Recent Results from Kaon Experiments at CERN

Evgueni Goudzovski

(University of Birmingham)

eg@hep.ph.bham.ac.uk

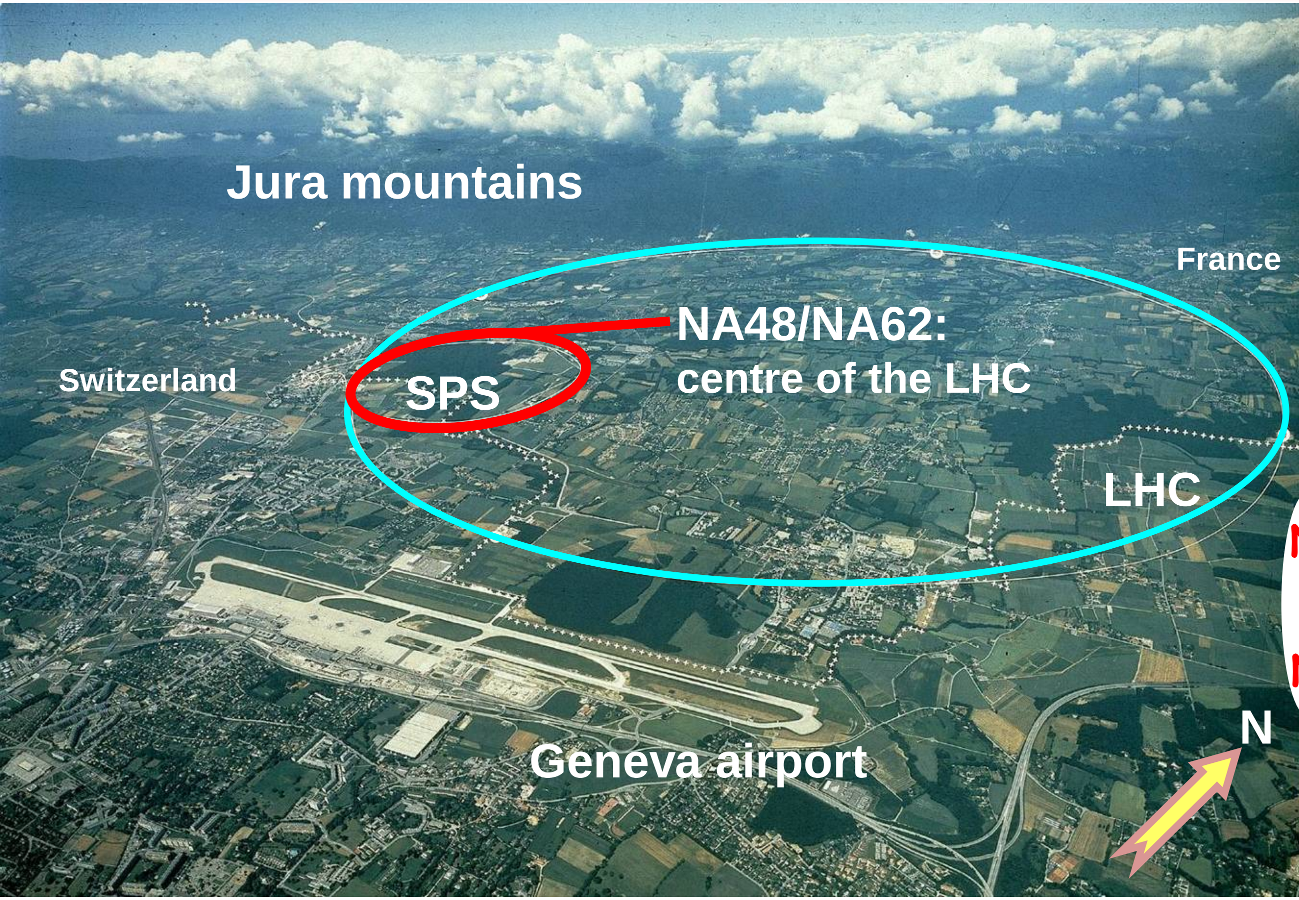
Outline:

1) Recent CERN kaon experiments: NA48/2 and NA62-R_K
2) Measurement of leptonic $K^{\pm}$ decays
3) Measurement of the $K^{\pm}\to\pi^{\pm}\gamma\gamma$ decay
4) Studies of the $K^{\pm}\to\pi\pi e^{\pm}\nu$ decays
5) Summary

Flavour Physics – Xth Rencontres du Vietnam

Quy Nhon • 30 July 2014

CERN NA48/NA62 experiments



Earlier: NA31

NA48 discovery of direct CPV
- 1997: ε'/ε: 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

NA48/2
- 2003: K^+/K^-
- 2004: K^+/K^-

NA62 R_K phase
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$ | tests

NA62
- 2012: technical run
- *2014:* 1st $K^+\to\pi^+\nu\bar{\nu}$ run

Kaon decay in flight experiments.

NA62: currently **~200** participants, **29** institutions

Recent $K^{\pm}$ experiments at CERN

Experiment	NA48/2 ($K^{\pm}$)	NA62-R_K ($K^{\pm}$)	*NA62* (*K^{+}; planned*)
Data taking period	2003–2004	2007–2008	*2014–2017*
Beam momentum, GeV/c	60	74	75
RMS momentum bite, GeV/c	2.2	1.4	0.8
Spectrometer thickness, X_0	2.8%	2.8%	1.8%
Spectrometer P_T kick, MeV/c	120	265	270
$M(K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-})$ resolution, MeV/c^2	1.7	1.2	0.8
K decays in fiducial volume	2×10^{11}	2×10^{10}	1.2×10^{13}
Main trigger	multi-track; $K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$	$e^{\pm}$	$K_{\pi\nu\nu}$ + ...

Same detector (NA48)

The new NA62 detector:

- beam spectrometer and kaon tagger;
- improved mass reconstruction and particle identification;
- hermetic photon veto.

NA48/2 and NA62-R_K detector

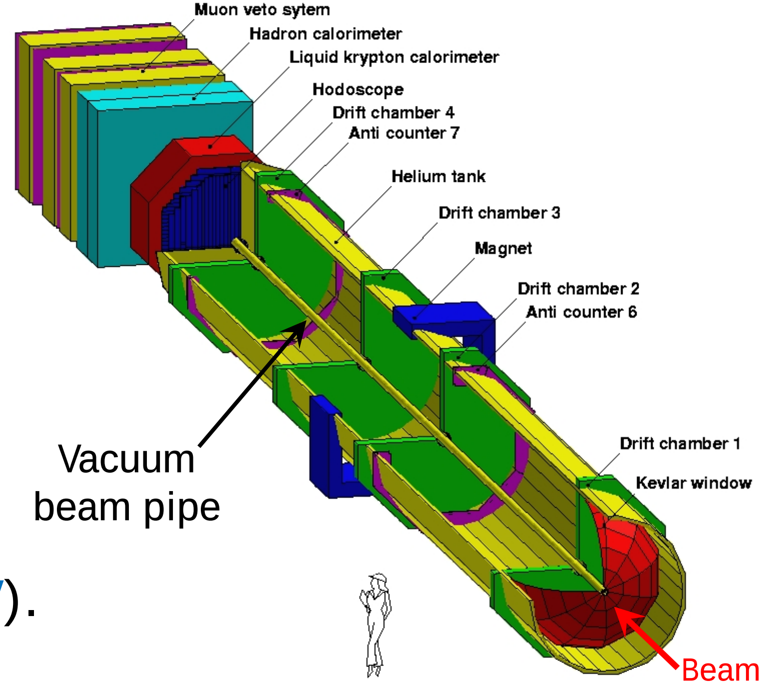
2003–2008: charged kaon beams,
the NA48 detector

Narrow momentum band $K^\pm$ beams:
P_K= 60 (74) GeV/c, $\delta P_K/P_K$ ~ 1% (rms).

- ❖ Maximum $K^\pm$ decay rate ~100 kHz;
- ❖ **NA48/2:** six months in 2003–04;
- ❖ **NA62-R_K:** four months in 2007.

Principal subdetectors:

- ❖ Magnetic spectrometer (4 DCHs)
  4 views/DCH: redundancy ⇒ efficiency;
  $\delta p/p = 0.48\% \oplus 0.009\% p$ [GeV/c] (in 2007)
- ❖ Scintillator hodoscope
  Fast trigger, time measurement (**150ps**).
- ❖ Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$ [GeV];
  $\sigma_x=\sigma_y=4.2\text{mm}/E^{1/2} \oplus 0.6\text{mm}$ (1.5mm@10GeV).



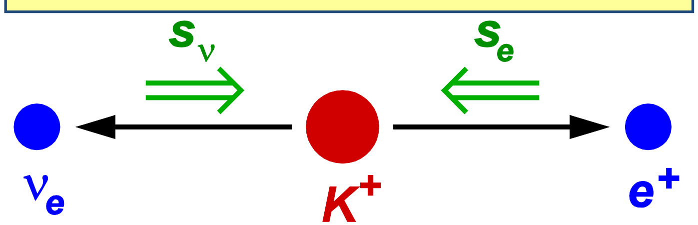
$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ in the SM

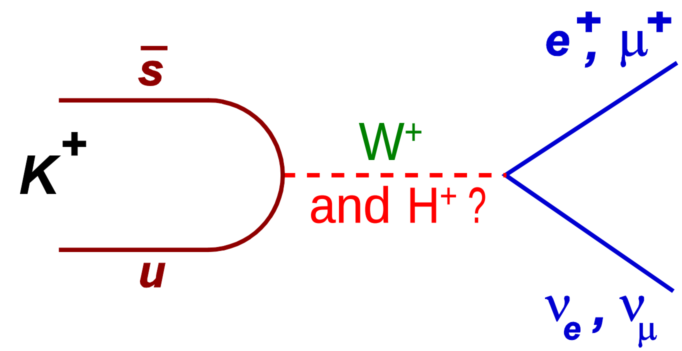
Lepton Universality test:

$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{rad.corr.})$$

Helicity suppression: f~10^{-5}

Radiative correction (well known, few %)





- **SM**: excellent sub-permille accuracy, not obstructed by hadronic uncertainties.
- Measurements of R_K and R_π have long been considered as LU tests.
- **Suppression of the SM contribution**: potentially accessible NP contributions.

$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

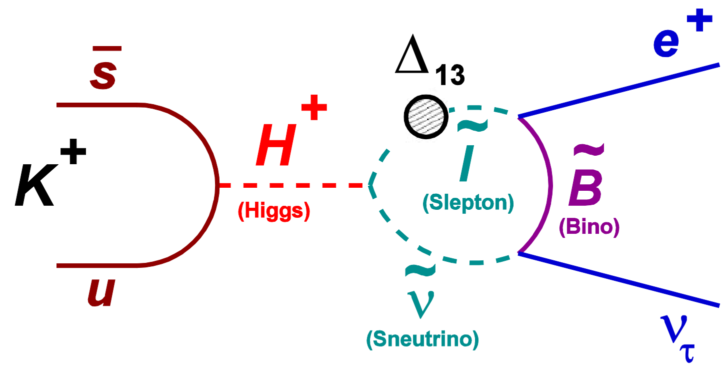
Cirigliano and Rosell, PRL99 (2007) 231801

$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ beyond the SM

2HDM - tree level

$K^\pm \to l^\pm \nu$ can proceed via charged Higgs $H^\pm$ (in addition to $W^\pm$) exchange

→ Does not affect the ratio R_K



2HDM - one-loop level

Dominant contribution to R_K: $H^\pm$ mediated LFV (rather than LFC) with emission of ν_τ

→ R_K enhancement can be experimentally accessible

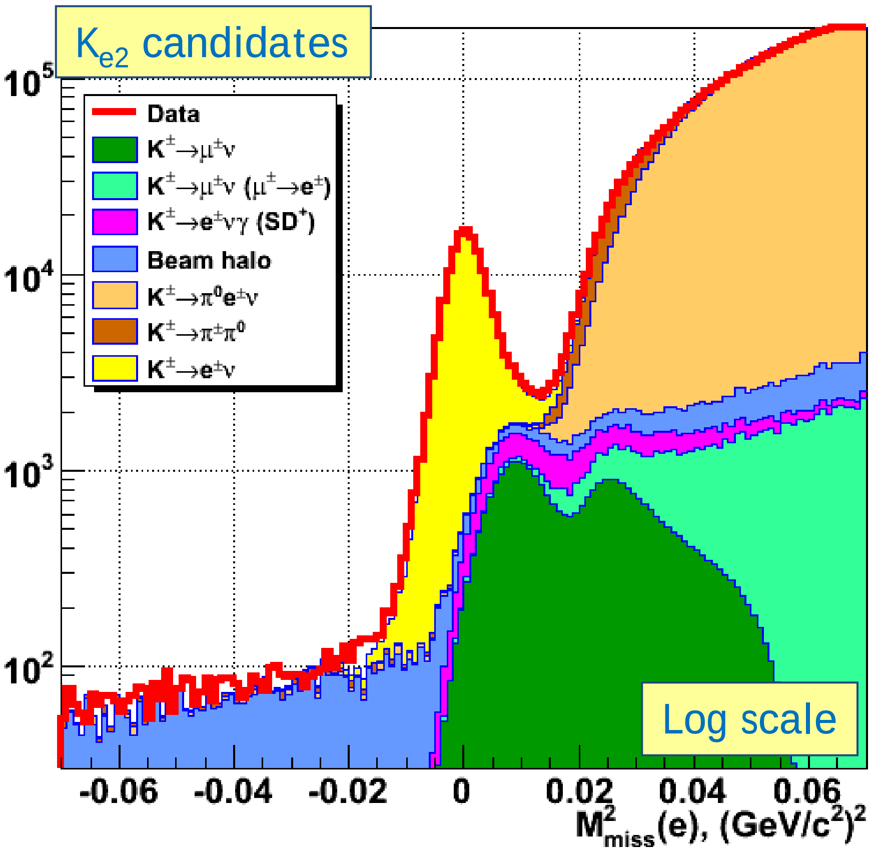
Masiero, Paradisi and Petronzio, PRD 74 (2006) 011701, JHEP 0811 (2008) 042

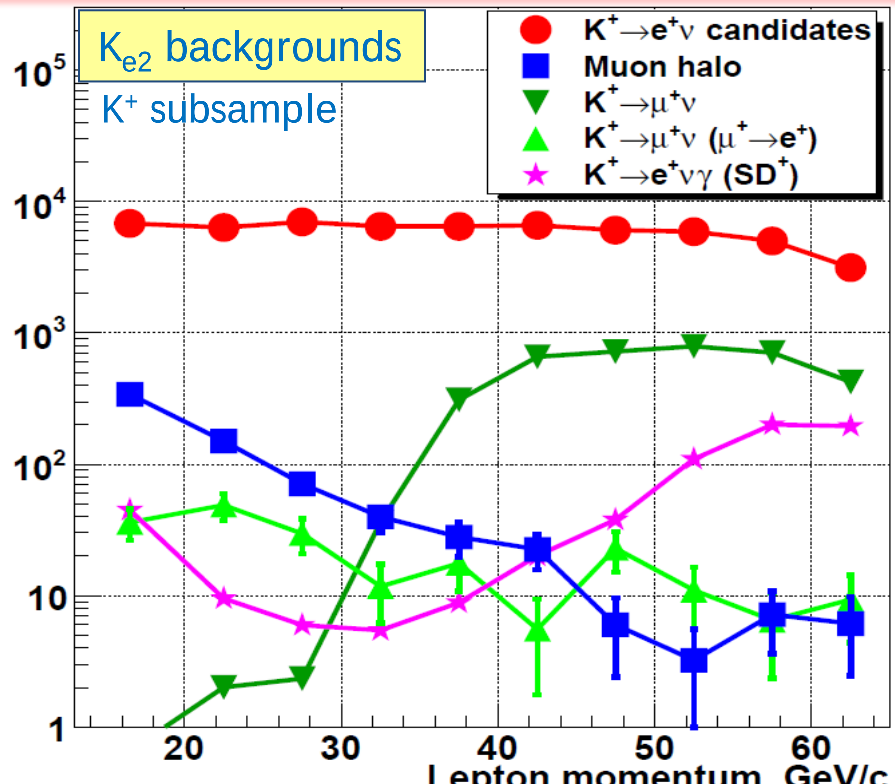
$$R_K^{LFV} \approx R_K^{SM} \left[1 + \left(\frac{m_K^4}{M_{H^\pm}^4} \right) \left(\frac{m_\tau^2}{M_e^2} \right) |\Delta_{13}|^2 \tan^6 \beta \right]$$

⇒ sensitive to slepton mixing

- MSSM: ~1% effect possible
  Girrbach and Nierste, arXiv:1202.4906
- However limited by $B_{(S)} \to \mu^+\mu^-$ measurements
  Fonseca, Romão and Teixeira, EPJC 72 (2012) 2228
- Sensitive to SM extensions with 4th generation, sterile neutrinos
  Lacker and Menzel, JHEP 1007 (2010) 006; Abada et al., JHEP 1302 (2013) 048

NA62-R_K data: K_{e2} sample





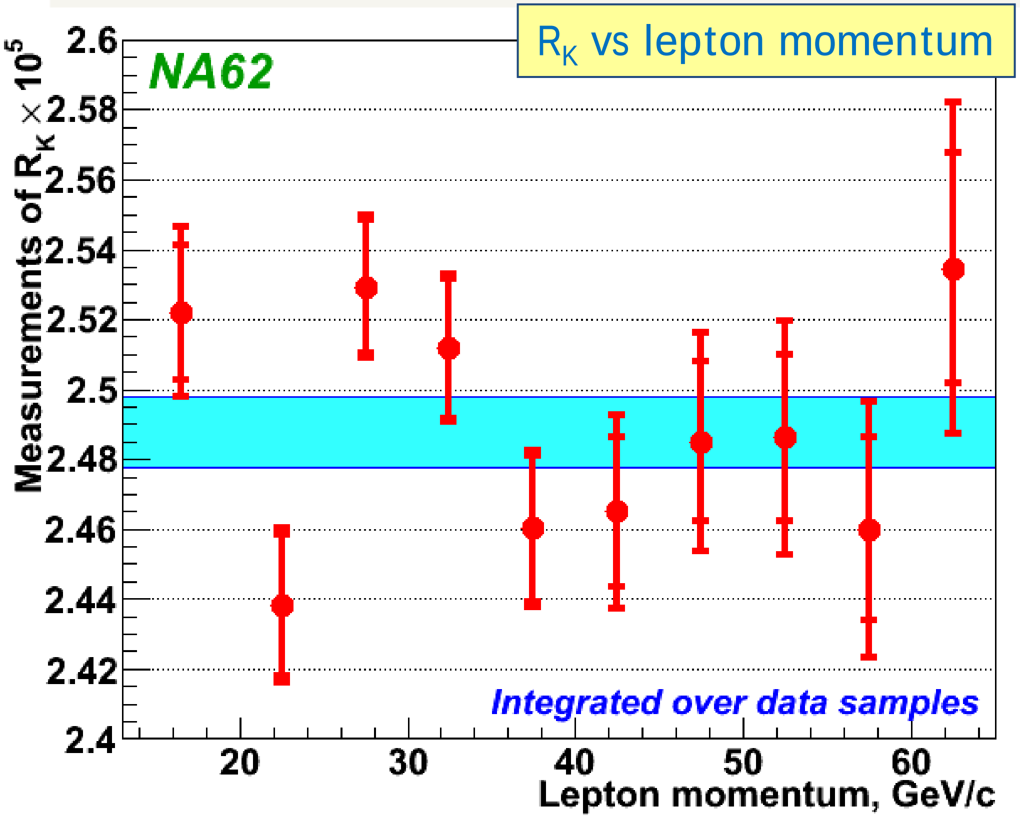
Source	B/(S+B)
$K_{\mu 2}$	(5.64±0.20)%
$K_{\mu 2}$ ($\mu \to e$)	(0.26±0.03)%
$K_{e2\gamma}$ (SD)	(2.60±0.11)%
$K_{e3(D)}$	(0.18±0.09)%
$K_{2\pi(D)}$	(0.12±0.06)%
Opposite sign K	(0.04±0.02)%
Beam halo	(2.11±0.09)%
Total	(10.95±0.27)%

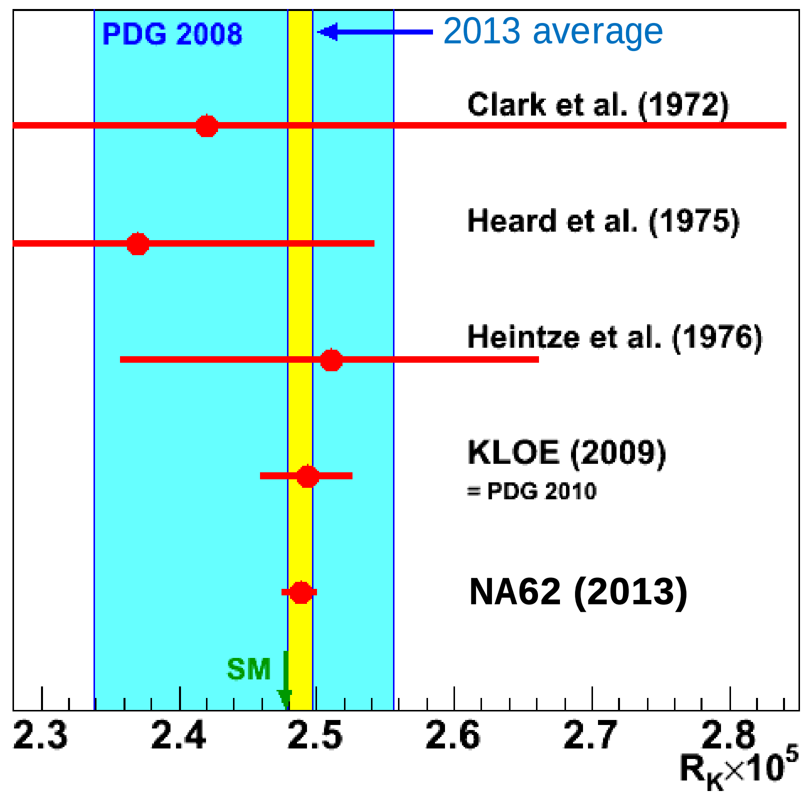
145,958 $K^{\pm} \to e^{\pm}\nu$ candidates.
Background: B/(S+B)=(10.95±0.27)%.
Electron ID efficiency: (99.28±0.05)%.

NA62-R_K final result

PLB719 (2013) 326

$$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$$
$$= (2.488 \pm 0.010) \times 10^{-5}$$



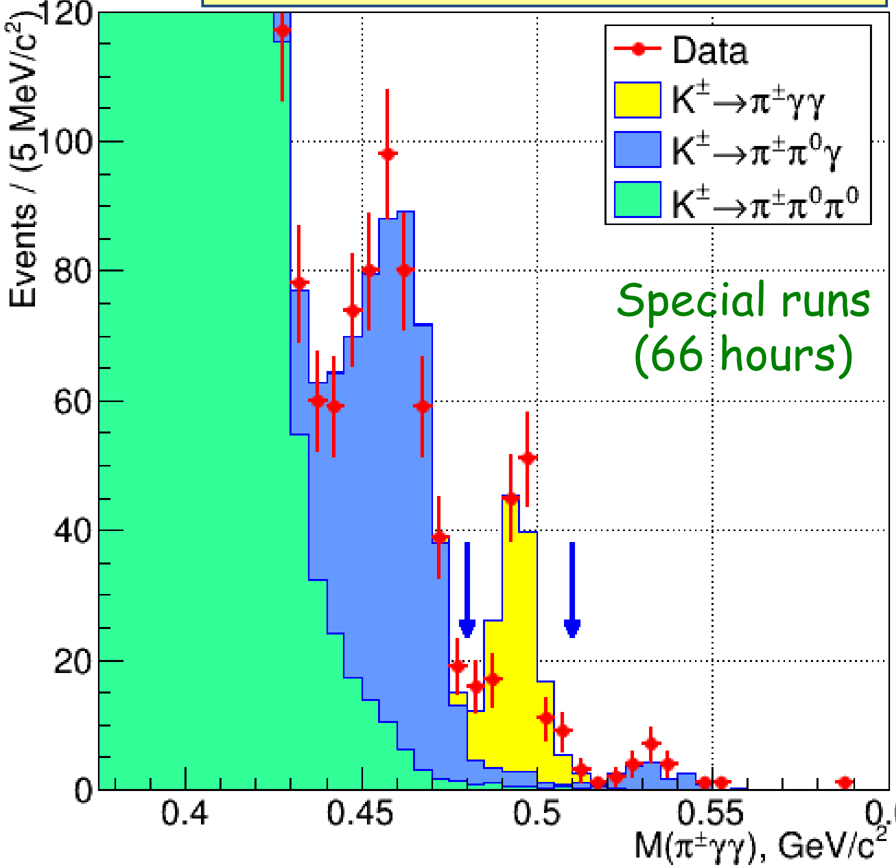


World average	$R_K \times 10^5$	Precision
PDG 2008	2.447±0.109	4.5%
2013	2.488±0.009	0.4%

NA62 prospects:
improve precision by a factor ~2.
Competitor: TREK@J-PARC.

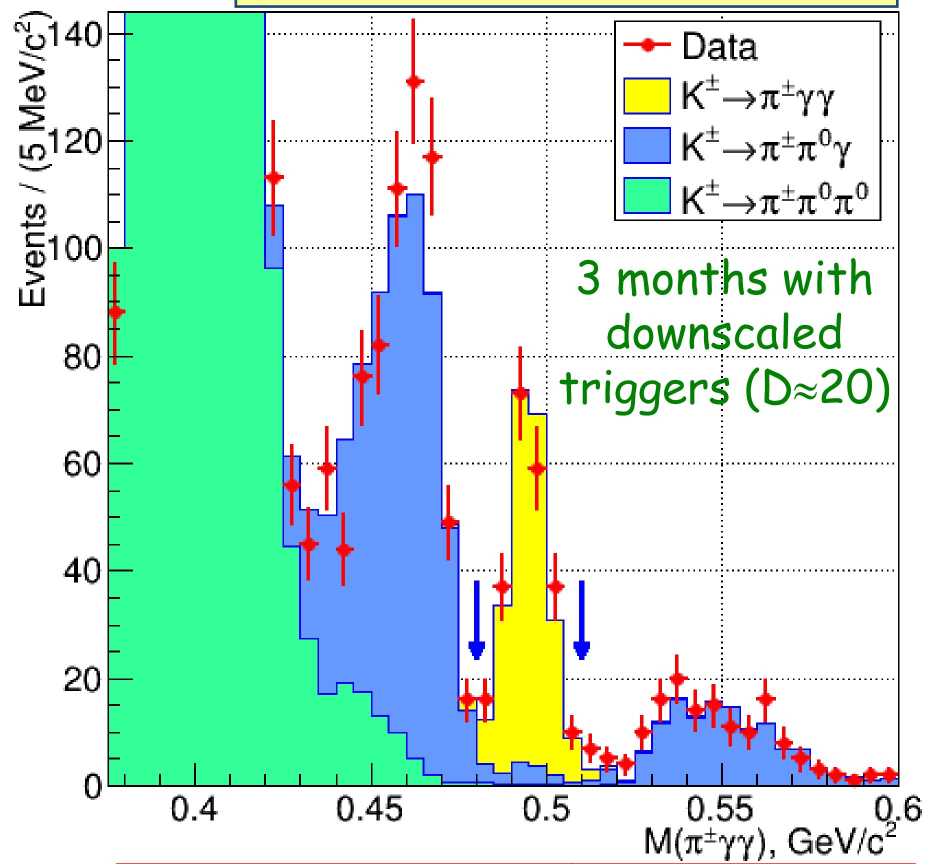
Minimum bias data: $K^{\pm}\to\pi^{\pm}\gamma\gamma$

NA48/2: PLB730 (2014) 141



$K_{\pi\gamma\gamma}$ candidates	149
$K_{2\pi(\gamma)}$ background	11.4±0.6
$K_{3\pi}$ background	4.1±0.4
$K_{\pi\gamma\gamma}$ signal	134±12

NA62-R_K: PLB732 (2014) 65

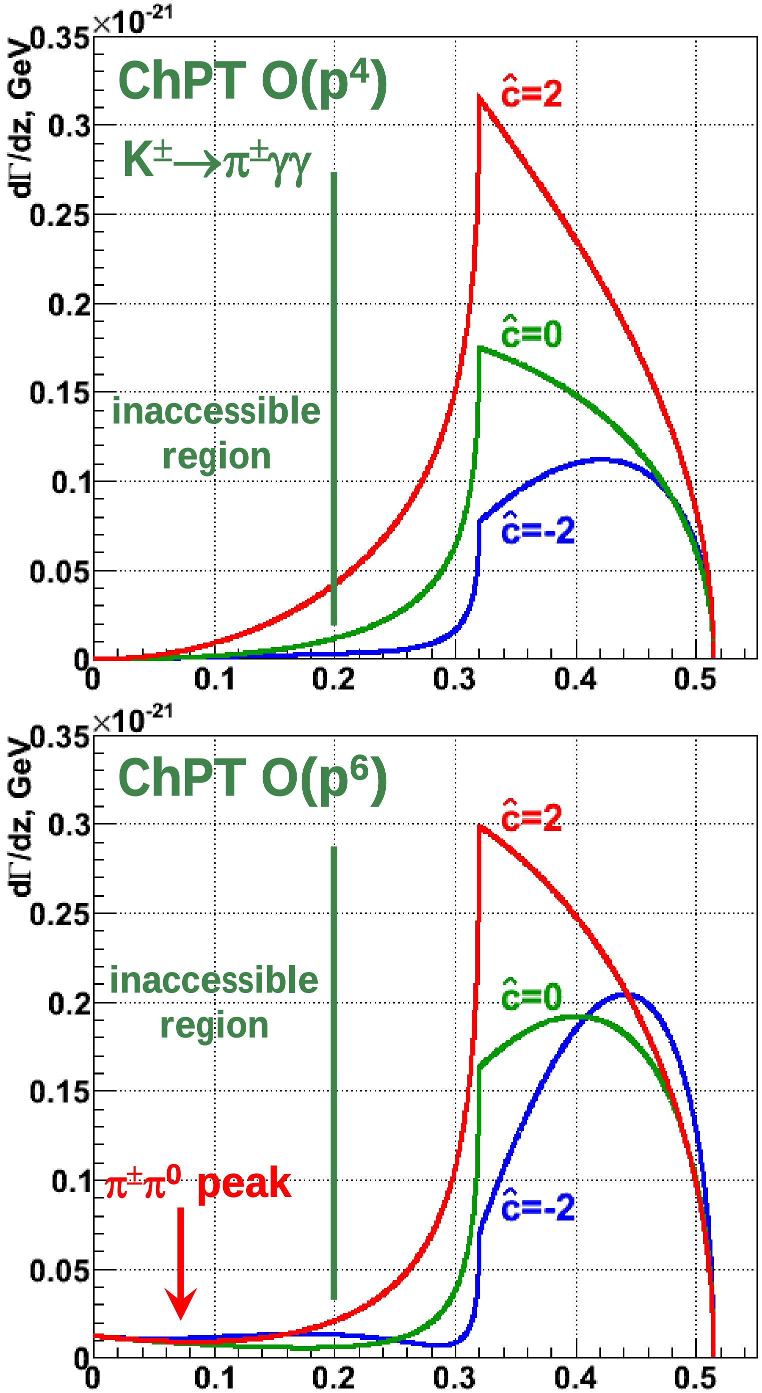


$K_{\pi\gamma\gamma}$ candidates	232
$K_{2\pi(\gamma)}$ background	15.3±1.1
$K_{3\pi}$ background	2.1±0.3
$K_{\pi\gamma\gamma}$ signal	215±15

ChPT description

D'Ambrosio, Portoles, PLB386 (1996) 403

$$z = \frac{(q_1+q_2)^2}{m_K^2} = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2, \quad y = \frac{p(q_1-q_2)}{m_K^2}$$

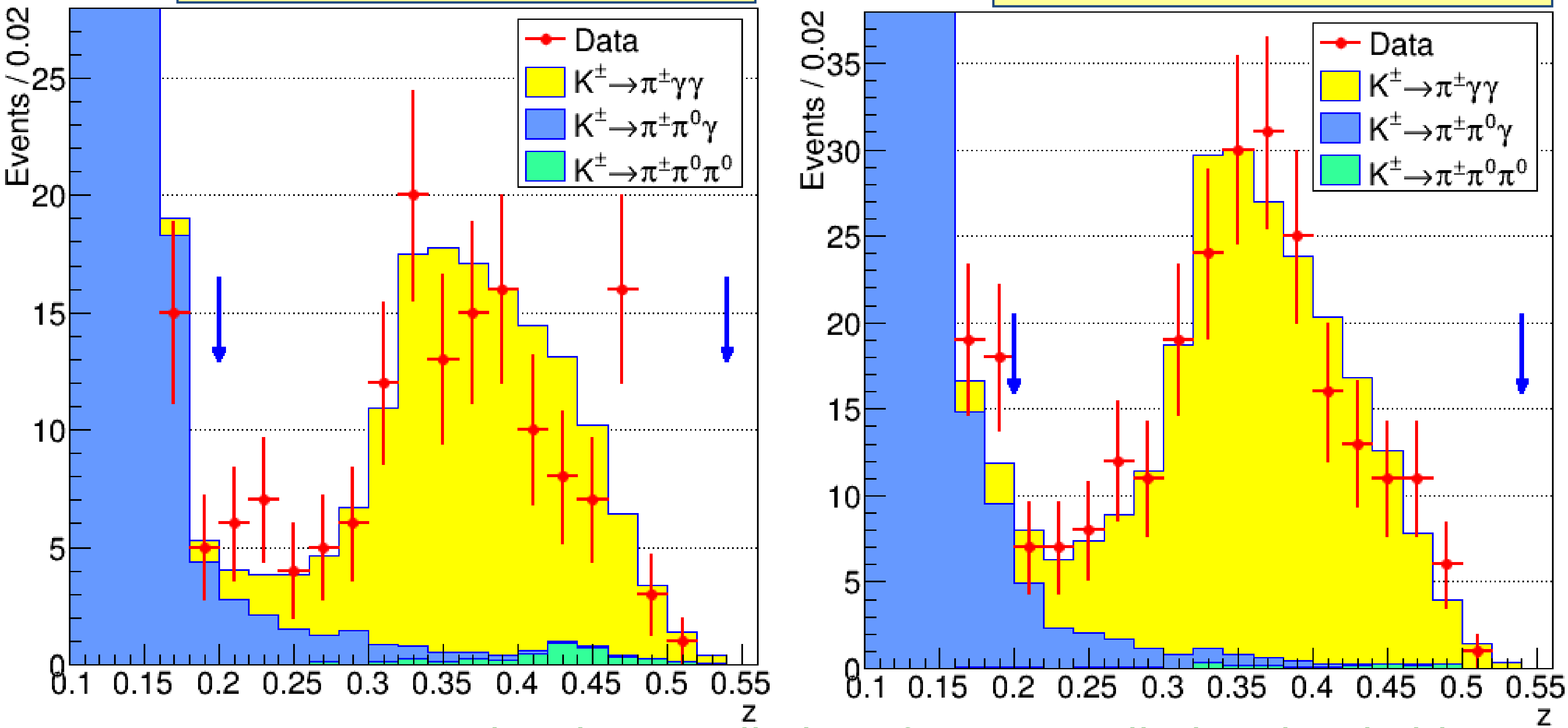


- Leading ChPT contribution at **$O(p^4)$**.
- Rate and spectrum determined by a single "unknown" parameter: **ĉ**.
- A number of fixed external inputs: **G_8**; at **$O(p^6)$**, **$K_{3\pi}$** amplitude parameters and "polynomial contributions" **η_i**.
- Dominated by pion loop amplitude: cusp at di-pion threshold **$z=(2m_\pi/m_K)^2=0.32$**.
- ChPT **$O(p^6)$**: non-zero **$d\Gamma/dz$** at **$z=0$** and (weak) **y**-dependence of **$d^2\Gamma/dz/dy$**.

Fits to ChPT description

NA48/2: PLB730 (2014) 141

NA62-R_K: PLB732 (2014) 65



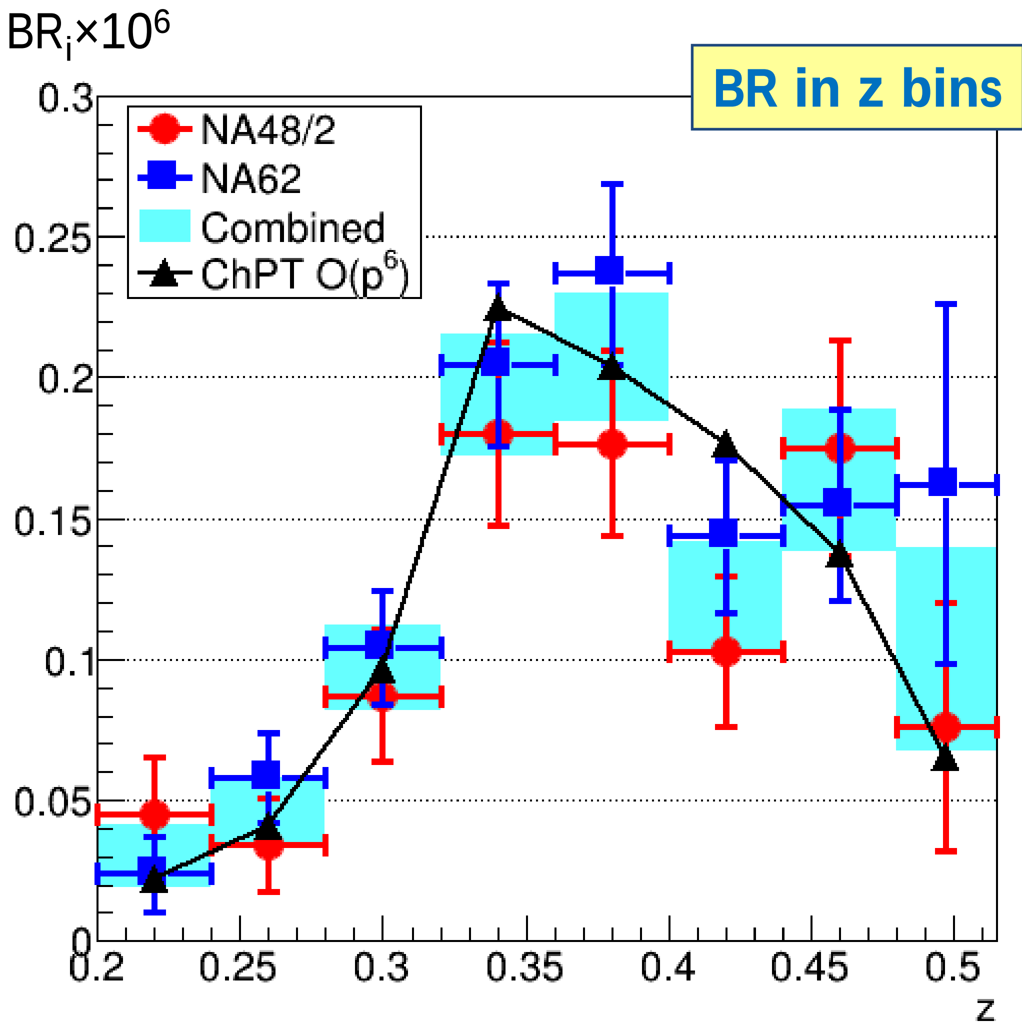
→ Data support the ChPT prediction of a cusp at di-pion threshold

NA48/2 & NA62-R_K combined measurement:

$\hat{c}_4 = 1.72\pm0.20_{stat}\pm0.06_{syst}$; $\hat{c}_6 = 1.86\pm0.23_{stat}\pm0.11_{syst}$

Improved precision wrt BNL E787 (31 $K^+\to\pi^+\gamma\gamma$ candidates, *PRL 79 (1997) 4079*) and NA48/2 (120 $K^{\pm}\to\pi^{\pm}\gamma e^+e^-$ candidates, *PLB659 (2009) 493*)

Model-independent BR($K^{\pm}\to\pi^{\pm}\gamma\gamma$)



Model-independent BR measurement in narrow **z** bins is possible:

✓ acceptance in bins is almost independent of the assumed **dΓ/dz**;

✓ weak **y**-dependence of the differential rate and acceptance.

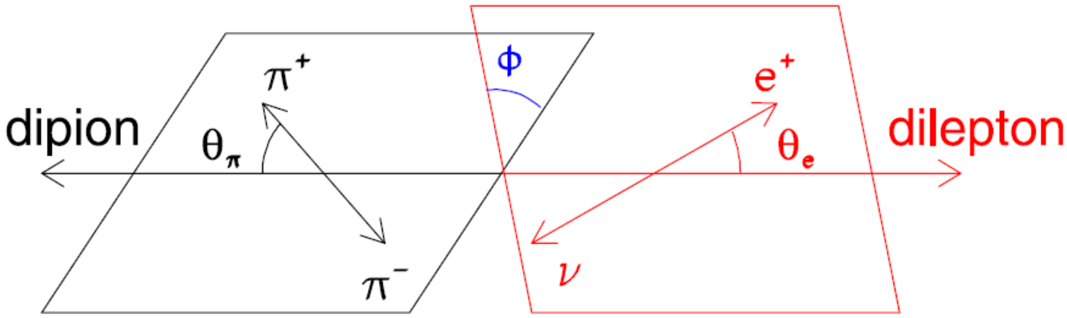
Final result with **349** events:

$BR_{MI}(z>0.2)$ = ($0.965\pm0.061_{stat}\pm0.014_{syst}$)×10^{-6}

PLB 730 (2013) 141, PLB 732 (2014) 65

K_{e4} decays: introduction

Five kinematic variables: $S_\pi=(m_{\pi\pi})^2$, $S_e=(m_{e\nu})^2$, $\cos\theta_\pi$, $\cos\theta_e$, Φ



[Cabibbo, Maksymowicz, PR137 (1965) B438]

Partial wave expansion and form factors [Pais, Treiman, PR168 (1968) 1858]

$$K^\pm \to \pi^+\pi^- e^\pm \nu \quad (K_{e4}^{+-})$$

$$F = F_s e^{i\delta_s} + F_p e^{i\delta_p}\cos\theta_\pi + \ldots$$

$$G = G_p e^{i\delta_g} + \ldots; \quad H = H_p e^{i\delta_h} + \ldots$$

axial:

$$F_s = f_s + f_s' q^2 + f_s'' q^4 + f_e' S_e/4m_\pi^2 + \ldots$$

$$F_p = f_p + f_p' q^2 + \ldots$$

$$G_p = g_p + g_p' q^2 + \ldots$$

vector:

$$H_p = h_p + h_p' q^2 + \ldots$$

$$\delta(q^2) = \delta_s - \delta_p\,.$$

$$K^\pm \to \pi^0\pi^0 e^\pm \nu \quad (K_{e4}^{00})$$

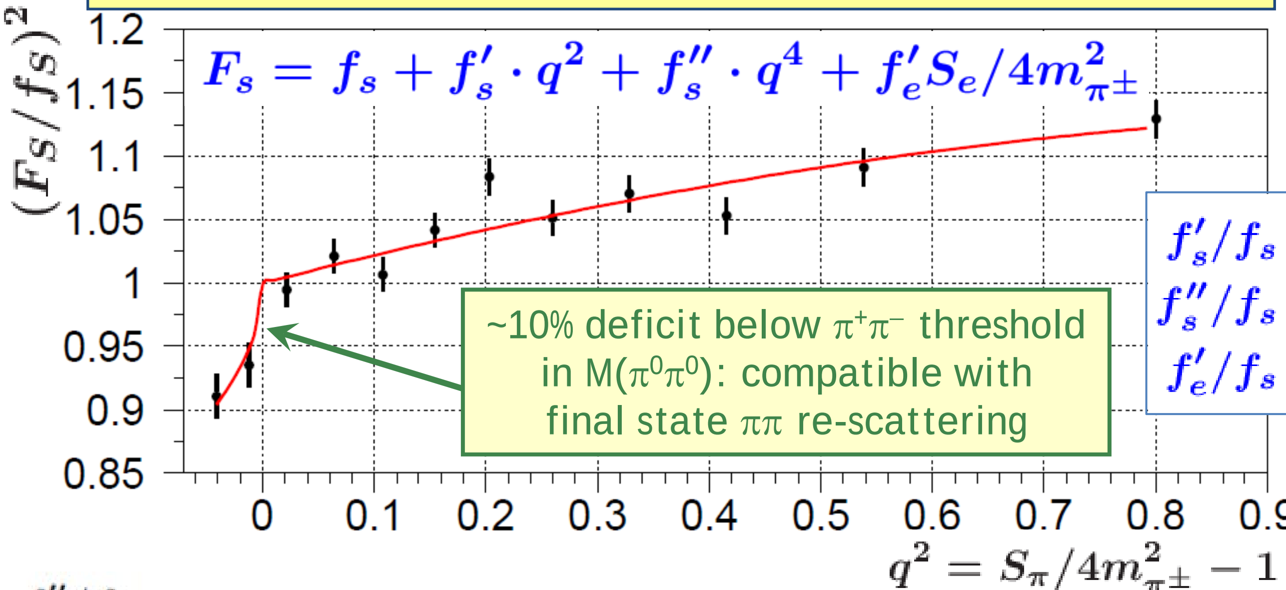
$$F = F_s e^{i\delta_s}$$

$\pi\pi$ s-wave scattering lengths can be extracted from variation of δ with S_π [Ananthanarayan et al., Phys.Rep. 353 (2001) 207; Colangelo, Gasser, Rusetsky, EPJC59 (2009) 777]

NA48/2: $K^{\pm}\to\pi^0\pi^0e^{\pm}\nu$ form factor

65.2K candidates, **1.0%** background (from $K^{\pm}\to\pi^{\pm}\pi^0\pi^0$, accidentals)

Form-factor measurement above $2m(\pi^{\pm})$ threshold

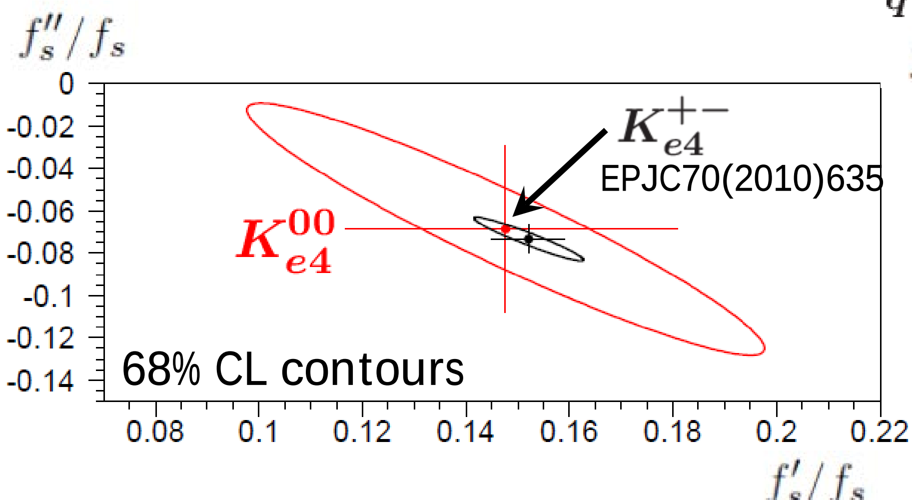


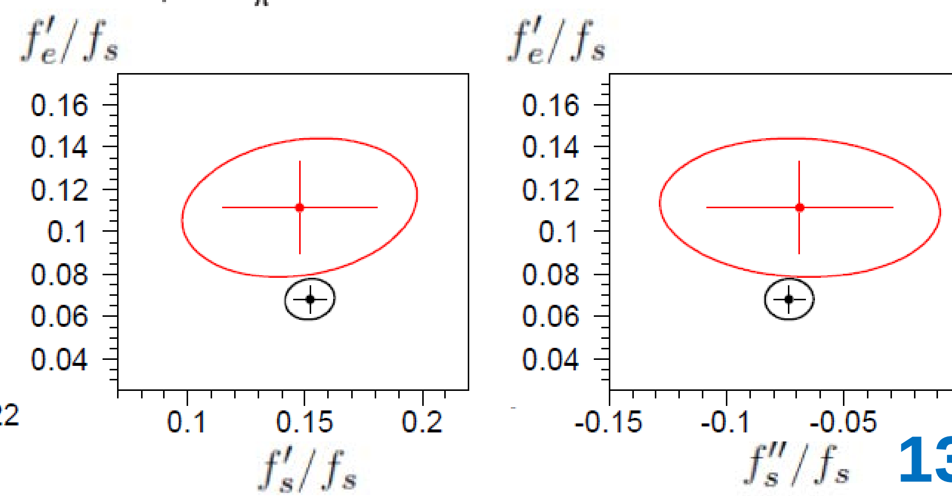
Final results:

[CERN-PH-2014-145, arXiv:1406.4749, submitted to JHEP]

$$f_s'/f_s = 0.149 \pm 0.033 \pm 0.014$$
$$f_s''/f_s = -0.070 \pm 0.039 \pm 0.013$$
$$f_e'/f_s = 0.113 \pm 0.022 \pm 0.007$$

Evidence for S_e-dependence of F_s





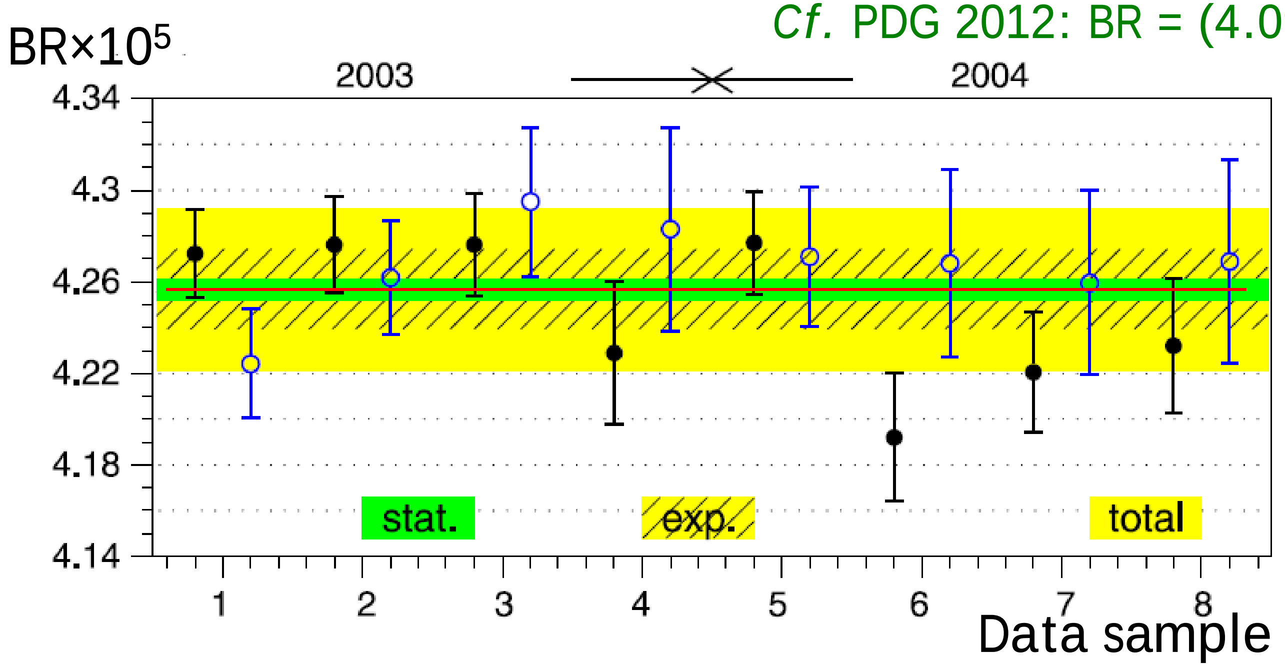
BR($K^\pm \to \pi^+\pi^- e^\pm \nu$) and f_s

BR measured with respect to normalisation mode: $K^\pm \to \pi^\pm\pi^+\pi^-$.
1.13M candidates, **0.6%** background (from $K^\pm \to \pi^\pm\pi^+\pi^-$, $K^\pm \to \pi^\pm\pi^0_D$ (π^0))

Final result: [PLB 715 (2012) 105]

$$\mathrm{BR}(K^\pm \to \pi^+\pi^- e^\pm \nu) = (4.257 \pm 0.004_{stat} \pm 0.016_{syst} \pm 0.031_{ext}) \times 10^{-5}$$

Cf. PDG 2012: BR = $(4.09\pm0.10)\times10^{-5}$



$\mathrm{BR}(K^\pm \to \pi^+\pi^- e^\pm \nu) = \tau_K (|V_{us}| f_s)^2 \times \mathfrak{I}$ → absolute f_s measurement.

Results: $|V_{us}| f_s = 1.285 \pm 0.001_{stat} \pm 0.004_{syst} \pm 0.005_{ext}$

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

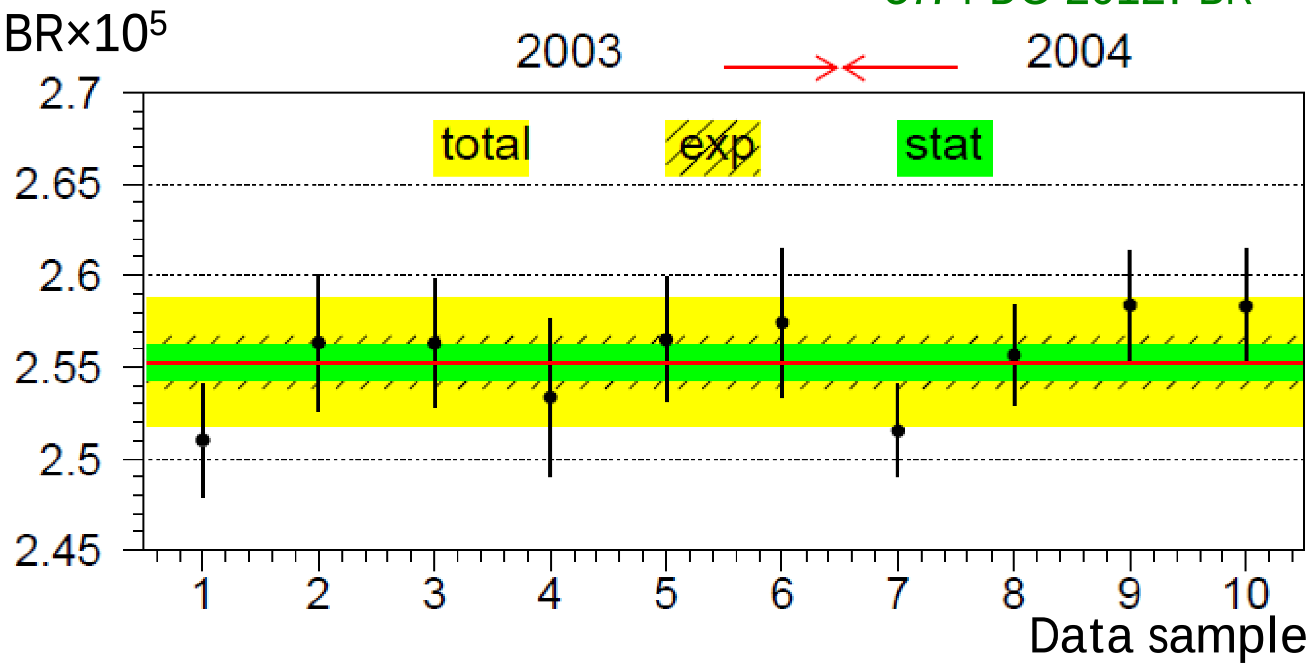
BR($K^\pm \to \pi^0\pi^0 e^\pm \nu$) and f_s

BR measured with respect to normalisation mode: $K^\pm \to \pi^\pm\pi^0\pi^0$.

Final result: [CERN-PH-2014-145, arXiv:1406.4749]

$$\mathbf{BR(K^\pm \to \pi^0\pi^0 e^\pm \nu) = (2.552 \pm 0.010_{stat} \pm 0.010_{syst} \pm 0.032_{ext}) \times 10^{-5}}$$

Cf. PDG 2012: BR = $(2.2\pm0.4)\times10^{-5}$



$\mathbf{BR(K^\pm \to \pi^0\pi^0 e^\pm \nu) = \tau_K (|V_{us}| f_s)^2 \times \mathfrak{I}}$ → absolute f_s measurement.

Neglecting EM corrections,

$$\mathbf{|V_{us}| f_s = 1.369 \pm 0.003_{stat} \pm 0.006_{syst} \pm 0.009_{ext}}$$

$$\mathbf{f_s = 6.079 \pm 0.012_{stat} \pm 0.027_{syst} \pm 0.046_{ext}}$$

Summary

❖ **NA48/2** (2003–2004): a multi-purpose $K^\pm$ experiment.

- ✓ $K^\pm$ physics at a new precision level (17 peer-reviewed papers so far);
- ✓ Further analyses of rare/forbidden $K^\pm$, π^0 decays in progress.

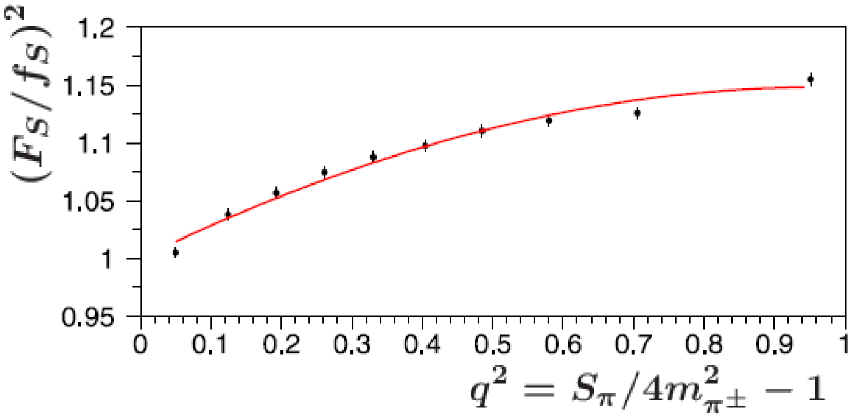
❖ **NA62-R_K** (2007–2008): minimum bias electron trigger.

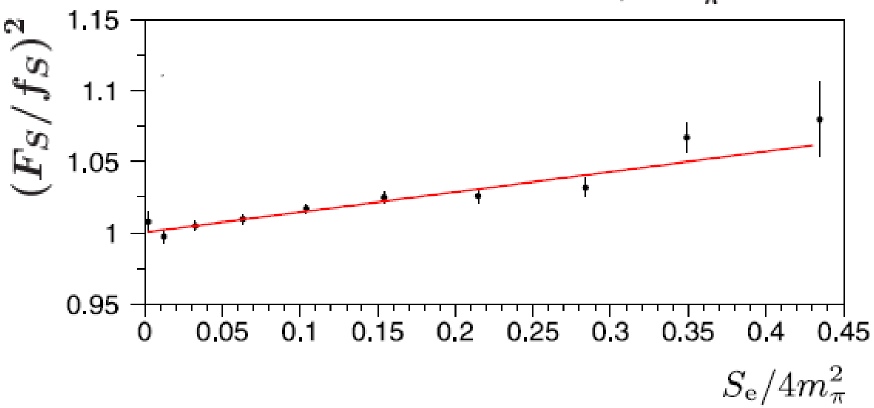
- ✓ Lepton Universality test at record **0.4%** precision:
  $BR(K^\pm \to e^\pm\nu)/BR(K^\pm \to \mu^\pm\nu) = (2.488 \pm 0.010)\times 10^{-5}$;
- ✓ further rare decay analyses completed or in progress.

❖ **Recent results presented:**
lepton universality test, $K^\pm \to \pi^\pm\gamma\gamma$ and $K^\pm \to \pi\pi e^\pm\nu$ decays.
More results are coming soon.

Spares

NA48/2: $K^{\pm}\to\pi^+\pi^-e^{\pm}\nu$ form factors





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

Final NA48/2 results [EPJC70 (2010) 635]
1.13M candidates, **0.6%** background
(from **$K^{\pm}\to\pi^{\pm}\pi^+\pi^-$**, **$K^{\pm}\to\pi^{\pm}\pi^0_D\ (\pi^0)$**)

s-wave pion scattering lengths