Latest results from the NA48 and NA62 experiments at CERN

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Windows on the Universe 2013
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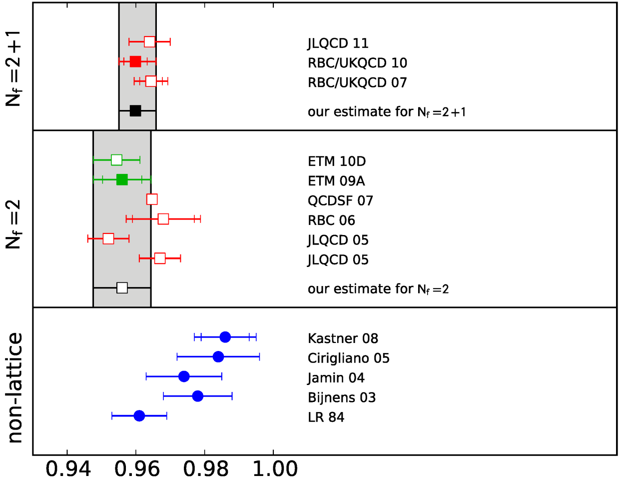
K_{l3} Form Factors

- $M = \frac{G_F}{2}|V_{us}|(f_+(t)(P_K + P_\pi)^\mu \overline{u}_l \gamma_\mu (1+\gamma_5) u_\nu + f_-(t) m_l \overline{u}_l (1+\gamma_5) u_\nu)$, $t = q^2$
- 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

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



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Parametrizations:

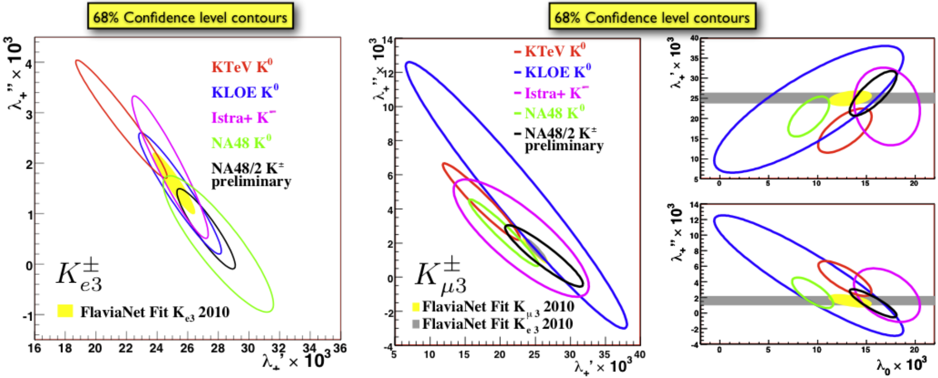
- Pole: assume the exchange of a vector(1^-) or scalar (0^+) resonances ($m_{V,S}$) $\overline{f}_{+,0}(t) = \frac{m_{V,S}^2}{m_{V,S}^2 - t}$
- Linear and quadratic (no physical meaning):
  $\overline{f}_{+,0}(t) = 1 + \lambda_{+,0} \frac{t}{m_\pi^2}$
  $\overline{f}_{+,0}(t) = 1 + \lambda'_{+,0} \frac{t}{m_\pi^2}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

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

NA48/2 Preliminary

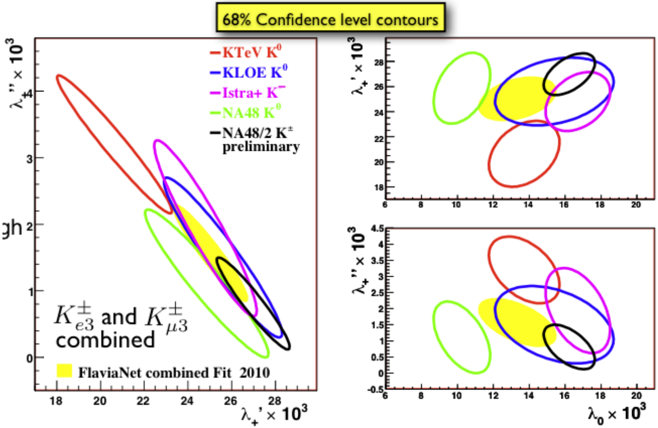
Quadratic ($\times 10^{-3}$)	λ'_+	λ''_+	λ'_0
$K \to \pi^0 \mu\nu_\mu$	$26.3 \pm 3.0_{stat} \pm 2.2_{syst}$	$1.2 \pm 1.1_{stat} \pm 1.1_{syst}$	$15.7 \pm 1.4_{stat} \pm 1.0_{syst}$
$K \to \pi^0 e\nu_e$	$27.2 \pm 0.7_{stat} \pm 1.1_{syst}$	$0.7 \pm 0.3_{stat} \pm 0.4_{syst}$	

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

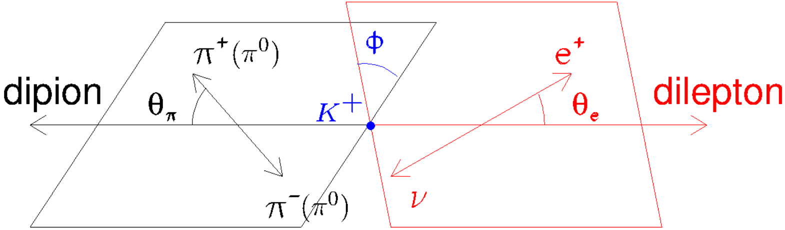
Quadratic ($\times 10^{-3}$)	λ'_+	λ''_+	λ'_0
	26.91 ± 1.11	0.81 ± 0.46	16.23 ± 0.95
Pole (MeV/c^2)	m_V		m_S
	877 ± 6		1176 ± 31



- 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}

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

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

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

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

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

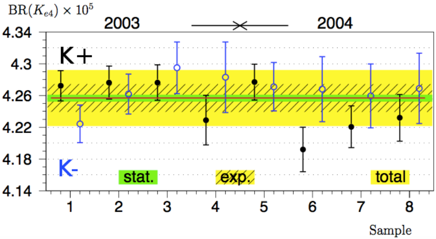
NA48/2 total statistics (2003 + 2004)

	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)

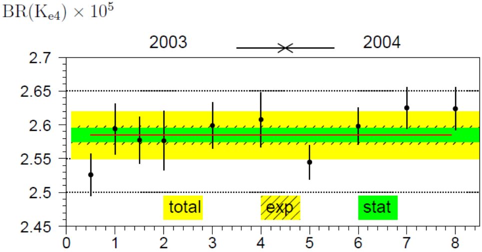
Overall form factor normalization: $BR[K^{\pm}_{e4}(+-)]$

f_s	=	5.705	$\pm$	0.003_{stat}	$\pm$	0.017_{syst}	$\pm$	0.031_{ext}
	=	5.705	$\pm$	0.035_{norm}				
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}

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 (6.6×10^{4}), background (1% of K_{e4}) and normalization (94×10^{6}) events
- signal and normalization acceptance (1.92% and 4.02%) and trigger efficiency (96.1% and 97.4%)
- $BR(K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}) = (1.761 \pm 0.022)\%$



Relative Uncertainty	(%)
Acceptance stability cuts	0.15
Form factor uncertainty	0.13
Background evaluation	0.02
Accidental activity	0.02
Trigger cut	0.08
Particle ID	0.25
Radiative events modeling	0.17
Simulation statistics	0.09
Trigger efficiency	0.03
Total systematics	0.38
External error $[BR(K_{3\pi})]$	1.25
Statistical error	0.39

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

Preliminary result
Analysis in progress

$$BR[K^{\pm}_{e4}(00)] = (2.585 \pm 0.010_{stat} \pm 0.010_{syst} \pm 0.032_{ext}) \times 10^{-5}$$

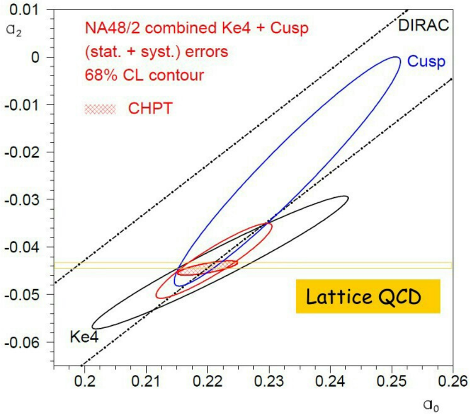
$K_{e4}(+-)$ decay and $\pi\pi$ scattering lengths (NA48/2)

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:

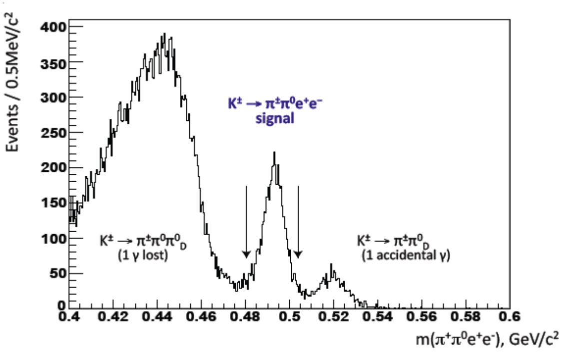
- from the phase shift $\delta(M_{\pi\pi}) = \delta_s - \delta_p$ in K_{e4} decay [Eur.Phys.J. C70 (2010) 635]
- from the cusp in $M_{\pi^0\pi^0}$ in $K^\pm \to \pi^\pm\pi^0\pi^0$ decay [Eur.Phys.J. C64 (2009) 589]

- 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



$K^\pm \to \pi^\pm \pi^0 e^+ e^-$ (NA48/2 analysis in progress)

- 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

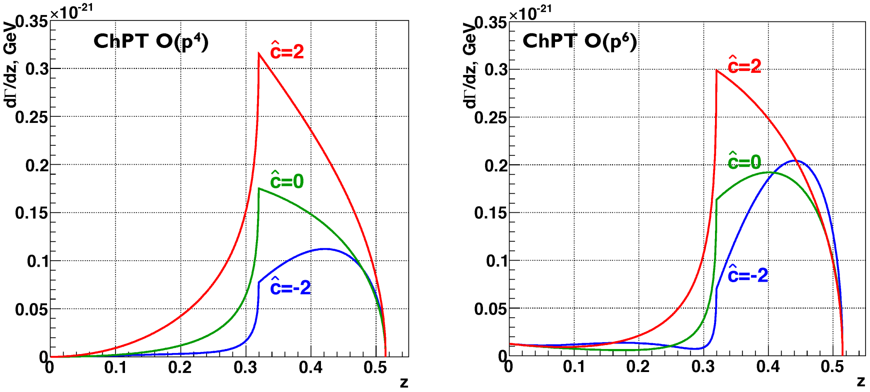


NA48/2 (2003+2004 data):

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

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

- $BR(z)$, $z = \frac{m^2_{\gamma\gamma}}{m^2_K}$, 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]



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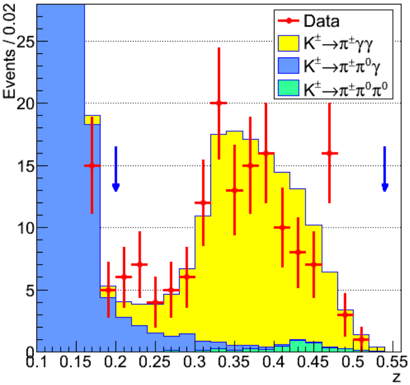
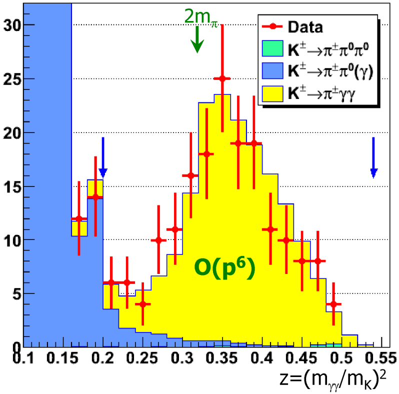
NA48/2 2004



NA62 2007



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

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

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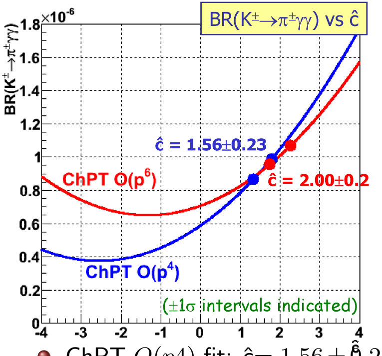
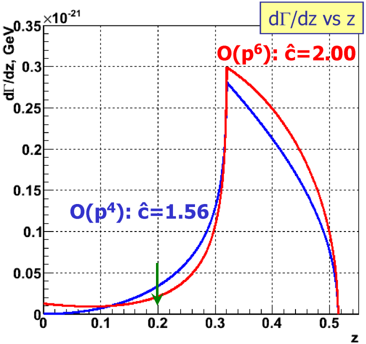
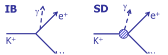


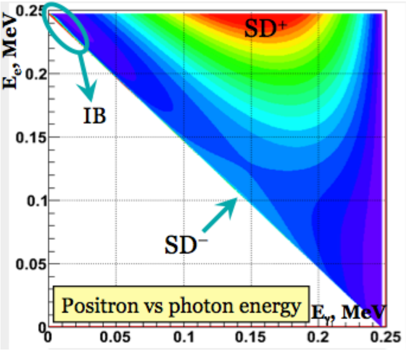


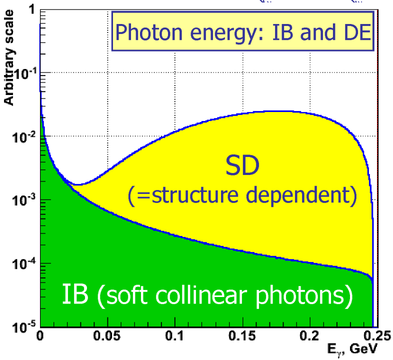
- ChPT $O(p4)$ fit: ĉ$= 1.56 \pm 0.22_{stat} \pm 0.07_{syst} = 1.56 \pm 0.23$ (preliminary)
- ChPT $O(p6)$ fit: ĉ$= 2.00 \pm 0.24_{stat} \pm 0.09_{syst} = 2.00 \pm 0.26$ (preliminary)
- $BR(z > 0.2) = (0.877 \pm 0.087_{stat} \pm 0.017_{syst}) \times 10^{-6}$ (model independent, final NA48/2)

$K \to e\nu_e\gamma$ 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, $x = \frac{2E^*_\gamma}{m_K}$, $y = \frac{2E^*_e}{m_K}$

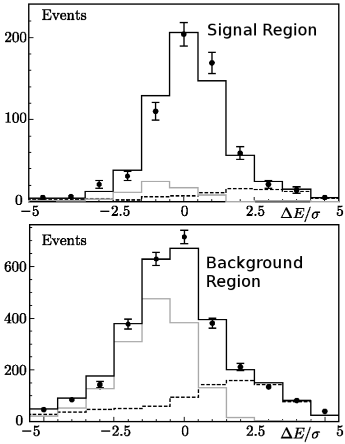


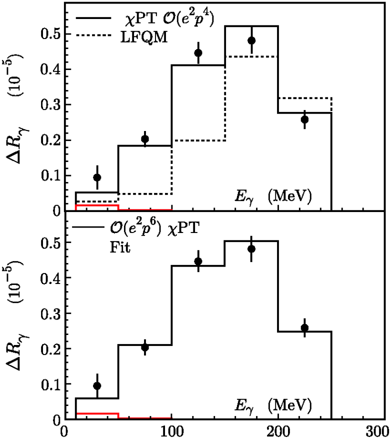




$K \to e\nu_e\gamma$ SD+

- $\frac{d^2\Gamma_{SD}}{dxdy} = \frac{m_K^5 \alpha G_F^2 |V_{us}|^2}{64\pi^2}\left[(F_V + F_A)^2 f_{SD+}(x,y) + (F_V - F_A)^2 f_{SD-}(x,y)\right]$
- 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]





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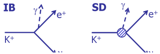
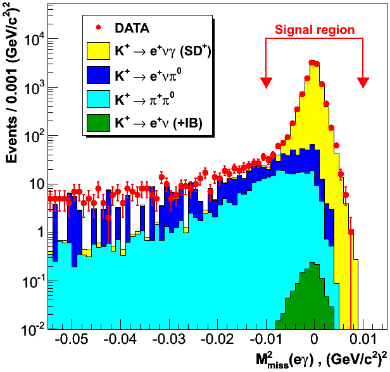
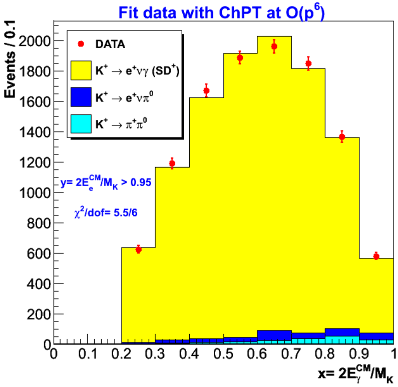
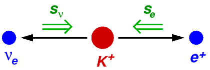


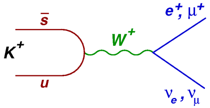




- NA62 preliminary
- ≈ 10000 event candidates

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]

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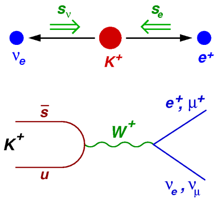
- In the SM:
  $R_K = (2.477 \pm 0.001)10^{-5}$
  - Hadronic uncertainties cancel in the ratio
  - Helicity suppression $\approx 10^{-5}$
  - Radiative correction (few %) due to $K \to e\nu_e\gamma(IB)$, by definition included into R_K

  [PRL 99 (2007), 231801]



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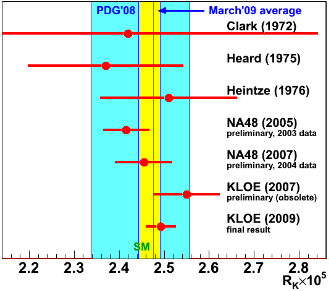


- Experimentally:
  - $R_K = (2.45 \pm 0.11)10^{-5}$ (PDG 2008, '70s measurements)
    $\delta R_K / R_K \approx 4.5\%$
  - $R_K = (2.493 \pm 0.031)10^{-5}$ (KLOE [Eur.Phys.J.C64 (2009) 627])
    $\delta R_K / R_K \approx 1.3\%$
  - It's worth to improve it because of its small and well predicted value

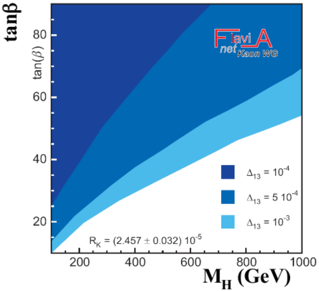
R_K in case of New Physics (MSSM)

- 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 $m_H = 500\text{GeV}/c^2$, $|\Delta_{13}| = 5\times 10^{-4}$ and $\tan\beta = 40$

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



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

R_K in case of New Physics (MSSM)

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

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

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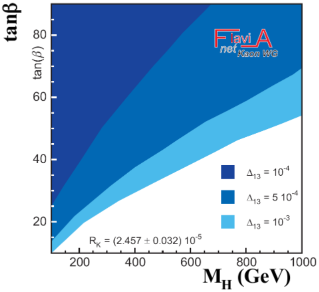

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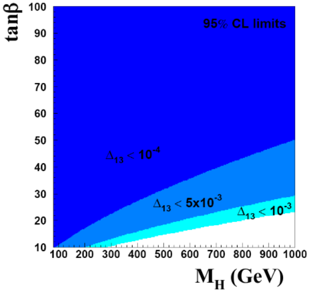

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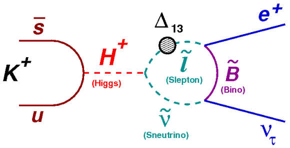


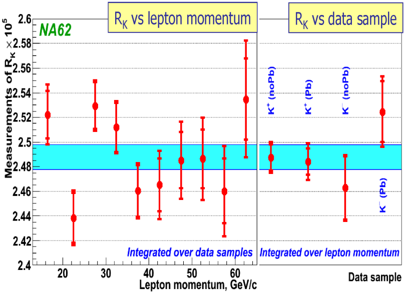
π and B have the same effect, but:

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

Final result

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: $(99.28 \pm 0.05)\%$
$B/(S+B) = (10.95 \pm 0.27)\%$

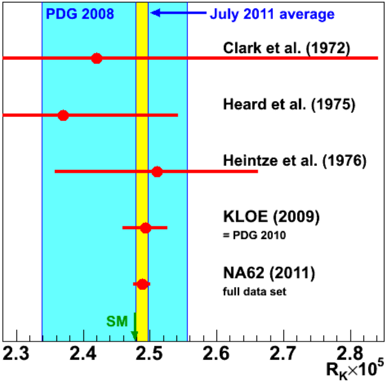
Fit over 40 measurements
4 data samples 10 momentum bins)
including correlations:
$\chi^2/ndf = 47/39$

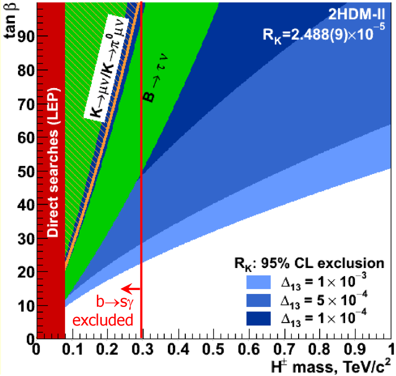
Result

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

[Phys.Lett. B719 (2013) 326-336]

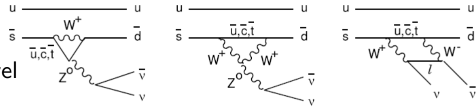
World Average





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

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

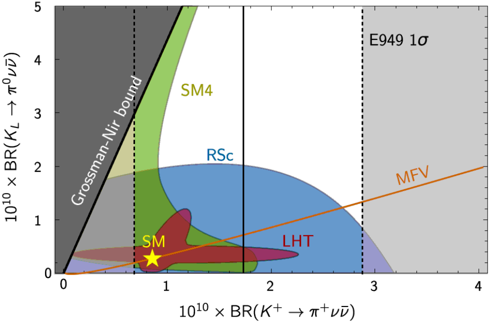


Ultra rare decay

- 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	$\pm$0.39	$\pm$0.06)	10^{-11}
$K^+ \to \pi^+\nu\overline{\nu}$	(7.81	$\pm$0.75	$\pm$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 $\to$



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

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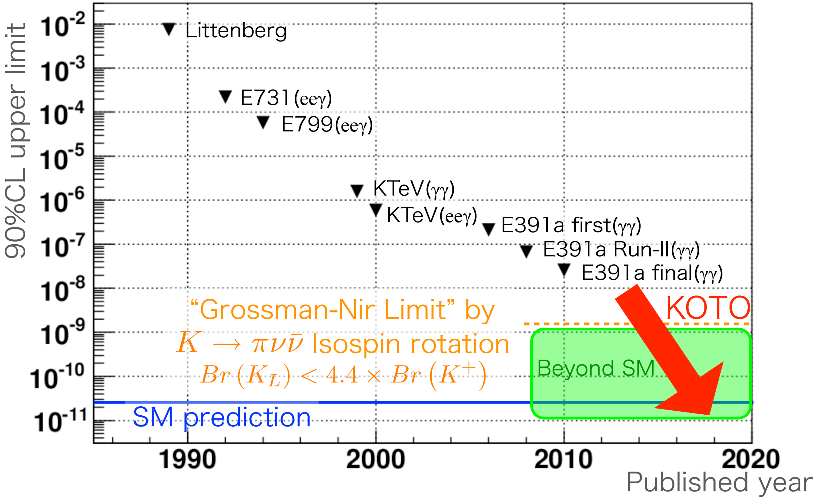

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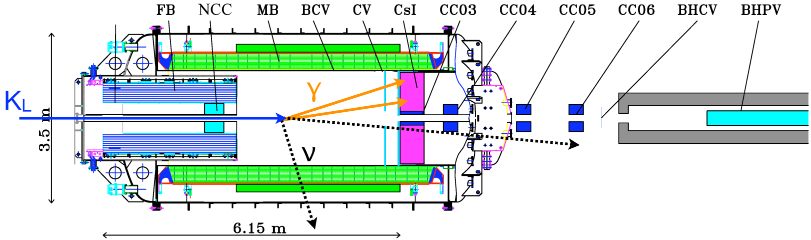

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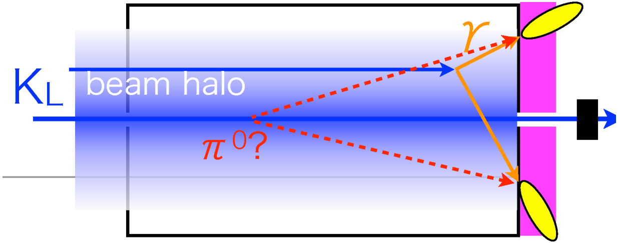
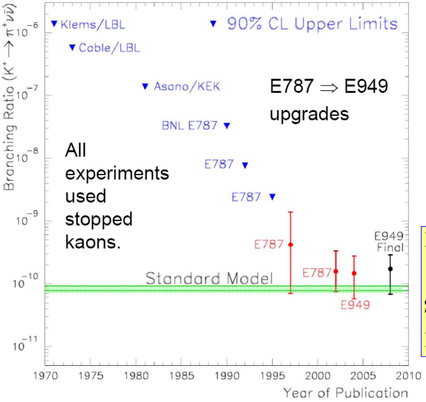
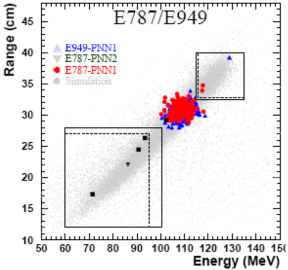


$K \to \pi\nu\bar{\nu}$ foreseen experiments

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





E787/E949 Final: 7 events observed

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

Standard Model:

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

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

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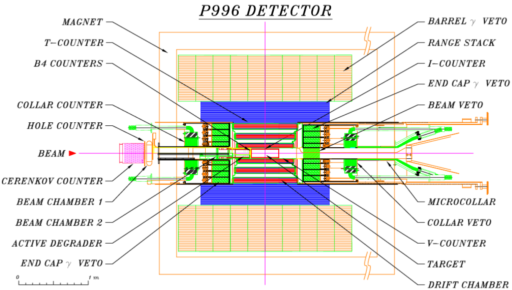
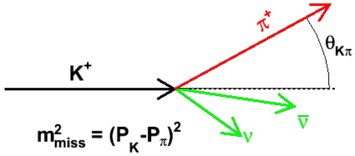


Measurement of $BR(K^+ \to \pi^+ \nu\overline{\nu})$ at NA62

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

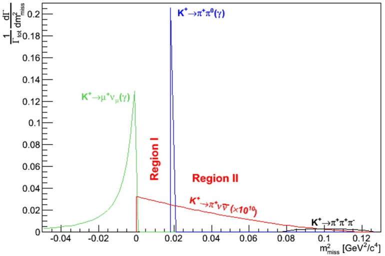
Missing mass



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

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

Separated by kinematic cuts



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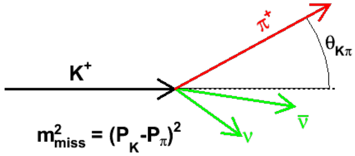

92% of K decays

- 2 signal regions
- Minimize multiple scattering

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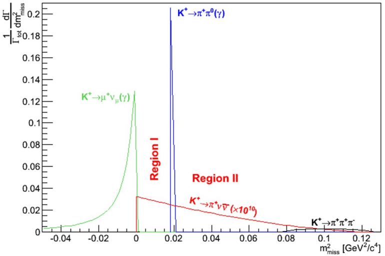
Measurement at 10% ($\approx$ SM prediction accuracy), 100 SM events

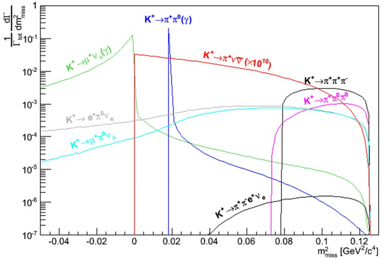
Separated by kinematic cuts



92% of K decays

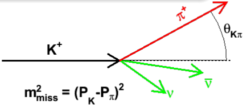
- 2 signal regions
- Minimize multiple scattering

Not separated by kinematic cuts



8% of K decays

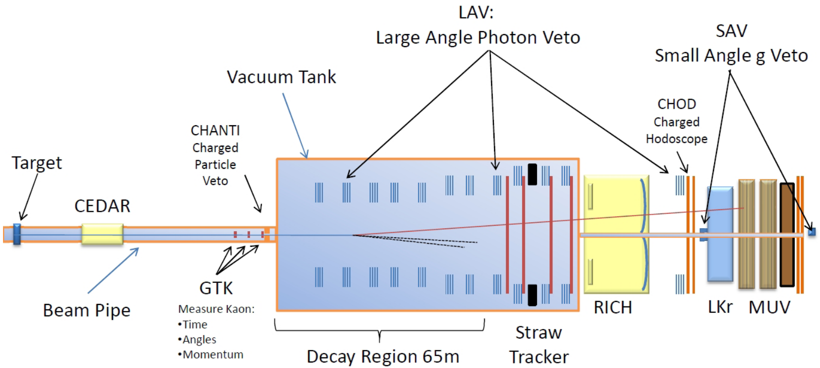
- Particle ID
- Photon vetoes



NA62: beam and experiment layout

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

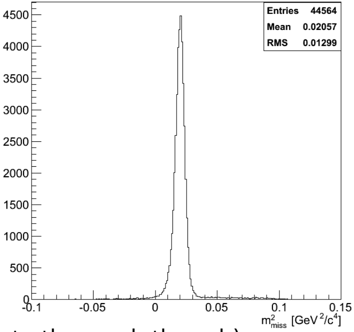
- SPS primary protons @ 400 GeV/c
- 75 GeV/c ($\Delta P/P \approx 1\%$)
- Area @ beam tracker 16 cm^2
- Kaon decays/year 4.8×10^{12}
- Unseparated secondary charged beam
- $p/\pi/K$ (positron free, $K \approx 6\%$, $p \approx 23\%$)
- Integrated average rate @ beam tracker 750 MHz



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

NA62 technical run 2012

- Partial set-up:
  - KTAG (50% PMs), 1 straw plane (64 channels readout), CHOD, LKr (30% readout), MUV2, MUV3
- Exploit the timing and spatial correlations between the subdetectors to define a Kaon candidate, pion candidate and a muon candidate
- Signal region:
  - $0 < m^2_{miss} < 0.04$ GeV$^2/c^4$
- Background @ % level
- $m^2_{miss} = (0.0199 \pm 0.0005)$ GeV$^2/c^4$
- $\sigma_{m^2_{miss}} = 3.8 \times 10^{-3}$ GeV$^2/c^4$
- $m^2_{\pi^+} = 0.0195$ GeV$^2/c^4$
- Time resolution: KTAG 150 ps, LKr 350 ps, CHOD 400 ps, MUV3 450 ps.
- KTAG efficiency about 87% (corresponding to 95% for a fully instrumented detector).



- 6% of events with a muon in-time (upper limit to the punch-through)
- This analysis will be used in the final analysis to monitor the tails of the reconstructed with the tracking system

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:
  - KoTO has started physics runs this year
  - NA62 is in construction, had a technical run with a partial set-up last year and will start taking data in next year
  - these detectors will be able to improve current measurements