Recent NA48/2 results on Ke4 and K3π decays and determination of the $\pi\pi$ scattering lenghts

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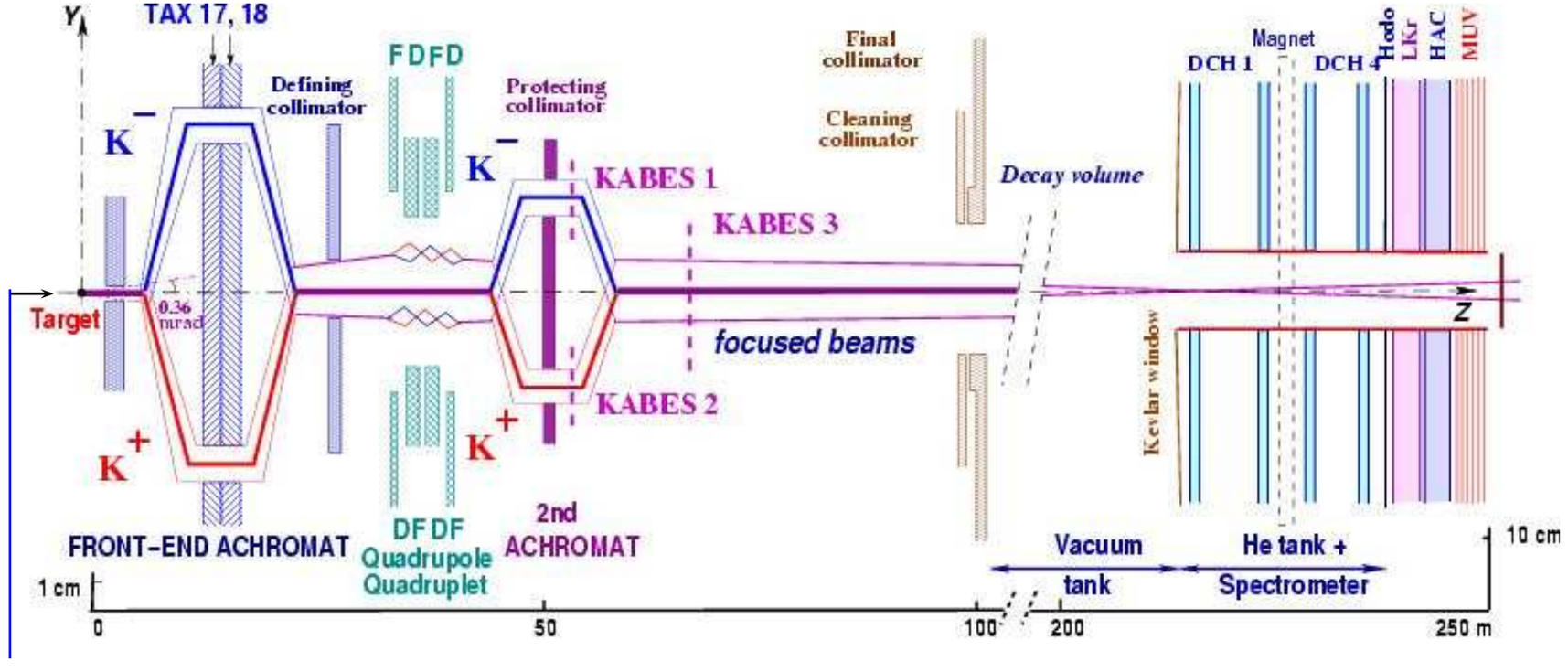
On behalf of the NA48/2 collaboration:

Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna

Outline

- The CERN NA48/2 experiment: setup and data
- Theory: ChPT, $\pi\pi$ S-wave scattering lengths, cusp(s):
  $\Rightarrow$ see A. Rusetsky's talk, Plenary Session 1
- $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$: new measurement on the "cusp"
  and extraction of the $\pi\pi$ scattering lengths
- $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$: measurement of form factors
  and pion scattering lengths

The NA48/2 experiment

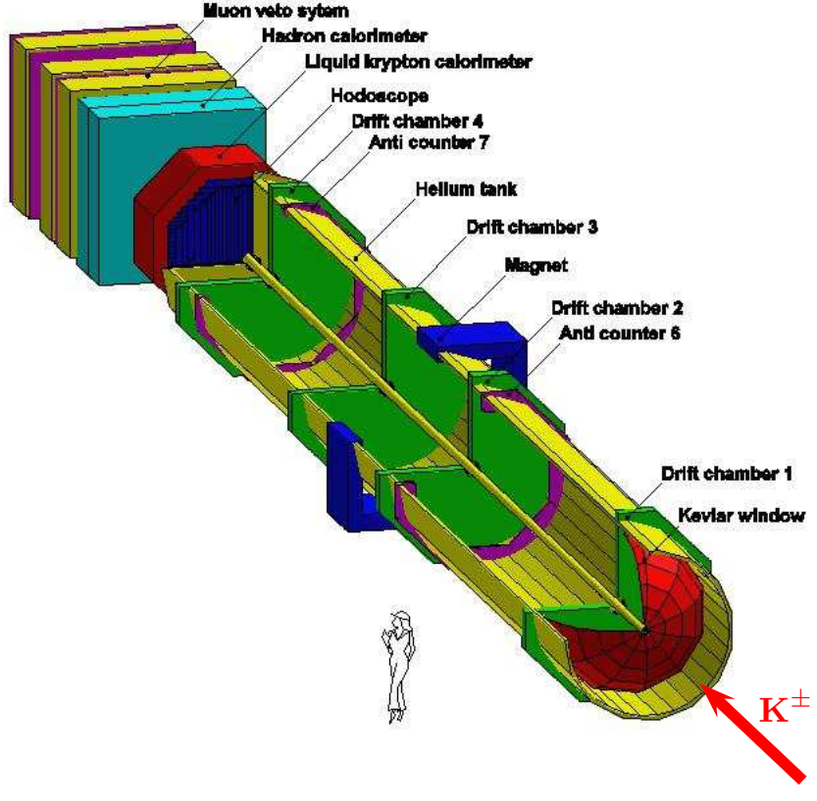


400 GeV/c protons
from CERN SPS

Simultaneous K^+/K^- beams: $P = 60 \pm 3$ GeV/c

$K^+/K^- \simeq 1.8$

The NA48 detectors



Liquid Kripton e.m. calorimeter:

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E/1\mathrm{GeV}}} \oplus \frac{9\%}{E/1\mathrm{GeV}} \oplus 0.42\%$$

Magnetic Spectrometer:

$$\frac{\sigma_P}{P} \simeq 1\% \oplus 0.044\% \frac{P}{(1\mathrm{GeV/c})}$$

Charged Hodoscope: $\sigma_t = 150$ ps

Hadron calorimeter, muon and photon vetos

- 1997-2001: NA48 K_L, K_S (ϵ'/ϵ)
- 2002: NA48/1 K_S
- 2003-2004: NA48/2 $K^\pm$ (Δg)
- 2007: NA62 $K^\pm$ $(K_{e2}/K_{\mu 2})$
- 2011: NA62 $K^+ \to \pi^+ \nu\bar{\nu}$

Main goal of NA48/2: search for CP violation in $K^\pm \to 3\pi$ Dalitz plots.
2003+2004 data: $4 \cdot 10^9$ $K^\pm \to \pi^\pm\pi^+\pi^-$; $1 \cdot 10^8$ $K^\pm \to \pi^\pm\pi^0\pi^0$; $1 \cdot 10^6$ K_{e4}.

$K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ event selection

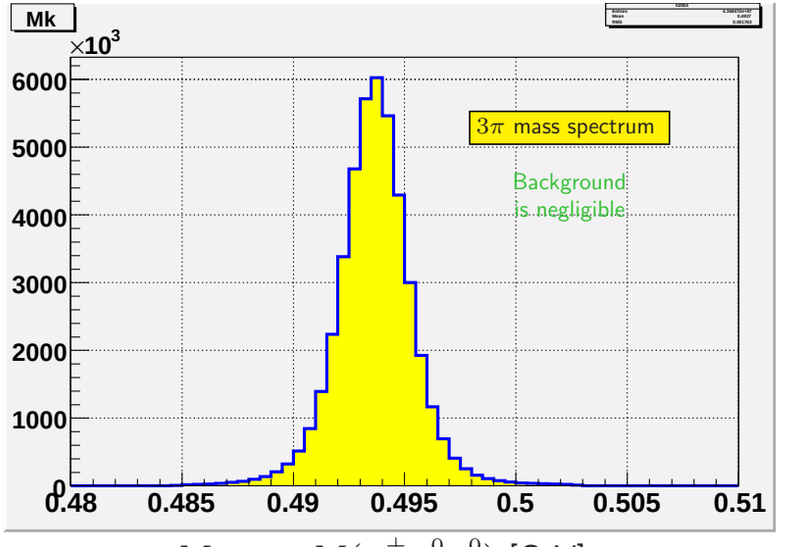
- require 1 track + 4 e.m. clusters
- cluster pairing ($\pi^0 \to \gamma\gamma$):
  - consider all (3) combinations
  - reconstruct each $\pi^0 \to \gamma\gamma$ vertex using π^0 mass
  - choose 2-vtx combination with closest vertices
- K decay vertex = average of π^0 vertices
- calculate $M_{00} \equiv M(\pi^0\pi^0)$ and $M_{\pm 00} \equiv M(\pi^{\pm}\pi^0\pi^0)$ invariant masses

$\sigma(M_{00})$ optimized for low M_{00} values:

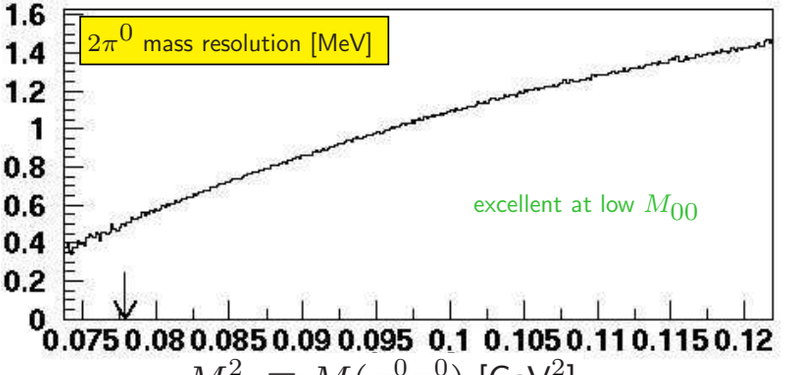
$\sigma(M_{00}) = 0.56$ MeV at $M_{00} = 2m_{\pi^+}$

First cusp result (2003 data, $2.3 \cdot 10^7$ events):
$\to$ published on PLB 633 (2006) 173

This analysis (2003 + 2004 data): $6 \cdot 10^7$ events



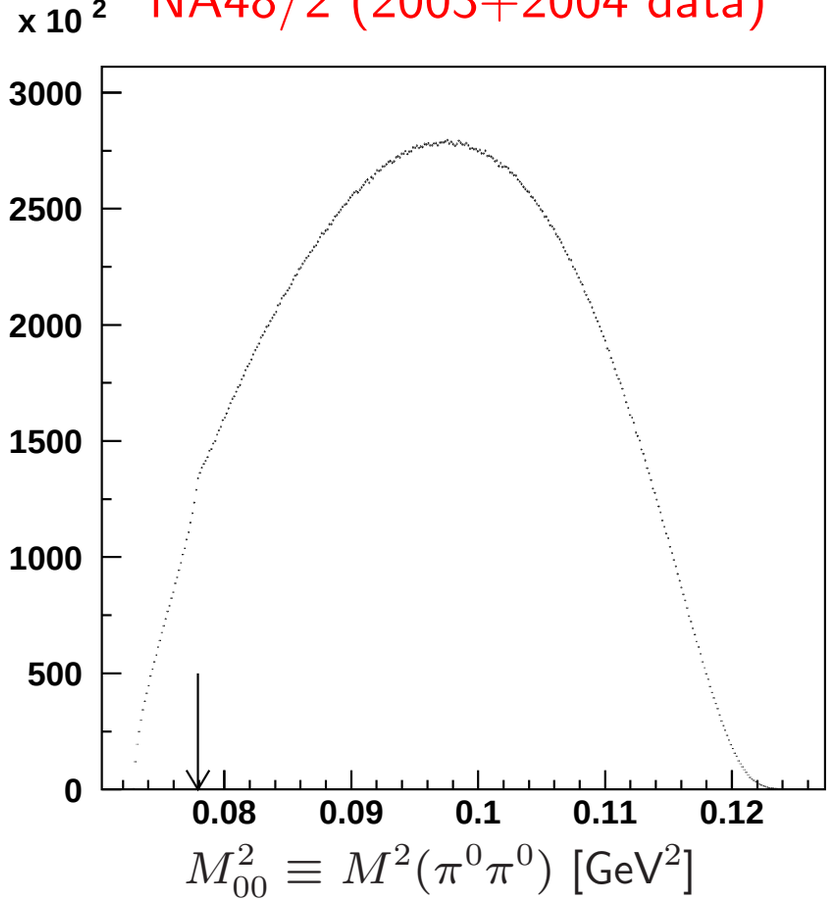
$M_{\pm 00} \equiv M(\pi^{\pm}\pi^0\pi^0)$ [GeV]



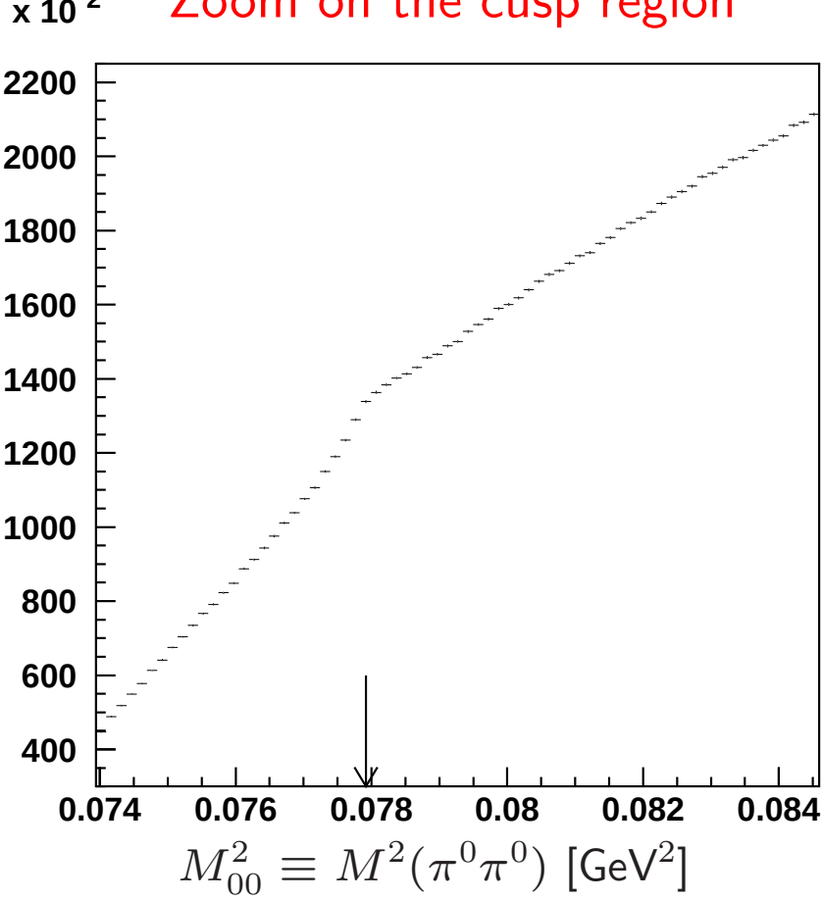
$M_{00}^2 \equiv M(\pi^0\pi^0)$ [GeV^2]

$M^2_{\pi^0\pi^0}$ distribution in $K^\pm \to \pi^\pm\pi^0\pi^0$ decays

NA48/2 (2003+2004 data)



Zoom on the cusp region



Evidence of a cusp at $M^2_{00} = (2m_{\pi^+})^2 \simeq 0.078$ GeV^2

Cusp interpretation

$\pi\pi$ rescattering: one -loop calculation

[N. Cabibbo, PRL 93(2004) 12181]

$\mathcal{M}(K^\pm \to \pi^\pm\pi^0\pi^0) = \mathcal{M}_0 + \mathcal{M}_1$

$\mathcal{M}_0$: $K^\pm \to \pi^\pm\pi^0\pi^0$ (direct)

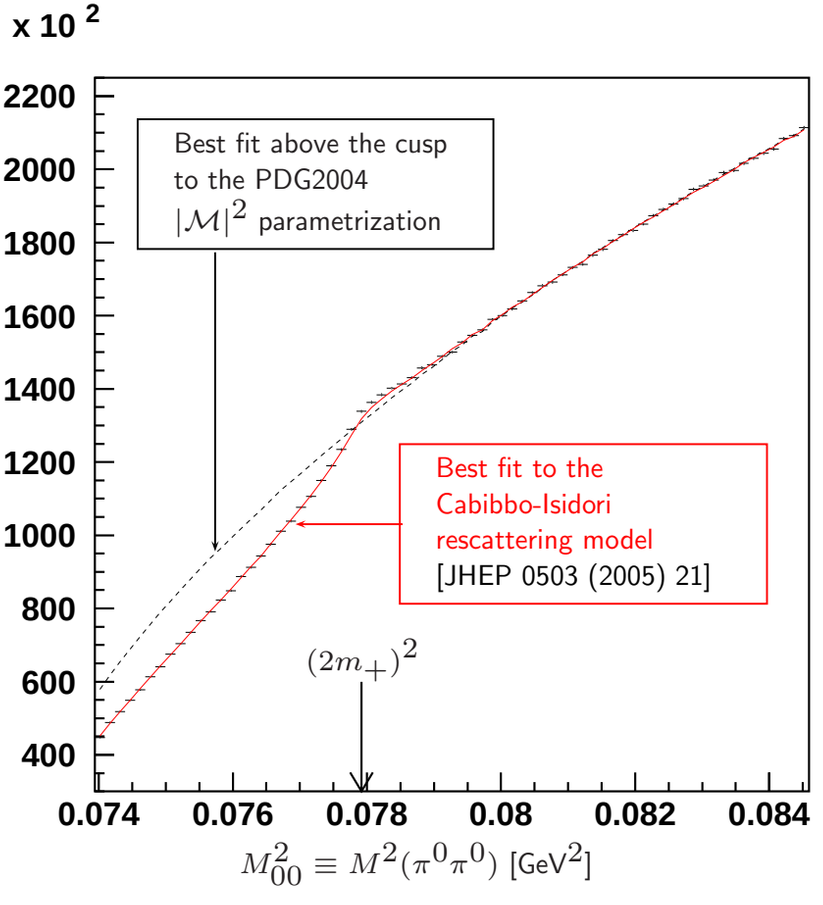
$\mathcal{M}_1$: $K^\pm \to \pi^\pm\pi^+\pi^-$, $\pi^+\pi^- \to \pi^0\pi^0$

$$\mathcal{M}_1 = -\frac{2}{3}(a_0 - a_2) m_+ \mathcal{M}_{+,thr} \sqrt{1 - \frac{4m_+^2}{M_{00}}}$$

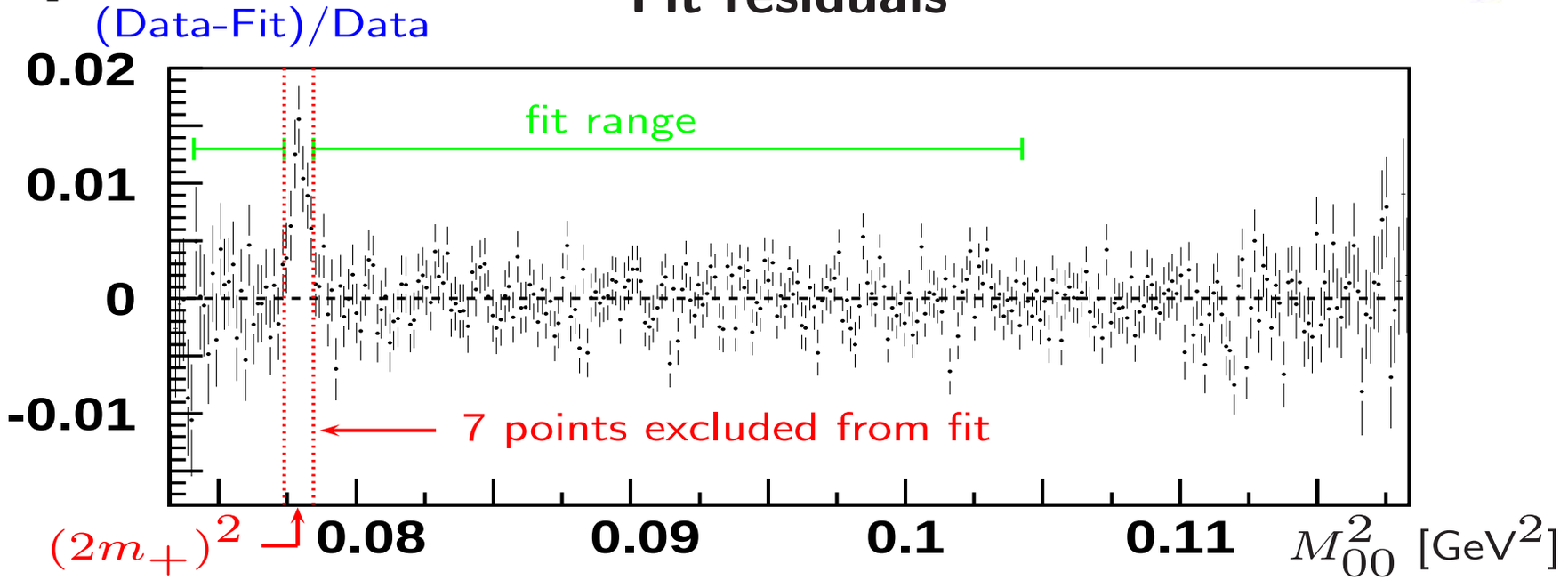
$[m_+ \equiv m_{\pi^+}$; $\mathcal{M}_+ \equiv \mathcal{M}(K^+ \to \pi^+\pi^+\pi^-)]$

interferes destructively with $\mathcal{M}_0$ below $\pi^+\pi^-$ threshold: integrated deficit $\approx 13\%$

Possibility to determine $(a_0\text{-}a_2)$ and its sign



Fit residuals



Observe an excess of events in the M_{00}^2 interval excluded from fit.

Rate $= (5.6 \pm 1.0) \cdot 10^{-5}$ per $K^\pm \to \pi^\pm\pi^0\pi^0$ decay

(adding a delta-function at $M_{00} = (2m_+)$ before taking into account detector resolution and using its integral as a free parameter)

Two contributions to the peak in the $M_{00} \simeq 2m_+$ region:

- pionium formation: $(\pi^+\pi^-)_{atom} \to \pi^0\pi^0$ (Silagadze, JETP Lett.60 (1994) 689)
- additional $\pi^+\pi^-$ unbound states with resonant structure $\to \pi^0\pi^0$ (Gevorkian, Tarasov, Voskresenskaya, hep-ph/0612129)

Cusp: fit results (I)

Data fitted using two different theoretical models:

- Cabibbo-Isidori (CI) rescattering model [JHEP 0503 (2005) 21]
- Colangelo-Gasser-Kubis-Rusetsky (CGKR) effective field theory [PLB 638 (2006) 187]

Fit with analiticity and chiral simmetry constraint between a_2 and $a_0 - a_2$

$a_2 m_+ = (-0.0444 \pm 0.0008) + 0.236(a_0 m_+ - 0.22) - 0.61(a_0 m_+ - 0.22)^2 - 9.9(a_0 m_+ - 0.22)^3$

[Colangelo, Gasser, Leutwyler, PRL 86 (2001) 5008]

(CI): $(a_0 - a_2)m_+ = 0.268 \pm 0.003_{stat} \pm 0.002_{syst} \pm 0.001_{ext}$

(CGKR): $(a_0 - a_2)m_+ = 0.266 \pm 0.003_{stat} \pm 0.002_{syst} \pm 0.001_{ext}$

External uncertainty: from the uncertainty on the ratio (PDG 2006)

$\frac{\Gamma(K^+ \to \pi^+\pi^+\pi^-)}{\Gamma(K^+ \to \pi^+\pi^0\pi^0)} = 3.182 \pm 0.047 \;\Rightarrow\; \frac{A(K^+ \to \pi^+\pi^+\pi^-)}{A(K^+ \to \pi^+\pi^0\pi^0)} = 1.975 \pm 0.015$

at the Dalitz plot centres (exact isospin symmetry predicts 2)

Theoretical uncertainty on $(a_0 - a_2)m_+$: ± 0.013 (CI), not given (CGKR)
(estimated from neglecting higher order diagrams and radiative corrections)

Cusp: fit results (II)

Fits imposing chiral symmetry constraint:

(CI): $(a_0 - a_2)m_+ = 0.268 \pm 0.003_{stat} \pm 0.002_{syst} \pm 0.001_{ext}$

(CGKR): $(a_0 - a_2)m_+ = 0.266 \pm 0.003_{stat} \pm 0.002_{syst} \pm 0.001_{ext}$

Fits not imposing the chiral symmetry constraint: possibility to measure a_2

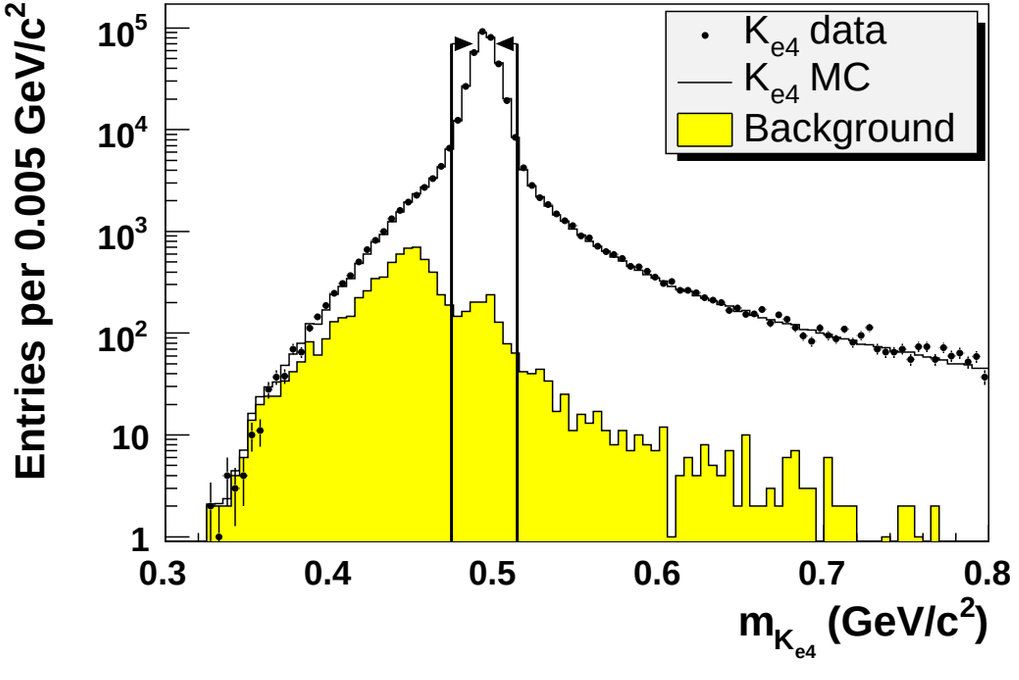
(CI): $(a_0 - a_2)m_+ = 0.266 \pm 0.005_{stat} \pm 0.002_{syst} \pm 0.001_{ext}$
$a_2\ m_+ = -0.039 \pm 0.009_{stat} \pm 0.006_{syst} \pm 0.002_{ext}$

(CGKR): $(a_0 - a_2)m_+ = 0.273 \pm 0.005_{stat} \pm 0.002_{syst} \pm 0.001_{ext}$
$a_2\ m_+ = -0.065 \pm 0.015_{stat} \pm 0.010_{syst} \pm 0.002_{ext}$

Theoretical uncertainty: $\pm 5\%$ (CI); not given (CGKR).

Ke4 ($K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu$)

Analysis of 2003 data (Eur. Phys. J. C 54 (2008) 411)



Rare decay:

B.R.$= (4.09 \pm 0.09) \cdot 10^{-5}$

Event selection:

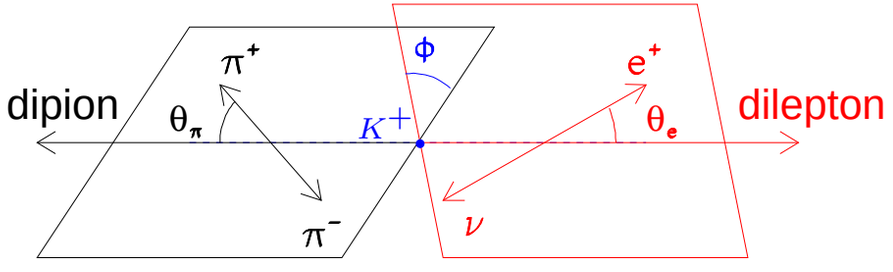
- 3 tracks
- missing energy and p_t
- E/p for e and π ID

$6.8 \cdot 10^5$ selected events

Background estimated from "wrong sing" events ($\pi^{\pm}\pi^{\pm}e^{\mp}$): $\approx 0.5\%$

Ke4 kinematics

$K^+(\text{at rest}) \rightarrow \pi^+\pi^- \quad e^+\nu$



Kinematics described by 5 independent Cabibbo-Maksymowicz variables:

$M^2_{\pi\pi}, \quad M^2_{e\nu}, \quad \theta_\pi, \quad \theta_e, \quad \phi$

Assuming CP symmetry:

$K^+ \rightarrow K^- \Rightarrow \quad \phi \rightarrow \phi + \pi \ , \quad \theta_e \rightarrow \pi - \theta_e$

Decay amplitude is described by two axial (F, G) and one vector (H) form factors, which can be partial wave expanded (s and p waves; d neglected):

$F = F_s(q^2)e^{i\delta s} + F_p(q^2)e^{i\delta p}\cos\theta_\pi$

$G = G_p(q^2)\ e^{i\delta p}$

$H = H_p(q^2)\ e^{i\delta p}$

$\delta(q^2) \equiv \delta_s - \delta_p$

$q^2 \equiv (M^2_{\pi\pi}/4m^2_\pi) - 1$

and further expanded in powers of q^2:

$F_s(q^2) = f_s + f'_s q^2 + f''_s q^4 + f_e(M^2_{ev}/4m^2_\pi) + \ldots$

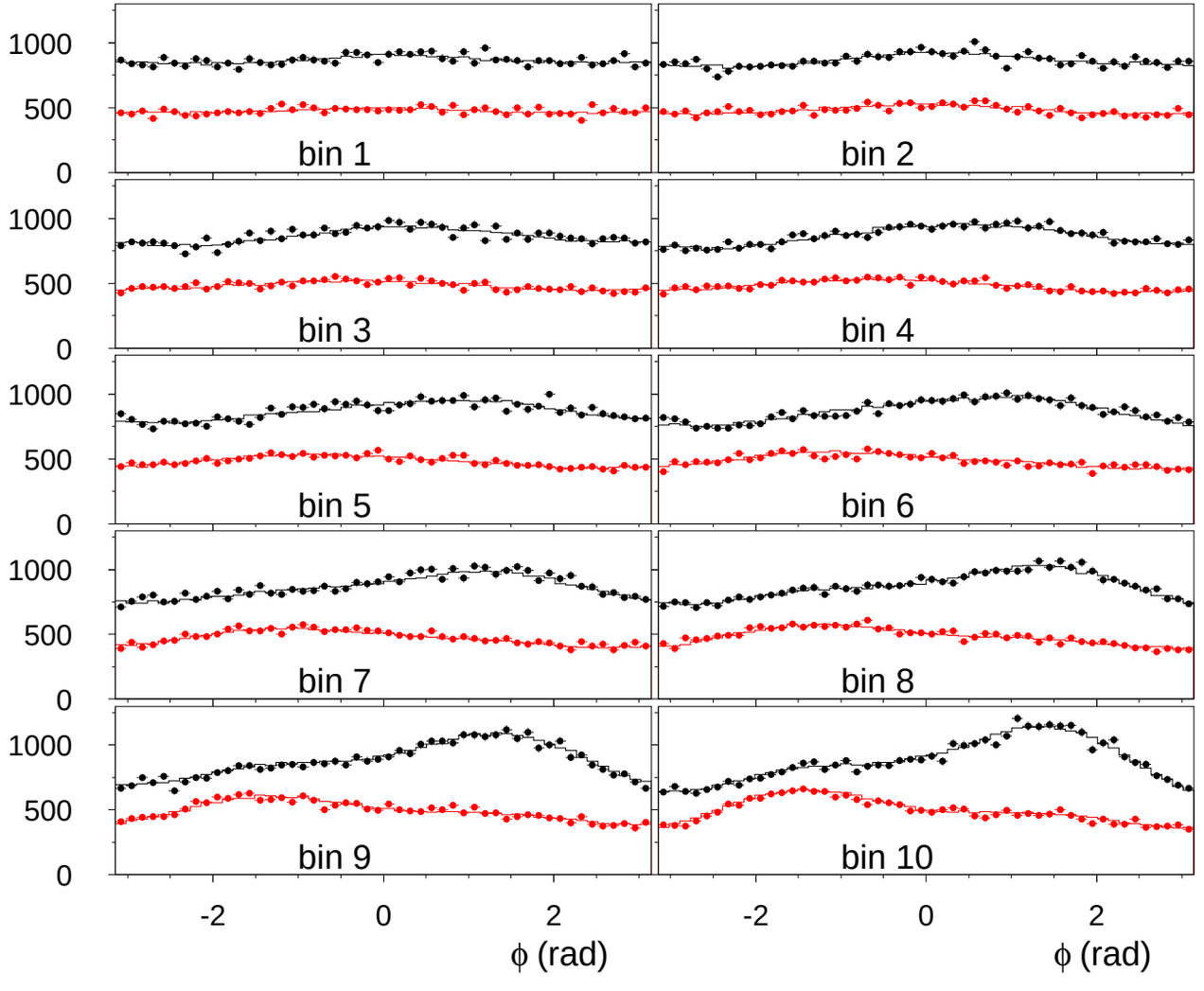
$F_p(q^2) = f_p + f'_p q^2 + \ldots$

$G_p(q^2) = f_p + g'_p q^2 + \ldots$

$H_p(q^2) = h_p + h'_p q^2 + \ldots$

$\delta \neq 0 \ \Rightarrow$ asymmetry in ϕ distribution, increasing with $M_{\pi\pi}$

Ke4 ϕ distributions



one plot per $M_{\pi\pi}$ bin

K^+ (black) and K^- (red):

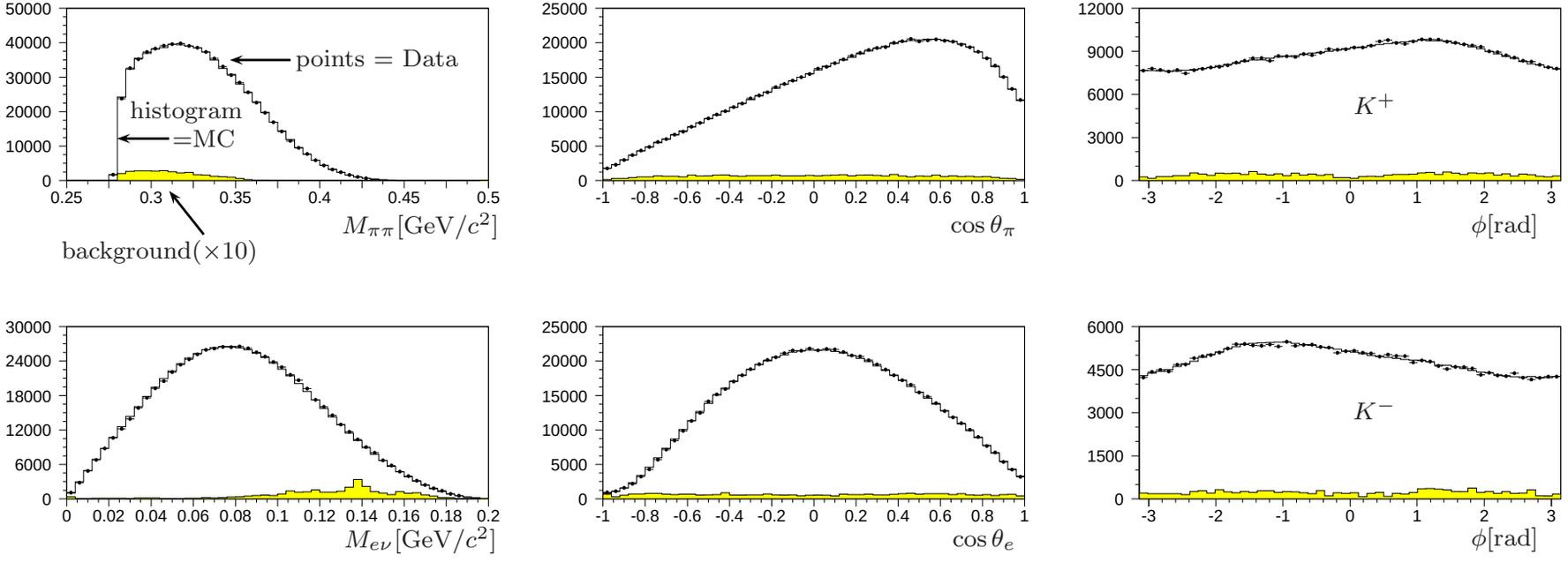
points = data

histogram = MC

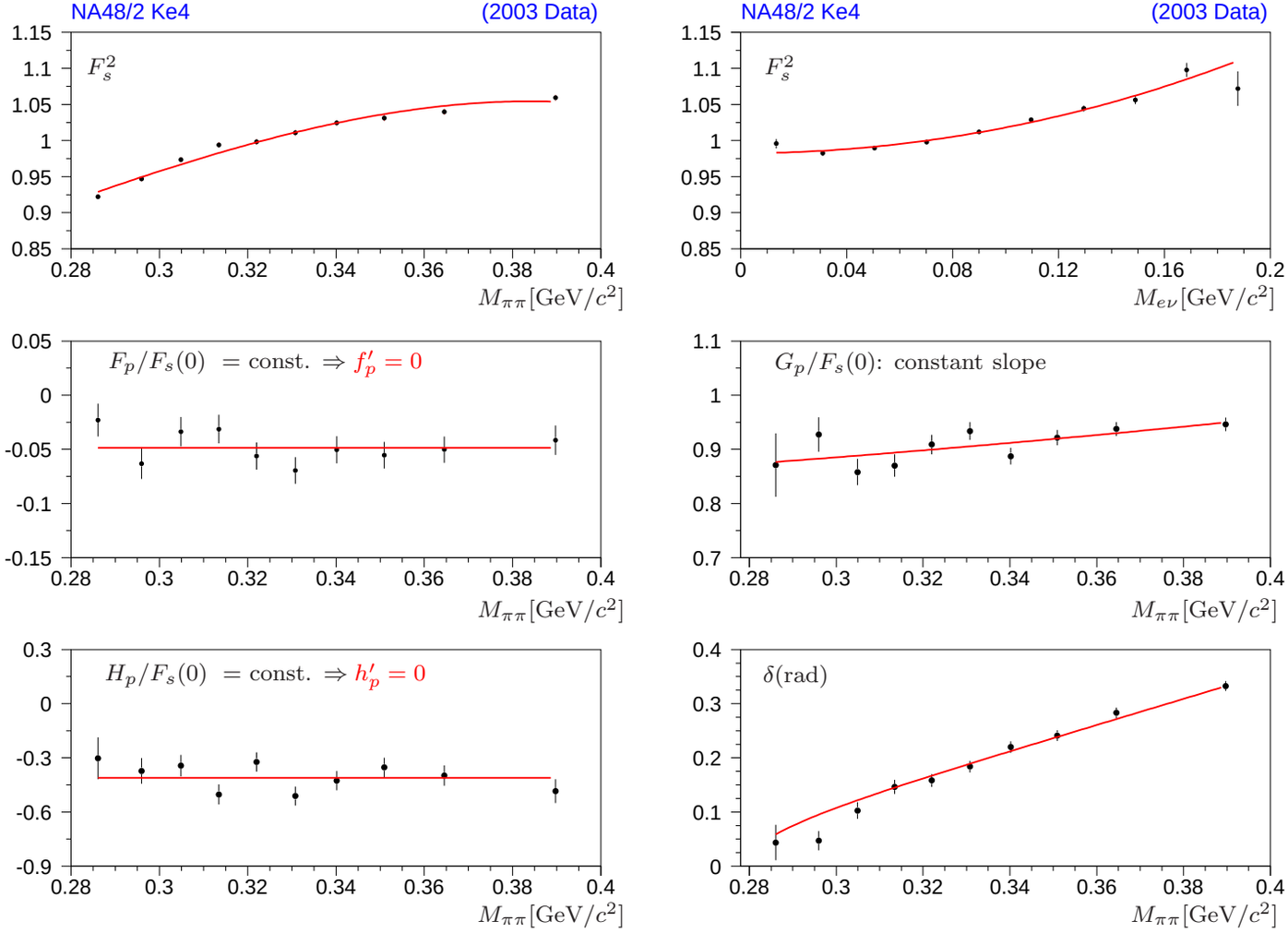
Ke4 form factors fit (I)

F_s, F_p, G_p, H_p and δ are extracted from a fit to
$10(M_{\pi\pi}) \times 5(M_{e\nu}) \times 5(\cos\theta_e) \times 5(\cos\theta_\pi) \times 12(\phi) = 15000$ equi-populated bins.

Event distributions in Cabibbo-Maksymowicz variables (2003 data, $6.8 \cdot 10^5$ events)



Ke4 form factors fit (II)



Ke4 form factors results (2003 data)

$f'_s/f_s = \quad 0.172 \pm 0.009_{stat} \pm 0.006_{syst}$

$f''_s/f_s = -0.090 \pm 0.009_{stat} \pm 0.007_{syst}$

$f'_e/f_s = \quad 0.081 \pm 0.008_{stat} \pm 0.009_{syst}$

$f_p/f_s = -0.048 \pm 0.004_{stat} \pm 0.004_{syst}$

$g_p/f_s = \quad 0.873 \pm 0.013_{stat} \pm 0.012_{syst}$

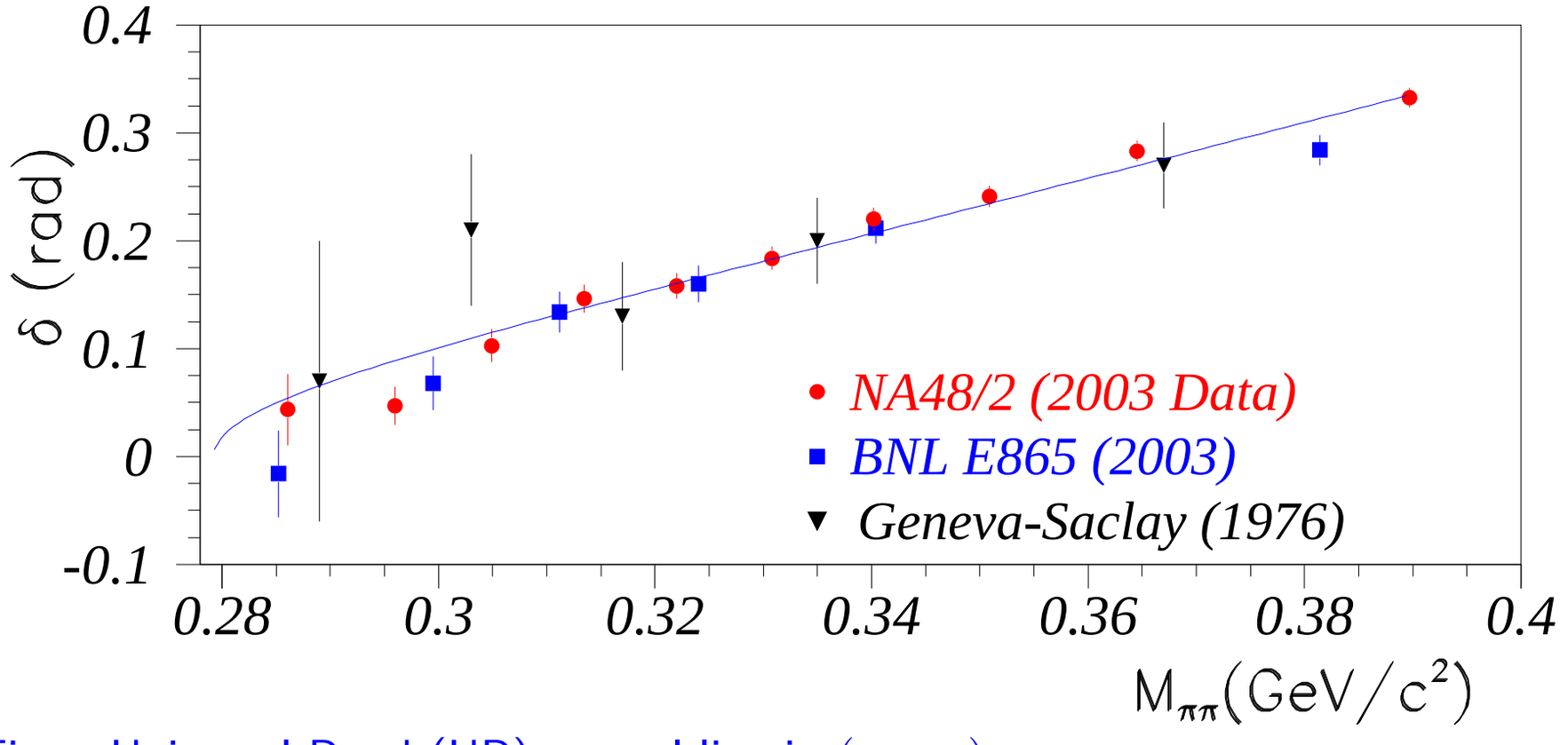
$g'_p/f_s = \quad 0.081 \pm 0.022_{stat} \pm 0.015_{syst}$

$h_p/f_s = -0.411 \pm 0.019_{stat} \pm 0.008_{syst}$

Relative form factors (normalized to f_s)

Separate measurents for K^+ and K^-, then combined

Ke4: $\delta(M_{\pi\pi})$ and scattering lengths



Fit to Universal Band (UB) central line in (a_0, a_2) space

(UB) = limits from experimental data at higher energies, extrapolated using Roy equations

[Ananthanarayan, Colangelo, Gasser, Leutwyler, Phys. Rep. 353 (2001) 207]

Ke4: $\pi\pi$ scattering lengths

Fit to Universal Band (UB) central line in $(a_0,\ a_2)$ space:

$a_0 m_+ = 0.256 \pm 0.006_{stat} \pm 0.002_{syst} {}^{+0.018}_{-0.017}{}_{ext}$

$a_2 m_+ = -0.0312 \pm 0.0011_{stat} \pm 0.0004_{syst} {}^{+0.0129}_{-0.0122}{}_{ext}$

("External" error: from central line to limits of UB)

Fit with 2 free parameters (a_0 and a_2):

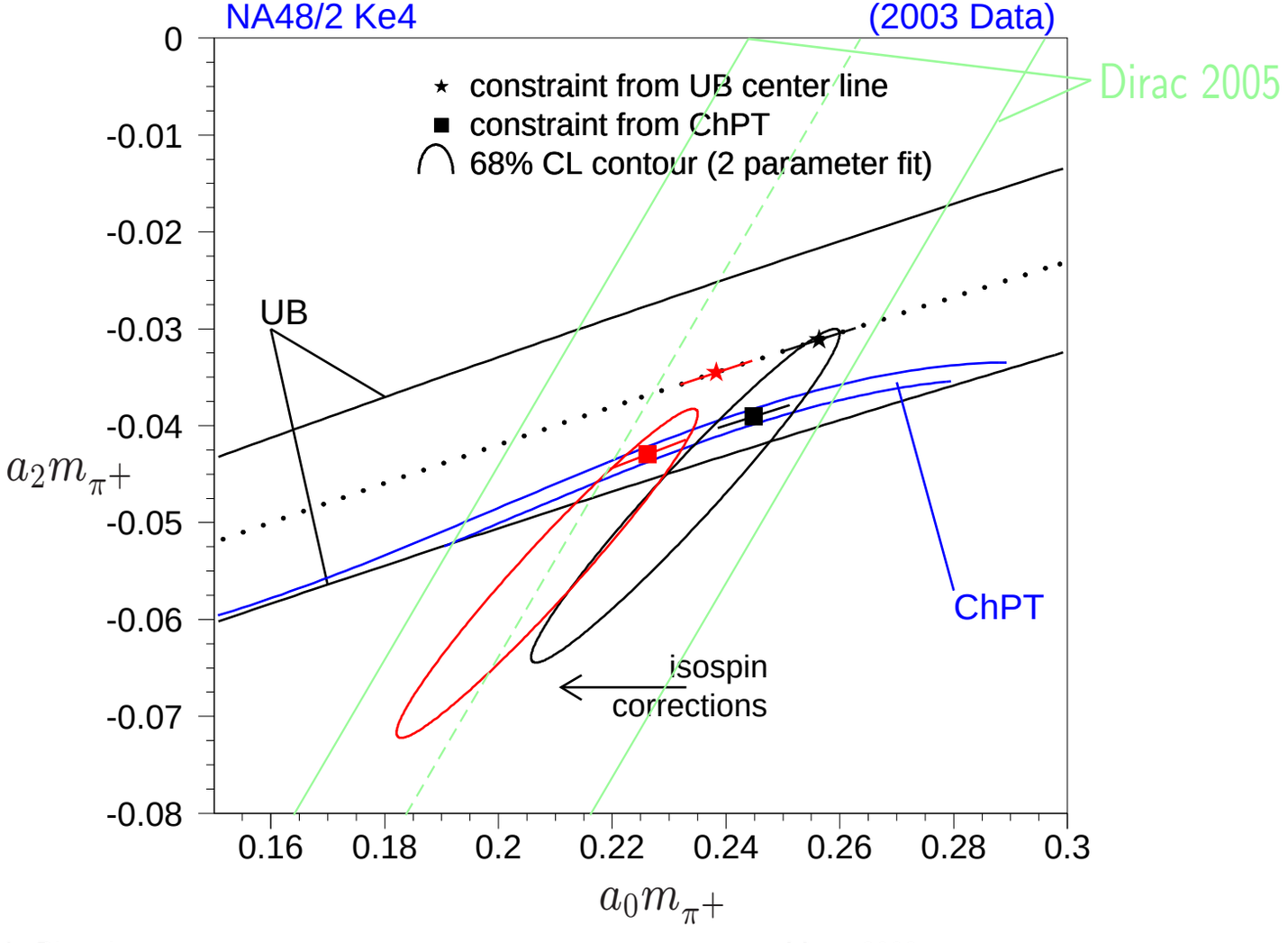
$a_0 m_+ = 0.233 \pm 0.016_{stat} \pm 0.007_{syst}$

$a_2 m_+ = -0.047 \pm 0.011_{stat} \pm 0.004_{syst}$

Fits performed assuming isospin symmetry
Expected corrections for isospin symmetry breaking: $10 \sim 15$ mrad on δ ;
≈ -0.02 on $a_0 m_+$.

The analysis of full (2003+2004) data sample (10^6 K_{e4} decays), including isospin symmetry breaking effects, is nearly finished.

Ke4: $\pi\pi$ scattering lengths



Conclusions and outlook

- $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$: full 2003+2004 sample (60 million events) analysed.
- $a_0 - a_2$ extracted from cusp analysis using both Cabibbo-Isidori and Colangelo-Gasser-Kubis-Rusetsky formulae, with reasonable agreement, especially in the ChPT-constrained fit.
- Results consistent with a_0 and a_2 determined from K_{e4} analysis of 2003 data [Eur.Phys.C 54 (2008) 411]
- K_{e4} analysis of 2003+2004 data (1 million events) nearly finished, will reach a statistical precision at the level of theoretical precision.