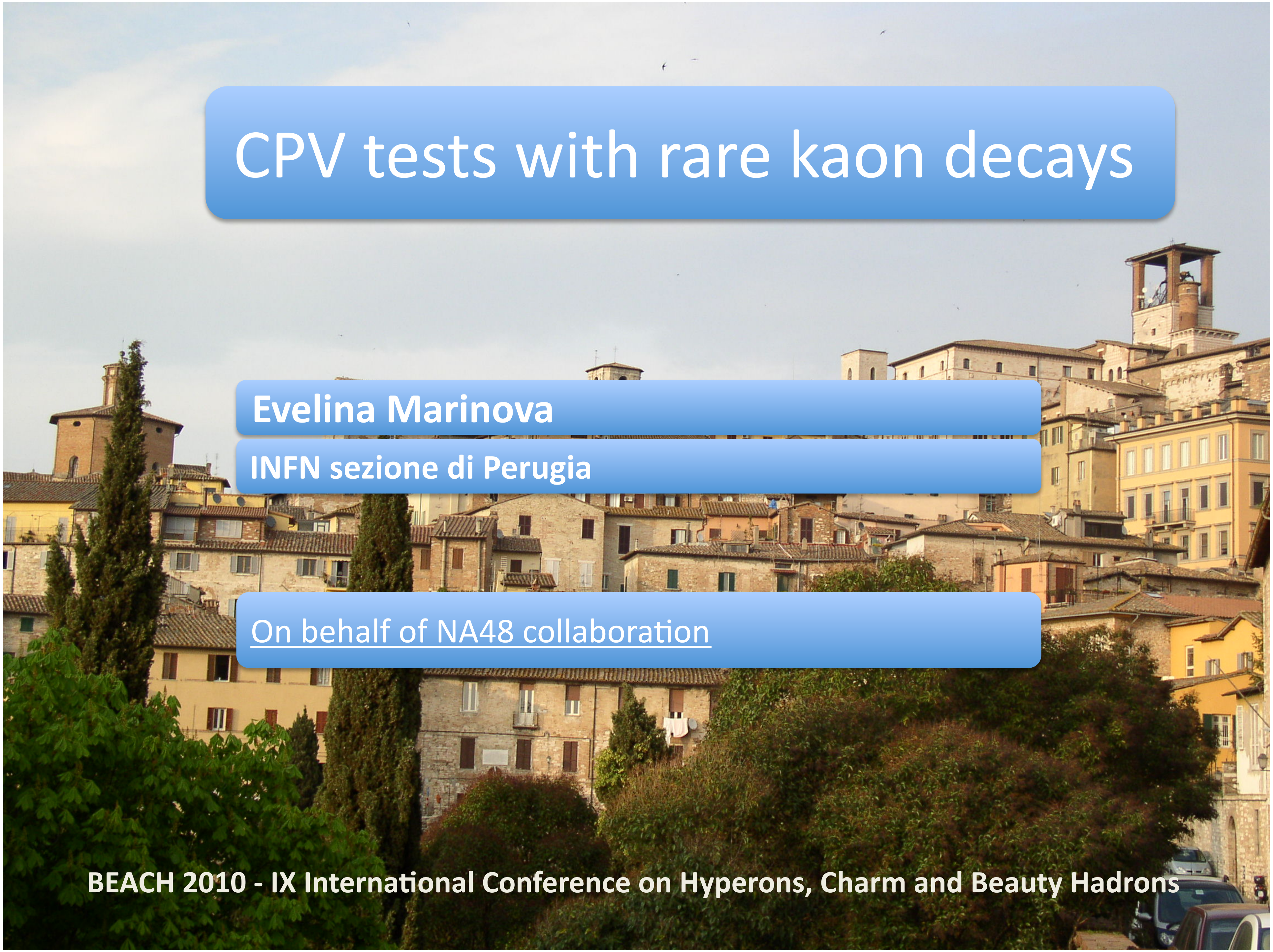

CPV tests with rare kaon decays

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INFN sezione di Perugia

On behalf of NA48 collaboration

BEACH 2010 - IX International Conference on Hyperons, Charm and Beauty Hadrons

NA48 & NA62 history line

NA48

Main goal: Search for direct CPV: Measurement of ε'/ε

Beams: K_L + K_S beam

1997

1998

1999

2000

2001

2002

2003

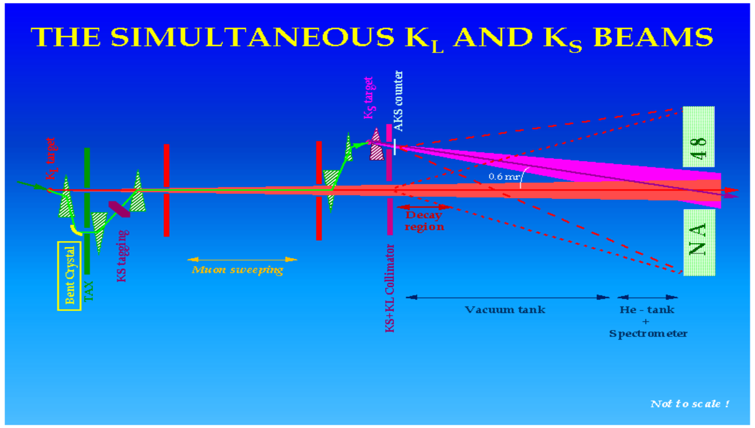
2004

2005

:

2013

:



NA48/2

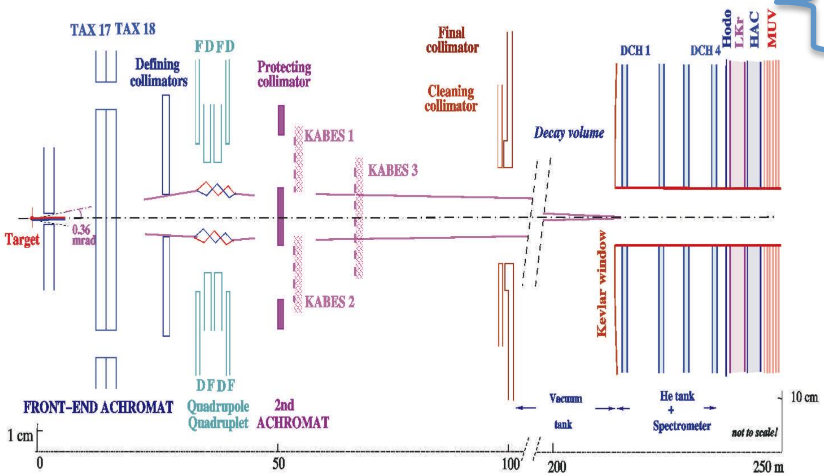
Main goal: Search for direct CPV: Charge asymmetry measurement

Beams: K^+ + K^- beam

NA48/1

Main goal: Rare K_S and hyperon decays

Beams: Ks beam



See talks by E.Goudzovskiy & G. Ruggiero

NA48 detector

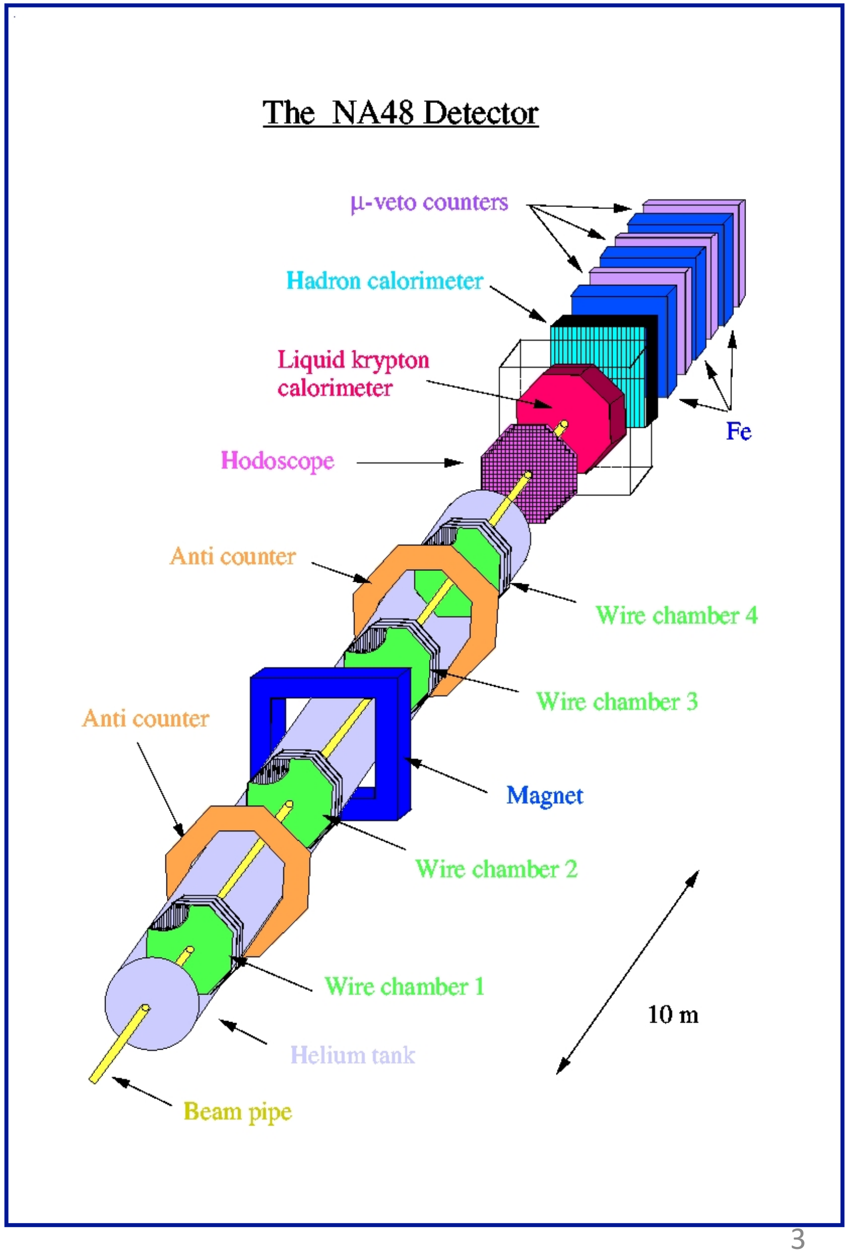
- ***Magnetic spectrometer (4 DCHs):***
  - **4 views : redundancy ⇒ high efficiency;**
  - **Δp/p = 1.0%⊕0.044%*p [GeV/c]**

- ***Hodoscope***
  - **fast trigger;**
  - **precise time measurement ($\sigma_t = 150$ ps) .**

- ***Liquid Krypton EM calorimeter (LKr)***
  - **Quasi-homogeneous ionization chamber**
  - **27 electromagnetic radiation lengths long active volume**
  - **Segmented transversally 13248 cells, 2x2 cm2**
  - **Energy resolution (E in GeV):**

$$\frac{\sigma(E)}{E} = \frac{0.032}{\sqrt{E}} \oplus \frac{0.09}{E} \oplus 0.0042$$

Presented by E. Goudzovskiy, this session



Rare decays with NA48/1

NA48/1 $K_S \to \pi^+\pi^- e^+e^-$ process

Unlike the $K_L \to \pi^+\pi^- e^+e^-$ decay mode in which the CP=+1 Inner Bremsstrahlung process competes with the CP=-1 Direct Emission (M1) term, the $K_S \to \pi^+\pi^- e^+e^-$ decay proceeds mainly via Inner Bremsstrahlung

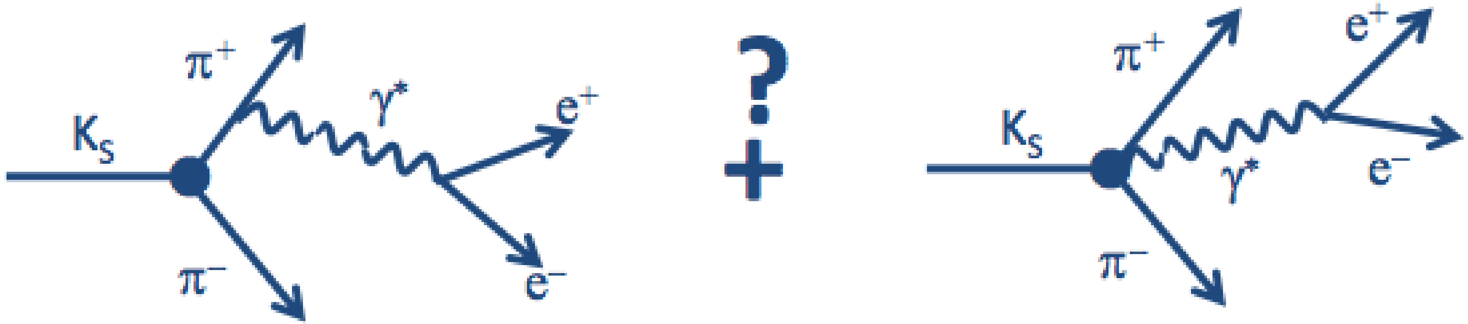
No sizeable interference between CP-even and CP-odd terms in KS mode

CP-violating $A\varphi$ asymmetry expected to be zero

$$A_\varphi = \frac{N_{\pi\pi ee}(\sin\varphi\cos\varphi > 0) - N_{\pi\pi ee}(\sin\varphi\cos\varphi < 0)}{N_{\pi\pi ee}(\sin\varphi\cos\varphi > 0) + N_{\pi\pi ee}(\sin\varphi\cos\varphi < 0)}$$

ϕ is the angle between e^+e^- and $\pi^+\pi^-$ planes in the kaon rest frame

Possible contribution from Direct Emission (E1) to the decay amplitude



Dominant Inner Bremsstrahlung *Direct Emission: E1, M1, E2, ….*

NA48/1 status and motivation

First observation by NA48 with '98 data (56 evts)

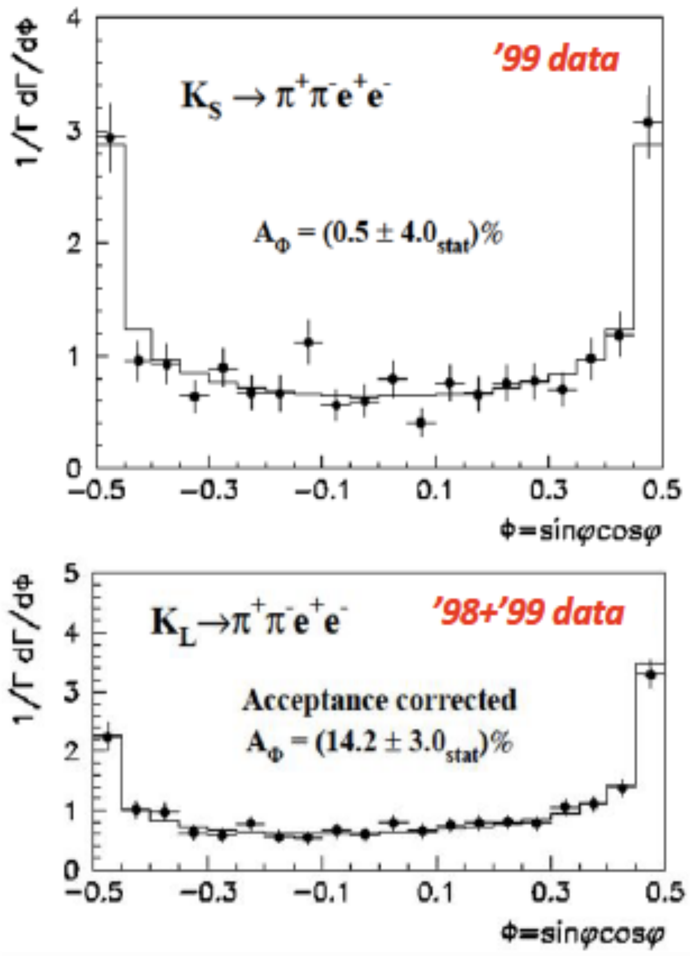
Full data set ('98+'99, HI KS):

677 candidates (mainly HI KS) ; bkg ~ 1 evt.

BR($K_S \rightarrow \pi^+\pi^-e^+e^-$) = $(4.69 \pm 0.30) \bullet 10^{-5}$

$A\phi$= (-1.1 ±4.1) %

EPJ C30, 33-49 (2003)



2002 NA48-1: more than 20 k $K_S \rightarrow \pi^+\pi^-e^+e$ decays

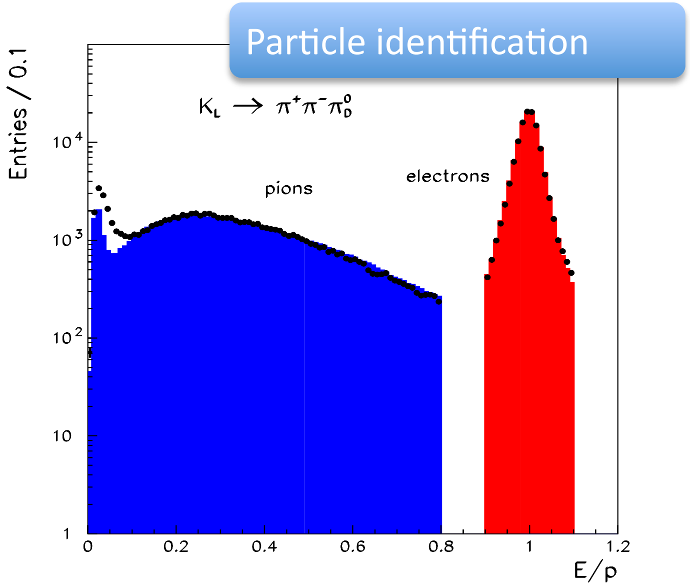
Improve significantly BR measurement

(Use **$K_L \rightarrow \pi^+\pi^-\pi^0_D$ decays as normalization –same selection criteria, one gamma in addition**)

Accuracy on $A\phi$ better than 1%

Look for direct emission (E1)

NA48/1 $K_L \rightarrow \pi^+\pi^-\pi^0_D$ normalization channel



MC simulation (bckg estimation; acc calculation)

Radiative corrections :

PHOTOS + coulomb corrections

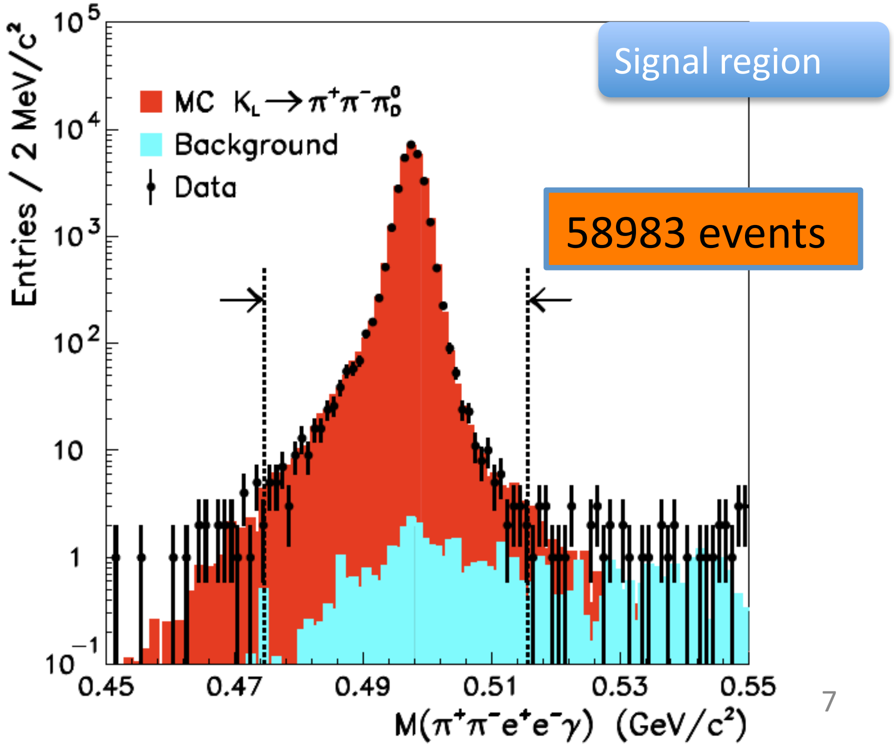
Kaon spectrum modified, beam shape tuned with $K_L \rightarrow \pi^+\pi^-\pi^0$ decays

DCH resolution functions, efficiencies included

Additional resolution on θ_{ee}

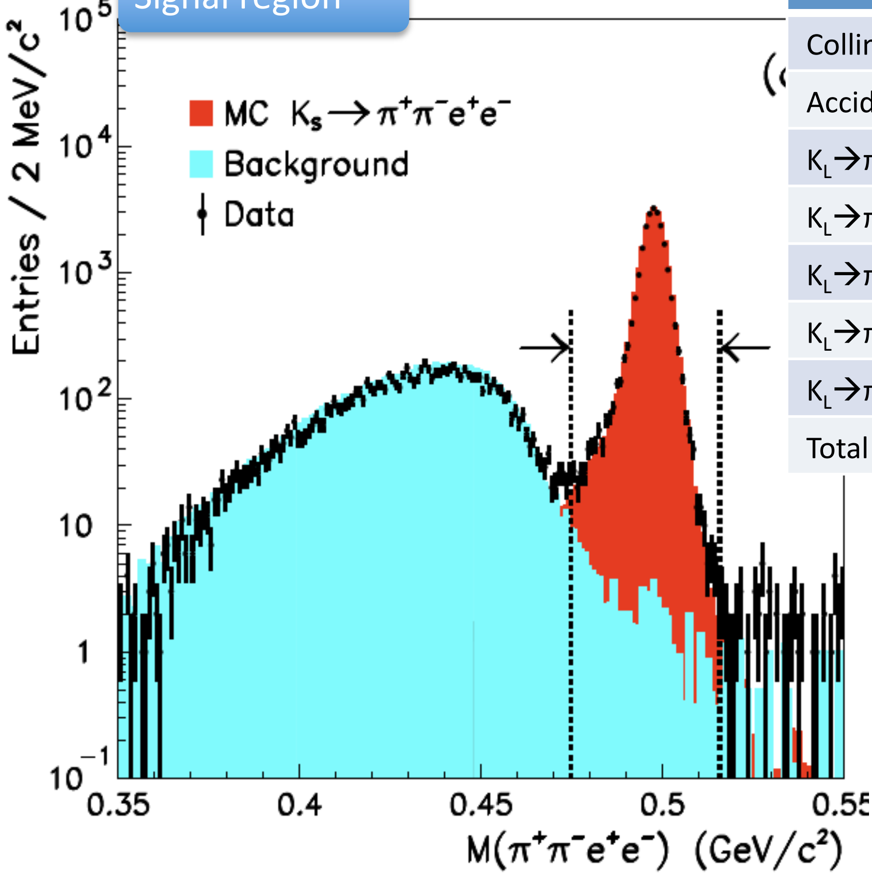
GEANT3 based

BACKGROUND Source	N events
Collimator scattering	3.7 ± 3.7
Accidental activity	8.0 ± 2.6
$K_S \rightarrow \pi^+\pi^- e^+e^-$ bremsstahlung	11.6 ± 1.4
$K_S \rightarrow \pi^+\pi^-\pi^0_D$	3.7 ± 5.8
$K_L \rightarrow \pi^+\pi^-\pi^0$; $\pi^0 \rightarrow e^+e^-e^+e^-$	27.0 ± 1.1
$K_L \rightarrow \pi^+\pi^-\gamma$; $\gamma \rightarrow e^+e^-$	1.1 ± 1.1
Total	55.1 ± 5.7



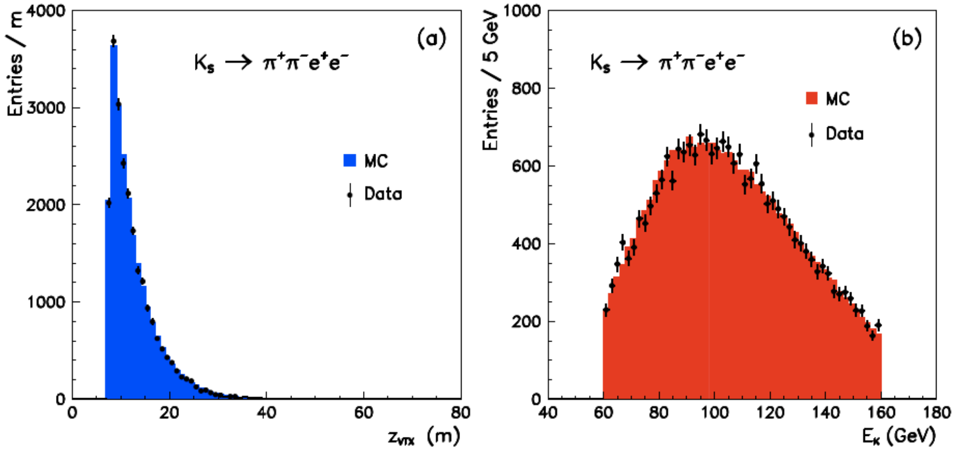
NA48/1 $K_S \to \pi^+\pi^-e^+e^-$ decay – signal and background

Signal region



BACKGROUND Source	N events
Collimator scattering	16.2 ± 5.7
Accidental activity	11.0 ± 3.2
$K_L \to \pi^+\pi^-e^+e^-$	12.4 ± 0.8
$K_L \to \pi^+\pi^-\pi^0_D$	52.0 ± 7.7
$K_L \to \pi^+\pi^-\pi^0$; $\pi^0 \to e^+e^-e^+e^-$	10.3 ± 1.1
$K_L \to \pi^+\pi^-\pi^0$; $\pi^0 \to e^+e^-$	0.6 ± 0.1
$K_L \to \pi^+\pi^-\gamma$; $\gamma \to e^+e^-$	0.5 ± 0.5
Total	103. 0 ± 10.2

Good Data/MC agreement



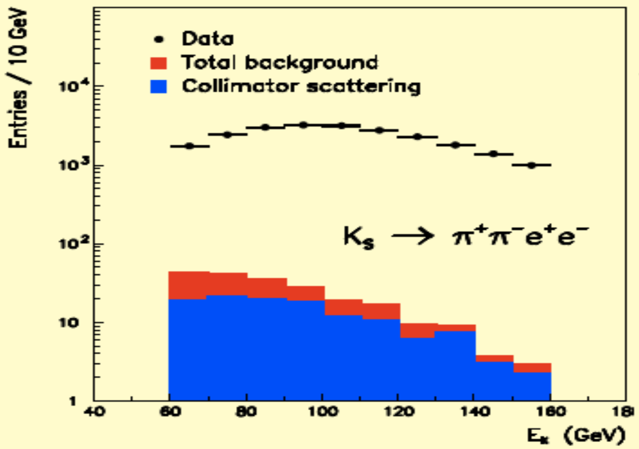
22966 candidate events

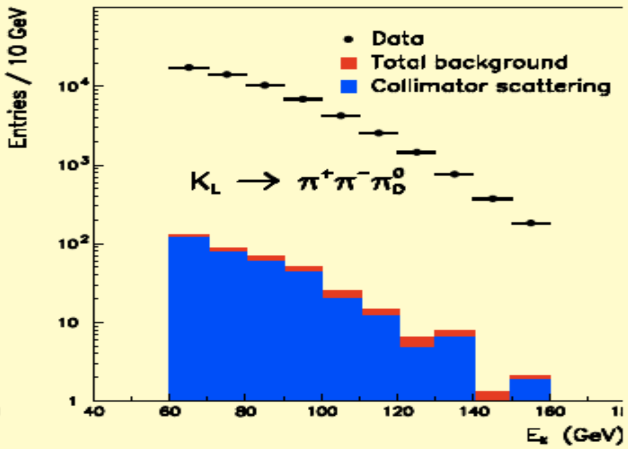
NA48/1 $K_S \to \pi\pi ee$ branching ratio measurement (inputs)

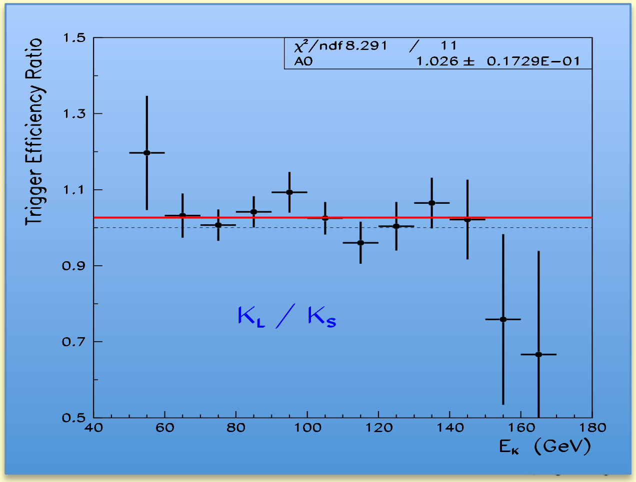
$$\frac{BR(K_S \to \pi^+\pi^-e^+e^-)}{BR(K_L \to \pi^+\pi^-\pi^0_D)} = \frac{N_{\pi\pi ee}}{N_{\pi\pi\pi^0_D}} \frac{A_{\pi\pi\pi^0_D}}{A_{\pi\pi ee}} R_\varepsilon R_K$$

$N_{\pi\pi ee}$, $N_{\pi\pi\pi^0_D}$: # of evts after bkg. subtr.
$A_{\pi\pi ee}$, $A_{\pi\pi\pi^0_D}$: acceptances
R_ε : trigger efficiency ratio
R_K : K_L / K_S flux ratio

Analysis performed in 10 bins of E_K (60 to 160 GeV)

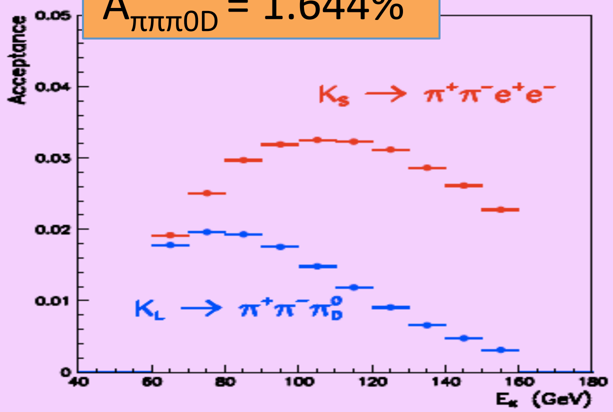


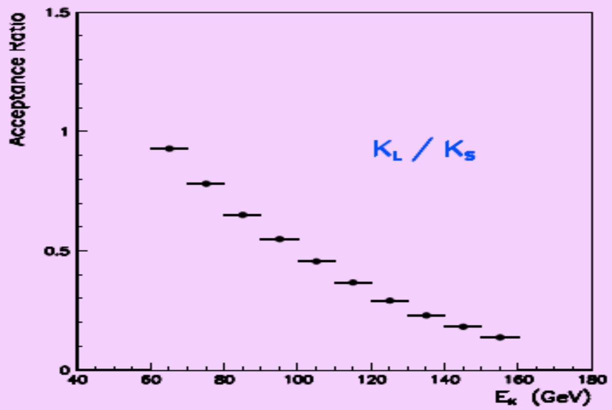




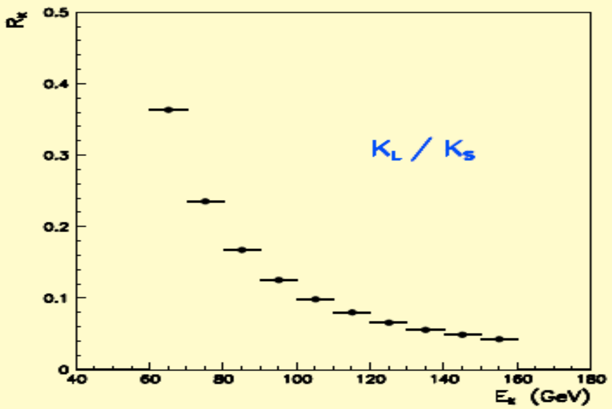
Acceptance

$A_{\pi\pi ee}$ = 2.804%
$A_{\pi\pi\pi 0D}$ = 1.644%

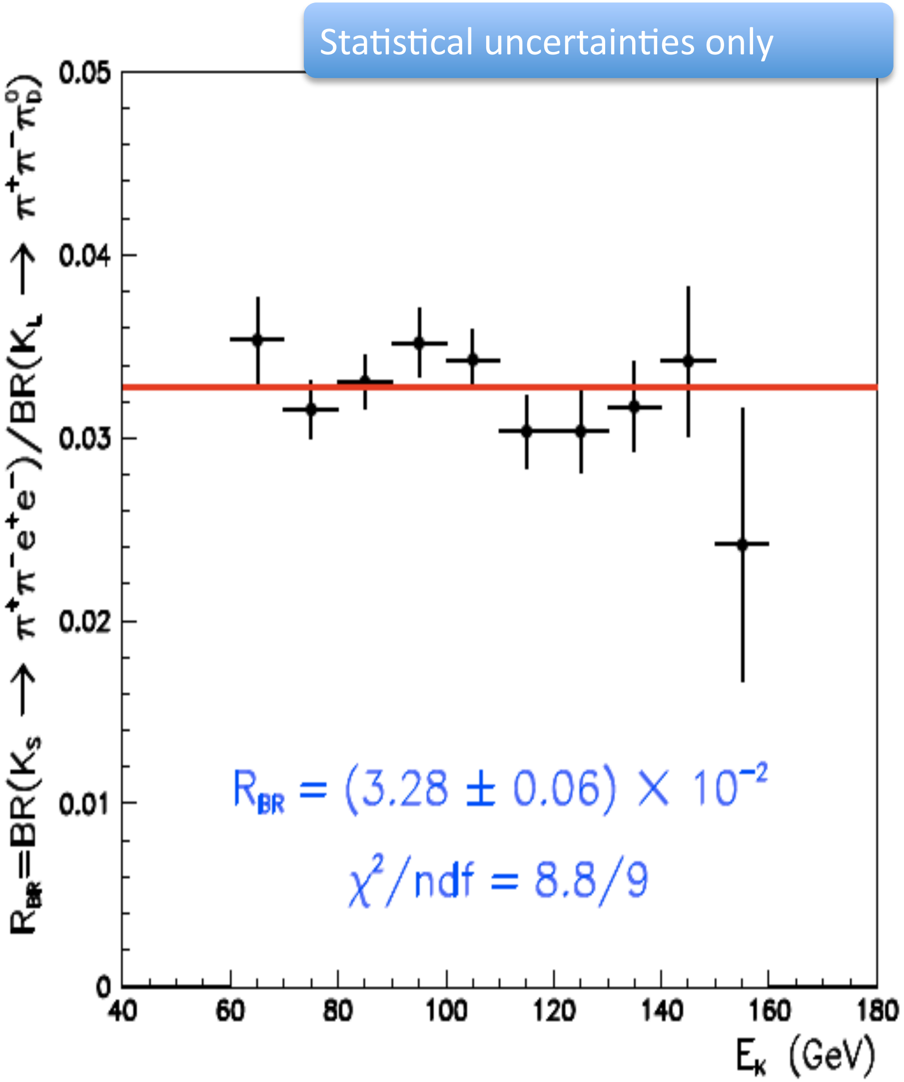




K_L / K_S flux ratio



NA48/1 1 $K_S \rightarrow \pi\pi ee$ branching ratio result & systematics



Source	σ_{syst} (%)
$K_L \rightarrow \pi^+\pi^-\pi^0$ matrix element	± 0.2
Background subtraction	± 0.1
Radiative corrections	± 0.4
Trigger efficiency	± 0.4
e – π separation	± 0.2
π decay	± 0.6
Beam parameters	± 0.1
Geometrical cuts	± 0.7
KL,S lifetimes	± 0.3
Kinematical cuts	± 0.3
Reconstruction	± 0.3
Total	± 1.2

NA48/1 $K_S \to \pi^+\pi^-e^+e^-$ results

Assuming no contribution from E1 direct emission:

$BR(K_S \to \pi^+\pi^-e^+e^-) / BR(K_L \to \pi^+\pi^-\pi^0_D) = (3.28 \pm 0.06\ stat \pm 0.04\ syst) \times 10^{-2}$

$= (3.28 \pm 0.07) \times 10^{-2}$

In agreement with '98 +'99 result

$(3.12 \pm 0.17) \times 10^{-2}$

$BR(K_S \to \pi^+\pi^-e^+e^-) = (4.93 \pm 0.14) \times 10^{-5}$

In agreement with '98 +'99 result

$(4.69 \pm 0.30) \times 10^{-5}$

Using

$BR(K_L \to \pi^+\pi^-e^+e^-) / BR(K_S \to \pi^+\pi^-e^+e^-) = |\eta_{+-}|^2(\tau_L/\tau_S)$:

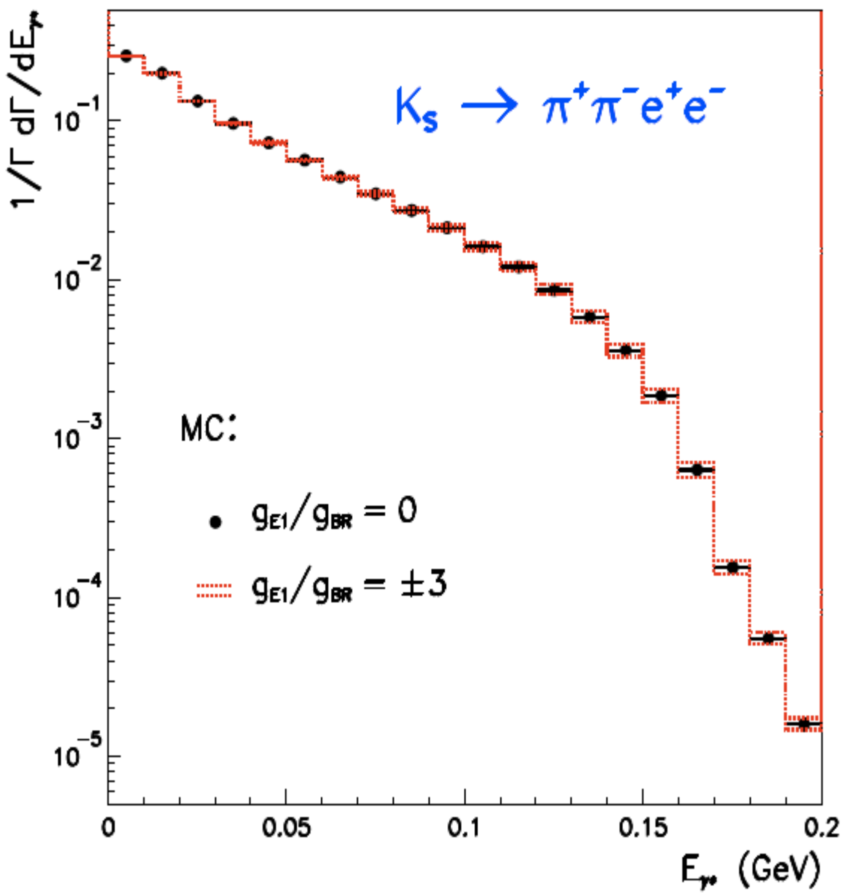
$BR(K_L \to \pi^+\pi^-e^+e^-) = (1.41 \pm 0.04) \times 10^{-7}$ CP violating part

Consistent with Sehgal and Wanninger ('92)

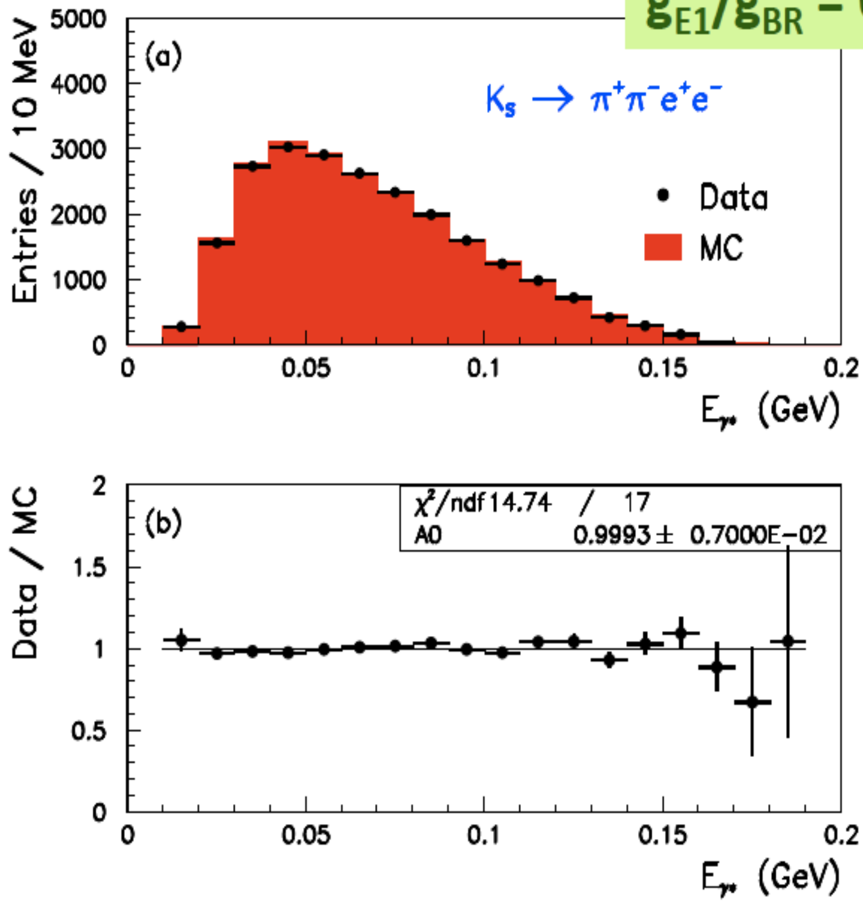
NA48/1 E1 direct emission

Following the formalism of Sehgal and Winningen ('92)

$$M = e|f_S| \{g_{BR} e^{i\delta_0}[p_{+\mu}/p_+\cdot k - p_{-\mu}/p_-\cdot k] + g_{E1} e^{i\delta_1}[(p_-\cdot k)p_{+\mu}] - (p_+\cdot k)p_{-\mu}]\} \{u(k-)\gamma^\mu v(k_+)/k^2\}$$

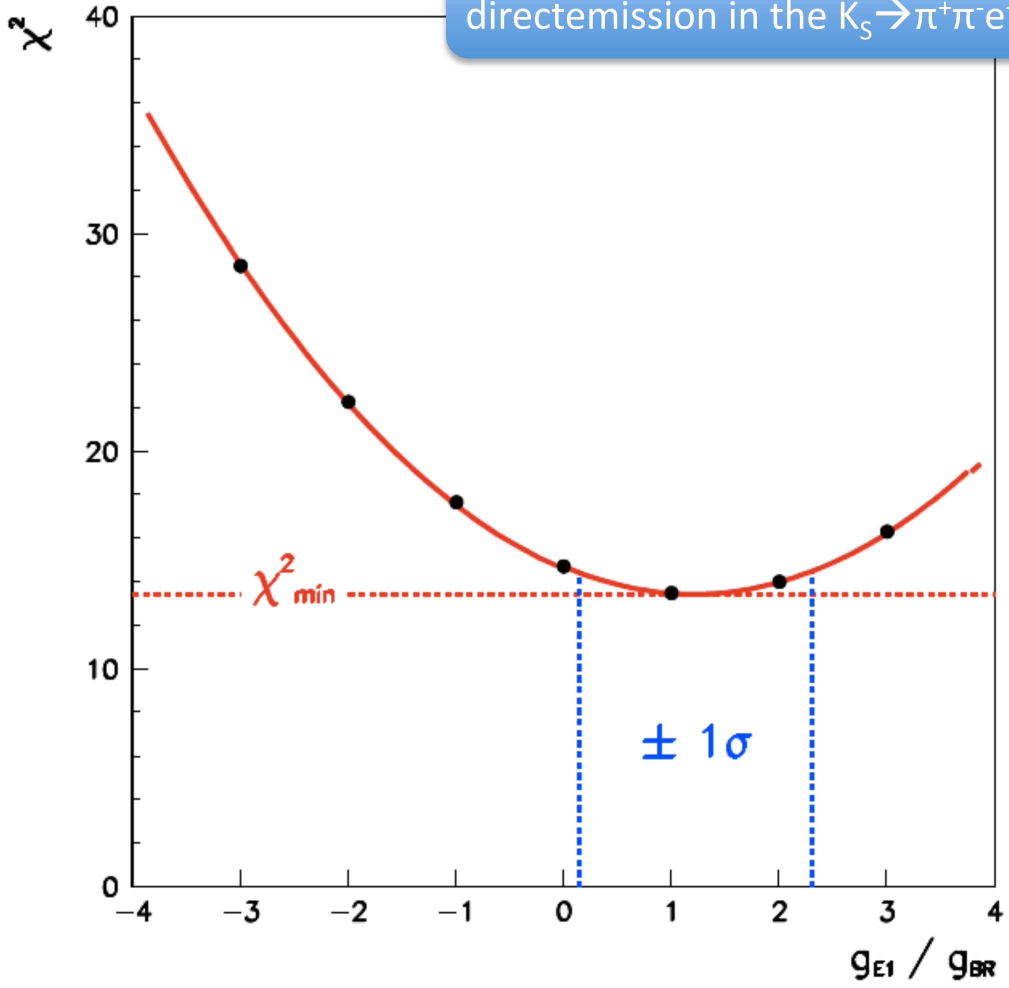


$g_{E1}/g_{BR} = 0$



NA48/1 – E1 –best fit estimation

This result is consistent with no observation of E1 directemission in the $K_S \rightarrow \pi^+\pi^-e^+e^-$ decay



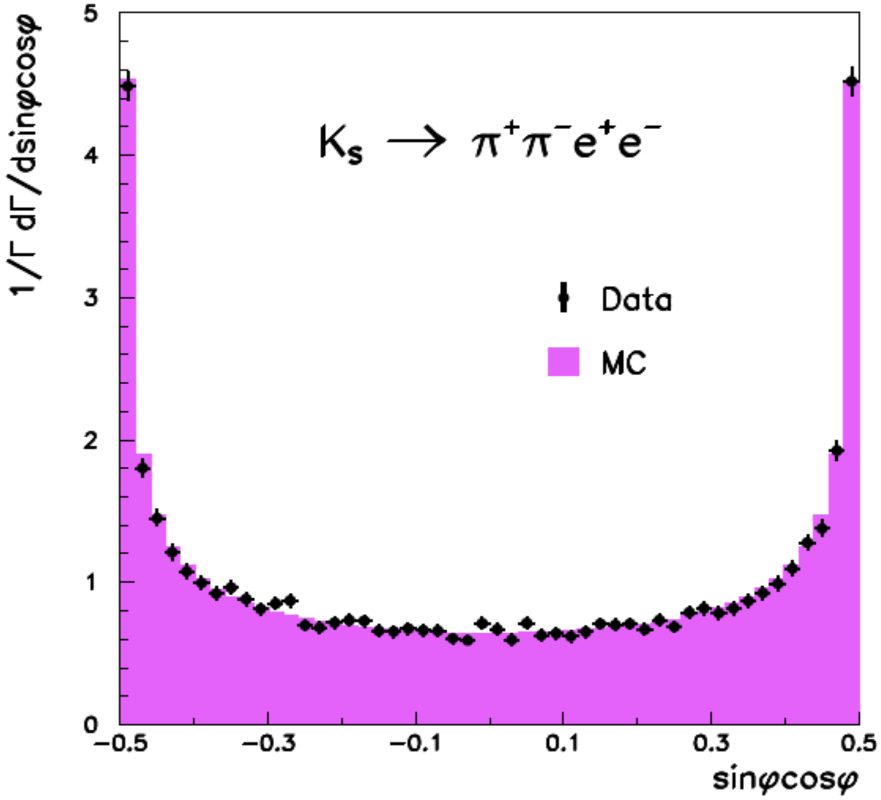
g_{E1}/g_{BR} = 1.5 ± 1.1 (χ2/ndf = 12.8/17)
$|g_{E1}|/|g_{BR}|$ < 3.0 @ 90% CL
(± 0.8% contribution to BR)

~10 times better than analysis by Sehgal and Wanninger ('92) of the KS → π+π-γ mode:
$Re(g_{E1}/g_{BR})$ = -8 ± 8

NA48/1 $K_S \rightarrow \pi^+\pi^-e^+e^-$ $A\phi$ measurement

Systematical uncertainties

Source	$\sigma_{A\phi}$ (%)
Radiative corrections	± 0.1
Geometrical cuts	± 0.3
Kinematical cuts	± 0.2
e – π separation	± 0.1
Trigger	± 0.1
π decay	± 0.1
Total	± 0.4



Largest contributions from e+e- opening angle and inner radii cuts in DCHs and LKr.

Result: Aφ = (- 0.4 ± 0.7stat ± 0.4syst) %

or Aφ = (- 0.4 ± 0.8) % |Aφ | *< 1.5 % @ 90% CL,*

No evidence for a CP-violating contribution in the $K_S \rightarrow \pi^+\pi^-e^+e^-$ decay amplitude was observed.

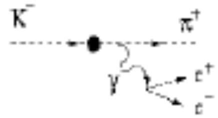
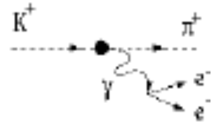
Rare decays with NA48/2

NA48/2: : $K^{\pm} \rightarrow \pi^{\pm} l^{+} l^{-}$ – motivation and theory

$$d\Gamma_{\pi ee}/dz \sim \rho(z)\cdot|W(z)|^2$$

$z=(M_{ee}/M_K)^2$, $\rho(z)$ phase space factor

- suppressed FCNC processes
- one-photon exchange
- useful test for ChPT

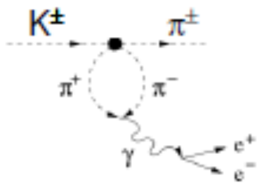




(1) polynomial: $W(z) = G_F M_K^2 \cdot f_0 \cdot (1+\delta z)$

(2) ChPT $O(p^6)$: $W(z) = G_F M_K^2 \cdot (a_+, b_+, z) + W^{\pi\pi}(z)$

(3) ChPT, large-Nc QCD: $W(z) = W(w, \beta, z)$

(4) Mesonic ChPT: $W(z) = W(M_a, M_\rho, z)$



(2) D'Ambrosio et al. JHEP 8 (1998) 4
(3) S. Friot et al. PLB 595 (2004) 301
(4) Dubnickova et al. hep-ph/0611175

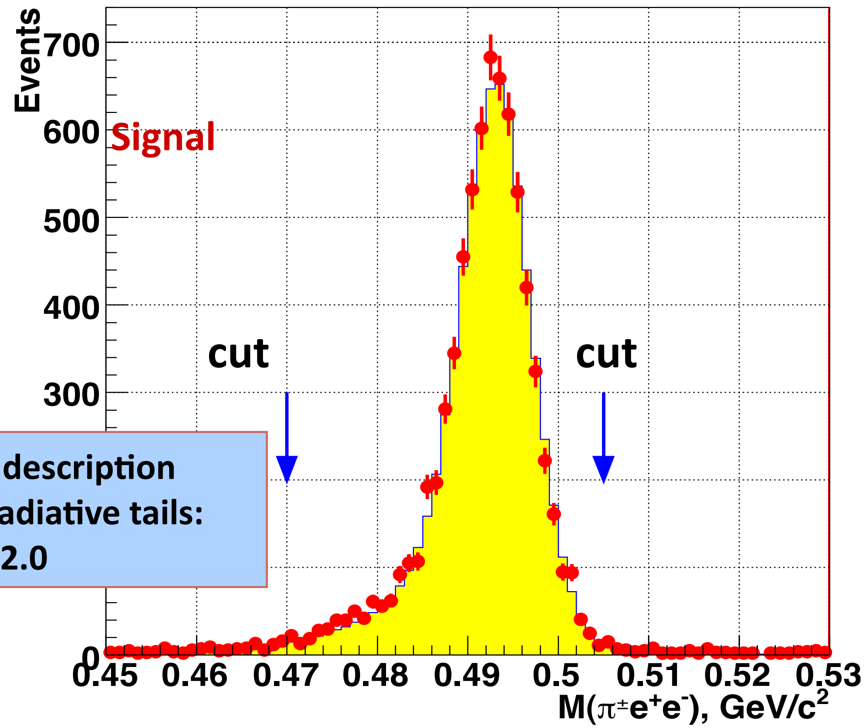
(f_0,δ) or (a_+,b_+) or (w, β) or (M_a,M_ρ) determine a model-dependent BR

- Parameters of models and BR in full kinematical range
- Model-independent BR ($z > 0.08$) in visible kinematical range
- CPV asymmetry $\Delta = BR_{K+} - BR_{K-} / BR_{K+} + BR_{K-}$
  (Theory: $\sim 10^{-5}$ SM; $\sim 10^{-3}$ SUSY)

NA48/2: $K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}$ - signal and normalization samples

Selections of both channels based on very similar conditions: systematics (trigger, PID) in the BR ratio cancel particially

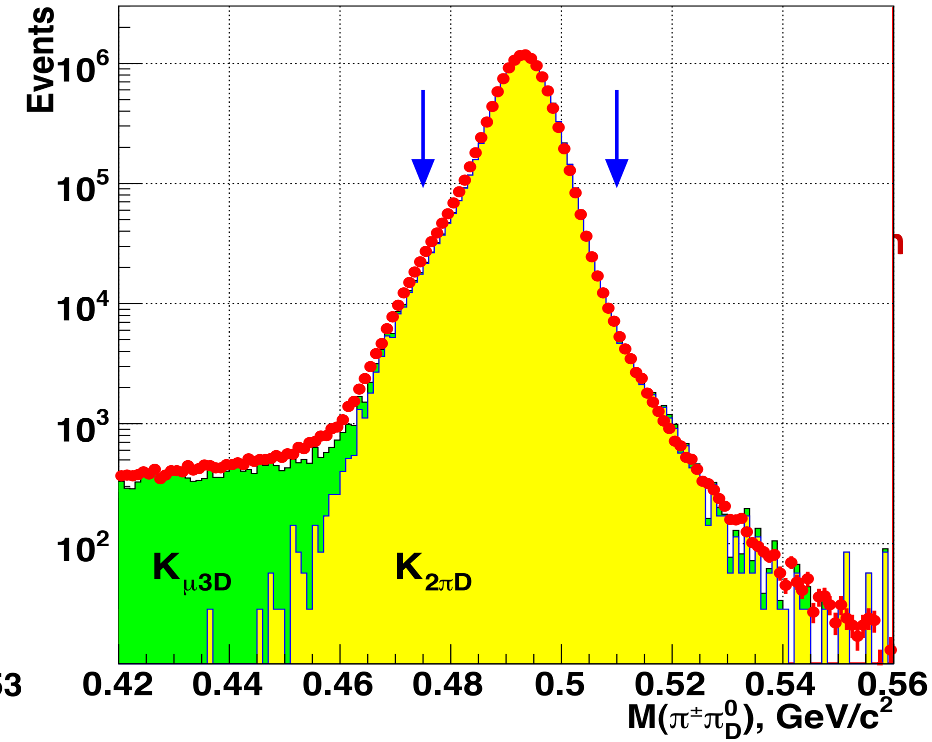
- **Mee > 140 MeV – cut for bg suppression**



Perfect description of the radiative tails: Photos 2.0

7253 candidates
BG: 71 events estimated with data BG/SIG. ~ 1.0%

- **Aditional γ in the normalisation channel**



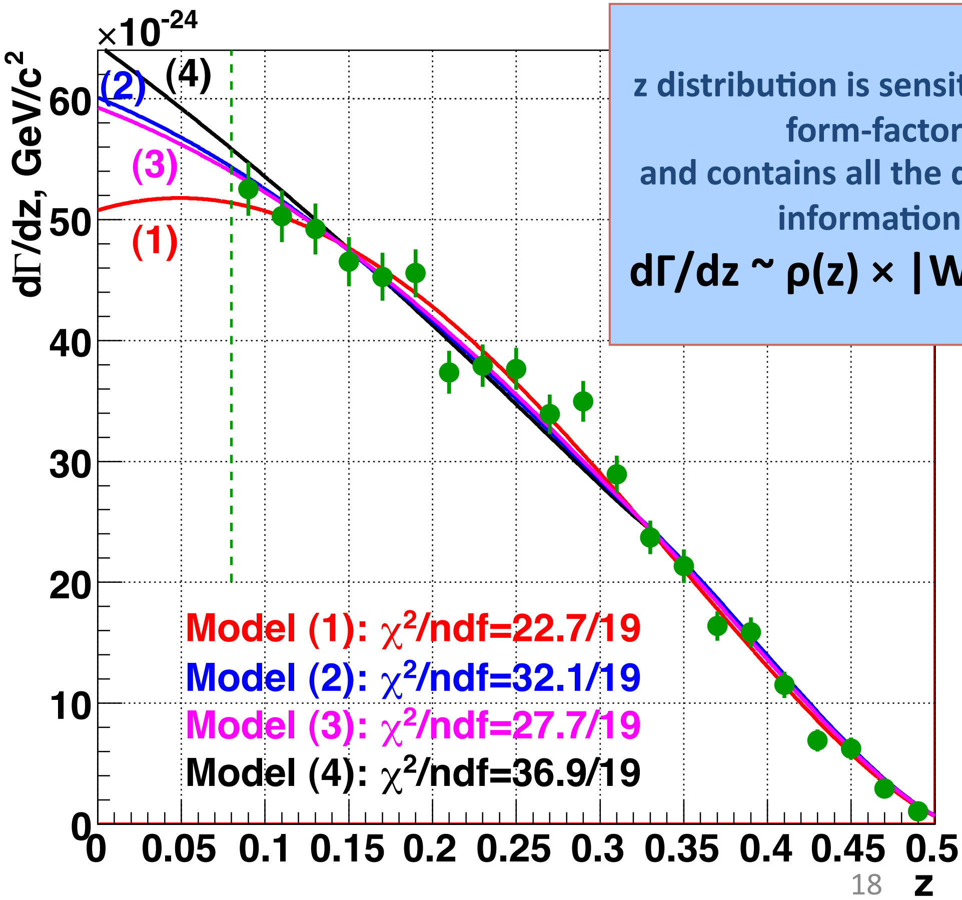
12.12 M candidates
BG/Signal ~ 0.15%
BG subtracted with MC

Kaon decay flux (2003+2004): $\Phi_K = 1.70\times10^{11}$ with Flavianet'08 $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ BR

NA48/2: $K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$ - form factor measurement

GOALS

- Model-independent BR integrating **dΓ/dz in the observable z region**
- Model dependent BRs using fit parameters.
- All models agree reasonably well with data



z distribution is sensitive to the form-factor and contains all the dynamical information:

$$d\Gamma/dz \sim \rho(z) \times |W(z)|^2$$

Fit results

$\delta = 2.32 \pm 0.18_{stat+syst}$

$|f_0| = 0.531 \pm 0.016_{stat+syst}$

$a_+ = -0.578 \pm 0.016_{stat+syst}$

$b_+ = -0.779 \pm 0.066_{stat+syst}$

$w = 0.057 \pm 0.007_{stat+syst}$

$\beta = 3.45 \pm 0.30_{stat+syst}$

$M_a = 0.974 \pm 0.035_{stat+syst}$ GeV

$M_\rho = 0.716 \pm 0.014_{stat+syst}$ GeV

NA48/2: Results – comparison with previous experiments

Model independent measurement

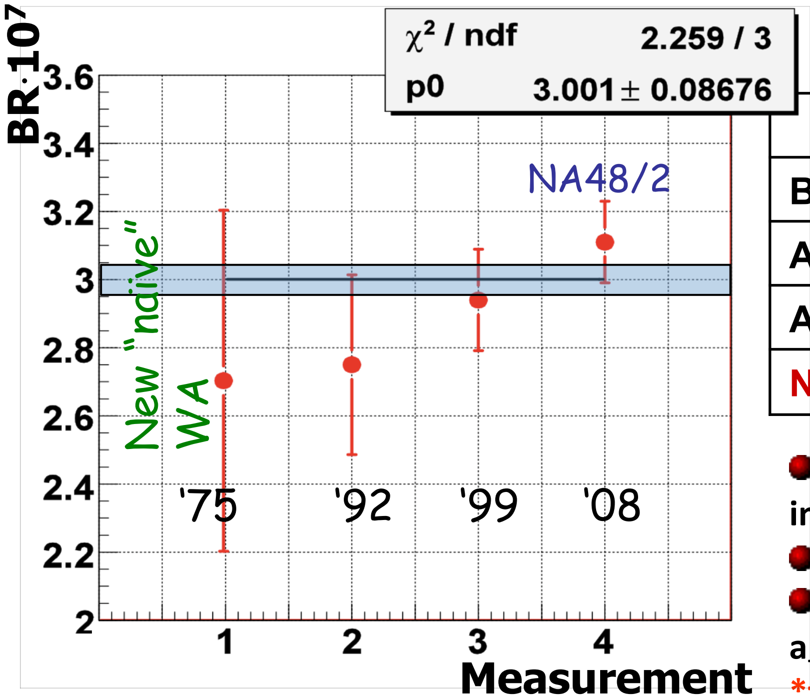
$$BR_{mi}\times10^{7}\ (M_{ee}>140\text{MeV}/c^2) = 2.28 \pm 0.03_{stat} \pm 0.04_{syst} \pm 0.06_{ext} = 2.28 \pm 0.08$$

Combined result of the 4 models

$$BR = (3.11\pm0.04_{stat}\pm0.05_{syst}\pm0.08_{ext}\pm 0.07_{model})\times10^{-7} = (3.11\pm0.12)\times10^{-7}$$

CP violating asymmetry (first measurement! correlated K^+/K^- uncertainties excluded):

$$\Delta(K^{\pm}_{\pi ee}) = (BR^+-BR^-) / (BR^++BR^-) = (-2.2\pm1.5_{stat}\pm0.6_{syst})\%$$



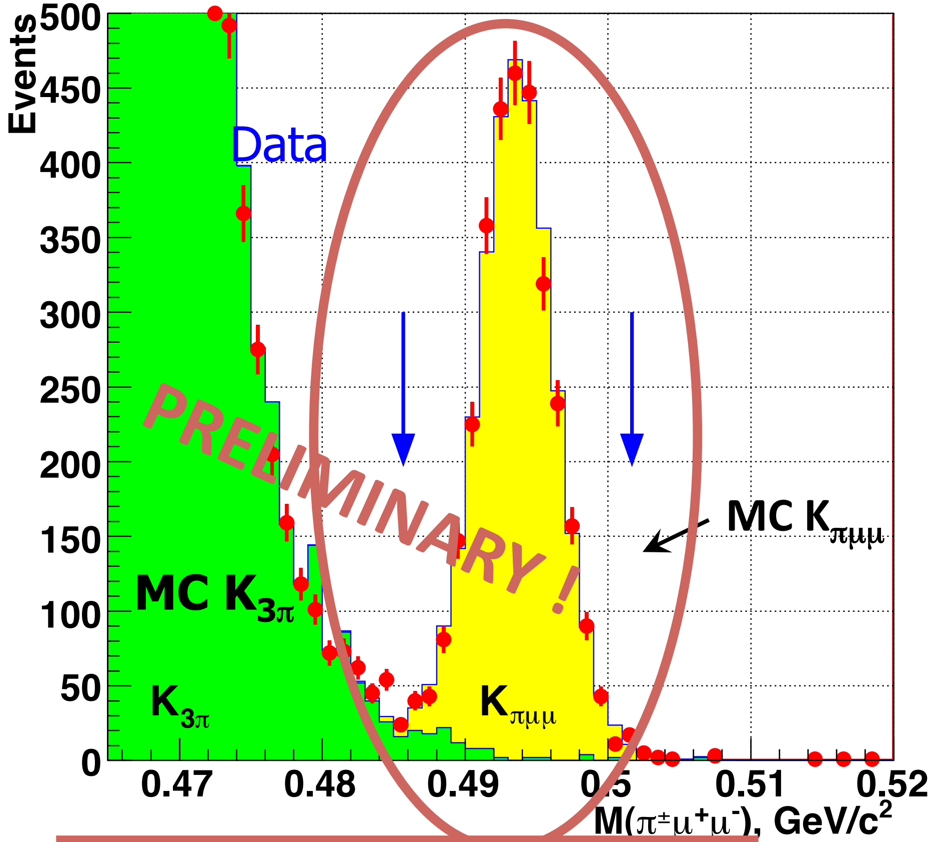
Measurement	events	BR×10⁷
Bloch et al., PL 56 (1975) B201	(41)	2.70±0.50
Alliegro et al.[E777], PRL 68 (1992) 278	(500)	2.75±0.26
Appel et al. [E865], PRL 83 (1999) 4482	(10000)	2.94±0.15
NA48/2 final (2009)	(7253)	3.11±0.12

- Form factor measurements for Model 1, 2 and 3* in agreement with previous measurements
- Model 4 – never tested before
- J.Prades, e-Print: arXiv:0707.1789 [hep-ph], predicts (up to its sign) $a_+ = -(0.6\ ^{+0.6}_{-0.23})$, in agreement with our result

*fit done by the authors of Model 3 using BNL E865 data

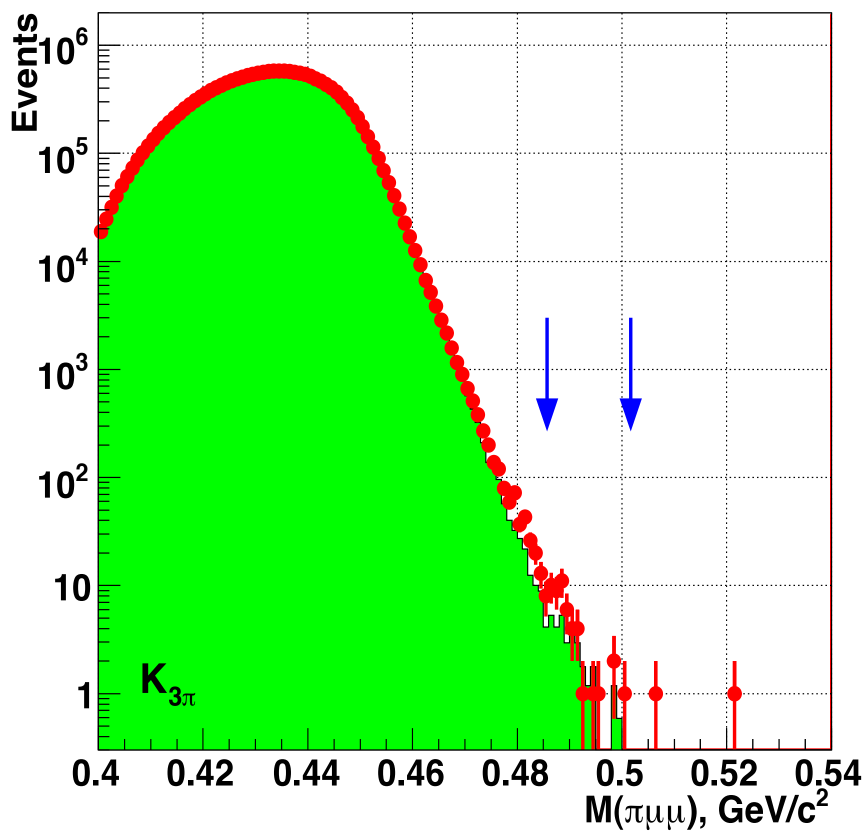
NA48/2: $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ - signal region and background

Data: Normal $\mu^{+}\mu^{-}$ candidates



3120 reconstructed events in the signal region:
4 times larger sample than the existing world statistics!

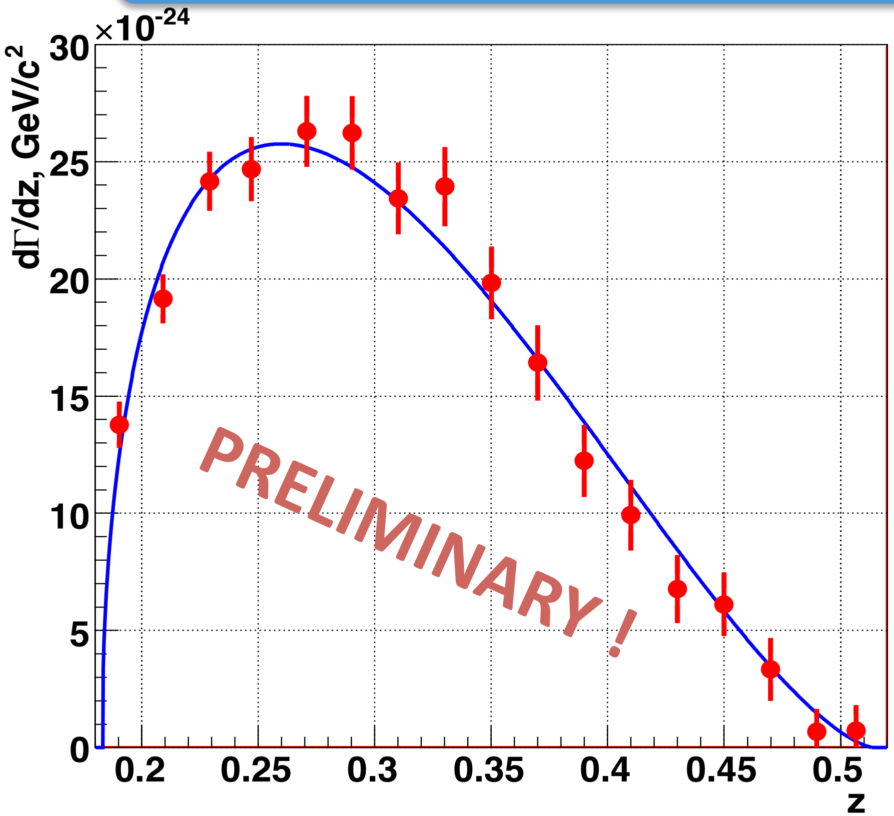
Same sign events



Good background control

$B/(S+B) = (3.3 \pm 0.5_{stat})\%$

NA48/2: : $K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$ - fit results



Linear
$f_0 = 0.470 \pm 0.039$
$\delta = 3.11 \pm 0.56$
$\chi^2/ndf = 12.0/15$

ChPT
$a_+ = -0.575 \pm 0.038$
$b_+ = -0.813 \pm 0.142$
$\chi^2/ndf = 14.8/15$

ChPT + large-N_c QCD
$w = 0.064 \pm 0.014$
$\beta = 3.77 \pm 0.61$
$\chi^2/ndf = 13.7/15$

"Meson" ChPT
$M_a = 1.014 \pm 0.090$
$M_\rho = 0.725 \pm 0.028$
$\chi^2/ndf = 15.4/15$

CPV charge asymmetry:
$\Delta(K^{\pm} \rightarrow \pi\mu\mu) = (1.1 \pm 2.3) \times 10^{-2}$

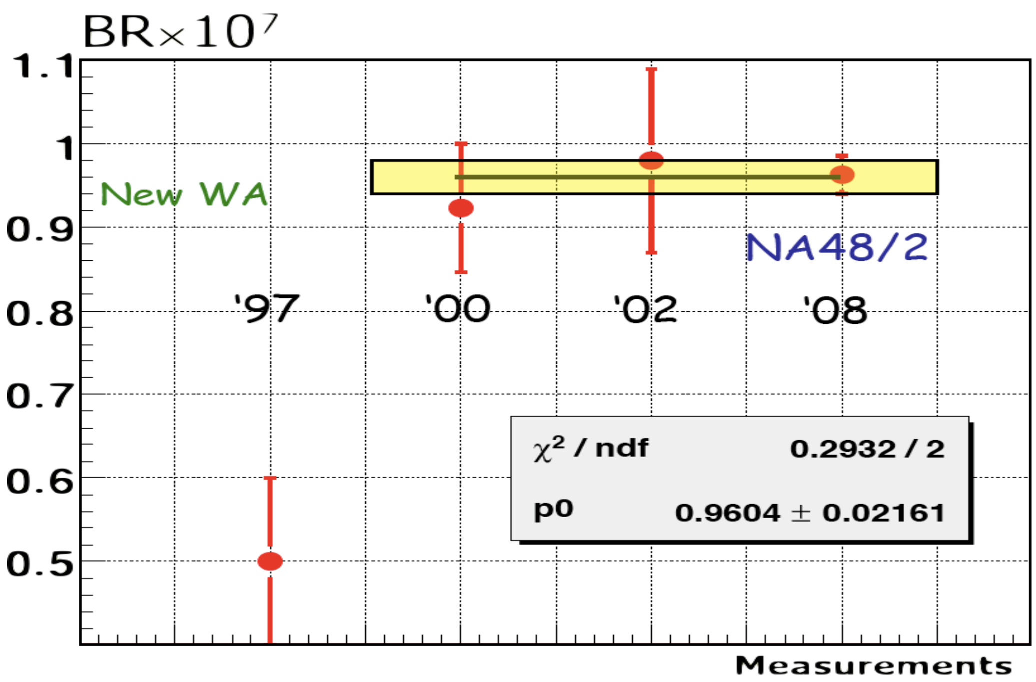
Forward-backward asymmetry:

$$A_{FB} = \frac{N(\cos\theta_{K\mu} > 0) - N(\cos\theta_{K\mu} < 0)}{N(\cos\theta_{K\mu} > 0) + N(\cos\theta_{K\mu} < 0)}$$

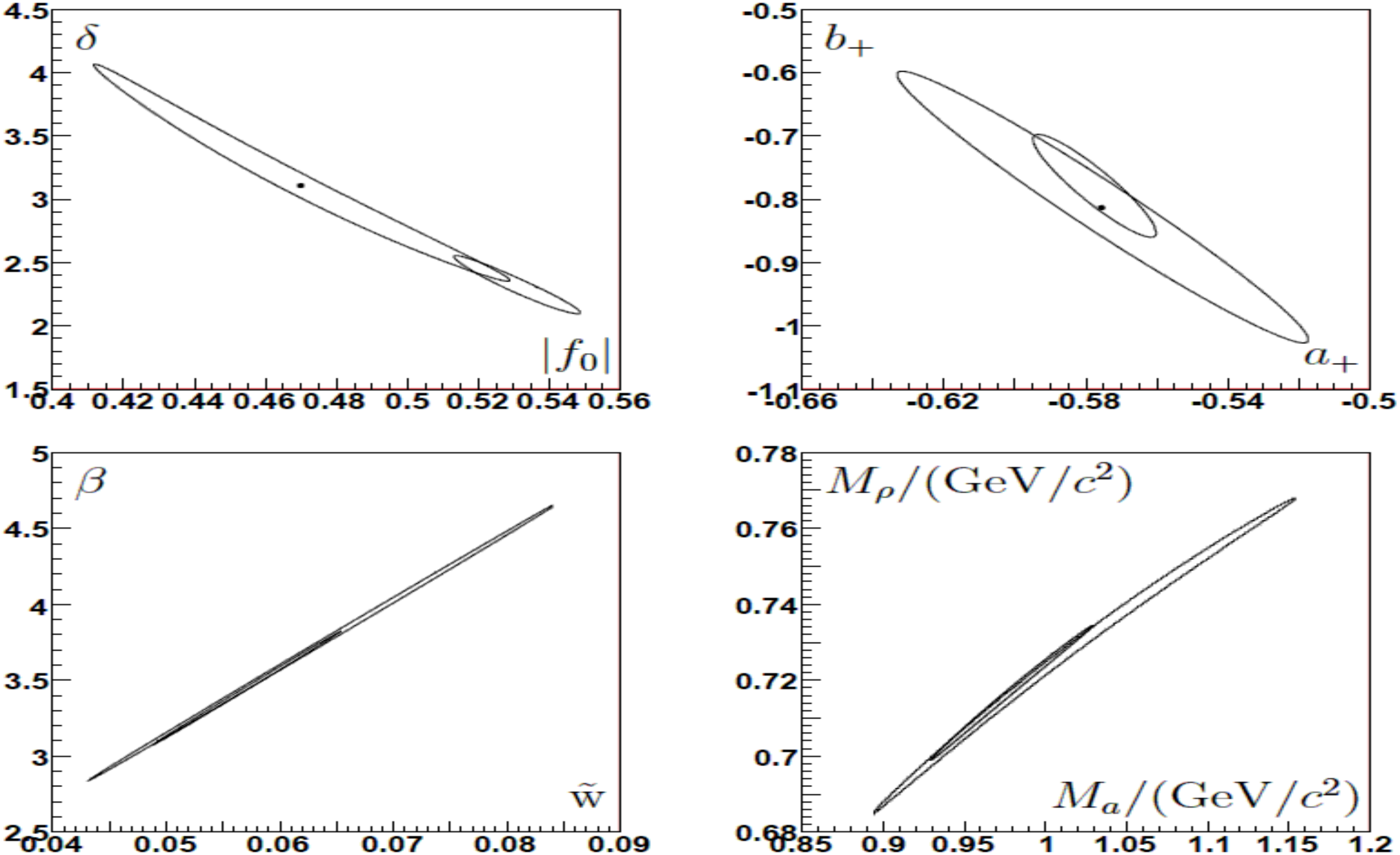
where $\Theta_{K\mu}$ is the angle between the kaon (or pion) and the opposite sign muon in dimuon rest frame.
$A_{FB} = (-2.4 \pm 1.8) \times 10^{-2}$

NA48/2: : $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ - comparison with previous measurements

Measurement	events	background	BR✖10^{8}
Adler et al. [E787], PRL 79 (1997) 2204	207	11%	5.0 ± 1.0
Ma et al. [E865], PRL 84 (2000) 2580	430	6.5%	9.22 ± 0.77
Park et al. [HyperCP], PRL 88 (2002) 111801	110	~3%	9.8 ± 1.1
NA48/2 (present analysis)	3120	3.3%	9.62 ± 0.23



NA48/2: Agreement between $K^{\pm} \to \pi^{\pm} e^{+} e^{-}$ and: $K^{\pm} \to \pi^{\pm} \mu^{+} \mu^{-}$



68% contours from K→πee and K→πμμ

Conclusions

- **Improved measurement of BR ($K_S \rightarrow \pi^+\pi^-e^+e^-$)/ BR($K_L \rightarrow \pi^+\pi^-\pi^0_D$) and of BR ($K_S \rightarrow \pi^+\pi^-e^+e^-$) with the 2002 data**

  New result !

  - Upper limit on g_{E1}/g_{BR} obtained
  - $A\varphi$ asymmetry consistent with zero.

    No CP-violating effect observed in the $K_S \rightarrow \pi^+\pi^-e^+e^-$ decay
  - All measurements indicate that the BR ($K_S \rightarrow \pi^+\pi^-e^+e^-$) decay can be well described by the Inner Bremsstrahlung process.
  - Paper prepared to submit to PLB

- **Precise measurement of $K^\pm \rightarrow \pi^\pm e^+e^-$**
  - Precision comparable with world's best;
  - BR and form factor measurements in agreement with ChPT and other measurements;
  - First limit on CPV asymmetry.
  - Paper published in PLB

- **Precise measurement of $K^\pm \rightarrow \pi^\pm \mu^+\mu^-$ - preliminary results**
  - Four times larger sample than the existing world statistics has been collected
  - Unprecedented precision achieved. Results in agreement with previous measurements and with NA48/2 results.
  - Limit on CPV asymmetry and forward back asymmetry.
  - Paper prepared to submit to PLB

BACK UP SLIDES

NA48/2 K→πμμ systematics

Model	Parameter	Statistical	Background	Muon ID	Pion ID	External
(1)	$\lvert f_0 \rvert$	0.036	0.014	0	0	0.002
	δ	0.52	0.20	0.01	0	0
(2)	a_+	0.034	0.017	0	0.002	0.002
	b_+	0.123	0.070	0.005	0.006	0.005
(3)	$\tilde{w}$	0.012	0.007	0	0.001	0
	β	0.54	0.29	0.02	0.02	0.02
(4)	M_a/GeV	0.070	0.044	0.002	0.001	0.001
	M_b/GeV	0.023	0.014	0.001	0.001	0.001
	$\mathrm{BR} \times 10^8$	0.20	0.04	0.04	0.08	0.07