Recent Results From NA48/2 Experiment @ CERN-SPS

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on Behalf of the NA48/2 Collaboration
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Outline

› NA48/2 Experimental Setup

› CP Violating Charge Asymmetry in $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ Decay

› "Cusp" Effect in $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ Decay

› Rare $K^{\pm}$ Decays

NA48/2 Experimental Setup

Some History

NA48 (1997-2001): Direct CP-Violation in neutral K

- $Re(\varepsilon'/\varepsilon) = (14.7 \pm 2.2)\cdot 10^{-4}$

NA48/1 (2002): Rare K_S decays

- $BR(K_S \to \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3} \pm 0.8)\cdot 10^{-9}$
- $BR(K_S \to \pi^0 \mu^+ \mu^-) = (2.8^{+1.5}_{-1.2} \pm 0.2)\cdot 10^{-9}$

NA48/2 (2003-2004): Direct CP-Violation in charged K

P326 (2009-2010): Very Rare K Decays

- $K^+ \to \pi^+ \nu\bar{\nu}$

…and many other results on kaon and hyperon **decays**

1997	ε'/ε run	$K_L + K_S$
1998	ε'/ε run	$K_L + K_S$
1999	ε'/ε run $K_L + K_S$	K_S Hi. Int.
2000	K_L only	K_S High Intensity (*NO Spectrometer*)
2001	ε'/ε run $K_L + K_S$	K_S High Int.
2002	K_S High Intensity	
2003	$K^\pm$ High Intensity	
2004	$K^\pm$ High Intensity	

Simultaneous Beam

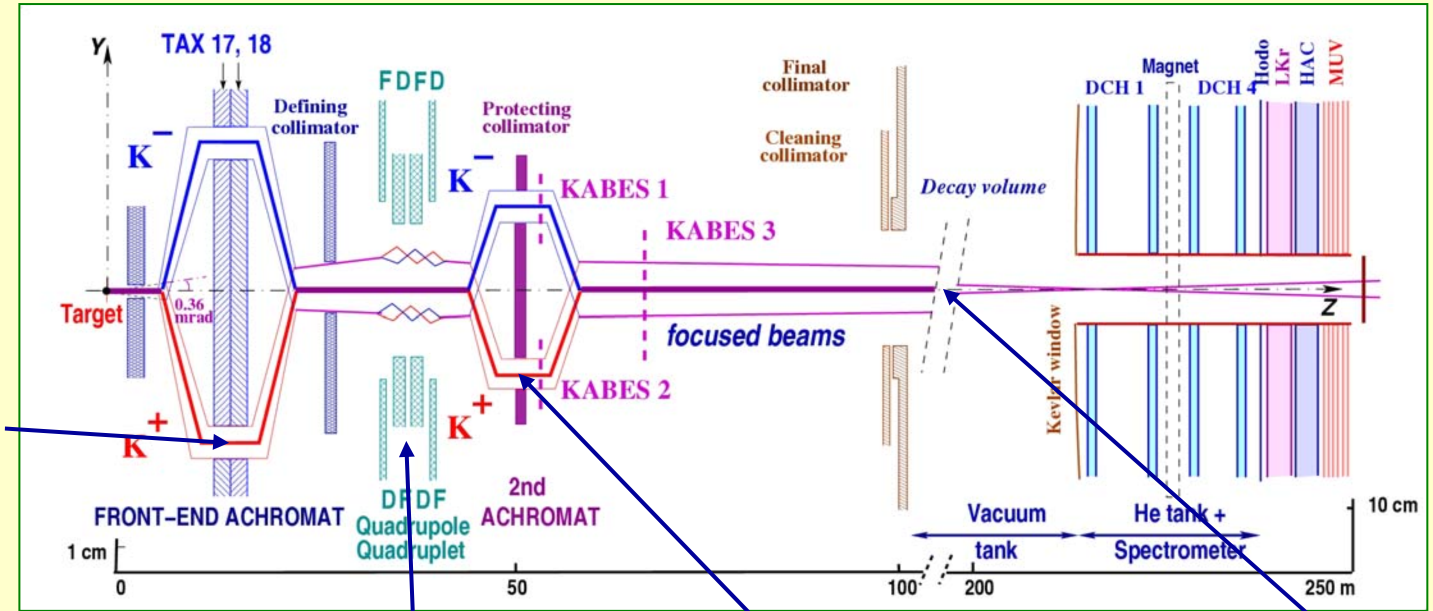
2-3M K/spill ($\pi/K \sim 10$)
π decay products stay in pipe
Flux ratio: $K^+/K^- \sim 1.8$

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

Beams coincide within
~1mm all along 114m decay
volume

$\sim 7 \cdot 10^{11}$
p/spil
400 GeV/c

Front-end achromat:
Momentum selection

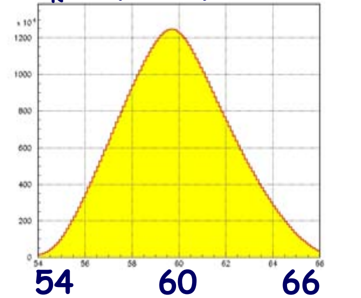


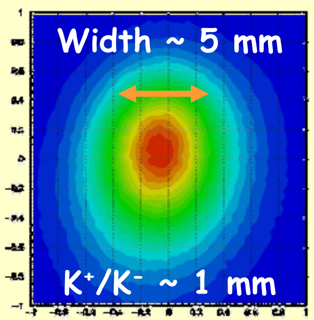
Quadrupole, Quadruplet:
Focusing
μ sweeping

Second achromat:
Cleaning
Beam spectrometer

$\delta P_K/P_K = 0.7\%$
$\delta_{x,y} \sim 100\ \mu m$

$P_K = (60 \pm 3)$ GeV/c





Detector

Magnetic spectrometer (4 DCHs):

- 4 view / DCH -> high efficiency
- $\sigma_P/P = 1.0\% \oplus 0.044\% \cdot P$ [GeV/c]

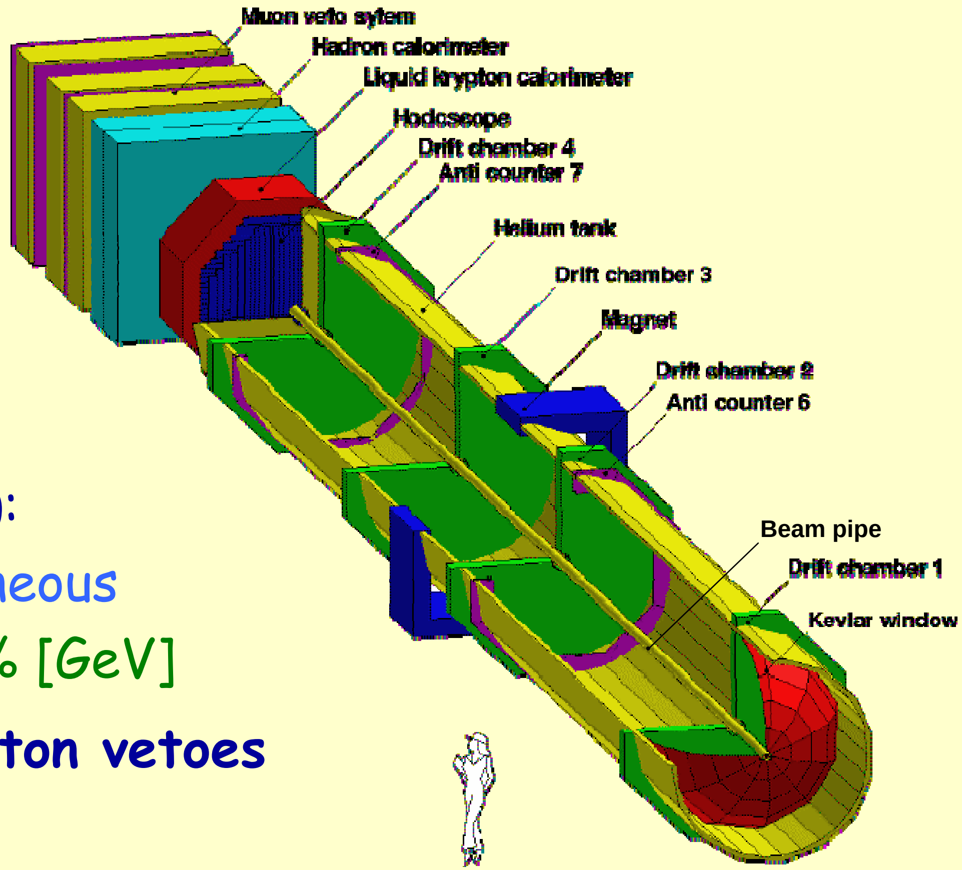
Hodoscope:

- Fast trigger
- σ_t = 150ps

Electromagnetic calorimeter (LKr):

- High granularity, quasi-homogeneous
- $\sigma_E/E = 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$ [GeV]

Hadron calorimeter, **muon** and **photon vetoes**



Trigger:

- Fast hardware trigger (L1): hodoscope & DCHs multiplicity
- Level 2 trigger (L2): on-line processing of DCHs & LKr information

Data Taking

Run periods:

- 2003: ~ 50 days
- 2004: ~ 60 days

Total statistics in 2 years:

- $K^\pm \to \pi^\pm\pi^+\pi^-$: ~ $4 \cdot 10^9$
- $K^\pm \to \pi^\pm\pi^0\pi^0$: ~ $1 \cdot 10^8$

-> >200 TB of data recorded

A view of the NA48/2 beam line

Rare $K^\pm$ decays can be measured down to BR ~ 10^{-9}

CP Violating Charge Asymmetry in $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ Decay

CP-Violation History

Major milestones in CP-Violation history:

- 1964: Indirect CP-Violation in K^0 (J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay)
- 1988, 1999: Direct CP-Violation in K^0 (NA31, E731, NA48, KTeV)
- 2001: Indirect CP-Violation in B^0 (BaBar, Belle)
- 2004: Direct CP-Violation in B^0 (Belle, BaBar)

Look for CP-Violation in $K^\pm$
(no mixing -> only Direct CPV is possible)

Introduction (I)

The best two $K^\pm$ decay modes:

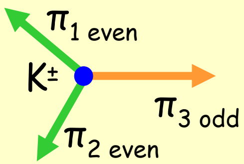
- $BR(K^\pm \to \pi^\pm\pi^+\pi^-) = 5.57\%$ "Charged"
- $BR(K^\pm \to \pi^\pm\pi^0\pi^0) = 1.73\%$ "Neutral"

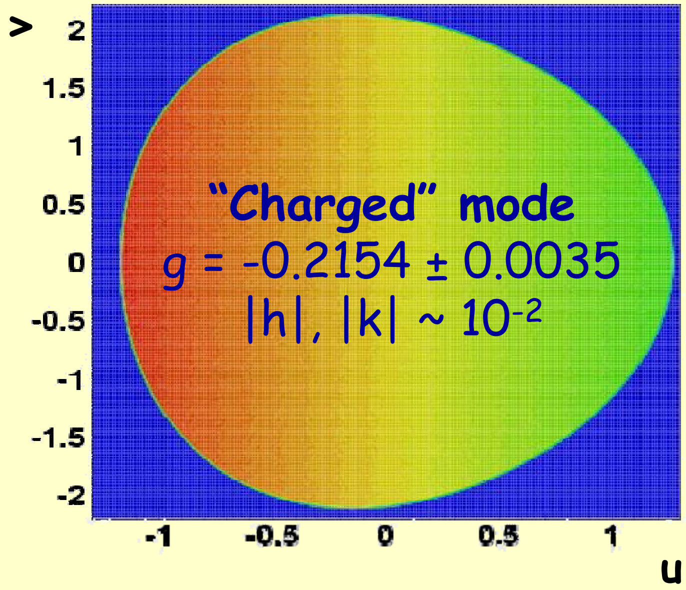
Matrix element:

$$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2$$

Kinematics:

$$s_i = (P_K - P_{\pi i})^2,\ i = 1,2,3\ (3 = \pi_{odd})$$
$$s_0 = (s_1 + s_2 + s_3) / 3$$
$$u = (s_3 - s_0) / m_\pi^2$$
$$v = (s_2 - s_1) / m_\pi^2$$





Kaon rest frame:

$$u = 2m_K \cdot (m_K/3 - E_{odd}) / m_\pi^2$$
$$v = 2m_K \cdot (E_1 - E_2) / m_\pi^2$$

Direct CP violating quantity: slope asymmetry

$$A_g = (g^+ - g^-) / (g^+ + g^-) \neq 0$$

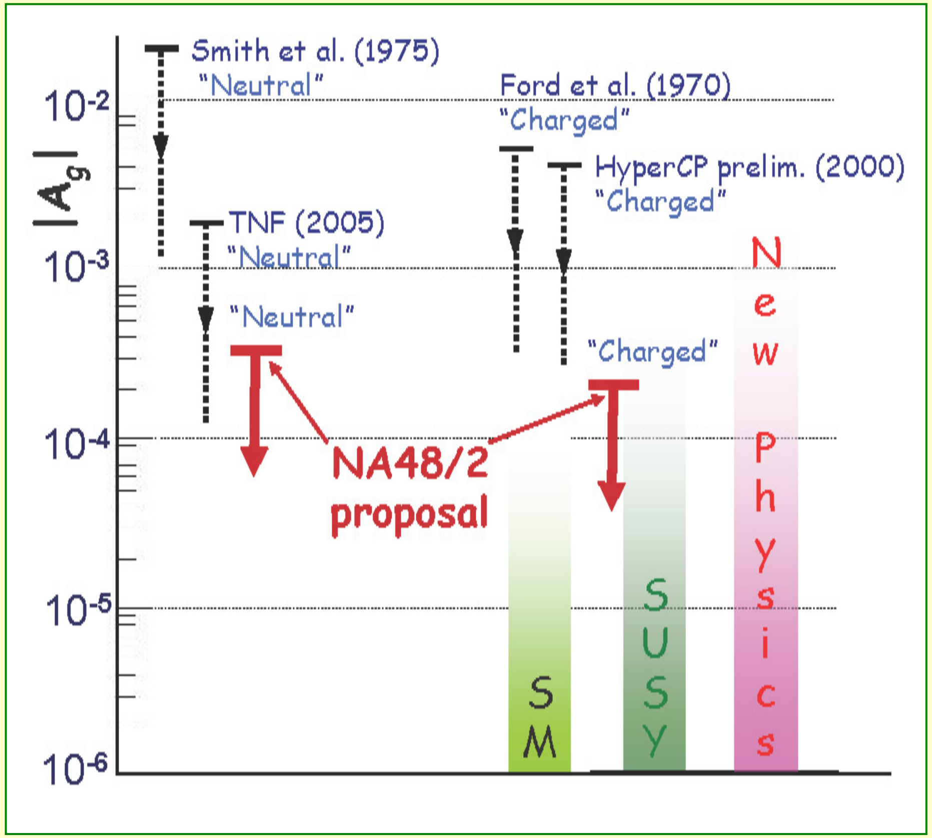
Introduction (II)

Theoretical predictions:

- Standard Model:

  $A_g = 10^{-6} \div 5 \cdot 10^{-5}$
- Models Beyond the SM:

  enhancement of the A_g value



Experimental results:

- "Charged" mode:

  $A_g = (22 \pm 15_{stat} \pm 37_{syst}) \cdot 10^{-4}$

  (HyperCP - $54 \cdot 10^6$ evt.)
- "Neutral" mode:

  $A_g = (2 \pm 19) \cdot 10^{-4}$

  (TNF - $620 \cdot 10^3$ evt.)

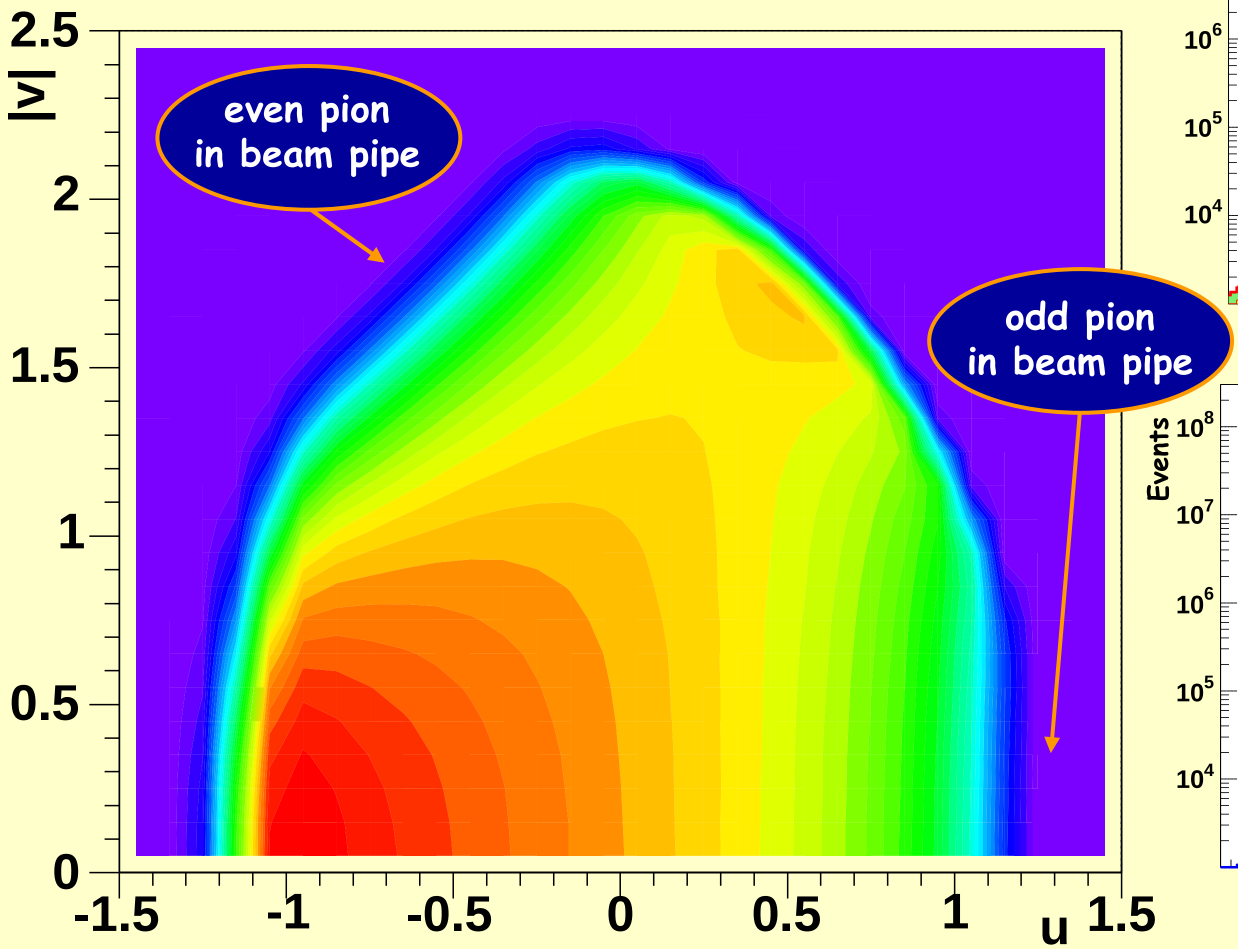
Introduction (III)

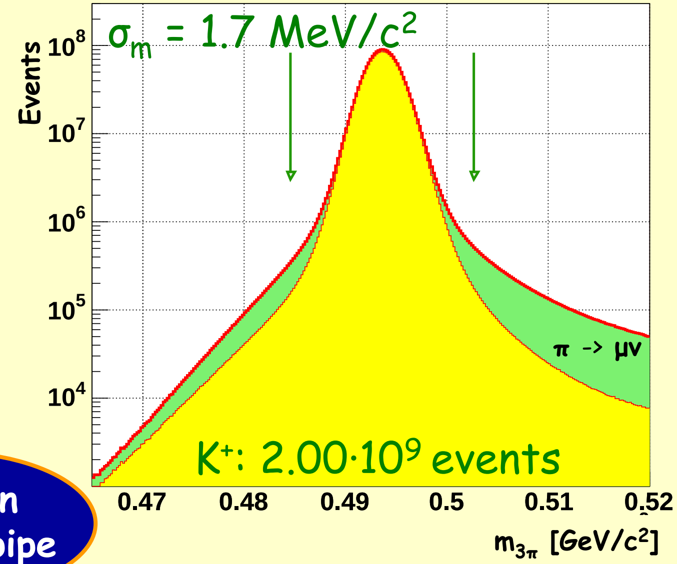
What's new in NA48/2 measurement?

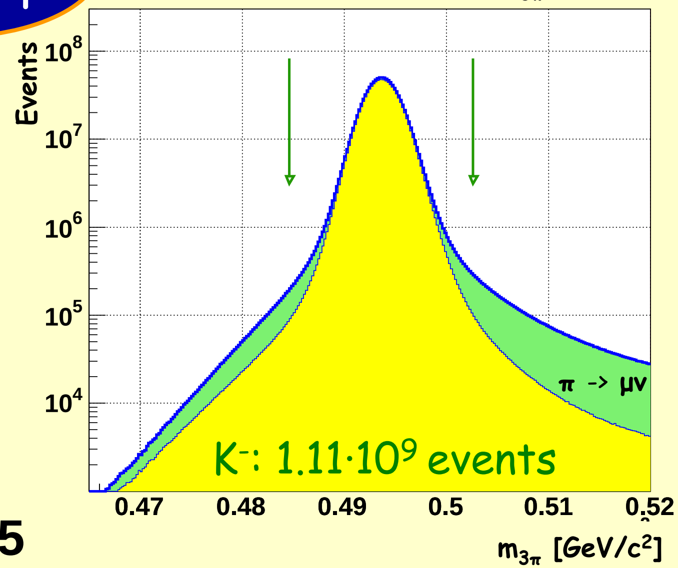
- Simultaneous K^+ and K^- beams, superimposed in space, with momentum spectra (60±3) GeV/c
- Equalize K^+ and K^- acceptances by frequently alternating polarities of relevant magnets
- Detect asymmetry exclusively considering slopes of ratios of normalized u distributions

Event Selection

In the 2003+2004 data sample $3.11 \cdot 10^9$ $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ have been selected:







Δg Fit In SuperSamples

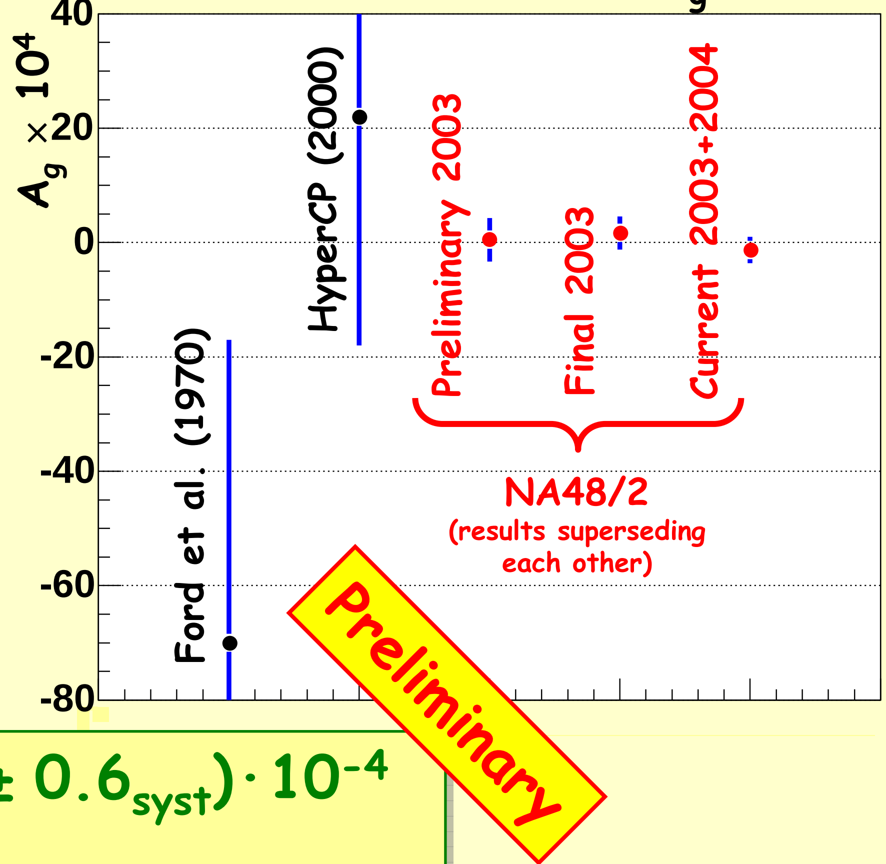
Results In SuperSamples

Run	SuperSample	$\Delta g \cdot 10^4$	χ^2 of the R(u) fit
2003	0	-0.8±1.8	30/26
	1	-0.5±1.8	24/26
	2	-1.4±2.0	28/26
	3	1.0±3.3	19/26
2004	4	-2.0±2.2	18/26
	5	4.4±2.6	20/26
	6	5.0±2.2	26/26
	7	1.5±2.1	10/26
	8	0.4±2.3	23/26
Combined		**0.6±0.7**	

Results

- A factor ~20 better precision than the previous measurements
- Uncertainties dominated by those of statistical nature
- Design goal reached. There is still some room to improve the systematic uncertainty
- Result compatible with the Standard Model predictions

Measurements of A_g



Based on the full 2003+2004 data sample

$$\Delta g = (0.6 \pm 0.7_{stat} \pm 0.4_{trig} \pm 0.6_{syst}) \cdot 10^{-4} = (0.6 \pm 1.0) \cdot 10^{-4}$$

$$A_g = (-1.3 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.4_{syst}) \cdot 10^{-4} = (-1.3 \pm 2.3) \cdot 10^{-4}$$

Final 2003 result published: PLB634 (2006) 474-482

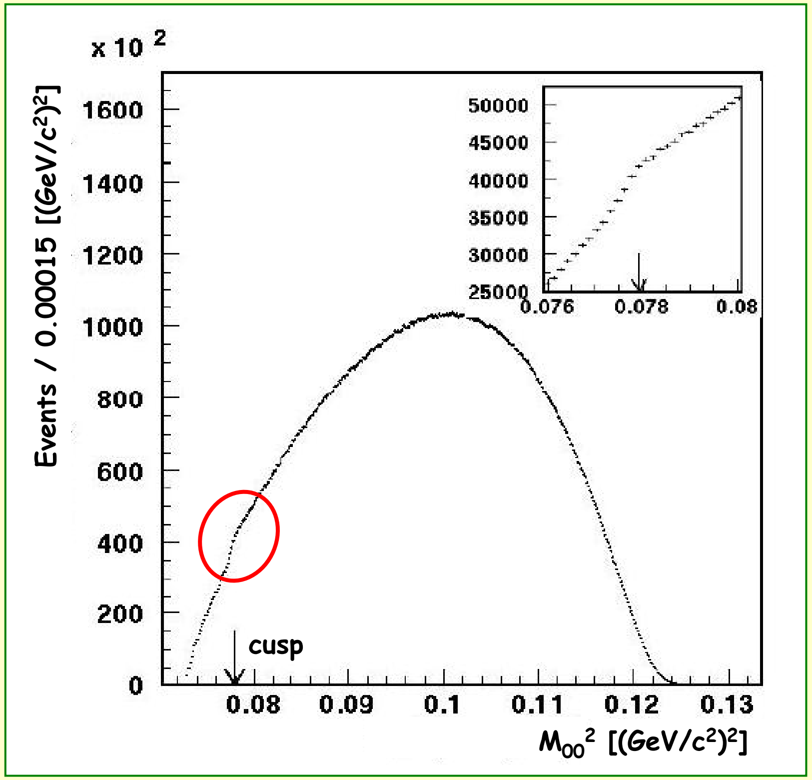
"Cusp" Effect in $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ Decay

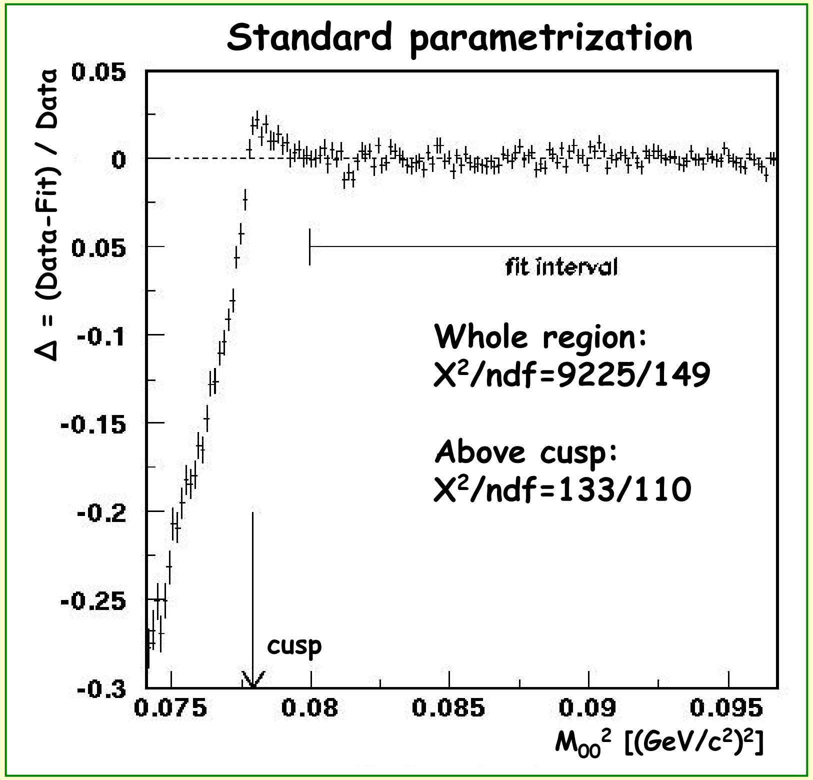
A "Cusp"

- From $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decay we observed an anomaly in the M_{00}^2 invariant mass distribution in the region around $M_{00}^2 = (2m_{\pi+})^2 = 0.07792\ (GeV/c^2)^2$
- This anomaly has been interpreted as a final state charge exchange scattering process of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ ($\pi^{+}\pi^{-} \to \pi^{0}\pi^{0}$)
- The parameter a_0-a_2 (difference between the S-wave ππ scattering lengths in the isospin I=0 and I=2 states) can be precisely measured using this sudden anomaly ("cusp")

Event Selection

Standard Dalitz plot parameterization shows deficit in data before “cusp”:

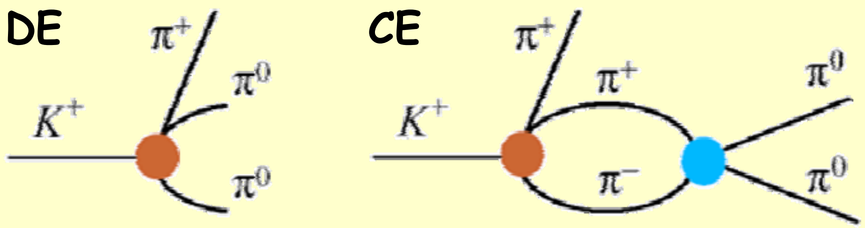




Interpretation

Re-scattering model: two amplitudes contribute to $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$

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



$$M_0 \propto 1 + \frac{1}{2} g_0 u \qquad M_1 \propto (a_0 - a_2) \cdot m_{\pi^+}$$

- M_0: Direct Emission
- M_1: Charge Exchange in final state of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ ($\pi^{+}\pi^{-} \to \pi^{0}\pi^{0}$)

The singularity in the invariant mass spectrum at $\pi^{+}\pi^{-}$ threshold is mainly caused by the destructive interference of M_0 and M_1

The effect is present below the threshold and not above it (re-scattering model at one-loop (N. Cabibbo: PRL 93 (2004) 121801))

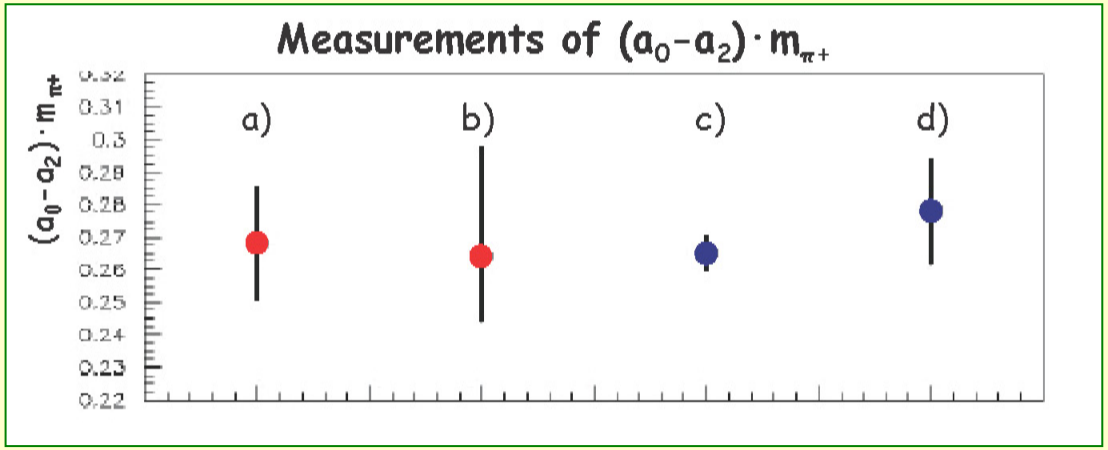
Results

More complete formulation of the model including all re-scattering processes at one-loop and two-loop level (N. Cabibbo and G. Isidori: JHEP 0503 (2005) 21) has been used to extract NA48/2 results (systematics: acceptance, trigger efficiency and fitting interval):

Based on partial sample of 2003 data

$$g_0 = 0.645 \pm 0.004_{stat} \pm 0.009_{syst}$$
$$h' = -0.047 \pm 0.012_{stat} \pm 0.011_{syst}$$
$$(a_0-a_2)\cdot m_{\pi+} = 0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$$
$$a_2\cdot m_{\pi+} = -0.041 \pm 0.022_{stat} \pm 0.014_{syst}$$

2003 results published: PLB 633 (2006) 173-182



a)	NA48 result	PLB 633 (2006)
b)	DIRAC result	PRL 619 (2005)
c)	G.Colangelo et al.	NPB 603 (2001)
d)	J.R.Pelaez et al.	PRD 71 (2005)

Rare $K^{\pm}$ Decays

Rare $K^\pm$ Decays

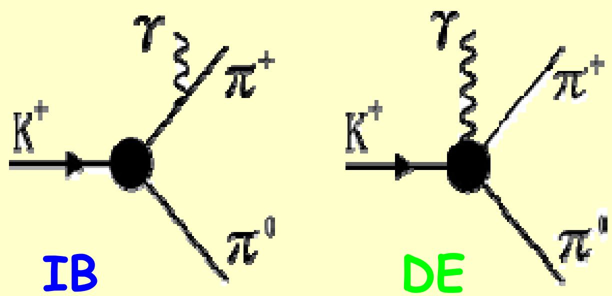
Statistics usually at least one order of magnitude above previous experiments. Several channels not yet observed.

- $K^\pm \to \pi^+\pi^-e^\pm\nu$ $(4.09 \pm 0.09)\cdot10^{-5}$
- $K^\pm \to \pi^0\pi^0e^\pm\nu$ $(2.2 \pm 0.4)\cdot10^{-5}$
- $K^\pm \to \pi^+\pi^-\mu^\pm\nu$ $(1.4 \pm 0.9)\cdot10^{-5}$
- $K^\pm \to \pi^\pm\pi^0\gamma$ $(2.75 \pm 0.15)\cdot10^{-4}$ Silvia Goy Lopez
- $K^\pm \to \pi^\pm\gamma\gamma$ $(1.10 \pm 0.32)\cdot10^{-6}$ Simone Bifani
- $K^\pm \to \pi^\pm e^+e^-\gamma$
- $K^\pm \to \pi^\pm\pi^0\gamma\gamma$
- $K^\pm \to \pi^\pm e^+e^-$ $(2.88 \pm 0.13)\cdot10^{-7}$

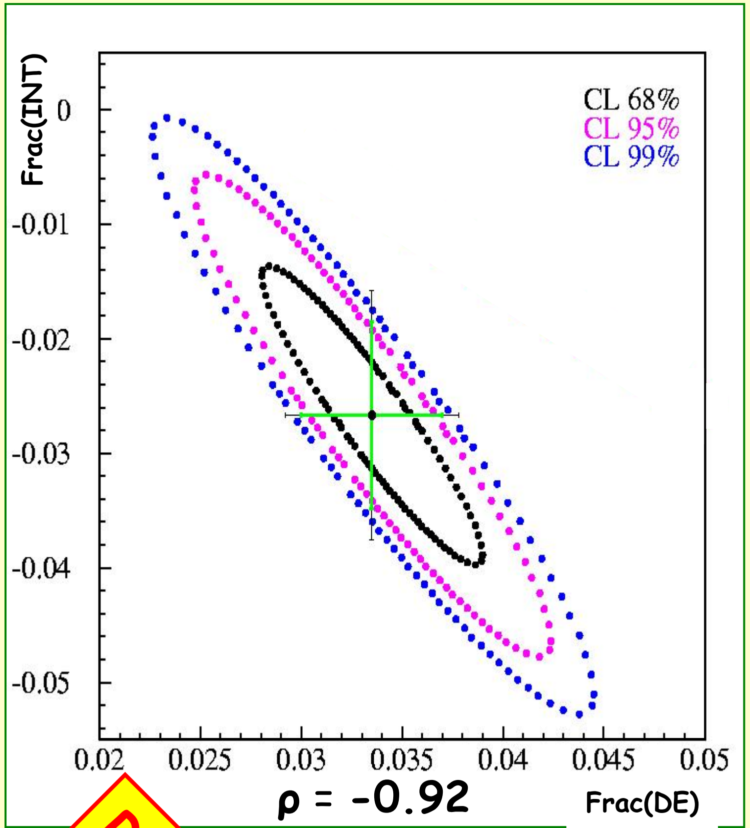
$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$

Two amplitudes:

- Inner Bremsstrahlung (IB)
- Direct Emission (DE)



Interference (INT) is possible between IB and electric part of DE



Preliminary

Based on a partial sample of 2003 data

Frac(DE) = $(3.35 \pm 0.35_{stat} \pm 0.25_{syst})$ %
Frac(INT) = $(-2.67 \pm 0.81_{stat} \pm 0.73_{syst})$ %

Summary

› The preliminary result on the Direct CP violating charge asymmetry in $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ based on the whole statistics is:

$$A_g = (-1.3 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.4_{syst}) \cdot 10^{-4}$$
$$= (-1.3 \pm 2.3) \cdot 10^{-4}$$

› A new "cusp" structure in $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ was observed ($\pi\pi$ final state charge exchange process of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$) which provides a new method for the extraction of the $\pi\pi$ scattering lengths:

$$(a_0 - a_2) \cdot m_{\pi+} = 0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{theor}$$

› The first measurement of Direct Emission and Interference terms in $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ based on ~30% of the total statistics has been performed:

$$Frac(DE) = (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\ \%$$
$$Frac(INT) = (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\ \%$$

Spares

Summary (I)

- The preliminary result on the Direct CP violating charge asymmetry in $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ based on the 2003+2004 data sample (whole statistics) is:

$$A_g = (-1.3 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.4_{syst}) \cdot 10^{-4}$$
$$= (-1.3 \pm 2.3) \cdot 10^{-4}$$

- The result have ~10 times better precision than the previous measurements
- The errors are dominated by statistics

Summary (II)

› A new "cusp" structure in $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ was observed ($\pi\pi$ final state charge exchange process of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$) which provides a new method for the extraction of the $\pi\pi$ scattering lengths:

$$(a_0 - a_2) \cdot m_{\pi+} = 0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{theor}$$

› The measurement is based on a 2003 data sample and agrees both with another independent measurement and with the theoretical predictions

› Parameter a_2 directly measured for the first time even though with low accuracy:

$$a_2 \cdot m_{\pi+} = -0.041 \pm 0.022_{stat} \pm 0.014_{syst}$$

Summary (III)

- The first measurement of Direct Emission and Interference terms in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ based on a 2003 data sample (~30% of the whole statistics) has been performed:

$$\mathrm{Frac(DE)} = (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\ \%$$

$$\mathrm{Frac(INT)} = (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\ \%$$

- A first evidence of a negative Interference has been found

CP Violating Charge Asymmetry

"Charged" Mode:
$K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

Measurement Strategy

If K^+ and K^- acceptances are equal for the same u and v value, any difference between the experimental distributions would be a sign of Direct CP-Violation. Integrated over v, A_g can be extracted from a fit to the ratio R(u) using the PDG value for g:

$$\Delta g = g^+ - g^- \ll 1$$

$$R(u) = \frac{N^+(u)}{N^-(u)} = n\,\frac{1 + g^+ \cdot u + h \cdot u^2 + \ldots}{1 + g^- \cdot u + h \cdot u^2 + \ldots} \sim n\left(1 + \frac{\Delta g \cdot u}{1 + g \cdot u + h \cdot u^2}\right) \rightarrow A_g = \Delta g / 2g$$

- The normalization is a free parameter in the fit and Δg does not depend on it
- For the "charged" mode a fit with linear function is suitable due to smallness of the slope g
- u calculation:
  - "Charged" mode: only the magnetic spectrometer is used
  - "Neutral" mode: only the calorimeter is used

Acceptance (I)

Magnetic fields present in both beam line and spectrometer: this leads to residual charge asymmetry of the setup

SuperSample (SS) data taking strategy:

- Beam line polarity (A) reversed on weekly basis
- Spectrometer magnet polarity (B) reversed on daily basis

The whole 2003+2004 data taking is subdivided in 9 SS in which all the field configurations are present

Data taking from August 6th to September 7th (2003)

Week 1	A–	B+	B–	B+	B–	B+	B–	SuperSample 1 12 subsamples
Week 2	A+	B+	B–	B+	B–	B+	B–	
Week 3	A–	B+	B–	B+	B–	B+	B–	SuperSample 2 12 subsamples
Week 4	A+	B+	B–	B+	B–	B+	B–	
Week 5	A–	B+	B–					SuperSample 3 4 subsamples
	A+	B+	B–					

Acceptance (II)

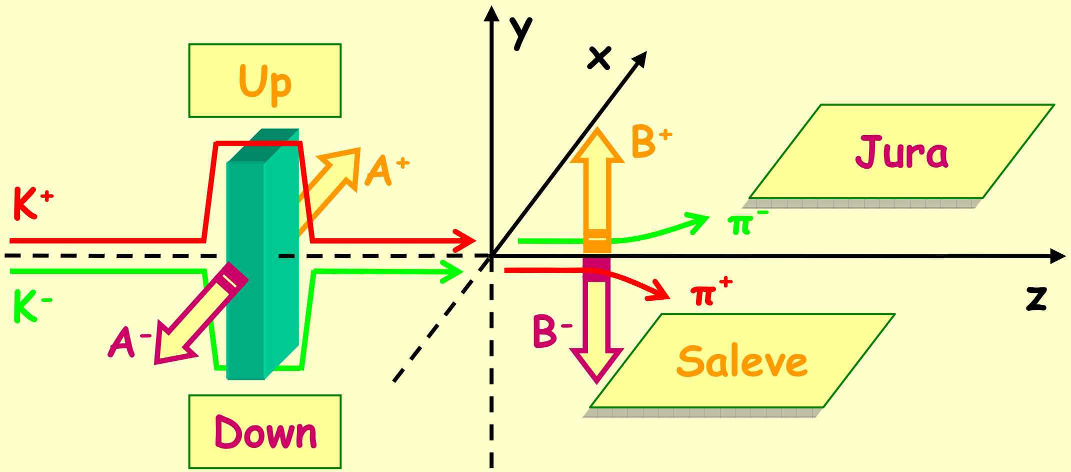
- In each ratio the odd pions are deflected towards the same side of the detector (left-right asymmetry)
- In each ratio the event at the numerator and denominator are collected in subsequent period of data taking (global time variations)

$$R_{US} = \frac{N^+(A^+B^+)}{N^-(A^+B^-)}$$

$$R_{UJ} = \frac{N^+(A^+B^-)}{N^-(A^+B^+)}$$

$$R_{DS} = \frac{N^+(A^-B^+)}{N^-(A^-B^-)}$$

$$R_{DJ} = \frac{N^+(A^-B^-)}{N^-(A^-B^+)}$$



R indices:

- U/D: beam line polarity
- S/J: π_{odd} direction after the spectrometer magnet field

Acceptance (III)

- **Double ratio**: cancellation of global time instabilities (rate effects, analyzing magnet polarity inversion)

$$R_U = R_{US} \times R_{UJ} \Longrightarrow f_2(u) = n^2 \cdot (1+\Delta g_U \cdot u)^2$$

$$R_D = R_{DS} \times R_{DJ} \Longrightarrow f_2(u) = n^2 \cdot (1+\Delta g_D \cdot u)^2$$

- **Double ratio**: cancellation of local beam line biases effects (slight differences in beam shapes and momentum spectra)

$$R_S = R_{US} \times R_{DS} \Longrightarrow f_2(u) = n^2 \cdot (1+\Delta g_S \cdot u)^2$$

$$R_J = R_{UJ} \times R_{DJ} \Longrightarrow f_2(u) = n^2 \cdot (1+\Delta g_J \cdot u)^2$$

- **Quadruple ratio**: both previous cancellations + left-right detector asymmetry cancellation

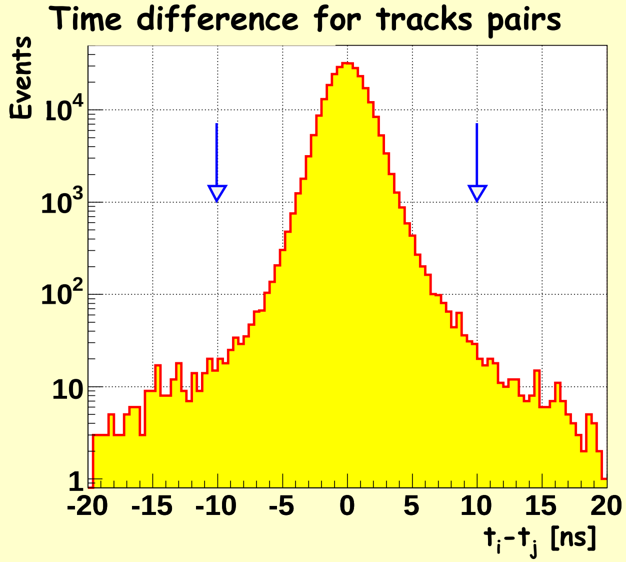
$$R = R_{US} \times R_{UJ} \times R_{DS} \times R_{DJ} \Longrightarrow f_4(u) = n^4 \cdot (1+\Delta g \cdot u)^4$$

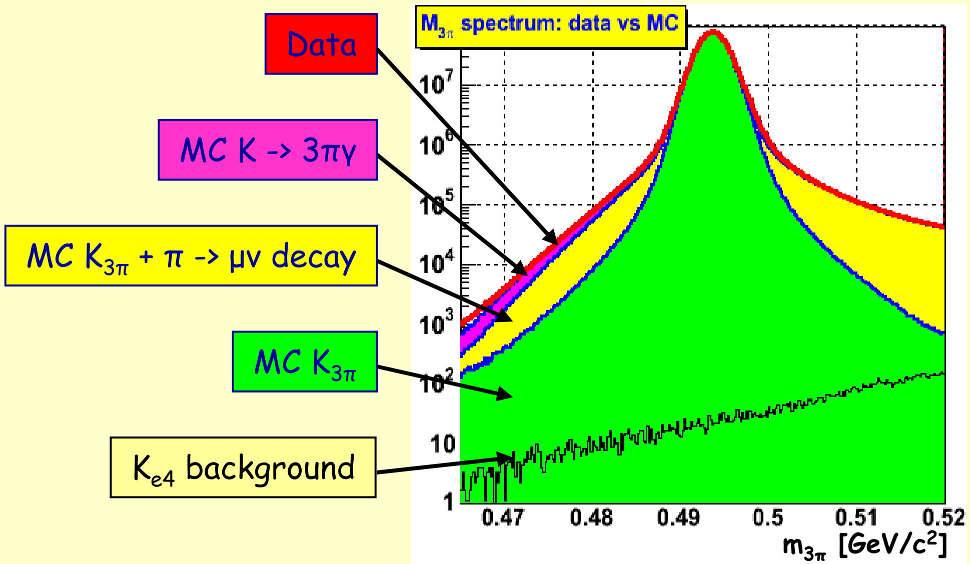
The method is independent of K^+/K^- flux ratio and relative sizes of the samples (important: simultaneous beams)

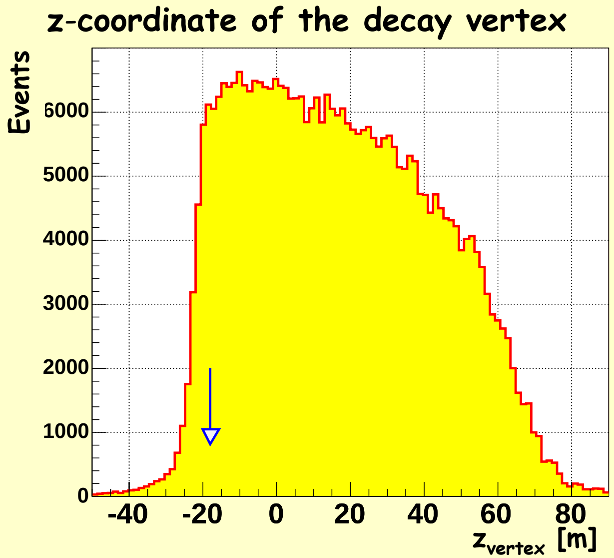
Event Selection (I)

Main requirements (simplicity, charge symmetry):

- Identification of the best 3-track vertex
- z_{vertex} > -18 m (downstream the last collimator)
- Track times: $|t_i - t_j| < 10$ ns -> probability of event pile-up ~ 10^{-4}
- $P_t < 0.3$ GeV/c (suppression of background decays)
- $|m_{3\pi} - m_K| < 9$ MeV/c^2 (5 times the resolution)







Systematics

Systematic effect	Effect on $\Delta g \cdot 10^4$
Spectrometer alignment	±0.1
Momentum scale	±0.1
Acceptance and beam geometry	±0.2
Pion decay	±0.4
Accidental activity (pile-up)	±0.2
Resolution effects	±0.3
Total systematic uncertainty	**±0.6**
L1 trigger: uncertainty only	±0.3
L2 trigger: correction	-0.1±0.3
Total trigger correction	**-0.1±0.4**
Systematic & trigger uncertainty	**±0.7**
Raw Δg	0.7±0.7
Δg corrected for L2 inefficiency	**0.6±0.7**

"Neutral" Mode:
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$

Introduction

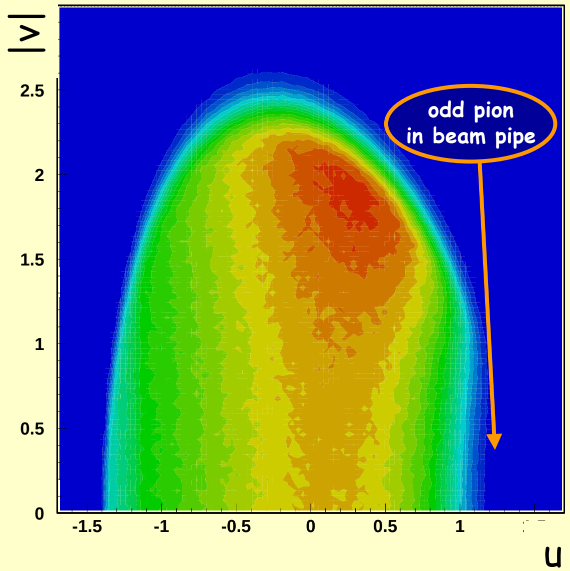
Statistical precision in A_g similar to "charged" mode:

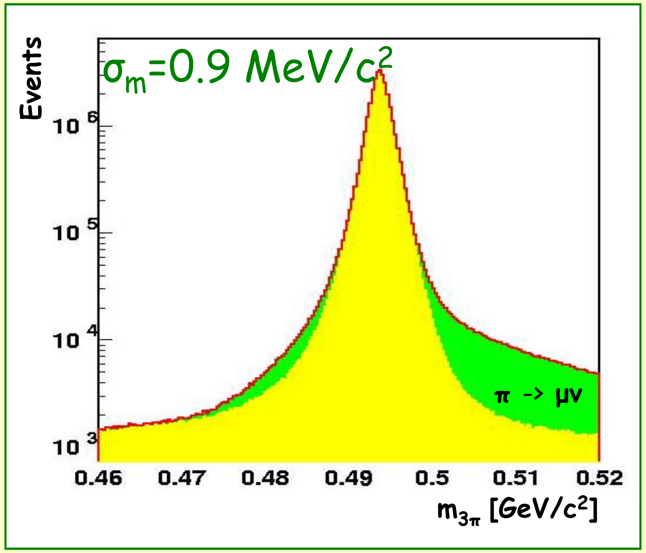
- Ratio of "neutral" to "charged" statistics: $N^0/N^{\pm} \sim 1/30$ ($91 \cdot 10^6$ $K^{\pm}$ have been selected in the 2003+2004 data sample)
- Ratio of slopes: $|g^0/g^{\pm}| \sim 1/3$
- More favourable Dalitz-plot distribution (gain factor ~1.5)

For u calculation only the energy of the two neutral pions in laboratory frame is used (only calorimeter information)

$$u = \frac{M_{00}^2 - s_0}{m_\pi^2}$$

$$s_0 = (s_1 + s_2 + s_3) / 3$$



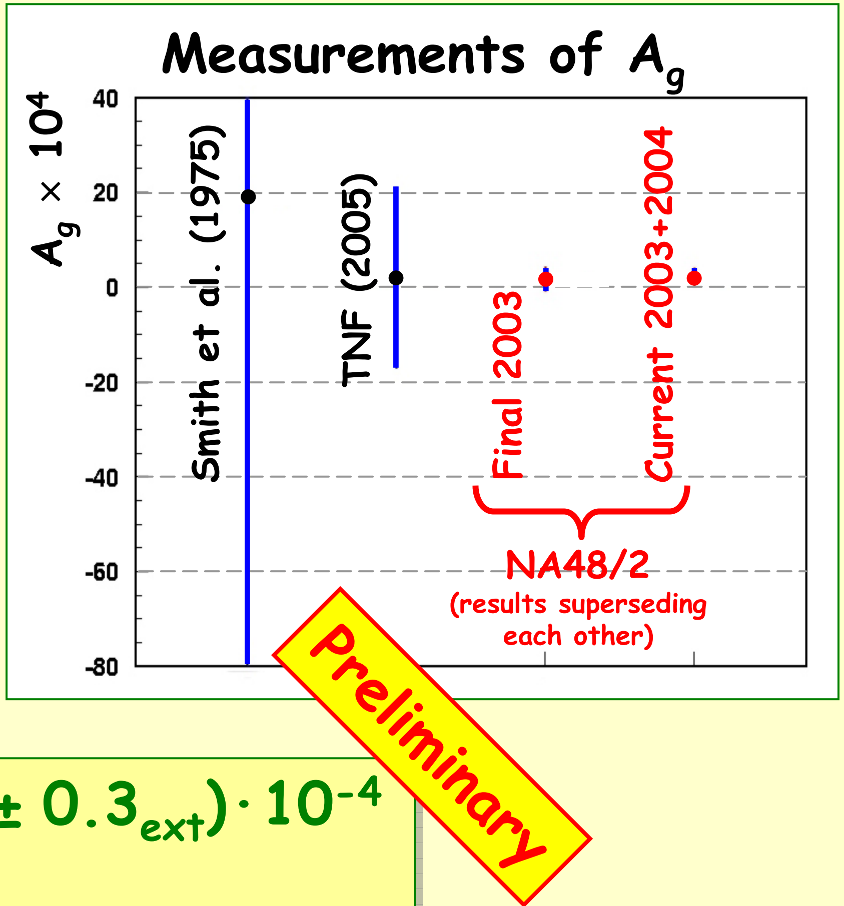


Results In SuperSamples

Run	SuperSample	$\Delta g \cdot 10^4$
2003	0	4.3±3.8
	1+2	0.5±5.0
	3	-2.0±8.2
2004	5	5.6±6.8
	6	4.7±5.1
	7	3.5±5.6
	8	-1.4±5.8
Combined		**2.7±2.0**

Results

- A factor ~10 better precision than the previous measurements
- The errors are dominated by statistics
- Design goal reached. Further improvements of the analysis are possible
- Result compatible with the Standard Model predictions



Based on the full 2003+2004 data sample

$$\Delta g = (2.7 \pm 2.0_{stat} \pm 1.2_{syst} \pm 0.3_{ext}) \cdot 10^{-4}$$
$$= (2.7 \pm 2.4) \cdot 10^{-4}$$

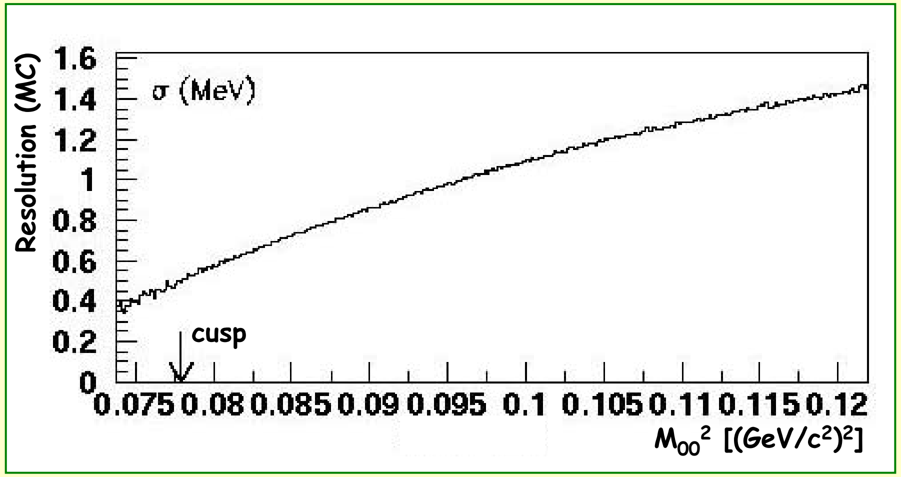
$$A_g = (2.1 \pm 1.6_{stat} \pm 1.0_{syst} \pm 0.2_{ext}) \cdot 10^{-4}$$
$$= (2.1 \pm 1.9) \cdot 10^{-4}$$

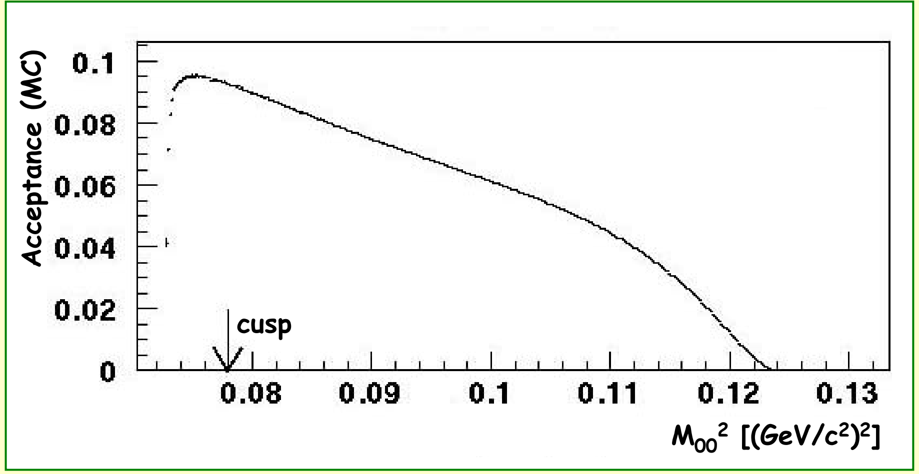
Final 2003 result published: PLB638 (2006) 22-29

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

Instrumental Effects (I)

Good resolution and linear acceptance near the "cusp" region:

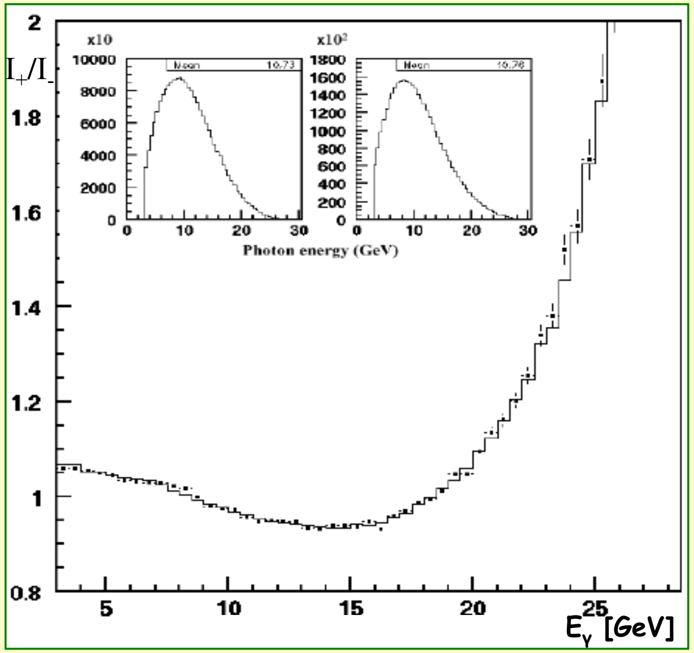




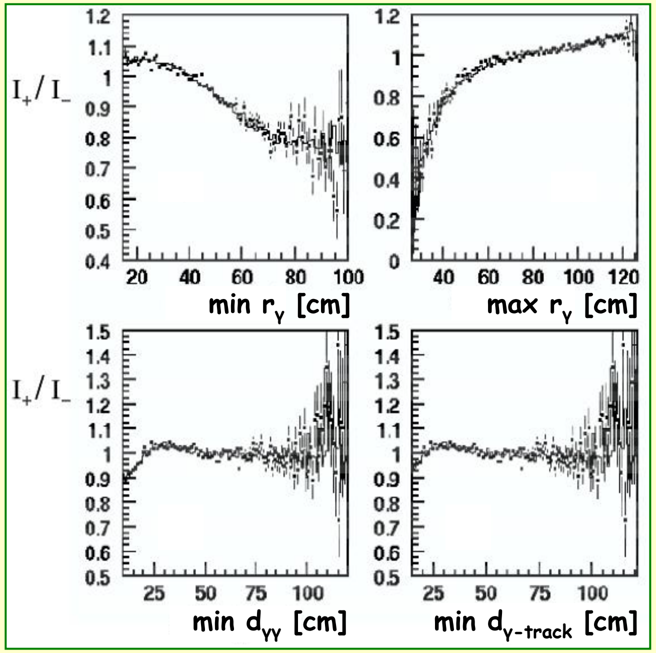
$\sigma \sim 0.5$ MeV/c^2 @ $M_{00} = 2m_{\pi+}$

Instrumental Effects (II)

Data-MC comparisons above and below “cusp”:



a/b ratios:
Data (dot)
vs.
MC (full)



Data distributions across the “cusp” agree with MC predictions without “cusp”

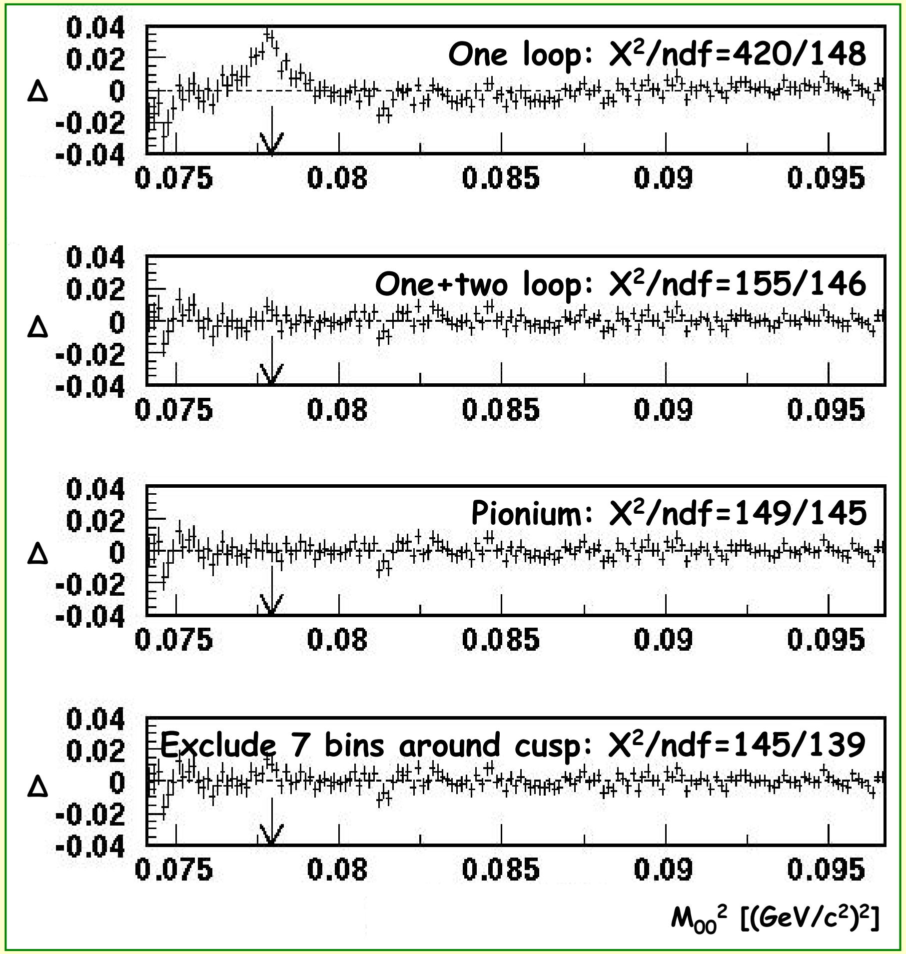
Event deficit is a real effect

Results (I)

Try fitting different theoretical models to M_{00}^2 distribution and evaluate:

$$\Delta = \frac{Data - Fit}{Data}$$

- Fitting up to 0.097 $(GeV/c^2)^2$
- 5 fitting parameters: norm, g_0, h', a_0-a_2 and a_2
- For final results pionium set to theoretical expectation and 7 bins around the "cusp" excluded from the fit in order to reduce sensitivity to Coulomb corrections



Results From $K^{\pm}_{e4}$

Preliminary

$a_0 \cdot m_{\pi+}$ (UB) = $0.256 \pm 0.008_{stat} \pm 0.007_{syst} \pm 0.018_{th}$

-> $a_2 \cdot m_{\pi+} = -0.031 \pm 0.015_{stat} \pm 0.015_{syst} \pm 0.019_{th}$

"Cusp"

$g_0 = 0.645 \pm 0.004_{stat} \pm 0.009_{syst}$
$h' = -0.047 \pm 0.012_{stat} \pm 0.011_{syst}$

$(a_0 - a_2) \cdot m_{\pi+} = 0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$
$a_2 \cdot m_{\pi+} = -0.041 \pm 0.022_{stat} \pm 0.014_{syst}$

Predictions in ChPT (PLB 488 (2000) 261):

- $a_0 \cdot m_{\pi+} = 0.220 \pm 0.005$
- $a_2 \cdot m_{\pi+} = -0.0444 \pm 0.0010$
- $(a_0 - a_2) \cdot m_{\pi+} = 0.265 \pm 0.004$

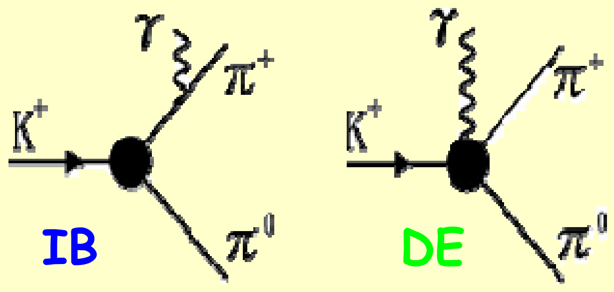
Rare Decays:

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$

Introduction (I)

Two amplitudes:
- Inner Bremsstrahlung (IB)
- Direct Emission (DE)

Two type of contributions:
- Electric ($j=l\pm1$) dipole (E_1)
- Magnetic ($j=l$) dipole (M_1)



Electric contributions come from L^4 CHPT Lagrangian, loops L^2 and are dominated by the IB term

Magnetic contributions are dominated by Chiral Anomaly

DE shows up only at order $O(p^4)$ in ChPT: is generated both by E and M contributions. Present experimental results seem to suggest a M dominated DE

Interference (INT) is possible between IB and electric part of DE:
- Measuring at the same time DE and INT gives measurement of M and E
- CP-Violation could appear in INT

	IB:	$(2.75 \pm 0.15)\cdot10^{-4}$
PDG (55 MeV < T^*_π < 90 MeV)	DE:	$(4.4 \pm 0.8)\cdot10^{-6}$
	INT:	not yet measured

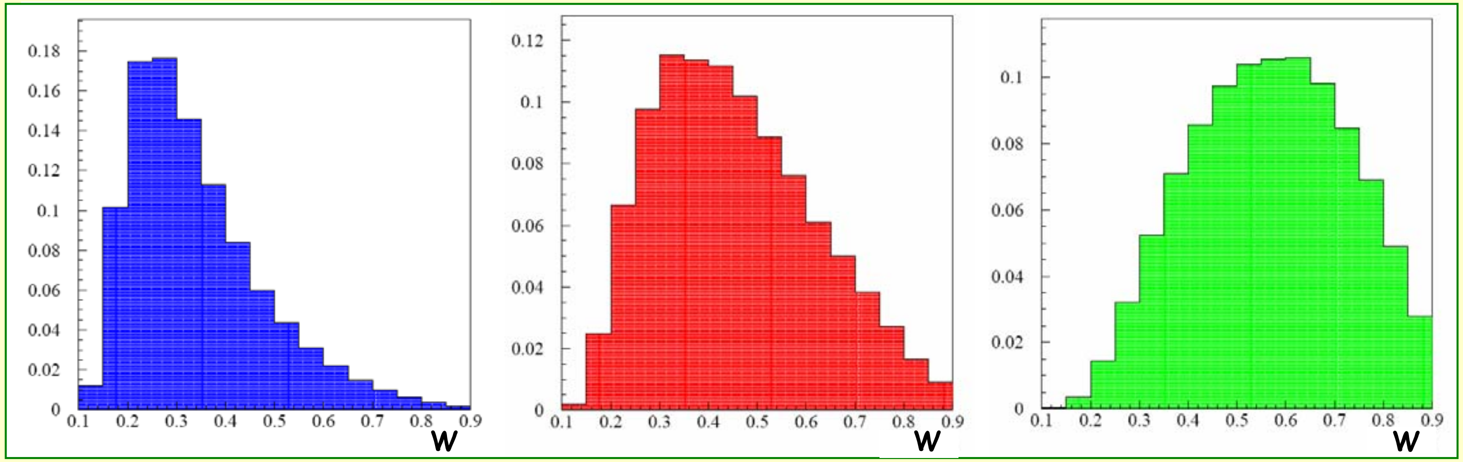
Introduction (II)

$$\frac{d\Gamma^{\pm}}{dW} \simeq \left(\frac{d\Gamma^{\pm}}{dW}\right)_{IB}\left[1 + 2\left(\frac{m_\pi}{m_K}\right)^2 W^2 |E| cos((\delta_1 - \delta_0) \pm \phi) + \left(\frac{m_\pi}{m_K}\right)^4 W^4 (|E|^2 + |M|^2)\right]$$

IB
from $K^{\pm} \to \pi^{\pm}\pi^0$

INT
sensitive to electric dipole

DE
sensitive to electric & magnetic dipole



$$W^2 = \frac{(P_K^* \cdot P_\gamma^*)(P_\pi^* \cdot P_\gamma^*)}{(m_k m_\pi)^2}$$

P^*_K = 4 momentum of the $K^{\pm}$
P^*_π = 4 momentum of the $\pi^{\pm}$
P^*_γ = 4 momentum of the radiative γ

Introduction (III)

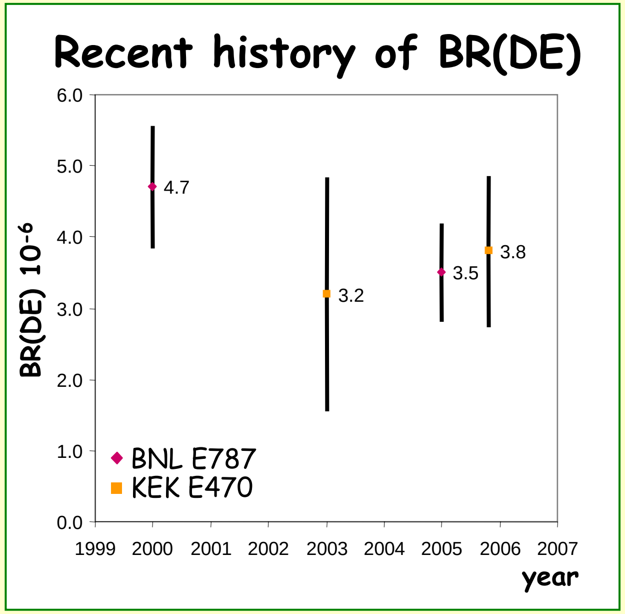
Interference found to be compatible with 0:

$$\mathrm{INT}=(-0.58^{+0.91}_{-0.83})\% \text{ of IB}$$ BNL E787

$$\mathrm{INT}=(-0.4 \pm 1.6)\% \text{ of IB}$$ KEK E470

-> Set INT = 0 and fit only DE (all measurements have been performed in the T^*_π region 55÷90 MeV to avoid $K^\pm \to \pi^\pm\pi^0\pi^0$ background)

Experiment	year	# of events	DE BR 10^{-6}
Abrams [5]	1972	2100	$15.6 \pm 3.5 \pm 5.0$
Smith [18]	1976	2461	23 ± 32
Bolotov [19]	1987	140	$20.5 \pm 4.6^{+3.9}_{-2.3}$
E787 [20]	2000	19836	$4.7 \pm 0.8 \pm 0.3$
E470 [21]	2003	4434	$3.2 \pm 1.3 \pm 1.0$
E787 [22]	2005	20571	$3.5 \pm 0.6^{+0.3}_{-0.4}$
E470 [23]	2005	10154	$3.8 \pm 0.8 \pm 0.7$



Introduction (IV)

What's new in NA48/2 measurement?

- Simultaneous K^+ and K^- beams -> check for CP-Violation
- Enlarged T^*_π region in the low energy part (0÷80 MeV)
- γ miss-tagging probability ~‰ for IB, DE and INT
- Negligible background contribution (<1% of the DE component)

Event Selection (I)

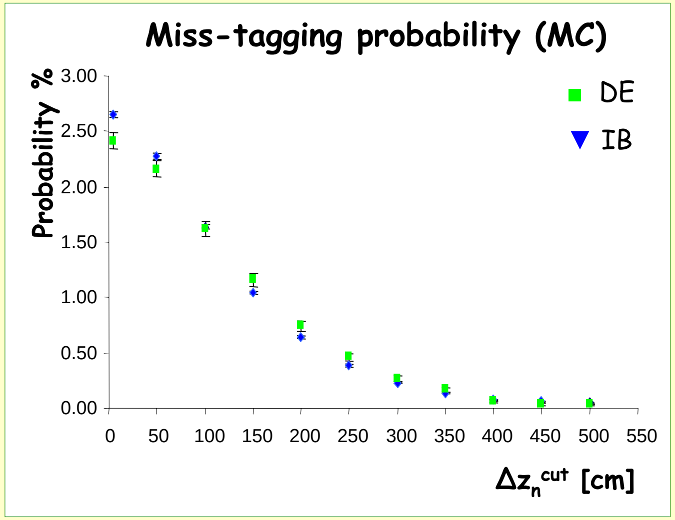
Event selection:

- Select 1 track and any number of clusters
- Require 3 γs with $E_\gamma > 3$ GeV outside 35 cm radius from π @ LKr γs and 10 cm away from other clusters
- Charged vertex (z_c): calculate the K decay point as the position where the $\pi^\pm$ track intersects the beam line
- Selecting the γ pairing for the π^0:
  - Three combinations are possible (choosing the wrong combination for the π^0 -> choosing the wrong odd γ (miss-tagging) -> distorts W)
  - Two possible methods used: select the combination giving the best π^0 or $K^\pm$ invariant mass
- Neutral vertex (z_n): from imposing π^0 mass to γ pairs; must be in agreement with charged vertex (within 400 cm)

Event Selection (II)

Miss-tagged events move to large W: this could induce a DE component if difference between Data-MC

- Demanding the charged vertex compatible with the best neutral vertex gives $P_{miss\text{-}tagging} \sim 2.5\%$
- Rejecting events with a second solution for neutral vertex close to the best one, $|z_n^{second} - z_n^{best}| < \Delta z_n^{cut}$, reduces the $P_{miss\text{-}tagging}$



$P_{miss\text{-}tagging} < 1.2$ ‰ @ $\Delta z_n^{cut} = 400$ cm

Background (I)

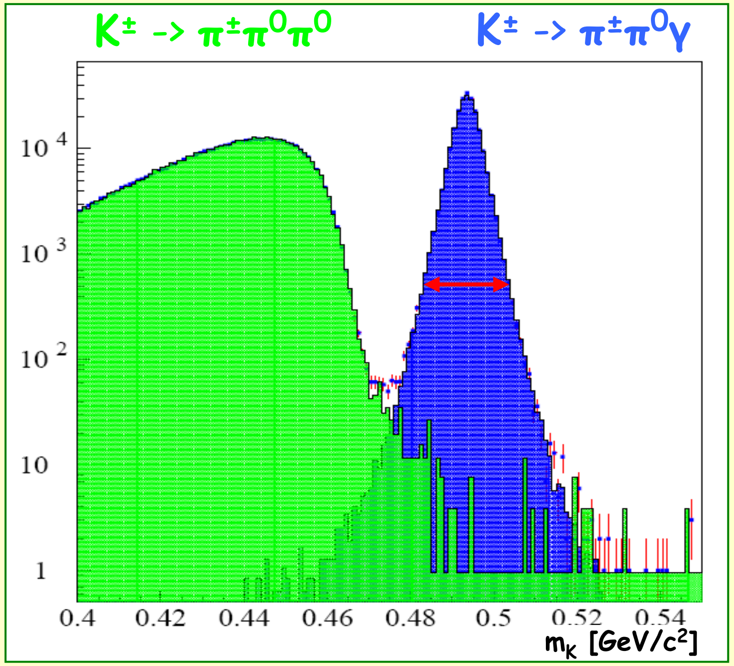
Decay	BR	Background mechanism
$K^\pm \to \pi^\pm\pi^0$	(21.13 ± 0.14) %	1 accidental γ or hadronic extra cluster
$K^\pm \to \pi^\pm\pi^0\pi^0$	(1.76 ± 0.04) %	1 missing or 2 overlapped γs
$K^\pm \to \pi^0 e^\pm \nu$	(4.87 ± 0.06) %	1 accidental γ and e misidentified as a π
$K^\pm \to \pi^0 \mu^\pm \nu$	(3.27 ± 0.06) %	1 accidental γ and μ misidentified as a π
$K^\pm \to \pi^0 e^\pm \nu(\gamma)$	$(2.66 \pm 0.2)\cdot 10^{-4}$	e misidentified as a π
$K^\pm \to \pi^0 \mu^\pm \nu(\gamma)$	$(2.4 \pm 0.85)\cdot 10^{-5}$	μ misidentified as a π

Backgrounds can be rejected using particle ID, COG, mass and time cuts

Background (II)

Cut on overlapping γs (allows avoiding T^*_π > 55 MeV):

- For every of the three γs in the event assume that its energy E_i is really the overlap of 2 γs of energies $E' = x \cdot E_i$ and $E'' = (1-x) \cdot E_i$
- Solve for sharing fraction (x) imposing that the two π^0 must come from the same vertex
- Reject event if any of the reconstructed π^0 vertex is compatible with charged vertex (within 400 cm)



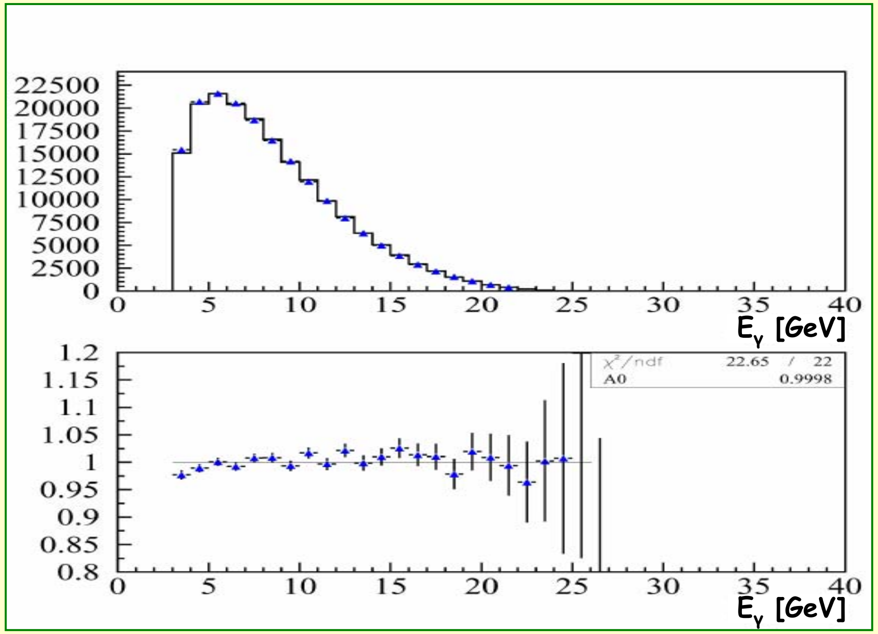
In addition need to use MUV detector to avoid miss-reconstruction of track momentum due to π -> μν decay in flight

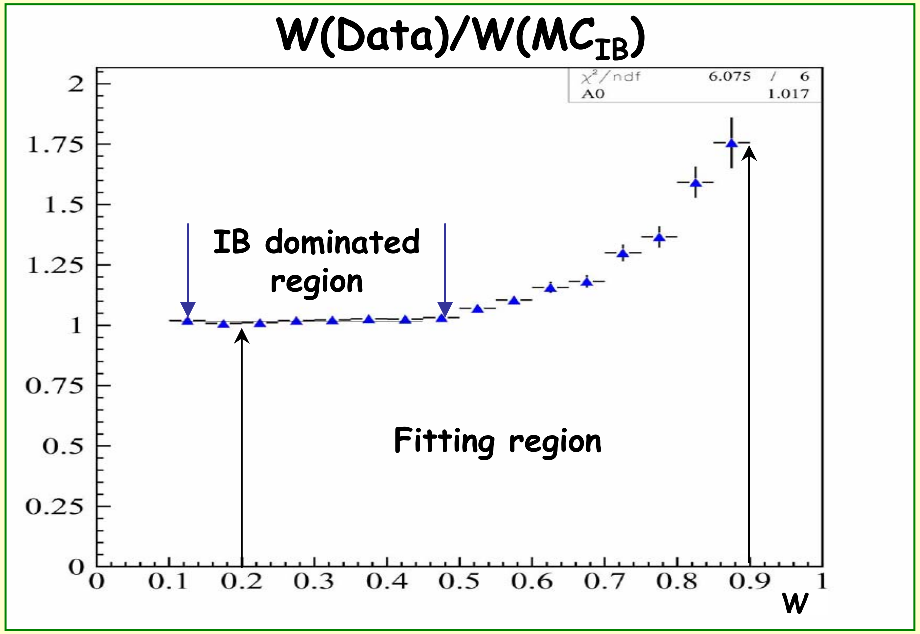
After all cuts the background estimation is <1% of DE and can be explained in terms of $K^\pm \to \pi^\pm\pi^0\pi^0$

Data/MC Comparison

In the 2003 data sample (~30% of the whole statistics) $220 \cdot 10^3$ $K^{\pm}$ have been selected:

- After trigger efficiency correction good agreement between Data and MC for E_γ, in particular for $E_\gamma > 5$ GeV (used for final result)
- The ratio $W(Data)/W(MC_{IB})$ is in good agreement for IB dominated region and clearly shows DE





Systematics

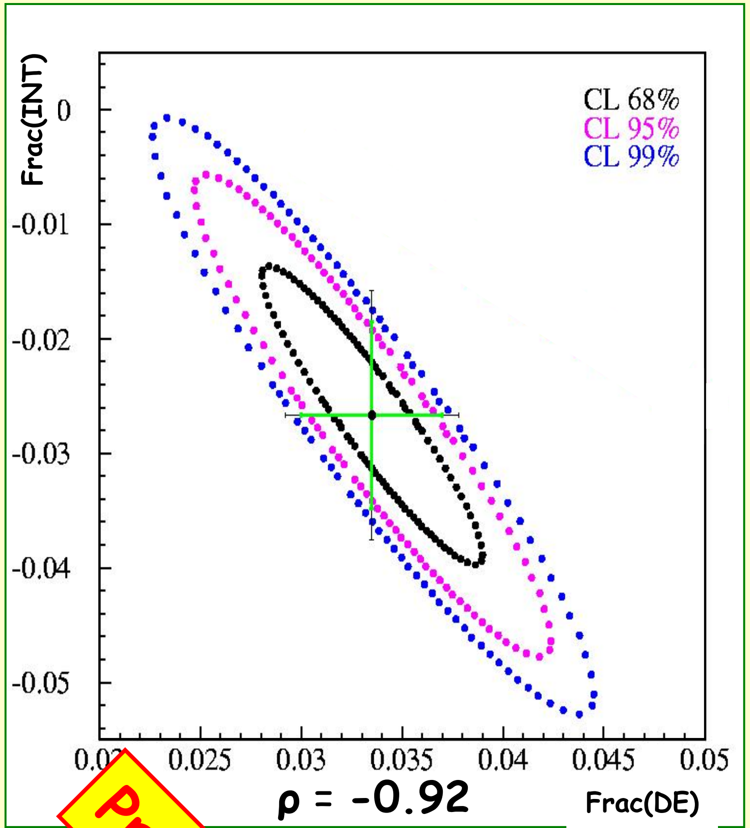
Systematic checks have been performed using both Data and MC

Systematic effect	Effect on DE	Effect on INT
Miss-tagging	-	±0.2
Energy scale	+0.09	-0.21
Resolutions difference	< 0.05	< 0.1
LKr non linearity	< 0.05	< 0.05
BG contributions	< 0.05	< 0.05
Fitting procedure	0.02	0.19
L1 trigger	**±0.17**	**±0.43**
L2 trigger	**±0.17**	**±0.52**
Total	**±0.25**	**±0.73**

Systematic effects dominated by the trigger (both L1 and L2 have been modified in 2004)

Results (I)

Use extended Maximum Likelihood for $0.2 < W < 0.9$ to fit in the region $0\ \text{MeV} < T^*_\pi < 80\ \text{MeV}$ (based on $124 \cdot 10^3$ events)



-> First evidence of Interference between Inner Bremsstrahlung and Direct Emission amplitudes

Based on a partial sample of 2003 data

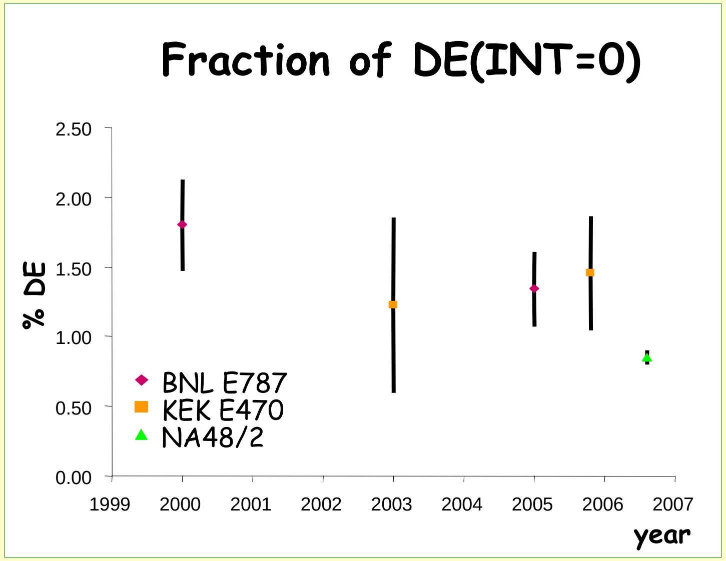
$\text{Frac(DE)} = (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\ \%$

$\text{Frac(INT)} = (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\ \%$

Results (II)

Setting INT = 0 for comparison, fitting between 0 MeV < T^*_π < 80 MeV and extrapolating to 55÷90 MeV

$$\text{Frac(DE)} = (0.85 \pm 0.05_{stat} \pm 0.02_{syst})\ \%$$



The analysis of fit residuals shows a bad X^2

A description in term of IB and DE only is unable to reproduce the W data spectrum