

Radiative kaon decays: results from NA48/2 at CERN

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on behalf of the **NA48/2** collaboration

(Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Florence, Mainz,
Northwestern, Perugia, Pisa, Saclay, Siegen, Turin, Vienna)

Outline:

- 1) $K^\pm \rightarrow \pi^\pm e^+ e^-$: spectrum and BR with full data set;
- 2) $K^\pm \rightarrow \pi^\pm \gamma \gamma$: measurement of BR assuming a ChPT spectrum shape;
- 3) $K^\pm \rightarrow \pi^\pm \gamma e^+ e^-$: spectrum and BR analysis with full data set;
- 4) Conclusions.



Flavianet Kaon Workshop
Anacapri • June 12th, 2008



NA48/NA62 experiments

NA48

1997: ϵ'/ϵ run K_L+K_S

1998: K_L+K_S

1999: K_L+K_S | K_S HI

2000: K_L only | K_S HI

2001: K_L+K_S | K_S HI

NA48/1

2002: K_S /hyperons HI

NA48/2

2003: K^+/K^-

2004: K^+/K^-

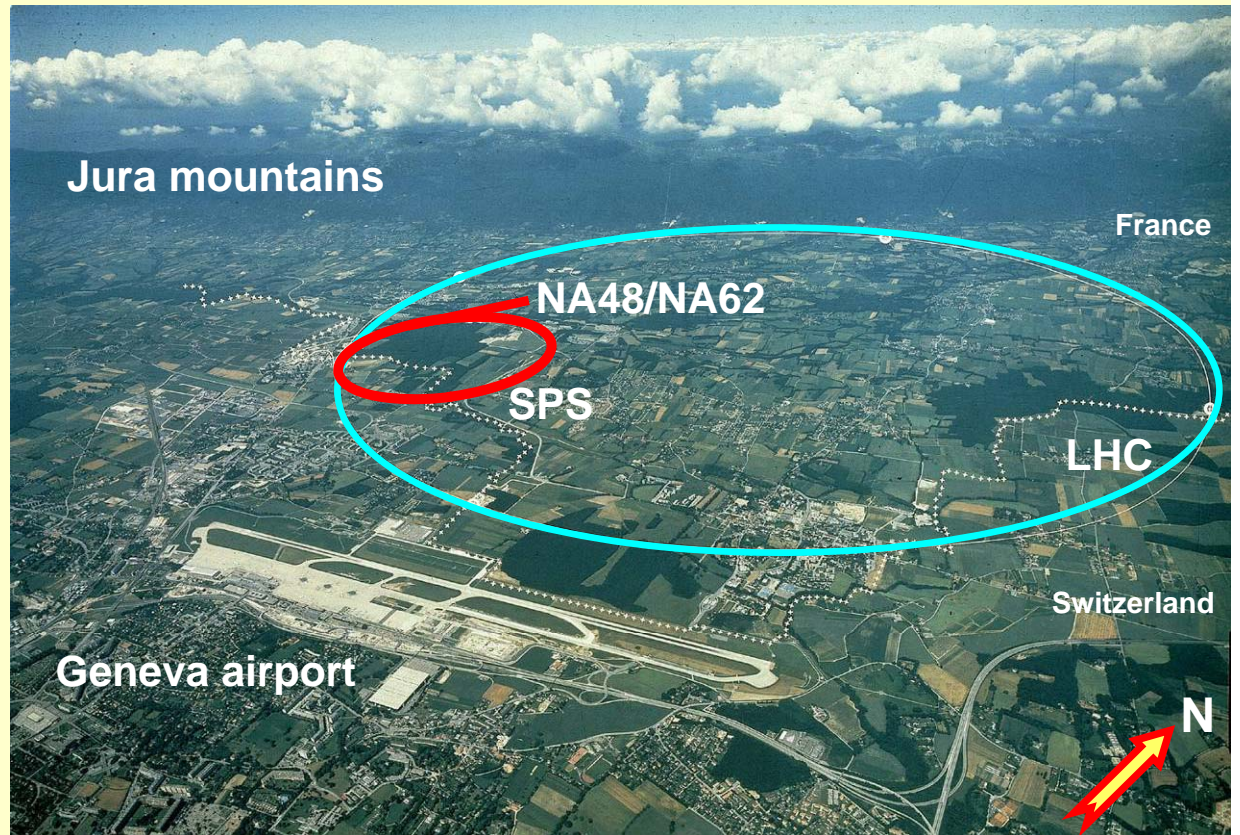
NA62
(phase I)

2007: $K_{e2}^+/K_{\mu2}^+$ | tests

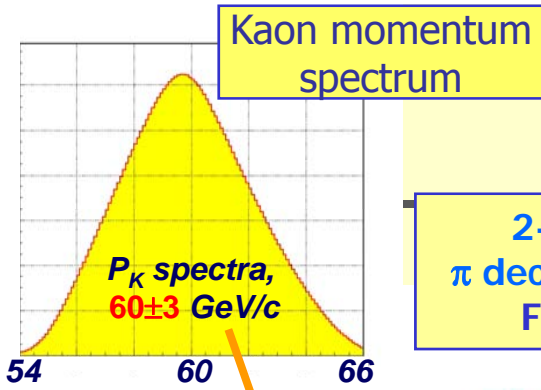
NA62
(proposed)

2006-2010:
design & construction
2011:
start of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ run

NA48/NA62: a series of experiments
Present-day CERN kaon physics programme

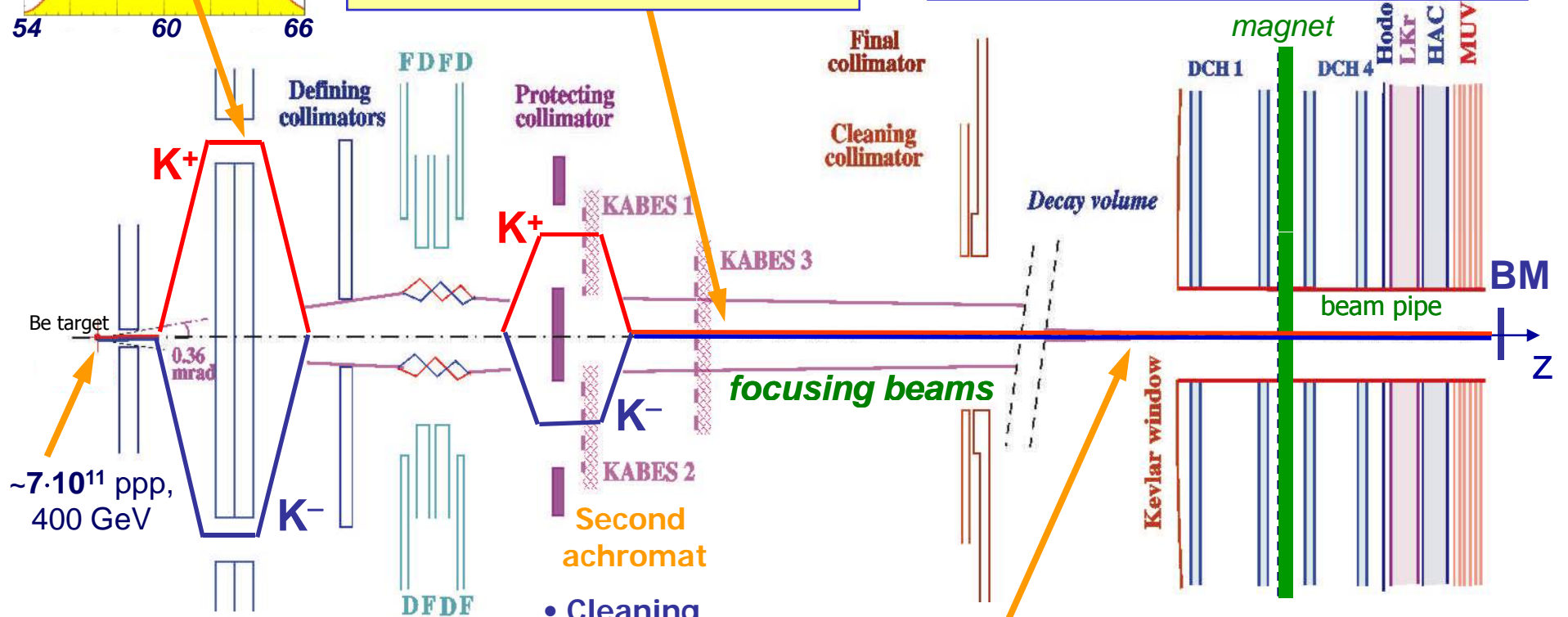


NA48/2: kaon beam line



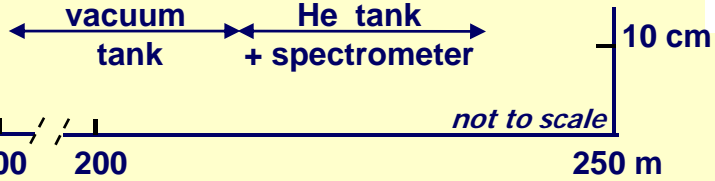
2-3M K/spill ($\pi/K \sim 10$),
 π decay products stay in pipe.
 Flux ratio: $K^+/K^- \approx 1.8$

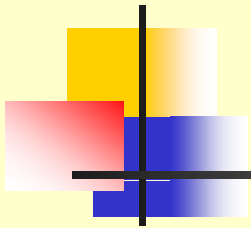
Simultaneous K^+ and K^- beams:
 large **charge symmetrization** of
 experimental conditions



- Front-end achromat**
 - Momentum selection
- Quadrupole quadruplet**
 - Focusing
 - μ sweeping
- Cleaning**
- Beam spectrometer (momentum resolution $\sim 0.7\%$)**

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

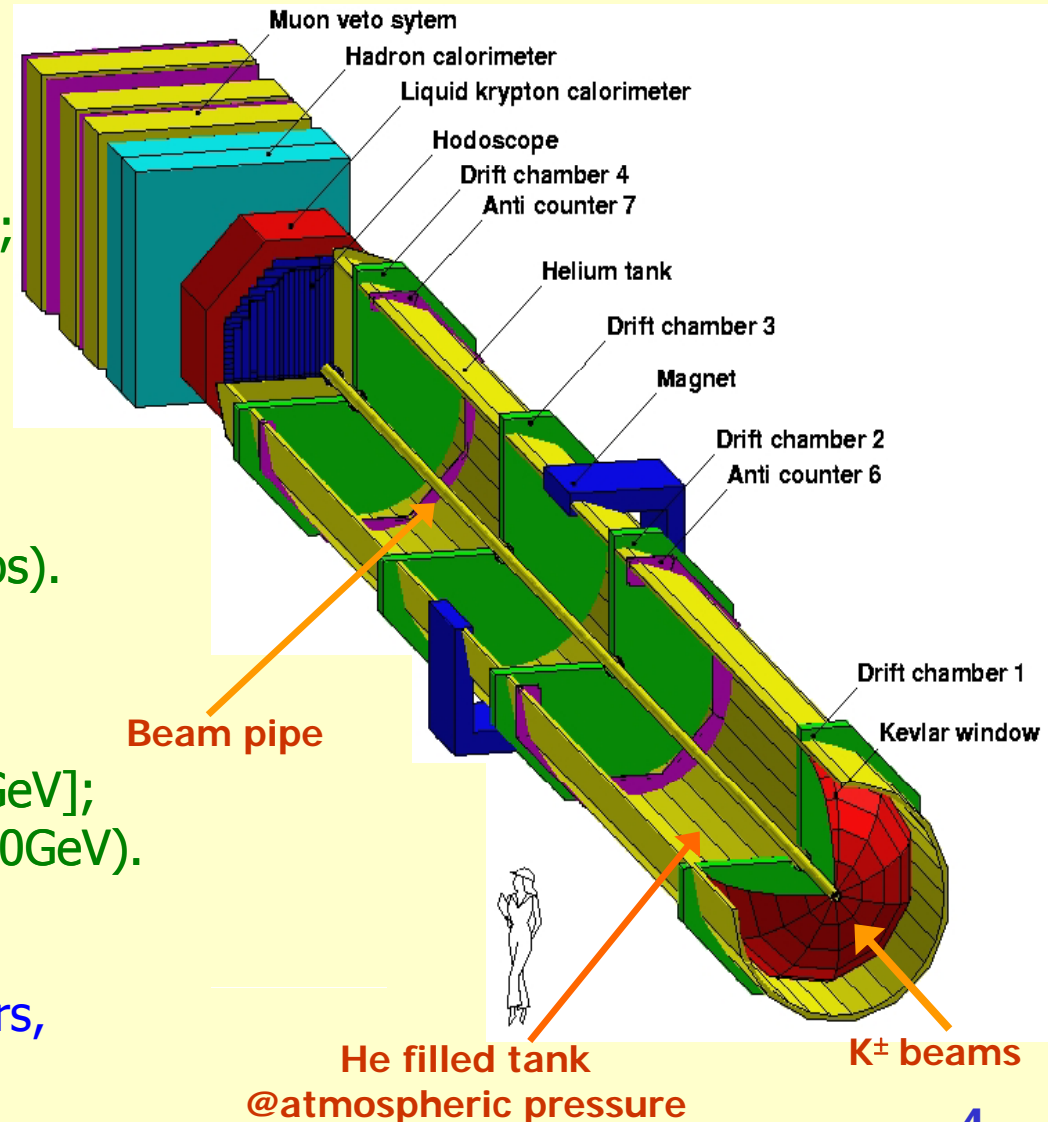




The NA48 detector

Main detector components:

- **Magnetic spectrometer (4 DCHs):**
4 views/DCH: redundancy \Rightarrow efficiency;
used in trigger logic;
 $\Delta p/p = 1.0\% + 0.044\% \cdot p$ [GeV/c].
- **Hodoscope**
fast trigger;
precise track time measurement (150ps).
- **Liquid Krypton EM calorimeter (LKr)**
High granularity, quasi-homogenous;
 $\sigma_E/E = 3.2\%/E^{1/2} + 9\%/E + 0.42\%$ [GeV];
 $\sigma_x = \sigma_y = 0.42/E^{1/2} + 0.6\text{mm}$ (1.5mm@10GeV).
Used for γ detection and particle ID.
- **Hadron calorimeter, muon veto counters, photon vetoes.**



NA48/2 data taking: completed

A view of the NA48/2 beam line



2003 run: ~ 50 days

2004 run: ~ 60 days

$K_{3\pi}$ statistics in 2 years:

$$K^{\pm} \rightarrow \pi^{-}\pi^{+}\pi^{\pm}: \sim 4 \cdot 10^9$$

$$K^{\pm} \rightarrow \pi^0\pi^0\pi^{\pm}: \sim 1 \cdot 10^8$$

Rare K^{\pm} decays:
BRs down to 10^{-9}
can be measured

>200 TB of data recorded

$K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$ decay

[Combined shape and BR analysis,
preliminary result]

Motivation & theory

$K^\pm \rightarrow \pi^\pm \gamma^* \rightarrow \pi^\pm |^+ |^-$: suppressed FCNC process proceeding through one-photon exchange. Weak interactions at low energy, ChPT tests.

$$d\Gamma_{\pi ee}/dz \sim P(z) \cdot |W(z)|^2 \quad z=(M_{ee}/M_K)^2, P(z) \text{ is a phase space factor}$$

Form-factor: [(2) ^{G. D'Ambrosio et al.} JHEP 8 (1998) 4, (3) ^{A. Dubnickova et al.} hep-ph/061175]

- (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) Dubna ChPT: $W(z) = W(M_a, M_\rho, z)$

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

Goals: 1) model-independent BR($z > 0.08$) in accessible kinematic range;
2) parameters of models and BRs in the full kinematic range.



Principal selection criteria

The $K^\pm \rightarrow \pi^\pm e^+ e^-$ is measured normalizing to $K^\pm \rightarrow \pi^\pm \pi^0_D \rightarrow \pi^\pm e^+ e^- \gamma$.
Thus particle ID efficiencies cancel in the first order.

Common selection criteria:

3-track vertex [consistent in space/time],
one π candidate, two opposite sign electron candidates.
Electron (pion) ID based on E deposition : $E/p > 0.95$ ($E/p < 0.85$).



Signal selection:

Kinematic suppression of $\pi^\pm \pi^0_D$
background: $M_{ee} > 140 \text{ MeV}/c^2$.
Limitations on reconstructed
 $\pi^\pm e^+ e^-$ invariant mass,
total & transverse momentum



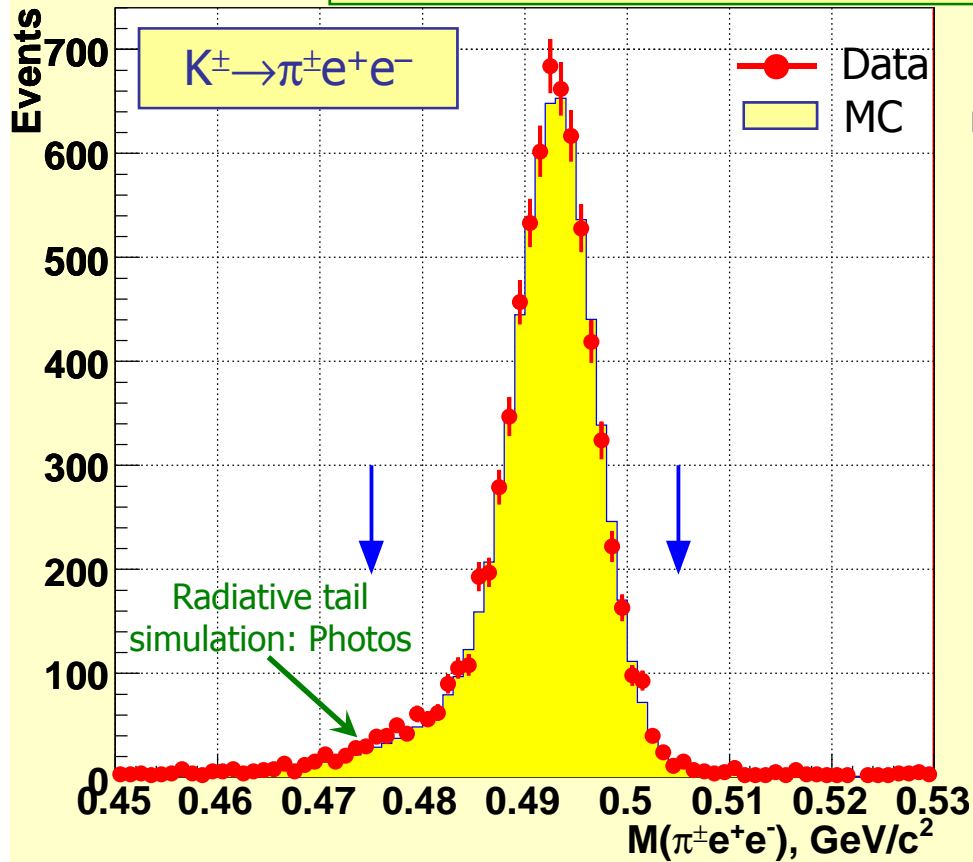
Normalization selection:

Selection of good γ candidate.
Limitations on reconstructed
 $e^+ e^- \gamma$ and $\pi^\pm e^+ e^- \gamma$ masses,
total & transverse momentum.

Signal & normalization samples

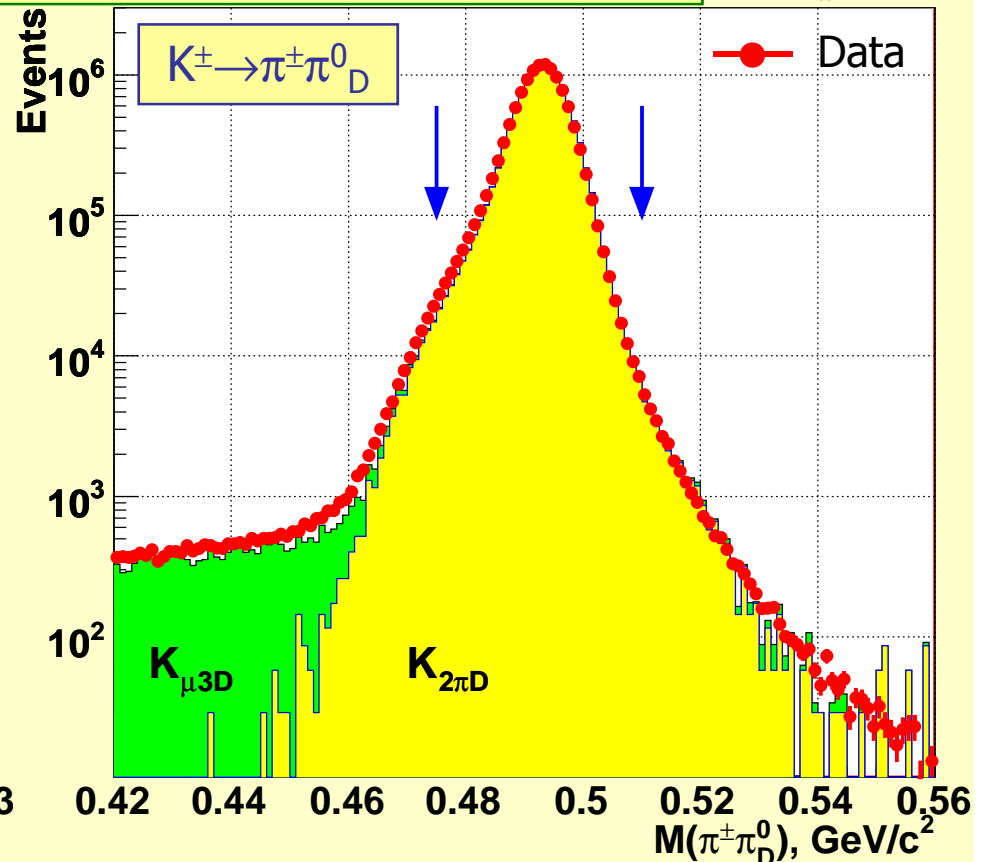
Kaon decay flux (2003+2004): $\Phi_K = 1.70 \times 10^{11}$

Flavianet '08
BR($K_{2\pi}$) used



7146 candidates

Background/Signal = 0.6%
($K^\pm \rightarrow \pi^\pm \pi^0_D$, $K^\pm \rightarrow \pi^0_D e^\pm \nu$ + particle misID,
subtracted with LFV same-sign candidates)

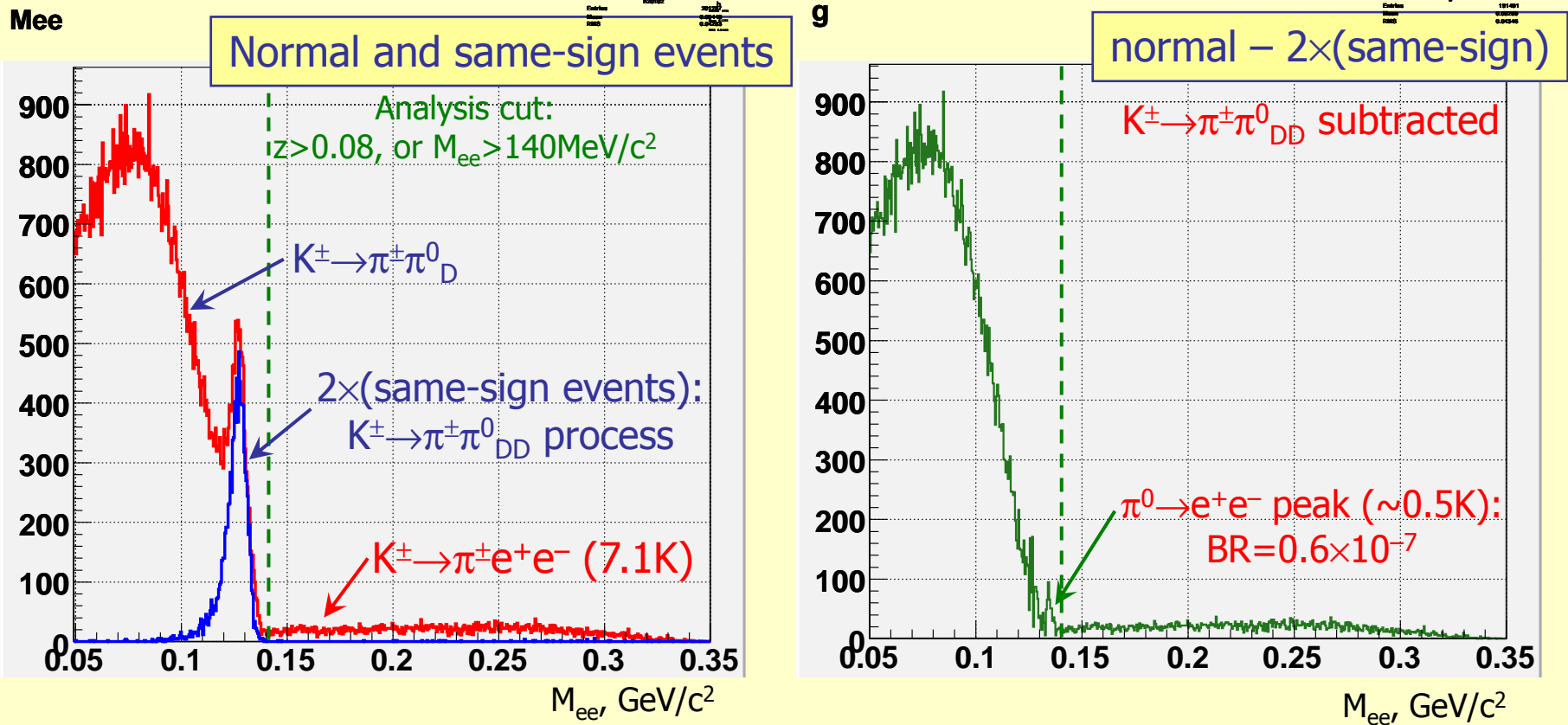


12.23 mln candidates

Background/Signal = 0.15%
($K^\pm \rightarrow \pi^0_D \mu^\pm \nu$, subtracted with simulation)

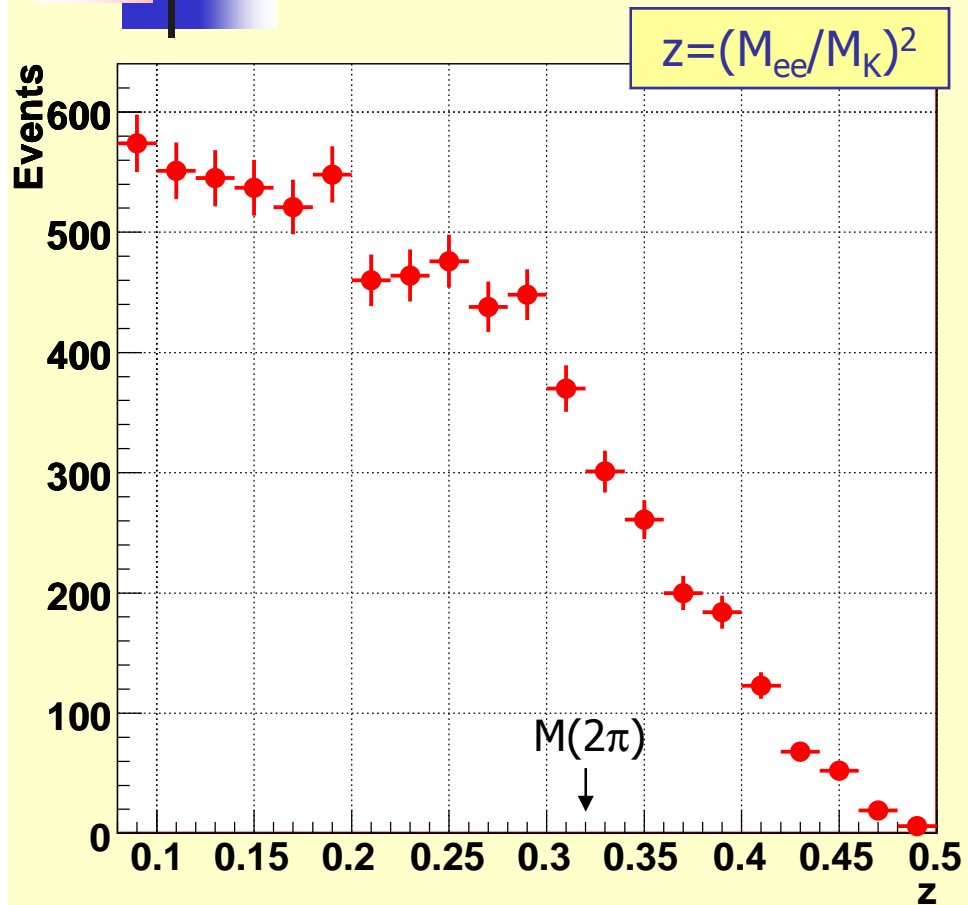
Accessible M_{ee} region

All analysis cuts except the M_{ee} cut applied

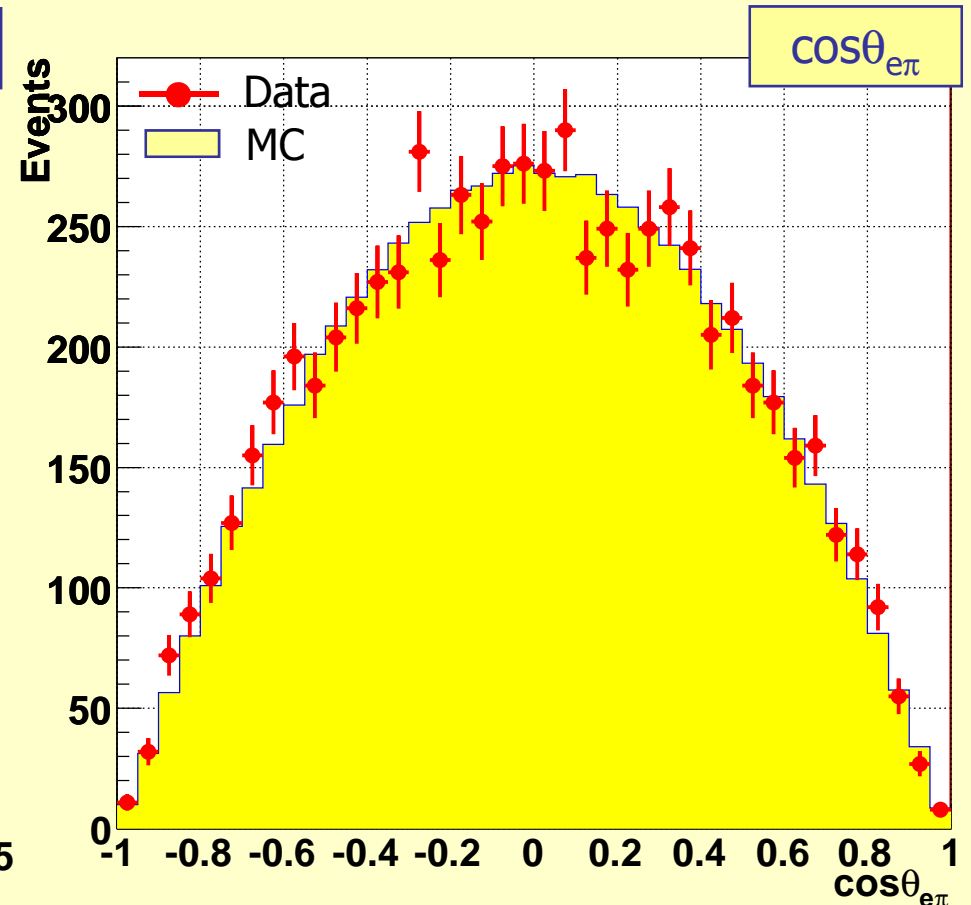


- The region $M_{ee} < 140 \text{ MeV}/c^2$ is dominated by background and not accessible;
- Subtraction of $K^{\pm} \rightarrow \pi^{\pm} \pi^0_{DD}$ reveals the $\pi^0 \rightarrow e^+ e^-$ signal (~ 500 events).

Kinematic variables: $(z, \cos\theta_{e\pi})$

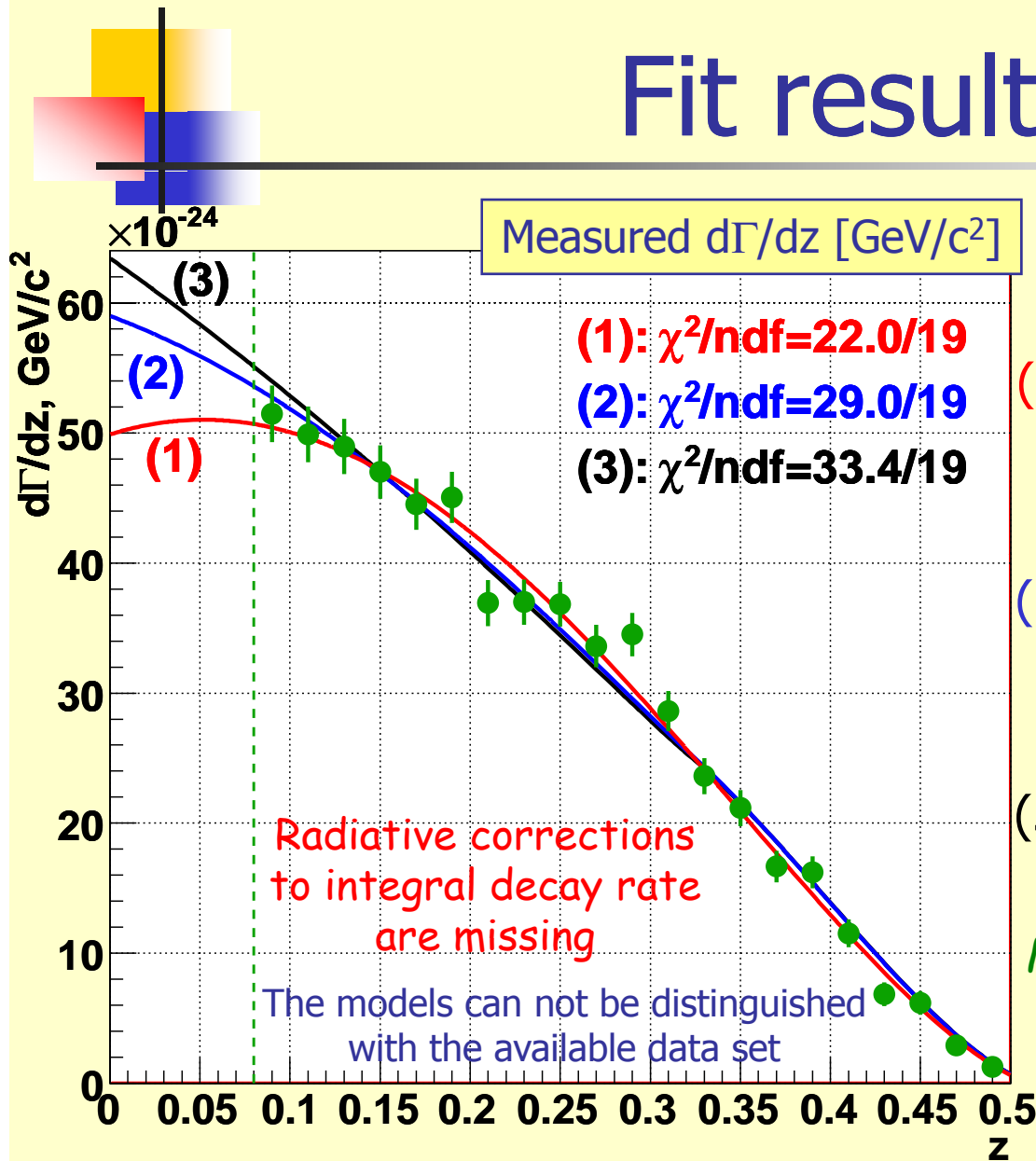


z distribution is sensitive to the form-factor and contains the dynamical information:
 $d\Gamma/dz \sim P(z) \times |W(z)|^2$.



Decay via one photon exchange:
 $d\Gamma/d\theta \sim \sin^2\theta = (1 - \cos^2\theta)$,
 θ = angle between (e^+, π) in (e^+, e^-) frame.
 No dynamical information in this projection.

Fit results [preliminary]



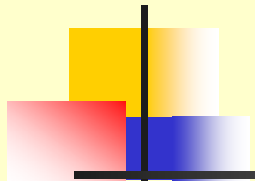
"Raw" values: no BKG/trigger corr., statistical errors only shown

- (1) $\left\{ \begin{array}{l} \delta = 2.42 \pm 0.15 \\ f_0 = 0.529 \pm 0.012 \\ \rho(\delta, f_0) = -0.963 \end{array} \right.$
- (2) $\left\{ \begin{array}{l} a_+ = -0.576 \pm 0.012 \\ b_+ = -0.830 \pm 0.053 \\ \rho(a_+, b_+) = -0.913 \end{array} \right.$
- (3) $\left\{ \begin{array}{l} M_a = (0.951 \pm 0.028) \text{ GeV} \\ M_\rho = (0.705 \pm 0.010) \text{ GeV} \\ \rho(M_a, M_\rho) = 0.998 \end{array} \right.$

Model-dependent BRs (in full range) computed using parameters, errors and correlation coefficients:

$$\begin{aligned} \text{BR}_1 &= (3.04 \pm 0.04_{\text{stat}}) \times 10^{-7} \\ \text{BR}_2 &= (3.13 \pm 0.04_{\text{stat}}) \times 10^{-7} \\ \text{BR}_3 &= (3.17 \pm 0.04_{\text{stat}}) \times 10^{-7} \end{aligned} \quad 12$$

Model-independent $\text{BR}_{\text{mi}}(z > 0.08) = 2.28 \times 10^{-7}$
 computed by integrating $d\Gamma/dz$



Corrections/uncertainties

Parameter	Electron ID	Beam simulation	Radiative corrections	Background to $K^\pm \rightarrow \pi^\pm e^+ e^-$	Trigger inefficiency	Fitting procedure	External (PDG)
$BR_{mi} \times 10^7$	0.02	0.01	0.01	-0.01 ± 0.01	-0.01 ± 0.01	0	0.06
Model (1): linear form-factor							
δ	0.01	0.04	0.05	-0.04 ± 0.04	-0.03 ± 0.03	0.03	0
f_0	0.001	0.006	0.004	$+0.002 \pm 0.002$	$+0.001 \pm 0.001$	0.003	0.007
$BR_1 \times 10^7$	0.02	0.02	0.01	-0.01 ± 0.01	-0.01 ± 0.01	0.02	0.08
Model (2): ChPT form-factor [D'Ambrosio, Ecker, Isidori, Portoles, hep-ph/9808289]							
a_+	0.001	0.005	0.004	-0.001 ± 0.001	-0.002 ± 0.002	0.004	0.007
b_+	0.009	0.015	0.022	$+0.017 \pm 0.017$	$+0.015 \pm 0.015$	0.010	0.017
$BR_2 \times 10^7$	0.02	0.02	0.01	-0.01 ± 0.01	-0.01 ± 0.01	0.02	0.08
Model (3): Dubna ChPT [Dubnickova et al., hep-ph/0611175]							
M_a/GeV	0.004	0.009	0.009	$+0.008 \pm 0.008$	$+0.006 \pm 0.006$	0.006	0.002
M_ρ/GeV	0.002	0.003	0.004	$+0.003 \pm 0.003$	$+0.003 \pm 0.003$	0.002	0.002
$BR_3 \times 10^7$	0.02	0.02	0.01	-0.01 ± 0.01	-0.01 ± 0.01	0.02	0.08

Results [preliminary]

$$BR_{mi} \times 10^7 = 2.26 \pm 0.03_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.06_{\text{ext}} = 2.26 \pm 0.08$$

$$\delta = 2.35 \pm 0.15_{\text{stat}} \pm 0.09_{\text{syst}} = 2.35 \pm 0.18$$

$$f_0 = 0.532 \pm 0.012_{\text{stat}} \pm 0.008_{\text{syst}} \pm 0.007_{\text{ext}} = 0.532 \pm 0.016$$

$$BR_1 \times 10^7 = 3.02 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.08_{\text{ext}} = 3.02 \pm 0.10$$

$$a_+ = -0.579 \pm 0.012_{\text{stat}} \pm 0.008_{\text{syst}} \pm 0.007_{\text{ext}} = -0.579 \pm 0.016$$

$$b_+ = -0.798 \pm 0.053_{\text{stat}} \pm 0.037_{\text{syst}} \pm 0.017_{\text{ext}} = -0.798 \pm 0.067$$

$$BR_2 \times 10^7 = 3.11 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.08_{\text{ext}} = 3.11 \pm 0.10$$

$$M_a = 0.965 \pm 0.028_{\text{stat}} \pm 0.018_{\text{syst}} \pm 0.002_{\text{ext}} = 0.965 \pm 0.033 \text{ [GeV/c]}$$

$$M_\rho = 0.711 \pm 0.010_{\text{stat}} \pm 0.007_{\text{syst}} \pm 0.002_{\text{ext}} = 0.711 \pm 0.013 \text{ [GeV/c]}$$

$$BR_3 \times 10^7 = 3.15 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.08_{\text{ext}} = 3.15 \pm 0.10$$

Including uncertainty due to the model dependence,

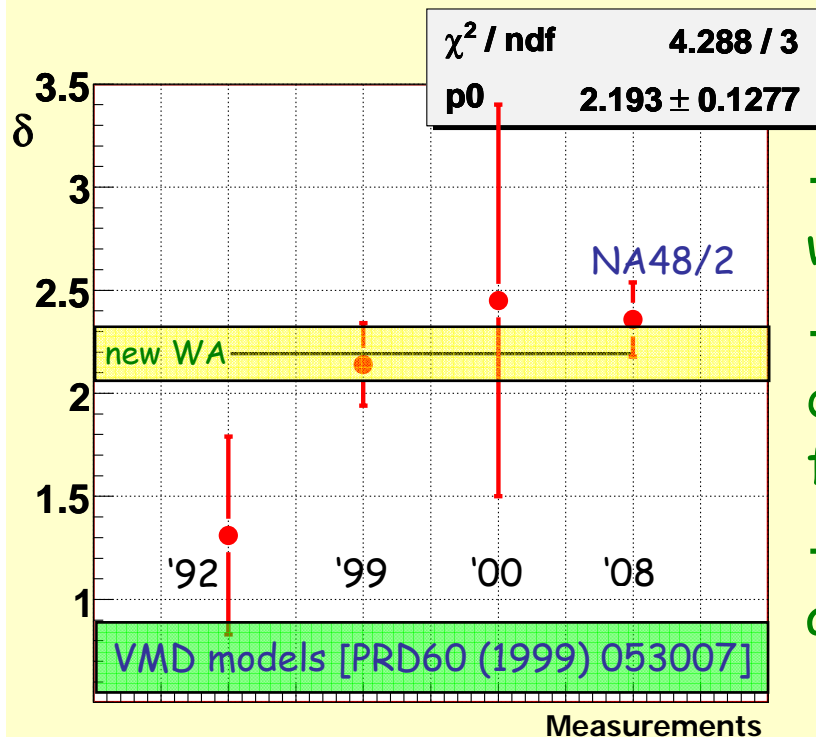
$$BR = (3.08 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.08_{\text{ext}} \pm 0.07_{\text{model}}) \times 10^{-7} = (3.08 \pm 0.12) \times 10^{-7}$$

CPV parameter (first measurement; correlated K^+/K^- uncertainties excluded):

$$\Delta(K_{\pi ee}^\pm) = (BR^+ - BR^-) / (BR^+ + BR^-) = (-2.1 \pm 1.5_{\text{stat}} \pm 0.3_{\text{syst}}) \%$$

Comparison: FF slope δ

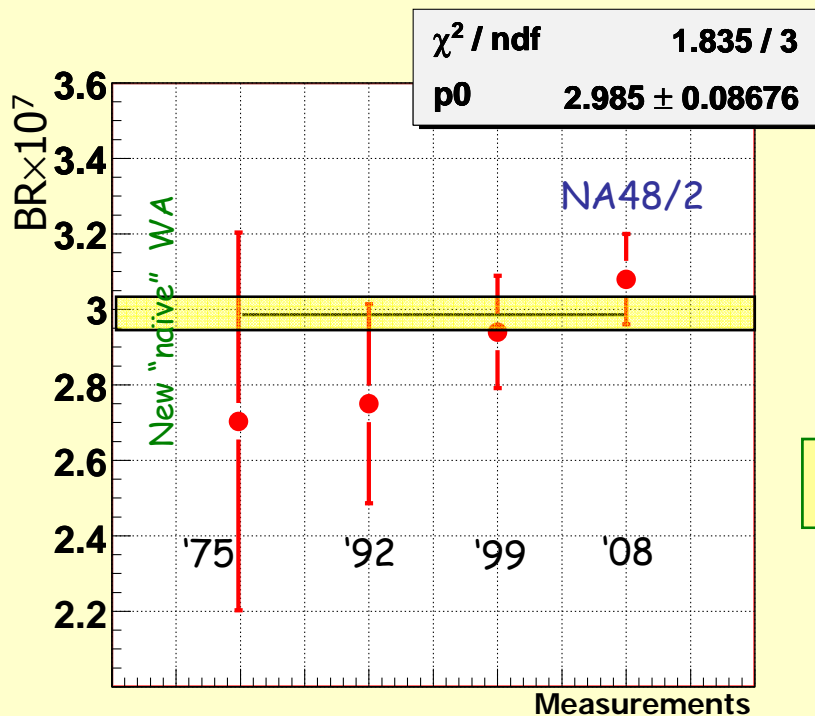
Measurement	Process	Result
Alliegro et al., PRL 68 (1992) 278	$K^+ \rightarrow \pi^+ e^+ e^-$	1.31 ± 0.48
Appel et al. [E865], PRL 83 (1999) 4482	$K^+ \rightarrow \pi^+ e^+ e^-$	2.14 ± 0.20
Ma et al. [E865], PRL 84 (2000) 2580	$K^+ \rightarrow \pi^+ \mu^+ \mu^-$	$2.45^{+1.30}_{-0.95}$
NA48/2 preliminary (2008)	$K^\pm \rightarrow \pi^\pm e^+ e^-$	2.35 ± 0.18



- NA48/2 measurement of δ is compatible with the earlier results, has high precision;
- A contradiction of the data to the meson dominance models observed earlier is further confirmed;
- NA48/2 values of (f_0, a_+, b_+) are in agreement with BNL E865 ones.

BR in full kinematic range

Measurement	Sample	BR×10 ⁷
Bloch et al., PL 56 (1975) B201	41 (K ⁺)	2.70±0.50
Alliegro et al., PRL 68 (1992) 278	500 (K ⁺)	2.75±0.26
Appel et al. [E865], PRL 83 (1999) 4482	10,300 (K ⁺)	2.94±0.15
NA48/2 preliminary (2008)	7,100 (K [±])	3.08±0.12



Comparison of E865 vs NA48/2 results:
 dismissing correlated uncertainties
 (normalization and model dependence)
 and using the same PDG BR(K→2π)

BR [E865, linear FF] = 2.88±0.11;
 BR [NA48, linear FF] = 3.056±0.056.

$\delta(\text{BR}) = (0.176 \pm 0.123) \rightarrow 1.4\sigma$ difference
 [15% probability]

Ongoing activities, plans:

- Minor refinements of the analysis.
- Radiative correction to decay rate.
- Combined fit with $K^{\pm} \rightarrow \pi^{\pm} \mu^+ \mu^-$ decay.

$K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$ and $K^{\pm} \rightarrow \pi^{\pm} \gamma e^{+} e^{-}$ decays

[$K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$: BR measurement with partial data set;
shape analysis not completed yet]

[$K^{\pm} \rightarrow \pi^{\pm} \gamma e^{+} e^{-}$: final result published, PLB659 (2008) 493]

$K^\pm \rightarrow \pi^\pm \gamma \gamma$ theory

Radiative non-leptonic decays $K^\pm \rightarrow \pi^\pm \gamma \gamma$ & $K^\pm \rightarrow \pi^\pm \gamma \gamma^* \rightarrow \pi^\pm \gamma e^+ e^-$:
a stringent test of the Chiral Perturbation Theory

$$\frac{\partial^2 \Gamma}{\partial y \partial z} = \frac{m_{K^+}}{(8\pi)^3} \left[z^2 (|A + B|^2 + |C|^2) + \left(y^2 - \frac{1}{4} \lambda(1, r_\pi^2, z) \right)^2 (|B|^2 + |D|^2) \right]$$

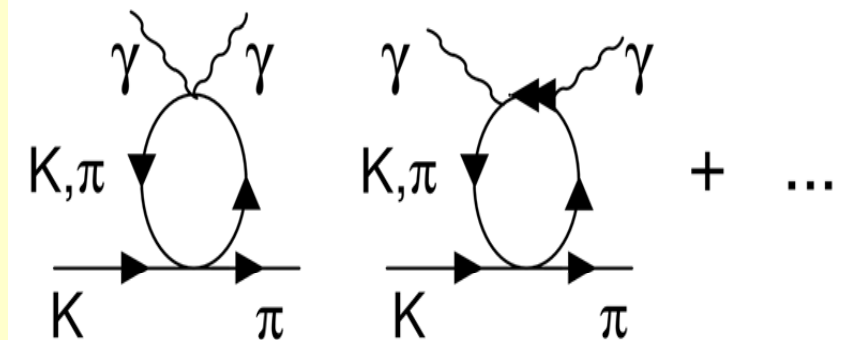
$$y = \frac{P \cdot (q_1 - q_2)}{M_K^2} \quad z = \frac{(q_1 + q_2)^2}{M_K^2} = \frac{M_{\gamma\gamma}^2}{M_K^2}$$

P = pion 4-momentum
 $q_{1,2}$ = photon 4-momenta

(only z is dynamically relevant)

A, B, C, D depend on z and the \hat{c} parameter

$$d\Gamma/dz = f(\hat{c}, z)$$

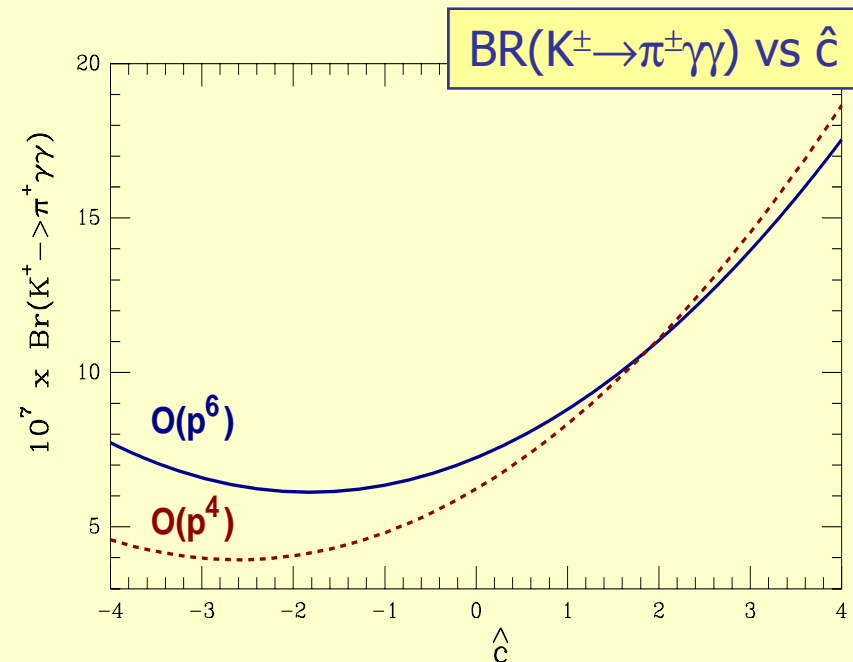
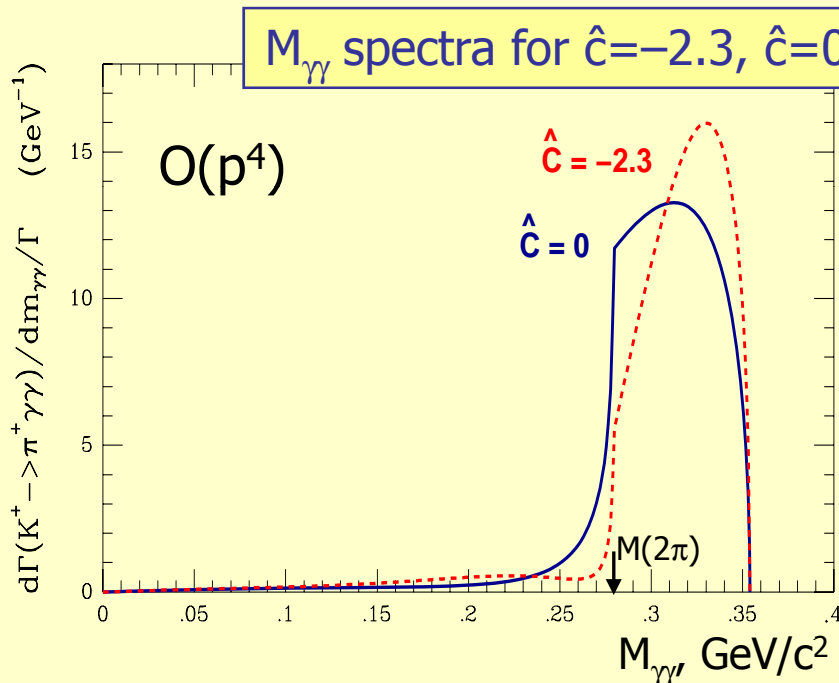


- ChPT $O(p^4)$, $O(p^6)$ calculations [D'Ambrosio, Portolés, PLB386 (1996) 403];
- Both decay spectrum and rate strongly depend on the single \hat{c} parameter;
- The $M_{\gamma\gamma}$ spectrum has a pronounced cusp-like behaviour at 2π threshold.

Spectrum & rate

$$BR(K^\pm \rightarrow \pi^\pm \gamma\gamma) = (5.26 + 1.64 \cdot \hat{c} + 0.32 \cdot \hat{c}^2 + 0.49) \times 10^{-7}$$

$$BR(K^\pm \rightarrow \pi^\pm \gamma\gamma) \geq 4 \times 10^{-7}$$



- ChPT $O(p^4)$, $O(p^6)$ calculations [D'Ambrosio, Portolés, PLB386 (1996) 403];
- Both decay spectrum and rate strongly depend on the single \hat{c} parameter;
- The $M_{\gamma\gamma}$ spectrum has a pronounced cusp-like behaviour at 2π threshold.

$K^\pm \rightarrow \pi^\pm \gamma \gamma$ analysis

Data set: $\sim 40\%$ of the full sample.

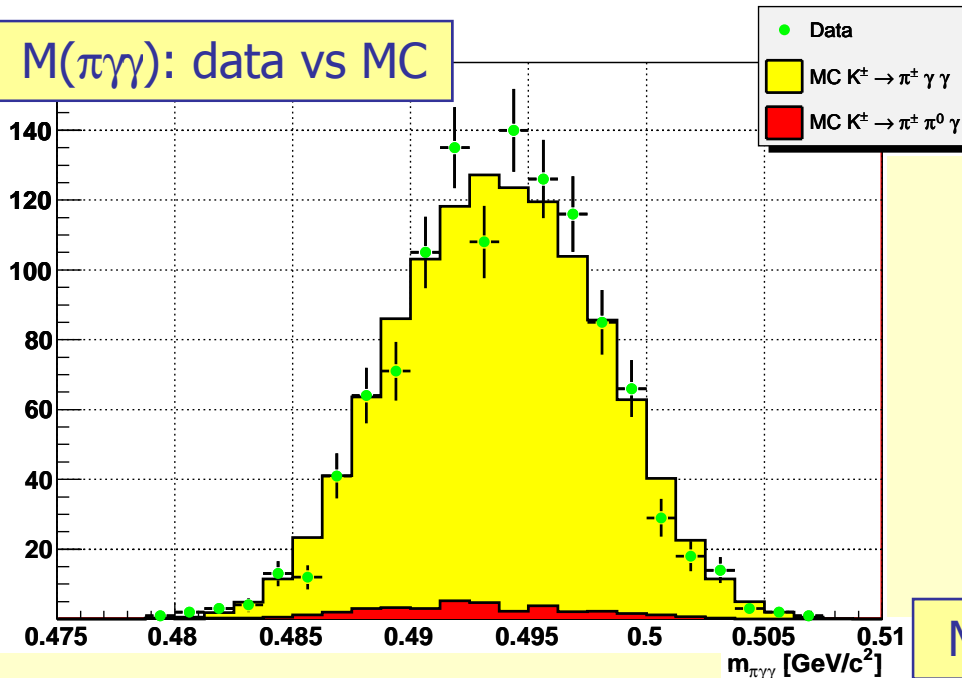
Normalization to $K^\pm \rightarrow \pi^\pm \pi^0$.

Kaon decay flux: $\Phi_K = 2.06 \times 10^{10}$.

$K^\pm \rightarrow \pi^\pm \gamma \gamma$ candidates: **1164**.

Background: **3.3%** [mostly $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$]

$M(\pi\gamma\gamma)$: data vs MC

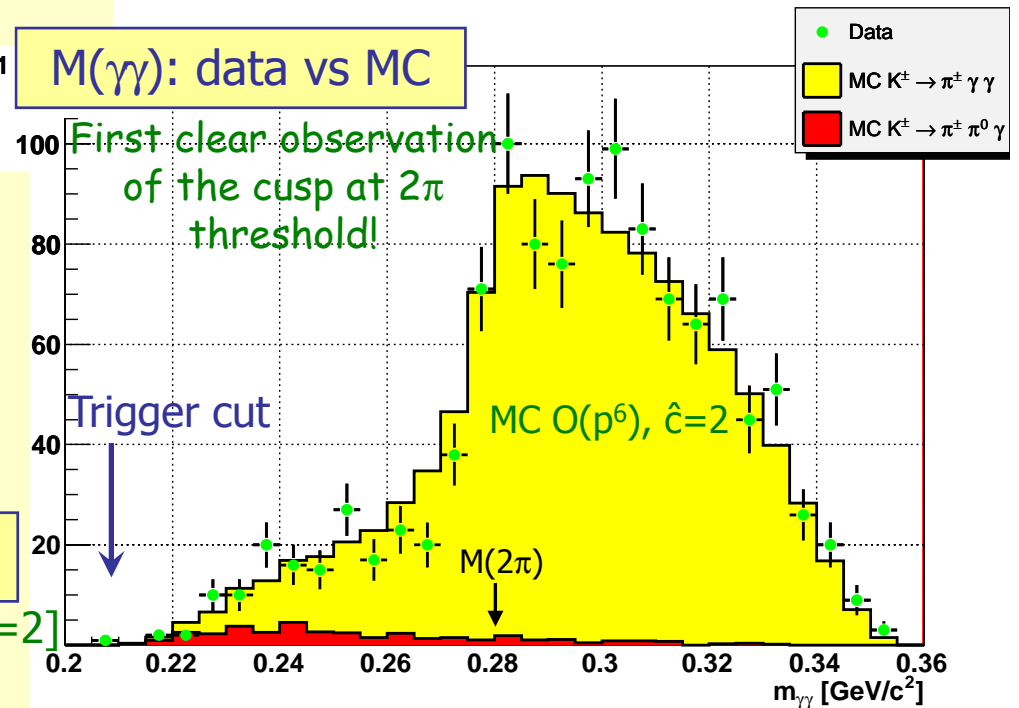


- The sample is ~ 40 times larger than the previous world sample.
- MC $O(p^6)$ and $\hat{c}=2$ for comparison: data shape follows ChPT prediction, possibility of precise \hat{c} measurement. [but no quantitative result on \hat{c} yet].

$$BR = (1.07 \pm 0.04_{\text{stat.}} \pm 0.08_{\text{syst.}}) \times 10^{-6}$$

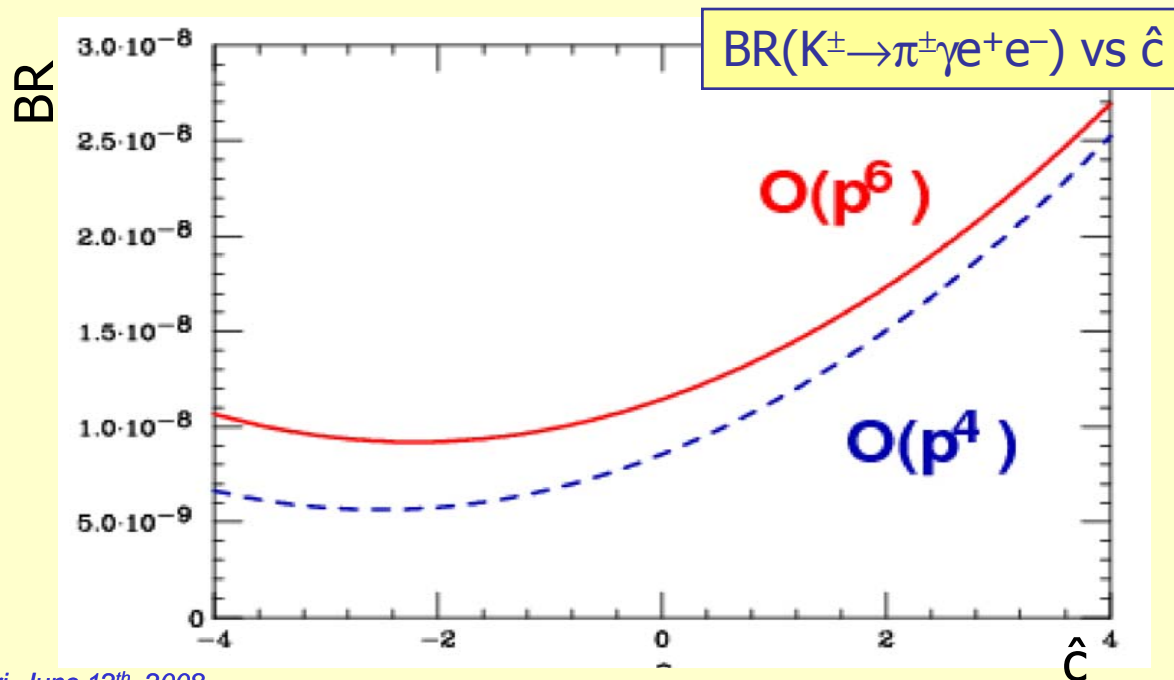
[preliminary; assuming $O(p^6)$ distribution with $\hat{c}=2$]

$M(\gamma\gamma)$: data vs MC



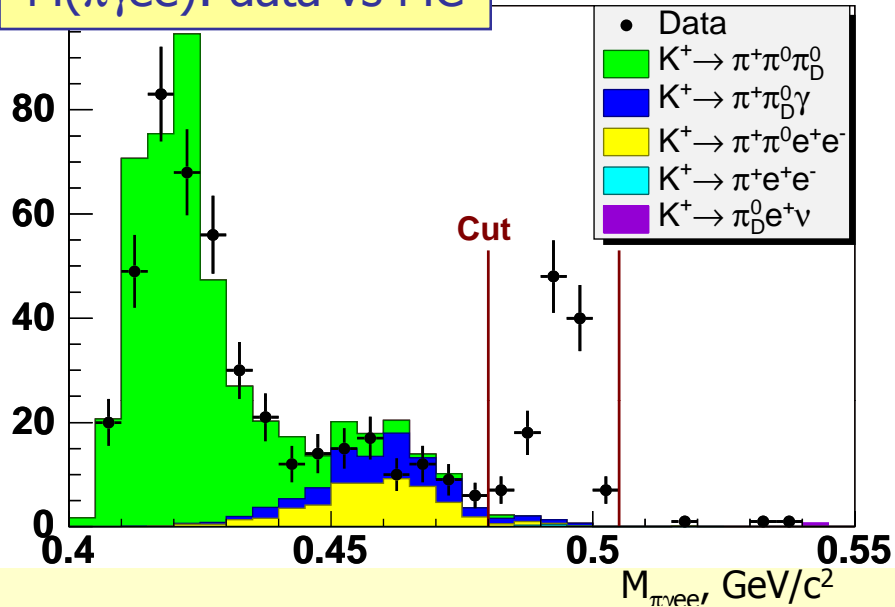
$K^\pm \rightarrow \pi^\pm \gamma e^+ e^-$ theory

- Theory is similar to $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decay.
Naively one expects $\text{BR}(K^\pm \rightarrow \pi^\pm \gamma e^+ e^-) \sim \text{BR}(K^\pm \rightarrow \pi^\pm \gamma \gamma) \times 2\alpha \sim 1.6 \times 10^{-8}$.
- Theoretical expectation: $(0.9-1.6) \times 10^{-8}$ [F.Gabbiani, PRD 59, 094022]
- BR and spectrum depend on \hat{c} parameter.
- Higher-order ($O(p^6)$) ChPT corrections increase the BR.



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

$M(\pi\gamma ee)$: data vs MC



- The first observation of the decay.
- Shape analysis [using ChPT $O(p^4)$ model, F. Gabbiani, PRD59 (1999) 094022]:

$$\hat{c} = (0.90 \pm 0.45)$$

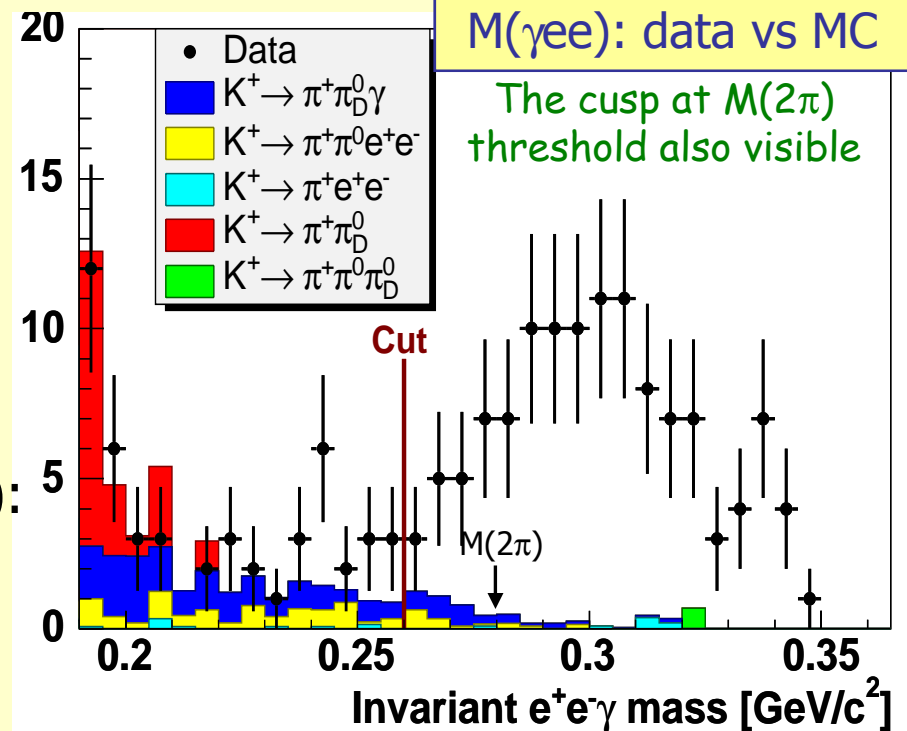
- Model-independent $BR(M_{\gamma ee} > 260 \text{ MeV}/c^2)$:

$$BR = (1.19 \pm 0.12_{\text{stat.}} \pm 0.04_{\text{syst.}}) \times 10^{-8}$$

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Data set: the full sample.
 Normalization to $K^\pm \rightarrow \pi^\pm \pi^0$.
 Kaon decay flux: $\Phi_K = 1.48 \times 10^{11}$.
 $K^\pm \rightarrow \pi^\pm \gamma e^+ e^-$ candidates: 120.
 Background: $(6.1 \pm 1.4)\%$.

$M(\gamma ee)$: data vs MC





Conclusions

NA48 experimental input for the Chiral Perturbation Theory

- Precise study of the $K^\pm \rightarrow \pi^\pm e^+ e^-$ decay ($BR \sim 10^{-7}$):
 - sample & precision comparable to world's best ones;
 - (BR, FF) in agreement with ChPT and other measurements;
 - first limit on the CP violating asymmetry obtained;
- Precise study of the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decay ($BR \sim 10^{-6}$):
 - clear evidence for 2π cusp, first possibility for shape study;
 - measured BR in agreement with ChPT;
 - shape analysis and a larger sample: work in progress;
- First observation of the $K^\pm \rightarrow \pi^\pm \gamma e^+ e^-$ decay ($BR \sim 10^{-8}$):
 - an independent evidence for 2π cusp;
 - measurement of shape and the BR published.