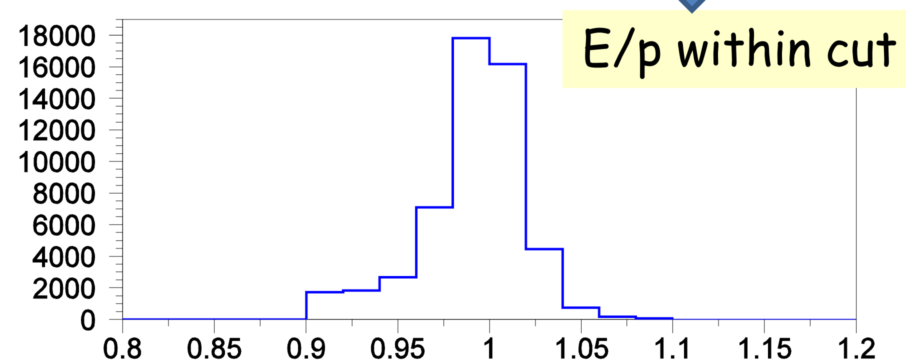
Ke4 (00) : electron identification

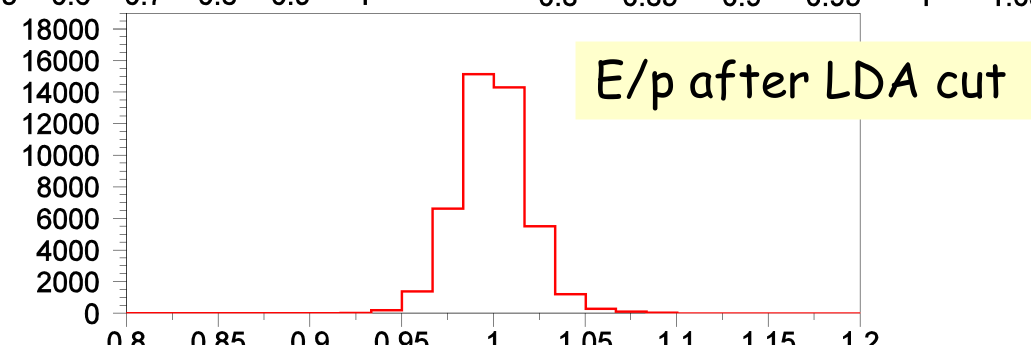
Electron identification :

- E(LKr)/p(DCH) ~1 for electrons
- Control region C1(C2) as [0.2(0.3),0.7] are pions only
- fake-electron rejection using a dedicated variable (Linear Discr.) based on shower properties and trained on real and fake electrons from data .



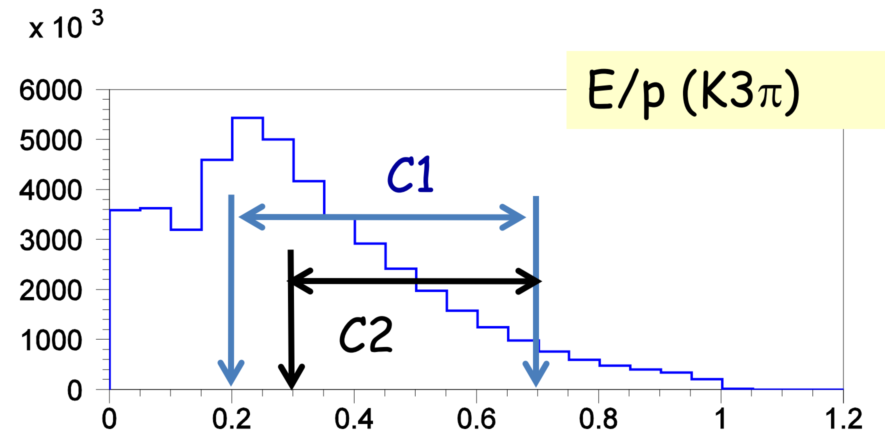


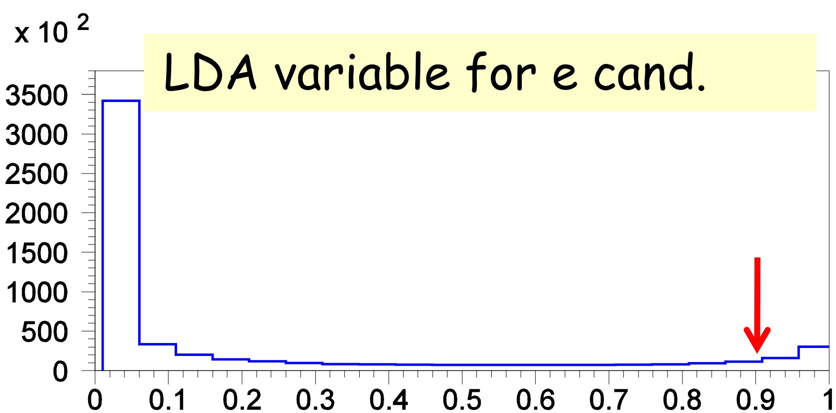


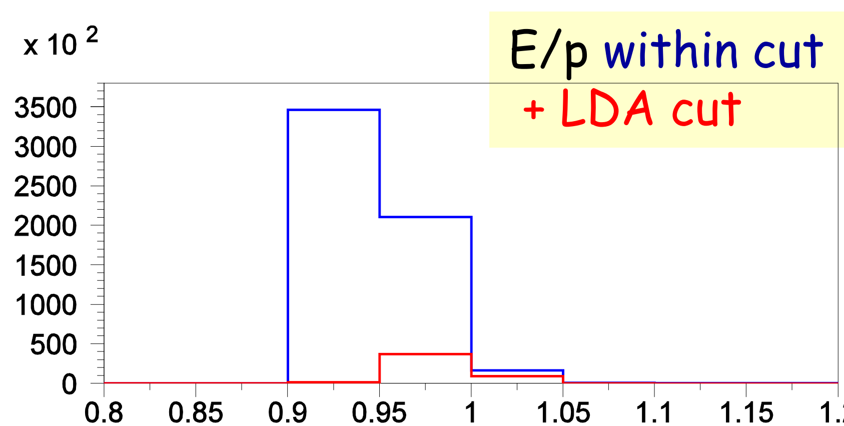


Ke4 (00) : background estimation

•Residual fake-electron background estimated from control region (s) of $K3\pi$ candidates: C1 (C2) = π only with E/p in [0.2(0.3),0.7]
• E/P in electron region [0.9,1.1] + cut on LDA variable : e/C1 = 0.166%
(e/C2 = 0.259%)
• multiply by Nobs in C1 (C2) for signal region= 598 (592) fake- electrons =
1.3% relative to Ke4 signal



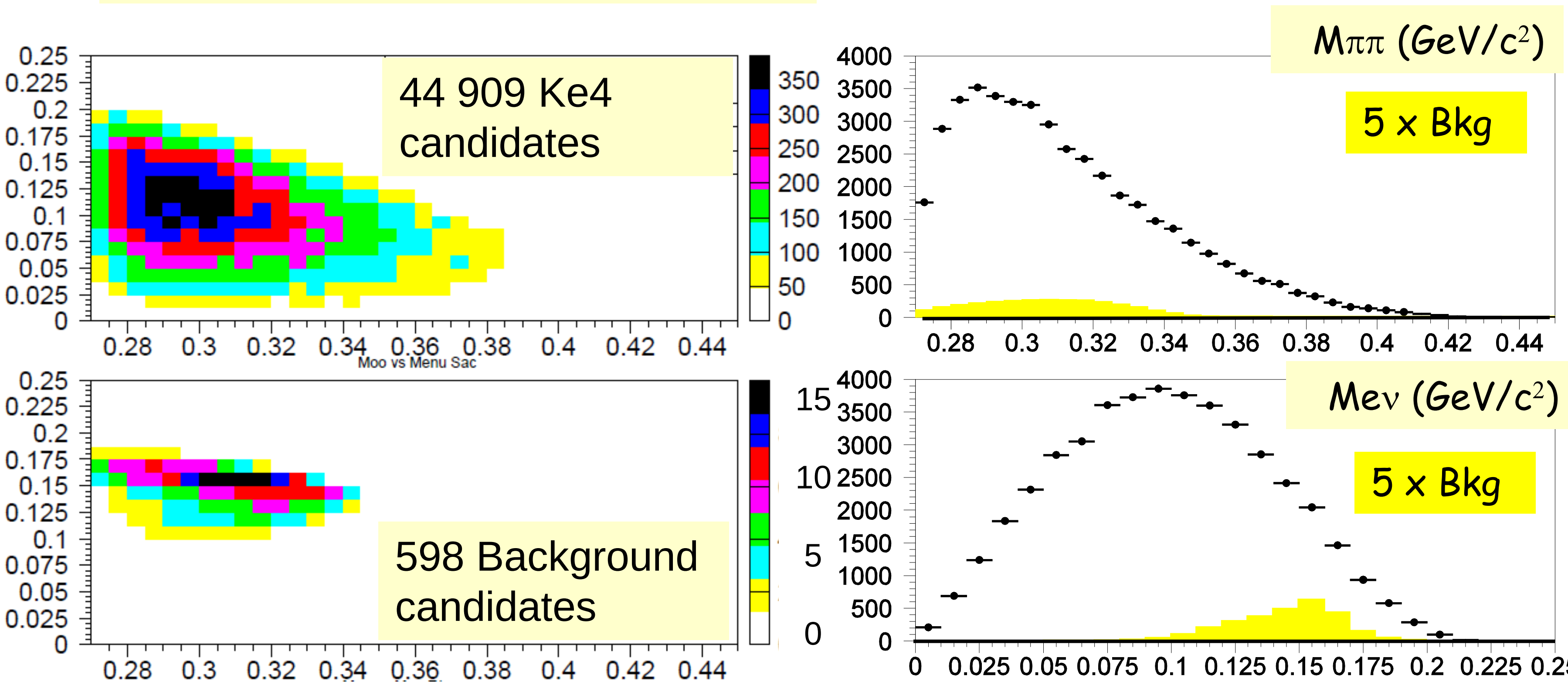




Ke4 (00) : Dalitz plot

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

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



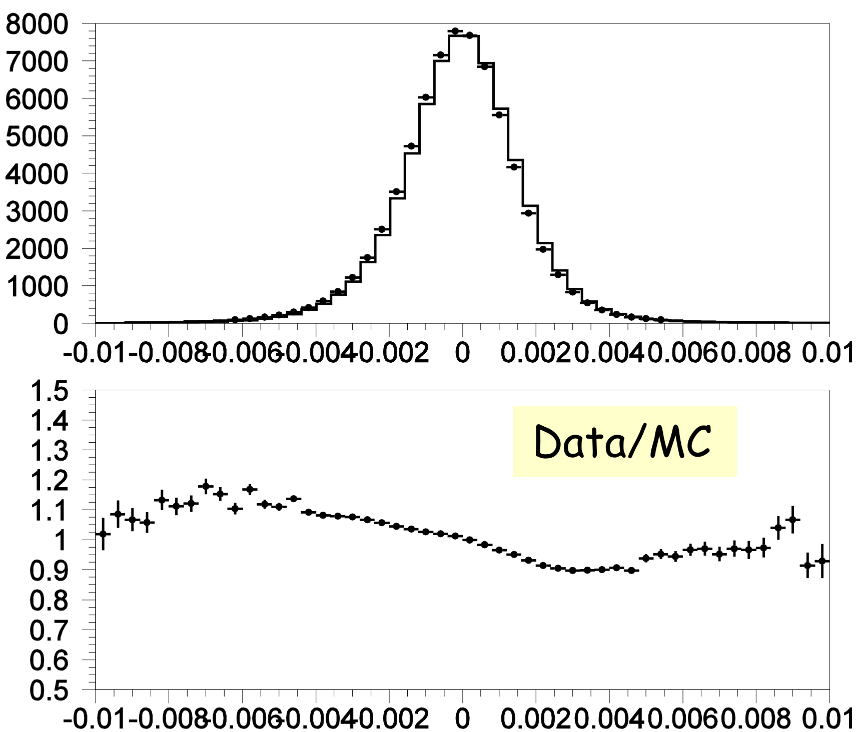
K3π (00) : energy scale /calibration control

•Reconstructed Kaon mass with expected 1.5 MeV/c2 resolution
small shift data vs MC (80 KeV/c2) consistent with beam geometry modeling and non-linearities corrections (LKr) control

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

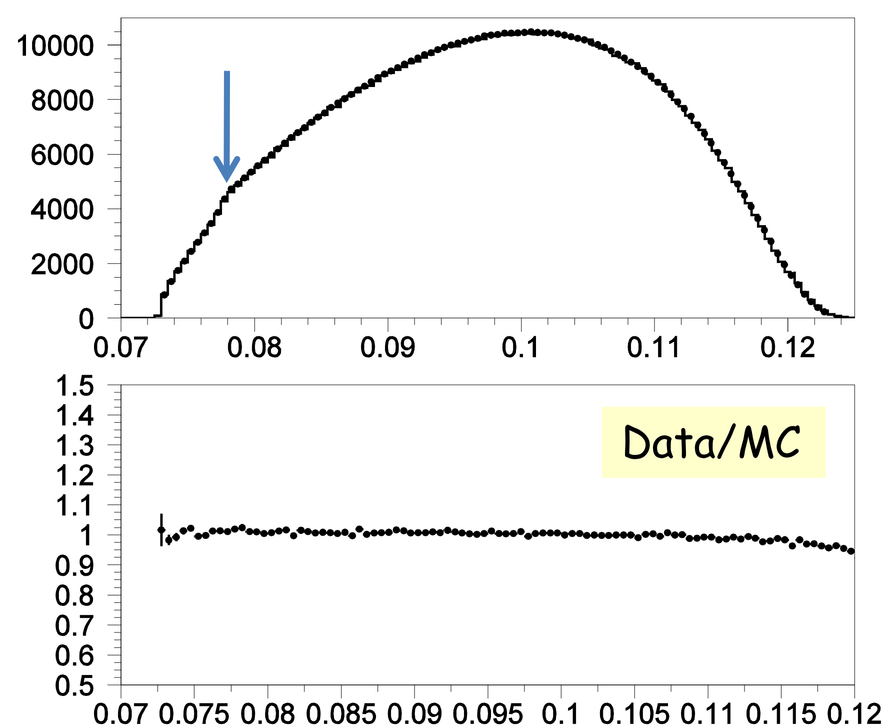
$M3\pi - MK$ (GeV/c^2)

x 10 ^{3}



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

x 10 ^{2}



Ke4 (00) : Br measurement

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

NKe4 candidates = 44909 Nbkg = 598 (1.3% of Ke4)
NK3π candidates = 70 984 882

Acceptances A4 = 1.77% A3 = 4.11 %
Trigger efficiency ε(Ke4) : 92% to 98% ,
ratio to ε (K3π) ~1 with local deviations
Normalization : Br = (1.761 ± 0.022) % (1.25% external error)

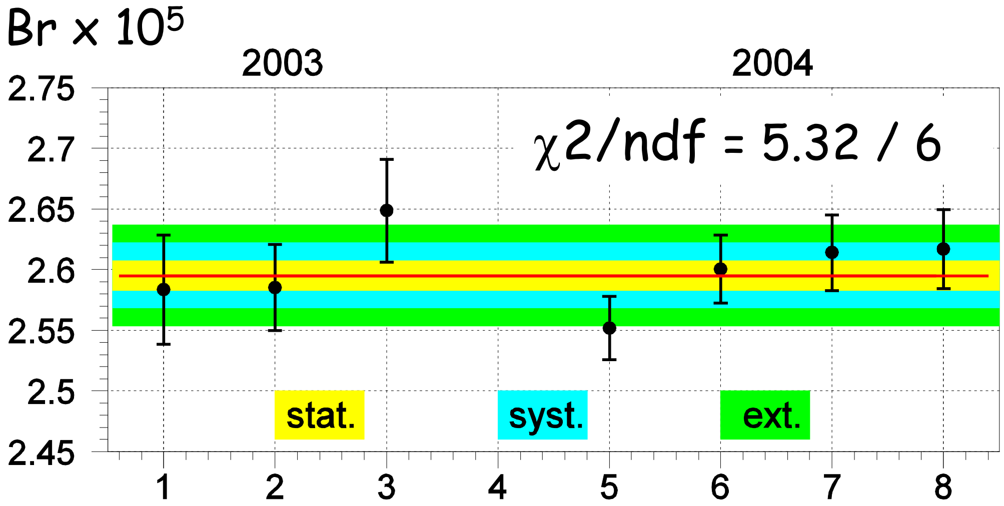
Systematic

Uncertainties	**[%]**
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

(preliminary thus conservative)

BR Ke4(00) =
(2.595 ± 0.012 stat ± 0.024 syst ± 0.032 ext) 10^{-5}

Ke4 (00) and Ke4 (+-) : Br measurements



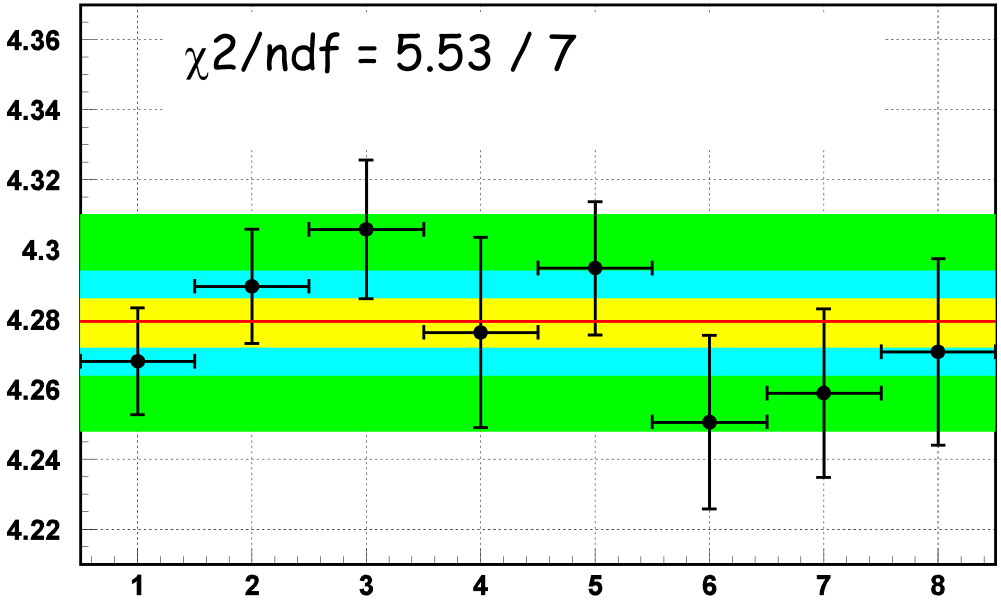
Ke4 (00) normalized to $K\pi^{\pm}\pi^0\pi^0$

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

stat syst ext

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

Preliminary results



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

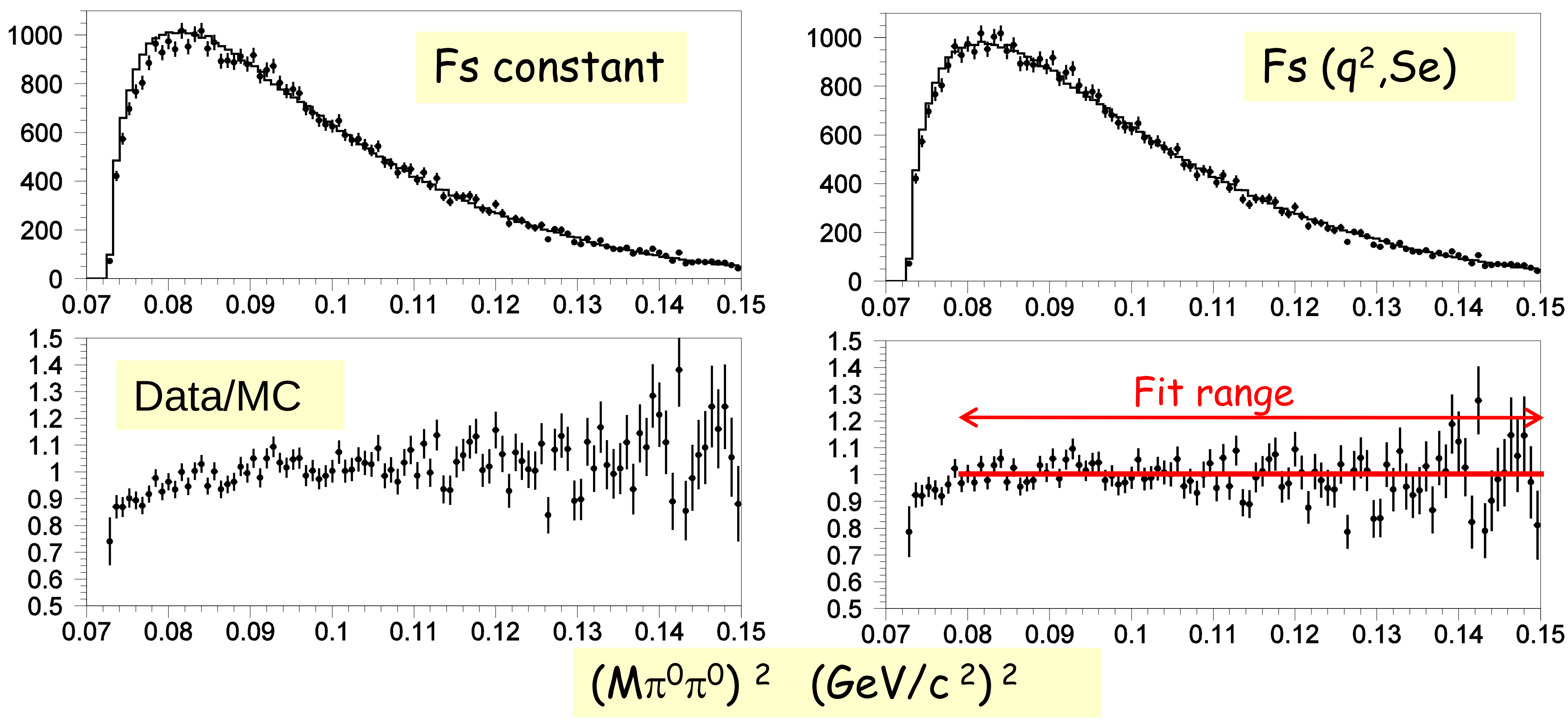
$(4.279 \pm 0.007 \pm 0.015 \pm 0.031)\ 10^{-5}$

stat syst ext

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

Ke4 (00) : First look at Form Factor

- Given the limited statistics (~45k events), the same precision as the Ke4(+-) cannot be reached
- compare $(M\pi^0\pi^0)^2$ distribution with the distribution obtained with
- simulation of a constant Form Factor Fs
- simulation of the Fs Form Factor from Ke4(+-): good agreement + cusp ??
  (explained by charge exchange scattering process)



Summary

NA48/2 has analyzed ~1.11 M Ke4 (+-) and 44 000 Ke4(00) events recorded among 2.5 10^{10} triggers in years (2003+2004)

1. Improved measurements for the Branching fractions have been obtained

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

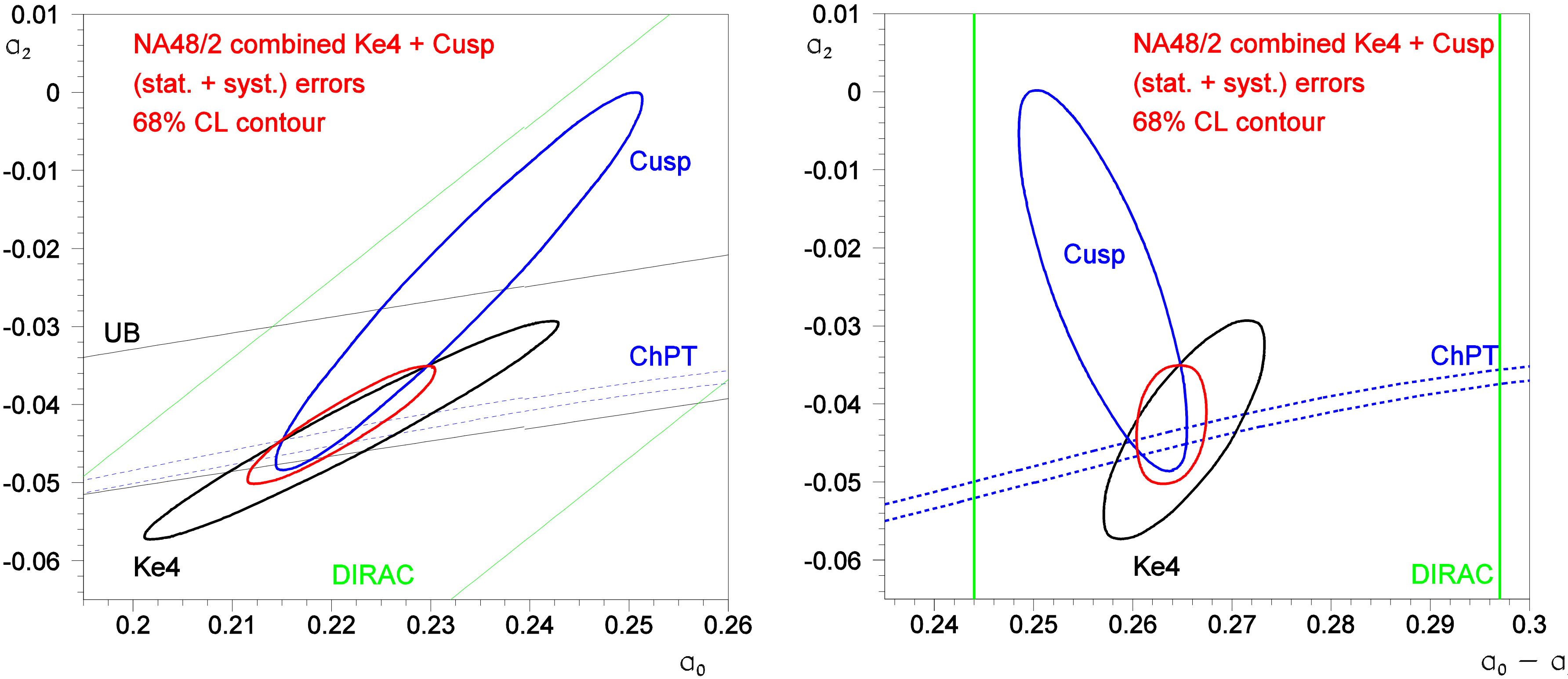
BR Ke4 (00) = (2.595 ± 0.042) 10^{-5} 1.6% rel. (factor >10 improvement /PDG)

errors in both modes are now dominated by the external error

2. When finalized, this will allow to give precise absolute values for all Form Factors of the decays
3. First approach to the Ke4(00) Fs Form factor measurement shows consistency with the Fs Ke4(+-) form factor. A cusp below the 2mπ+ threshold can be explained by charge exchange scattering effects of the ($\pi^0\pi^0$) system to ($\pi^+\pi^-$) with negative interference below threshold.
4. This study will complete the overall picture of Ke4 decays and will bring precise measurements to be compared with the most elaborated predictions from ChPT.
5. Future studies will look for Kμ4 decays where several 1000 events are expected in NA48 data while very little is known (7 events observed in the (+-) mode (1967), none in the (00) mode). Predictions from ChPT include the extra R form Factor not (yet) measured …

Back up plots

Combined results on scattering lengths from cusp and Ke4



Including the ChPT constraint: 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 Δa_2 : ± 0.0009 Δa_0 : ± 0.0034 $\Delta (a_0 - a_2)$: ± 0.0026

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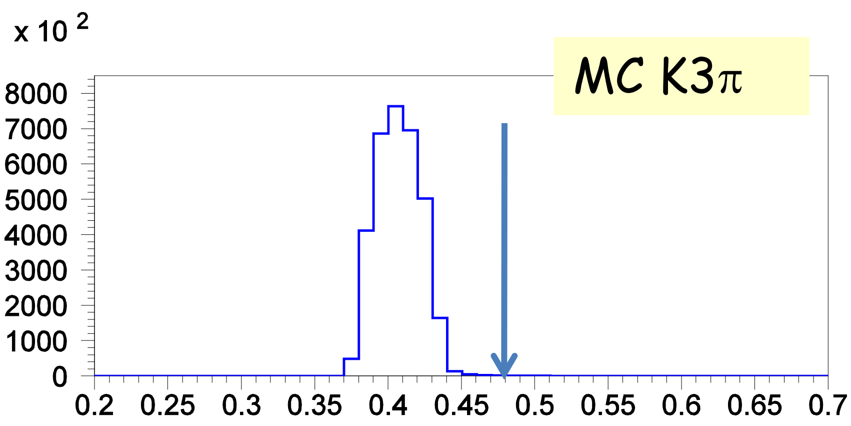
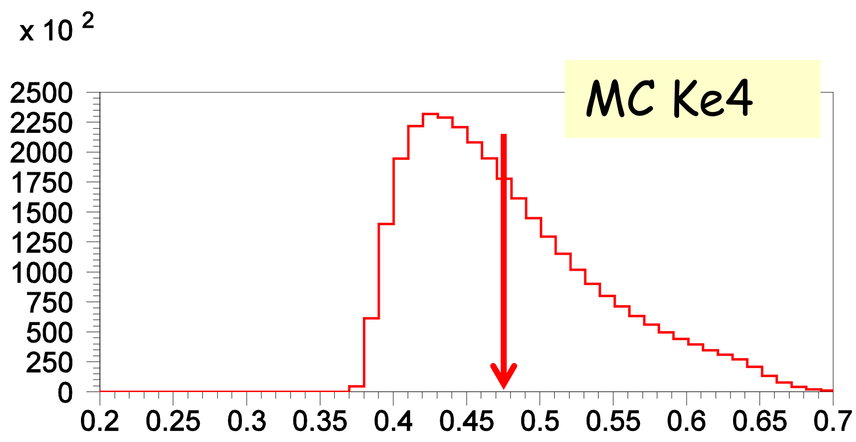
Ke4 (00) : trigger control

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

Level 2 : Q1 (1 Hodoscope quad hit) x Software trigger from fast DCH Track reconstruction

Level 2 Trigger cut rejects K $\pi\pi^0$: M(K-π) < 0.475 GeV/c^2

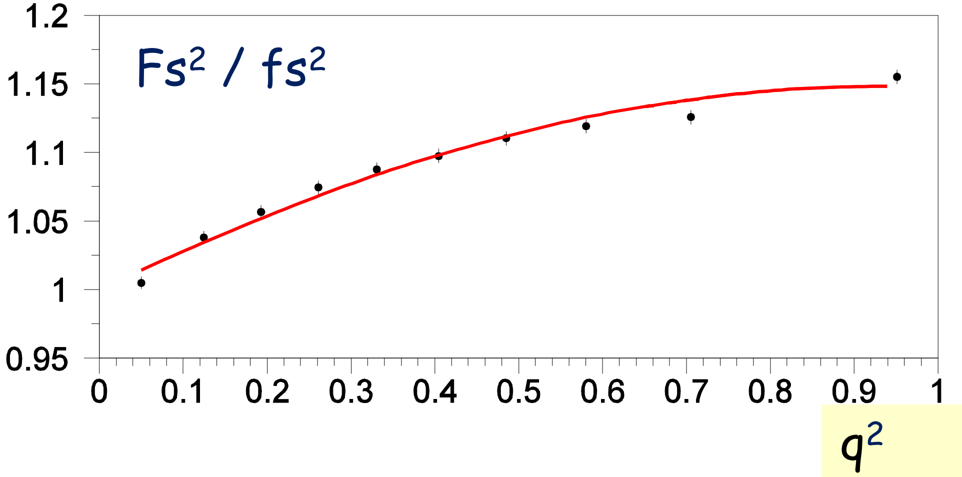


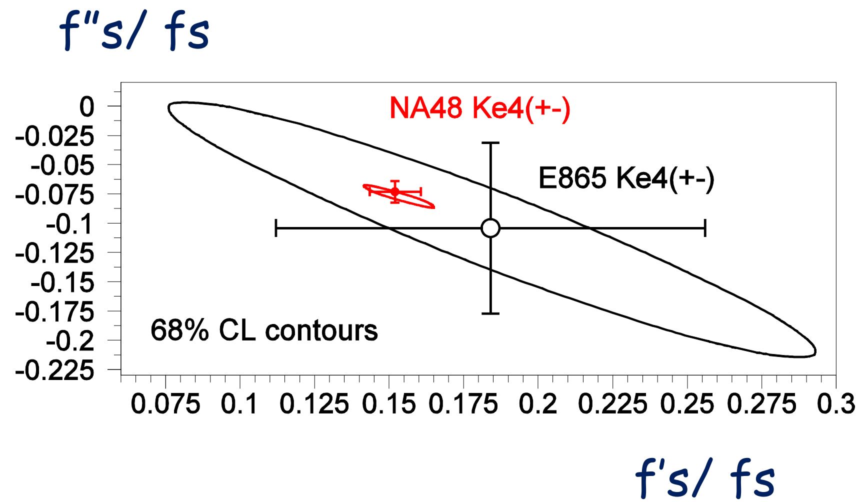


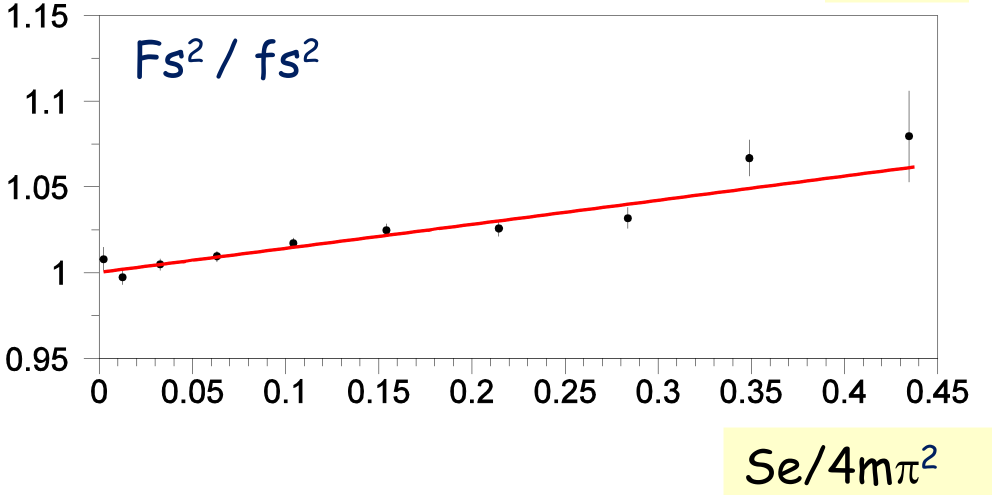
Ke4 (+-) : Fs^2 variation with q^2 and $Se/4m\pi^2$

$$F_s^2 = f_s^2(1 + f_s'/f_s\, q^2 + f_s''/f_s\, q^4 + f_e'/f_s\, S_e/4m_\pi^2)^2$$

$q^2 = S\pi/4m\pi^2 - 1$

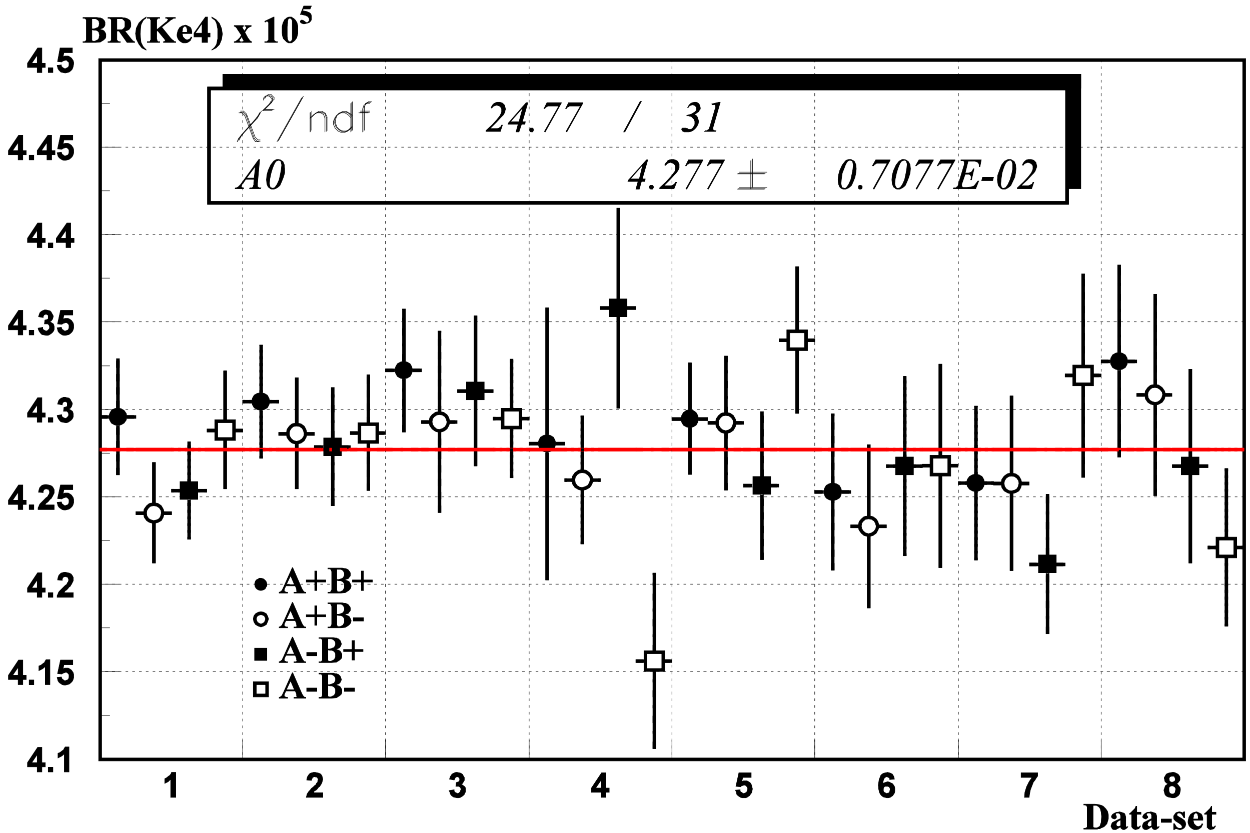






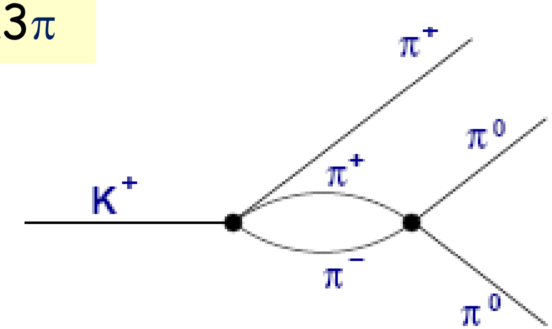
	NA48/2	E865
f's/ fs	0.152(9)	0.184(72)
f"s/ fs	-0.073(9)	-0.104(73)
f'e/ fs	0.068(9)	0.000(46)

Ke4 (+-) : BR Stability with time and data taking conditions

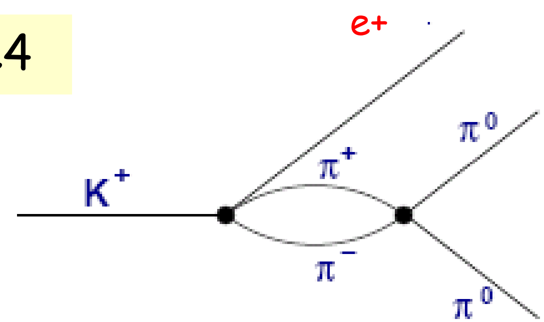


Rescattering in the ππ system

K3π



Ke4



Charge exchange scattering process in the K3π system can be seen also in the Ke4 system !

M0 ≈ Fs leading order, real
complemented by M1 real above threshold
imaginary below

$M1 \approx Fs\,(2/3)\,(a0\text{-}a2)\,\mathrm{sqrt}\,(1-(4m\pi^2/S\pi))$

a0,a2 (S-wave ππ scattering lengths ,I=0,2)

a0-a2 = 0.264 ± 0.0021 from Ke4(+-) analysis

Fs^2 becomes
$(M0 + M1)^2$ above threshold
$|M0 + i\,M1|^2$ below threshold

Cabibbo , PRL 93(2004) 1-loop calculation
Cabibbo-Isidori ,JHEP 0503 (2005)) 2-loop calculation
Colangelo et al. PLB 638 (2006) Eff. Lagrangian + rad.corr