

# Review of Chiral Perturbation Theory experimental results in kaon decays

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NA48 collaboration

INFN - Sezione di Pisa

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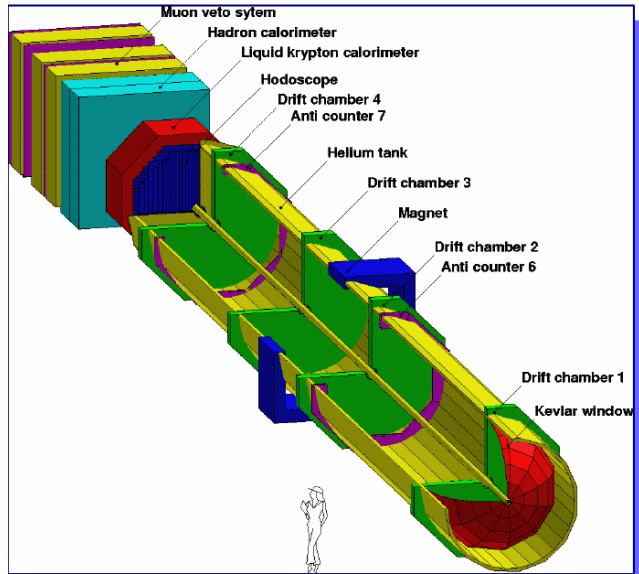
# Outline

- Recent and less recent results on kaon decays
  - Mainly from NA48, KTeV and Kloe
- With an excursus in the  $\eta$  sector
- And references to other talks in this conference
  - $K^+ \rightarrow \pi^+ \pi^0 \gamma$  will be discussed in the talk by M. Raggi
  - Results from Istra+ on charged kaons will be discussed by V. Duk
  - Results on  $K_L \rightarrow \pi^0 \pi^0 \gamma$  presented yesterday by H. Nguyen

# Chiral perturbation theory

- $\chi$ PT is an effective field theory of Standard Model at low energies where QCD is non-perturbative
- Processes are described in perturbative expansion of momenta and masses:  
 $p^2 / (4\pi F_\pi)^2, m^2 / (4\pi F_\pi)^2$  where  $(4\pi F_\pi)^2 \sim 1.2 \text{ GeV}^2$
- Higher order boson loops are divergent, they are compensated by counter-terms with effective couplings determined from experiments.
- Ideal to describe kaon and eta decays ( $m_{K,\eta} \approx 0.5 \text{ GeV}$ )

# Kaon decay detectors



NA48 400 GeV/c

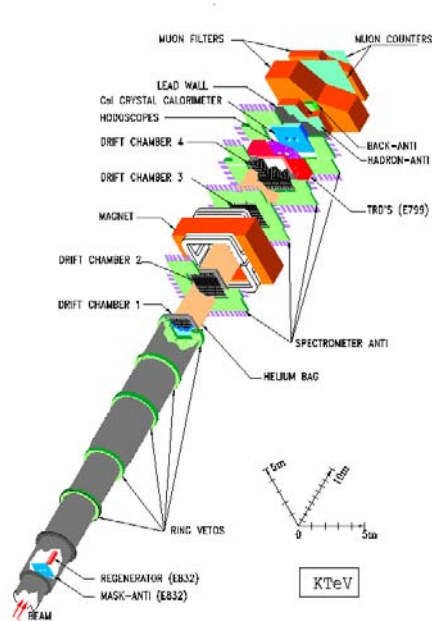
At different times:

Intense KL beam

Intense KS beam

Simultaneous  $K^\pm$  beams

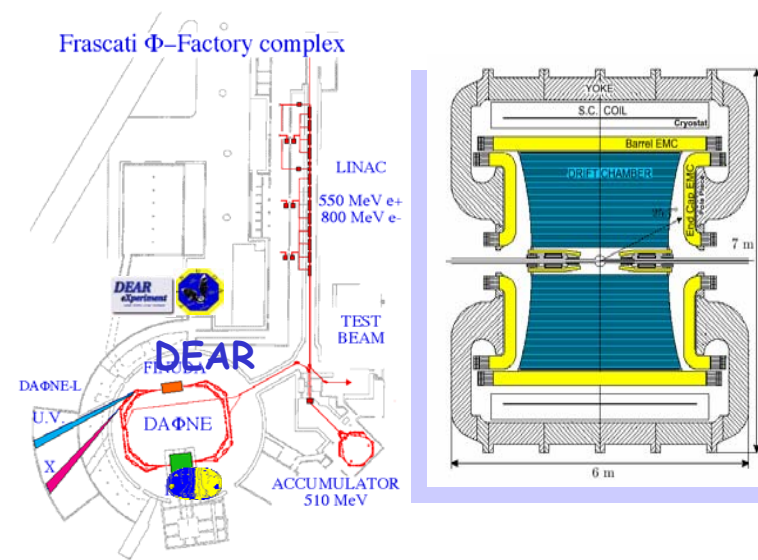
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KTeV 800 GeV/c

Very intense KL beam

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KLOE  $\sqrt{s} = 1020 \text{ MeV}$

Production of  $K_L/K_S$  or  $K^+/K^-$  pairs

Production of  $\eta$

Low energy

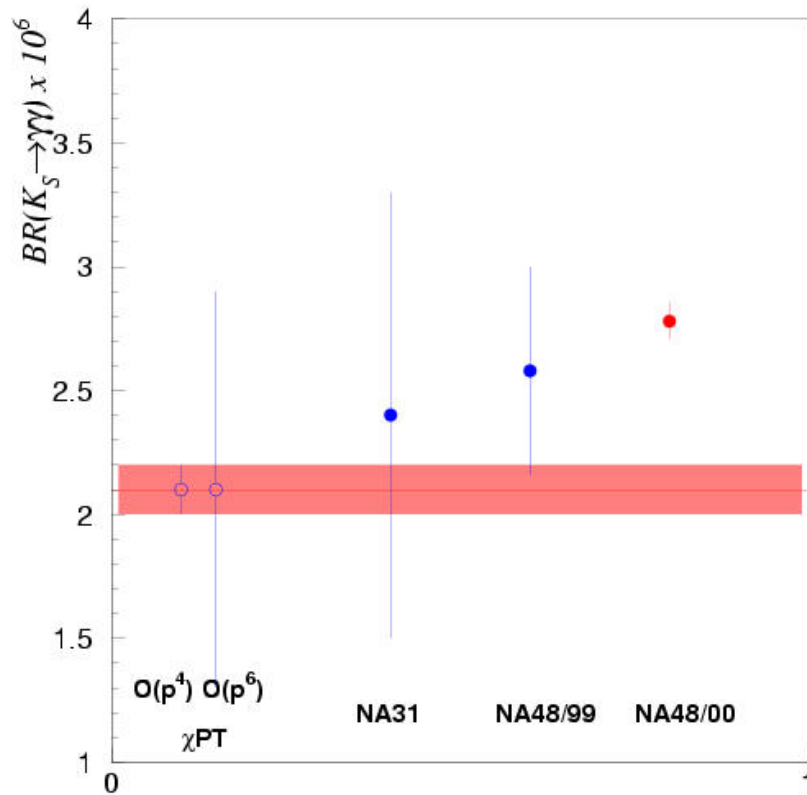
Different systematics

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$$K_S \rightarrow \gamma\gamma$$

- $K_S \rightarrow \gamma\gamma$  is interesting because it is calculable in  $\chi$ PT with no counter-terms and it is sensitive to loops
  - Theoretical prediction:  $BR(K_S \rightarrow \gamma\gamma) = (2.1 \pm 0.2) \cdot 10^{-6}$
  - Result from NA31:  $BR(K_S \rightarrow \gamma\gamma) = (2.4 \pm 0.9) \cdot 10^{-6}$
- Published result from 1999 HIKs run with dedicated trigger
  - $BR(K_S \rightarrow \gamma\gamma) = (2.58 \pm 0.36_{st} \pm 0.22_{sy}) \cdot 10^{-6}$
  - Phys. Lett. B493 (2000) 29
  - Systematic error limited by the error on PDG  $BR(K_L \rightarrow \gamma\gamma)$

# $K_S \rightarrow \gamma\gamma$ - Result



Number of  $K_S \rightarrow \gamma\gamma$   $7461 \pm 172$

$BR(K_S \rightarrow \gamma\gamma) = (2.78 \pm 0.06_{st} \pm 0.02_{MCst} \pm 0.06_{sy}) \times 10^{-6}$

[Phys. Lett. B551 (2003) 7]

- The NA48 result is compatible with the previous measurements
- It shows 30% difference wrt  $O(p^4)$   $\chi PT$  predictions
- There is an indication for a large  $O(p^6)$  contribution

• Kloe is planning an analysis of this channel

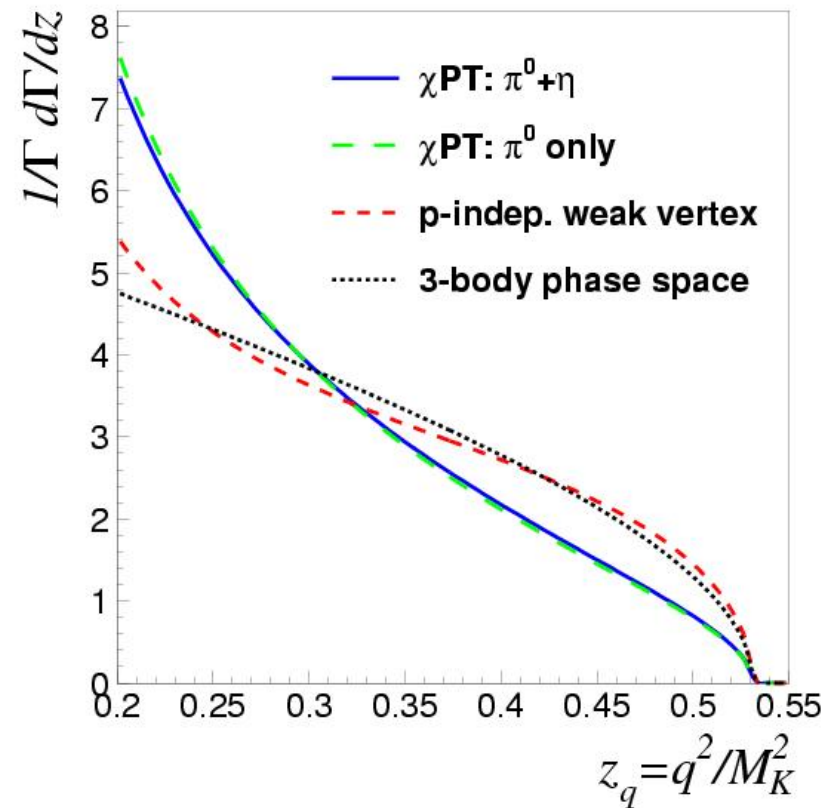


PDG value =  $(2.77 \pm 0.08) \cdot 10^{-3}$

- $O(p^4)$  contributions vanishes
- $O(p^6)$  contributions mediated by pseudoscalar mesons depend on the value of singlet-octet mixing
- Measurement of  $\Gamma(K_L \rightarrow \gamma\gamma)/\Gamma(K_L \rightarrow 3\pi^0)$ 
  - By NA48 using  $K_L$  only data collected in 2000
  - By Kloe with a sample of  $\sim 1.6 \cdot 10^8$   $K_L$  tagged by  $K_S \rightarrow \pi^+\pi^-$
  - Results:
    - $\Gamma(K_L \rightarrow \gamma\gamma)/\Gamma(K_L \rightarrow 3\pi^0) = (2.81 \pm 0.01_{st} \pm 0.02_{sy}) \cdot 10^{-3}$  (NA48)
    - $\Gamma(K_L \rightarrow \gamma\gamma)/\Gamma(K_L \rightarrow 3\pi^0) = (2.79 \pm 0.02_{st} \pm 0.02_{sy}) \cdot 10^{-3}$  (Kloe)
  - The corresponding decay width agrees with  $O(p^6)$  predictions provided that the mixing angle is close to the measured value by Kloe of  $-12.9^{+1.9}_{-1.6}$  degrees

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

- Previously never observed
- NA48 from 1999 data:  
 $BR(K_S \rightarrow \pi^0 \gamma \gamma)_{z_q > 0.2} < 3.3 \cdot 10^{-7}$  90% CL
- Predictions from  $\chi$ PT:  
 $BR(K_S \rightarrow \pi^0 \gamma \gamma)_{z_q > 0.2} = 3.8 \cdot 10^{-8}$   
 Cut on  $Z_q = m_{\gamma\gamma}^2 / m_K^2$  to avoid the  $2\pi^0$  pole  
 Weak vertex momentum dependence
- In principle it is possible to study the structure of the weak vertex from the  $z_q$  distribution



# $K_S \rightarrow \pi^0 \gamma \gamma$ - The result

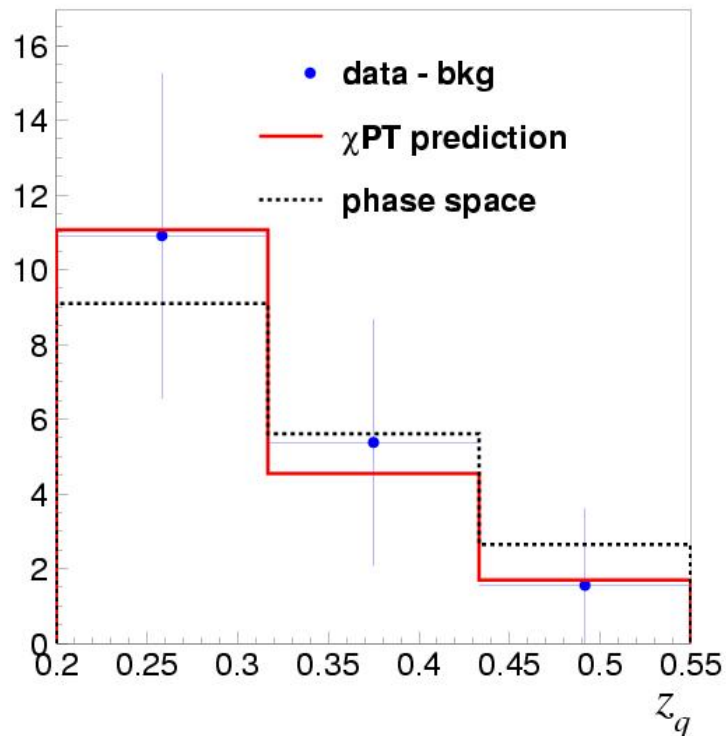
- **First observation :**

$$BR(K_S \rightarrow \pi^0 \gamma \gamma)_{Z_q > 0.2} = (4.9 \pm 1.6_{\text{stat}} \pm 0.8_{\text{sys}}) * 10^{-8}$$

$$\text{Prediction from } \chi\text{PT} : BR(K_S \rightarrow \pi^0 \gamma \gamma)_{Z_q > 0.2} = 3.8 * 10^{-8}$$

31.0  $\pm$  5.6 events in the signal region

13.6  $\pm$  2.8 estimated bckg events to be subtracted



- Insufficient statistics to verify the chiral structure of the vertex

$$K_L \rightarrow \pi^0 \gamma \gamma$$

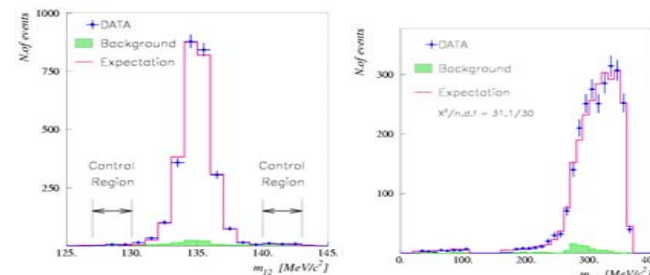
## • Motivation

- At one loop  $\chi$ PT ( $O(p^4)$ ) the decay rate is finite, but only gives 1/3 of the measured rate
- Calculations of  $O(p^6)$  including vector meson exchange reproduce the measured rate and allows a tail at low  $M_{\gamma\gamma}$
- VMD contribution parametrized by  $\alpha_v$ , to be measured, which determines the CPC amplitude to  $K_L \rightarrow \pi^0 e^+e^-$

## $\chi$ PT prediction of $O(p^6)$

- $BR(K_L \rightarrow \pi^0 \gamma \gamma) = 1.5 * 10^{-6}$
- $\alpha_v = -0.7$

NA48: ~2500 candidates in the signal region ( $132 < m_{12} < 138$  MeV)



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# $K_L \rightarrow \pi^0 \gamma \gamma$ - Results

- **NA48 fit:**  $a_v = -0.46 \pm 0.03_{st} \pm 0.03_{sy} \pm 0.02_{th}$
- **Using this  $a_v$**   $BR(K_L \rightarrow \pi^0 \gamma \gamma) = (1.36 \pm 0.03_{st} \pm 0.03_{sy} \pm 0.03_{norm}) * 10^{-6}$
- **The systematics of both results are limited by background evaluation and acceptance calculation**
- **The value of  $a_v$  implies a negligible CP conserving contribution to  $K_L \rightarrow \pi^0 e^+ e^-$**

$$BR(K_L \rightarrow \pi^0 e^+ e^-)_{CPC} = (4.7 \pm 2.2) * 10^{-13}$$

KTeV

Phys. Lett. B536 (2002) 229

$$BR(K_L \rightarrow \pi^0 \gamma \gamma) = (1.68 \pm 0.10)$$

$$a_v = -0.72 \pm 0.08$$

KTeV is planning to complete the analysis with the full data sample

$$K_L \rightarrow \pi^+ \pi^- \pi^0 \gamma \text{ and } K_L \rightarrow \pi^+ \pi^- \pi^0 e^+ e^-$$

- No published results on these decays
  - $K_L \rightarrow \pi^+ \pi^- \pi^0 \gamma$  dominated by inner bremsstrahlung
    - $\text{BR}(E_\gamma > 10 \text{ MeV}) = (1.65 \pm 0.03) \cdot 10^{-4}$
  - Direct emission estimated to be very small
  - No theoretical predictions for  $K_L \rightarrow \pi^+ \pi^- \pi^0 e^+ e^-$
- First observation by KTeV of both decays

# $K_L \rightarrow \pi^+ \pi^- \pi^0 \gamma$ and $K_L \rightarrow \pi^+ \pi^- \pi^0 e^+ e^-$

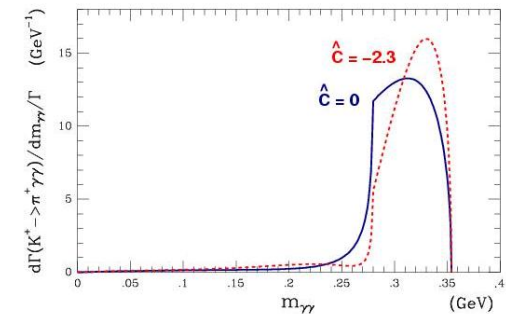
- $K_L \rightarrow \pi^+ \pi^- \pi^0 \gamma$ 
  - 2853 candidates, normalized to  $K_L \rightarrow \pi^+ \pi^- \pi^0$
  - $BR(E_\gamma > 10 \text{ MeV}) = (1.70 \pm 0.03_{st} \pm 0.04_{sy} \pm 0.03_{norm}) \cdot 10^{-4}$
- $K_L \rightarrow \pi^+ \pi^- \pi^0 e^+ e^-$ 
  - 132 candidates, normalized to  $K_L \rightarrow \pi^+ \pi^- \pi^0$
  - Estimated background of  $1.2 \pm 0.9$  events
  - 40% of KTeV data analyzed
  - $BR(E_{ee} > 20 \text{ MeV}) = (1.60 \pm 0.18_{st}) \cdot 10^{-7}$
  - Plans to measure DE and Charge radius in the near future

## An excursus: $\eta \rightarrow \pi^0 \gamma \gamma$

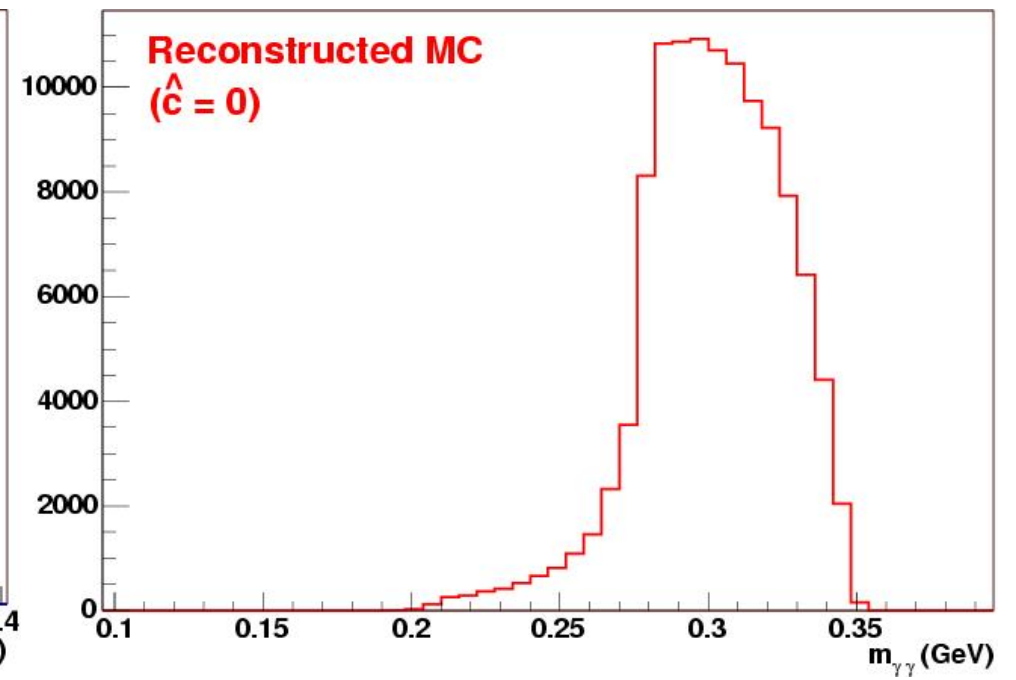
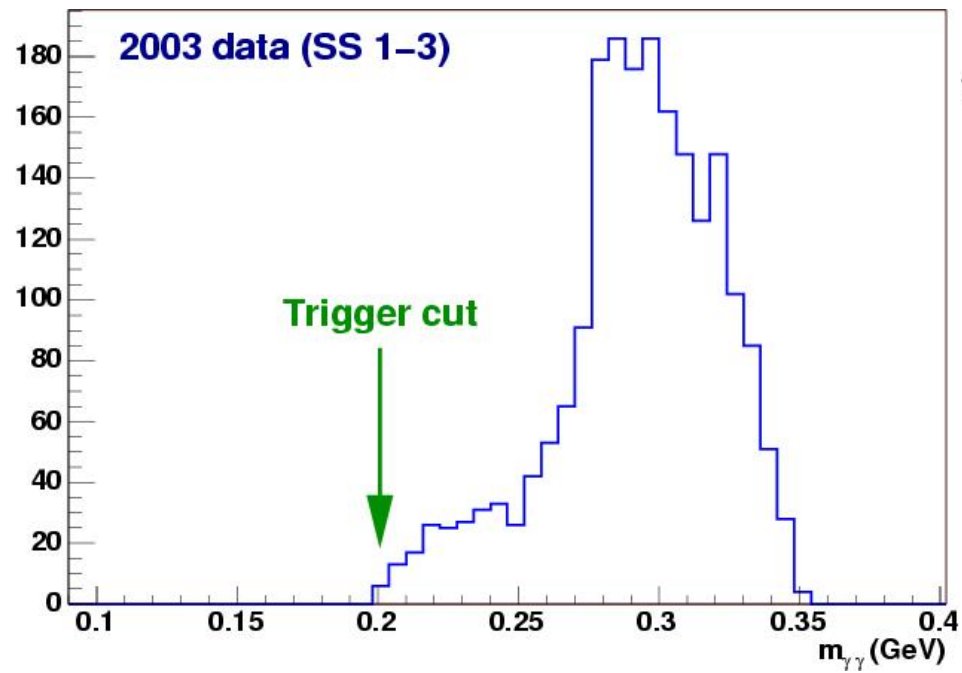
- Many predictions within  $\chi$ PT
  - All span in the interval  $0.11 \text{ eV} < \Gamma < 0.92 \text{ eV}$
  - This means  $8.5 < \text{BR} < 71 (10^{-5})$
- KLOE result
  - $68 \pm 23$  signal events, normalized to  $\eta \rightarrow \pi^0 \pi^0 \pi^0$
  - Many sources of background
  - $\text{BR} (\eta \rightarrow \pi^0 \gamma \gamma) = (8.4 \pm 2.7_{\text{st}} \pm 1.4_{\text{sy}}) \cdot 10^{-5}$
- In agreement with  $O(p6)$  with VMD resonance saturation and also with Belkov NJL

$$K^+ \rightarrow \pi^+ \gamma \gamma$$

- **Interesting test of  $\chi$ PT**
  - No tree level  $O(p^2)$  contribution
  - Leading contributions at  $O(p^4)$ 
    - With one undetermined constant  $c_{\text{hat}}$  of  $O(1)$
  - Interplay with  $K_L \rightarrow \pi^0 \gamma \gamma$
  - 30-40% corrections to BR expected due to  $O(p^6)$  terms
  - Different models give values for the BR around  $7 \cdot 10^{-7}$
- **First observation by BNL E787**
  - $5.1 \pm 3.3$  events for  $100 \text{ MeV}/c < P_\pi < 180 \text{ MeV}/c$
  - $\text{BR} = (6.0 \pm 1.5_{\text{st}} \pm 0.7_{\text{sy}}) \cdot 10^{-7}$
- **NA48 is working on this analysis**
  - About 2000 events in 2003 data, very small backgrounds
  - At least similar amount in 2004 data, still to look at



$$K^+ \rightarrow \pi^+ \gamma \gamma$$





- The form factor in the amplitude for this decay contains two parameters  $a_i, b_i$  to parametrize contributions at  $O(p^4)$  and  $O(p^6)$  respectively
- Results from BNL- E865 have been used to fit

$$a_+ = -0.587 \pm 0.010 \quad b_+ = -0.655 \pm 0.044$$

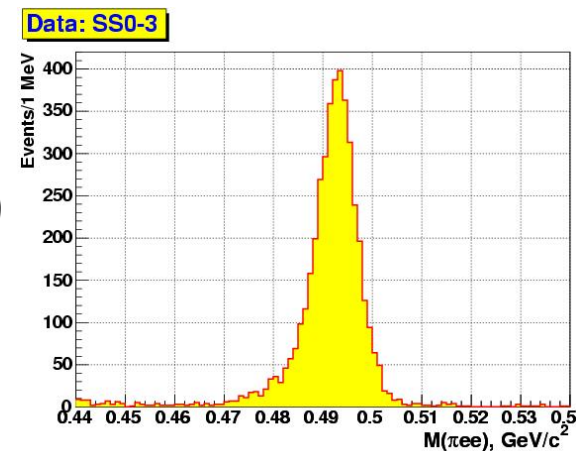
$$BR = (2.94 \pm 0.05_{st} \pm 0.13_{sy} \pm 0.05_{model}) \cdot 10^{-7}$$

Consistent with  $\chi$ PT calculations

10K events

With 1.2% bck

- NA48 is working on this analysis
  - About 4000 events (only 2003 data)
  - At least double with 2004 data
  - Less than 1% background



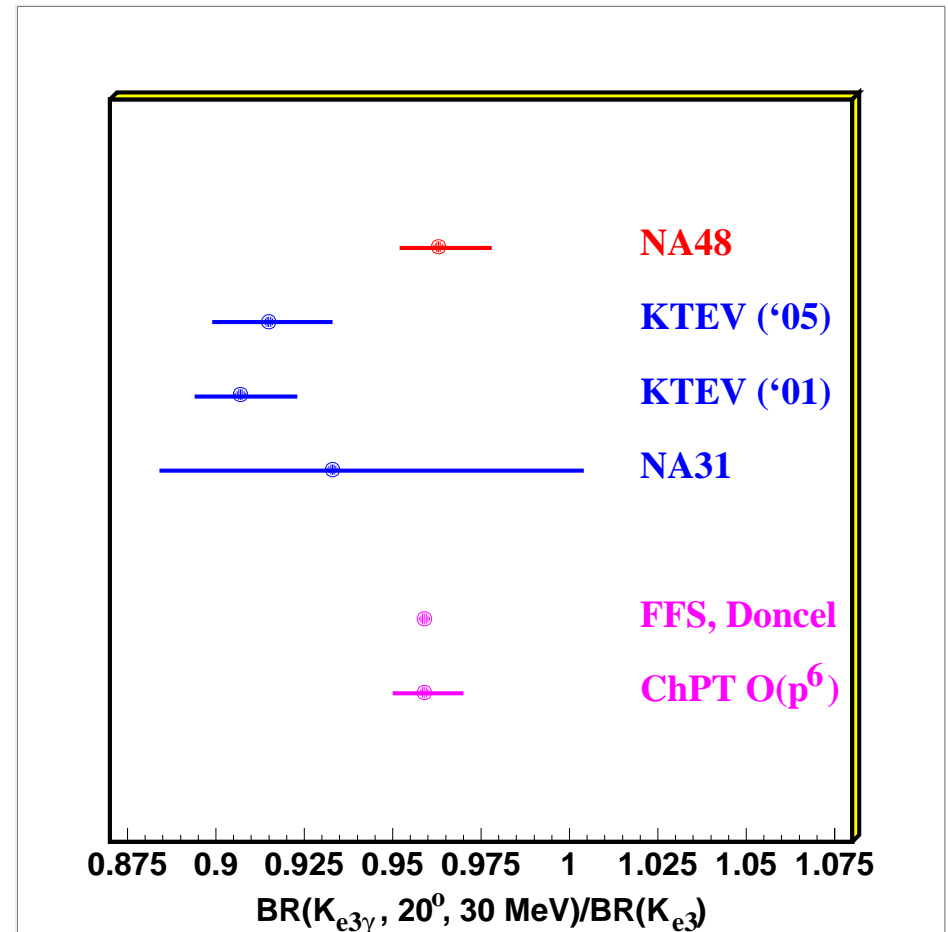
# Radiative semileptonic decays

- $K_L$  and  $K^\pm$  semileptonic radiative decays give info on the kaon structure In  $K^\pm$  study also T-odd variables  $\rightarrow$  CPV...
- The ratio  $R$  (with constraints to avoid divergences) is predicted to be between 0.95% and 0.99%
- Two different theoretical approaches
  - Current algebra (Fearing, Fischbach, Smith) (Doncel)
  - $\chi$ PT continuously improved. Latest estimate  $(0.96 \pm 0.01)\%$
  - Both basically agree
- A recent measurement from KTeV gives  $R = (0.908 \pm 0.008^{+0.013}_{-0.012})\%$ , in disagreement with the prediction

$$R = \frac{\Gamma(K_{e3\gamma}, E_\gamma^* > 30 \text{ MeV}, \theta_{e\gamma}^* > 20^\circ)}{\Gamma(K_{e3})}$$

# Radiative semileptonics

- NA48 results
  - 18977  $K_{e3\gamma}$  events
  - 6 million  $K_{e3}$  events
  - Less than 1% background
- $R = (0.964 \pm 0.008^{+0.011}_{-0.009})\%$
- In full agreement with the predictions
- Analysis in progress by NA48 on  $K^\pm$  radiative semileptonic decay



# Radiative semileptonics

- For completeness I must cite the ISTRA+ work
  - To be treated in more detail by V. Duk, just in 10 minutes...
  - First observation of  $K^- \rightarrow \mu^- \pi^0 \gamma \nu$ 
    - *Good agreement with  $\chi PT$*
  - High statistics studies of  $K^- \rightarrow e^- \pi^0 \gamma \nu$ 
    - *Almost 5000 events with 20% background*
    - *BR and kinematic distributions agree well with  $\chi PT$*

# $K_{e4}$

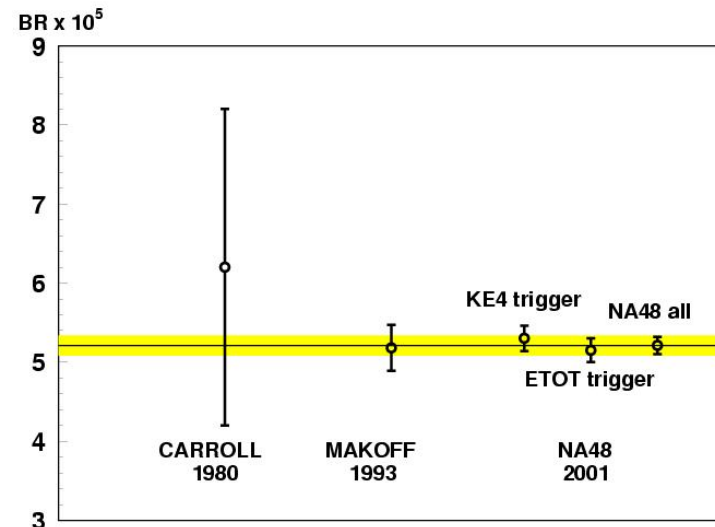
- Another good test for  $\chi$ PT
  - Determination of  $\pi\pi$  partial wave expansion parameters
    - $\pi\pi$  scattering length can be related to the quark condensate
    - Complete set of  $\chi$ PT parameters calculated at  $O(p^4)$
    - F and G form factors + quark condensates at  $O(p^6)$
  - $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ 
    - Recent result by E865: 400000 events,  $a_0^0 = 0.216 \pm 0.013$
    - NA48 analysis in progress. Preliminary result at QCD06 and ICHEP. 350000 events (1/3 of the sample) with 0.1-0.2% background
  - $K^+ \rightarrow \pi^0 \pi^0 e^+ \nu$ 
    - First results from NA48 in the talk by M. Raggi

# $K_{e4}$

- Completed NA48 analysis:  $K_L \rightarrow \pi^\pm \pi^0 e^\pm \nu$

- Phys. Lett. B595 (2004) 75
- 5500 events with  $\sim 1\%$  background
- Measure BR and form factors

- $BR = (5.21 \pm 0.07_{st} \pm 0.09_{sy}) \cdot 10^{-5}$
- $f_s = (0.052 \pm 0.006_{st} \pm 0.002_{sy})$
- $f_p = (-0.051 \pm 0.011_{st} \pm 0.005_{sy})$
- $\lambda_g = (0.087 \pm 0.019_{st} \pm 0.006_{sy})$
- $h = (-0.32 \pm 0.12_{st} \pm 0.07_{sy})$



- The chiral coupling parameter  $L_3$  is estimated to be

- $L_3 = (-4.1 \pm 0.2) \cdot 10^{-3}$

# Pending analyses

- **NA48**

- $K^\pm \rightarrow \pi^\pm e^+ e^- \gamma$
- $K^\pm \rightarrow \pi^\pm \pi^- \pi^+ \gamma$
- $K^\pm \rightarrow \pi^\pm \pi^0 \gamma \gamma$

...and may be more

- **Kloe**

- $K_S \rightarrow \gamma \gamma$
- $K_L \rightarrow \pi e \nu \gamma$

Istra+ is also active

- **KTeV**

- $K_L \rightarrow \pi^0 \gamma \gamma$
- $K_L \rightarrow \pi e \nu e^+ e^-$
- $\pi^0 \rightarrow e^+ e^-$

← Not pending anymore...

← H. Nguyen presented the results yesterday...

# Conclusion

- Chiral perturbation theory is a powerful tool to study kaon (and eta) decays
- All the existing kaon experiments have analyzed specific channels to test  $\chi$ PT predictions
- In several cases the need for  $O(p^6)$  calculations has been pointed out
- More analyses are going on to test more predictions or to complement existing measurement
- Let's have fun!
  
- A special acknowledgment to C. Bloise (KLOE) and B. Tschirhart (KTeV) for the information about the latest status of their analyses