Review of Rare Kaon Decays (NA48/2 and NA62)

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on behalf of NA48/2 and NA62 collaborations

Outline:

1) Introduction to CERN kaon programme
2) Study of the rare decay $K^\pm \to \pi^\pm \gamma\gamma$
3) Precision measurements of $K^\pm \to \pi^+\pi^- e^\pm \nu$ and $K^\pm \to \pi^0\pi^0 e^\pm \nu$
4) Summary

UNIVERSITY OF BIRMINGHAM

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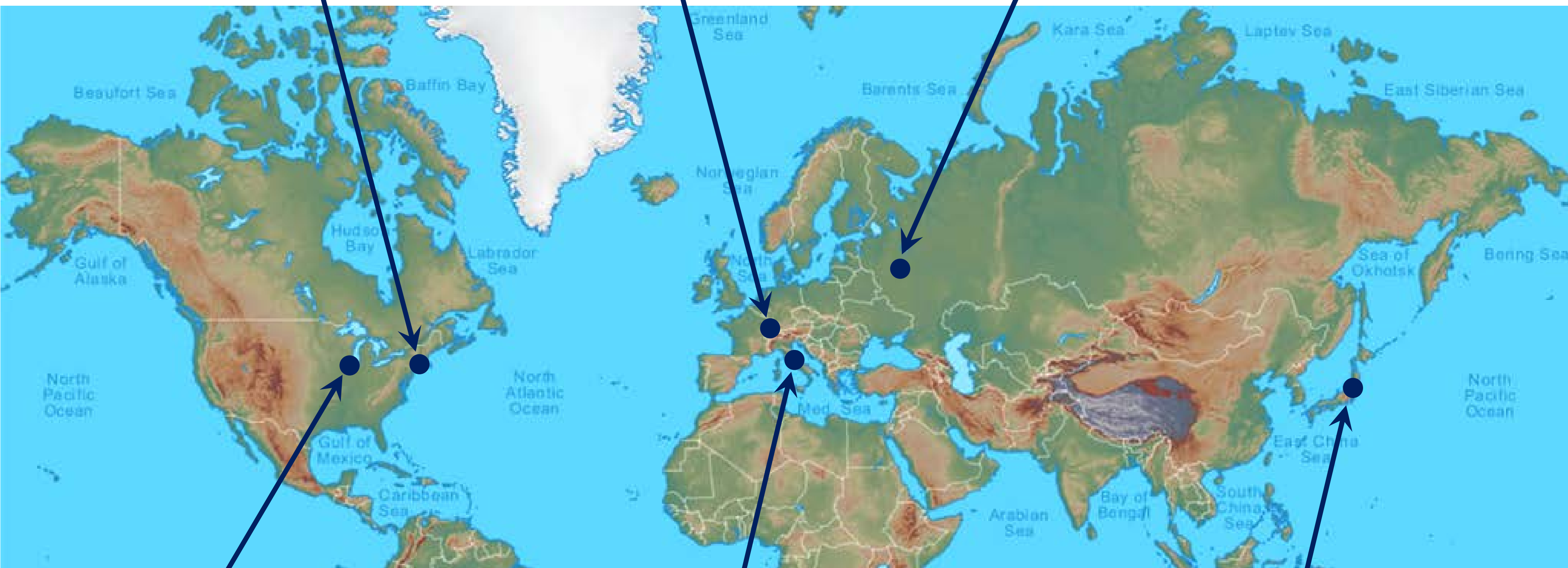
EXCELLENCE IN SCIENCE

Kaon physics facilities

BNL
E865, E777, E787, E949

CERN
NA48, *NA62*

IHEP
ISTRA+, *OKA*



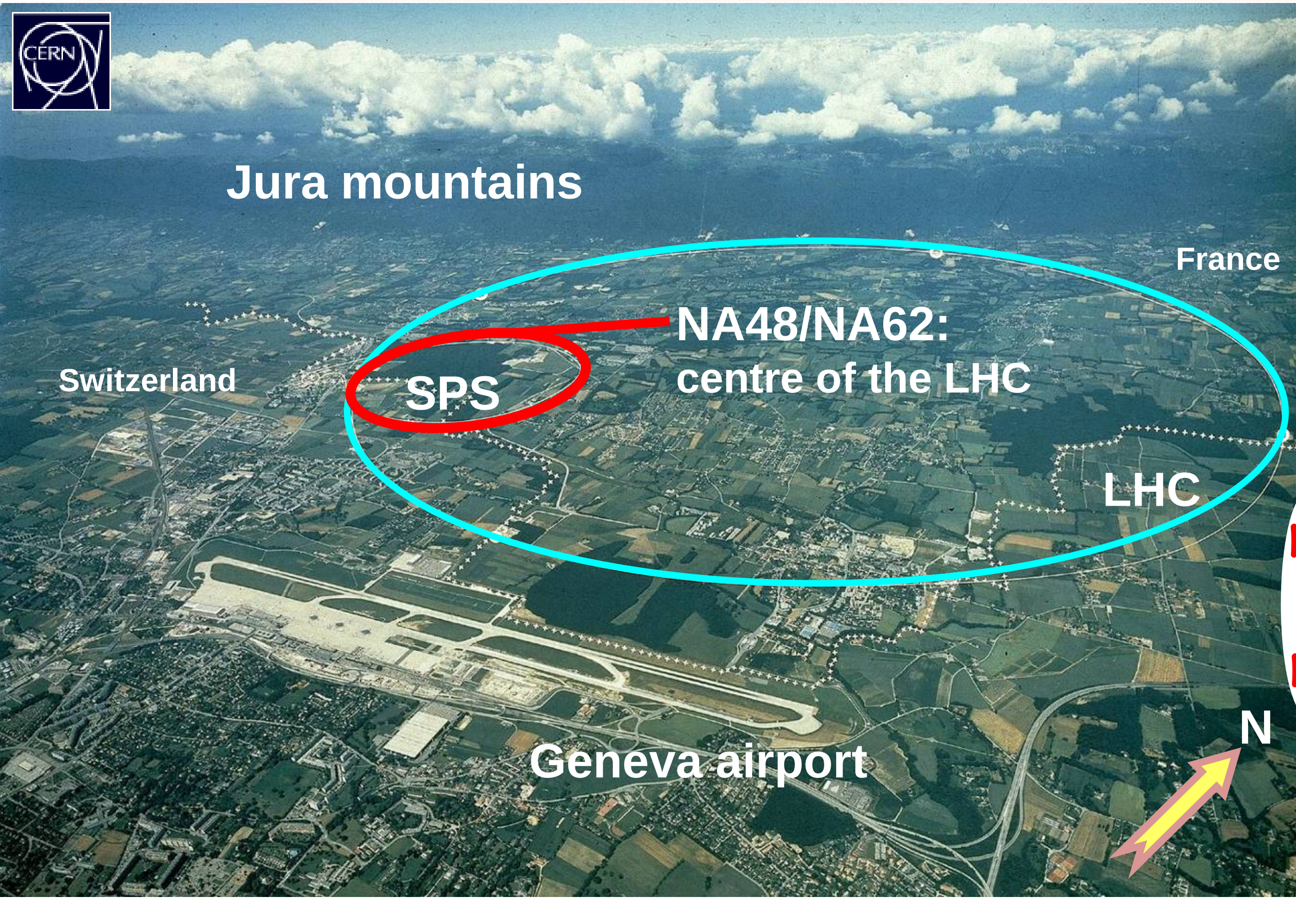
FNAL
KTeV, *ORKA*

LNF
KLOE, *KLOE2*

KEK/J-PARC
E391a, *KOTO*, *TREK*

A variety of experimental techniques:
K decay-in-flight (e.g. CERN), stopped **K^+** and a ϕ factory

CERN NA48/NA62 experiments



NA48/NA62 talks in Flavour Physics session:
(semi)leptonic $K^{\pm}$ decays by Riccardo Fantechi,
future programme by Gianluca Lamanna.

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: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests

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

Detector: NA48/2 and NA62-R_K

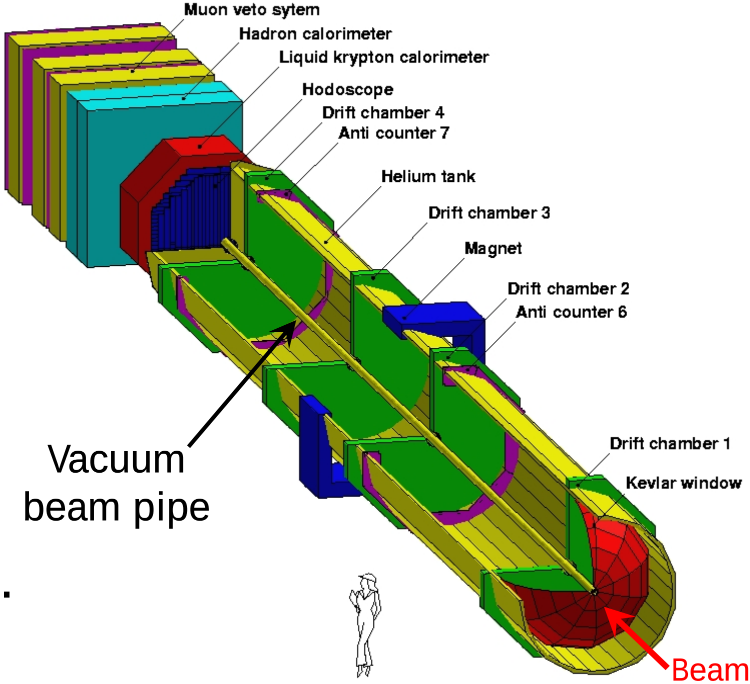
2003-2008: charged kaon beams, the NA48 detector

Narrow momentum band $K^{\pm}$ beams:
P_K= 60 (74) GeV/c, $\delta P_K/P_K$ = 1...4% (rms).

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



Recent $K^{\pm}$ data samples

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**
$M(K^+\to\pi^+\pi^+\pi^-)$ resolution, MeV/c^2	**1.7**	**1.2**	**0.8**
K decays in fiducial volume	**1.9×10^{11}**	**2.5×10^{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) [NA48/2 and NA62-R_K]

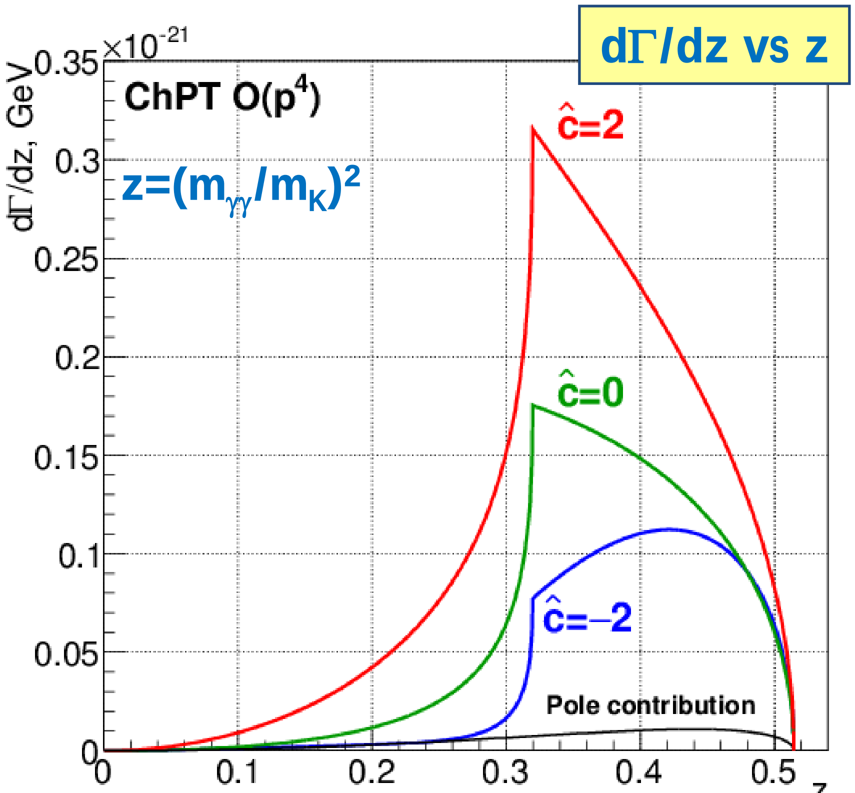
$K^{\pm}\to\pi^{\pm}\gamma\gamma$: introduction

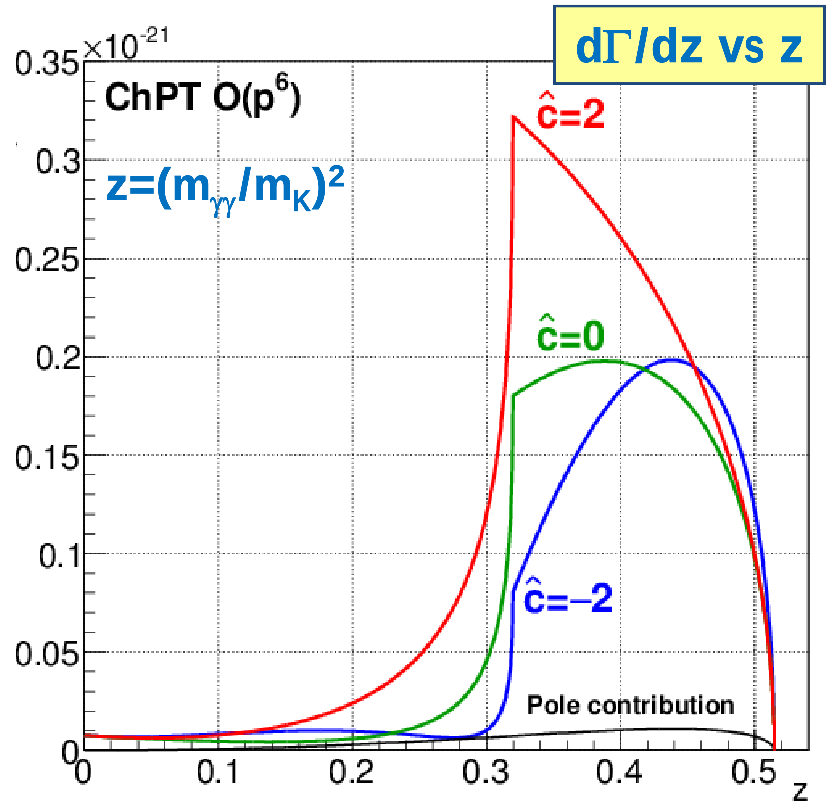
ChPT: spectrum determined by $\hat{c}$ parameter.
Dominated by pion loop: cusp at $2\pi^{\pm}$ threshold
[Ecker, Pich, de Rafael, NPB303 (1988) 665]

$O(p^6)$: significant correction;
non-zero rate at $m_{\gamma\gamma}=0$.
[D'Ambrosio, Portolés, PLB386 (1996) 403]
[Gérard, Smith, Trine, NPB730 (2005) 1]

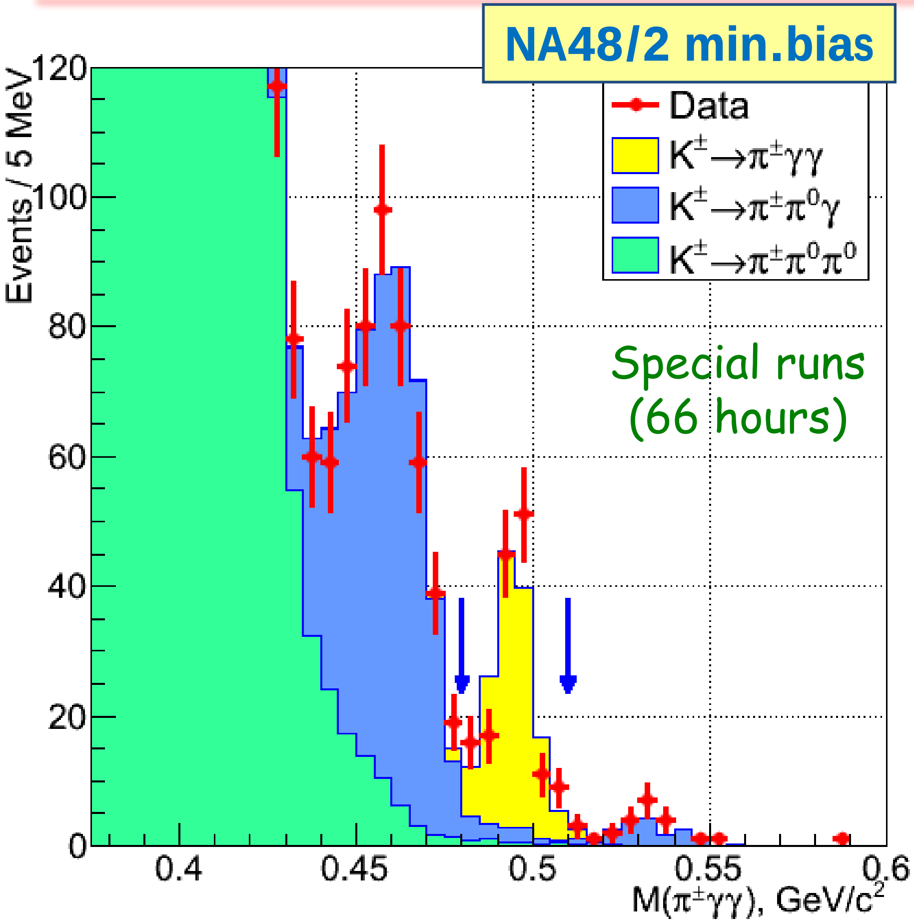
Experimental status:

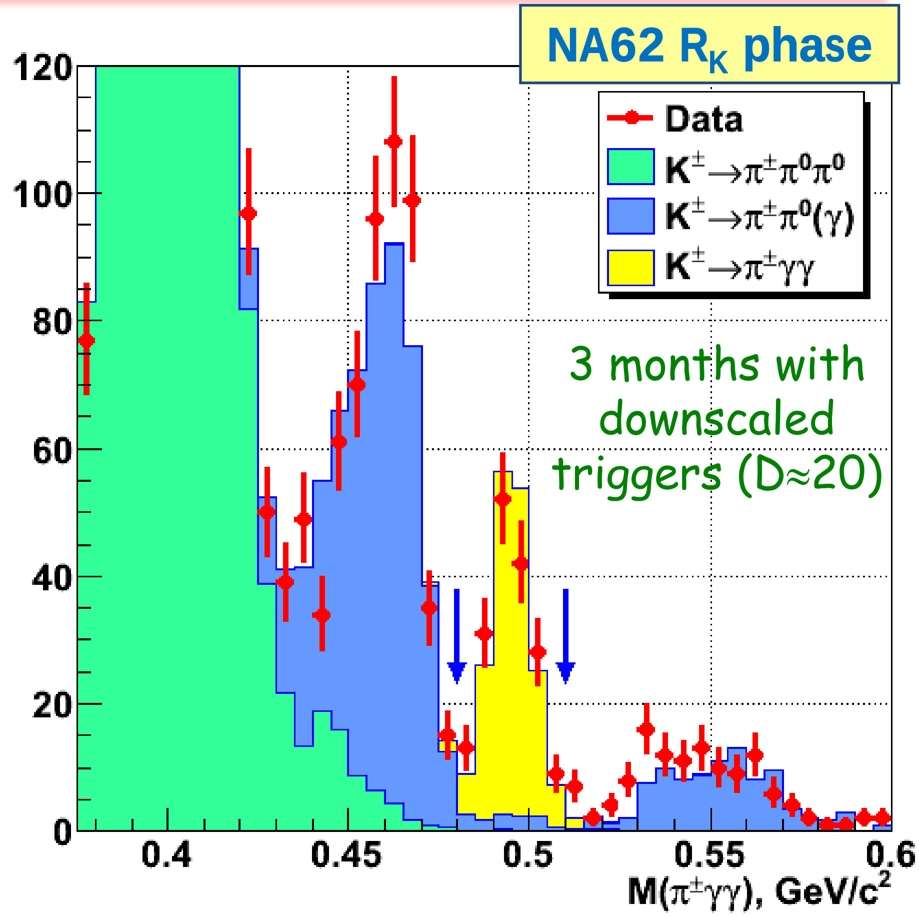
- ❖ BNL E787: 31 candidates, **BR = $(1.10\pm0.32)\times10^{-6}$**. [PRL79 (1997) 4079]
- ❖ NA48/2, NA62: using low beam intensity minimum bias samples





Minimum bias data samples





$K_{\pi\gamma\gamma}$ 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

$K_{\pi\gamma\gamma}$ candidates	175
$K_{2\pi(\gamma)}$ background	11.1±1.0
$K_{3\pi}$ background	1.3±0.3
$K_{\pi\gamma\gamma}$ signal	163±13

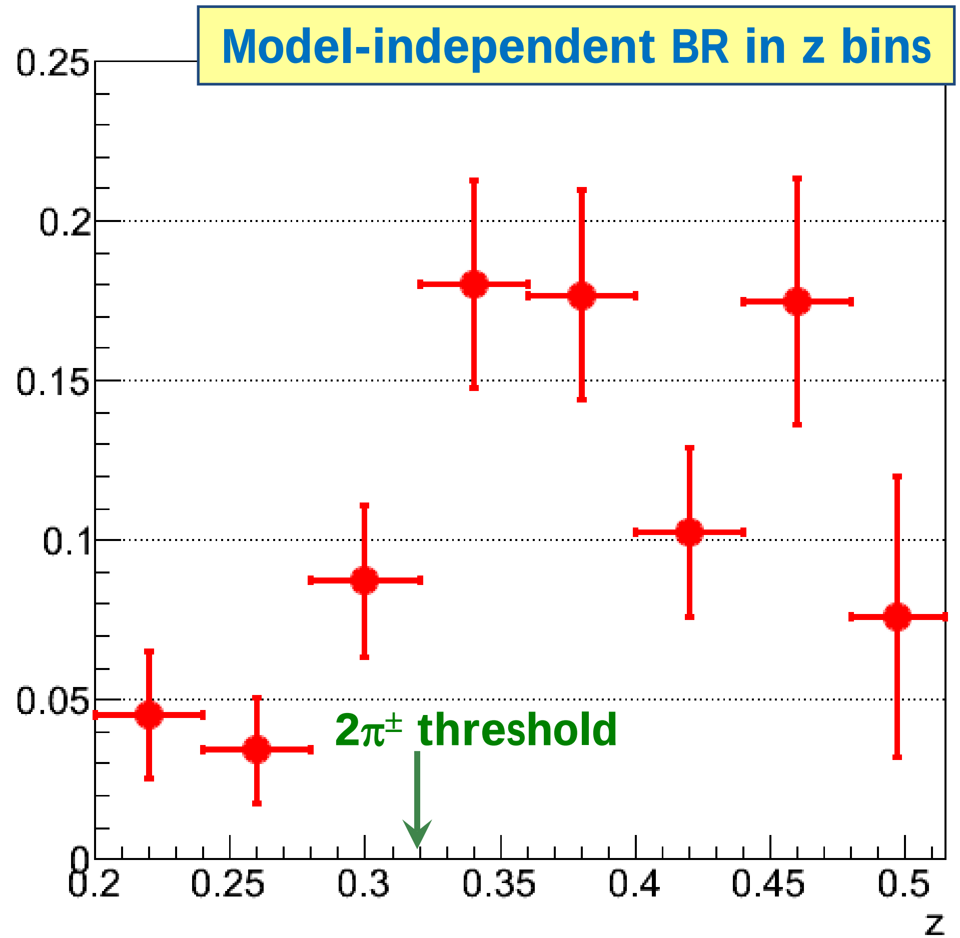
NA48/2: model-independent BR

NEW: July 2013

THE FINAL NA48/2 RESULT

Sufficiently small **z** bins: acceptance almost independent of kinematical distribution

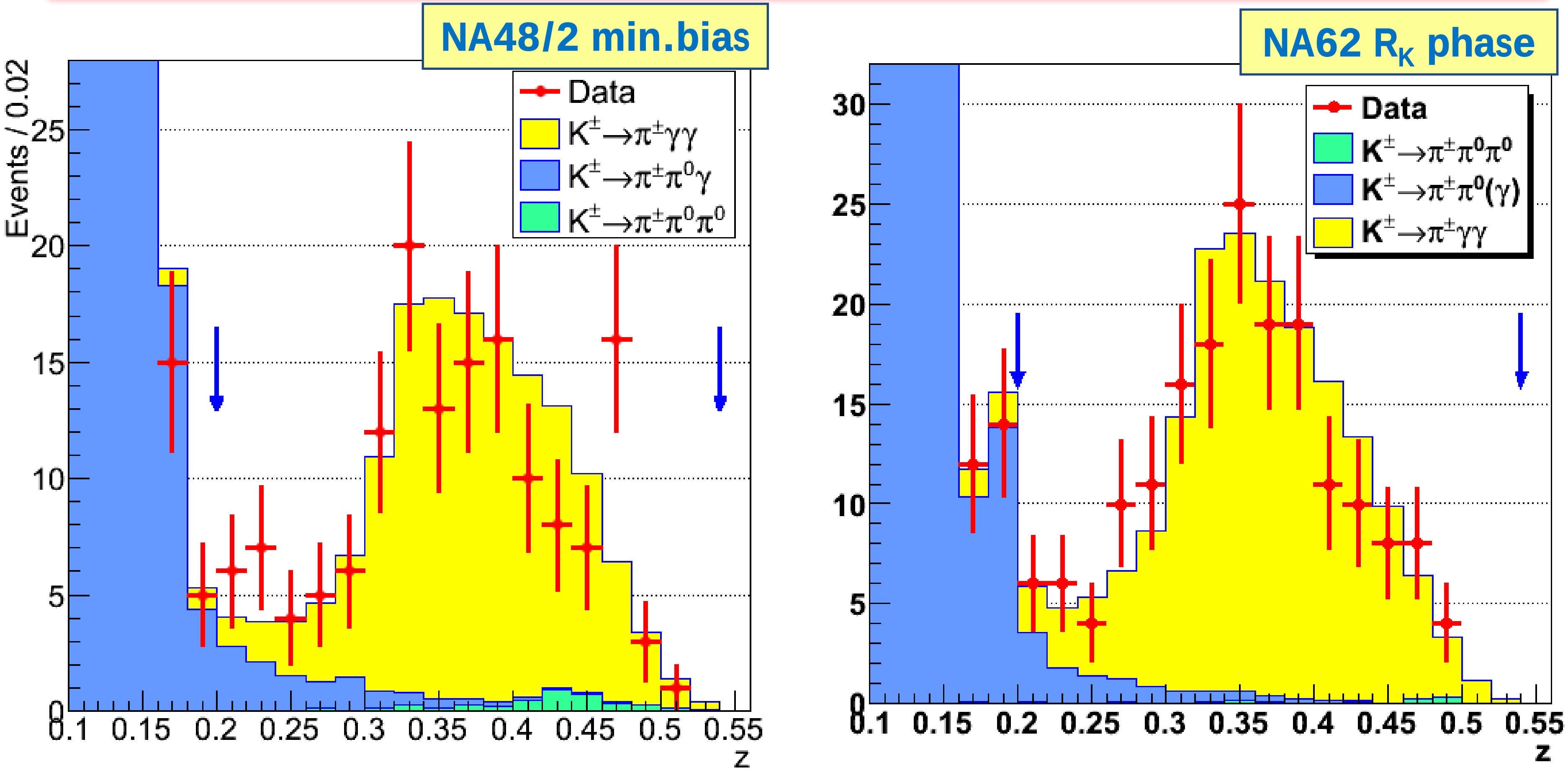
z range	N_j	N_j^B	A_j	$\mathcal{B}_j \times 10^6$
0.20–0.24	13	4.89	0.194	0.045 ± 0.020
0.24–0.28	9	2.73	0.198	0.034 ± 0.016
0.28–0.32	18	2.33	0.194	0.087 ± 0.024
0.32–0.36	33	1.30	0.190	0.180 ± 0.033
0.36–0.40	31	0.98	0.184	0.177 ± 0.033
0.40–0.44	18	1.61	0.173	0.103 ± 0.027
0.44–0.48	23	1.21	0.135	0.175 ± 0.038
$z > 0.48$	4	0.52	0.049	0.076 ± 0.044



$$BR_{MI}(z>0.2) = (0.877 \pm 0.087_{stat} \pm 0.017_{syst}) \times 10^{-6}$$

Main systematic effect: background estimate (LKr cluster merging)

Fits to ChPT description



External parameters of the **$O(p^6)$** fit:
$K_{3\pi}$ amplitude parameters: from fit to experimental data [NPB648 (2003) 317];
polynomial contributions: **η_1=2.06**, **η_2=0.24**, **η_3=–0.26** [PLB386 (1996) 403].

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

Fits to ChPT: results

ChPT formulation: D'Ambrosio, Portolés, PLB386 (1996) 403

PRELIMINARY

NA48/2 (minimum bias)

ChPT $O(p^4)$:

$\hat{c} = 1.36 \pm 0.33_{stat} \pm 0.07_{syst} = 1.36 \pm 0.34$

ChPT $O(p^6)$:

$\hat{c} = 1.67 \pm 0.39_{stat} \pm 0.09_{syst} = 1.67 \pm 0.40$

NA62 (2007)

ChPT $O(p^4)$:

$\hat{c} = 1.71 \pm 0.29_{stat} \pm 0.06_{syst} = 1.71 \pm 0.30$

ChPT $O(p^6)$:

$\hat{c} = 2.21 \pm 0.31_{stat} \pm 0.08_{syst} = 2.21 \pm 0.32$

⇓

Combined

(correlated systematic uncertainties)

ChPT $O(p^4)$ fit:

$\hat{c} = 1.56 \pm 0.22_{stat} \pm 0.07_{syst} = 1.56 \pm 0.23$

ChPT $O(p^6)$ fit:

$\hat{c} = 2.00 \pm 0.24_{stat} \pm 0.09_{syst} = 2.00 \pm 0.26$

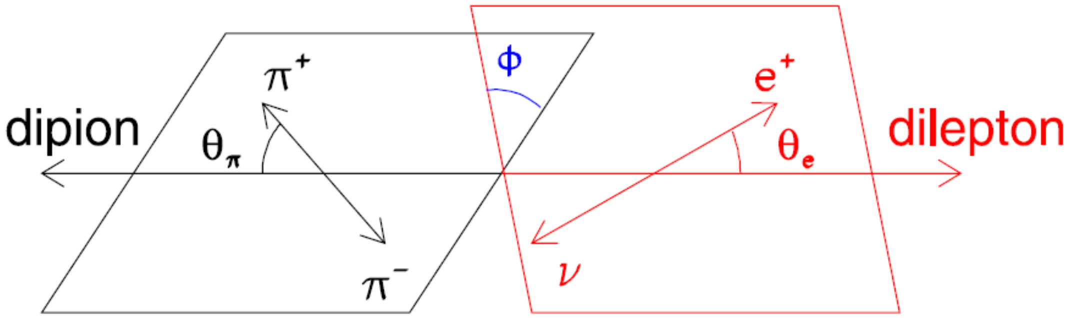
$BR_6 = (1.01 \pm 0.06) \times 10^{-6}$

(model-dependent BR in full phase space)

Cf. PDG (=BNL E787): $BR_6 = (1.10 \pm 0.32) \times 10^{-6}$

K_{e4} decays: introduction

Five kinematic variables: S_π, S_e, $\cos\theta_\pi$, $\cos\theta_e$, Φ



[Cabibbo, Maksymowicz, PR137 (1965) B438]

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

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

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

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

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

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

axial

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

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

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

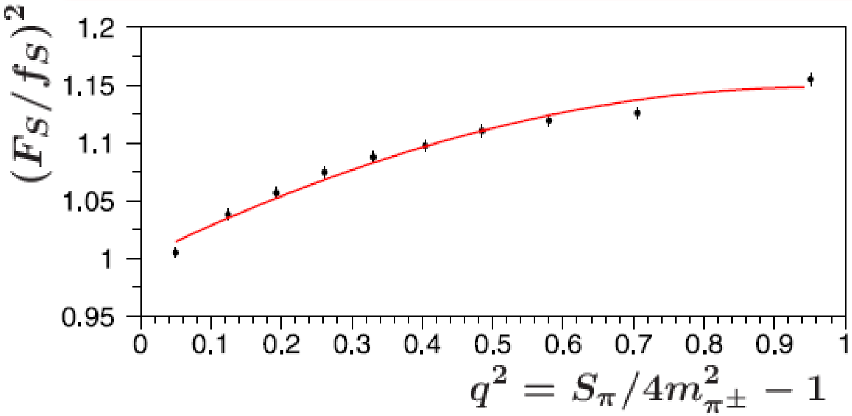
$$H_p = h_p + h_p' q^2 + \ldots$$

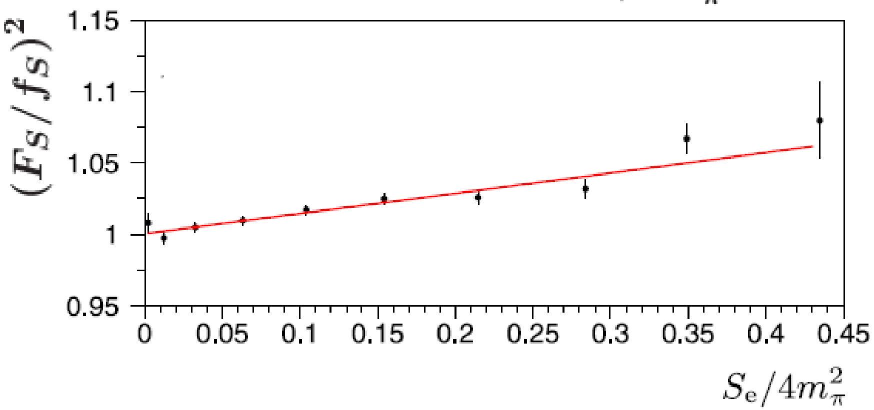
vector

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

$\pi\pi$ 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]

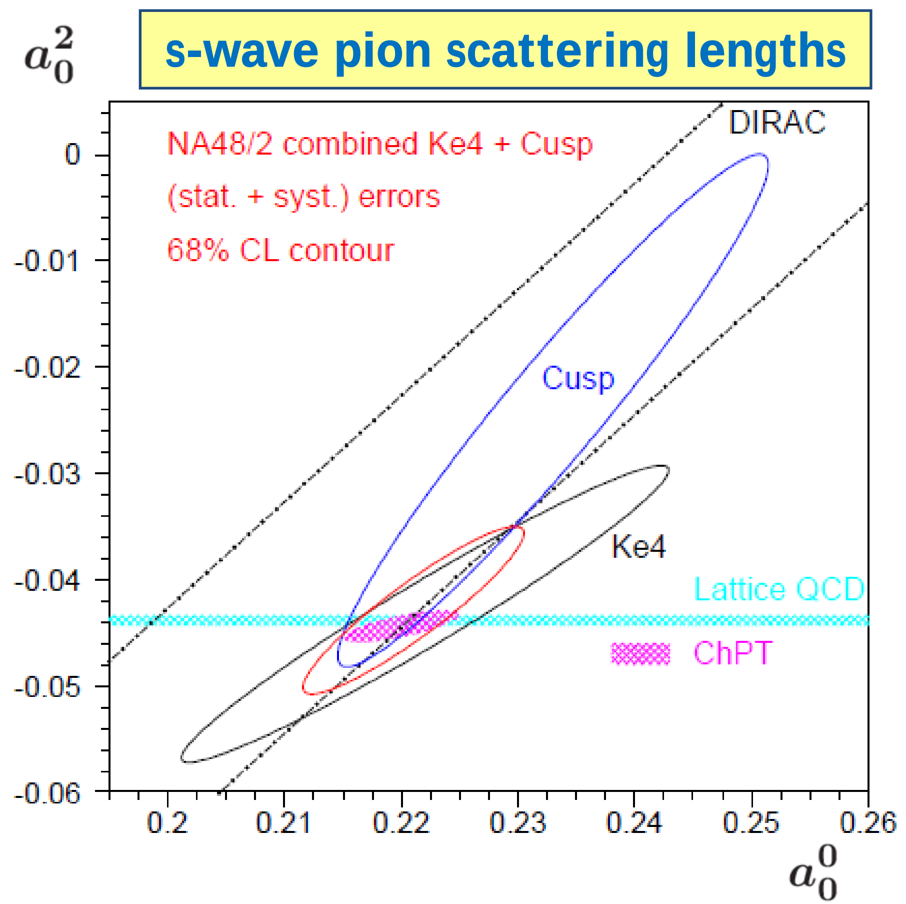
NA48/2: $K^{\pm}\to\pi^{+}\pi^{-}e^{\pm}\nu$ form factors





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 $K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$, $K^{\pm}\to\pi^{\pm}\pi^{0}_{D}$ (π^0))



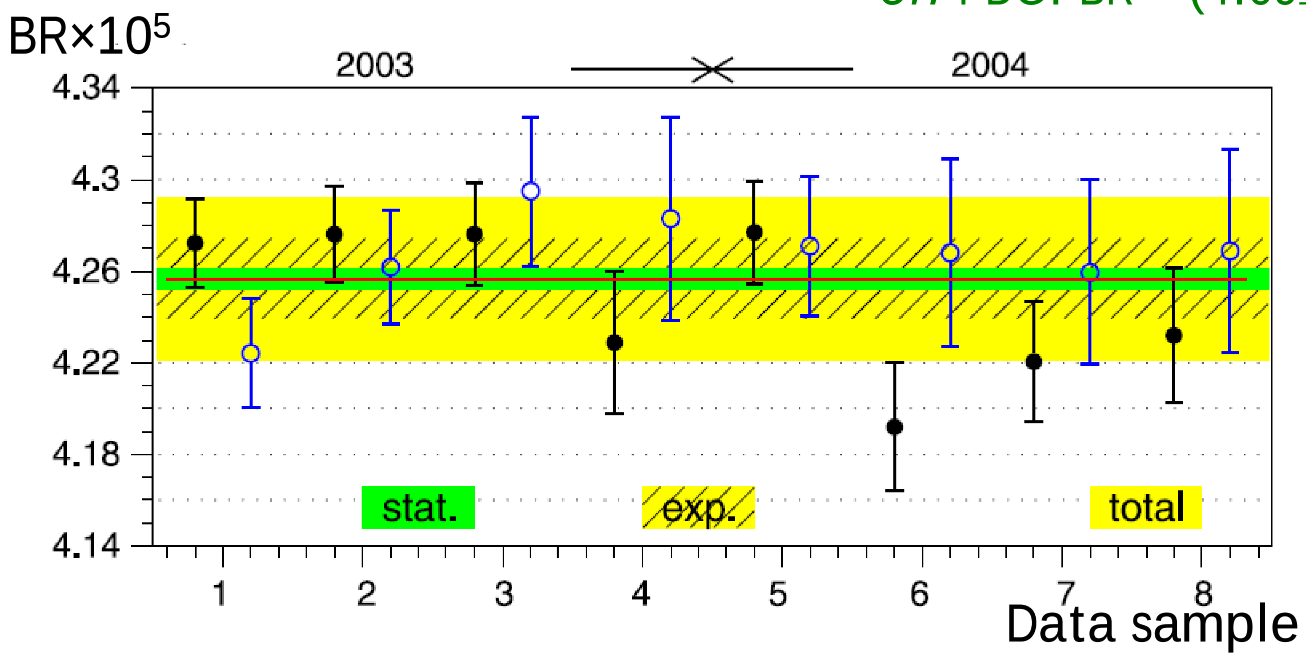
NA48/2: BR($K^{\pm}\to\pi^{+}\pi^{-}e^{\pm}\nu$) and f_s

BR measured with respect to normalisation mode: $K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$.

Final result: [PLB715 (2012) 105]

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



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

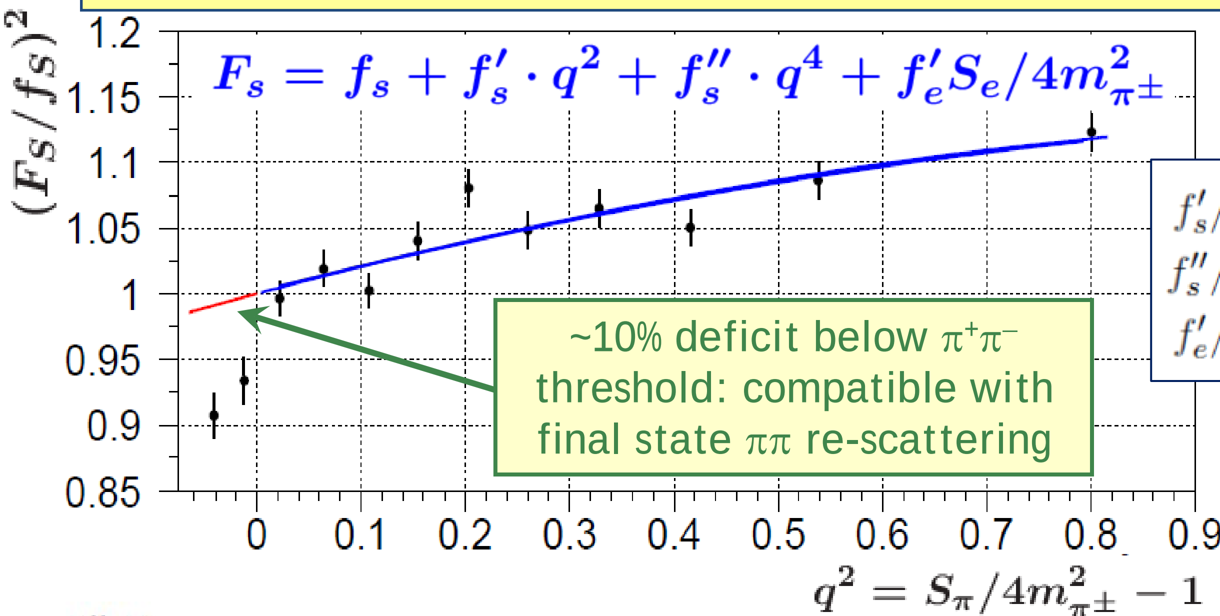
Results: $|V_{us}| f_s = 1.285 \pm 0.001_{stat} \pm 0.004_{syst} \pm 0.005_{ext}$

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

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

66K candidates, **1.07%** background (**$K^{\pm}\to\pi^{\pm}\pi^0\pi^0$**; accidentals)

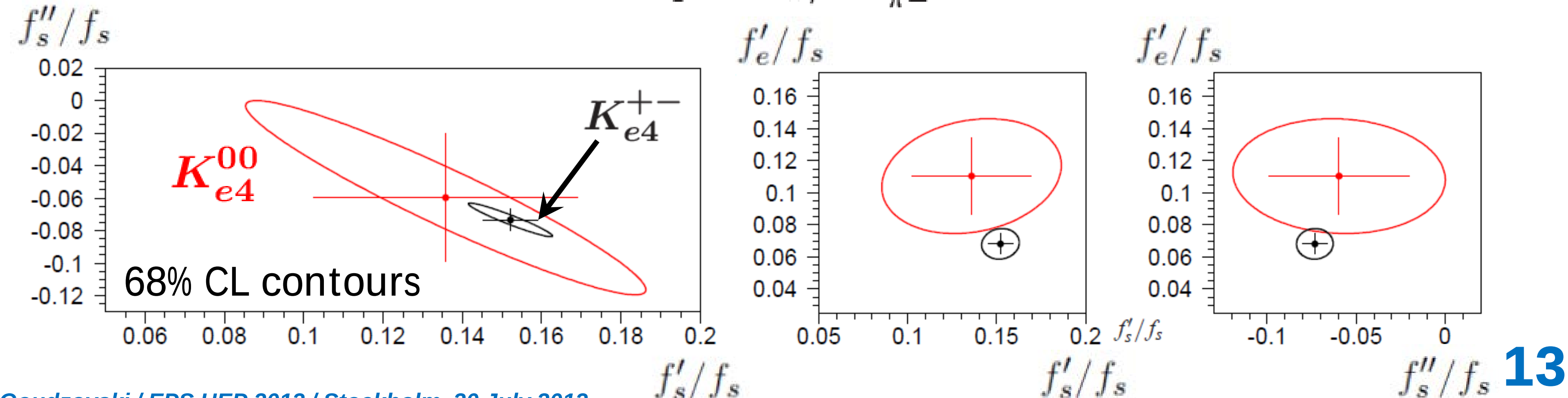
Form-factor measurement above $2m(\pi^{\pm})$ threshold



Preliminary results:

$$f'_s/f_s = 0.136 \pm 0.033_{stat} \pm 0.015_{syst}$$
$$f''_s/f_s = -0.060 \pm 0.039_{stat} \pm 0.015_{syst}$$
$$f'_e/f_s = 0.110 \pm 0.024_{stat} \pm 0.022_{syst}$$

Evidence for S_e-dependence of F_s



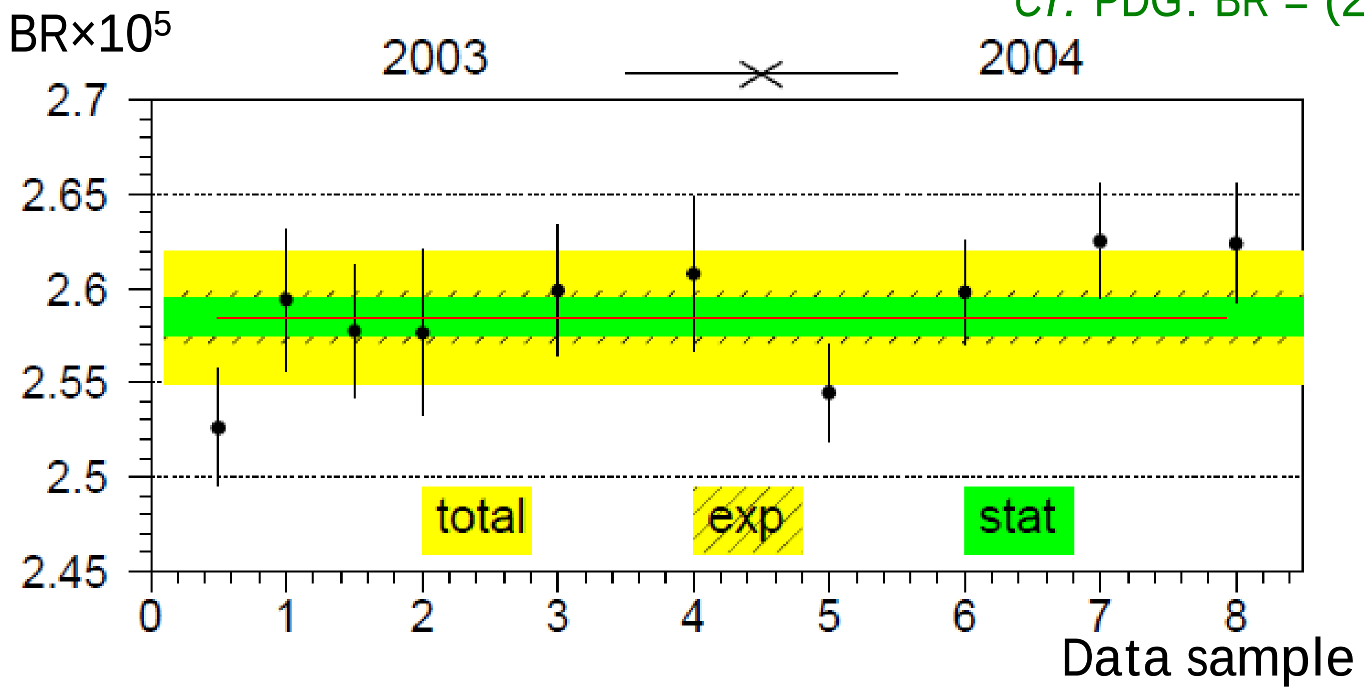
NA48/2: BR($K^\pm \to \pi^0\pi^0 e^\pm \nu$) and f_s

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

Preliminary result:

BR($K^\pm \to \pi^0\pi^0 e^\pm \nu$) = (2.585 ± 0.010$_{stat}$ ± 0.010$_{syst}$ ± 0.032$_{ext}$) × 10^{-5}

Cf. PDG: BR = (2.2±0.4)×10^{-5}



BR($K^\pm \to \pi^0\pi^0 e^\pm \nu$) = τ_K (|V_{us}| f_s)^2 × $\Im$ → absolute **f_s** measurement.

Results: **|V_{us}| f_s = 1.372 ± 0.003$_{stat}$ ± 0.004$_{syst}$ ± 0.008$_{ext}$**

f_s = 6.092 ± 0.012$_{stat}$ ± 0.017$_{syst}$ ± 0.045$_{ext}$

Summary

New precision inputs to low energy QCD

❖ Rare decay **$K^{\pm}\to\pi^{\pm}\gamma\gamma$** with NA48/2 and NA62 minimum bias samples:

- ✓ a new result: model-independent **BR(z>0.2)**;
- ✓ data agree with ChPT description (dominated by pion loop);
- ✓ final results and publications are **in preparation**.

❖ **$K^{\pm}\to\pi^{+}\pi^{-}e^{\pm}\nu$** decay with main NA48/2 sample (**complete**):

✓ precision measurements of form factors, pion scattering lengths and BR.

❖ **$K^{\pm}\to\pi^{0}\pi^{0}e^{\pm}\nu$** decay with main NA48/2 sample (**work in progress**):

- ✓ preliminary measurements of the form factor and BR;
- ✓ cusp-like structure due to final state re-scattering observed in **S_{π}** spectrum.