CP VIOLATION IN $D \to \pi\pi$ & $D \to KK$: STANDARD MODEL OR NOT?

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Introduction

Isospin amplitudes from BR's

Unitarity constraints & CP asymmetries

How large can penguins be?

Conclusions

INTRODUCTION

- Some basic facts known for a long time:

1) To obtain a good description of SCS D BR's need:
   - final state interactions and corrections to factorization
   - sizable SU(3) breaking
2) The SM expectation for direct CPV is $\lesssim 10^{-3}$

See for example Buccella et al. '95

INTRODUCTION II

- Very recently, LHCb and CDF provided evidence of $\Delta A_{CP}=A_{CP}(K^+K^-)-A_{CP}(\pi^+\pi^-)$
- Combining LHCb, CDF and B-factories:

$$a_{\rm CP}^{\rm dir}(\pi^+\pi^-) = (0.45 \pm 0.26)\ \%$$

$$a_{\rm CP}^{\rm dir}(K^+K^-) = (-0.21 \pm 0.24)\ \%$$

$$\Delta a_{\rm CP}^{\rm dir} = a_{\rm CP}^{\rm dir}(K^+K^-) - a_{\rm CP}^{\rm dir}(\pi^+\pi^-) = (-0.66 \pm 0.16)\ \%$$

INTRODUCTION III

- Can we envisage a mechanism to enhance the SM prediction for CPV by one order of magnitude to reproduce the exp result?

Brod, Kagan & Zupan '11; Pirtskhalava & Uttayarat '11; Bhattacharya, Gronau & Rosner '12; Cheng & Chiang '12; Brod, Grossman, Kagan & Zupan '12

- Can anything analogous to the $\Delta I=1/2$ rule take place in SCS charm decays?

Golden & Grinstein, '89

ISOSPIN & UNITARITY

- Let us start from the basic knowledge:
  - SU(3) breaking is large $\Rightarrow$ use only isospin
  - corrections to factorization are large $\Rightarrow$ use a general parameterization
  - final state interactions are important $\Rightarrow$ implement unitarity & external info on rescattering

Franco, Mishima & LS '12

ISOSPIN AMPLITUDES

$$A(D^+ \to \pi^+\pi^0) = \frac{\sqrt{3}}{2}\mathcal{A}_2^\pi ,$$

r_{CKM}=6.4 10^{-4}

$$A(D^0 \to \pi^+\pi^-) = \frac{\mathcal{A}_2^\pi - \sqrt{2}(\mathcal{A}_0^\pi + i r_{\rm CKM}\mathcal{B}_0^\pi)}{\sqrt{6}} ,$$

$$A(D^0 \to \pi^0\pi^0) = \frac{\sqrt{2}\mathcal{A}_2^\pi + \mathcal{A}_0^\pi + i r_{\rm CKM}\mathcal{B}_0^\pi}{\sqrt{3}} ,$$

A CP-even

B CP-odd

$$A(D^+ \to K^+\bar{K}^0) = \frac{\mathcal{A}_{13}^K}{2} + \mathcal{A}_{11}^K + i r_{\rm CKM}\mathcal{B}_{11}^K ,$$

$$A(D^0 \to K^+K^-) = \frac{-\mathcal{A}_{13}^K + \mathcal{A}_{11}^K - \mathcal{A}_0^K + i r_{\rm CKM}\mathcal{B}_{11}^K - i r_{\rm CKM}\mathcal{B}_0^K}{2} ,$$

$$A(D^0 \to K^0\bar{K}^0) = \frac{-\mathcal{A}_{13}^K + \mathcal{A}_{11}^K + \mathcal{A}_0^K + i r_{\rm CKM}\mathcal{B}_{11}^K + i r_{\rm CKM}\mathcal{B}_0^K}{2} .$$

NUMERICAL RESULTS FROM BR's

$$|\mathcal{A}_2^\pi| = (3.08 \pm 0.08) \times 10^{-7}\ \mathrm{GeV}\,,$$
$$|\mathcal{A}_0^\pi| = (7.6 \pm 0.1) \times 10^{-7}\ \mathrm{GeV}\,,$$
$$\arg(\mathcal{A}_2^\pi/\mathcal{A}_0^\pi) = (\pm 93 \pm 3)^\circ\,.$$

No ΔI=1/2 rule for D decays, large strong phases

$$|\mathcal{A}_{13}^K - \mathcal{A}_{11}^K - \mathcal{A}_0^K| = (5.0 \pm 0.4) \times 10^{-7}\ \mathrm{GeV}$$

Should vanish in the SU(3) limit, but is O(1)!!

UNITARITY CONSTRAINTS

$$S = \left(\begin{array}{c|cccc} D\to D & D\to\pi\pi & D\to KK & \cdots \\ \hline \pi\pi\to D & \pi\pi\to\pi\pi & \pi\pi\to KK & \cdots \\ KK\to D & KK\to\pi\pi & KK\to KK & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{array}\right) \equiv \begin{pmatrix} 1 & -i(T)^T \\ -i\,\mathrm{CP}(T) & S_S \end{pmatrix}$$

implies

$$T^R = S_S(T^R)^*, \qquad T^I = S_S(T^I)^*$$

Elastic case: $S = e^{2i\delta} \Rightarrow$ Watson theorem:

$T^R=|T^R|e^{i\delta}$, $T^I=|T^I|e^{i\delta}$

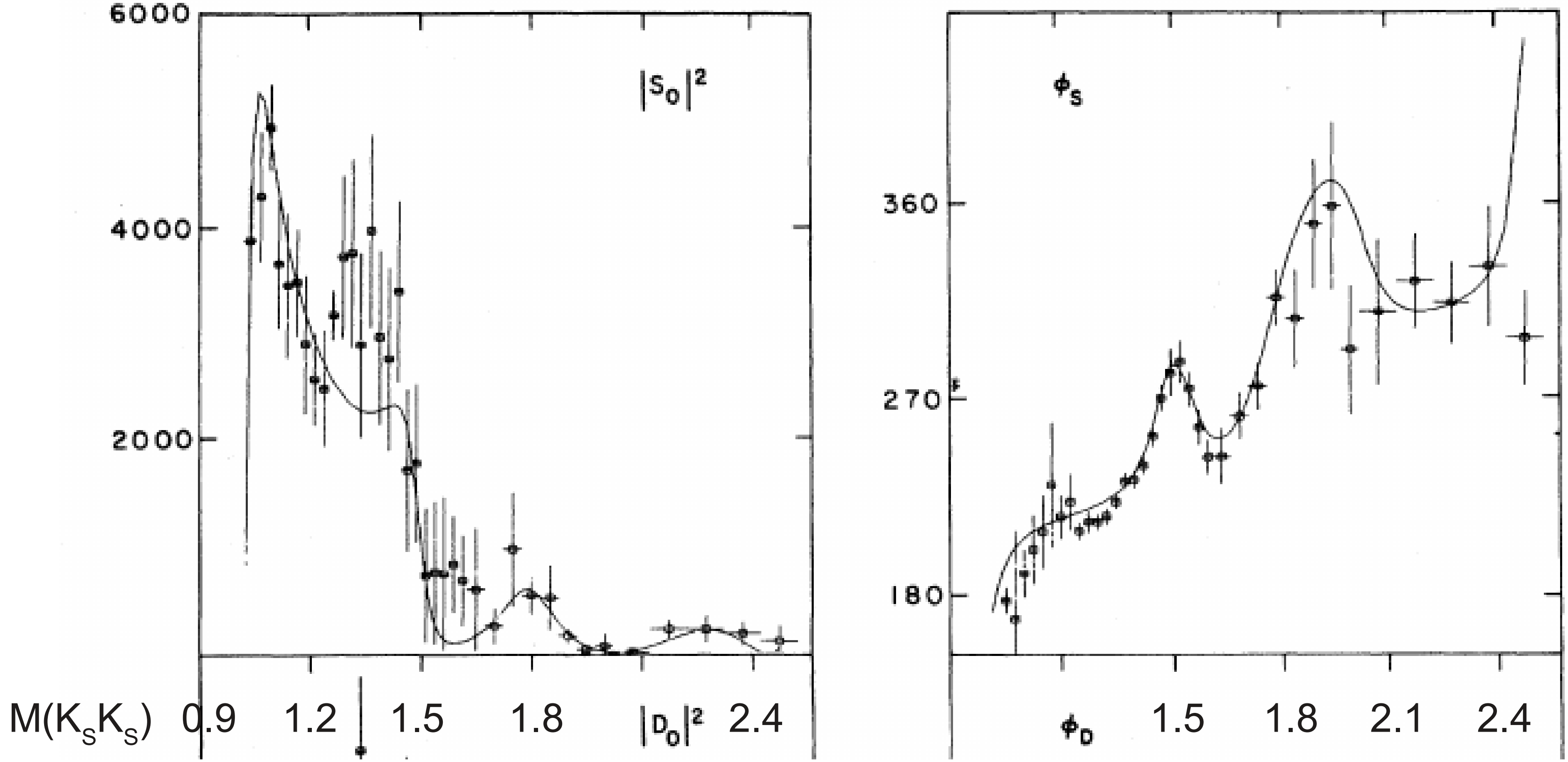
2-CHANNEL UNITARITY

$$\begin{pmatrix} \mathcal{A}_0^\pi \\ \mathcal{A}_0^K \end{pmatrix} = \begin{pmatrix} \eta\, e^{2i\delta_1} & \pm i\sqrt{1-\eta^2}\, e^{i(\delta_1+\delta_2)} \\ \pm i\sqrt{1-\eta^2}\, e^{i(\delta_1+\delta_2)} & \eta\, e^{2i\delta_2} \end{pmatrix} \begin{pmatrix} (\mathcal{A}_0^\pi)^* \\ (\mathcal{A}_0^K)^* \end{pmatrix}$$

Obtain constraints on magnitudes and phases of amplitudes

For η close to 1, magnitudes almost unconstrained but phases close to δ_1 and δ_2

Is the 2-channel S-matrix unitary at the D mass?



Etkin et al. '82

S_{12} has small amplitude and small phase.

Is this compatible with measured S_{11}?

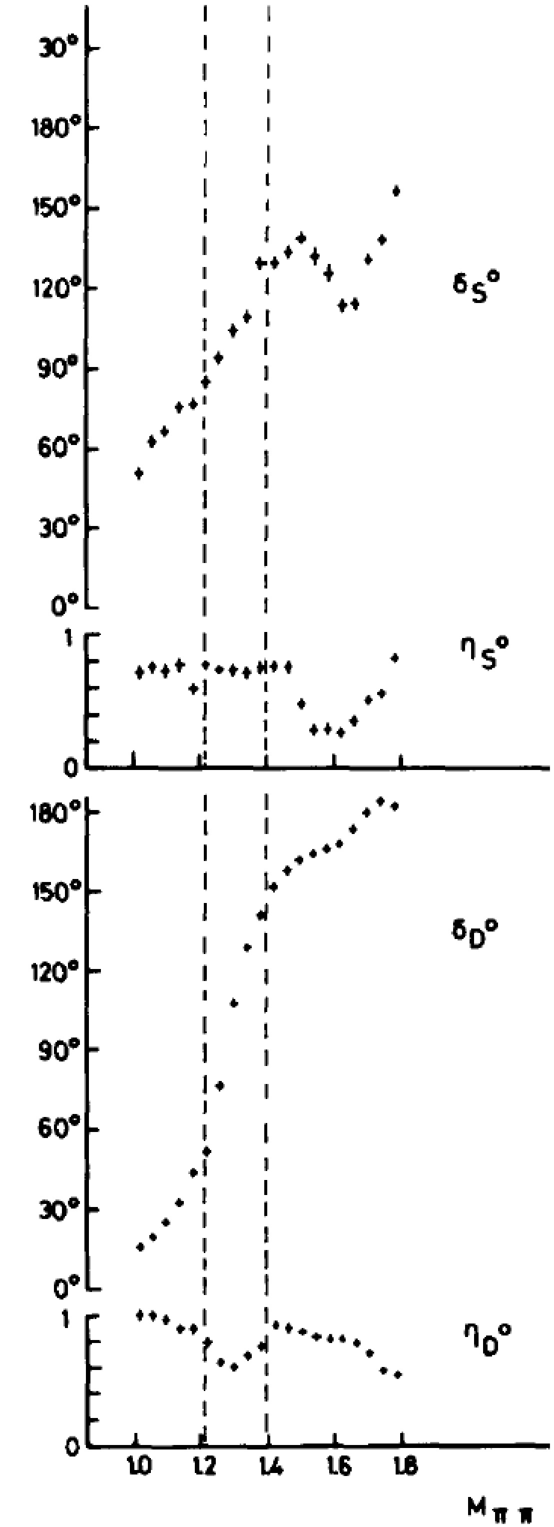


Fig. 4. Soluti

Unfortunately, πN scattering alone is ambiguous; different fits corresponding to discrete ambiguities yield widely different results close to the D mass. 2- and 3-channel unitarity possible.

Hyams et al. '73

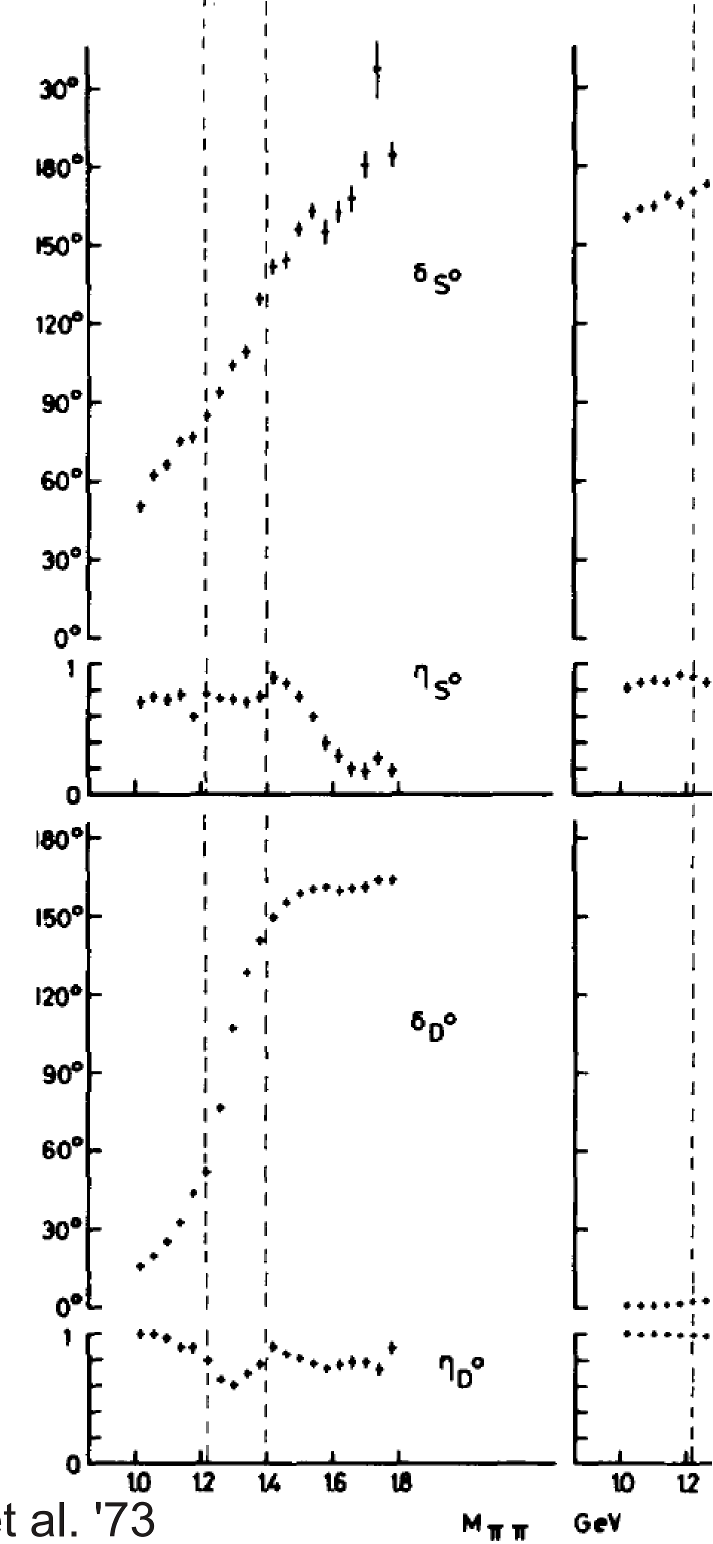


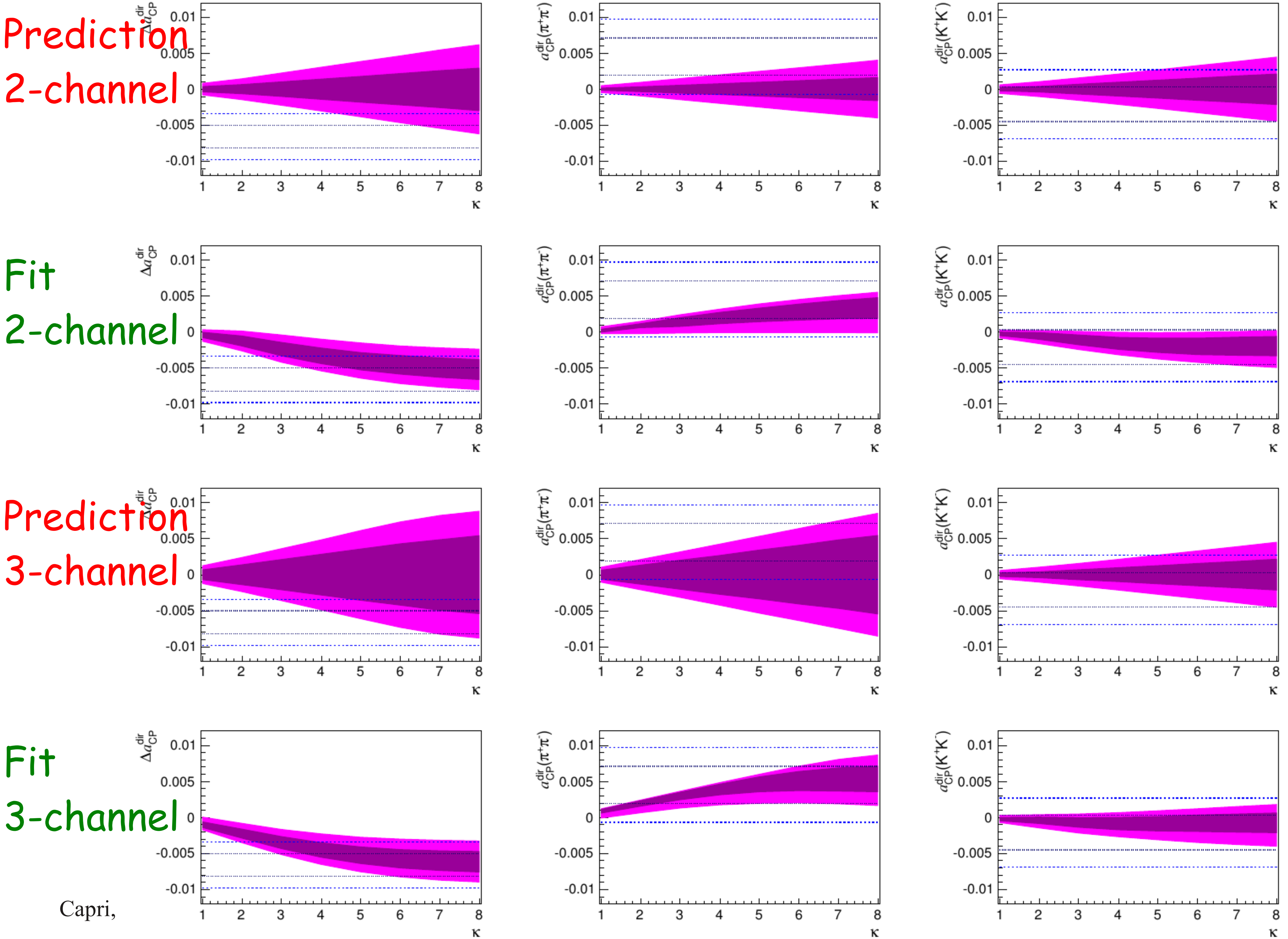
Fig. 3. Solution (– – –).

CP ASYMMETRIES

- One can study the CP asymmetries as a function of the upper bound on the size of CPV contributions in the two- and three-channel scenarios. We write

$$|\mathcal{B}_0^\pi| < \kappa |\mathcal{A}_0^\pi| \,,$$
$$|\mathcal{B}_0^K - \mathcal{A}_0^K| < \kappa |\mathcal{A}_0^K| \,,$$
$$|\mathcal{B}_{11}^K - (\mathcal{A}_{11}^K - \mathcal{A}_{13}^K)| < \kappa |\mathcal{A}_{11}^K - \mathcal{A}_{13}^K| \,,$$

and consider predictions and fit results for CP asymmetries



Prediction
2-channel
Fit
2-channel
Prediction
3-channel
Fit
3-channel
Δa_{CP}^{dir}
$a_{CP}^{dir}(\pi^+\pi^-)$
$a_{CP}^{dir}(K^+K^-)$
0.01
0.005
0
-0.005
-0.01
1 2 3 4 5 6 7 8
κ

CONCLUSIONS FROM UNITARITY

- The prediction does not reach the exp value within 2σ even for κ=8 in the 2-channel case
- Without unitarity constraints, the prediction reaches the exp value at the 2σ level for κ>5, but even for κ=8 it is still 1σ below
- How large can κ be?
  - translate fit results into RGI parameters
  - compare with K and B

FROM ISOSPIN AMPLITUDES TO RGI PARAMETERS

- The BR fit results can be translated into results for RGI parameters (aka topologies). Neglecting for simplicity $O(1/N_c^2)$ terms:

$$E_1(\pi) + E_2(\pi) = (1.72 \pm 0.04) \times 10^{-6}\, e^{i\delta}\ \mathrm{GeV}\,,$$
$$E_1(\pi) + A_2(\pi) - P_1^{\mathrm{GIM}}(\pi) = (2.10 \pm 0.02) \times 10^{-6}\, e^{i(\delta \pm (71\pm 3)^\circ)}\ \mathrm{GeV}\,,$$
$$E_2(\pi) - A_2(\pi) + P_1^{\mathrm{GIM}}(\pi) = (2.25 \pm 0.07) \times 10^{-6}\, e^{i(\delta \mp (62\pm 2)^\circ)}\ \mathrm{GeV}$$

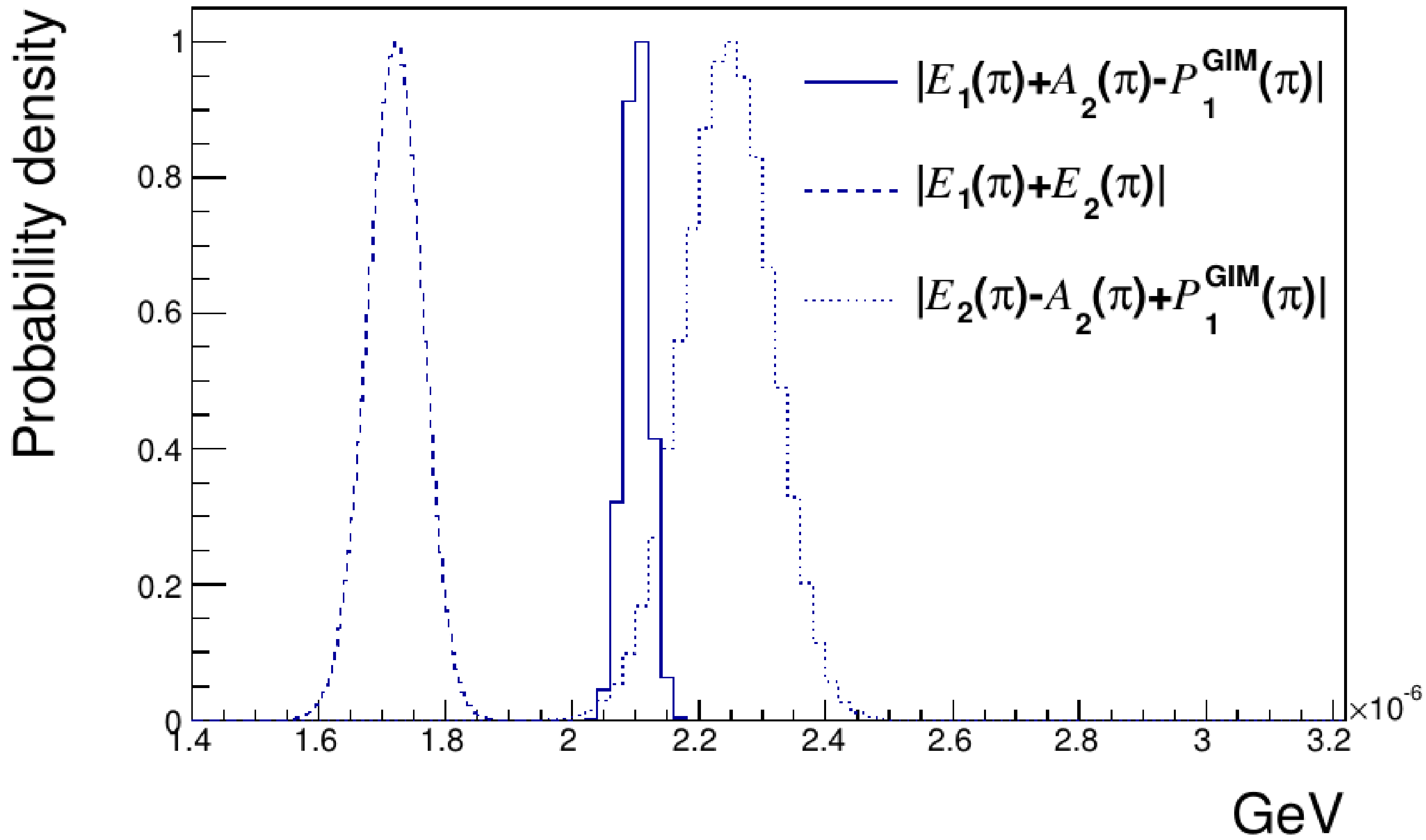
- E_1 does not dominate the amplitudes $\Rightarrow$ we are away from the infinite mass limit
- All amplitudes of same size, w. large phases

THE MEANING OF κ

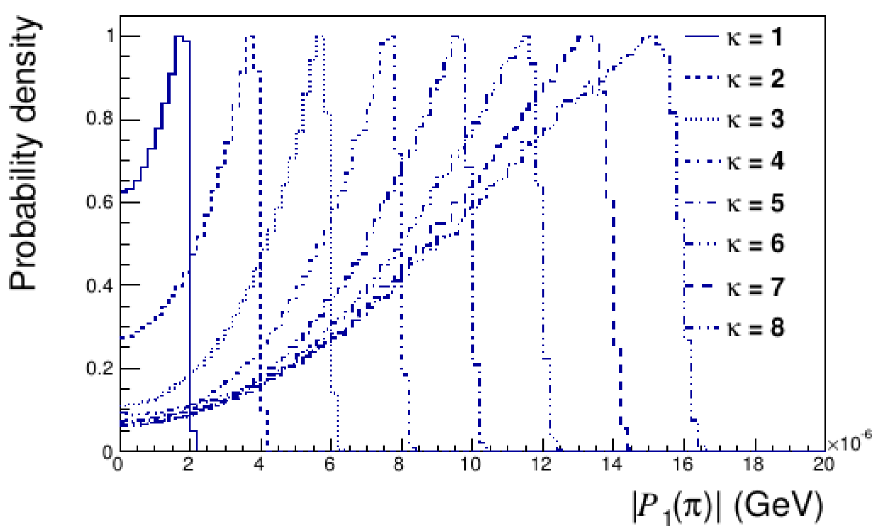
- The condition $|\mathcal{B}_0^\pi| < \kappa |\mathcal{A}_0^\pi|\,,$ means

$$|P_1(\pi)| \leq \kappa \left| \frac{2}{3} E_1(\pi) - \frac{1}{3} E_2(\pi) + A_2(\pi) - P_1^{\rm GIM}(\pi) \right|$$

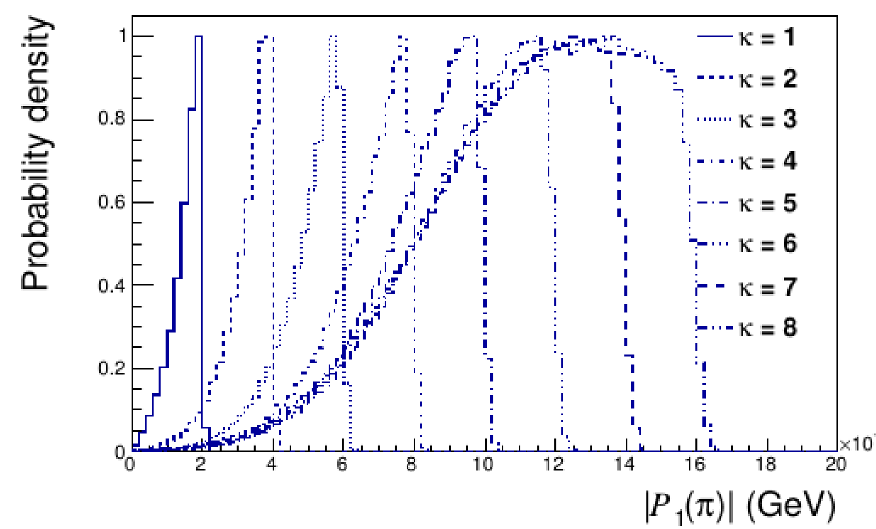
- κ is the ratio of $|P_1|$ over all other topologies
- Notice that $P_1 \sim P_b - P_s$ while $P_1^{GIM} \sim P_d - P_s$
- How large should $|P_1|$ be to reproduce Δa_{CP}^{dir}?



2-channel



3-channel



Ca

DYNAMICAL ARGUMENTS

- The amplitudes for K, D and B $\to \pi\pi$ are formally the same, with the obvious flavour and CKM replacements.
- In the Kaon system, one has

$$(P_u - P_c) \sim 3\,(P_t - P_c) \sim 25\,(E_1 + E_2)$$

- No enhancement expected for P_u (will be checked on the lattice soon), while P_c and P_t generate local operators with chirally enhanced matrix elements (SVZ)

DYNAMICAL ARGUMENTS II

- In charm decays, no chiral enhancement is present, so that one expects

$$|P_1| = |P_b - P_s| \leq |E_1|, |E_2|, |A_1|, |A_2|, |P_1^{GIM}|$$

i.e. $\kappa \leq 1$.

- In B decays one is much closer to the infinite mass limit so that $|E_1|$ and $|E_2|$ dominate, with all other contractions power suppressed.

CONCLUSIONS

- We have performed a phenomenological analysis of Δa_{CP}^{dir} with minimal assumptions as a function of κ ~ relative size of $|P_1|$
- From the BR we confirm large nonfactorizable contributions, large strong phases and large SU(3) breaking
- Unfortunately, data on $\pi\pi$ scattering at the D mass are not able to fully determine the relevant FSI

CONCLUSIONS II

- In the most conservative scenario (no constraints from unitarity), values of $\kappa > 5$ are needed to reach at 2σ the experimental result
- We cannot find any reasonable dynamical origin for such a large value of $|P_1|$
- If the central value stays with improved errors, we have strong indications of NP