Review of Chiral Perturbation Theory experimental results in kaon decays

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NA48 collaboration

INFN - Sezione di Pisa

BEACH2006 – Lancaster July 4th, 2006

Outline

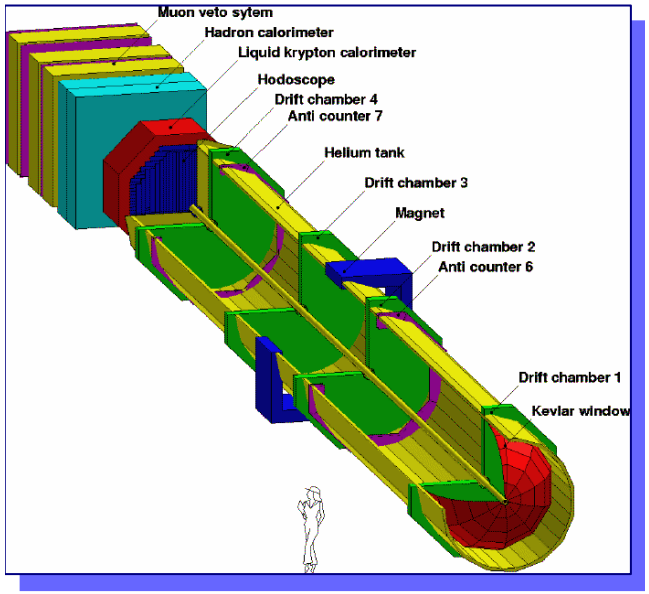
- Recent and less recent results on kaon decays
  - Mainly from NA48, KTeV and Kloe
- With an excursus in the η sector
- And references to other talks in this conference
  - $K^+ \to \pi^+ \pi^0 \gamma$ will be discussed in the talk by M. Raggi
  - Results from Istra+ on charged kaons will be discussed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

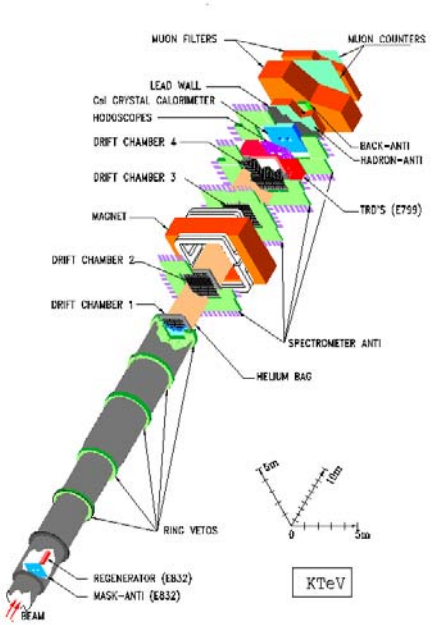
Chiral perturbation theory

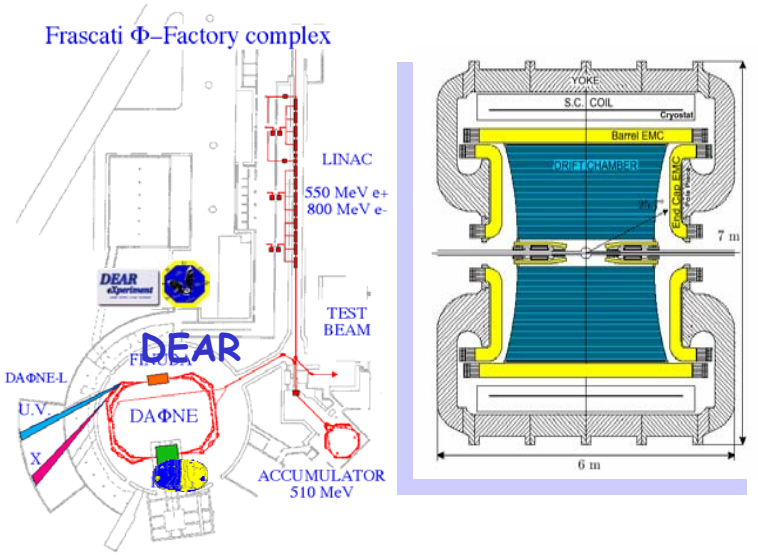
- χPT is an effective field theory of Standard Model at low energies where QCD is non-perturbative
- Processes are described in perturbative expansion of momenta and masses:

  $p^2 / (4\pi F_\pi)^2$, $m^2 / (4\pi F_\pi)^2$ where $(4\pi F_\pi)^2 \sim 1.2$ GeV
- 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 ($m_{K,\eta} \approx 0.5$ GeV)

Kaon decay detectors







NA48 400 GeV/c KTeV 800GeV/c KLOE $\sqrt{s}$ = 1020 MeV

At different times:

Intense KL beam

Intense KS beam

Simultaneous $K^{\pm}$ beams

Very intense KL beam

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

Production of η

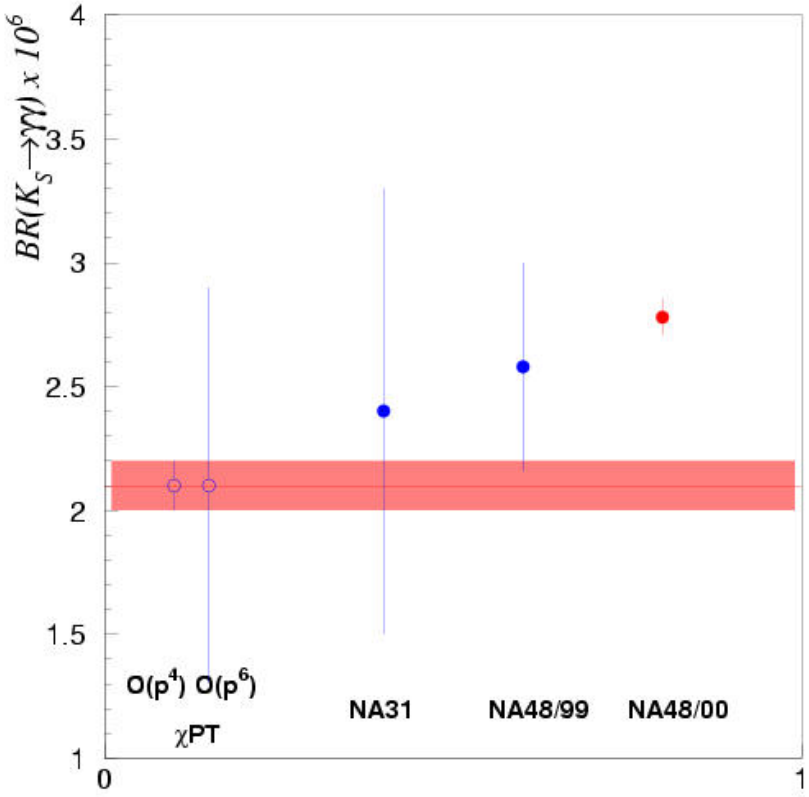
Low energy

Different systematics

$K_S \to \gamma\gamma$

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

$K_S \to \gamma\gamma$ - Result



Number of $K_S \to \gamma\gamma$ 7461 ± 172

$BR(Ks \to \gamma\gamma)=(2.78 \pm 0.06_{st} \pm 0.02_{MCst} \pm 0.06_{sy})*10^{-6}$

[Phys. Lett. B551 (2003) 7]

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

- Kloe is planning an analysis of this channel

$K_L \to \gamma\gamma$

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

- $O(p^4)$ contributions vanishes
- $O(p^6)$ contributions mediated by pseudoscalar mesons depend on the value of singlet-octet mixing
- Measurement of $\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0)$
  - By NA48 using K_L only data collected in 2000
  - By Kloe with a sample of ~$1.6 \cdot 10^8$ K_L tagged by $K_S \to \pi^+\pi^-$
  - Results:

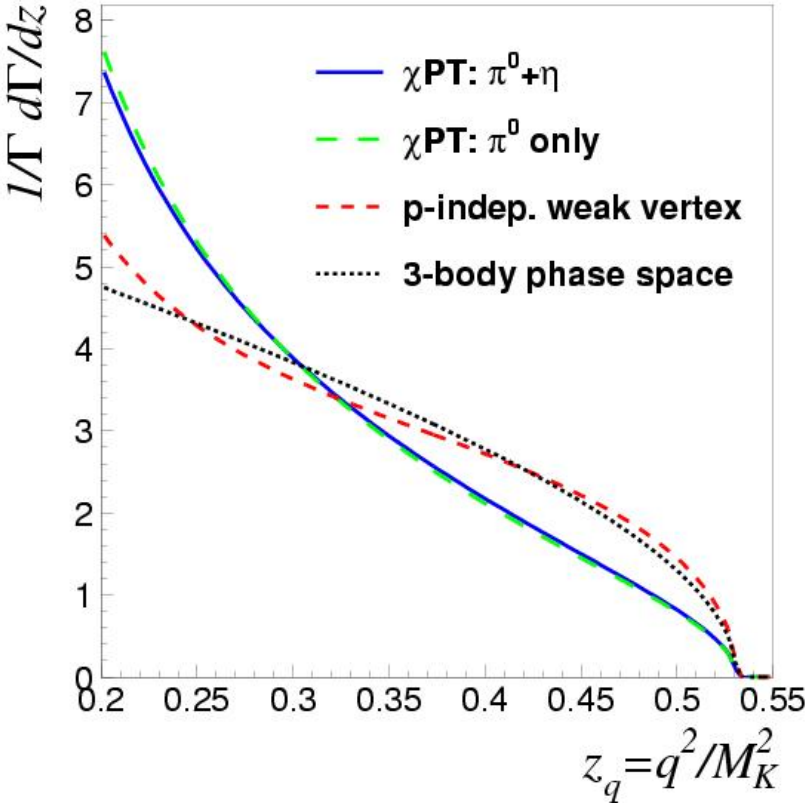
$\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0) = (2.81 \pm 0.01_{st} \pm 0.02_{sy}) \cdot 10^{-3}$ (NA48)

$\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0) = (2.79 \pm 0.02_{st} \pm 0.02_{sy}) \cdot 10^{-3}$ (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

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

- Previously never observed
- NA48 from 1999 data:
  $BR(K_S \to \pi^0\gamma\gamma)_{zq>0.2} < 3.3*10^{-7}$ 90% CL
- Predictions from χPT:
  $BR(K_S \to \pi^0\gamma\gamma)_{zq>0.2} = 3.8*10^{-8}$
  Cut on $Zq=m_{\gamma\gamma}^2/m_K^2$ 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



$K_S \to \pi^0\gamma\gamma$ - The result

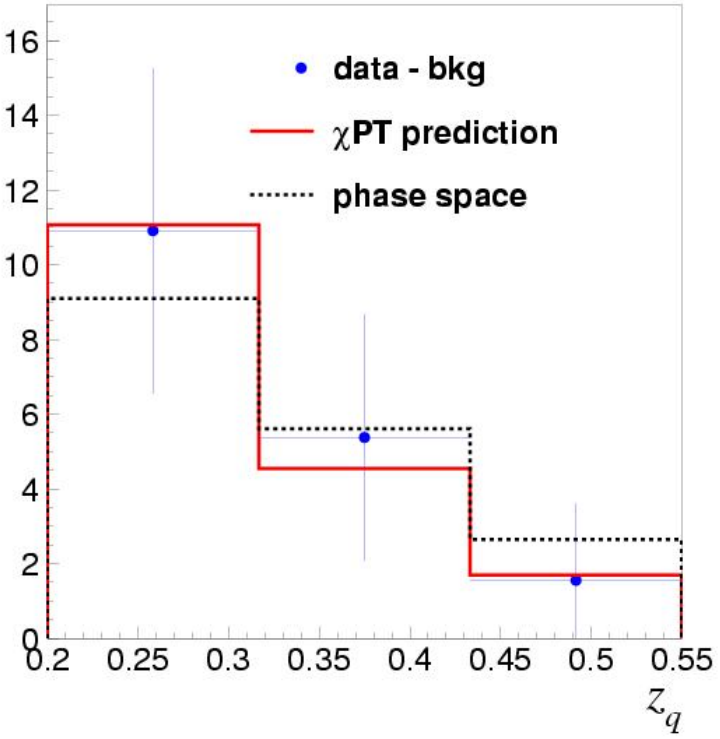
•First observation :

$BR(K_S \to \pi^0\gamma\gamma)_{Zq>0.2} = (4.9 \pm 1.6_{stat} \pm 0.8_{syst})*10^{-8}$

Prediction from χPT : $BR(K_S \to \pi^0\gamma\gamma)_{Zq>0.2} = 3.8*10^{-8}$

31.0 ± 5.6 events in the signal region

13.6 ± 2.8 estimated bckg events to be subtracted

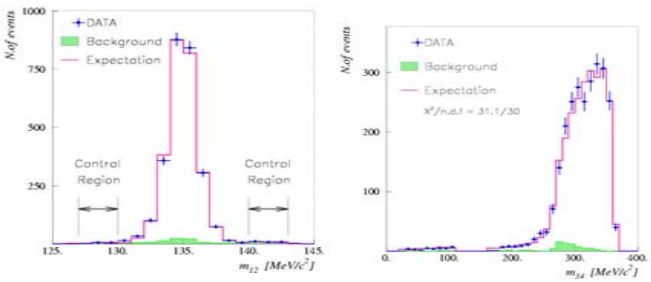


- Insufficient statistics to verify the chiral structure of the vertex

$K_L \to \pi^0 \gamma\gamma$

- **Motivation**
  - At one loop χPT ($O(p^4)$) 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 a_v, to be measured, which determines the CPC amplitude to $K_L \to \pi^0 e^+e^-$

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



χPT prediction of $O(p^6)$

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

$K_L \to \pi^0 \gamma\gamma$ - Results

- NA48 fit: $a_v = -0.46 \pm 0.03_{st} \pm 0.03_{sy} \pm 0.02_{th}$
- Using this a_v BR $(K_L \to \pi^0 \gamma\gamma) = (1.36 \pm 0.03_{st} \pm 0.03_{sy} \pm 0.03_{norm})*10^{-6}$
- 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 $K_L \to \pi^0 e^+e^-$

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

KTeV Phys. Lett. B536 (2002) 229

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

$a_v = -0.72 \pm 0.08$

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

$K_L \to \pi^+ \pi^- \pi^0 \gamma$ and $K_L \to \pi^+ \pi^- \pi^0 e^+ e^-$

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

$K_L \to \pi^+ \pi^- \pi^0 \gamma$ and $K_L \to \pi^+ \pi^- \pi^0 e^+ e^-$

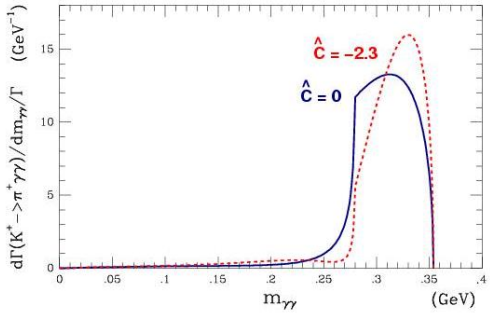
- $K_L \to \pi^+ \pi^- \pi^0 \gamma$
  - 2853 candidates, normalized to $K_L \to \pi^+ \pi^- \pi^0$
  - BR(E_γ > 10 MeV) = $(1.70 \pm 0.03_{st} \pm 0.04_{sy} \pm 0.03_{norm}) \cdot 10^{-4}$
- $K_L \to \pi^+ \pi^- \pi^0 e^+ e^-$
  - 132 candidates, normalized to $K_L \to \pi^+ \pi^- \pi^0{}_D$
  - Estimated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

An excursus: $\eta \to \pi^0 \gamma\gamma$

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

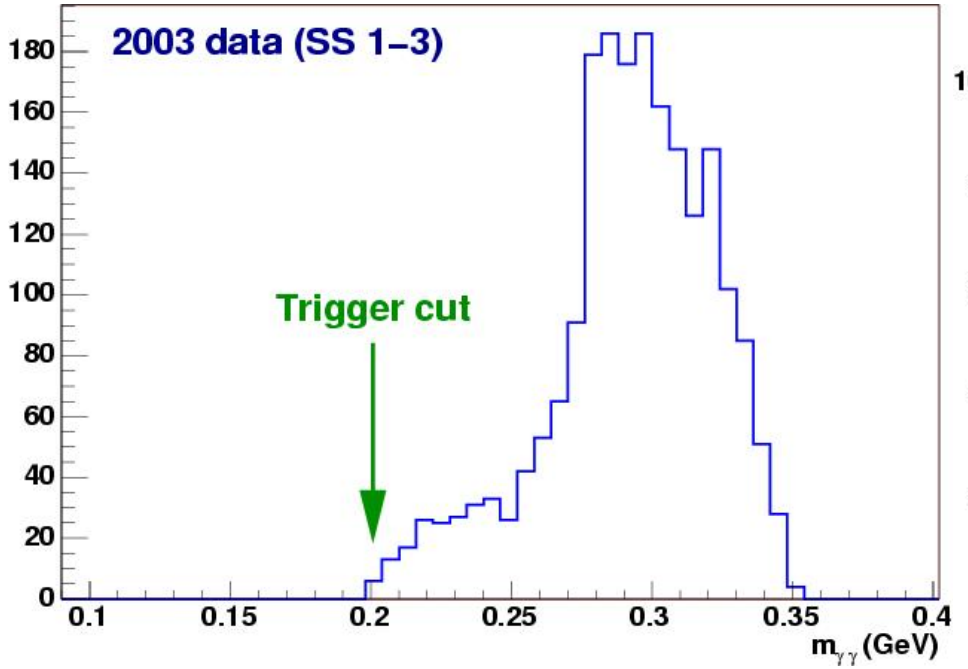
$K^+ \to \pi^+\gamma\gamma$

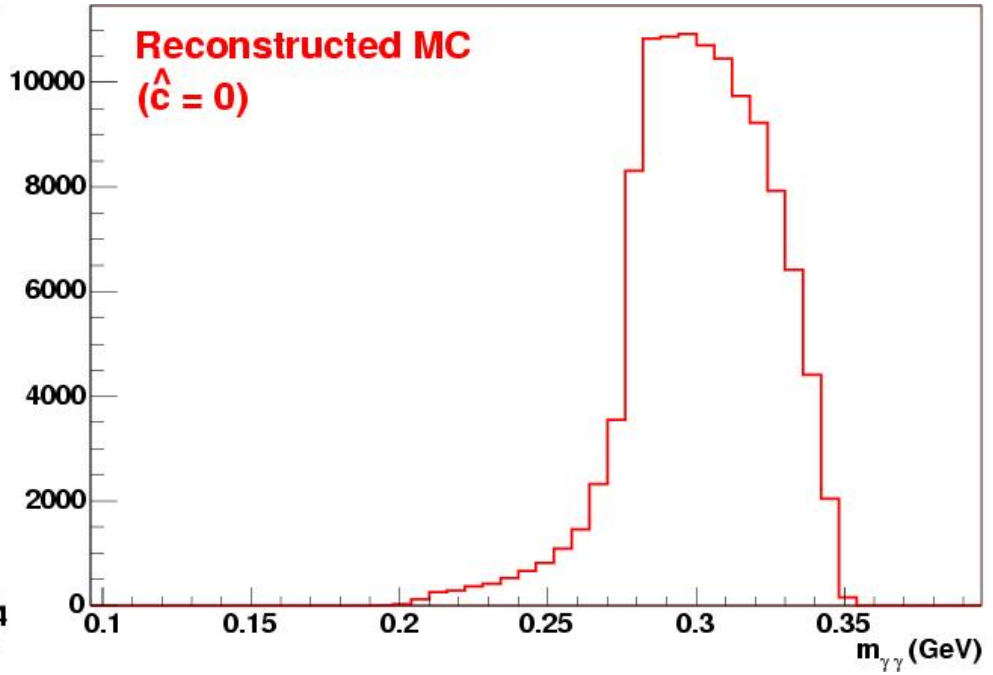
- Interesting test of χPT
  - No tree level $O(p^2)$ contribution
  - Leading contributions at $O(p^4)$
    - With one undetermined constant c_{hat} of $O(1)$
  - Interplay with $K_L \to \pi^0 \gamma \gamma$



  - 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 ± 3.3 events for 100 MeV/c < P_π < 180 MeV/c
  - BR = $(6.0 \pm 1.5_{st} \pm 0.7_{sy}) \cdot 10^{-7}$
- 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

$K^+ \to \pi^+\gamma\gamma$





$K^+ \to \pi^+ e^+ e^-$

- 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

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

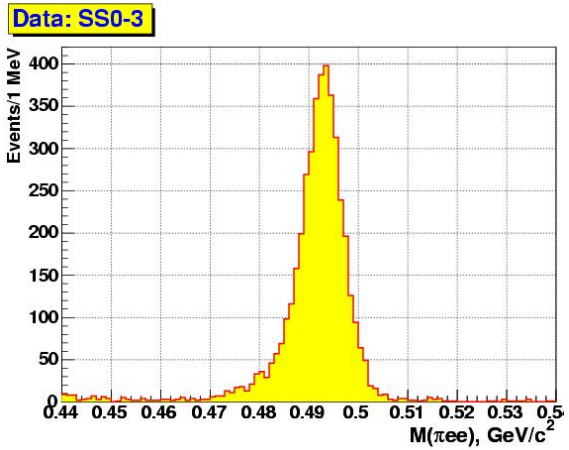
  $BR=(2.94 \pm 0.05_{st} \pm 0.13_{sy} \pm 0.05_{model}) \cdot 10^{-7}$

  Consistent with χPT 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

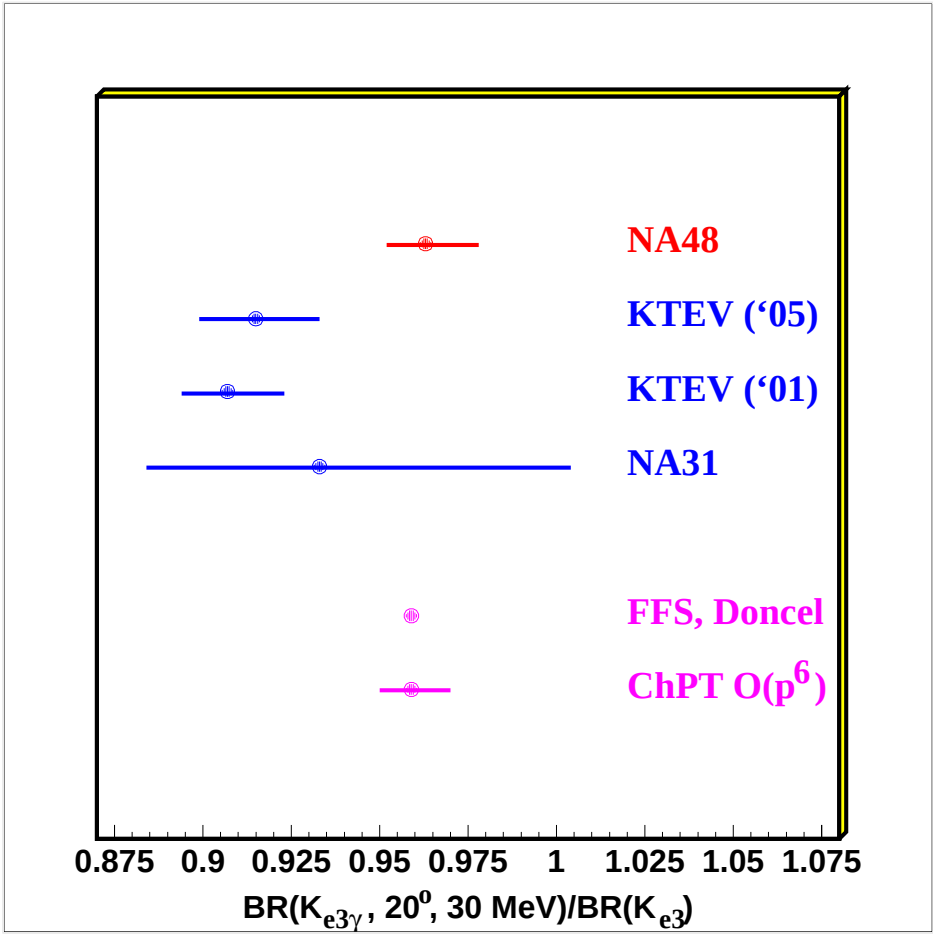
- K_L and $K^{\pm}$ semileptonic radiative decays give info on the kaon structure
  In $K^{\pm}$ study also T-odd variables→CPV…
- The ratio R (with constraints to avoid divergences) is predicted to be between 0.95% and 0.99%
- Two different theoretical approaches
  - Current algebra (Fearing, Fischbach, Smith) (Doncel)
  - χPT continuosly improved. Latest estimate (0.96±0.01)%
  - Both basically agree

$$R = \frac{\Gamma(K_{e3\gamma}, E^*_\gamma > 30\,MeV\,, \theta^*_{e\gamma} > 20^\circ)}{\Gamma(K_{e3})}$$

- A recent measurement from KTeV gives $R=(0.908\pm0.008^{+0.013}_{-0.012})\%$, in disagreement with the prediction

Radiative semileptonics

- NA48 results
  - 18977 $K_{e3\gamma}$ events
  - 6 million K_{e3} events
  - Less than 1% background
- $R=(0.964\pm0.008^{+0.011}_{-0.009})\%$
- In full agreement with the predictions
- Analysis in progress by NA48 on $K^{\pm}$ radiative semileptonic decay



Radiative semileptonics

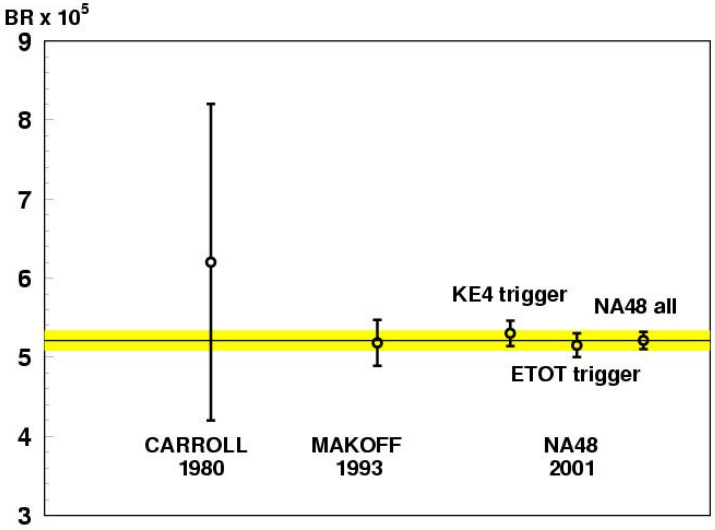
- For completeness I must cite the ISTRA+ work
  - To be treated in more detail by V. Duk, just in 10 minutes…
  - First observation of $K^- \to \mu^- \pi^0 \gamma \nu$
    - *Good agreement with χPT*
  - High statistics studies of $K^- \to e^- \pi^0 \gamma \nu$
    - *Almost 5000 events with 20% background*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

K_{e4}

- Another good test for χPT
  - Determination of $\pi\pi$ partial wave expansion parameters
    - $\pi\pi$ scattering length can be related to the quark condensate
    - Complete set of χPT 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: $K_L \to \pi^{\pm}\pi^0 e^{\pm}\nu$
  - Phys. Lett. B595 (2004) 75
  - 5500 events with ~1% background
  - Measure BR and form factors
    - $BR=(5.21\pm0.07_{st}\pm0.09_{sy}) \cdot 10^{-5}$
    - $f_s=(0.052\pm0.006_{st}\pm0.002_{sy})$
    - $f_p=(-0.051\pm0.011_{st}\pm0.005_{sy})$
    - $\lambda_g=(0.087\pm0.019_{st}\pm0.006_{sy})$
    - $h=(-0.32\pm0.12_{st}\pm0.07_{sy})$



  - The chiral coupling parameter L_3 is estimated to be
    - $L_3 = (-4.1\pm0.2) \cdot 10^{-3}$

Pending analyses

- NA48
  - $K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma$
  - $K^{\pm} \to \pi^{\pm} \pi^{-}\pi^{+}\gamma$
  - $K^{\pm} \to \pi^{\pm} \pi^{0}\gamma\gamma$
- Kloe
  - $K_S \to \gamma\gamma$
  - $K_L \to \pi e \nu \gamma$
- KTeV
  - $K_L \to \pi^{0}\gamma\gamma$
  - $K_L \to \pi e \nu\ e^{+}e^{-}$ ← Not pending anymore…
  - $\pi^{0} \to e^{+}e^{-}$ ← H. Nguyen presented the results yesterday…

…and may be more

Istra+ is also active

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 χPT 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