QCD tests at the NA48/2 experiment at CERN

Brigitte Bloch-Devaux

CEA Saclay, IRFU-SPP

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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

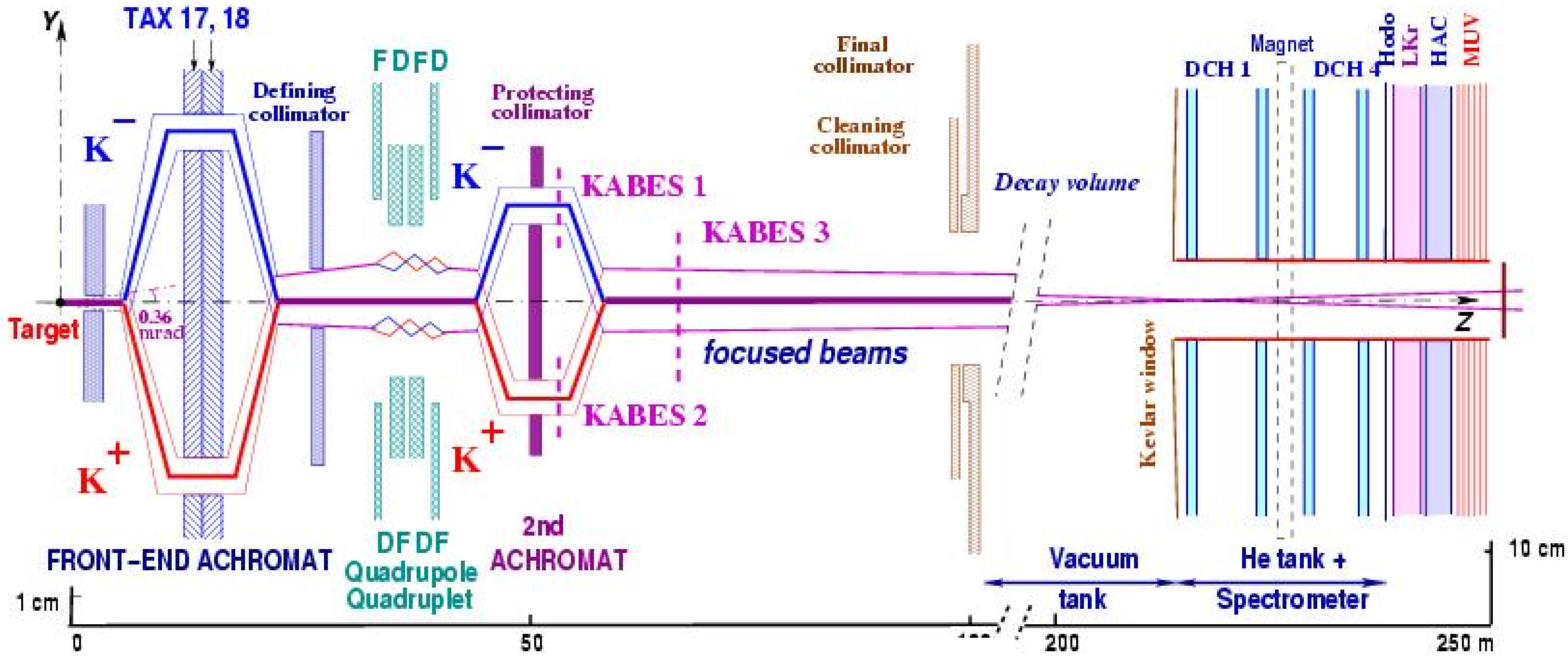
- Introduction to NA48/2
- QCD tests from study of Kaon decays
- Ke4 decays ($K^{\pm} \rightarrow \pi^{+}\pi^{-} e^{\pm} \nu$) :

  Form Factors and $\pi\pi$ scattering lengths
- K3π decays ($K^{\pm} \rightarrow \pi^{0}\pi^{0}\pi^{\pm}$) : the "cusp" effect

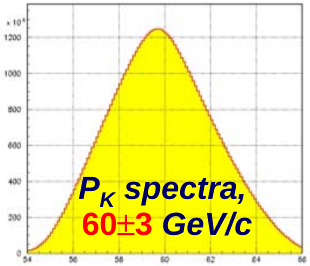
  Dalitz plot parameters and $\pi\pi$ scattering lengths
- Summary

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



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

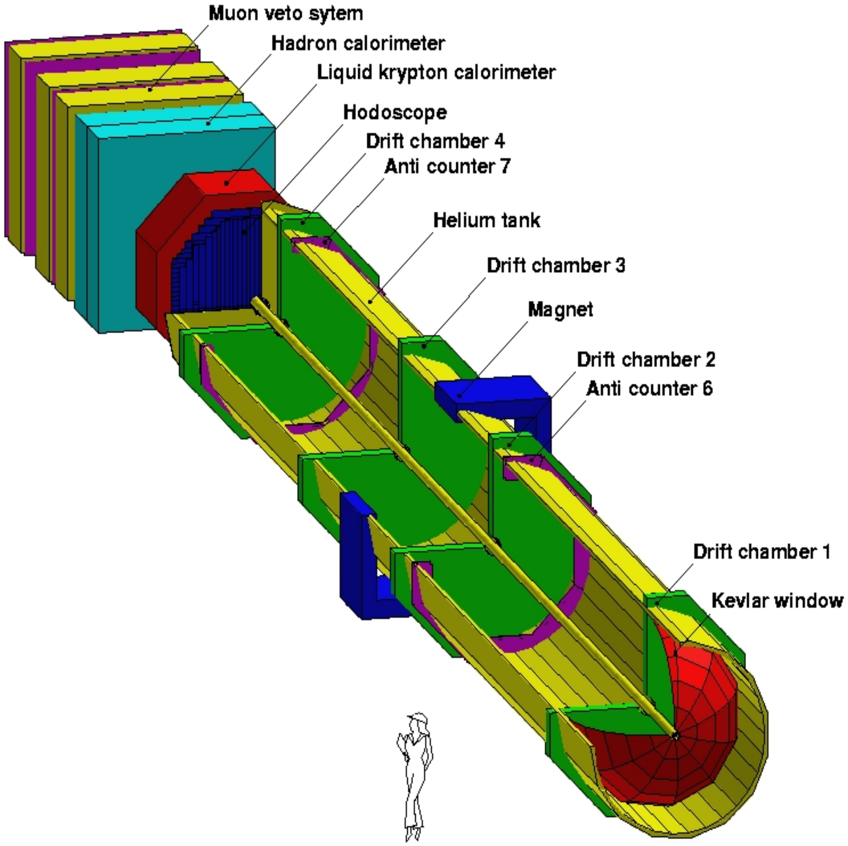
Magnetic spectrometer :
4 high-resolution DCH's + dipole magnet
$\Delta p/p = (1.0 \oplus 0.044\ p)\%$ (p in GeV/c)
Very good resolution for charged invariant masses: $\sigma(M3\pi^{\pm}) = 1.7$ MeV/c^2

Hodoscope for charged fast trigger

$\sigma t = 150$ ps

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 ($\pi^0 \rightarrow \gamma\gamma$)
$\sigma(M\pi\pi^0\pi^0) = 1.4$ MeV/c^2

E/p ratio used for e /π discrimination



Kaon decays : what can be learned on QCD @ Low Energy ?

preliminary

Hadronic decay modes into 3 pions:

- large Br's : $K^{\pm} \rightarrow \pi^0\pi^0\pi^{\pm}$ (1.7 %) and $K^{\pm} \rightarrow \pi^+\pi^-\pi^{\pm}$ (5.6 %),

60 Millions events now analyzed (PRL B633 (2006) partial sample)

- three pions ➔ $\pi^0\pi^0$ system + nearby hadron
- accessible $M\pi\pi$ range from threshold to (M_K-M_{π})

preliminary

Semileptonic decay mode Ke4:

- small Br's : $K^{\pm} \rightarrow \pi^+\pi^- e^{\pm} \nu$ (4.1 10^{-5}),

  1.1 **Million events now analyzed** (EPJC 54 (2008) partial sample)

- only two $\pi^+\pi^-$ pions, very clean environment
- accessible $M\pi\pi$ range from threshold to $(M_K-M_e) = M_K$

Two different but complementary approaches to $\pi\pi$ scattering near threshold ➔ extract s-wave scattering lengths (a0, a2) for Isospin I = 0 and I = 2

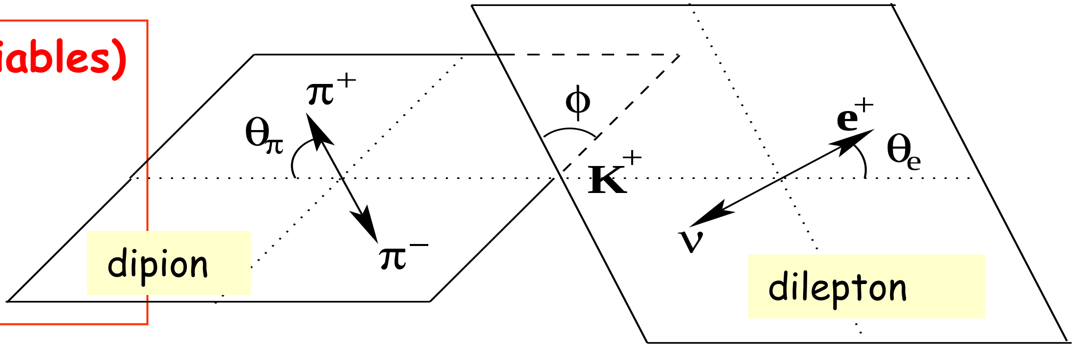
Ke4 decays : formalism

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.



Partial Wave expansion of the amplitude (Pais-Treiman 1968) into s and p waves

F, G = 2 Axial Form Factors

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

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

H = 1 Vector Form Factor

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

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

The fit parameters are :

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

Ke4 decays: event selection and background rejection

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

- 3 charged tracks and a good vertex
- two opposite sign pions,
- 1 electron (LKr info E/p ~ 1),
- some missing energy and p_T (ν)
- reconstruct PK (missing ν hypothesis)

Background main sources :

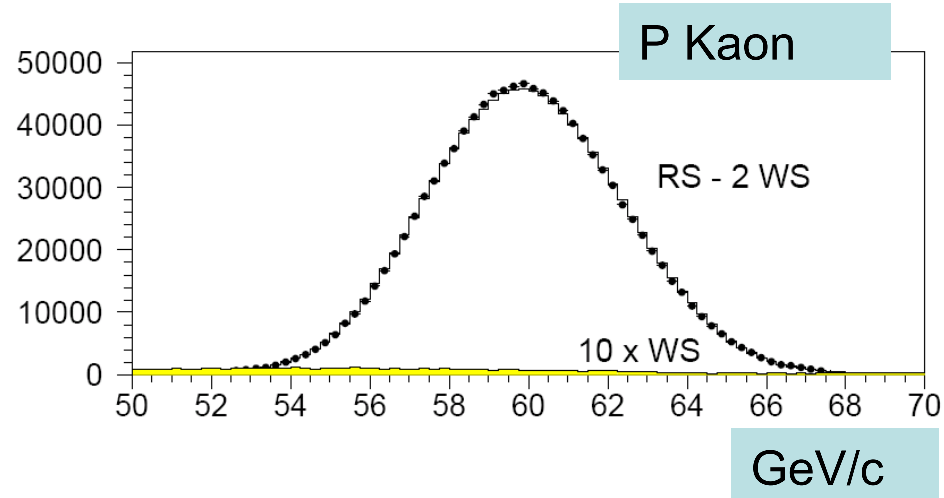
$K^\pm \rightarrow \pi^+\pi^-\pi^\pm$ (dominant)
↳ $e\,\nu$ or misidentified as e

$K^\pm \rightarrow \pi^0 (\pi^0)\, \pi^\pm$
↳ ($e^+e^-\gamma$) + 1e misidentified as π
and γ (s) undetected

Control sample from data ($\Delta S=\Delta Q$ valid)
$K^\pm \rightarrow \pi^\pm \pi^\pm e^\mp \nu$ "Wrong Sign" events

- total charge (±1) as Right Sign events
- electron charge opposite to total charge

Rate (RS/WS) events:
2 if coming from $K3\pi$
1 if coming from $K2\pi(\pi^0)$



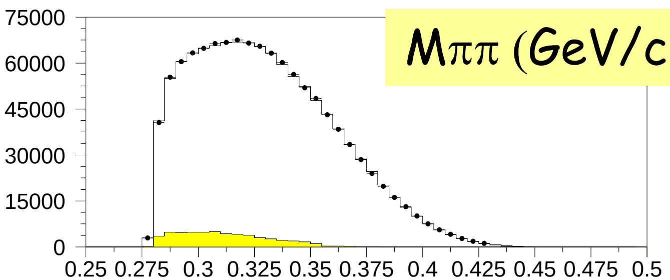
Total background level can be kept at ~ 0.5 % relative level estimated from WS events rate and checked from MC simulation

Ke4 decays: fitting procedure and Form Factors

Total statistics 1.1 Millions Ke4 decays distributed over a grid of **15000 iso populated** boxes = $10(M_{\pi\pi}) \times 5(M_{e\nu}) \times 5(\cos\theta_\pi) \times 5(\cos\theta_e) \times 12(\Phi)$

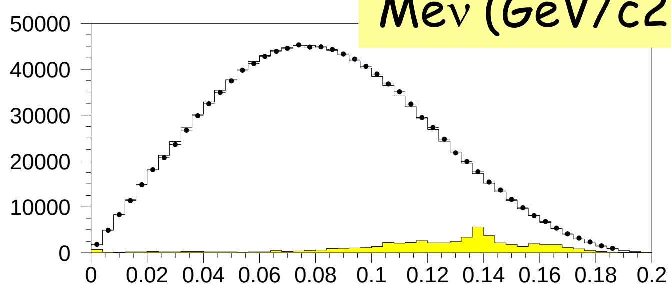
Fits are repeated in each $M_{\pi\pi}$ bin for K^+ and K^- separately without any assumption of Form Factor dependence with q^2 ($S_\pi/4m_\pi^2 - 1$) and $Se/4m_\pi^2$ using a large (~30 Millions) simulated sample to account for acceptance and experimental conditions.

Mππ (GeV/c2)



• = Data
hist = Simulation after fit

Meν (GeV/c2)



= WS Background (x10 to be visible)

Taylor expansion of Form Factors used to characterize bin to bin variation with q^2, q^4 and Se (valid in the isospin symmetry limit)

Preliminary

	value	stat error	syst error(2003)
f'_s/f_s	0.158	± 0.007	± 0.006
f''_s/f_s	-0.078	± 0.007	± 0.007
f'_e/f_s	0.067	± 0.006	± 0.009
f_p/f_s constant	-0.049	± 0.003	± 0.004
g_p/f_s	0.869	± 0.010	± 0.012
g'_p/f_s	0.087	± 0.017	± 0.015
h_p/f_s constant	-0.402	±0.014	± 0.008

Ke4 decays: from phase shifts to scattering lengths (a0,a2)

$\pi\pi$ phases at threshold can be predicted from data above 0.8 GeV using **Roy equations** (unitarity, analyticity and crossing symmetries) and 2 subtraction constants **a0 and a2**

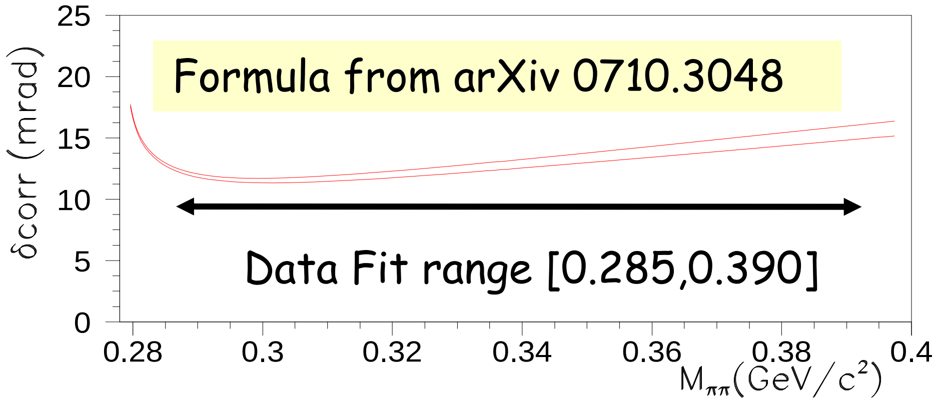
→ **Numerical solutions** have been developed (ACGL Phys.Rep.353(2001), DFGS EPJ C24(2002)) valid in the **Isospin symmetry limit**, broken in the experimental world. **(Universal Band)**

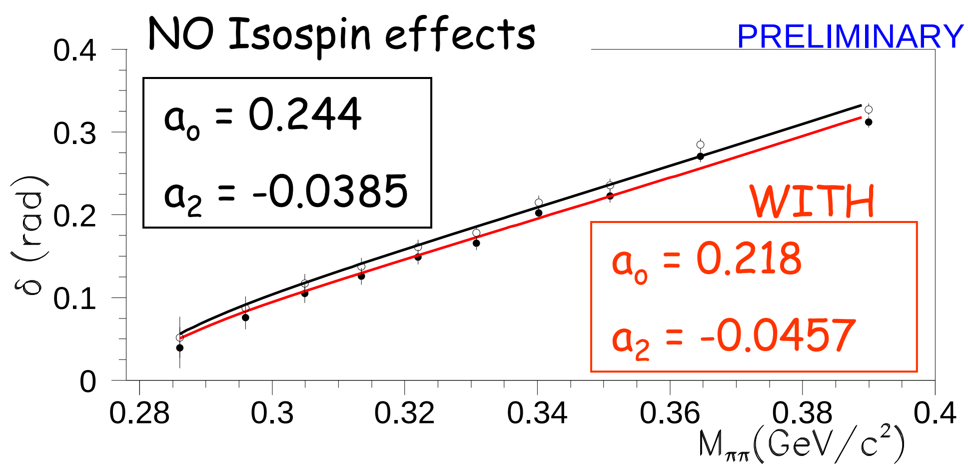
Radiative effects: included in the simulation,
Mass effects: recently computed as a correction to the measurements, even larger than current experimental precision !
(CGR hep-ph/0811.0775 , DK in progress)

→ Induces a large **2 σ_{exp} change** on (a0,a2) values from a 2p fit:

σ(a0): ± 0.013 (stat) ± 0.007 (sys)

σ(a2): ± 0.0084 (stat) ± 0.0041 (sys)





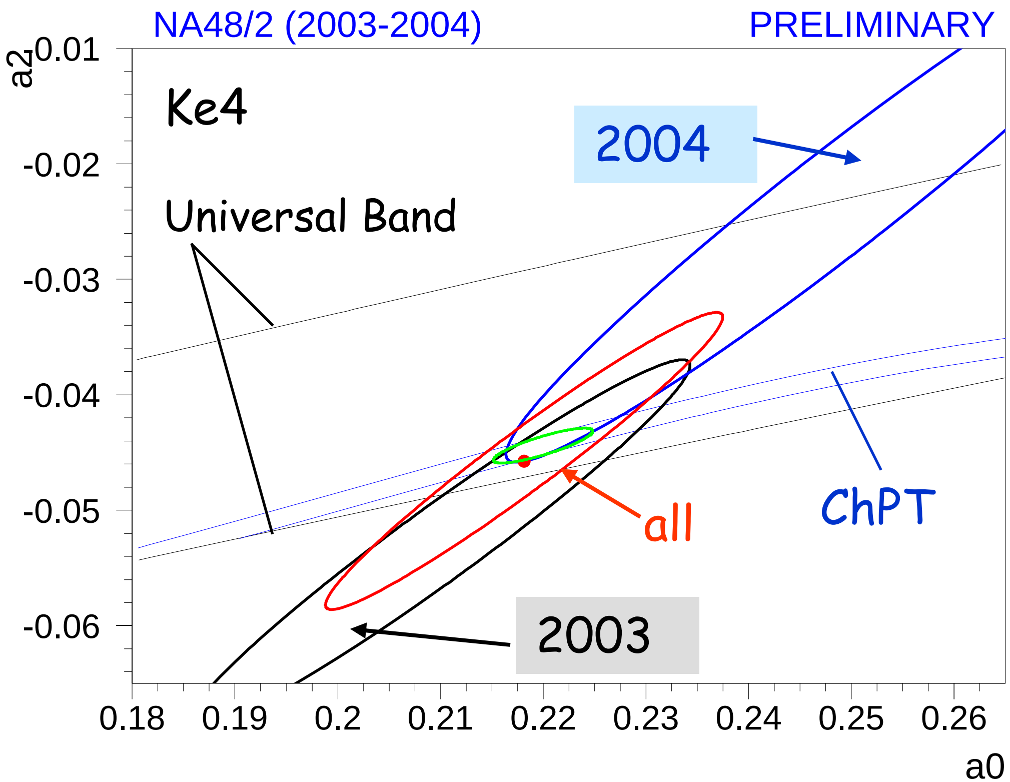
Ke4 decays: comparison with theoretical predictions

Using more inputs from ChPT and low energy constants, the prediction is better constrained (CGL NPB603(2001)):

$a_0 = 0.220 \pm 0.005$

$a_2 = -0.0444 \pm 0.0008$

a_0 ChPT 1p fit	0.220 ± 0.005 stat ± 0.002 syst* ± 0.006 theo **
a_0 free	0.218 ± 0.013 stat ± 0.007 syst* ± 0.017 theo**
a_2 free 2p fit	-0.0457 ± 0.0084 stat ± 0.0041 syst* ± 0.0030 theo**



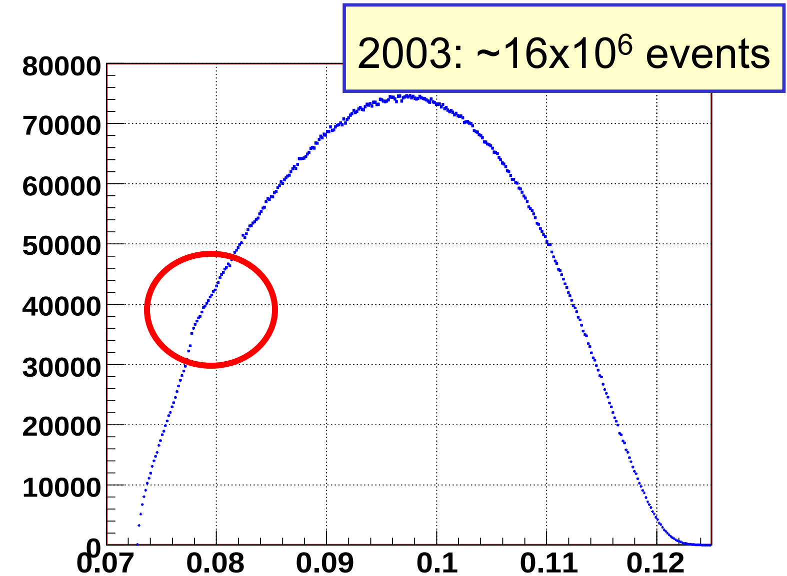
*systematics from 2003 data

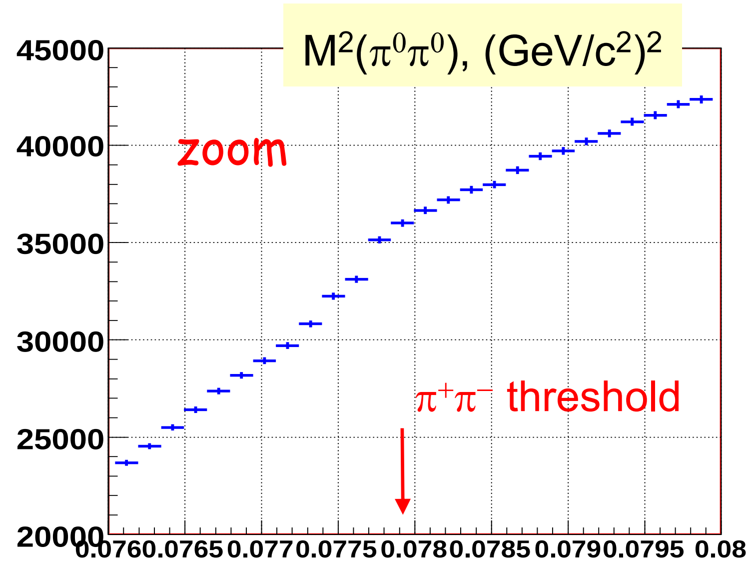
**Theory error evaluated from control of the isospin corrections, inputs to Roy equation numerical solutions (CGR arXiv:0811.0775)

Cusp effect : first observation and interpretation (Cabibbo PRL93(2004))

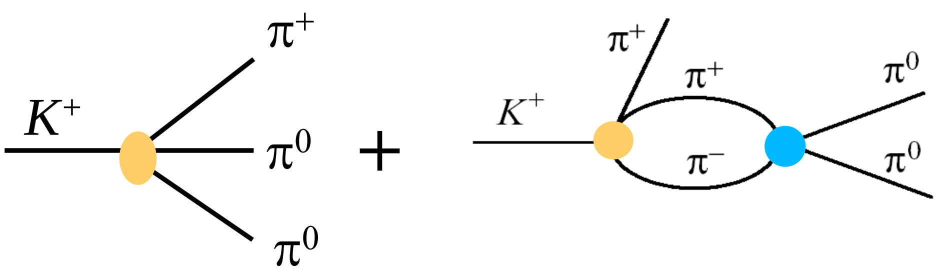
In $K^{\pm} \to \pi^0 \pi^0 \pi^{\pm}$ decay, the matrix element is usually described as a polynomial expansion using the Dalitz Plot variables u and v

First observation of a cusp structure was made with 16 M events collected in 2003 thanks to the very good mass resolution.





The structure at $\pi^+ \pi^-$ threshold was interpreted as due to the $\pi\pi$ rescattering in the $K^{\pm} \to \pi^+ \pi^- \pi^{\pm}$ final state



increased statistics with 44 M more data from 2004

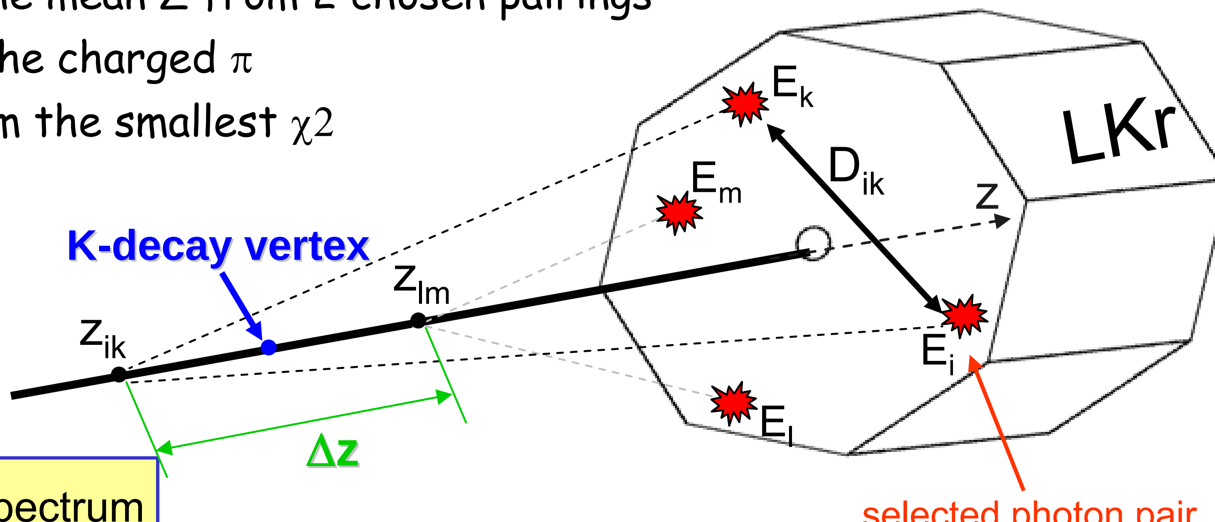
CUSP effect: $K^\pm \to \pi^\pm\pi^0\pi^0$ event selection

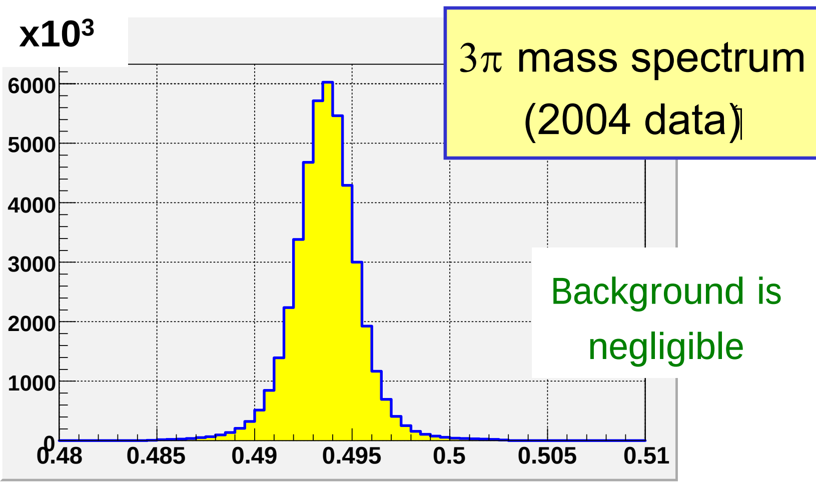
- Each photon pair (i,k) defines a decay vertex under the assumption of $\pi^0 \to \gamma\gamma$ decay

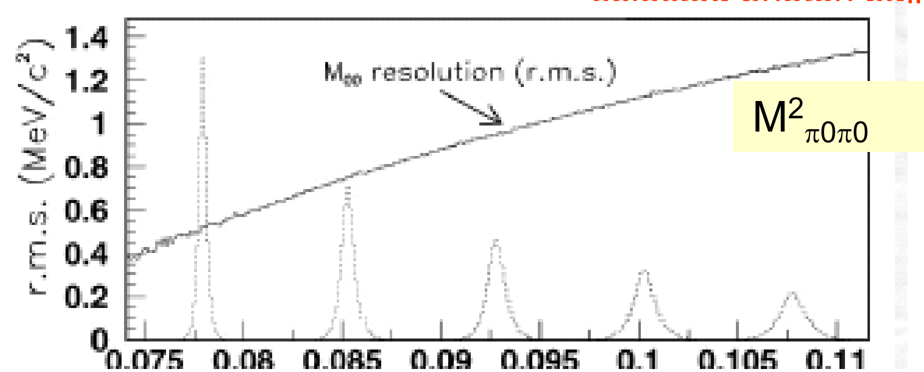
$$Z_{ik}^2 \cong E_i E_k D_{ik}^2 / m_{\pi^0}^2$$

- Neutral vertex defined as the mean Z from 2 chosen pairings
- Reconstruct K mass adding the charged π
- Chose the best 2 γ pairs from the smallest $\chi 2$

$$\chi^2 = \left(\frac{\Delta Z}{\sigma_Z}\right)^2 + \left(\frac{\Delta m_K}{\sigma_{m_K}}\right)^2$$







CUSP effect: fitting procedure : two approaches

Cabibbo-Isodori JHEP 0503(2005)

Without re-scattering, M_0 parameterization (as PDG)

$$M_0 = A_0(1+g_0u/2+h'_0u^2/2+k'_0v^2/2)$$

- First order term M1 describes loop diagrams

$$M_1 = -\frac{2}{3}(a_0 - a_2)m_{\pi^+}M_+ \sqrt{1 - M_{00}^2/2m_{\pi^+}}$$

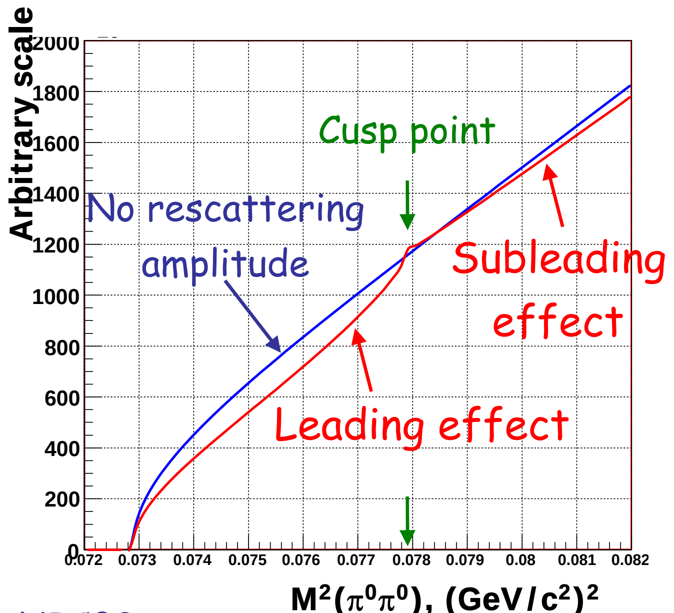
above threshold $|M|^2 = |M_0|^2 + |M_1|^2$

below threshold $|M|^2 = |M_0|^2 + |M_1|^2 + 2 M_0 M_1$

- Second order effects included
- Radiative corrections not (yet) included

Bern-Bonn Effective field theory CGKR PLB638 (2006), BFGKR arXiv:0807.0515

- electromagnetic effects included in the amplitudes
- two-loop formulation different from CI introduces different correlations between parameters



Cusp : experimental fitting procedure

Fit the M^2_{00} projection using the detector response matrix Rij obtained from a Monte-Carlo simulation and 4 physics parameters ($g, h, a_0 - a_2, a_2$) for both approaches

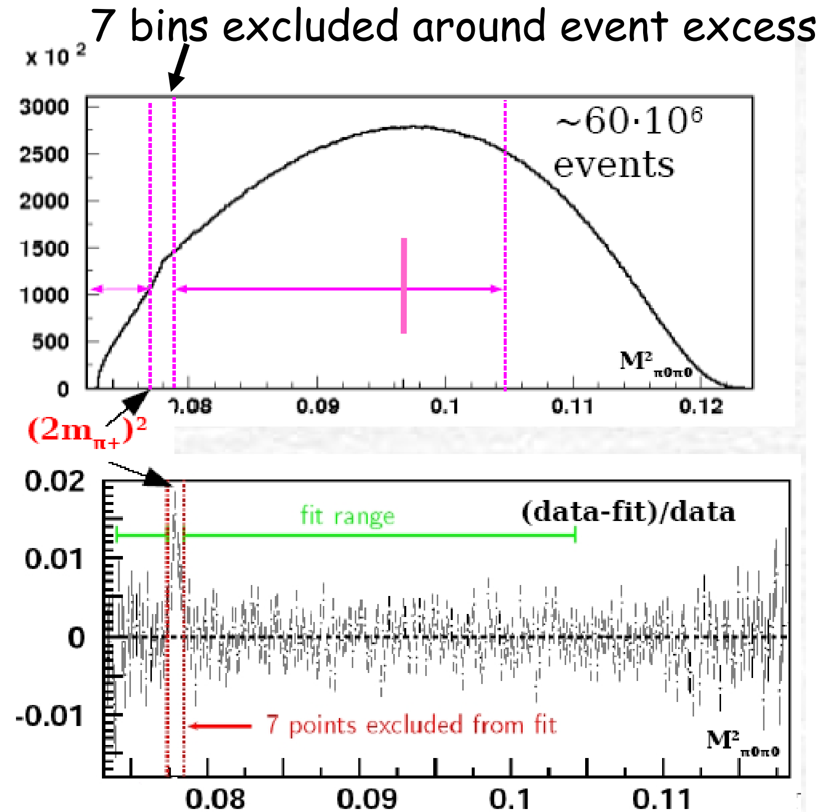
the constant k'_0 (v-dependent term) is fixed to the value recently measured by a 2d fit of the $K^\pm \to \pi^\pm\pi^0\pi^0$ Dalitz plot

$k'_0 = 0.0095 \pm 0.0002$ stat ± 0.0005 syst

The M_+ amplitude for $K^\pm \to \pi^\pm\pi^+\pi^-$

$M_+ = A_+(1 + g_+ u/2 + h'_+ u^2/2 + k'_+ v^2/2)$

- fixed from NA48/2 measurement PLB649(2007) for CI
- fitted in a simultaneous fit of both Dalitz plots for CGKR



Event excess around the $M(\pi^+\pi^-)$ threshold can be explained as Pionium decay to $\pi^0\pi^0$ (Silagadze, JETP Lett.60 (1994))

$R = \Gamma(K^\pm \to \pi^\pm A_{2\pi}) / \Gamma(K^\pm \to \pi^\pm \pi^+\pi^-)$
$= (1.8 \pm 0.3) \times 10^{-5}$

while the prediction is $R = 0.8 \times 10^{-5}$

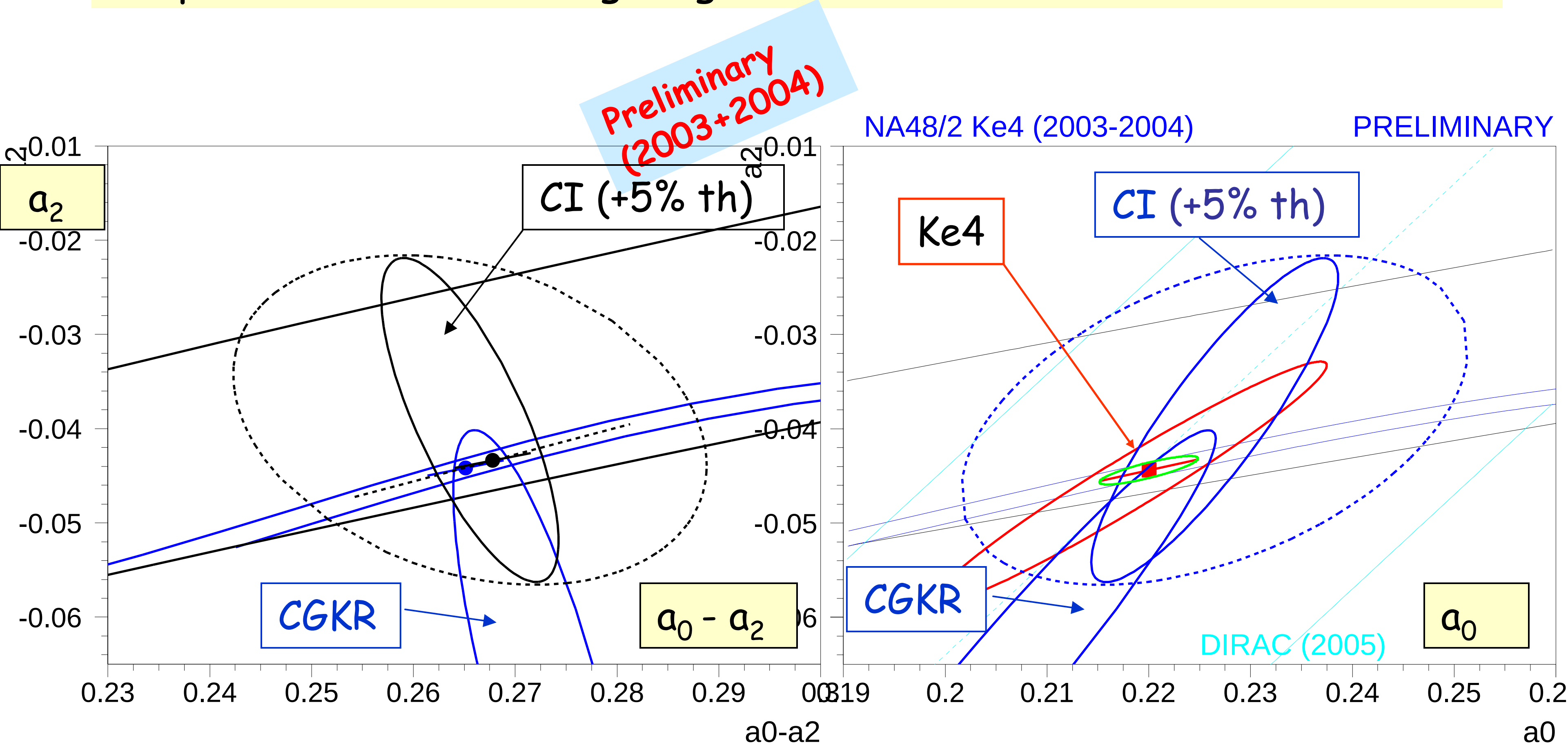
Cusp: scattering lengths results

Preliminary (2003+2004)

Using ChPT constraint	Note : ext is mainly due to $R=A_+/A_0=1.975\pm0.015$ th(CI) ~5% probably pessimistic (under evaluation)
CI model	$a_0-a_2 = 0.268 \pm 0.003stat \pm 0.002syst \pm 0.001ext \pm 0.013th$
CGKR model	$a_0-a_2 = 0.266 \pm 0.003stat \pm 0.002syst \pm 0.001ext$

a_2 free	Note : correlations between a_2 and other parameters are larger in CGKR model
CI model	$a_0-a_2 = 0.266 \pm 0.005stat \pm 0.002syst \pm 0.001ext \pm 0.013th$ $a_2 = -0.039 \pm 0.009stat \pm 0.006syst \pm 0.002ext$
CGKR model	$a_0-a_2 = 0.273 \pm 0.005stat \pm 0.002syst \pm 0.001ext$ $a_2 = -0.065 \pm 0.015stat \pm 0.010syst \pm 0.002ext$

Cusp and Ke4 : scattering lengths results



Two statistically independent measurements by NA48/2

Large overlap in the (a2,a0) plane

Impressive agreement with ChPT predictions (green ellipse)

Summary and Comparison with other experimental measurements

Ke4 : apply isospin corrections to published phase points of all experiments and perform a_0 ChPT fit

Note : E865 number dominated by highest energy data point, otherwise compatible

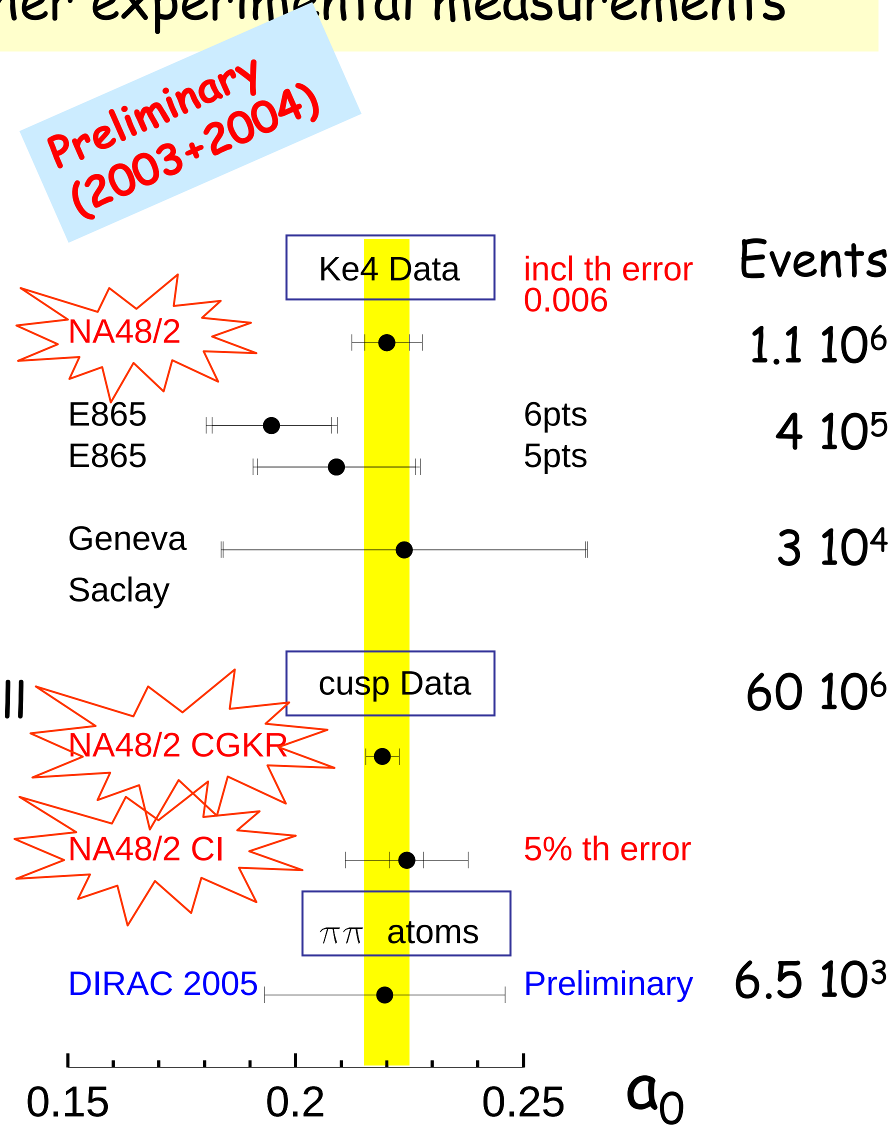
Cusp : $(a_0 - a_2)$ ChPT fit with 2 models

ππ atoms DIRAC: $|a_0 - a_2|$ errors from PLB619 (2005), use ChPT constraint (still being revisited + more Data analyzed)

Yellow band is ChPT prediction

$a_0 = 0.220 \pm 0.005$

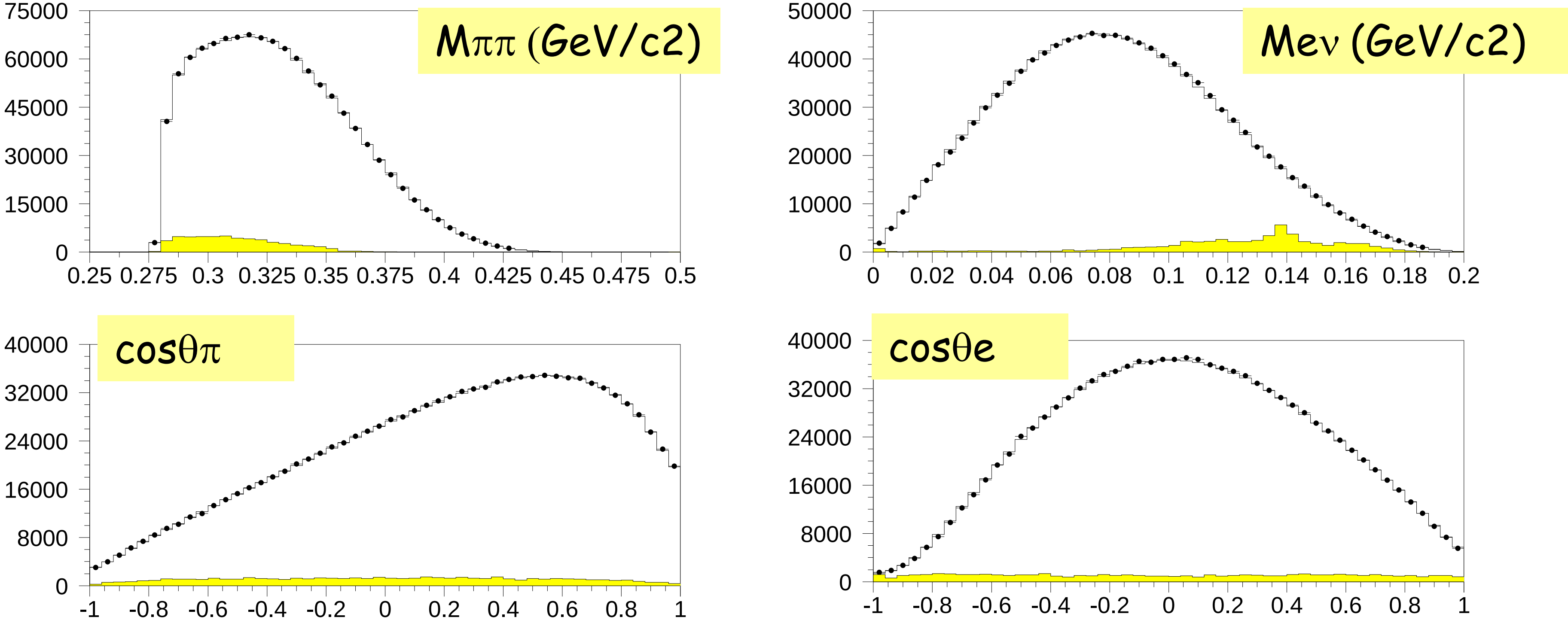
NA48/2 experimental precision now at the same level !

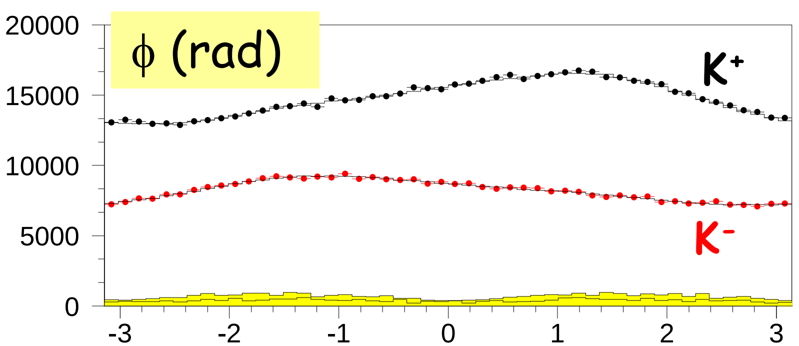


Final publications coming soon, fruitful collaboration with theory groups

spares

Ke4 decays : Data/MC comparison after fit





= Data

histogram = Simulation after fit

Yellow hist = WS Background (x 10 to be visible)

CP symmetry : (K^+) ϕ distribution is opposite of (K^-) ϕ distribution

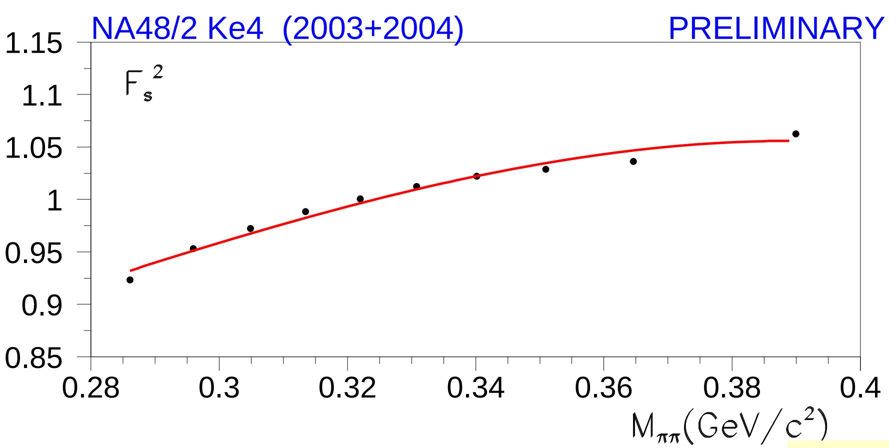
Ke4 decays : getting F,G,H form factors and phase shift

- Ten independent fits, one in each $M_{\pi\pi}$ bin, assuming ~constant form factors over each box. This allows a model independent analysis.
- Without the overall normalization (Branching fraction), one can quote relative form factors and their variations with q^2,q^4 (q^2= ($S_\pi/4m_\pi^2$ -1) and Se/$4m_\pi^2$

•Fs^2 is obtained from the relative bin to bin normalization Data/MC after fit

•if projected along Meν, a residual variation is observed.

•a 2-dimension fit of the normalization is performed to get the 3 slopes



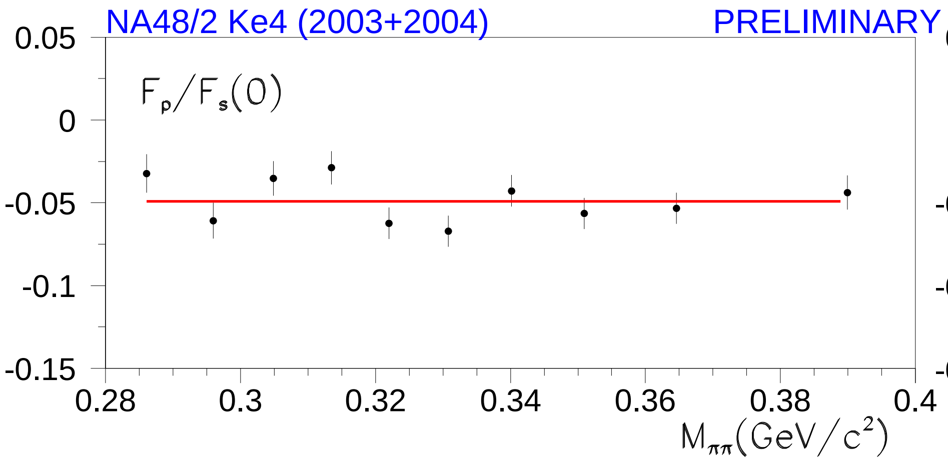
The 3 slopes are correlated

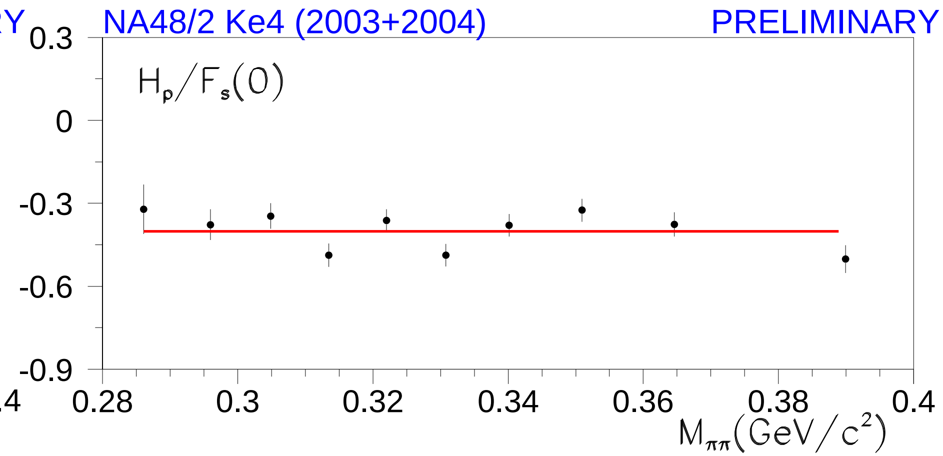
$Fs^2 \propto (1 + f's\, q^2 + f''s\, q^4 + f'e\, Se/4m\pi^2)^2$

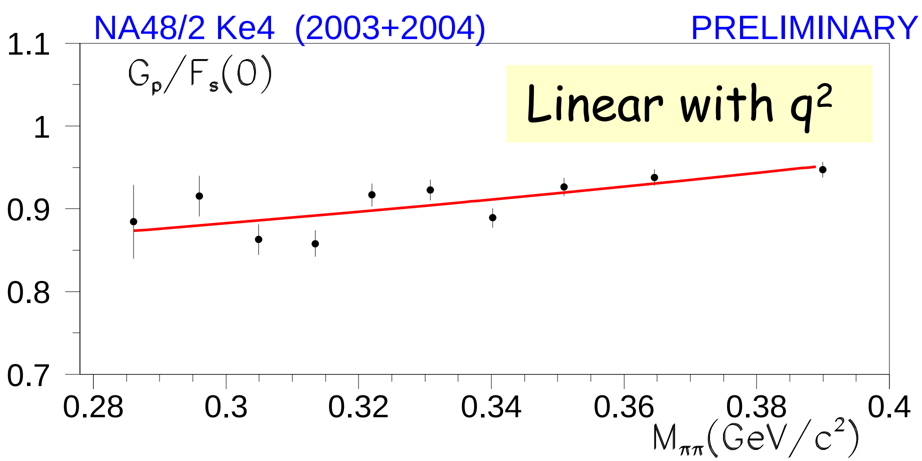
	f″s	f′e
f′s	-0.95	0.08
f″s		0.02

Other parameterizations could be easily tried if the Taylor expansion does not apply..

Getting Fp, Gp, Hp



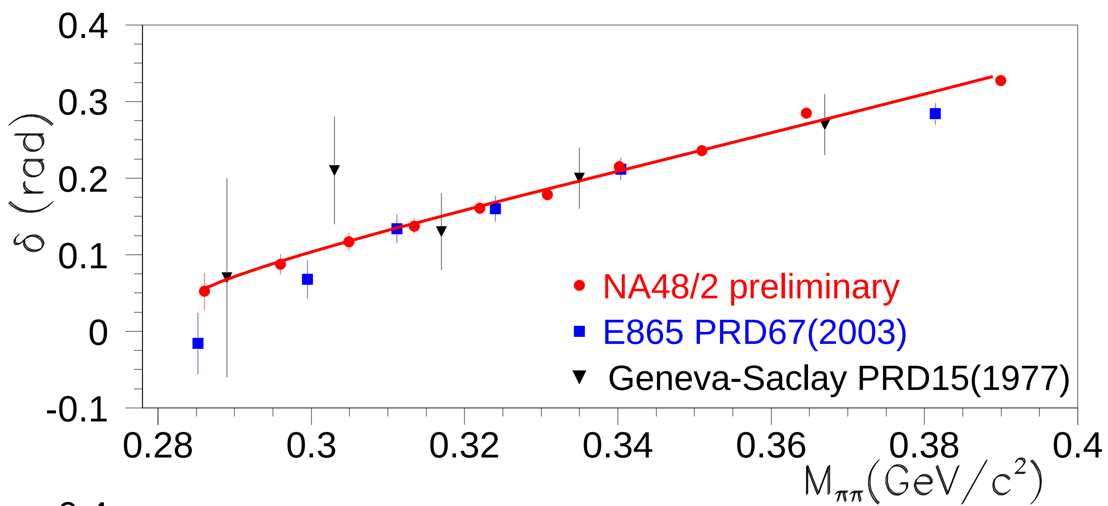


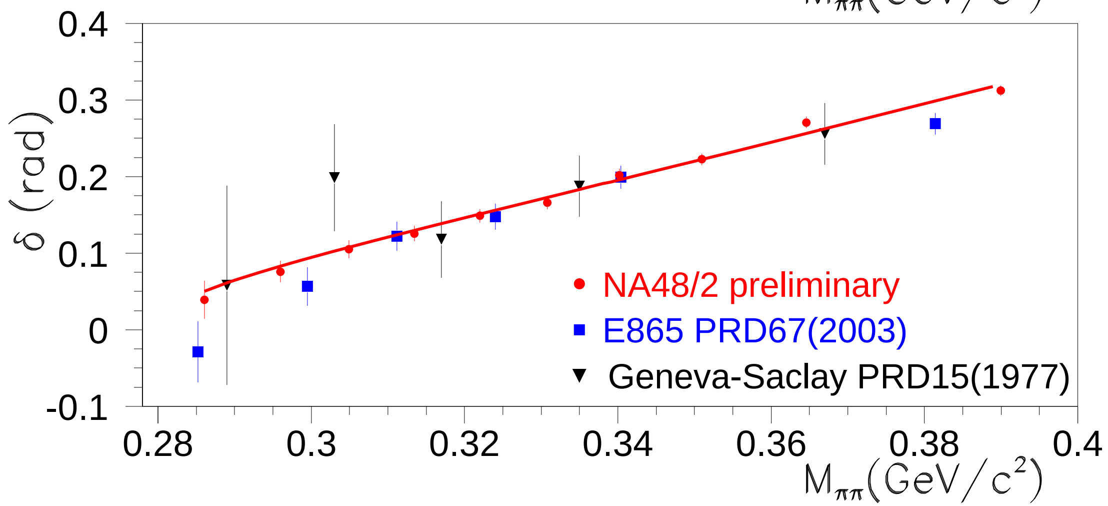


Correlation

	g'_p
$g_p(0)$	-0.914

Comparison of Ke4 phase experimental measurements





Phase points without isospin corrections

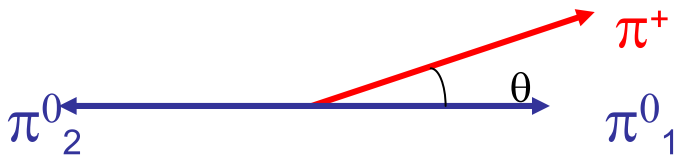
Line from a 2p fit to NA48 data alone

All Phase points corrected for isospin mass effects

K3π : measurement of the k' term

Going to a 2D fit would imply to use(M^2_{00},M^2_{+0}) variables. An alternate choice is (M^2_{00} ,cosθ) where θ is the angle between the charged π and the direction of the π^0's in their rest frame.

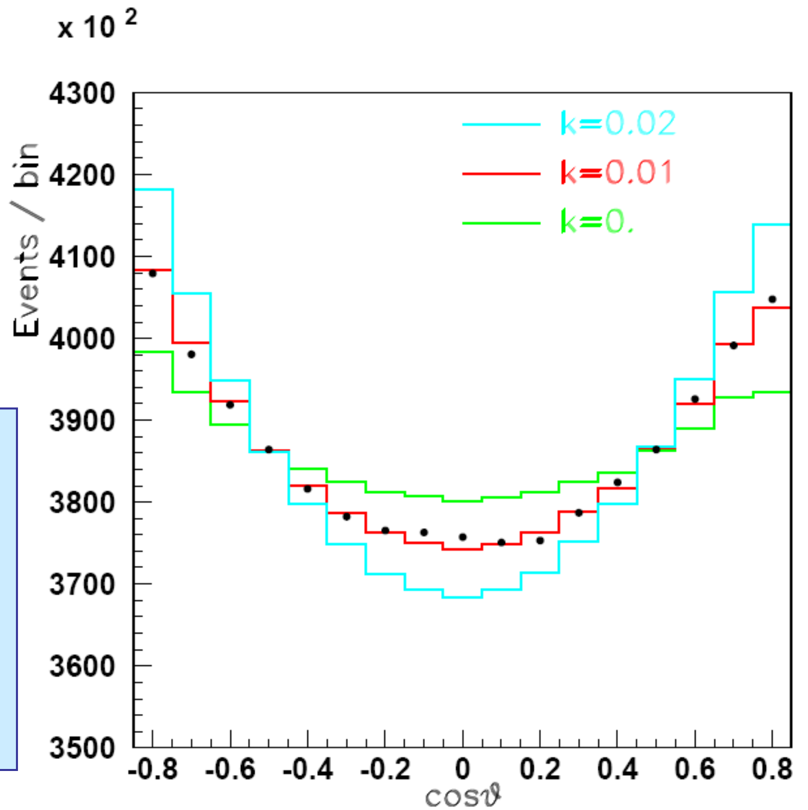
Use a modified matrix element :



$$M_0 = A_0\left(1 + \frac{1}{2} g_0 u + \frac{1}{2} h' u^2 + \frac{1}{2} k' v^2\right)$$

re-fit in M^2_{00} range [0.082, 0.097] $(GeV/c^2)^2$)

no incidence on previous **(a_0-a_2)** result.



Preliminary result (2003+2004 data, K^+ and K^-)

$k' = 0.0095 \pm 0.0002_{stat} \pm 0.0005_{syst}$

Note: the different meaning (g_0,h',k') wrt PDG (g_0,h,k)

Cusp: Dalitz plot slopes result

Reminder: $M(K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}) = M_0 + M_1$

$M_0 \sim (1+g_0 u/2+h'_0 u^2/2+k'_0 v^2/2)$ but …

$|M_0|^2$ (PDG) $\sim (1+gu+hu^2+kv^2)$ so $g_0 \approx g$, $h'_0 \approx h - g^2/4$, $k'_0 \approx k$

- k'_0 is extracted from a 2-dimensional fit
- Other parameters are fitted including a fixed k'_0 value

Preliminary (2003+2004)

$k'_0 = 0.0095 \pm 0.0002$stat. ± 0.0005syst

	g_0	h'_0
CI model	0.652 ± 0.001stat ± 0.003syst	−0.039 ± 0.001stat ± 0.003syst
CGKR model	0.621 ± 0.001stat ± 0.003syst	−0.049 ± 0.001stat ± 0.003syst
ChPT fit	CI a0-a2 = 0.268 a0 = 0.2244 a2 = -0.0434	GCKR a0-a2 = 0.266 a0 = 0.2191 a2 = -0.0470