Recent results on Rare Kaon Decays by the NA48 experiment at CERN

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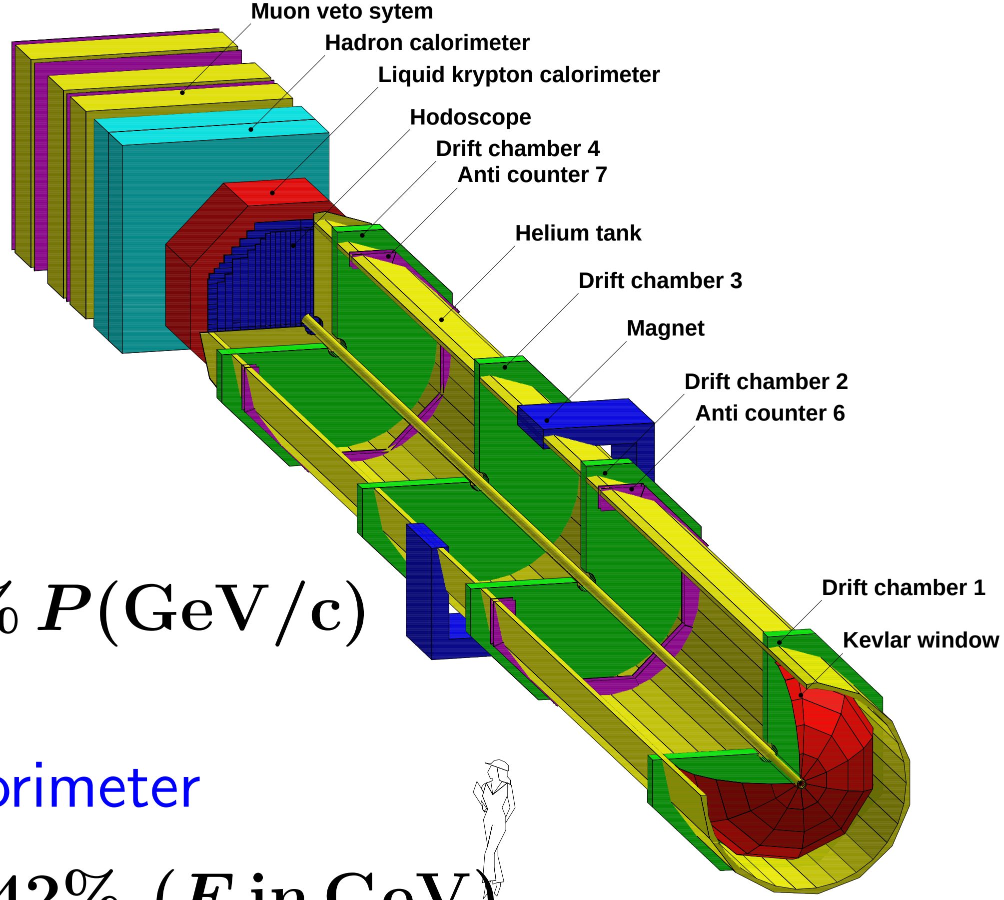
WIN'03 Workshop, Lake Geneva, WI, U.S.A.
October 6th - 11th, 2003

On behalf of the NA48 Collaboration:
Cagliari-Cambridge-CERN-Chicago-Dubna-Edinburgh-Ferrara-Firenze-Mainz-Northwestern-Orsay-Perugia-Pisa-Saclay-Siegen-Torino-Vienna-Warsaw

Outline

- NA48 Detector and Neutral Kaon Beam Lines
- $K_S \longrightarrow \pi^0 e^+ e^-$
- $K_S \longrightarrow \pi^0 \pi^0 \pi^0$
- $K_S \longrightarrow \pi^0 \gamma\gamma$
- $K_S \longrightarrow \gamma\gamma$
- $K_{L,S} \longrightarrow \pi^+ \pi^- e^+ e^-$
- Charged Kaon Decays
- Summary and Outlook

The NA48 Detector



Two main components:

- Magnetic Spectrometer*

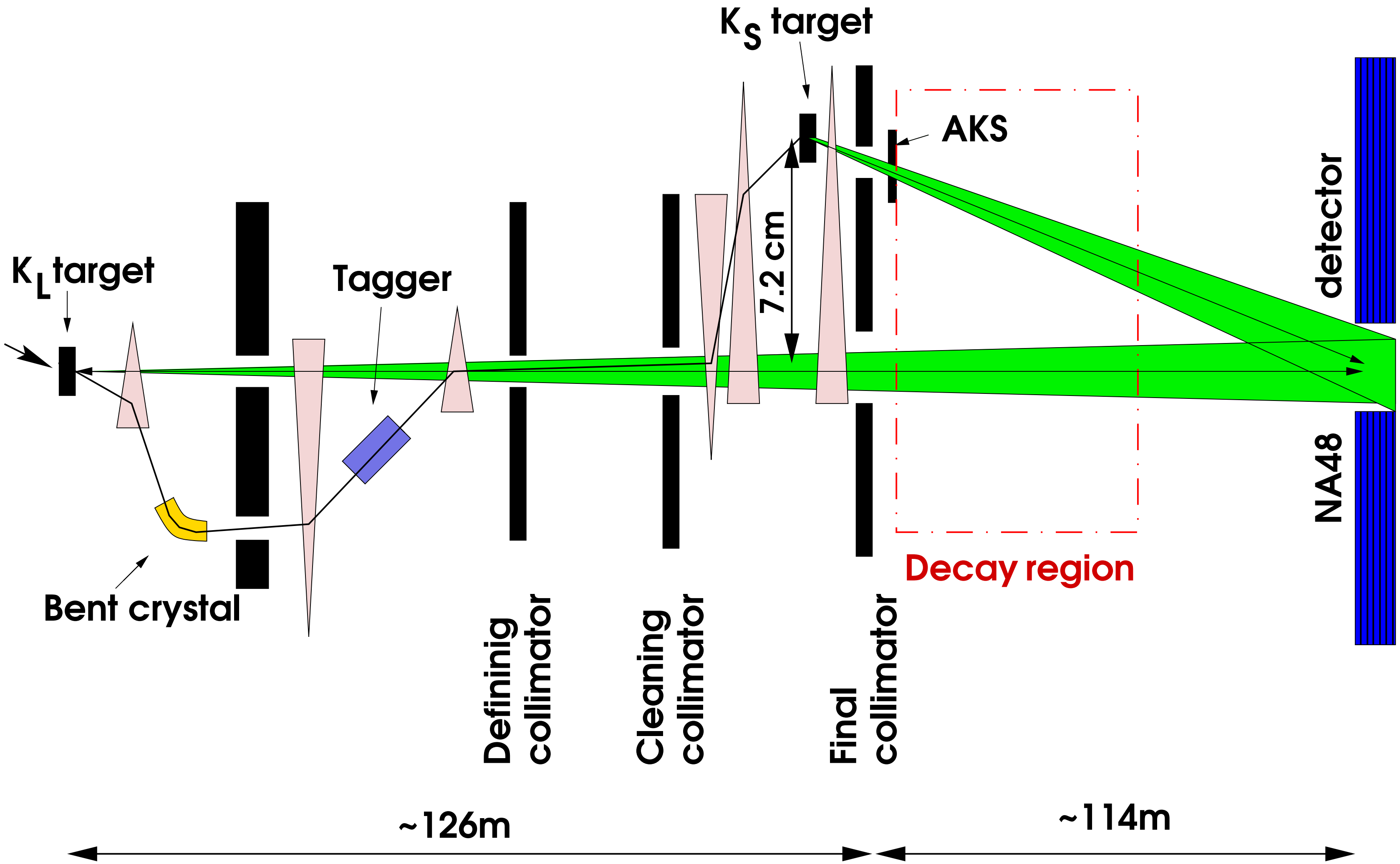
$$\frac{\sigma_P}{P} \simeq 0.5\% \oplus 0.009\%\, P(\mathrm{GeV/c})$$

- LKr Electromagnetic Calorimeter

$$\frac{\sigma_E}{E} \simeq \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\% \;\; (E\,\mathrm{in\,GeV})$$

* unavailable in 2000

The K_L and K_S beam lines



$$K_S \rightarrow \pi^0 e^+ e^-$$

$K_S \to \pi^0 e^+ e^-$

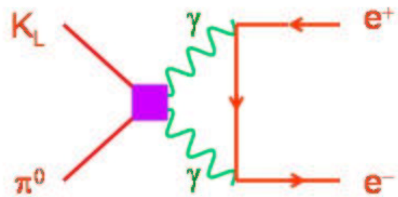
A measurement of the $K_S \to \pi^0 e^+ e^-$ decay allows to improve SM predictions of the CP violating part of the $K_L \to \pi^0 e^+ e^-$ decay rate...

The $K_L \to \pi^0 e^+ e^-$ decay amplitude has three components:

❖ CP conserving

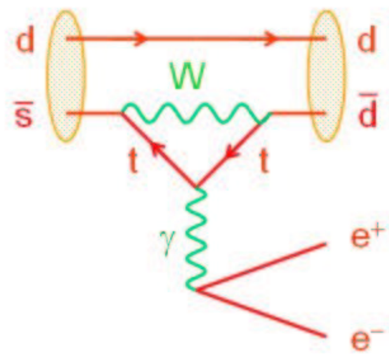
- dominated by the two-photon process $K_L \to \pi^0 \gamma^* \gamma^*$
- can be obtained from the low $m_{\gamma\gamma}$ tail in $K_L \to \pi^0 \gamma\gamma$
- NA48: BR$(K_L \to \pi^0 e^+ e^-)_{\text{CPC}} = 0.47^{+0.22}_{-0.18} \times 10^{-12}$

[PLB 536 (2002) 229]



❖ Direct CP violating

- probe of short-distance effects
- amplitude proportional to Im(λ_t)=Im$(V_{ts}^* V_{td})$
- expected BR$(K_L \to \pi^0 e^+ e^-)_{\text{CPV}^{\text{dir}}} \approx 2 - 3 \times 10^{-12}$



❖ Indirect CP violating

- BR$(K_L \to \pi^0 e^+ e^-)_{\text{CPV}^{\text{ind}}} = \frac{\tau_L}{\tau_S} |\varepsilon|^2 \text{BR}(K_S \to \pi^0 e^+ e^-)$

$K_S \to \pi^0 e^+ e^-$

Interference between direct and indirect CP violation amplitudes in the $K_L \to \pi^0 e^+ e^-$ *decay can give rise to sizeable effects...*

✦ Theoretical predictions:

$$\mathrm{BR}(K_L \to \pi^0 e^+ e^-)_{\mathrm{CPV}} \times 10^{12} = 15.3\, a_S^2 - 6.8 \left(\frac{\mathrm{Im}(\lambda_t)}{10^{-4}}\right) a_S + 2.8 \left(\frac{\mathrm{Im}(\lambda_t)}{10^{-4}}\right)^2$$

$$\mathrm{BR}(K_S \to \pi^0 e^+ e^-) \times 10^{9} = 5.2\, a_S^2 \qquad \text{with } a_S \sim \mathcal{O}(1)$$

[AEIP: G. D'Ambrosio, G. Ecker, G. Isidori and J. Portoles, JHEP 8 (1998) 4]*

✦ Experimental published limits (@ 90% CL):

$\mathrm{BR}(K_L \to \pi^0 e^+ e^-) < 5.1 \times 10^{-10}$ KTeV [PRL 86 (2001) 397]

$\mathrm{BR}(K_S \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7}$ NA48 [PLB 514 (2001) 253]

NA48/1 measures both $K_S \to \pi^0 e^+ e^-$ *and* $K_S \to \pi^0 \mu^+ \mu^-$ *modes (2002 data)...*

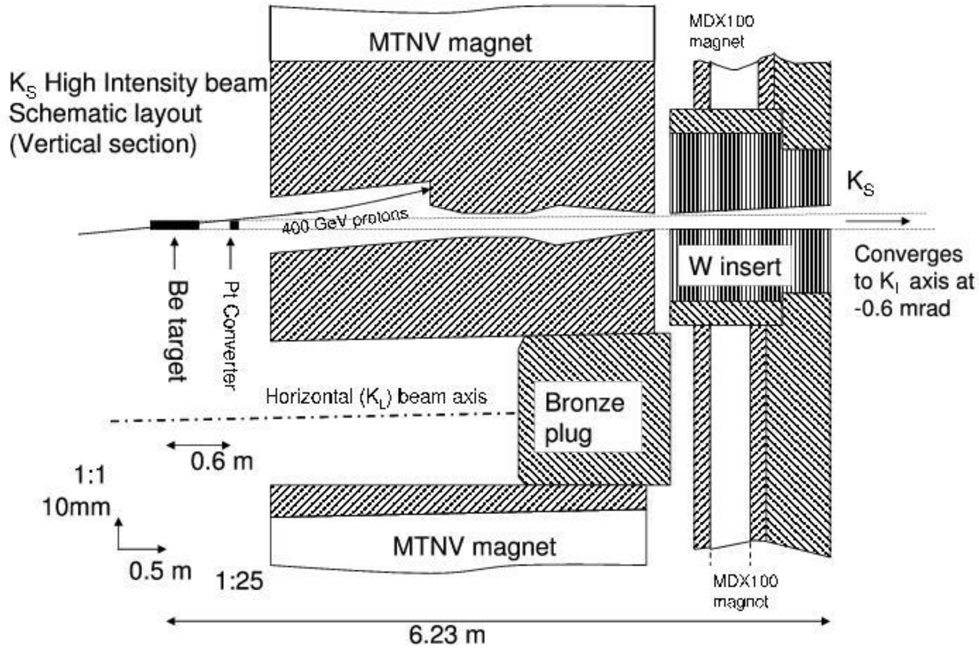
Theory: $\dfrac{\mathrm{BR}(K_S \to \pi^0 \mu^+ \mu^-)}{\mathrm{BR}(K_S \to \pi^0 e^+ e^-)} \simeq 0.23$ **in the VDM framework** [AEIP]

* *See also G. Buchalla, G. D'Ambrosio and G. Isidori, hep-ph/0308008 [BDI]*

$K_S \rightarrow \pi^0 e^+ e^-$

2002 High Intensity K_S run...

- 5×10^{10} p/spill (@ 400 GeV/c)
- spill: 4.8 s every 16.2 s
- 4.2 mrad production angle
- $4 \times 10^{10} K_S$ decays in 89 days
- modified K_S target+collimator region
- LKr and DCH read-out upgraded
- 50 K events/spill
- 40 Tbytes data volume



Trigger efficiency $> 99\%$ measured with $K_S \rightarrow \pi^0 \pi^0_D$ reconstructed decays.

$K_S \to \pi^0 e^+ e^-$

✦ Event selection

- Select candidates with $40 < E_K < 240$ GeV and $\tau < 2.5\,\tau_S$ of final collimator
- 4 in-time clusters in LKr with 2 tracks forming one good e^+e^- vertex
- Particle id.: $|E/P - 1| < 0.05$ and no signal in μVETO or HAC
- Energy COG at LKr < 6 cm from beam axis
- No extra in-time track or cluster
- $m_{ee\gamma\gamma} : m_K \pm 2.5\,\sigma_{m_K}$ assuming $\gamma\gamma$ pair originates from charged vertex
- $m_{\gamma\gamma} : m_{\pi^0} \pm 2.5\,\sigma_{m_{\pi^0}}$ assuming $\gamma\gamma$ pair originates from vertex imposing m_K

$$(\sigma_{m_K} = 4.6\,\text{MeV/c}^2 \quad \text{and} \quad \sigma_{m_{\pi^0}} = 1.0\,\text{MeV/c}^2)$$

✦ Background sources:

- $K_S \to \pi^0\pi^0_D$, $\pi^0\pi^0_D$ + conversion(s) , $\pi^0\pi^0_{DD}$, $\pi^0\pi^0(ee)$, $\pi^0_D\pi^0_D$
- $K_L \to ee\gamma\gamma$, $ee\gamma$ + bremsstrahlung , $\pi^0\pi^+\pi^-$, $\pi^0\pi^\pm e^\mp\nu$
- $\Xi^0 \to \Lambda(p\pi^-)\pi^0$, $\Lambda(pe^-\nu)\pi^0$, $\Sigma^+(p\pi^0)e^-\nu$
- Accidental activity: $\phi(K_S K_L)$, $K_L + K_S$ from different proton interactions

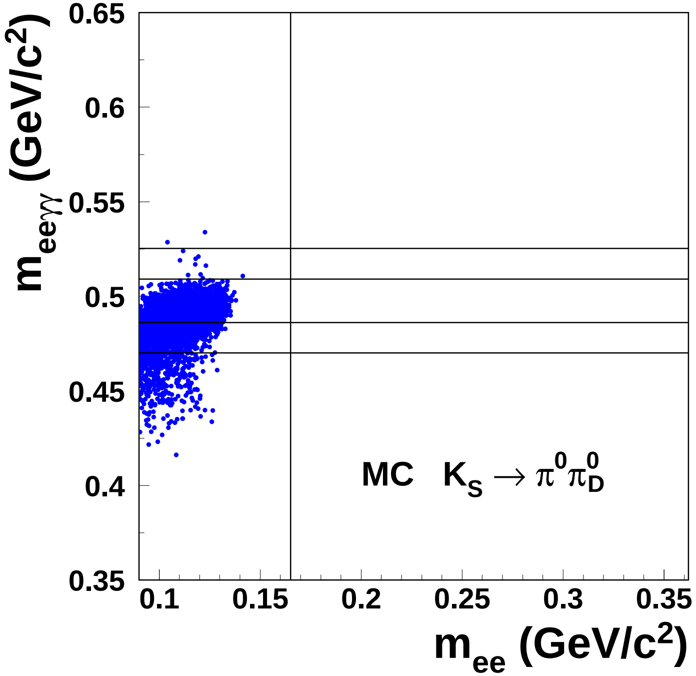
Perform blind analysis ... Keep expected background level in signal region small!

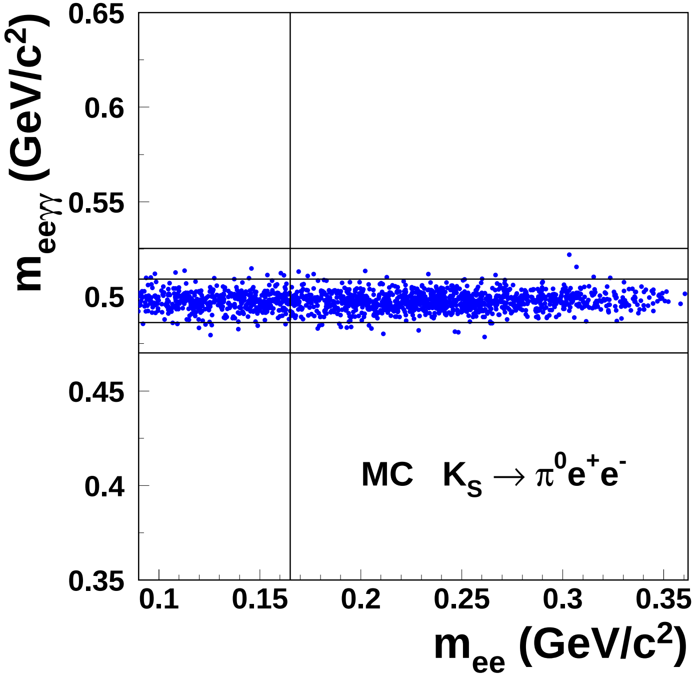
Signal region: $2.5\,\sigma_{m_K} \times 2.5\,\sigma_{m_{\pi^0}}$ **Control region:** $6.0\,\sigma_{m_K} \times 6.0\,\sigma_{m_{\pi^0}}$

$K_S \rightarrow \pi^0 e^+ e^-$

Reject huge $K_S \rightarrow \pi^0\pi^0_D(e^+e^-\gamma)$ *background* $(3 \times 10^8$ *in* $0 < \tau < 2.5\tau_S)$*:*

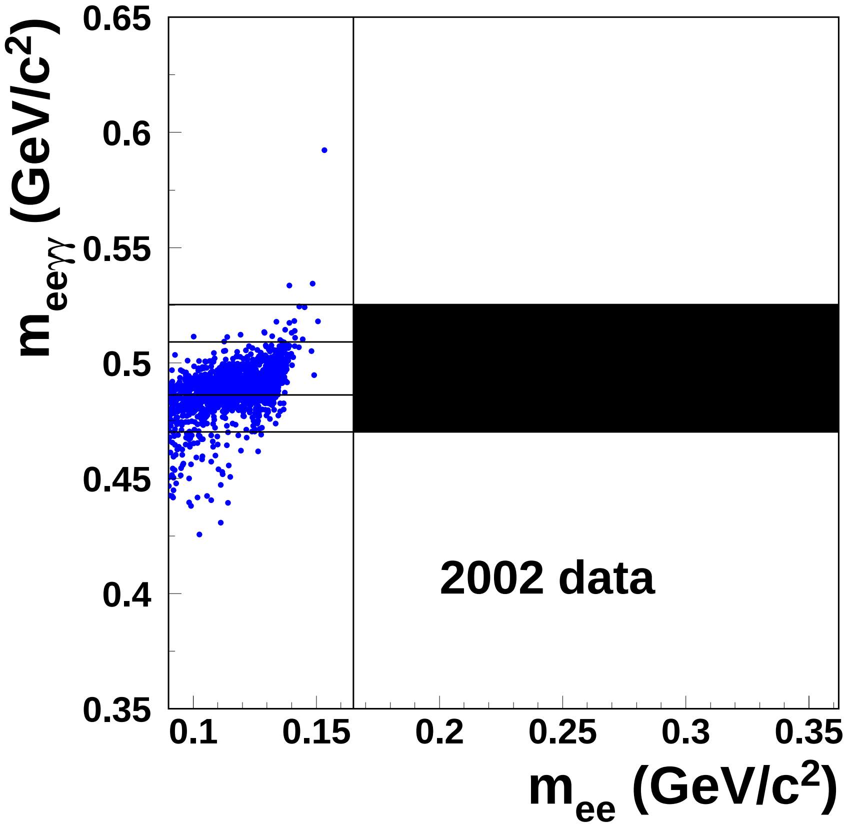
- $d_{ee}^{DCH1} > 2\,$cm to reject events with small θ_{ee}
- $m_{ee} > .165\,\mathrm{GeV/c^2}$ $(30\,\sigma_{m_{\pi^0}}$ above $m_{\pi^0})$

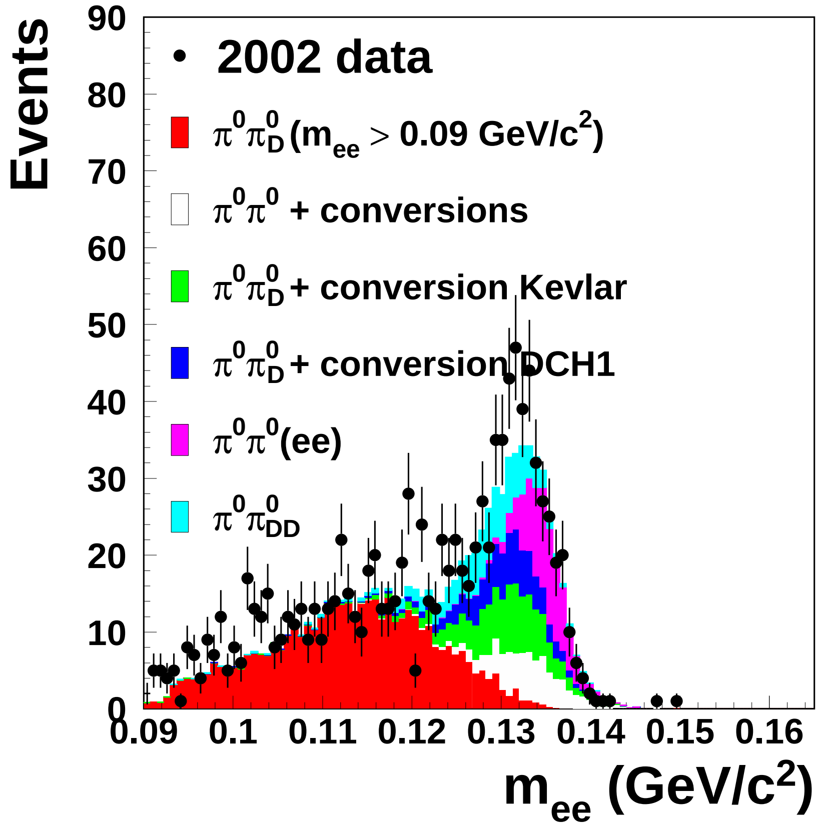




$K_S \to \pi^0 e^+ e^-$

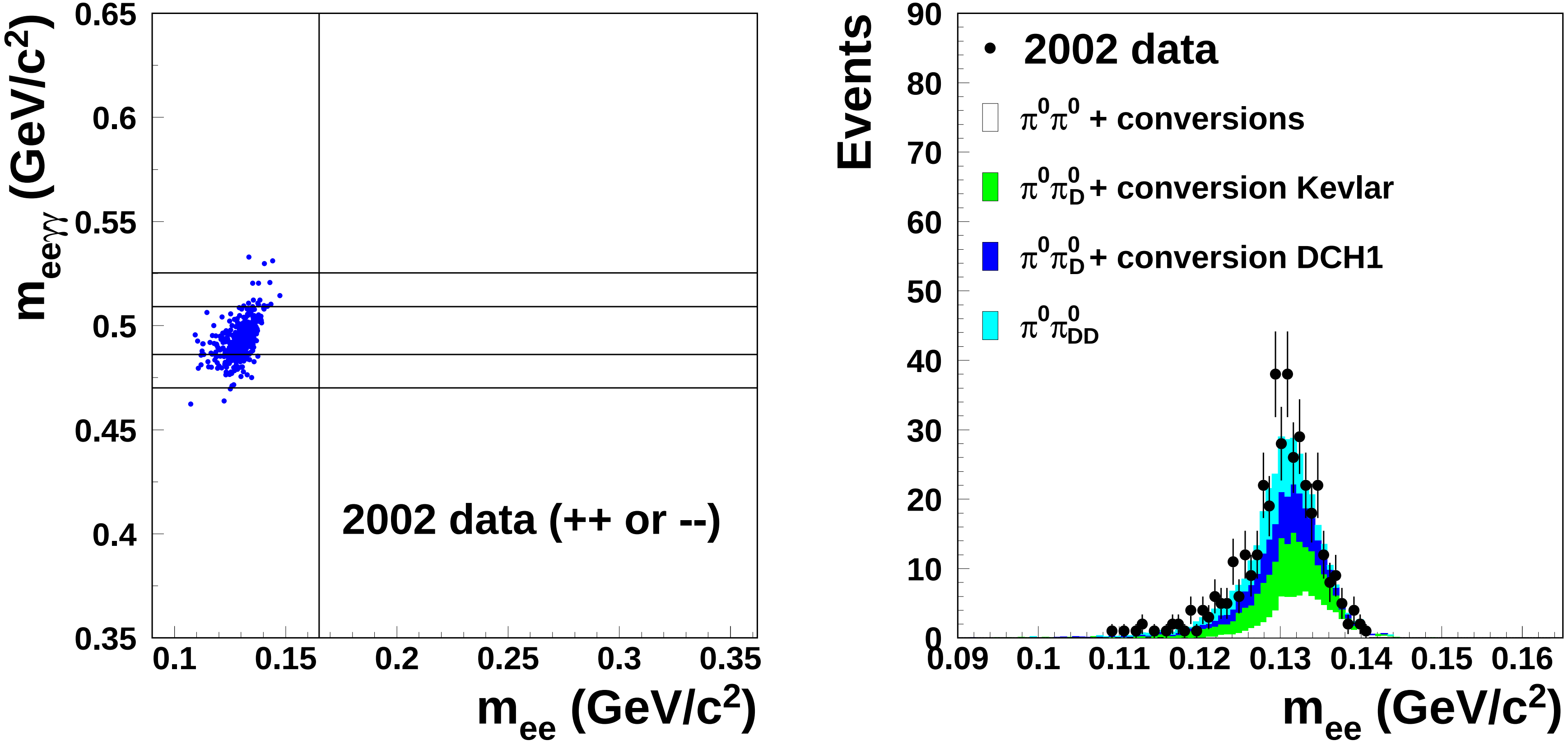
Background from $K_S \to \pi^0\pi^0_D$, $\pi^0\pi^0_{DD}$, $\pi^0\pi^0(ee)$, γ *conversions ...*





$K_S \to \pi^0 e^+ e^-$

Like-sign e^+e^+ or e^-e^- pairs ...

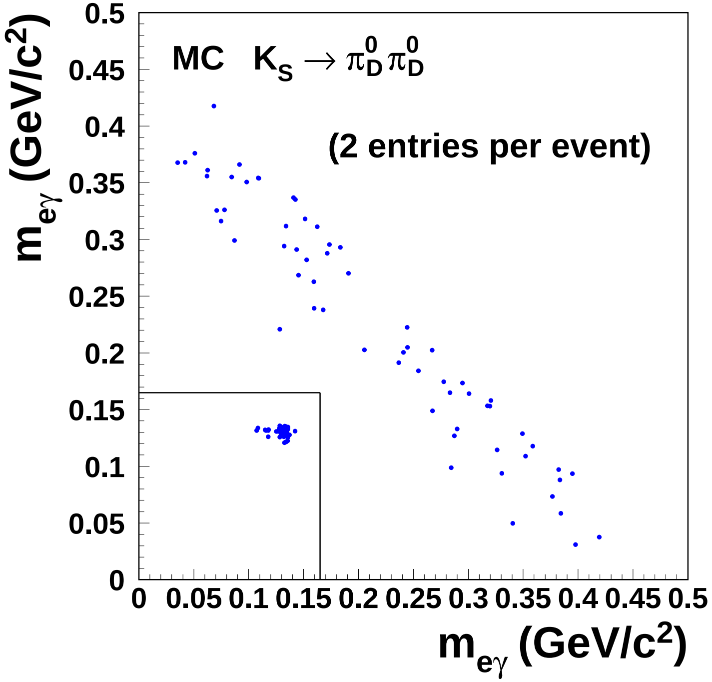


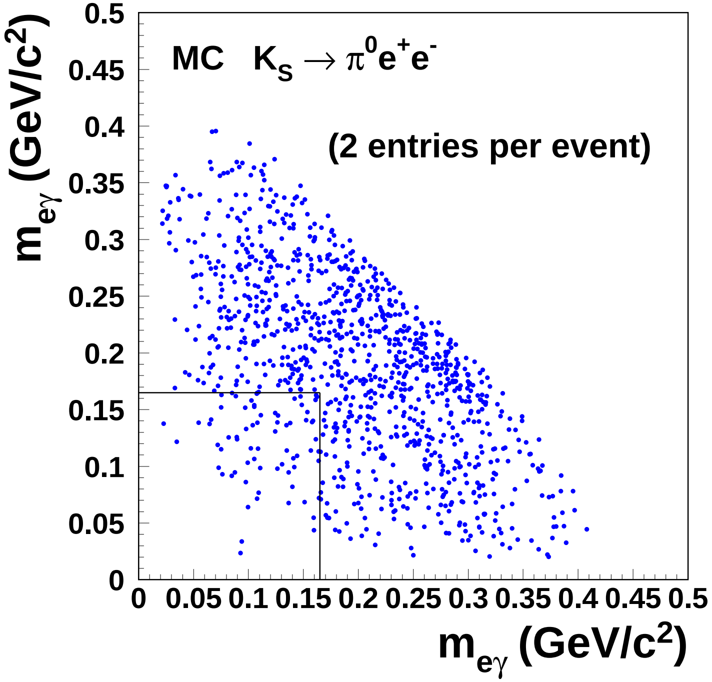
No event observed in signal and control regions ...

$K_S \to \pi^0 e^+ e^-$

Background from $K_S \to \pi^0_D \pi^0_D$ ...

Require $(m_{e\gamma}, m_{e\gamma}) > .165\,\mathrm{GeV/c^2}$ to reject low-energy e^+, e^- escaping detection $\Longrightarrow (m_{e\gamma}, m_{e\gamma}) \sim (m_{\pi^0}, m_{\pi^0})$ when $m_{ee\gamma\gamma} \sim m_K$



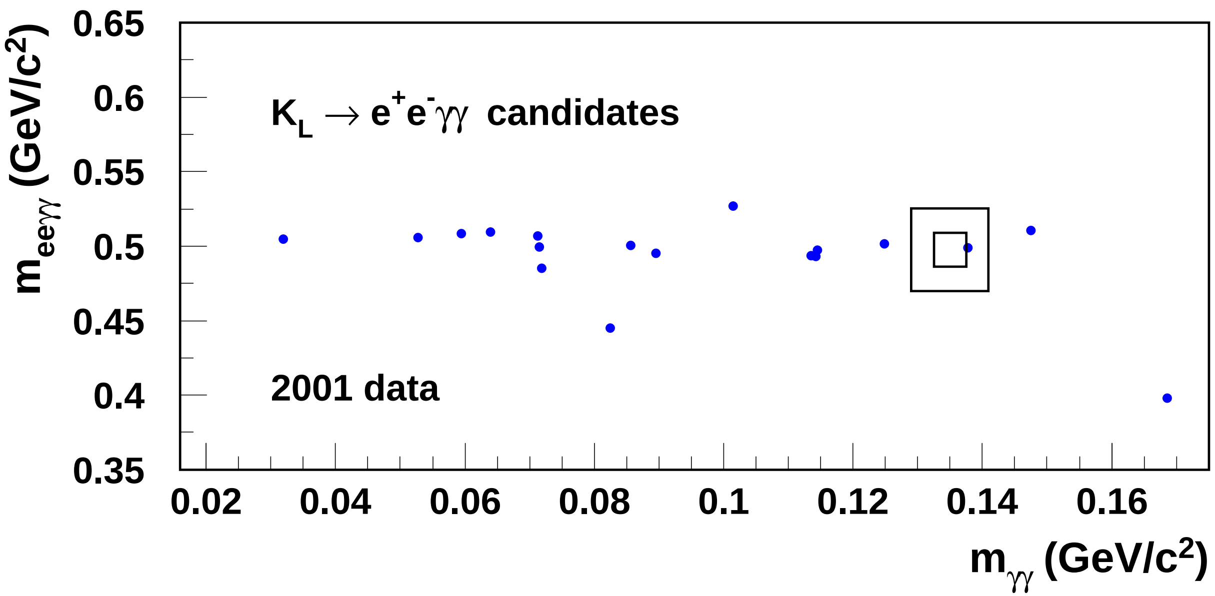


No event found in signal region from MC sample $\sim 30 \times 2002$ statistics (1 event in control region) ...

$K_S \to \pi^0 e^+ e^-$

Background from $K_{L,S} \to e^+e^-\gamma\gamma$ *...*

Estimated from $K_L \to e^+e^-\gamma\gamma$ decays with 2001 data
($\sim 10 \times 2002$ expected $e^+e^-\gamma\gamma$ statistics)

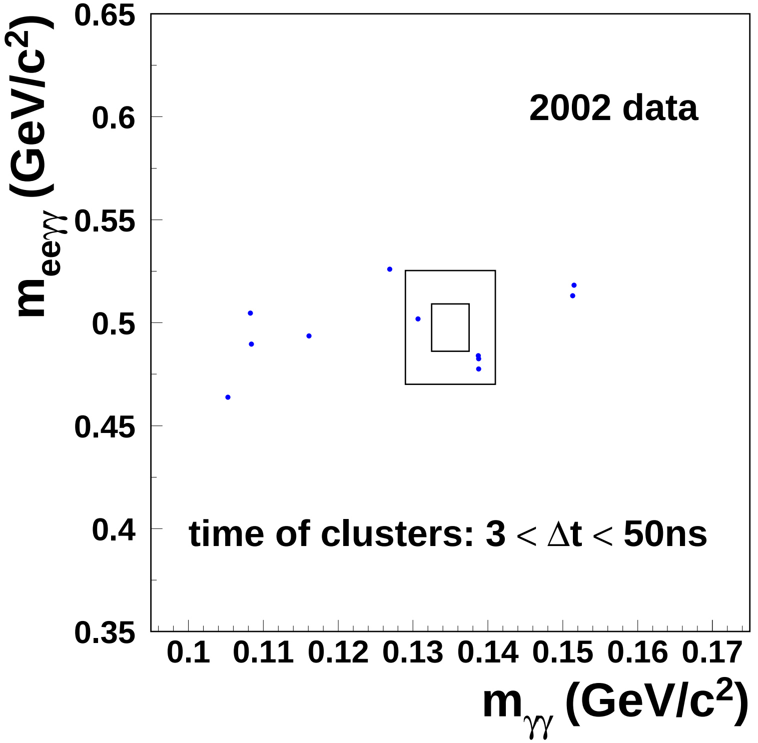


Background in the signal region: $0.08^{+0.03}_{-0.02}$ *event ...*

$K_S \to \pi^0 e^+ e^-$

Accidental activity ...

Estimated from events in $(\Delta t = |t_{ee} - t_{\gamma\gamma}|)$ time sidebands



Background in the signal region: $0.07^{+0.07}_{-0.03}$ *event ...*

$K_S \to \pi^0 e^+ e^-$

Summary of the most significant background contributions ...

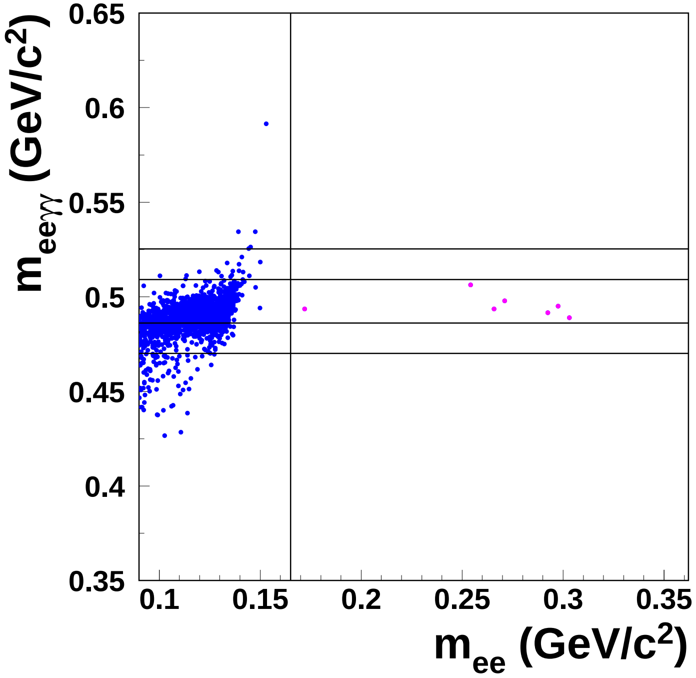
Background source	Control region	Signal region
$K_S \to \pi^0_D \pi^0_D$	0.03	< 0.01
$K_L \to ee\gamma\gamma$	0.11	$0.08^{+0.03}_{-0.02}$
Accidentals	0.19	$0.07^{+0.07}_{-0.03}$
Total	0.33	$0.15^{+0.10}_{-0.04}$

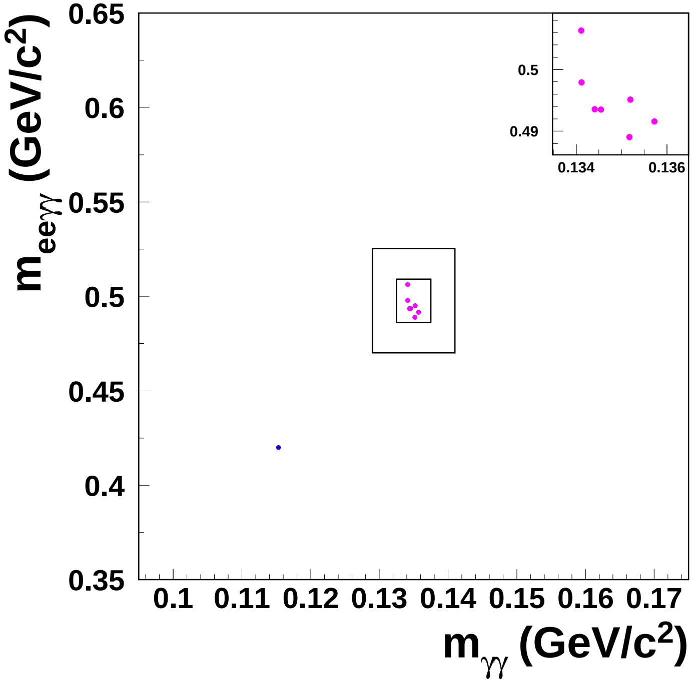
All other investigated sources of background were found to be negligible (e.g. $K_S \to \pi^0 \pi^0_D$, Ξ^0 decays, $K_L \to \pi^+\pi^-\pi^0$, ϕ decays, etc.).

Control and signal regions remained masked until the study of the background was completed ...

$K_S \rightarrow \pi^0 e^+ e^-$

Unmasking control and signal regions ...





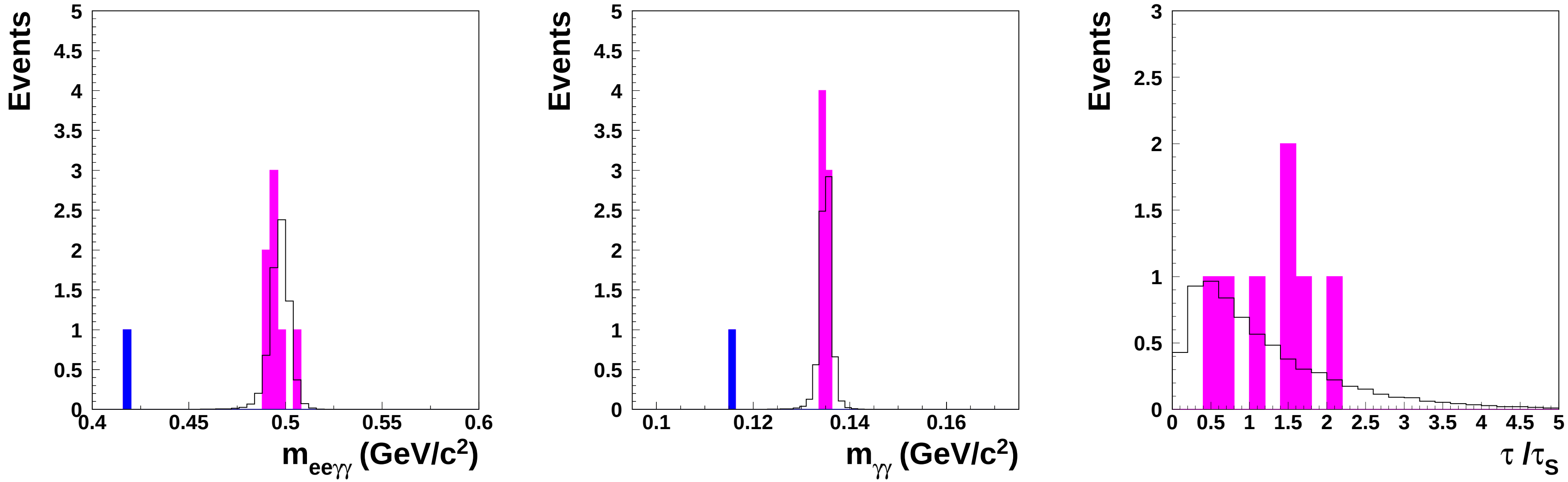
7 events in signal region (bkg.=0.15) and 0 in control region (bkg.=0.33)

Probability that all 7 events are background is $\sim 10^{-10}$

$\Longrightarrow$ *First observation of the decay* $K_S \rightarrow \pi^0 e^+ e^-$

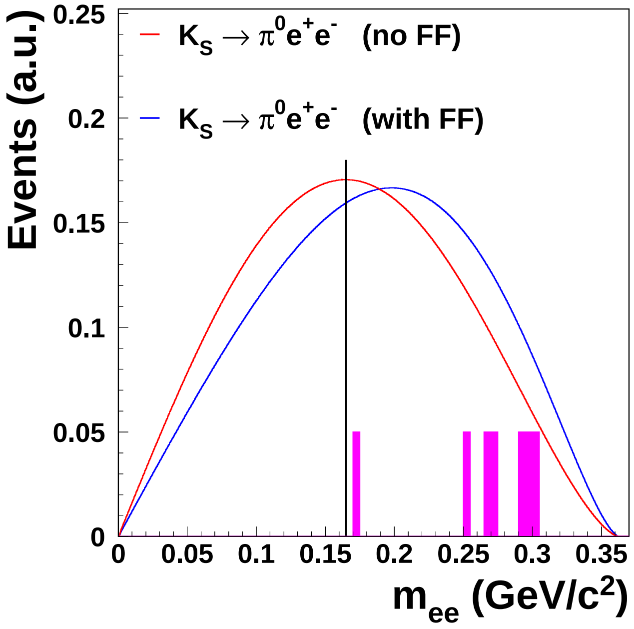
$K_S \rightarrow \pi^0 e^+ e^-$

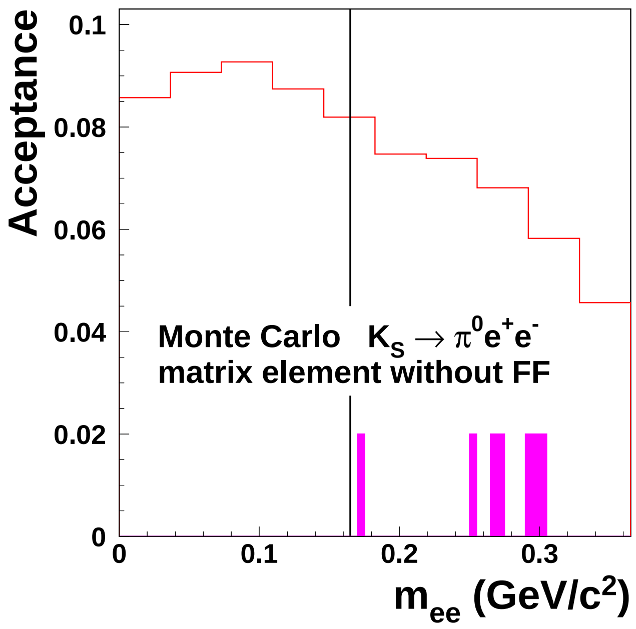
Data -vs- Monte Carlo ...



$K_S \rightarrow \pi^0 e^+ e^-$

Decay amplitude from χPT model of AEIP (vector interaction + FF)





$N_{\pi^0 ee} = 6.85^{+3.8}_{-1.8}$ K_S flux $= (3.51 \pm 0.17) \times 10^{10}$ (from $K_S \rightarrow \pi^0 \pi^0_D$ decays)

Acceptance (no FF)$= (6.6 \pm 0.4)\%$

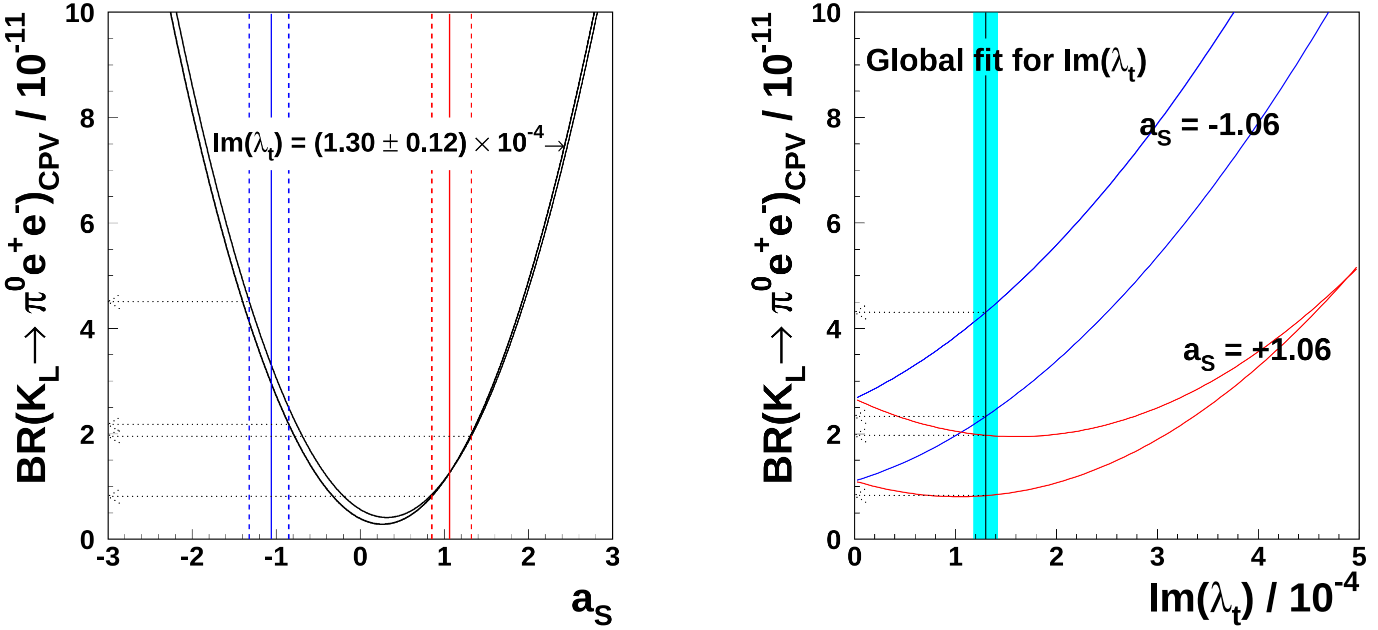
BR($K_S \rightarrow \pi^0 e^+ e^-, m_{ee} > 0.165$ GeV/c^2)$= (3.0^{+1.5}_{-1.2}\,_{stat} \pm 0.2\,_{syst}) \times 10^{-9}$

BR($K_S \rightarrow \pi^0 e^+ e^-$) $= (5.8^{+2.8}_{-2.3}\,_{stat} \pm 0.8\,_{syst}) \times 10^{-9}$

$$\Longrightarrow |a_S| = 1.06^{+0.26}_{-0.21}{}_{stat} \pm 0.07_{syst}$$

$K_S \to \pi^0 e^+ e^-$

Sensitivity of BR($K_L \to \pi^0 e^+ e^-$) to Im(λ_t) ...



$$\mathrm{BR}(K_L \to \pi^0 e^+ e^-)_{\mathrm{CPV}} \simeq (17.2_{\mathrm{indirect}} \pm 9.4_{\mathrm{interference}} + 4.7_{\mathrm{direct}}) \times 10^{-12}$$

$\mathrm{Im}(\lambda_t) = (1.30 \pm 0.12) \times 10^{-4}$ [S.H. Kettell, L.G. Landsberg and H. Nguyen, hep-ph/0212321]

If a_S is negative then BR($K_L \to \pi^0 e^+ e^-$) retains some sensitivity to Im(λ_t) through the interference term ...

A measurement of BR($K_S \to \pi^0 \mu^+ \mu^-$) by NA48/1 will come soon!

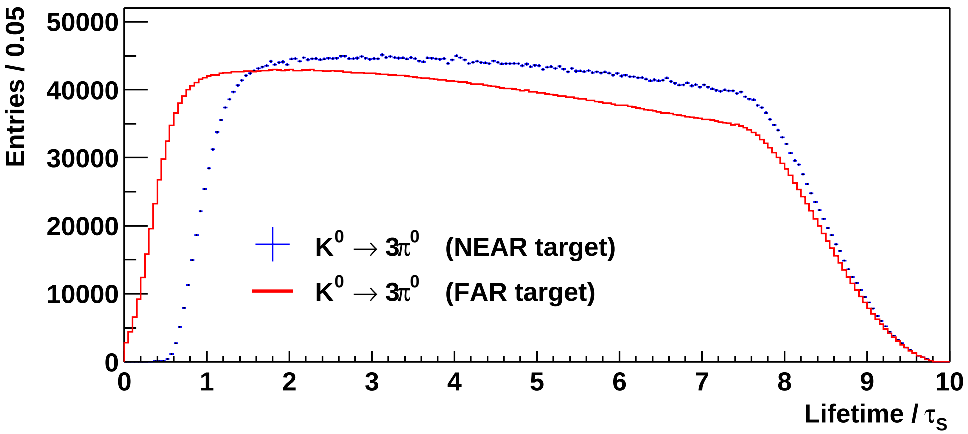
$$K_S \rightarrow \pi^0\pi^0\pi^0$$

$K_S \rightarrow \pi^0\pi^0\pi^0$

$$\eta_{000} = \frac{A(K_S\rightarrow\pi^0\pi^0\pi^0)}{A(K_L\rightarrow\pi^0\pi^0\pi^0)}$$

If CPT conserved: $\eta_{000}=\varepsilon + i\frac{\text{Im}(A_1)}{\text{Re}(A_1)}$

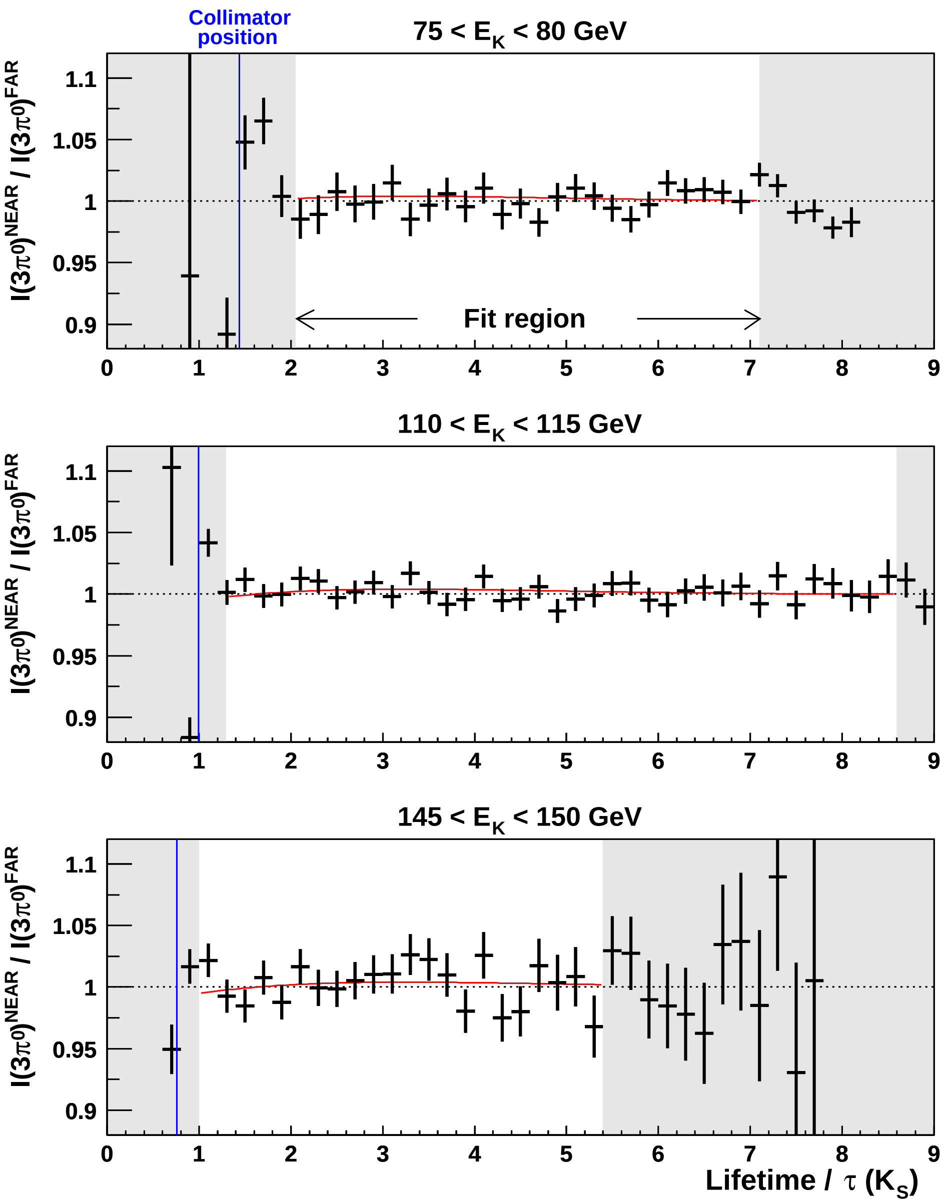
- **2000 NEAR target data**
  - 5.9×10^6 $3\pi^0$ events
- **2000 FAR target data**
  - 1.3×10^8 $K_L \rightarrow 3\pi^0$ decays
  - 1^{st} order accept. corr.
- **Monte Carlo**
  - 2^{nd} order accept. corr.
- **Analysis in energy bins**



$$f(E,t) = \frac{I^{NEAR}_{3\pi^0}}{I^{FAR}_{3\pi^0}} = A(E)[1 + |\eta_{000}|^2\, e^{(\Gamma_L-\Gamma_S)\,t} +$$
$$2D(E)\,(\text{Re}(\eta_{000})cos\Delta m\, t - \text{Im}(\eta_{000})sin\Delta m\, t)\, e^{\frac{1}{2}\,(\Gamma_L-\Gamma_S)\,t}]$$

Fit parameters $A(E)$, $\text{Re}(\eta_{000})$, $\text{Im}(\eta_{000})$ $\quad$ $D(E)$: K^0-$\overline{K^0}$ dilution (from NA31)

$K_S \to \pi^0\pi^0\pi^0$



- **Extract** $\mathrm{Re}(\eta_{000})$ **and** $\mathrm{Im}(\eta_{000})$ **from a fit in energy bins:**

$$(70 < E < 170\,\mathrm{GeV})$$

$$\mathrm{Re}(\eta_{000}) = -0.026 \pm 0.010_{stat}$$
$$\mathrm{Im}(\eta_{000}) = -0.034 \pm 0.010_{stat}$$

$$\rho = 0.78 \qquad \chi^2/ndf = 415/405$$

- **Systematics:**

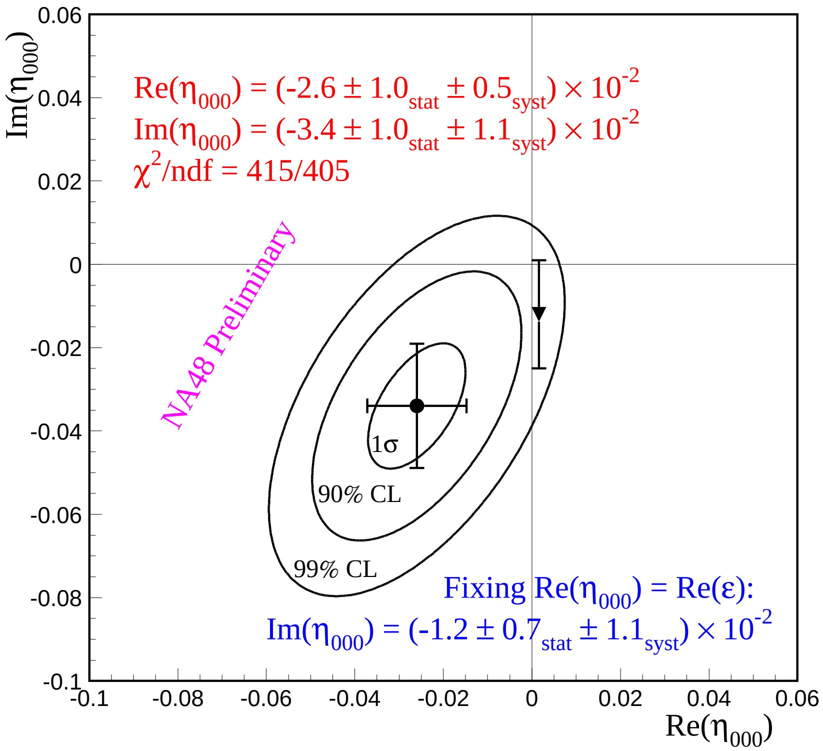
Source	$\mathrm{Re}(\eta_{000})$	$\mathrm{Im}(\eta_{000})$
Acceptance	$\pm$ 0.003	$\pm$ 0.003
Accid. activity	$\pm$ 0.001	$\pm$ 0.006
Energy scale	$\pm$ 0.001	$\pm$ 0.001
$K^0\overline{K^0}$ dilution	$\pm$ 0.003	$\pm$ 0.004
Fit	$\pm$ 0.001	$\pm$ 0.002
Total	$\pm$ 0.005	$\pm$ 0.011

- **NA48 Preliminary Result:**

$$\mathrm{Re}(\eta_{000}) = -0.026 \pm 0.010_{stat} \pm 0.005_{syst}$$
$$\mathrm{Im}(\eta_{000}) = -0.034 \pm 0.010_{stat} \pm 0.011_{syst}$$

$K_S \rightarrow \pi^0\pi^0\pi^0$

NA48 Preliminary Results



CPLEAR (1998):

$Re(\eta_{000}) = (18 \pm 14_{stat} \pm 6_{syst}) \times 10^{-2}$

$Im(\eta_{000}) = (15 \pm 20_{stat} \pm 3_{syst}) \times 10^{-2}$

$Im(\delta) = (2.4 \pm 5.0) \times 10^{-5}$

SND (1999):

$BR(K_S \rightarrow \pi^0\pi^0\pi^0) < 1.4 \times 10^{-5}$ 90% CL

- **If $Re(\eta_{000}) = Re(\varepsilon)$ (CPT):**

$BR(K_S \rightarrow \pi^0\pi^0\pi^0) < 3.0 \times 10^{-7}$ 90% CL

- **CPT test (BS unitarity relation):**

$$(1 + i \tan\phi_{SW})[Re(\varepsilon) - i\, Im(\delta)] = \sum_f \alpha_f$$

α_f	$10^3 \times Re(\alpha_f)$	$10^3 \times Im(\alpha_f)$
α_{+-}	1.136 ± 0.013	1.071 ± 0.013
α_{00}	0.517 ± 0.010	0.486 ± 0.010
$\alpha_{+-\gamma}$	0.003 ± 0.001	0.003 ± 0.000
α_{l3}	0.004 ± 0.003	0.003 ± 0.004
α_{+-0}	0.000 ± 0.002	0.000 ± 0.004
α_{000}	0.029 ± 0.040	-0.026 ± 0.058

- **NA48:**

$Re(\alpha_{000}) = (-0.009 \pm 0.004) \times 10^{-3}$

$Im(\alpha_{000}) = (\ \ 0.012 \pm 0.005) \times 10^{-3}$

$\Longrightarrow \quad Im(\delta) = (-1.2 \pm 3.0) \times 10^{-5}$

If CPT is conserved in the decay:

$m_{K^0} - m_{\overline{K^0}} = (-1.7 \pm 4.2) \times 10^{-19}$ GeV/c²

$K_S \rightarrow \pi^0\gamma\gamma$

$K_S \to \pi^0\gamma\gamma$

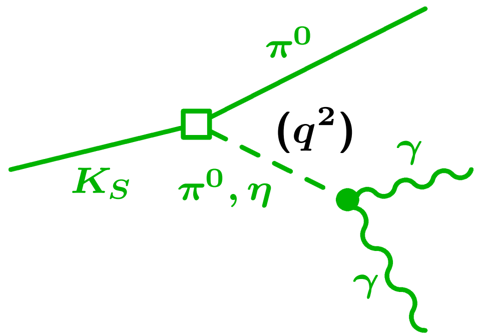
- **χPT predictions:**

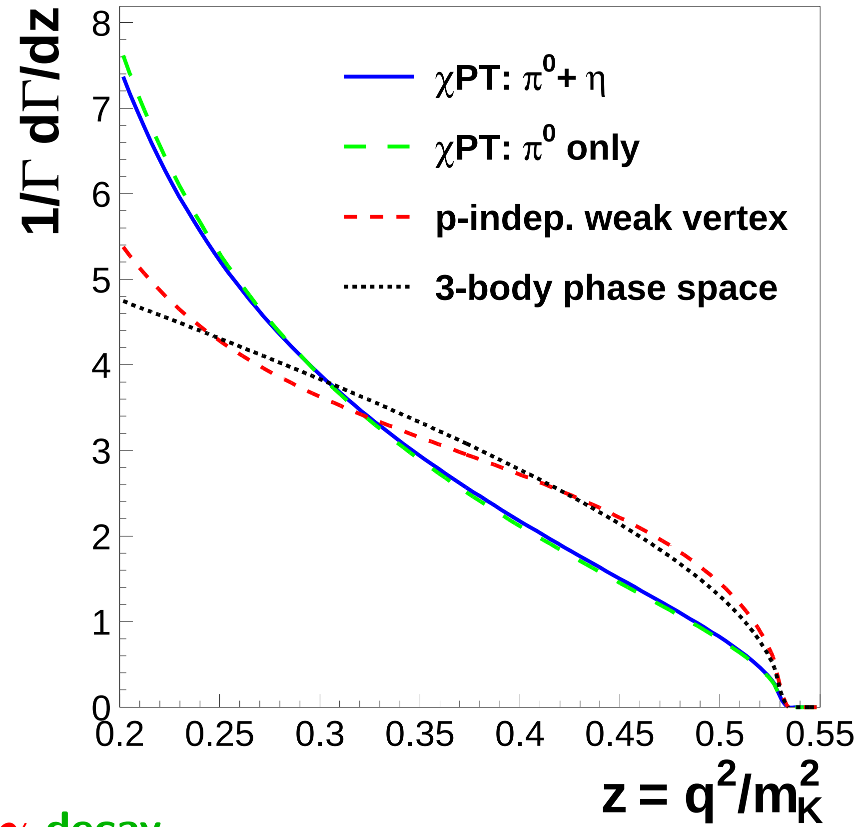
  - BR($K_S \to \pi^0\gamma\gamma$)$_{z>0.2} = 3.8\times10^{-8}$

    [G. Ecker, A. Pich, E. de Rafael, PLB 189 (1987) 363]

  - total rate dominated by the π^0 pole
  - momentum dependent weak vertex

$\Longrightarrow$ Chiral structure of the weak vertex can be tested from the shape of the $z = (m_{34}/m_K)^2$ distribution





- **NA48/1:**

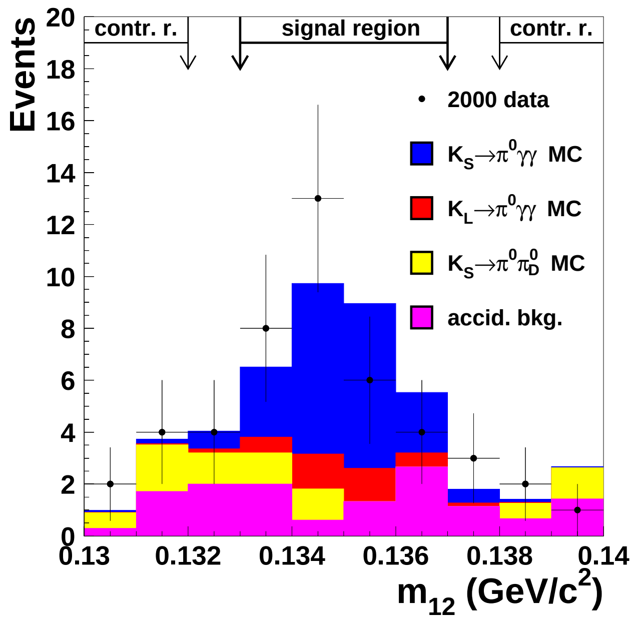
  - 2000 NEAR target data
  - $K_S \to \pi^0\pi^0$ decays as normalization

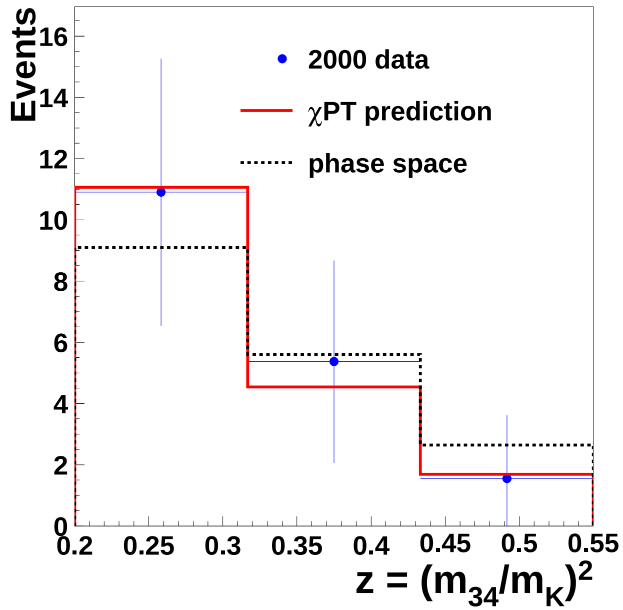
$\Longrightarrow$ First observation of the $K_S \to \pi^0\gamma\gamma$ decay

$K_S \to \pi^0\gamma\gamma$

31 candidates observed in signal region

($|m_{12} - m_{\pi^0}| < 2$ MeV/c^2 and $z > 0.2$)





Background	Events
$K_L \to \pi^0\gamma\gamma$	3.8 ± 0.2
$K_S \to \pi^0\pi^0_D$	2.4 ± 1.2
Hadrons	0.1 ± 0.1
Accidentals	6.8 ± 2.9
$K_S \to \pi^0 e^+ e^-$	0.6 ± 0.3
Total	13.7 ± 3.2

BR$(K_S \to \pi^0\gamma\gamma)_{z>0.2}$=$(4.9 \pm 1.6_{stat} \pm 0.9_{syst}) \times 10^{-8}$

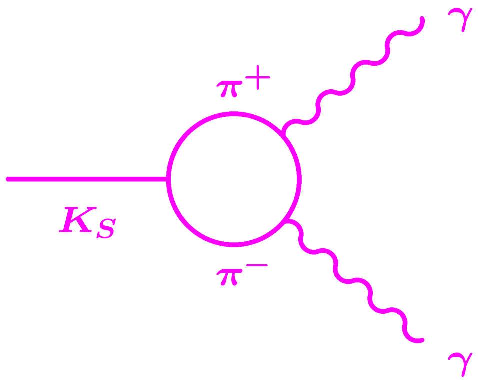
BR$(K_S \to \pi^0\gamma\gamma)_{z>0.2}$=$(4.9 \pm 1.8) \times 10^{-8}$

in agreement with χPT ... but more statistics needed

to check the chiral structure of the weak vertex ...

$$K_S \to \gamma\gamma$$

$K_S \to \gamma\gamma$



❖ χPT:

- Unambiguous and clean $\mathcal{O}(p^4)$ prediction
- BR($K_S \to \gamma\gamma$) $= 2.1 \times 10^{-6}$

  [G. D'Ambrosio and D. Espriu, PLB 175 (1986) 237]

  [J.L. Goity, ZPC 34 (1987) 341]

❖ NA48/1:

- 2000 **NEAR** target data (normalize to $K_S \to \pi^0\pi^0$ decays)
- Choose decays close to collimator exit to reject background from $K_S \to \pi^0\pi^0$ with only 2 showers in LKr calorimeter

  $\Longrightarrow$ Reconstructed vertex moves downstream due to missing energy

- 2000 **FAR** target data to measure $\frac{\mathrm{BR}(K_L \to \gamma\gamma)}{\mathrm{BR}(K_L \to 3\pi^0)}$ and to estimate the irreducible $K_L \to \gamma\gamma$ background:

$$\frac{\mathrm{BR}(K_L \to \gamma\gamma)}{\mathrm{BR}(K_L \to 3\pi^0)} = (2.81 \pm 0.01_{stat} \pm 0.02_{syst}) \times 10^{-3}$$

$K_S \to \gamma\gamma$

$$\mathrm{BR}(K_S \to \gamma\gamma) = (2.78 \pm 0.06_{stat} \pm 0.03_{syst} \pm 0.02_{norm}) \times 10^{-6}$$

- **NA48/1 result:**

  $\mathrm{BR}(K_S \to \gamma\gamma) = (2.78 \pm 0.07) \times 10^{-6}$

- **Much more precise than previous measurements:**

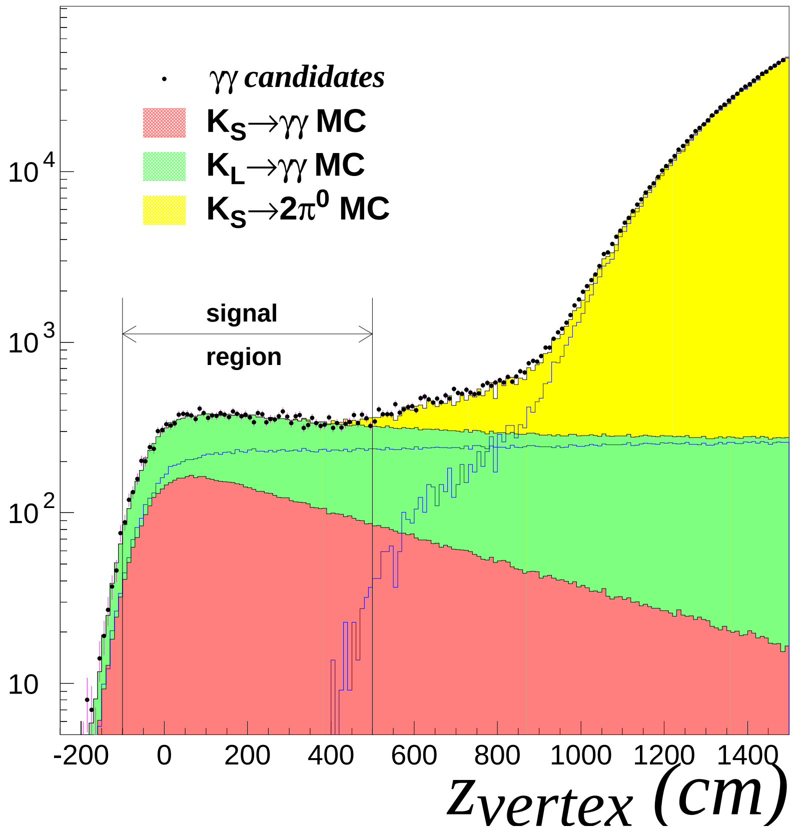
  - **NA48 (1999):** $(2.58 \pm 0.42) \times 10^{-6}$
  - **NA31:** $(2.4 \pm 0.9) \times 10^{-6}$

- **Decay rate larger by 30% w.r.t. $\mathcal{O}(p^4)$ prediction of χPT**

$\Longrightarrow$ **Indication of a large $\mathcal{O}(p^6)$ contribution:**

$$\frac{8m_K^2}{F_\pi^2}\, a_1 = 1.0 \pm 0.3 \quad \text{[BDI]}$$

7461 ± 172 $K_S \to \gamma\gamma$ decays



$$K_{L,S} \rightarrow \pi^+\pi^-e^+e^-$$

$K_{L,S} \rightarrow \pi^+\pi^-e^+e^-$

- $K_L \rightarrow \pi^+\pi^-e^+e^-$

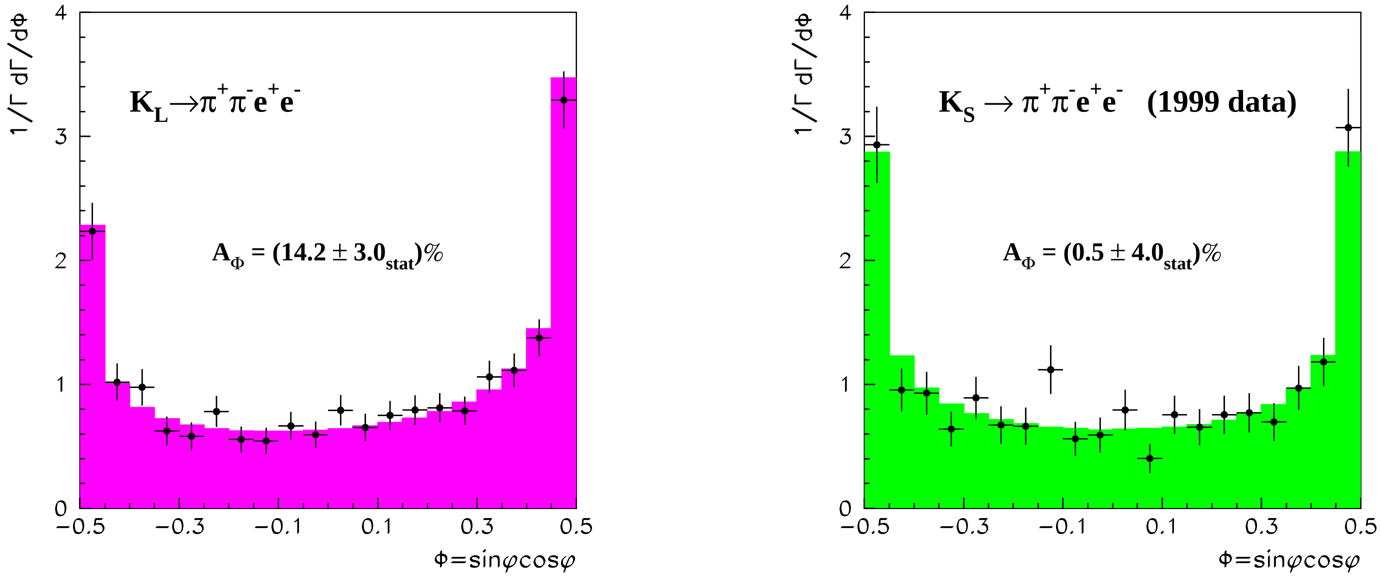
  The interference between the dominant M1 (CP=-1) and IB (CP=+1) components gives rise to a large CP-violating asymmetry ($\mathcal{A}_\phi \sim 14\%$) in the ϕ distribution between the $\pi^+\pi^-$ and e^+e^- planes in the kaon c.m.

  [P. Heiliger and L.M. Sehgal, PRD 48 (1993) 4146]

- $K_S \rightarrow \pi^+\pi^-e^+e^-$

  Mainly due to IB ... no such asymmetry expected ...

1998+1999 NA48 data



$\mathcal{A}_\phi \neq 0$ *is an unambiguous signature of CP violation*

$K_{L,S} \to \pi^+\pi^-e^+e^-$

NA48 Final Results [EPJC 30 (2003) 33]

- $K_S \to \pi^+\pi^-e^+e^-$ (1998+1999 data) 56+621 candidates

$$\text{BR}(K_S \to \pi^+\pi^-e^+e^-) = (4.69 \pm 0.30) \times 10^{-5}$$

$$\mathcal{A}_\phi^S = (-1.1 \pm 4.1)\,\%$$

Measurements will be improved with the 2002 data: > 40 k events

- $K_L \to \pi^+\pi^-e^+e^-$ (1998+1999 data) 1162 candidates and S/B=31

$$\text{BR}(K_L \to \pi^+\pi^-e^+e^-) = (3.08 \pm 0.20) \times 10^{-7}$$

$$\mathcal{A}_\phi^L = (14.2 \pm 3.6)\,\%$$

$$\Longrightarrow \frac{\Gamma(K_L \to \pi^+\pi^-e^+e^-)^{\text{CPV}}}{\Gamma(K_L \to \pi^+\pi^-e^+e^-)^{\text{CPC}}} = (0.833 \pm 0.066)$$

Measurements in agreement with theoretical models based on a phenomenological description of radiative kaon decays

M1 direct emission FF parameters:

$$\tilde{g}_{M1} = 0.99^{+0.28}_{-0.27}\,_{stat} \pm 0.07_{syst} \qquad a_1/a_2 = (-0.81^{+0.07}_{-0.13}\,_{stat} \pm 0.02_{syst})\ \text{GeV}^2$$

K^0 Charge Radius parameter:

$$g_P = 0.19 \pm 0.04_{stat} \pm 0.02_{syst}$$

Charged Kaon Decays

Charged Kaon Decays

Run 2003 (Jun-Sept): $\sim$60 days of data-taking devoted to the study of $K^\pm$ decays

- Search for Direct CP violation through the asymmetry $\mathcal{A}_g$ in the Dalitz plot for $K^\pm \to \pi^\pm\pi^+\pi^-$

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

$$u=(s_3\text{-}s_0)/m_\pi^2 \qquad v=(s_1\text{-}s_2)/m_\pi^2 \qquad s_0=(s_1+s_2+s_3)/3$$

$$s_i = (P_K - P_i)^2$$ *(i=3 for the odd pion)*

$$\mathcal{A}_g = \frac{g^+ - g^-}{g^+ + g^-}$$

If CP holds then $g^+ = g^-$ and $\mathcal{A}_g = 0$

- Current experimental value: $\mathcal{A}_g=(-7\pm5)\times10^{-3}$ [Ford et al.,1970]

  NA48/2 aims at a precision of $\sim 10^{-4}$ on $\mathcal{A}_g$

- Theoretical predictions for $\mathcal{A}_g$: $\mathcal{O}(10^{-6}) - \mathcal{O}(10^{-4})$

  e.g. NLO in χPT: $\mathcal{A}_g=(-2.7\pm1.3)\times10^{-5}$ [E. Gámiz et al., hep-ph/0309172]

  Some models beyond the SM can give $\mathcal{A}_g \sim \mathcal{O}(10^{-4})$
  [G. D'Ambrosio et al., PLB 480 (2000) 164]

- CP violation can also be investigated in $K^\pm \to \pi^\pm\pi^0\pi^0$ or $K^\pm \to \pi^\pm\pi^0\gamma$ decays

Charged Kaon Decays

❖ Measurement strategy

- use of simultaneous 60 GeV/c K^+ and K^- beams (ΔP_{rms} : ± 2.4 GeV/c)
- 7-10$\times 10^{11}$ p/spill on target $\Rightarrow$ $20 - 30$ Mhz rate of $\pi^{\pm}$,$K^{\pm}$,$e^{\pm}$,p ...
- focussed beams @ DCH1-DCH2 to minimize differential acceptance effects
- alternate magnet polarity of spectrometer (1/day)
- alternate K^+/K^- beam positions in achromat (1/week)

  $\Rightarrow$ minimize sensitivity to beam and detector instabilities with time

- measure normalized ratio

$$\mathrm{R} = \frac{N^+(u)}{N^-(u)} \approx 1 + \mathcal{A}_g \cdot 2g\,u$$

- 80 Tbytes data volume and $\sim 1.25\times 10^9$ reconstructed $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays

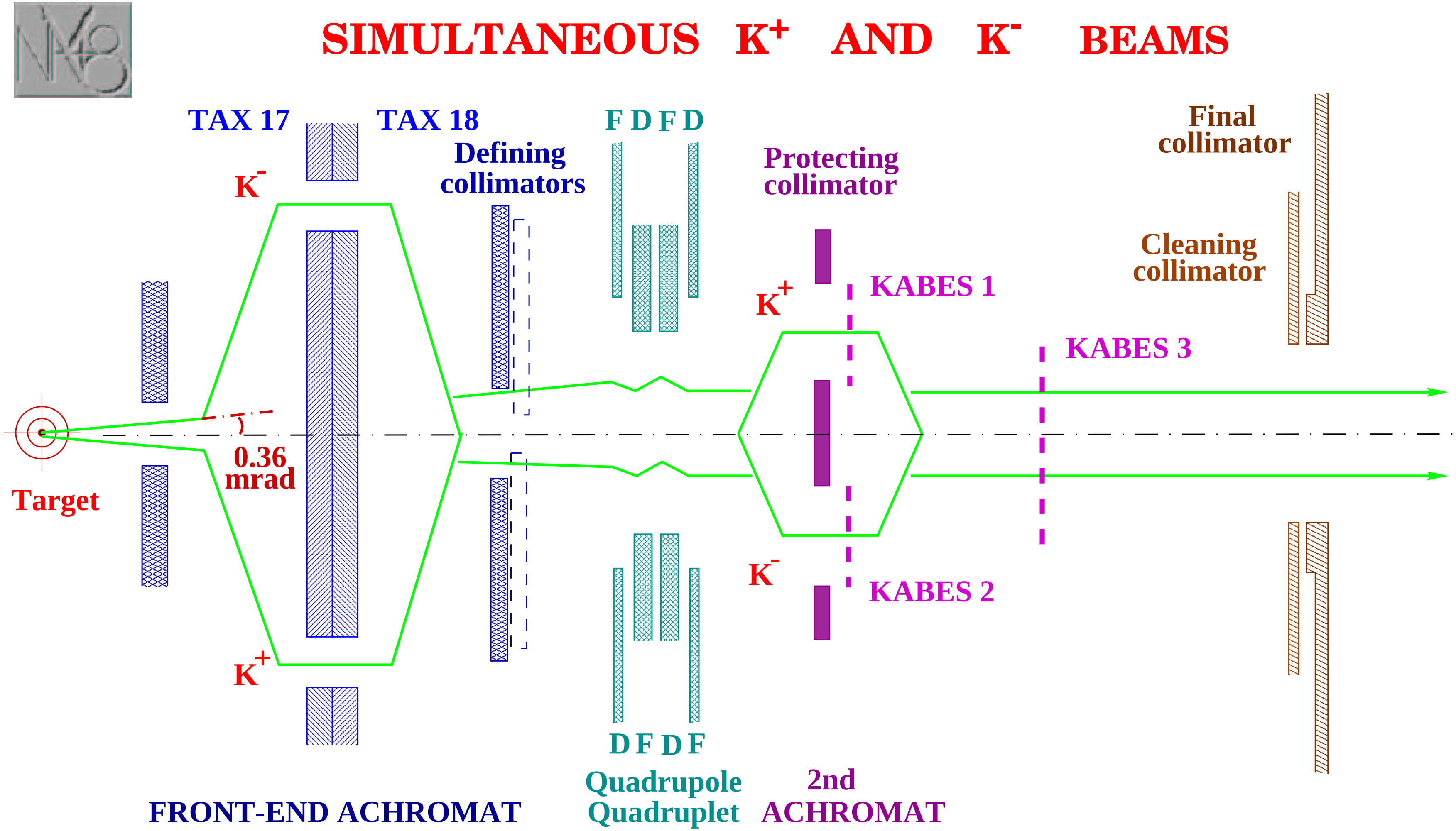
$$\Rightarrow \sigma(\mathcal{A}_g) \sim 2.3\times 10^{-4}\ (stat)$$

❖ Main systematics sources

- beam geometry (K^+ and K^- beams coincide to better than 1 mm / 120 m)
- spectrometer mis-alignment (20-30 μm)
- drift chambers and trigger inefficiencies ($\sim 1 - 2\%$)
- backgrounds (small) and accidentals
- differential acceptance effects

Systematic uncertainties must be kept $< 10^{-4}$

The $K^{\pm}$ beams



Charged Kaon Decays

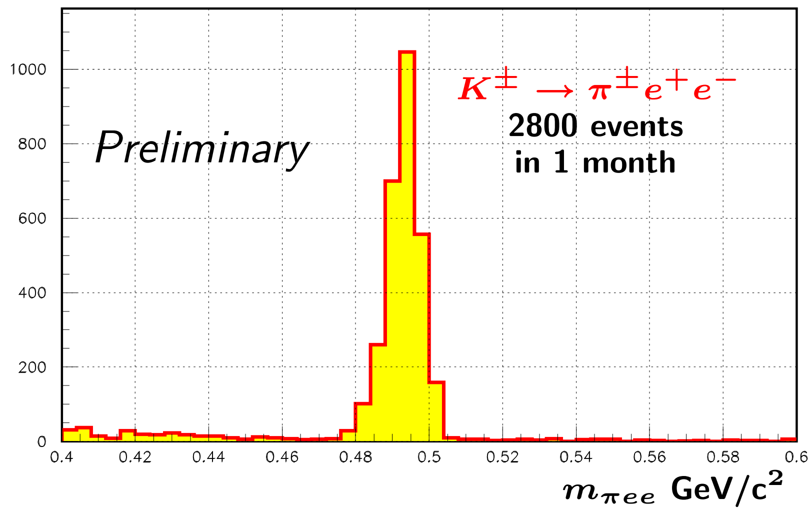
NA48/2 Trigger versatility and DAQ allows the study of many rare $K^{\pm}$ decays

- **$K^{\pm}_{e4}$ ($K^{\pm}_{\mu4}$) decays**
  - extract $\pi^+\pi^-$ elastic scattering length a_0^0 with a precision of < 0.01

    $\Rightarrow$ determine size of quark condensate $\langle 0|q\bar{q}|0\rangle \simeq F_\pi^2 \frac{m_\pi^2}{m_u+m_d}$
  - expect $\sim$700 k reconstructed $K^{\pm}_{e4}$ decays in 2003
  - electron id using E/P + NN technique (keep bkg $< 1\%$)

  BNL E865: $a_0^0 = 0.216 \pm 0.013_{stat} \pm 0.002_{syst} \pm 0.02_{theor}$ with 400 k events

- **$K^{\pm} \rightarrow \pi^{\pm}e^+e^-$ and $K^{\pm} \rightarrow \pi^{\pm}\mu^+\mu^-$**



  - 4-5 k $K^{\pm} \rightarrow \pi^{\pm}e^+e^-$ events
  - BR and FF measurements
  - Test of NLO χPT

Charged Kaon Decays

- **Study of several other Kaon decays (test χPT predictions)**

$$K^\pm \rightarrow \pi^\pm\pi^0\gamma,\ \pi^\pm\pi^0\gamma\gamma,\ \pi^\pm\pi^0 l^+l^-,\ l^\pm\nu l^+l^-,\ \ldots$$

- **Beam Spectrometer (KABES)**
  - High-rate capability and high-resolution TPC based on micromegas-type chambers (50 μm amplification gap)
  - provides accurate P, t and (X,Y) coordinates of incident beam particles
  - tested up to 40 MHz
  - gives useful kinematical constraints for decays with only 1 charged track or with neutrinos in the final state: e.g. $K^\pm_{e3}$, $K^\pm_{\mu3}$, $K^\pm_{\mu2}$, $K^\pm \rightarrow \pi^\pm\pi^0\pi^0$, ... $K^\pm \rightarrow \pi^\pm\nu\overline{\nu}$!
  - allows to recover $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ events when one pion escapes detection

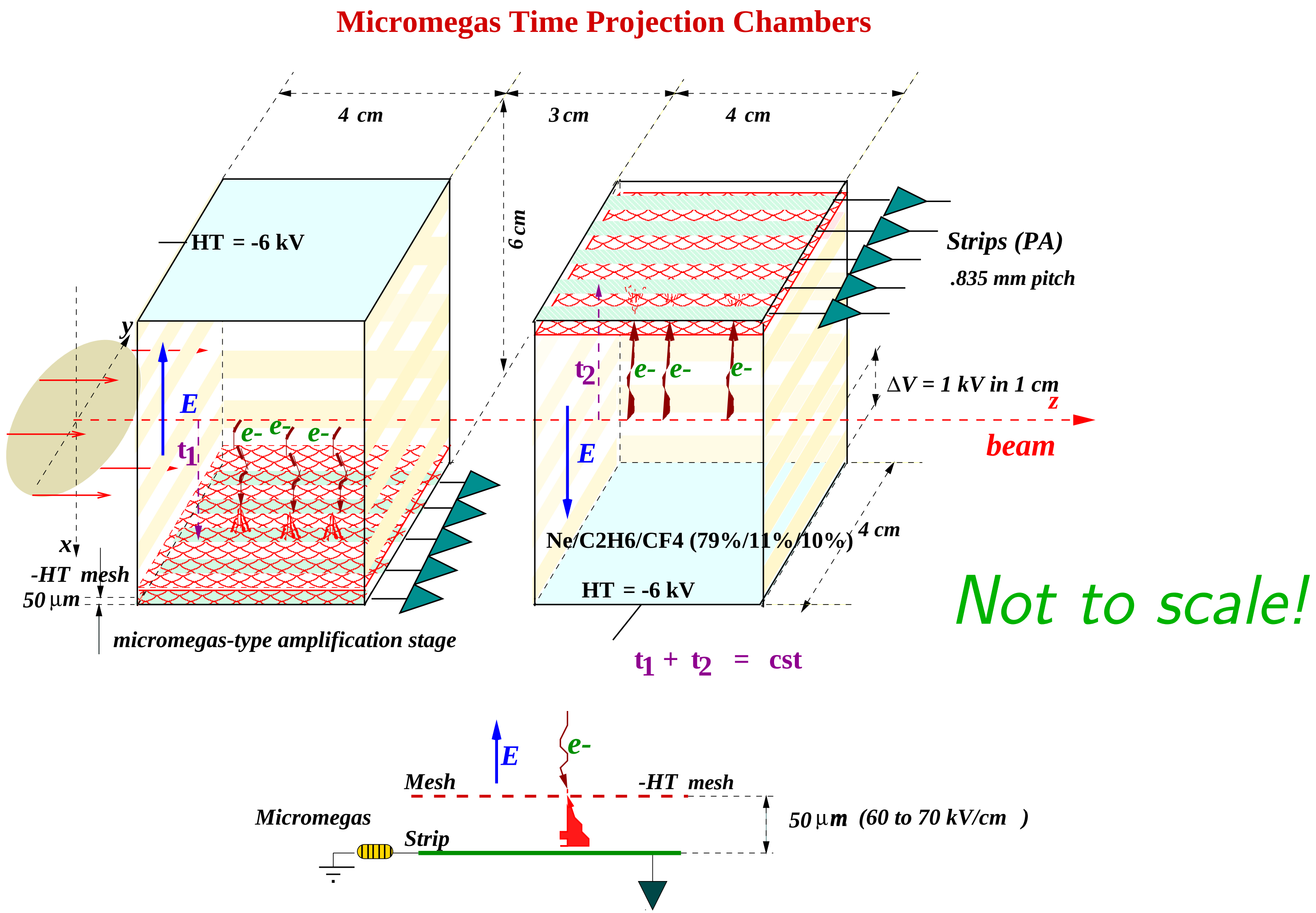
- **Dedicated V_{us} run**
  - short run ($\sim$8 hours) at reduced beam intensity ($1/10$)
  - use highly efficient minimum bias 1 track trigger
  - collect all important $K^\pm$ decay channels ($\sum$ BR$_i \sim 1$):

$$\mu\nu(\gamma),\ \pi^\pm\pi^0,\ \pi^\pm\pi^0\pi^0,\ \pi^\pm\pi^+\pi^-,\ K^\pm_{e3},\ K^\pm_{\mu3},\ \ldots$$

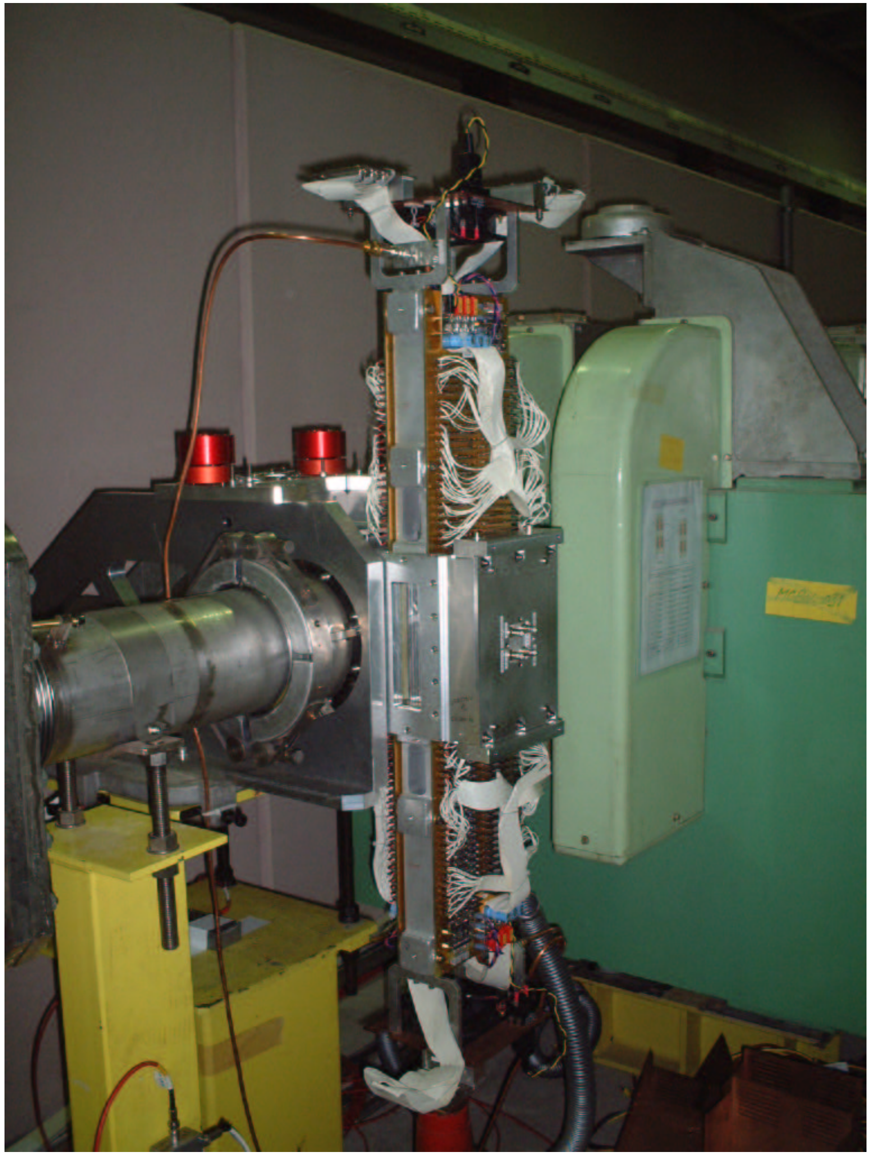
  - more than 100 k $K^\pm_{e3}$ and $K^\pm_{\mu3}$ events

Aim to measure BR($K^\pm_{e3}$) and BR($K^\pm_{\mu3}$) to better than 1 %

The KAon BEam Spectrometer

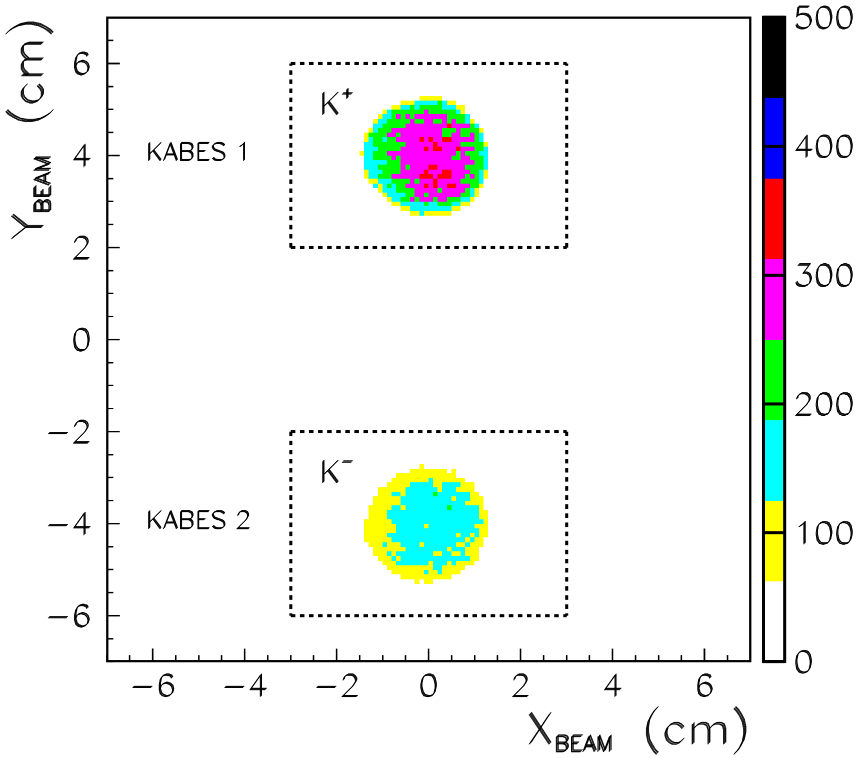


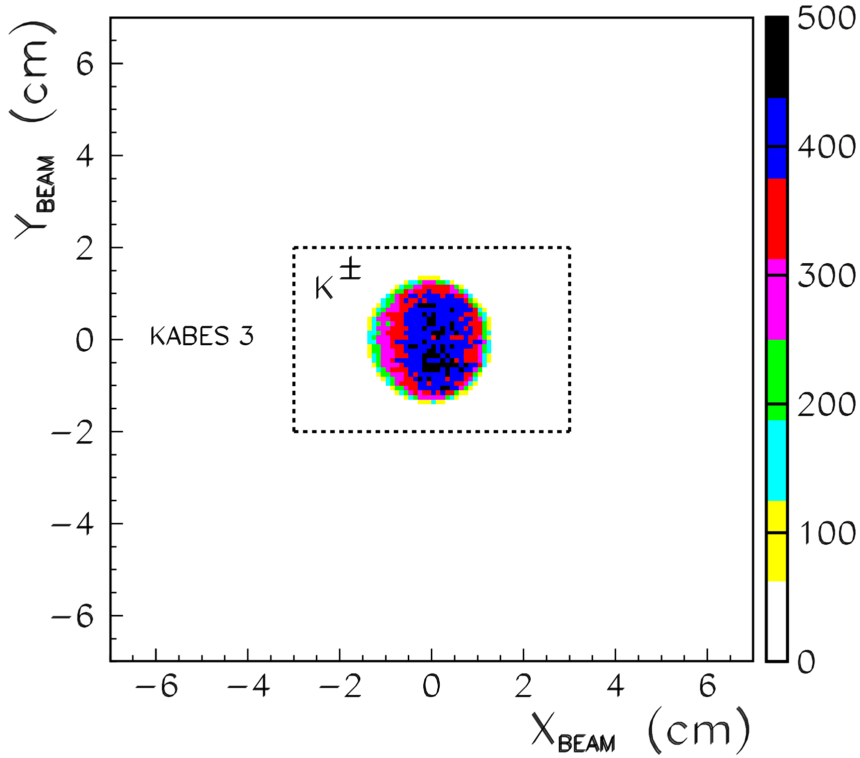
The KAon BEam Spectrometer



KAon BEam Spectrometer

Tagging incident $K^{\pm}$ with $K^{\pm} \rightarrow \pi^{+}\pi^{-}\pi^{\pm}$ decays at 20 MHz

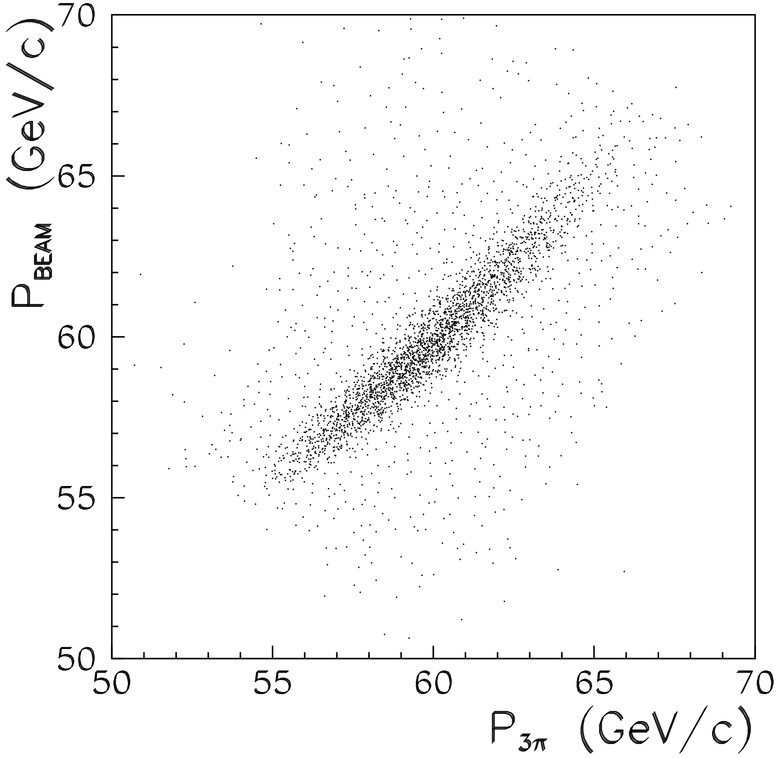


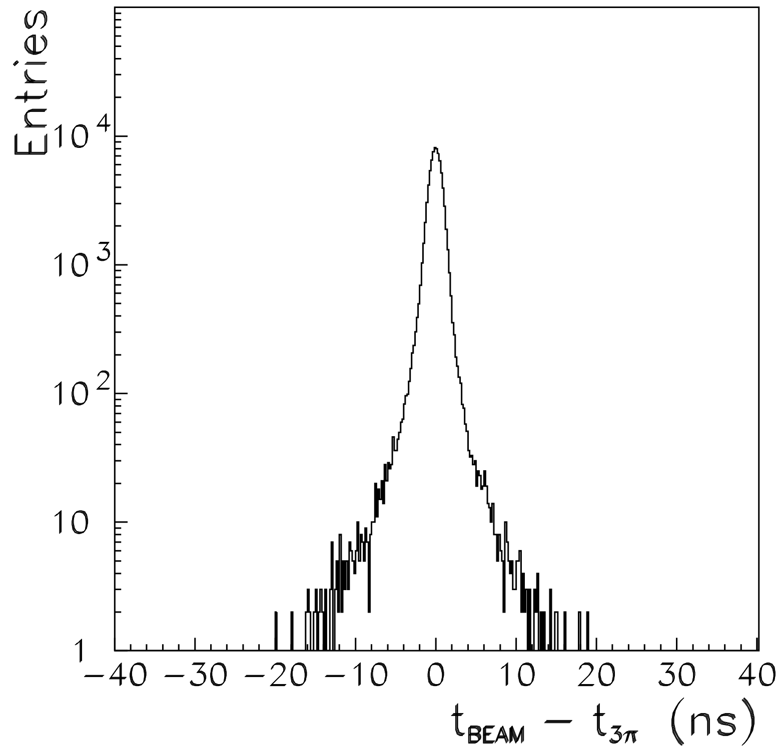


$$\sigma(\mathbf{X}_{\mathbf{BEAM}}) \approx \sigma(\mathbf{Y}_{\mathbf{BEAM}}) \sim 120\,\mu m$$

KAon BEam Spectrometer

Tagging incident $K^\pm$ with $K^\pm \to \pi^+\pi^-\pi^\pm$ decays at 20 MHz





$\sigma(P_{BEAM})/P_{BEAM} < 1\,\%$ $\sigma(t_{BEAM}) < 1$ ns

efficiency: $\sim 100\,\%$ **mistagging probability: *few* %**

Summary and Outlook

- The use of high intensity K_L and K_S beams by the NA48 experiment has made possible the precise investigation of several rare kaon decays for tests of CP, CPT asymmetries as well as χPT. The recent observation of 7 clean $K_S \rightarrow \pi^0 e^+ e^-$ events allows to significantly improve the SM predictions for the golden $K_L \rightarrow \pi^0 e^+ e^-$ mode. Additional information from the study of the $K_S \rightarrow \pi^0 \mu^+ \mu^-$ channel will come very soon.

- New results from the study of rare neutral kaon decays (e.g. $K_L \rightarrow e^+ e^- \gamma$, K^0_{e3}, K^0_{e4}, $K_L \rightarrow \pi^0 \pi^0 \gamma$, etc.) and from the radiative and semileptonic Ξ^0 decays will also be available soon.

- The 2003 run, dedicated to the high-precision investigation of charged kaon decays, has been successfully completed. More than 10^9 $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ decays have been collected for a measurement of the CP-violation $\mathcal{A}_g$ asymmetry with a precision of a $few\, 10^{-4}$. Several other rare charged kaon decays are also investigated. Additional beam time to run in 2004 at CERN is being requested.