Recent results from Kaon Physics

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Outline

- Yesterday: a brief historical tour (with some news)
    - Kaons and CP
    - Chiral Perturbation Theory
    - CP violation and CPT tests
- Today: latest results
    - Form Factors
    - Rare and radiative decays
    - Lepton universality
- Tomorrow: a new generation of experiments
    - FCNC
    - KoTO, NA62, ORKA

Discovery of Kaons

Discovered in the '40s(cosmics) - '50s(lab):

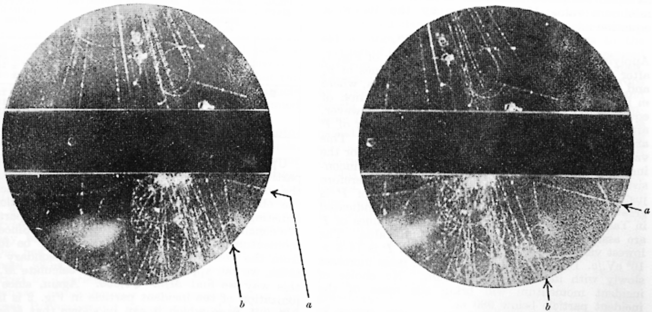

Fig. 1. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*) IN THE GAS. THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN AN ANTICLOCKWISE DIRECTION

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Discovery of Kaons

Discovered in the '40s(cosmics) - '50s(lab):

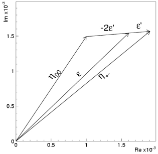
- Introduction of Strangeness
- K^0 and $\overline{K}^0$ with the same mass? No
- Weak interactions do not conserve Strangeness
- K^0 and $\overline{K}^0$ are not mass eigenstates
- Assuming CP is conserved:
  - $CP\ K^0 = \overline{K}^0$
  - $K_1 = \frac{1}{\sqrt{2}}(K^0 + \overline{K}^0)$
  - $K_2 = \frac{1}{\sqrt{2}}(K^0 - \overline{K}^0)$
  - K_1 and K_2 are CP and (maybe) mass eigenstates

Discovery of CP Violation

- If K_1 and K_2 were mass eigenstates
  - K_1 $(CP = +1)$ would not decay in $\pi^+\pi^-\pi^0$ $(CP = -1)$
  - K_2 $(CP = -1)$ would not decay in $\pi^+\pi^-$ $(CP = +1)$
  - So the lifetime of K_1 would be $<<$ of the K_2's one (≈ 600 times)
- It's almost true:
  - "Sometimes" "K_2" decays in $\pi^+\pi^-$
- Then it's not true, therefore:
  - The mass eigenstates are K_S e K_L:
    - $K_S = K_1 + \epsilon K_2$
    - $K_L = K_2 + \epsilon K_1$
  - E CP is not conserved

CP Violation in the Standard Model

- ϵ is the indirect CP violation (mixing)
- Classical parameters:
  - $\eta_{+-} = \frac{K_L \to \pi^+\pi^-}{K_S \to \pi^+\pi^-} = \epsilon + \epsilon'$
  - $\eta_{00} = \frac{K_L \to \pi^0\pi^0}{K_S \to \pi^0\pi^0} = \epsilon - 2\epsilon'$
  - $\Delta\phi = \phi_{00} - \phi_{+-} = -3Im(\frac{\epsilon'}{\epsilon})$



- ϵ' is the dirct CP violation (decay)
- All described in the Standard Model by the Kobayashi-Maskawa mechanism, that predicted the third generation of quarks

$$\begin{pmatrix} c_{12}c_{13} & s_{12}s_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$

Measuring ϵ and ϵ'

- ϵ $O(10^{-3})$
  - η_{+-} or η_{00}, because $\epsilon' << \epsilon$, but better in the interference region
  - $2Re(\epsilon) = \frac{K_L \to \pi^- l^+ \nu \; - \; K_L \to \pi^+ l^- \overline{\nu}}{K_L \to \pi^- l^+ \nu \; + \; K_L \to \pi^+ l^- \overline{\nu}}$
- ϵ' $O(10^{-6})$:
  - not accessible from the previous measurements
  - $|\frac{\eta_{00}}{\eta_{+-}}|^2 = 1 - 6Re(\frac{\epsilon'}{\epsilon})$
- In practice?
  - ϵ was measured in both ways since '64
  - $\frac{\epsilon'}{\epsilon}$ had to wait the end of '90s

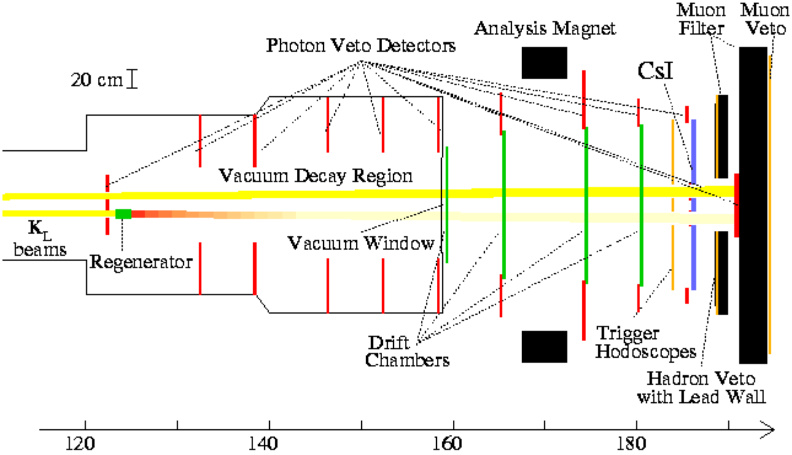
Low energy QCD

- Most kaon decays governed by long distance physics
- Non perturbative QCD
- Chiral Perturbation Theory:
  - effective field theory in terms of QCD Goldstone bosons
  - expansion in powers of momenta and quark masses over $\Lambda_\chi \approx 1$ GeV
  - theoretical framework both for (semi)leptonic and nonleptonic decays, including radiative decays
  - pseudoscalar-octet $+$ electroweak operators
  - a set of Low Energy Constants to be extracted from experiments by measuring Form Factors

ϵ'/ϵ

- Measuring all the 4 decays simultaneously to exploit cancellation of systematics
- NA48 and KTeV were designed to do so:
  - Intense K_L beams at high momentum (for $K_L \rightarrow \pi^0\pi^0$) with decay regions $\approx 100m$ for both experiments
  - Production of K_S by means of a regenerator (KTeV) or a second target close to the decay region (NA48)

ϵ'/ϵ



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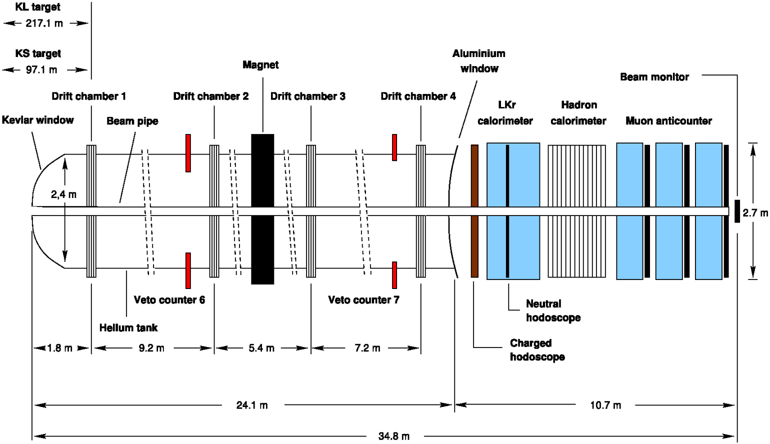

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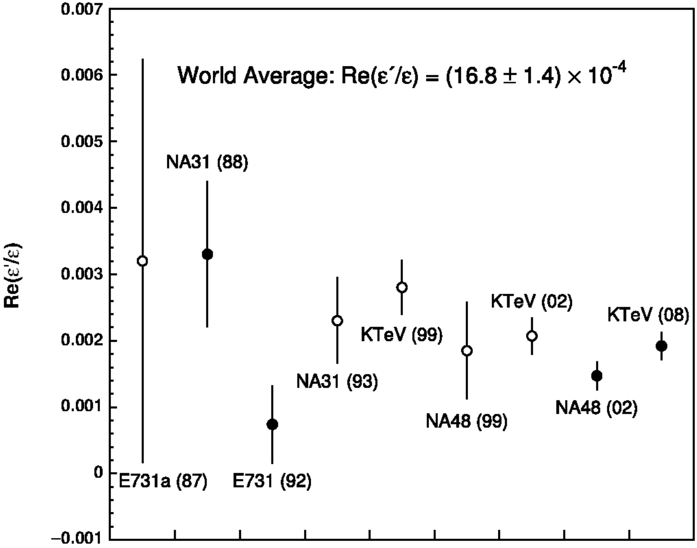
  - KTeV: $Re(\frac{\epsilon'}{\epsilon}) = (2.071 \pm 0.148_{stat} \pm 0.239_{syst})10^{-3} = (2.07 \pm 0.28)10^{-3}$
  - NA48: $Re(\frac{\epsilon'}{\epsilon}) = (1.47 \pm 0.14_{stat} \pm 0.09_{stat/syst} \pm 0.15_{syst})10^{-3} = (1.47 \pm 0.22)10^{-3}$

ϵ'/ϵ



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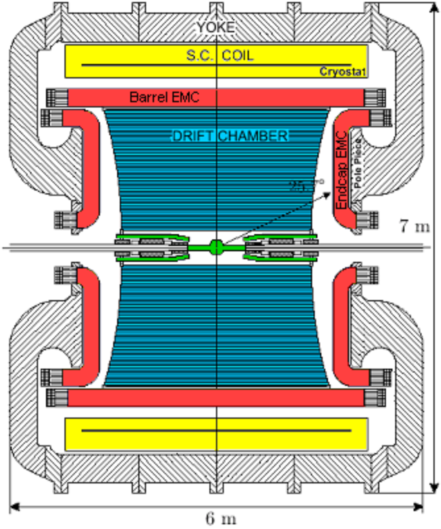
- World average $Re(\frac{\epsilon'}{\epsilon}) = (16.8 \pm 1.4)10^{-4}$
- Lattice QCD result with poor precision [Phys. Rev. D68 (2003) 114506]
- New approach: using experimental value as input to lQCD [arxiv:1206.5142[hep-lat]]

$K_S \longrightarrow \pi^0\pi^0\pi^0$

- $\eta_{000} = \frac{K_L \to 3\pi^0}{K_S \to 3\pi^0} = \epsilon + \epsilon'_{000}$ ($\epsilon'_{000} = -2\epsilon'$ to lowest order ChPT)
- Standard Model prediction: $BR(K_S \to 3\pi^0) = 1.9 \times 10^{-9}$
- SND (direct search) 1999: $BR(K_S \to 3\pi^0) < 1.4 \times 10^{-5}$
- NA48 (interference measurement) 2004: $BR(K_S \to 3\pi^0) < 7.4 \times 10^{-7}$
- KLOE (direct search) 2005: $BR(K_S \to 3\pi^0) < 1.2 \times 10^{-7}$
- KLOE (direct search) 2012 (full statistics): $BR(K_S \to 3\pi^0) < 2.7 \times 10^{-8}$
- First observation feasible in KLOE-2:
  - new inner tracker
  - small calorimeters for better photon coverage near the interaction point

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



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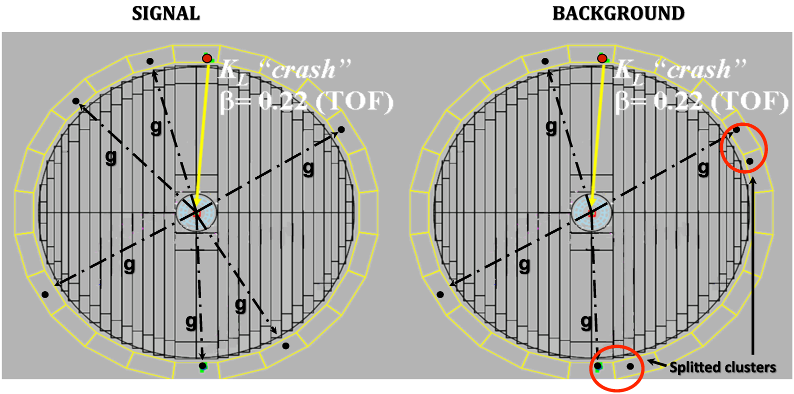

$K_S \to 3\pi^0 \to 6\gamma$

$K_S \to 2\pi^0$ + accidental/splitted clusters

$K_L \to 3\pi$, $K_S \to \pi^+\pi^-$ („fake K_L-crash")

coverage near the interaction point

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

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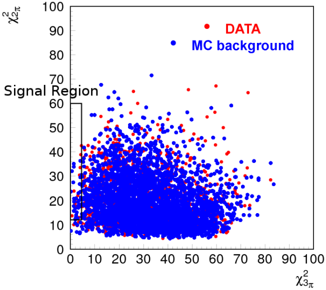

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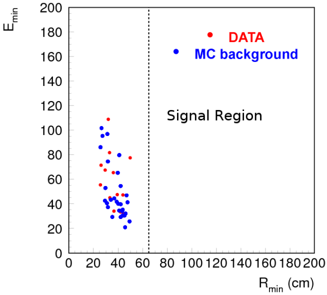
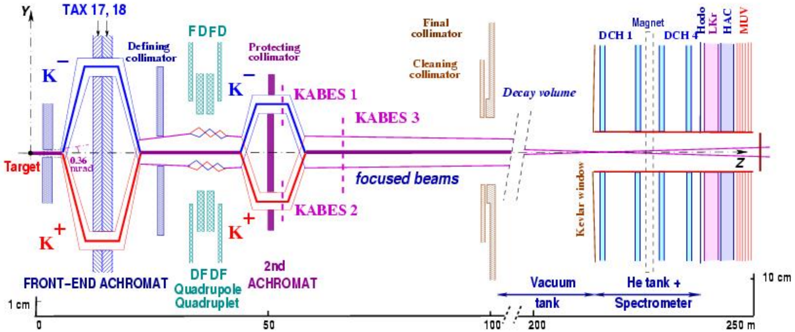


Charge asymmetries in NA48/2

- $\Gamma(K^{\pm} \rightarrow \pi^{\pm}\pi\pi) \propto 1 + g \cdot u + h \cdot u^2 + k \cdot v^2$
- $A_g = \frac{g^+ - g^-}{g^+ + g^-}$: CPV in decay
- SM expectation $O(10^{-5} - 10^{-6})$

	A_g	
$K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$	(-1.5 ± 2.2)	10^{-4}
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$	(1.8 ± 1.8)	10^{-4}
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$	(0.0 ± 1.2)	10^{-3}
$K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}$	(-2.2 ± 1.6)	10^{-2}
$K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$	(1.2 ± 2.3)	10^{-2}

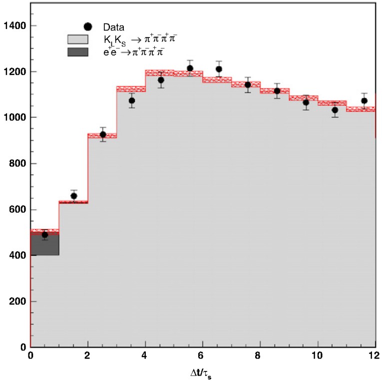
Charge asymmetries in NA48/2



CPT and quantum mechanics

In the CP-violating process $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^-\pi^+\pi^-$

- $I(\Delta t) \propto e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2(1-\zeta_{SL})e^{-\frac{\Gamma_L+\Gamma_S}{2}\Delta t} cos(\Delta m \Delta t)$
- $\Delta m = m_{K_L} - m_{K_S}$, Δt decay time difference, ζ_{SL} decoherence parameter
- $\rightarrow 2\zeta_{SL}\left(1 - \frac{\Gamma_L+\Gamma_S}{2}\Delta t\right)$, $\Delta t \rightarrow 0$



KLOE:

$\zeta_{SL} = 0.018 \pm 0.040_{stat} \pm 0.007_{syst}$

[Phys. Lett. B 642 (2006) 315]

CPT and Lorentz invariance

Standard Model Extension (SME): a phenomenological effective model providing a framework for CPT and Lorentz violation

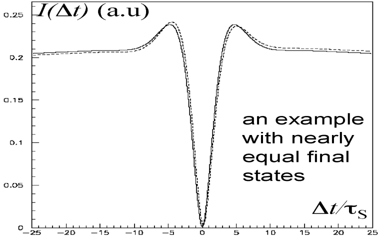
[Kostelecky PRD61, 016002, PRD64, 076001]

- $\epsilon_{S,L} = \epsilon \pm \delta$
- $\delta = i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a})/\Delta m$
- Δa_0, $\Delta\vec{a}$ are four parameters associated to SME lagrangian terms and related to CPT and Lorentz violation

Exploiting interferometry:

$$I(\Delta t) \propto |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - 2|\eta_1||\eta_2| e^{-\frac{\Gamma_L + \Gamma_S}{2}\Delta t} cos(\Delta m \Delta t)$$

- $\eta_1^{+-} = \epsilon(1 - \delta(\vec{p}, t))$
- $\eta_2^{+-} = \epsilon(1 - \delta(-\vec{p}, t))$
- $Im(\delta)$ from small Δt
- $Re(\delta)$ from large Δt



an example with nearly equal final states

CPT and Lorentz invariance

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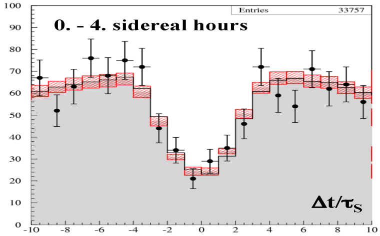
KLOE with L=1 fb^{-1} (preliminary):

- $\Delta a_x = (-6.3 \pm 6.0) \times 10^{-18}$ GeV
- $\Delta a_y = (2.8 \pm 5.8) \times 10^{-18}$ GeV
- $\Delta a_z = (2.4 \pm 9.7) \times 10^{-18}$ GeV

KTeV: Δa_x, $\Delta a_y < 9.2 \times 10^{-22}$ GeV



$K_{l3}(K \rightarrow \pi^0 e\nu_e,\, K \rightarrow \pi^0 \mu\nu_\mu)$

- $\Gamma(K_{l3(\gamma)}) = \frac{m_K^5 G_F^2}{192\pi^3} C_K^2 S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^l (1 + 2\delta^l_{SU(2)} + 2\delta^l_{EM})$
  $C_K^2 = 1$ for K^0, $= 1/2$ for $K^{\pm}$, $S_{EW} = 1.0232$ (short distance EW correction)
- from experiments: $\Gamma(K_{l3(\gamma)})$, I_K^l (form factors integral)
- from theory: $f_+(0)$ (hadronic matrix element at $q^2 = 0$), $\delta^l_{SU(2)}$, δ^l_{EM} (SU(2) breaking and long distance EM corrections)
- extraction of $|V_{us}|$ allows to test CKM unitarity:
  $\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1$
- FlaviaNet 2010:
  $|V_{us}| = 0.2254 \pm 0.0013$
  $\Delta_{CKM} = -0.0001 \pm 0.0006$

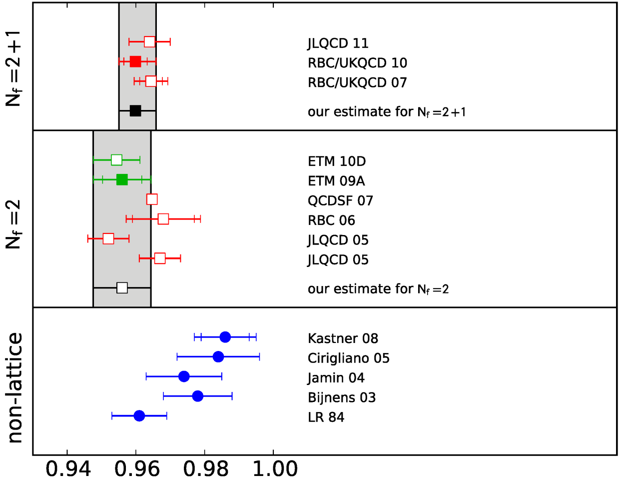
K_{l3} Form Factors

- $M = \frac{G_F}{2}|V_{us}|(f_+(t)(P_K + P_\pi)^\mu \overline{u}_l \gamma_\mu (1+\gamma_5) u_\nu + f_-(t) m_l \overline{u}_l (1+\gamma_5) u_\nu)$, $t = q^2$
- scalar FF $f_0(t)$ as linear combiation of vector FF: $f_0(t) = f_+(t) + \frac{t}{m_K^2 - m_\pi^2} f_-(t)$
- $f_+(0)$ not measurable but $\overline{f}_+(t) = \frac{f_+(t)}{f_+(0)}$, $\overline{f}_0(t) = \frac{f_0(t)}{f_+(0)}$ are accessible

K_{l3} Form Factors

- M $l\nu)$,
  $t =$
- sca
  $f_0($
- f_+
  acc

FLAG-2 update (G. Colangelo at Lattice 2012)



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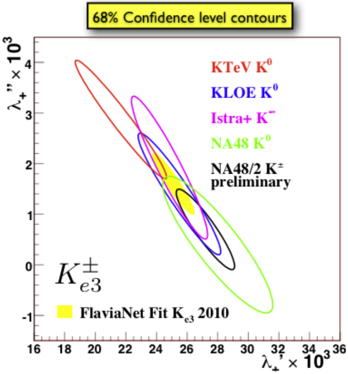
Parametrizations:

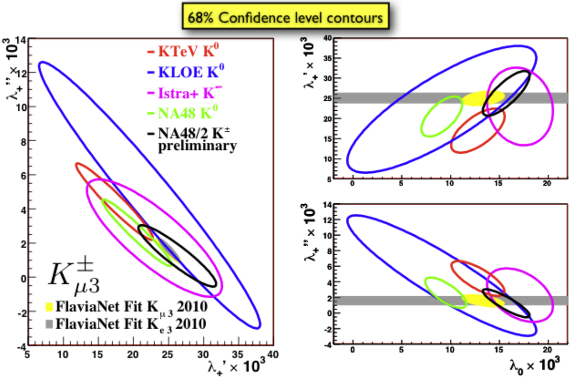
- Pole: assume the exchange of a vector(1^-) or scalar (0^+) resonances $(m_{V,S})$ $\overline{f}_{+,0}(t) = \frac{m_{V,S}^2}{m_{V,S}^2 - t}$
- Linear and quadratic (no physical meaning):
  $\overline{f}_{+,0}(t) = 1 + \lambda_{+,0} \frac{t}{m_\pi^2}$
  $\overline{f}_{+,0}(t) = 1 + \lambda'_{+,0} \frac{t}{m_\pi^2} + \lambda''_{+,0} \left(\frac{t}{m_\pi^2}\right)^2$

Results from $K \to \pi^0 e\nu_e$, $K \to \pi^0 \mu\nu_\mu$

NA48/2 Preliminary

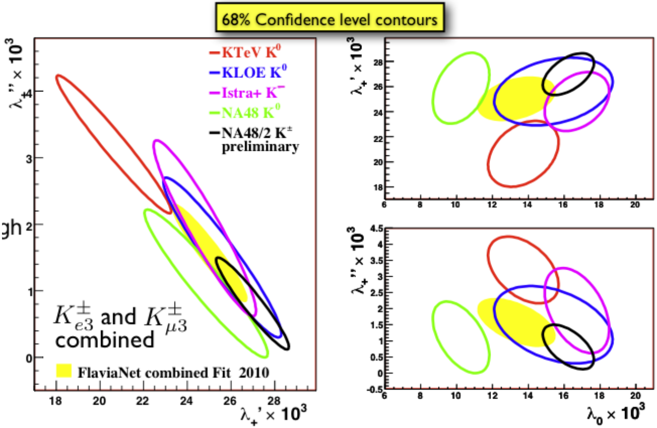
Quadratic ($\times 10^{-3}$)	λ'_+	λ''_+	λ'_0
$K \to \pi^0 \mu\nu_\mu$	$26.3 \pm 3.0_{stat} \pm 2.2_{syst}$	$1.2 \pm 1.1_{stat} \pm 1.1_{syst}$	$15.7 \pm 1.4_{stat} \pm 1.0_{syst}$
$K \to \pi^0 e\nu_e$	$27.2 \pm 0.7_{stat} \pm 1.1_{syst}$	$0.7 \pm 0.3_{stat} \pm 0.4_{syst}$	
Pole (MeV/c^2)	m_V		m_S
$K \to \pi^0 \mu\nu_\mu$	$873 \pm 8_{stat} \pm 9_{syst}$		$1183 \pm 31_{stat} \pm 16_{syst}$
$K \to \pi^0 e\nu_e$	$879 \pm 3_{stat} \pm 7_{syst}$		





Combined results from $K \to \pi^0 e\nu_e$, $K \to \pi^0 \mu\nu_\mu$

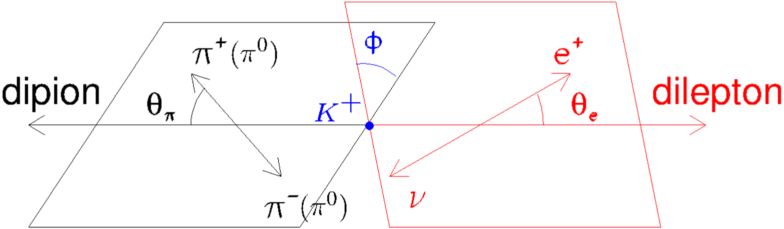
Quadratic ($\times 10^{-3}$)	λ'_+	λ''_+	λ'_0
	26.91 ± 1.11	0.81 ± 0.46	16.23 ± 0.95
Pole (MeV/c^2)	m_V		m_S
	877 ± 6		1176 ± 31



- Results for K_{e3} and $K_{\mu3}$ from NA48/2 in good agreement
- High precision preliminary results, competitive with other measurements. Smallest error in the combined result.

K_{e4}

- $K \to \pi^+\pi^- e\nu_e$, called $K_{e4}(+-)$
- $K \to \pi^0\pi^0 e\nu_e$, called $K_{e4}(00)$



Five kinematic variables (Cabibbo-Maksymowicz 1965):

$s_\pi = M^2_{\pi\pi} \quad s_e = M^2_{e\nu} \quad cos\theta_\pi \quad cos\theta_e \quad \phi$

K_{e4} Form Factors

Partial Wave expansion, limited to S and P waves
[Pais-Treiman (1968) + Watson theorem (T invariance)]

Partial Wave expansion:

- 2 Axial Form Factors (F and G):
  - $F = F_s e^{i\delta_s} + F_p e^{i\delta_p} cos\theta_\pi$
  - $G = G_p e^{i\delta_p}$
- 1 Vector Form Factors (H):
  - $H = H_p e^{i\delta_p}$

The fit parameters (real) are:

- (+-) F_s, F_p , G_p , H_p, $\delta = \delta_s - \delta_p$
- (+-) F_s only (no P-wave)

q^2 dependence can be studied from FF fitted in q^2 bins [J.Phys. G25, (1999) 1607]

$$F_s^2 = f_s^2 \left[1 + \frac{f'_s}{f_s} q^2 + \frac{f''_s}{f_s} q^4 + \frac{f'_e}{f_s}\frac{M_{e\nu}^2}{4m_\pi^2}\right]$$

$$\frac{G_p}{f_s} = \frac{g_p}{f_s} + \frac{g'_p}{f_s} q^2,\ F_p = f_p,\ H_p = h_p$$

$$q^2 = \left[\frac{M_{\pi\pi}^2}{4m_\pi^2} - 1\right]$$

$K_{e4}(+-)$ relative Form Factors: fit results (NA48/2)

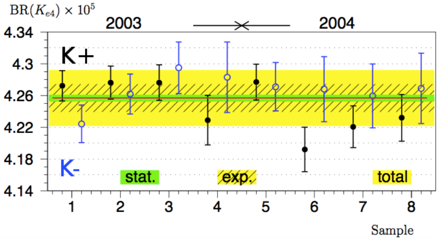
NA48/2 total statistics (2003 + 2004)

	value	stat	syst
$\frac{f_s'}{f_s}$	0.152	± 0.007	± 0.005
$\frac{f_s''}{f_s}$	-0.073	± 0.007	± 0.006
$\frac{f_e'}{f_s}$	0.068	± 0.006	± 0.007
$\frac{f_p}{f_s}$	-0.048	± 0.003	± 0.004
$\frac{g_p}{f_s}$	0.868	± 0.010	± 0.010
$\frac{g_p'}{f_s}$	0.089	± 0.017	± 0.013
$\frac{h_p}{f_s}$	-0.398	± 0.015	± 0.008

Published in Eur. Phys J. C70 (2010) 635

$K_{e4}(+-)$ branching fraction (NA48/2)

- Use $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays as normalization
- number of signal (1.11×10^{6}), background (0.95% of K_{e4}) and normalization (1.9×10^{9}) events
- signal and normalization acceptance (18.19% and 23.97%) and trigger efficiency (98.5% and 97.7%)
- $BR(K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = (5.59 \pm 0.04)\%$



Relative Systematic Uncertainty	(%)
Acceptance, beam geom.	0.18
Muon vetoing	0.16
Accidental activity	0.21
Particle ID	0.09
Background	0.07
Radiative effects	0.08
Trigger efficiency	0.11
Simulation statistics	0.05
Total systematics	0.37
External error $[BR(K_{3\pi})]$	0.72

PDG 2012: $(4.09 \pm 0.10) \times 10^{-5}$

K^{-}: first measurement

Published in
Physics Letters B 715 (2012) 105

$BR(K^{+}_{e4}) = (4.255 \pm 0.008) \times 10^{-5}$ $BR(K^{-}_{e4}) = (4.261 \pm 0.011) \times 10^{-5}$

$$BR[K^{\pm}_{e4}(+-)] = (4.257 \pm 0.004_{stat} \pm 0.016_{syst} \pm 0.031_{ext}) \times 10^{-5}$$

$K_{e4}(+-)$ absolute Form Factors (NA48/2)

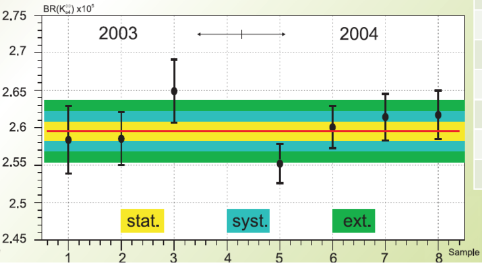
Overall form factor normalization: $BR[K^{\pm}_{e4}(+-)]$

$$
\begin{array}{lrlll}
f_s & = 5.705 & \pm\ 0.003_{stat} & \pm\ 0.017_{syst} & \pm\ 0.031_{norm} \\
 & = 5.705 & \pm\ 0.035_{norm} & & \\
\hline
f'_s & = 0.867 & \pm\ 0.040_{stat} & \pm\ 0.029_{syst} & \pm\ 0.005_{norm} \\
f''_s & = -0.416 & \pm\ 0.040_{stat} & \pm\ 0.034_{syst} & \pm\ 0.003_{norm} \\
f'_e & = 0.388 & \pm\ 0.034_{stat} & \pm\ 0.040_{syst} & \pm\ 0.002_{norm} \\
 & & & & \\
f_p & = -0.274 & \pm\ 0.017_{stat} & \pm\ 0.023_{syst} & \pm\ 0.002_{norm} \\
 & & & & \\
g_p & = 4.952 & \pm\ 0.057_{stat} & \pm\ 0.057_{syst} & \pm\ 0.031_{norm} \\
g'_p & = 0.508 & \pm\ 0.097_{stat} & \pm\ 0.074_{syst} & \pm\ 0.003_{norm} \\
 & & & & \\
h_p & = -2.271 & \pm\ 0.086_{stat} & \pm\ 0.046_{syst} & \pm\ 0.014_{norm}
\end{array}
$$

Published in Physics Letters B 715 (2012) 105

$K_{e4}(00)$ branching fraction (NA48/2)

- Use $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ decays as normalization
- number of signal (4.49×10^4), background (1.3% of K_{e4}) and normalization (71×10^6) events
- signal and normalization acceptance (1.77% and 4.11%) and trigger efficiency (92-98%)
- $BR(K^{\pm} \to \pi^{\pm}\pi^0\pi^0) = (1.761 \pm 0.022)\%$



Relative Systematic Uncertainty	(%)
Background	0.35
Simulation statistics	0.12
Form factor dependence	0.20
Radiative effects	0.23
Trigger efficiency	0.80
Particle ID	0.10
Beam geometry	0.10
Total systematics	0.94
External error $[BR(K_{3\pi})]$	1.25

PDG 2012: $(2.2 \pm 0.4) \times 10^{-5}$

Preliminary result
Analysis in progress

$$BR[K^{\pm}_{e4}(00)] = (2.595 \pm 0.012_{stat} \pm 0.024_{syst} \pm 0.032_{ext}) \times 10^{-5}$$

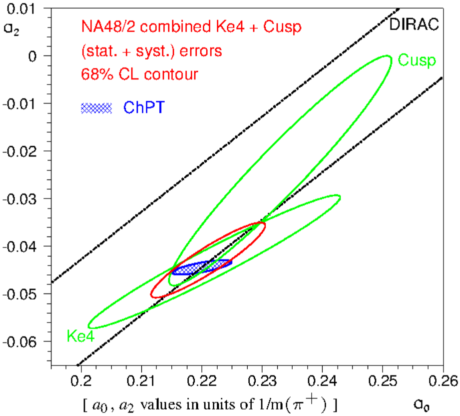
$K_{e4}(+-)$ decay and $\pi\pi$ scattering lengths (NA48/2)

The S-wave $\pi\pi$ scattering lengths a_0 and a_2 (I = 0 and I = 2) are precisely predicted by ChPT [NPB 603 (2001) 125, PRL 86 (2001) 5008]

Two statistically independent measurements by NA48/2:

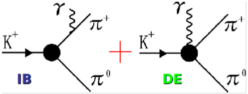
- from the phase shift $\delta(M_{\pi\pi}) = \delta_s - \delta_p$ in K_{e4} decay [Eur.Phys.J. C70 (2010) 635]
- from the cusp in $M_{\pi^0\pi^0}$ in $K^\pm \to \pi^\pm\pi^0\pi^0$ decay [Eur.Phys.J. C64 (2009) 589]

- Different systematics: eletron misID and background vs. calorimeter and trigger
- Different theoretical inputs: Roy equations and isospin breaking correction vs. rescattering in final state and ChPT expansion
- Large overlap in the a_0, a_2 plane
- Impressive agreement with ChPT



$K^\pm \to \pi^\pm \pi^0 \gamma$

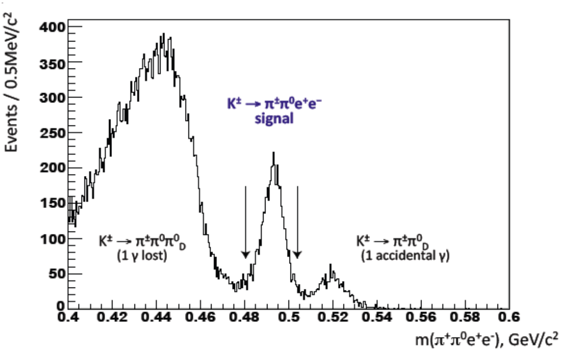
- γ from Inner Bremsstrahlung and Direct Emission
- decay amplitude:



  - $T^*_\pi = \pi^\pm$ kinetic energy
  - $W^2 = \frac{(p_\pi \cdot p_\gamma)(p_K \cdot p_\gamma)}{m_K^2 m_\pi^2}$
  - integrating T^*_π: $\frac{d\Gamma^\pm}{dW} = \frac{d\Gamma^\pm_{IB}}{dW}[1+2m_K^2 m_\pi^2 cos(\pm\phi+\delta_1^1-\delta_0^1)X_E W^2+m_K^4 m_\pi^4(|X_E|^2+|X_M|^2)W^4]$
  - IB is known from $K^\pm \to \pi^\pm \pi^0$ + QED corrections
  - DE amplitude contains electric XE and magnetic XM dipole terms
  - INT is interference between IB and electric DE (XE) amplitudes
- final NA48/2 results: [EPJC68 (2010) 75]
  - Frac(DE) $= (3.32 \pm 0.15 \pm 0.14)10^{-2}$
  - Frac(INT) $= (-2.35 \pm 0.35 \pm 0.39)10^{-2}$ (first evidence)
  - $A_{CP} = \left|\frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}\right| < 1.5 \times 10^{-3}$ (first measurement)

$K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ (NA48/2 preliminary)

- Mainly from $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma^{*} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ [EPJC 72, (2012) 1872]
- DE and INT depend on XE and XM form factors
- Short distance contributions, sensitive to New physics
- First observation

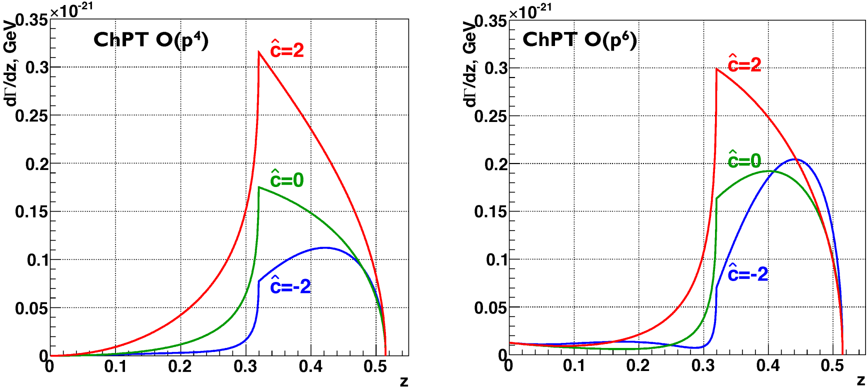


NA48/2 (2003+2004 data):

- ≈ 4500 events in signal region
- $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}_{D}$ $(\pi^{0}_{D} \to e^{+}e^{-}\gamma_{LOST})$
- $K^{\pm} \to \pi^{\pm}\pi^{0}_{D}$ $(\pi^{0}_{D} \to e^{+}e^{-}) + \gamma_{ACC}$

$K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$

- $BR(z)$, $z = \frac{m^2_{\gamma\gamma}}{m^2_K}$, depends on a single unknown $O(1)$ parameter ĉ
- BNL E787: 31 candidates, $BR = (1.10 \pm 0.32) \times 10^{-6}$ [PRL79 (1997) 4079]



$K^\pm \to \pi^\pm\gamma\gamma$

- $BR(z)$, $z = \frac{m^2_{\gamma\gamma}}{m^2_K}$, depends on a single unknown $O(1)$ parameter ĉ
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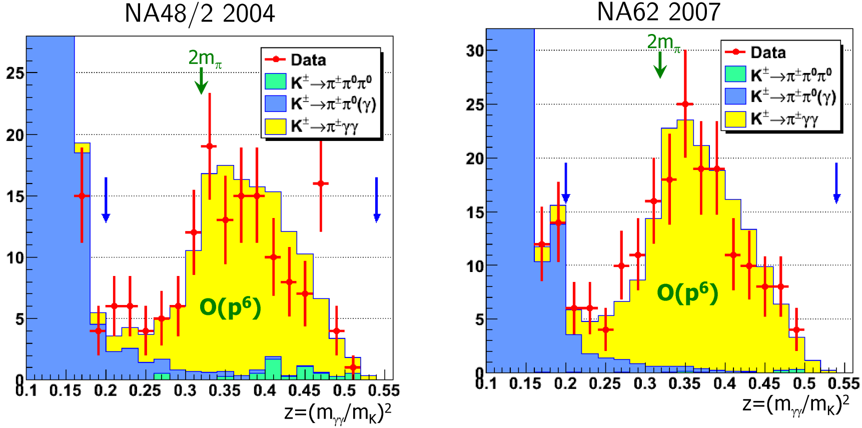


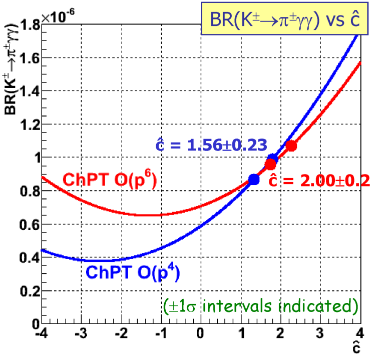
NA48/2 2004

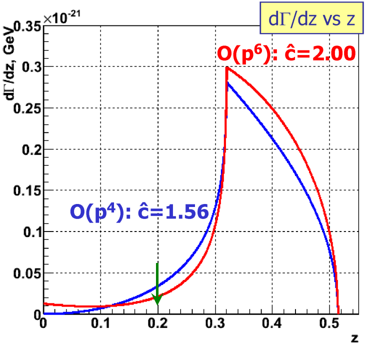
NA62 2007

- ≈ 300 event candidates with $O(10\%)$ background ($z > 0.2$)

$K^\pm \to \pi^\pm\gamma\gamma$

- $BR(z)$, $z = \frac{m^2_{\gamma\gamma}}{m^2_K}$, depends on a single unknown $O(1)$ parameter ĉ
- BNL E787: 31 candidates, $BR = (1.10 \pm 0.32) \times 10^{-6}$ [PRL79 (1997) 4079]

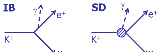


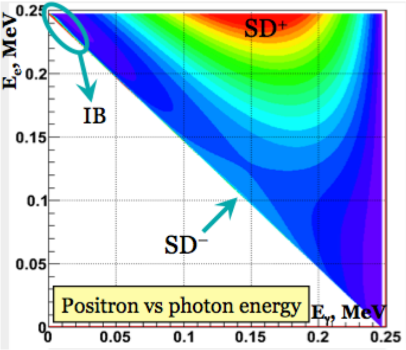


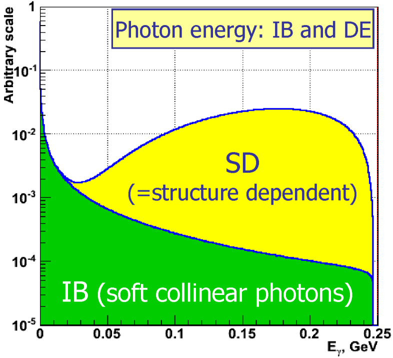
- ChPT $O(p4)$ fit: ĉ$= 1.56 \pm 0.22_{stat} \pm 0.07_{syst} = 1.56 \pm 0.23$
- ChPT $O(p6)$ fit: ĉ$= 2.00 \pm 0.24_{stat} \pm 0.09_{syst} = 2.00 \pm 0.26$
- $BR = (1.01 \pm 0.06) \times 10^{-6}$ (model dependent)

$K \to e\nu_e\gamma$ SD+

- $\frac{d^2\Gamma_{SD}}{dx\,dy} = \frac{m_K^5 \alpha G_F^2 |V_{us}|^2}{64\pi^2}\left[(F_V + F_A)^2 f_{SD+}(x,y) + (F_V - F_A)^2 f_{SD-}(x,y)\right]$
- f_{SD+}, f_{SD-} known kinematics, $x = \frac{2E^*_\gamma}{m_K}$, $y = \frac{2E^*_e}{m_K}$

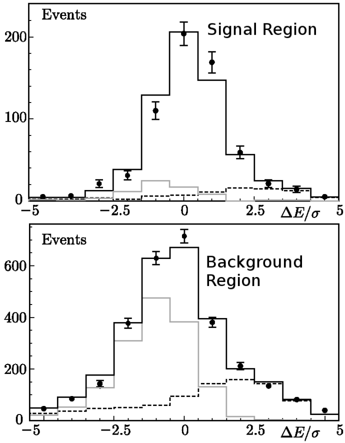


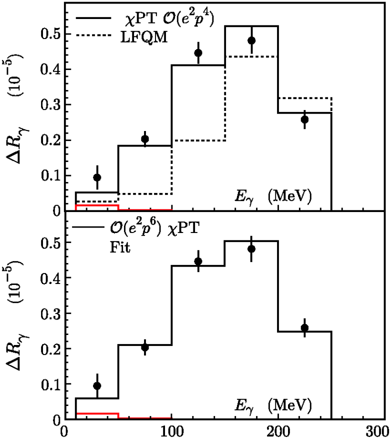




$K \to e\nu_e\gamma$ SD+

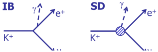
- $\frac{d^2\Gamma_{SD}}{dx\,dy} = \frac{m_K^5 \alpha G_F^2 |V_{us}|^2}{64\pi^2}\left[(F_V+F_A)^2 f_{SD+}(x,y) + (F_V-F_A)^2 f_{SD-}(x,y)\right]$
- f_{SD+}, f_{SD-} known kinematics, $x = \frac{2E^*_\gamma}{m_K}$, $y = \frac{2E^*_e}{m_K}$
- KLOE 2009: 4% accuracy, compatible with $O(p^4)$ Form Factor (constant) [Eur. Phys. J. C64 (2009) 627]

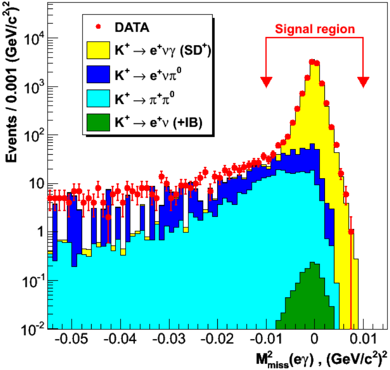


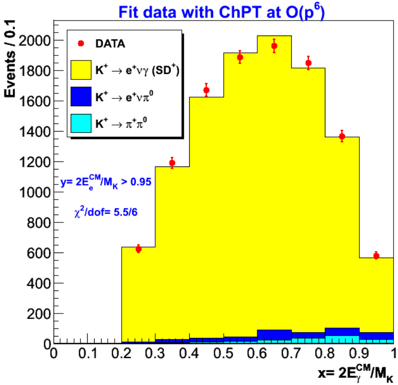


$K \to e\nu_e\gamma$ SD+

- $$\frac{d^2\Gamma_{SD}}{dx\,dy} = \frac{m_K^5 \alpha G_F^2 |V_{us}|^2}{64\pi^2}\left[(F_V + F_A)^2 f_{SD+}(x,y) + (F_V - F_A)^2 f_{SD-}(x,y)\right]$$
- f_{SD+}, f_{SD-} known kinematics, $x = \frac{2E^*_\gamma}{m_K}$, $y = \frac{2E^*_e}{m_K}$

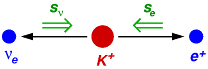


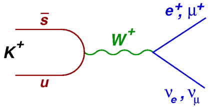




- NA62 preliminary
- ≈ 10000 event candidates

R_K - LFV test





- $R_K = \frac{\Gamma(K \to e\nu_e)}{\Gamma(K \to \mu\nu_\mu)}$
- $BR(K \to e\nu) \approx O(10^{-5})$
  $BR(K \to \mu\nu) \approx 63\%$
- In the SM:
  $$R_K = \underbrace{\left(\frac{m_e}{m_\mu}\right)^2}_{helicity} \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \underbrace{\delta R_{QED}}_{Rad\ Corr}) = (2.477 \pm 0.001)10^{-5}$$
  [PRL 99 (2007), 231801]

R_K - LFV test

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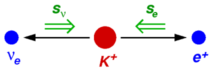
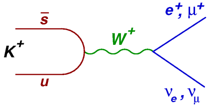
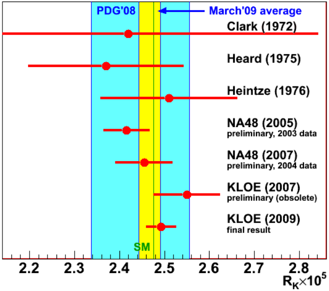
- $BR(K \to e\nu) \approx O(10^{-5})$
  $BR(K \to \mu\nu) \approx 63\%$
- In the SM:
  $R_K = (2.477 \pm 0.001)10^{-5}$
  - Hadronic uncertainties cancel in the ratio
  - Helicity suppression $\approx 10^{-5}$
  - Radiative correction (few %) due to $K \to e\nu_e\gamma(IB)$, by definition included into R_K

[PRL 99 (2007), 231801]





R_K - LFV test



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  - Radiative correction (few %) due to $K \to e\nu_e\gamma(IB)$, by definition included into R_K

  [PRL 99 (2007), 231801]
- Experimentally:
  - $R_K = (2.45 \pm 0.11)10^{-5}$ (PDG 2008, '70s measurements)
    $\delta R_K / R_K \approx 4.5\%$
  - $R_K = (2.493 \pm 0.031)10^{-5}$ (KLOE [Eur.Phys.J.C64 (2009) 627])
    $\delta R_K / R_K \approx 1.3\%$
  - It's worth to improve it because of its small and well predicted value

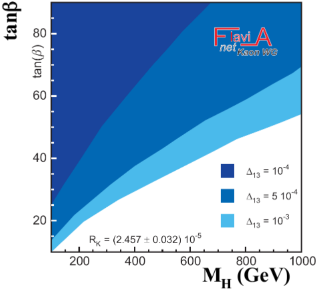
R_K in case of New Physics (MSSM)

- Expected effects within $\delta R_K/R_K \approx 10^{-4} - 10^{-2}$
- A specific case:

$$R_K^{MSSM} = R_K^{SM}\left[1 + \left(\frac{m_K}{m_H}\right)^4 \left(\frac{m_\tau}{m_e}\right)^2 |\Delta_{13}|^2 \tan^6\beta\right]$$

with $m_H = 500\text{GeV}/c^2$,$|\Delta_{13}| = 5\times10^{-4}$ e $\tan\beta = 40$

$R_K^{MSSM} = R_K^{SM}(1+0.013)$ [PRD 74 (2006) 011701, JHEP 0811 (2008) 042]



$\delta R_K/R_K \approx 1.3\%$

R_K in case of New Physics (MSSM)

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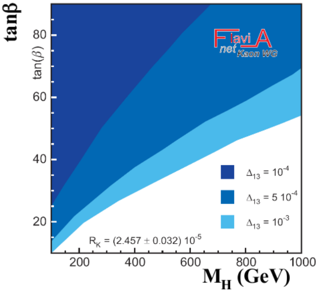
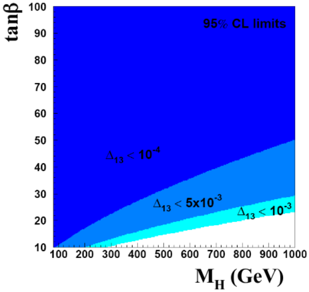


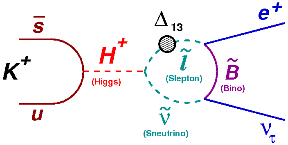
$\delta R_K / R_K \approx 1.3\%$



$\delta R_K / R_K \approx 0.3\%$

R_K in case of New Physics (MSSM)

- Expected effects within $\delta R_K/R_K \approx 10^{-4} - 10^{-2}$
- A specific case:
  $$R_K^{MSSM} = R_K^{SM}\left[1 + \left(\frac{m_K}{m_H}\right)^4 \left(\frac{m_\tau}{m_e}\right)^2 |\Delta_{13}|^2 \tan^6\beta\right]$$
  with $m_H = 500\text{GeV}/c^2$,$|\Delta_{13}| = 5\times10^{-4}$ e $\tan\beta = 40$
  $R_K^{MSSM} = R_K^{SM}(1 + 0.013)$ [PRD 74 (2006) 011701, JHEP 0811 (2008) 042]



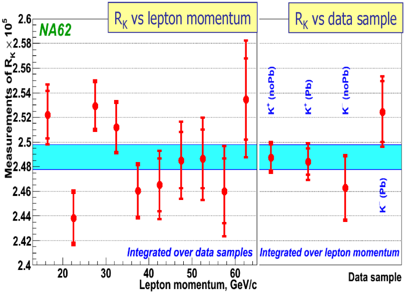
π and B have the same effect, but:

- in R_π it's suppressed by $(m_\pi/m_K)^4 \approx 10^{-3}$
- $B \to e\nu_e$ is out of reach and $\frac{B\to\mu\nu_\mu}{B\to\tau\nu_\tau}$ has $\approx 50\%$ enhancement

Final result (full data sample)

Uncertainties

Source	$\delta R_K \times 10^5$
Statistical	0.007
$K \to \mu\nu_\mu$	0.004
$K \to e\nu_e\gamma\ (SD^+)$	0.002
$K \to \pi^0 e\nu_e,\ K \to \pi\pi^0$	0.003
Beam halo	0.002
Matter composition	0.003
Acceptance	0.002
Positron ID	0.001
DCH alignmnent	0.001
1-track trigger	0.001
Total	0.010



Precision and accuracy

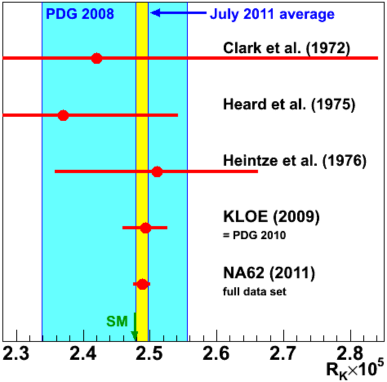
145,958 K_{e2} candidates
Positron ID efficiency: $(99.28 \pm 0.05)\%$
$B/(S+B) = (10.95 \pm 0.27)\%$

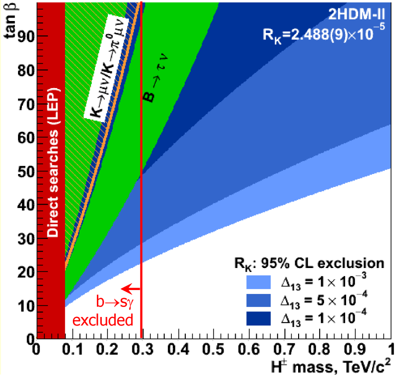
Fit over 40 measurements
4 data samples 10 momentum bins)
including correlations:
$\chi^2/ndf = 47/39$

Result

$$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$$

World Average

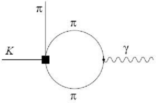




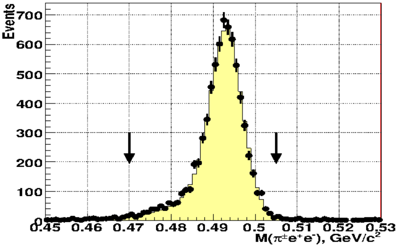
World average	$R_K \times 10^5$	Precision
PDG 2010	(2.493 ± 0.025)	1.0%
July 2011	(2.488 ± 0.009)	0.36%

$K^\pm \rightarrow \pi^\pm l^+ l^-$ (NA48/2)

- FCNC process suppressed ($BR \approx 10^{-7}$)
- Loop induced ($K^\pm \rightarrow \pi^\pm \gamma^*$)

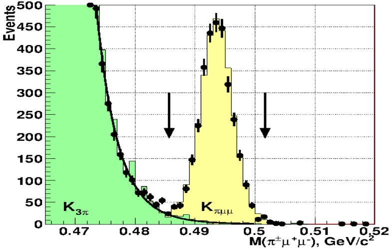


$K^\pm \rightarrow \pi^\pm e^+ e^-$ [PLB 677, (2009) 246]



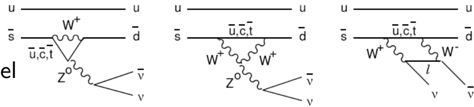
- ≈ 7200 event candidates
- $< 1\%$ background
- $BR = (3.11 \pm 0.12) \times 10^{-7}$
- $A_{CP} < 2.1 \times 10^{-2}$

$K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$ [PLB 697, (2011) 107]



- ≈ 3100 event candidates
- $(3.3 \pm 0.7)\%$ background
- $BR = (9.62 \pm 0.25) \times 10^{-8}$
- $A_{CP} < 2.9 \times 10^{-2}$

$K \longrightarrow \pi\nu\overline{\nu}$

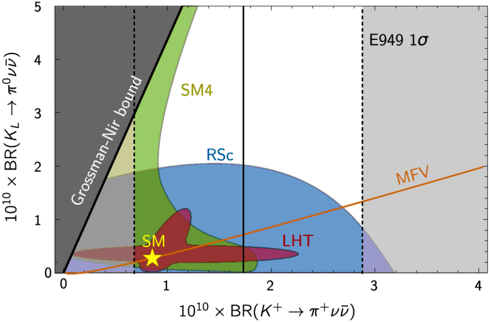


Ultra rare decay

- FCNC process forbidden at tree-level
- Very clean theoretical prediction: hadronic matrix element extracted from $BR(K \to \pi e \nu)$
- Golden modes:

	BR_{SM}	from CKM	from theory	
$K_L \to \pi^0\nu\overline{\nu}$	(2.43	±0.39	±0.06)	10^{-11}
$K^+ \to \pi^+\nu\overline{\nu}$	(7.81	±0.75	±0.29)	10^{-11}

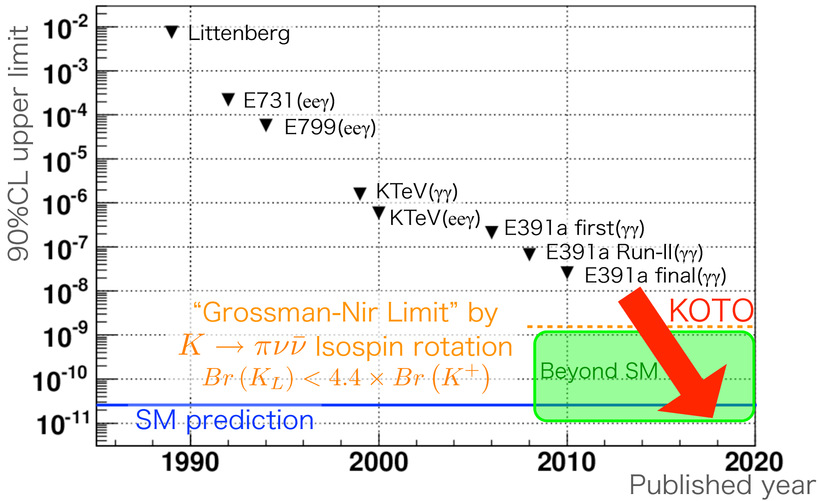
- Current existing measurement based on 7 events (E787/949): $(1.73^{+1.15}_{-1.05})10^{-10}$
- Lead to measurement of $V_{td} \approx 7\%$
- New Physics scenario →



$K \rightarrow \pi\nu\overline{\nu}$ foreseen experiments

Expt	Primary beam	Intensity (ppp)	SM evts/yr	Start date + run yrs	Total SM evts
NA62	SPS 450 GeV	3 ± 10^{12}	55	2014+2	110
FNAL $K^{\pm}$	Project X 8 GeV	2 ± 10^{14}	250	2018+5	1250
ORKA	Tevatron up <150 GeV	5 ± 10^{13}	120	2018+5	600
E14(KoTO)	JPARC-I 30 GeV	2 ± 10^{14}	1-2	2013+3	3-7
E14	JPARC-II 30 GeV	3 ± 10^{14}	30	2020+3?	100
FNAL KL	Booster 8 GeV	2 ± 10^{13}	30	2016+2	60
FNAL KL	Project X 8 GeV	2 ± 10^{14}	300	2018+5	1500

$K \to \pi\nu\bar{\nu}$ foreseen experiments



"Grossman-Nir Limit" by
$K \to \pi\nu\bar{\nu}$ Isospin rotation
$Br(K_L) < 4.4 \times Br(K^+)$

$K \to \pi\nu\bar{\nu}$ foreseen experiments

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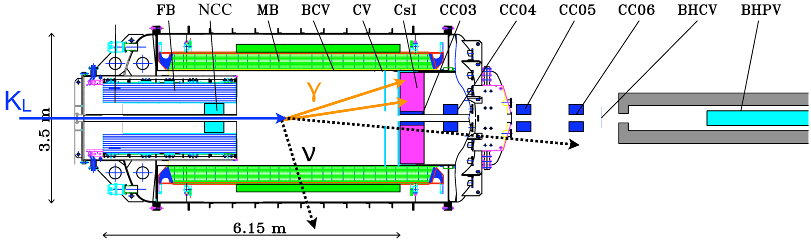

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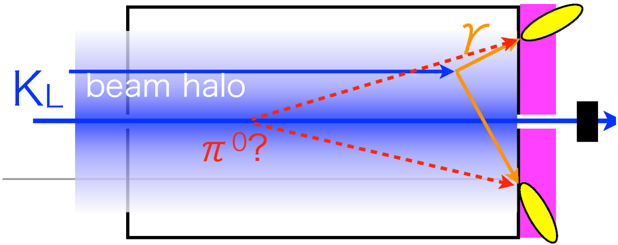
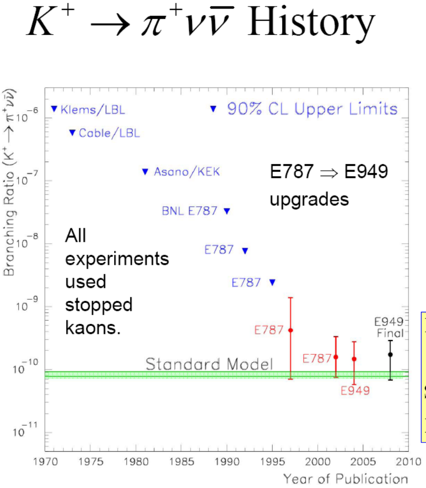


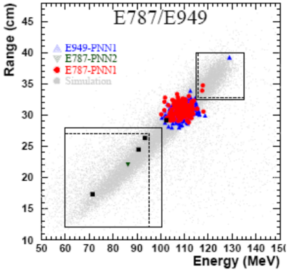
$K \longrightarrow \pi\nu\bar{\nu}$ foreseen experiments



$K^+ \to \pi^+\nu\bar{\nu}$ History

E787 ⇒ E949 upgrades

All experiments used stopped kaons.



E787/E949 Final: 7 events observed

$$B(K^+ \to \pi^+\nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$$

Standard Model:

$$B(K^+ \to \pi^+\nu\bar{\nu}) = (0.85 \pm 0.07)x10^{-10}$$

$K \to \pi\nu\overline{\nu}$ foreseen experiments

Expt	Primary beam	Intensity (ppp)	SM evts/yr	Start date + run yrs	Total SM evts
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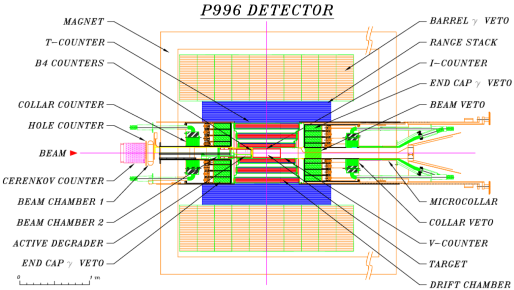
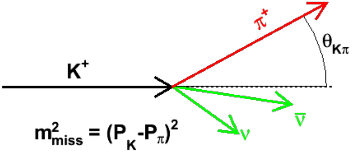


Measurement of $BR(K^+ \to \pi^+ \nu\overline{\nu})$ at NA62

Measurement at 10% ($\approx$ SM prediction accuracy), 100 SM events

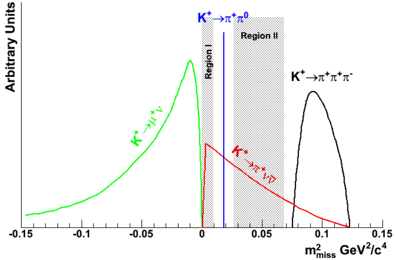
Missing mass



Measurement of $BR(K^+ \to \pi^+ \nu\overline{\nu})$ at NA62

Measurement at 10% ($\approx$ SM prediction accuracy), 100 SM events

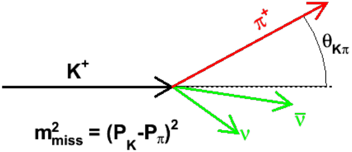
Separated by kinematic cuts



92% of K decays

- 2 signal regions
- Minimize multiple scattering

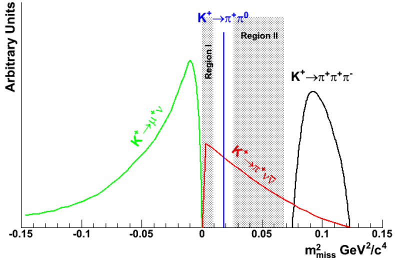
Missing mass



Measurement of $BR(K^+ \to \pi^+\nu\bar{\nu})$ at NA62

Measurement at 10% (≈ SM prediction accuracy), 100 SM events

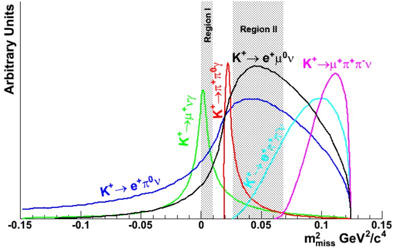
Separated by kinematic cuts



92% of K decays

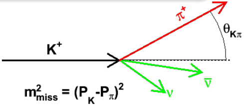
- 2 signal regions
- Minimize multiple scattering

Not separated by kinematic cuts



8% of K decays

- Particle ID
- Photon vetoes

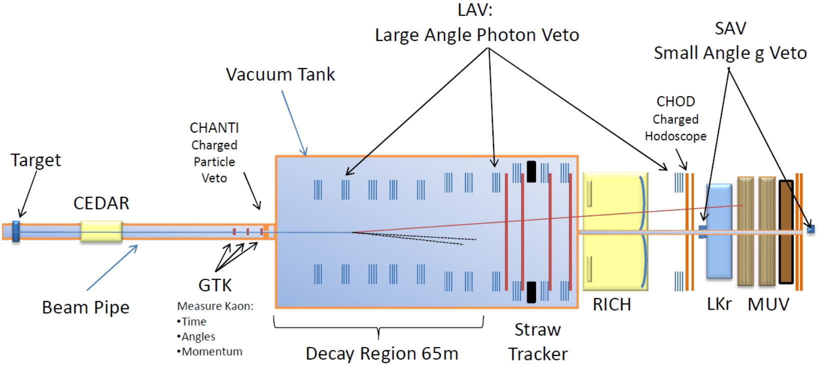


NA62: beam and experiment layout

State of the art detectors for new precision frontier down to 10^{-12}

- SPS primary protons @ 400 GeV/c
- 75 GeV/c ($\Delta P/P \approx 1\%$)
- Area @ beam tracker 16 cm^2
- Kaon decays/year 4.8×10^{12}

- Unseparated secondary charged beam
- $p/\pi/K$ (positron free, $K \approx 6\%$, $p \approx 23\%$)
- Integrated average rate @ beam tracker 750 MHz



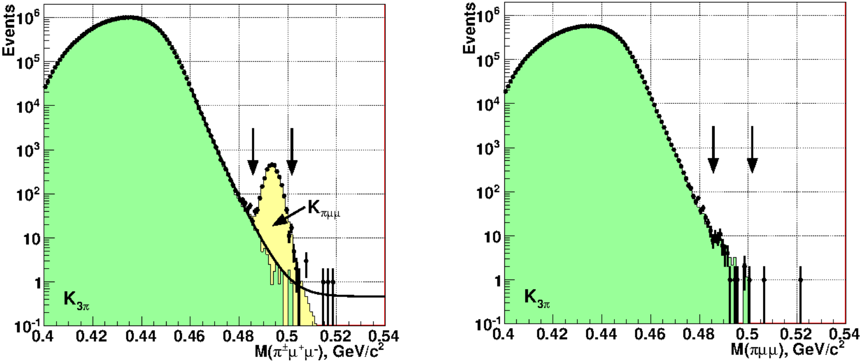
Technical run in 2012 and physics data taking in 2014-2016

$K^\pm \to \pi^\pm \mu^+ \mu^+$ (NA48/2)

- Lepton Number Violating $(\Delta L = 2)$ decays
- Look for wrong-sign events in $\pi^\pm \mu^+ \mu^-$ data

$K^\pm \to \pi^\pm \mu^+ \mu^-$ FCNC candidates

$K^\pm \to \pi^\mp \mu^\pm \mu^\pm$ LNV candidates



$BR(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 1.1 \times 10^{-9}$ (90% CL)

3 times better w.r.t. E865 [PRL 85, (2000) 2877]

Summary

- Kaon physics continues to be a good tool for investigation in the flavour sector
- Chiral Perturbation Theory and experimental determination of form factors provide a constantly improving tool for future precision measurements
- All measurements are currently in agreement with the SM
- A new generation of experiments is starting to explore ultra rare decays, opening a new chapter of tests for the SM and precision measurements previously not accessible:
  - NA62 and KoTO are in construction and will start taking data in the next two years
  - these detectors will be able to improve current measurements