SAS1

Thoughts on Direct CP in K, D and B decays

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05/24/21

Slide 1

SAS1 Soni, Amarjit S, 5/19/2021

Outline

- **Motivation**
- **Progress in longstanding issues in K decays**
- **Resonance enhancement in Charm CP**
- **Recent significant exptal progress B-CP**
- **Are there any reliable indications of anomalies**
- **Summary**

- **Talk is based primarily on, arXiv 2004.09440 [RBC-UKQCD]; Schacht + AS, arxiv 21 + WIP**

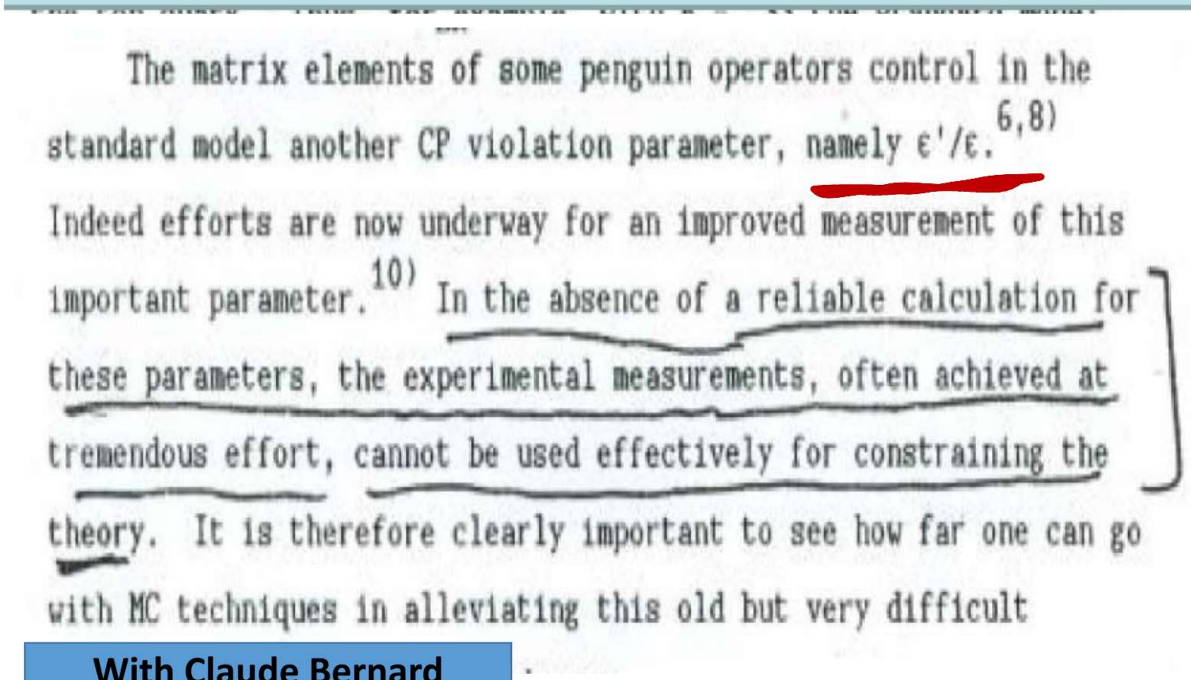
Motivation

In 1964 in the BNL-Noble prize {Cronin-Fitch] winning expt CP violation was discovered for the 1st time.

- **This means CP is NOT a symmetry of nature => new physics should therefore be accompanied by non-vanishing (new) CP-odd phase(s) since no symmetry exists to make the phase(s) zero….Most important reason for understanding CP violation as quantitatively as possible**
- **Of course CKM-CP (SM) is unable to account for baryongenesis though this is a rather challenging task**

- Direct CP in K=>pi pi, eps’
  Deemed very important as eps’~O(10^{-6})
  i.e. very small so likely to be rather
  amenable to perturbations.

A.S. in Proceedings of Lattice '85 (FSU)..1st Lattice meeting ever attended



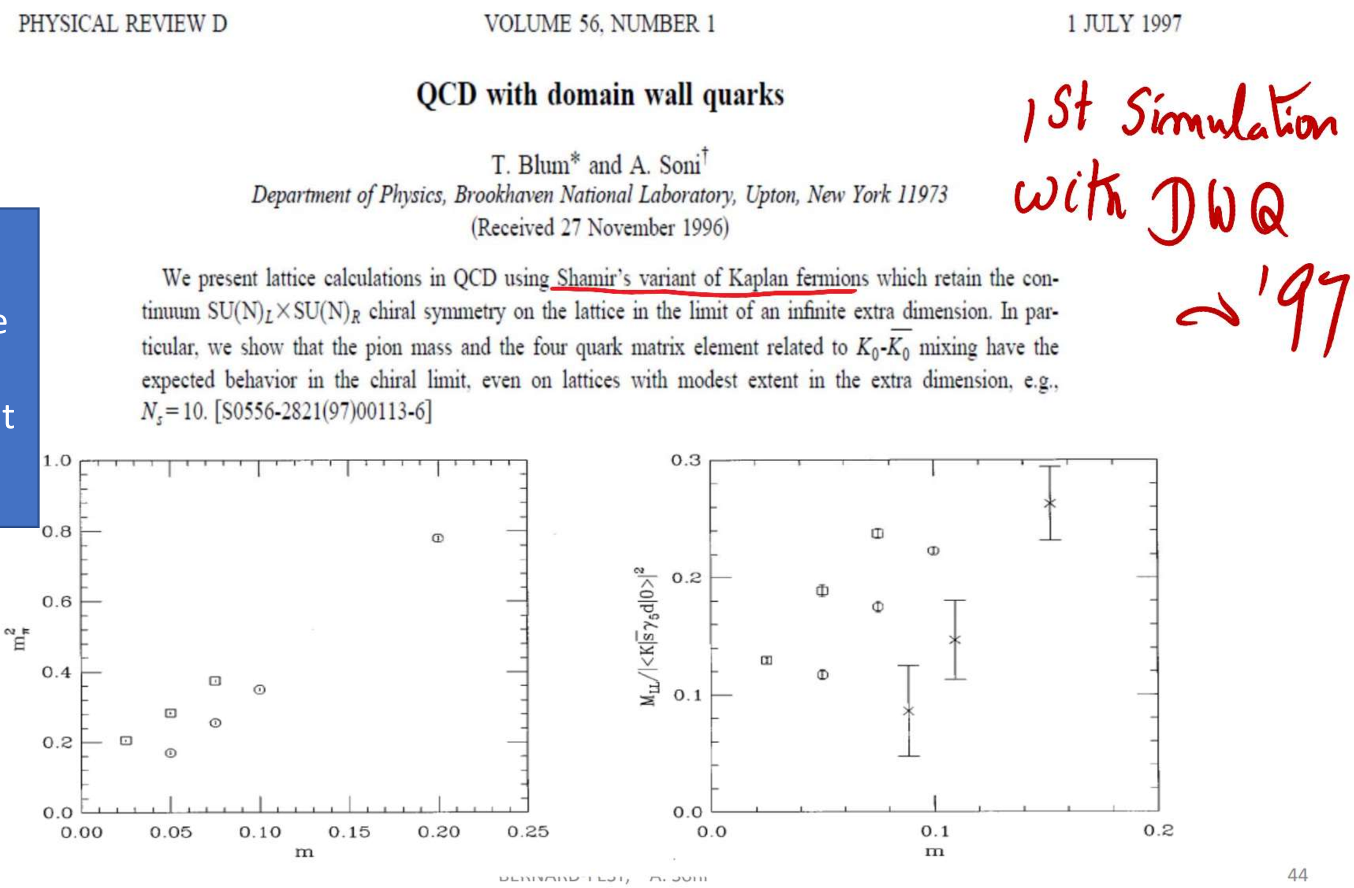
The matrix elements of some penguin operators control in the standard model another CP violation parameter, namely ϵ'/ϵ.[6,8] Indeed efforts are now underway for an improved measurement of this important parameter.[10] In the absence of a reliable calculation for these parameters, the experimental measurements, often achieved at tremendous effort, cannot be used effectively for constraining the theory. It is therefore clearly important to see how far one can go with MC techniques in alleviating this old but very difficult .

With Claude Bernard [UCLA]

BERNARD-FEST; A. Soni

Had to overcome multitude of obtacles..
Took Decades..
O(12) PhD Thesises

Earlier works of Yigal Shamir showed in the limit of infinite 5th Dim. EXACT CS even at Finite lattice spacing



PHYSICAL REVIEW D VOLUME 56, NUMBER 1 1 JULY 1997

QCD with domain wall quarks

T. Blum* and A. Soni†
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 27 November 1996)

We present lattice calculations in QCD using Shamir's variant of Kaplan fermions which retain the continuum $SU(N)_L \times SU(N)_R$ chiral symmetry on the lattice in the limit of an infinite extra dimension. In particular, we show that the pion mass and the four quark matrix element related to K_0-$\overline{K_0}$ mixing have the expected behavior in the chiral limit, even on lattices with modest extent in the extra dimension, e.g., $N_s = 10$. [S0556-2821(97)00113-6]

1st Simulation with DWQ ~'97

isospin partners

$\tau^+/\tau^0 \simeq 450$!

PHYSICAL REVIEW D **102**, 054509 (2020)

Editors' Suggestion **Featured in Physics**

Direct *CP* violation and the $\Delta I = 1/2$ rule in $K \to \pi\pi$ decay from the standard model

R. Abbott,[1] T. Blum,[2,3] P. A. Boyle,[4,5] M. Bruno,[6] N. H. Christ,[1] D. Hoying,[3,2] C. Jung,[4] C. Kelly,[4] C. Lehner,[7,4] R. D. Mawhinney,[1] D. J. Murphy,[8] C. T. Sachrajda,[9] A. Soni,[4] M. Tomii,[2] and T. Wang[1]

(RBC and UKQCD Collaborations)

aCP

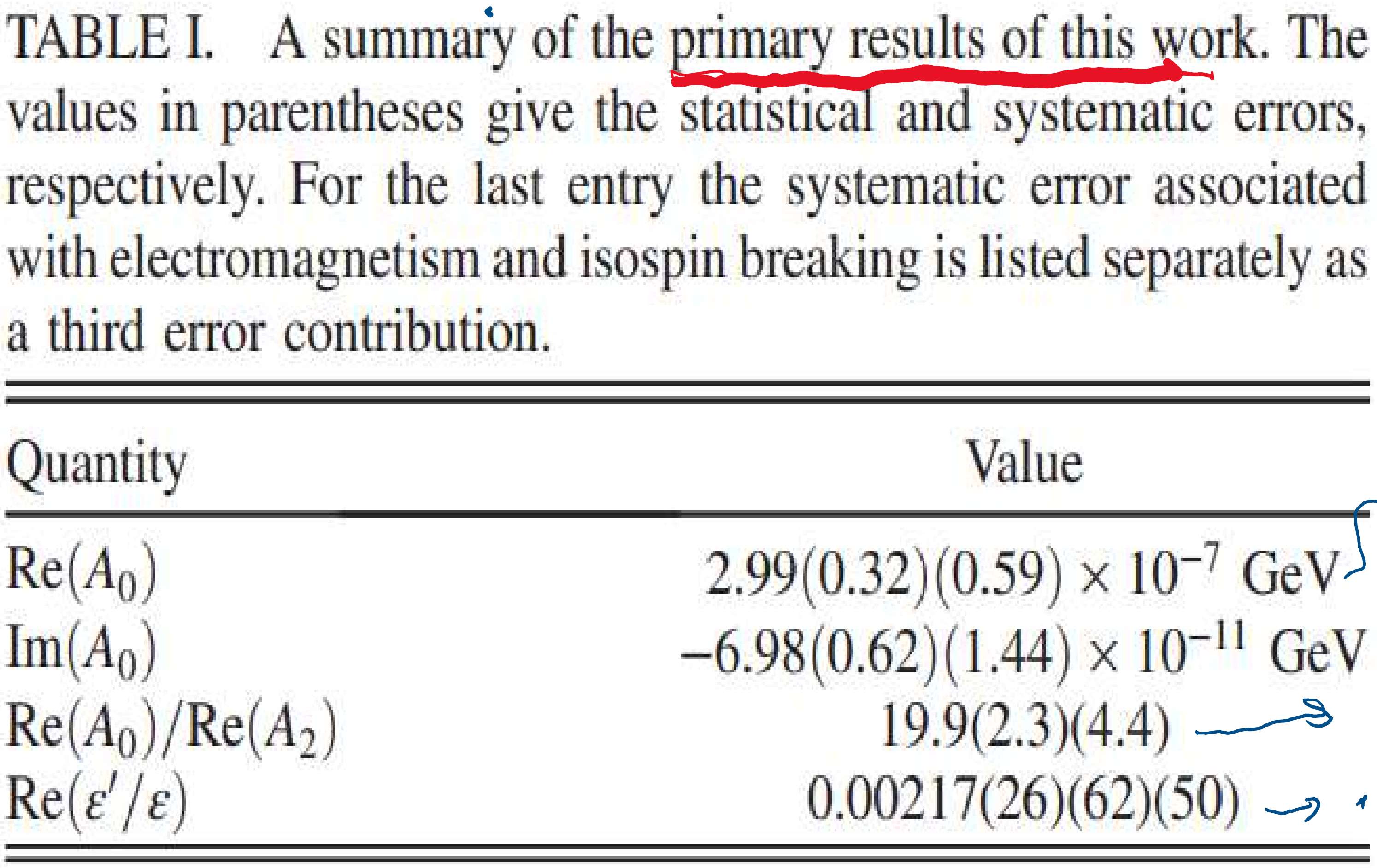


TABLE I. A summary of the primary results of this work. The values in parentheses give the statistical and systematic errors, respectively. For the last entry the systematic error associated with electromagnetism and isospin breaking is listed separately as a third error contribution.

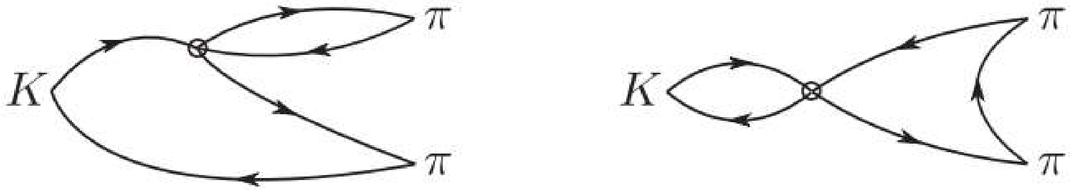
Quantity	Value
$\mathrm{Re}(A_0)$	$2.99(0.32)(0.59) \times 10^{-7}$ GeV
$\mathrm{Im}(A_0)$	$-6.98(0.62)(1.44) \times 10^{-11}$ GeV
$\mathrm{Re}(A_0)/\mathrm{Re}(A_2)$	19.9(2.3)(4.4)
$\mathrm{Re}(\varepsilon'/\varepsilon)$	0.00217(26)(62)(50)

Expt

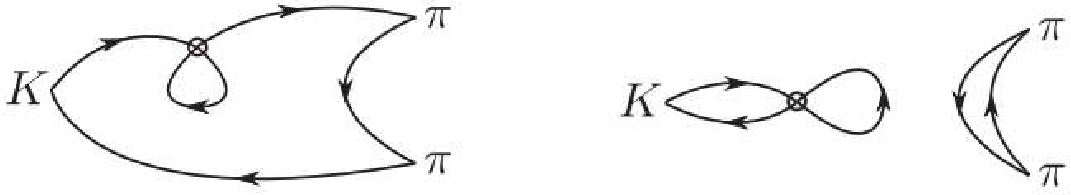
→ 3.32×10^{-7}

→ 22.45

→ .00166(23)



(a) *type1* (b) *type2*



(c) *type3* (d) *type4*

extremely difficult

FIG. 2. The four classes of $K \to \pi\pi$ Wick contractions.

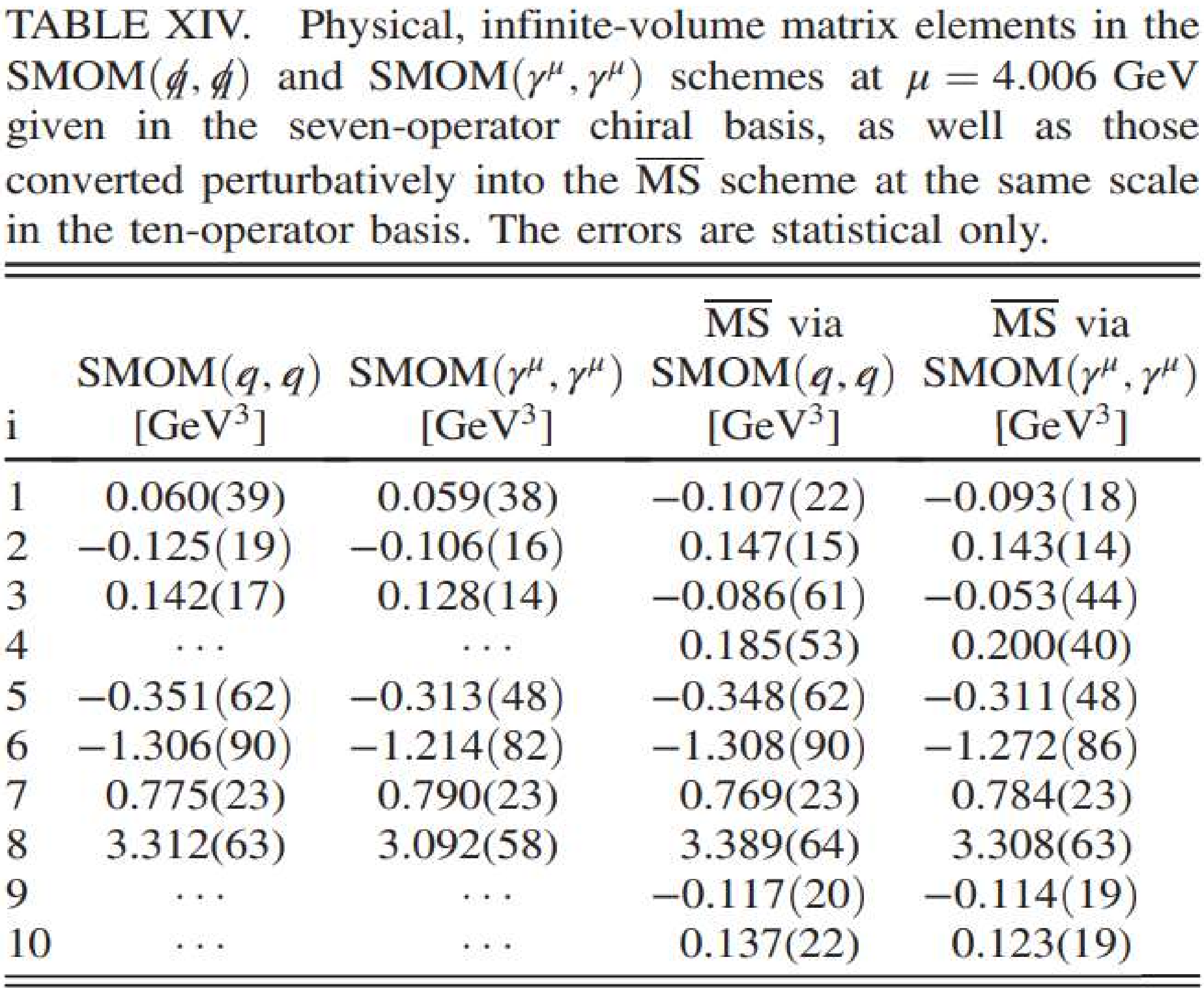


TABLE XIV. Physical, infinite-volume matrix elements in the SMOM($\not{q},\not{q}$) and SMOM(γ^μ,γ^μ) schemes at $\mu = 4.006$ GeV given in the seven-operator chiral basis, as well as those converted perturbatively into the $\overline{\mathrm{MS}}$ scheme at the same scale in the ten-operator basis. The errors are statistical only.

i	SMOM(q,q) [GeV^3]	SMOM(γ^μ,γ^μ) [GeV^3]	$\overline{\mathrm{MS}}$ via SMOM(q,q) [GeV^3]	$\overline{\mathrm{MS}}$ via SMOM(γ^μ,γ^μ) [GeV^3]
1	0.060(39)	0.059(38)	−0.107(22)	−0.093(18)
2	−0.125(19)	−0.106(16)	0.147(15)	0.143(14)
3	0.142(17)	0.128(14)	−0.086(61)	−0.053(44)
4	...	...	0.185(53)	0.200(40)
5	−0.351(62)	−0.313(48)	−0.348(62)	−0.311(48)
6	−1.306(90)	−1.214(82)	−1.308(90)	−1.272(86)
7	0.775(23)	0.790(23)	0.769(23)	0.784(23)
8	3.312(63)	3.092(58)	3.389(64)	3.308(63)
9	...	...	−0.117(20)	−0.114(19)
10	...	...	0.137(22)	0.123(19)

TABLE XVIII. The contributions of each of the ten four-quark operators to $\mathrm{Re}(A_0)$ and $\mathrm{Im}(A_0)$ for the two different RI-SMOM intermediate schemes. The scheme and units are listed in the column headers. The errors are statistical, only.

	$\mathrm{Re}(A_0)$		$\mathrm{Im}(A_0)$	
i	$(\not{q},\not{q})$ $(\times 10^{-7}$ GeV)	(γ^μ,γ^μ) $(\times 10^{-7}$ GeV)	$(\not{q},\not{q})$ $(\times 10^{-11}$ GeV)	(γ^μ,γ^μ) $(\times 10^{-11}$ GeV)
1	0.383(77)	0.335(64)	0	0
2	2.89(30)	2.81(28)	0	0
3	0.0081(58)	0.0050(42)	0.20(14)	0.12(10)
4	0.081(23)	0.088(17)	1.24(35)	1.34(27)
5	0.0380(68)	0.0339(53)	0.552(99)	0.492(77)
6	−0.410(28)	−0.398(27)	−8.78(60)	−8.54(57)
7	0.001863(56)	0.001900(56)	0.02491(75)	0.02540(75)
8	−0.00726(14)	−0.00708(13)	−0.2111(40)	−0.2060(39)
9	$-8.7(1.5) \times 10^{-5}$	$-8.5(1.4) \times 10^{-5}$	−0.133(22)	−0.128(21)
10	$2.37(38) \times 10^{-4}$	$2.13(32) \times 10^{-4}$	−0.0304(49)	−0.0273(41)
Total	2.99(32)	2.86(31)	−7.15(66)	−6.93(64)

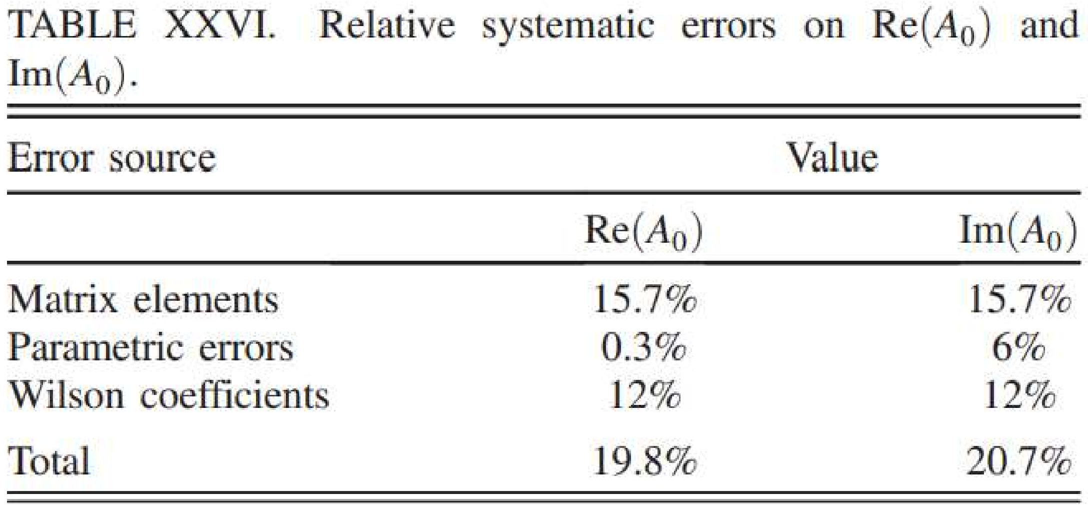
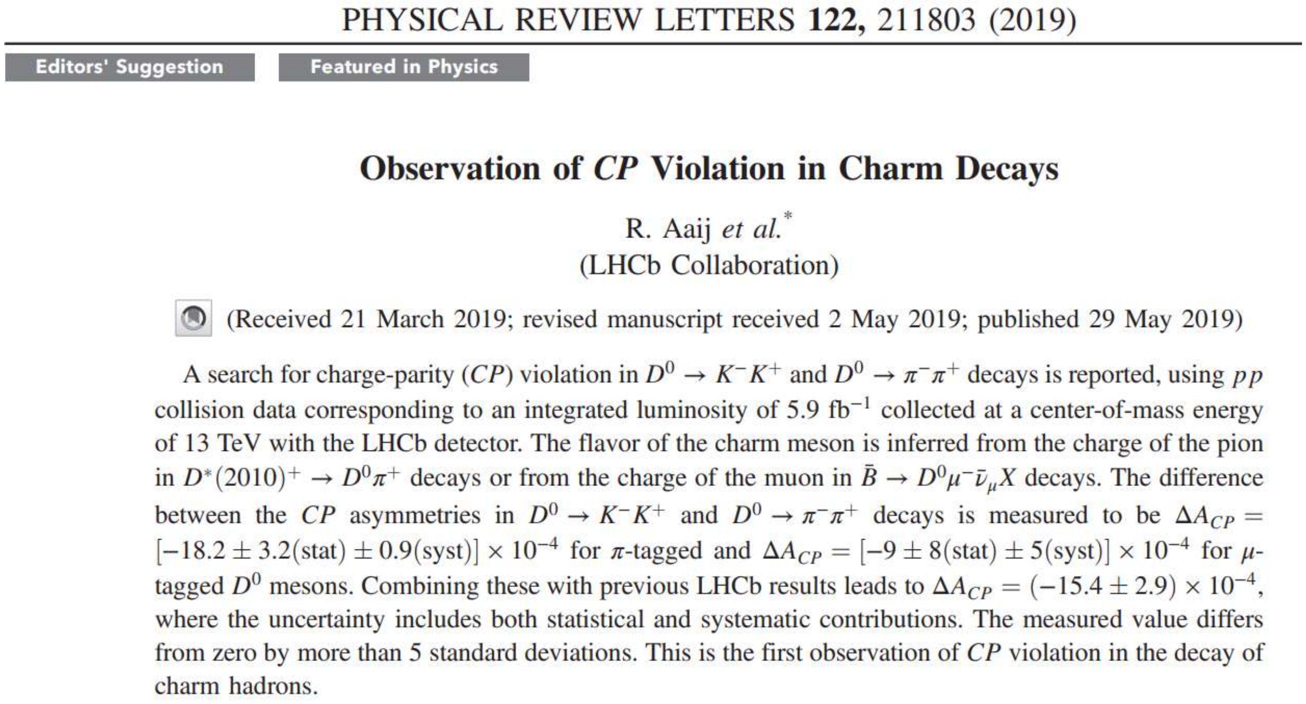


TABLE XXVI. Relative systematic errors on $\mathrm{Re}(A_0)$ and $\mathrm{Im}(A_0)$.

Error source	Value	
	$\mathrm{Re}(A_0)$	$\mathrm{Im}(A_0)$
Matrix elements	15.7%	15.7%
Parametric errors	0.3%	6%
Wilson coefficients	12%	12%
Total	19.8%	20.7%

Next update in ~ 2–3 years

Dir CP in charm system



PHYSICAL REVIEW LETTERS **122,** 211803 (2019)

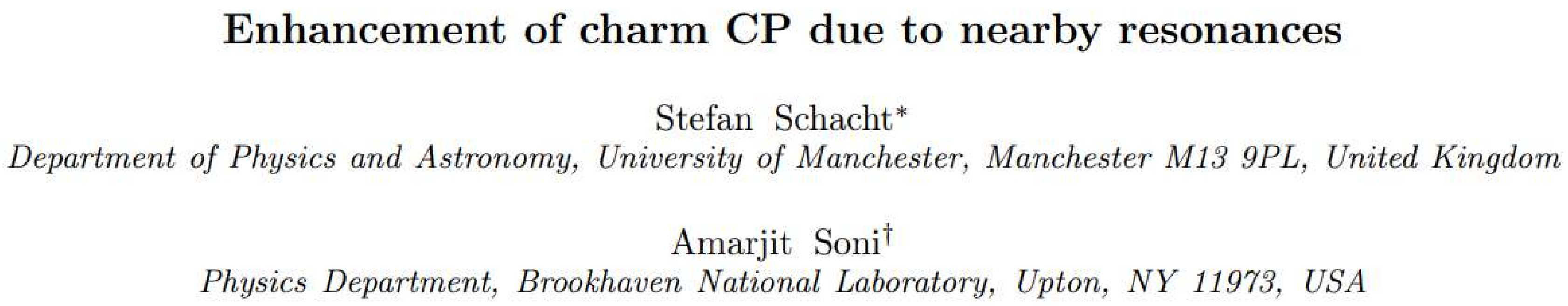
Editors' Suggestion **Featured in Physics**

Observation of *CP* Violation in Charm Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 21 March 2019; revised manuscript received 2 May 2019; published 29 May 2019)

A search for charge-parity (*CP*) violation in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays is reported, using pp collision data corresponding to an integrated luminosity of 5.9 fb^{-1} collected at a center-of-mass energy of 13 TeV with the LHCb detector. The flavor of the charm meson is inferred from the charge of the pion in $D^*(2010)^+ \to D^0 \pi^+$ decays or from the charge of the muon in $\bar{B} \to D^0 \mu^- \bar{\nu}_\mu X$ decays. The difference between the *CP* asymmetries in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays is measured to be $\Delta A_{CP} = [-18.2 \pm 3.2(\mathrm{stat}) \pm 0.9(\mathrm{syst})] \times 10^{-4}$ for π-tagged and $\Delta A_{CP} = [-9 \pm 8(\mathrm{stat}) \pm 5(\mathrm{syst})] \times 10^{-4}$ for μ-tagged D^0 mesons. Combining these with previous LHCb results leads to $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$, where the uncertainty includes both statistical and systematic contributions. The measured value differs from zero by more than 5 standard deviations. This is the first observation of *CP* violation in the decay of charm hadrons.



Enhancement of charm CP due to nearby resonances

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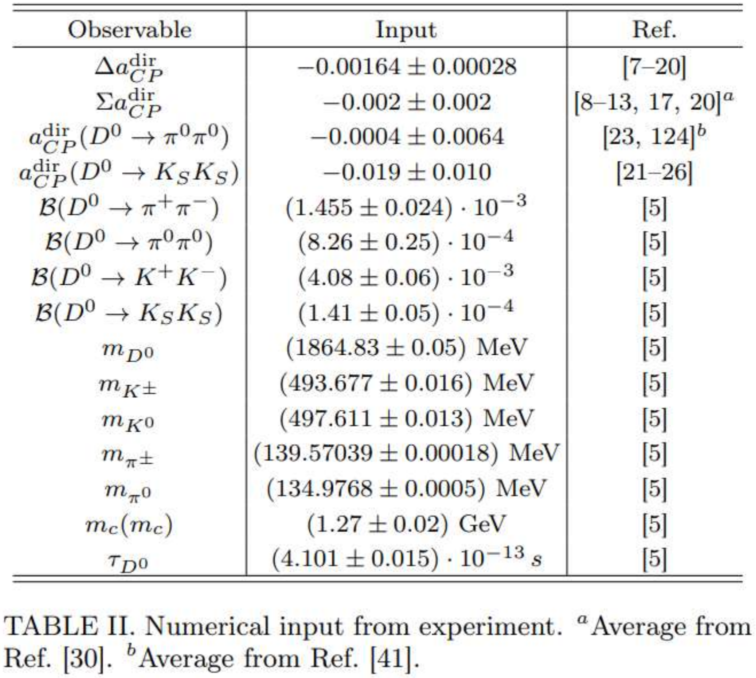
Department of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom

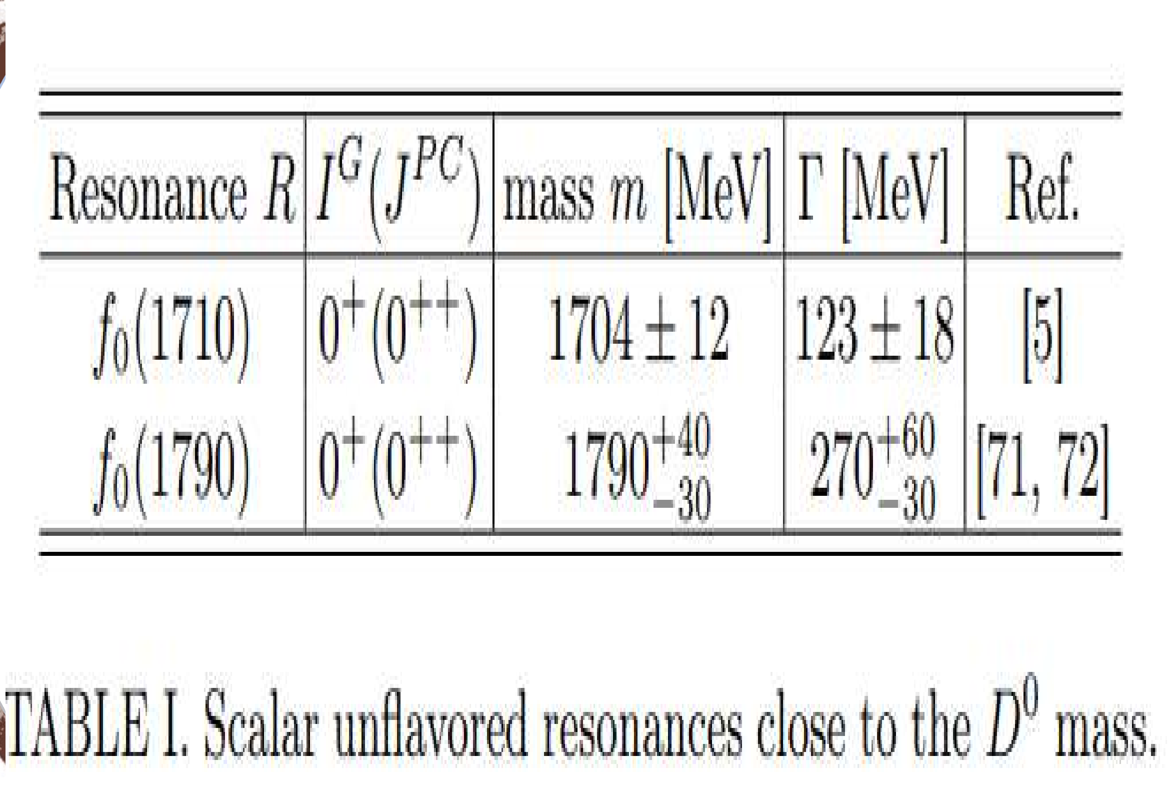
Amarjit Soni†
Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

arxiv 2105....



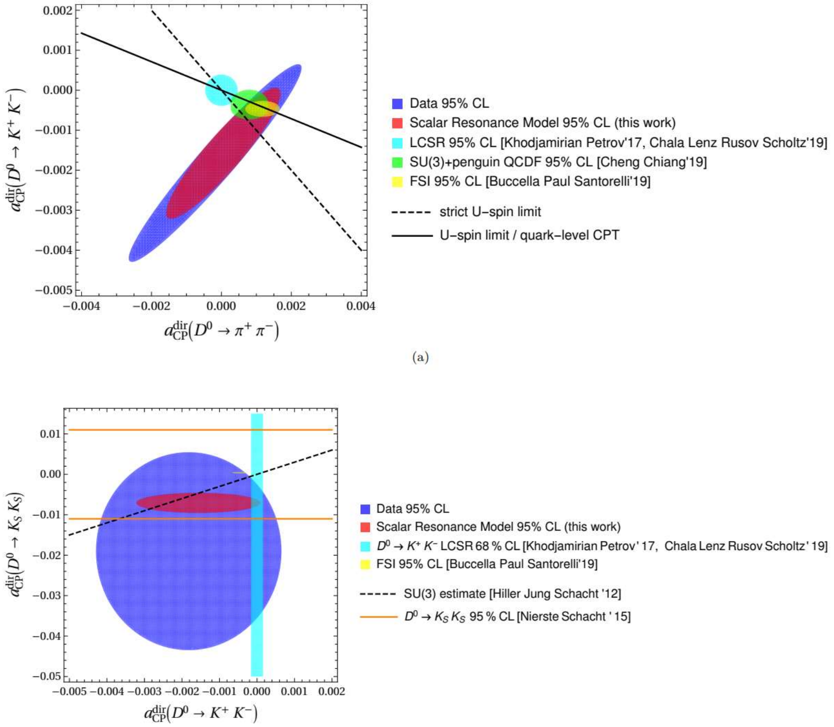
Observable	Input	Ref.
$\Delta a_{CP}^{\rm dir}$	-0.00164 ± 0.00028	[7–20]
$\Sigma a_{CP}^{\rm dir}$	-0.002 ± 0.002	[8–13, 17, 20][a]
$a_{CP}^{\rm dir}(D^0 \to \pi^0\pi^0)$	-0.0004 ± 0.0064	[23, 124][b]
$a_{CP}^{\rm dir}(D^0 \to K_S K_S)$	-0.019 ± 0.010	[21–26]
$\mathcal{B}(D^0 \to \pi^+\pi^-)$	$(1.455 \pm 0.024) \cdot 10^{-3}$	[5]
$\mathcal{B}(D^0 \to \pi^0\pi^0)$	$(8.26 \pm 0.25) \cdot 10^{-4}$	[5]
$\mathcal{B}(D^0 \to K^+K^-)$	$(4.08 \pm 0.06) \cdot 10^{-3}$	[5]
$\mathcal{B}(D^0 \to K_S K_S)$	$(1.41 \pm 0.05) \cdot 10^{-4}$	[5]
m_{D^0}	(1864.83 ± 0.05) MeV	[5]
$m_{K^\pm}$	(493.677 ± 0.016) MeV	[5]
m_{K^0}	(497.611 ± 0.013) MeV	[5]
$m_{\pi^\pm}$	(139.57039 ± 0.00018) MeV	[5]
m_{π^0}	(134.9768 ± 0.0005) MeV	[5]
$m_c(m_c)$	(1.27 ± 0.02) GeV	[5]
τ_{D^0}	$(4.101 \pm 0.015) \cdot 10^{-13}\,s$	[5]

TABLE II. Numerical input from experiment. [a] Average from Ref. [30]. [b] Average from Ref. [41].



Resonance R	$I^G(J^{PC})$	mass m [MeV]	Γ [MeV]	Ref.
$f_0(1710)$	$0^+(0^{++})$	1704 ± 12	123 ± 18	[5]
$f_0(1790)$	$0^+(0^{++})$	1790^{+40}_{-30}	270^{+60}_{-30}	[71, 72]

TABLE I. Scalar unflavored resonances close to the D^0 mass.

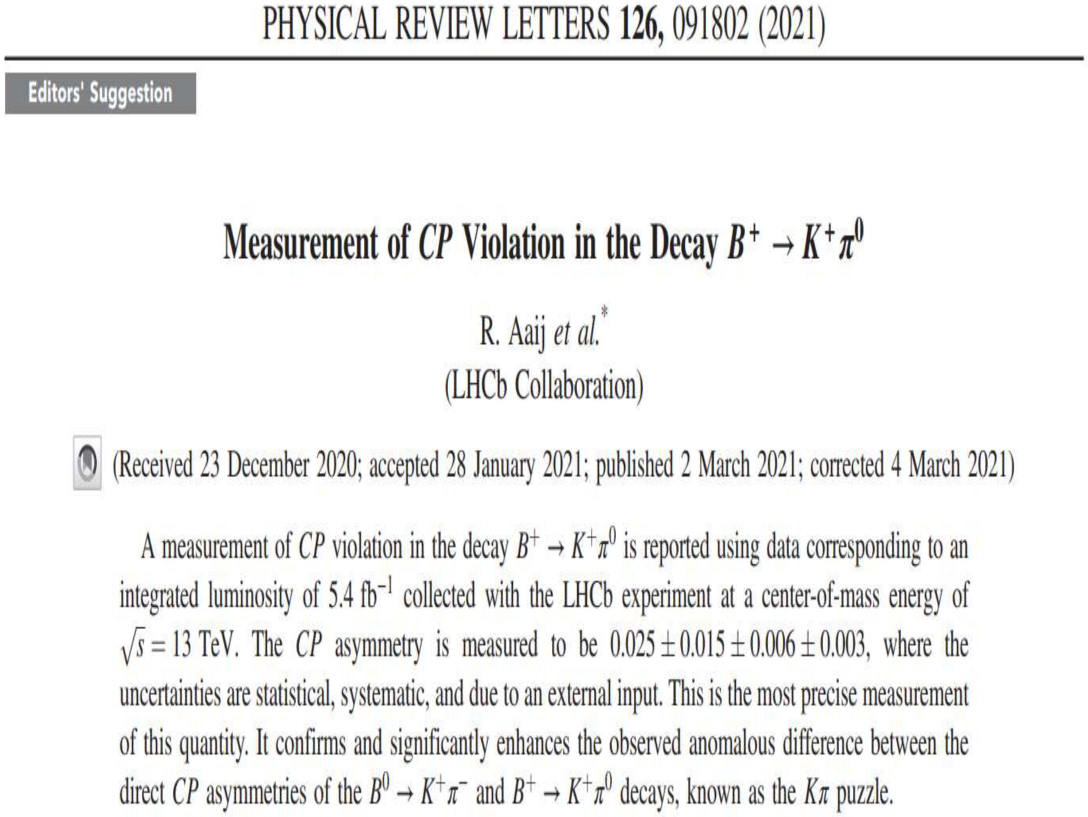


(a)

(b)

FIG. 2. Comparison of data and theory scenarios. We show several additional results from the literature, namely [Khodjamirian Petrov'17] [29], [Chala Lenz Rusov Scholtz'19] [28] [Cheng Chiang'19] [131] [Buccella Paul Santorelli '19] [52] [Hiller Jung Schacht'12] [39] and [Nierste Schacht '15] [27]. The LCSR bounds in (a) are interpreted as regions with central value at the origin. The shown bound on $a_{CP}^{\rm dir}(D^0 \to K_S K_S)$ from [Nierste Schacht'15] in (b) is the one-dimensional 95% CL bound. The shown LCSR bound on $a_{CP}^{\rm dir}(D^0 \to K^+ K^-)$ in (b) is the one-dimensional 68% CL bound. In all other cases, we construct the two-dimensional 95% CL region from the one-dimensional 68% CL regions by constructing a corresponding χ^2 and employing $\Delta\chi^2 \leq 5.99$, neglecting any correlations. Likewise, for our scalar resonance model, due to the currently large uncertainties of the input data for the scalar resonances, see Sec. IV , we do not calculate correlations, but overlay directly the implications of the (symmetrized) one-dimensional results, namely Eqs. (69), (70) for (a) and Eqs. (73), (74) for (b). Regarding the U-spin limit relation Eq. (75), we show the central value only.

Direct CP in the B-system



PHYSICAL REVIEW LETTERS **126,** 091802 (2021)

Editors' Suggestion

Measurement of *CP* Violation in the Decay $B^+ \to K^+\pi^0$

R. Aaij *et al.*[*]
(LHCb Collaboration)

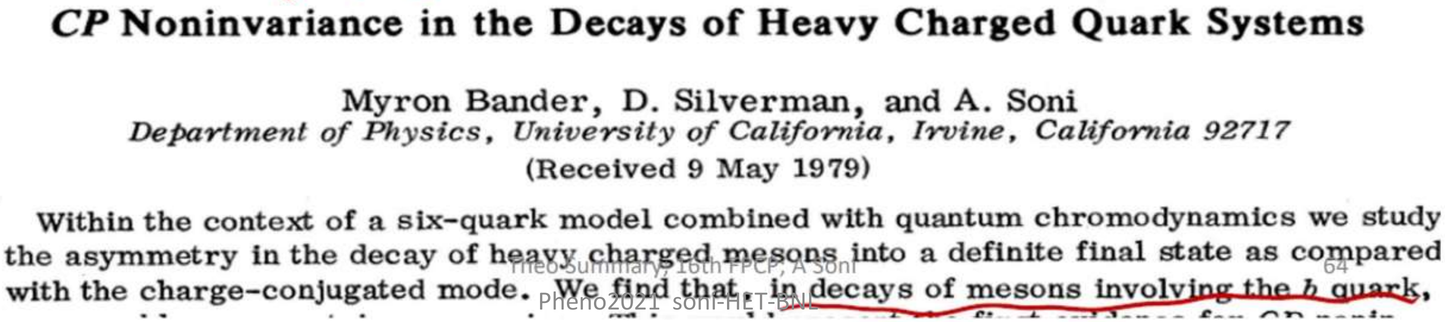
(Received 23 December 2020; accepted 28 January 2021; published 2 March 2021; corrected 4 March 2021)

A measurement of *CP* violation in the decay $B^+ \to K^+\pi^0$ is reported using data corresponding to an integrated luminosity of 5.4 fb^{-1} collected with the LHCb experiment at a center-of-mass energy of $\sqrt{s} = 13$ TeV. The *CP* asymmetry is measured to be $0.025 \pm 0.015 \pm 0.006 \pm 0.003$, where the uncertainties are statistical, systematic, and due to an external input. This is the most precise measurement of this quantity. It confirms and significantly enhances the observed anomalous difference between the direct *CP* asymmetries of the $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays, known as the $K\pi$ puzzle.

Dedicated to the memory of Myron Bander , who decades ago started
me off in the interesting and important path of Direct CP

My 1st paper
on B-physics

PRL



CP Noninvariance in the Decays of Heavy Charged Quark Systems

Myron Bander, D. Silverman, and A. Soni
Department of Physics, University of California, Irvine, California 92717

(Received 9 May 1979)

Within the context of a six-quark model combined with quantum chromodynamics we study the asymmetry in the decay of heavy charged mesons into a definite final state as compared with the charge-conjugated mode. We find that, in decays of mesons involving the *b* quark,

A great personal treat; thanks to

ADS: $B^{\pm} \to Dh^{\pm}, D \to \pi^{+}K^{-}$

$$\boxed{A^{\pi K}_{\mathrm{ADS}(K)} = -0.403 \quad \pm 0.056 \quad \pm 0.011}$$

8σ

Malcolm John@EW
MORIOND

Huge *direct CP* [tailor made] ~20 ago!
ADS PRL'97

[Recall $\epsilon' \sim 10^{-6}$!]

DESIGNED for MAXIMAL INTERFERENCE

DATA DRIVEN METHODS

Theo Summary; 16th F

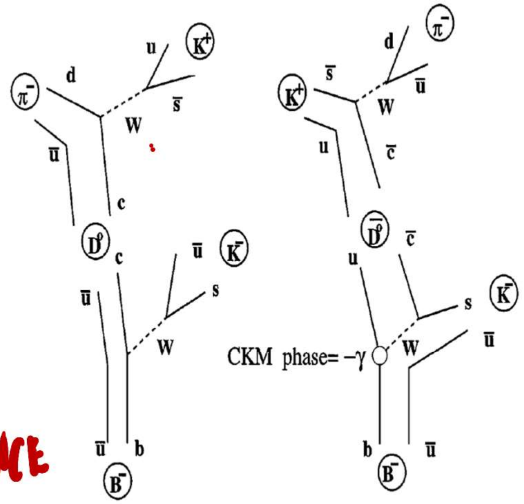


FIG. 1. Diagrams for the two interfering processes: B^- — K^-D^0 (color-allowed) followed by $D^0 \longrightarrow K^+\pi^-$ (doubl Cabibbo suppressed) and $B^- \longrightarrow K^-\bar{D}^0$ (color-suppressec followed by $\bar{D}^0 \longrightarrow K^+\pi^-$ (Cabibbo allowed).

ADS

hep-ph/000809

PRD~01

STILL Untapped potential in γ extraction using DALITZ Decays MODL Indep.

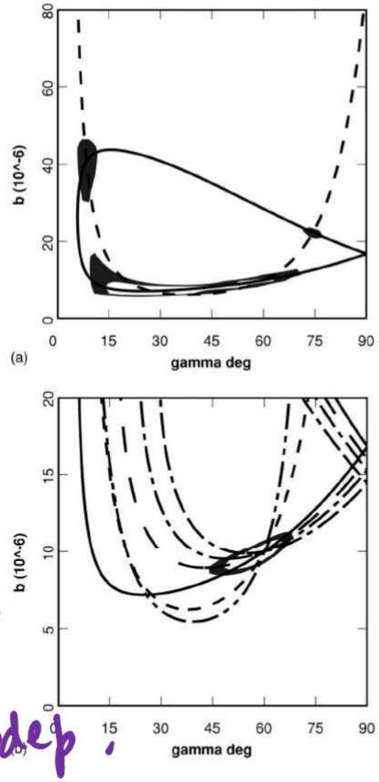


FIG. 3. (a) The likelihood distribution is shown as a function of γ and $b(K^*)$ assuming that $\tilde{N}_B^{3\sigma}=10^8$ with the branching ratios considered in Table II and assuming only the $K^+\pi^-$ and $K_s\pi^0$ modes are measured. The outer edge of the shaded regions correspond to 90% confidence while the inner edge corresponds to 68% confidence. The solid lines show the locus of points which give exactly the $K^+\pi^-$ results while the short dashed curve shows the points which give the $K_s\pi^0$ results. (b) The likelihood distribution as in (a) is shown assuming all of the modes in Table II are used. The solution for the $K^+\pi^-$ data is shown with the solid curve; that for the $K_S\pi^0$ data is shown with the short dashed curve; the one for the $K^+\rho^-$ data is shown with the long dashed curve; the one for the $K^+a_1^-$ data is shown with the dash-dot curve; the one for the $K_s\rho^0$ data is shown with the dash-dot-dot curve and the solution for the

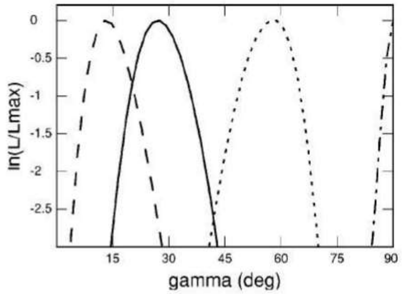


FIG. 4. The ratio between the the likelihood distribution and the maximum likelihood is shown as a function of γ with the parameters as in Fig. 3(b) except γ is taken to be 15° (dashed curve); 30° (solid curve); 60° (dotted curve); 90° (dash-dot curve).

It should be realized that three body states $K^+\rho^-$, $K_s\rho^0$ and $K^{*+}\pi^-$ can all lead to the common final state $K_s\pi^+\pi^-$. If one examines the distribution in phase space, then the vector resonances overlap to some extent and the channels will interfere with each other. In the following section, we will discuss how the additional information implicit in this situation can assist in extracting the value of γ.

$\leftarrow K_s\pi^+\pi^-$....

VI. USING THREE BODY DECAYS

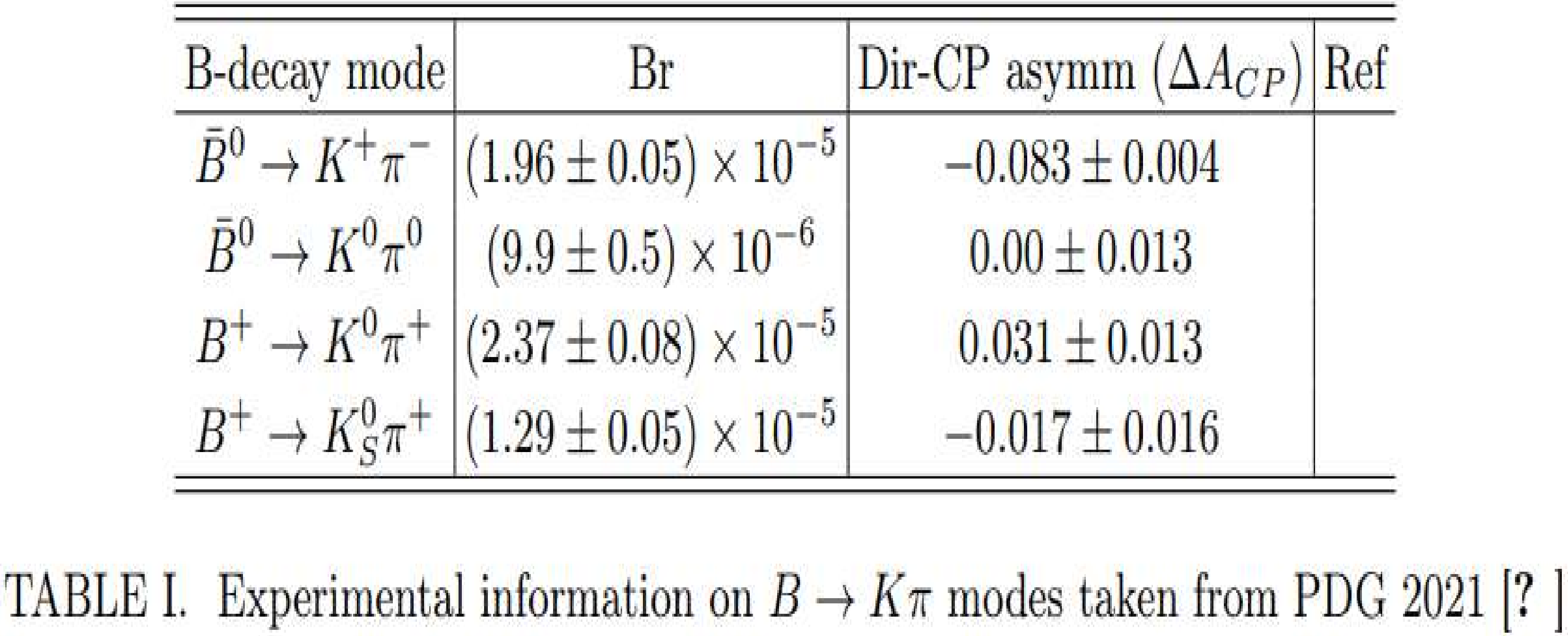
Here we will consider the generalizations of the two approaches considered in Sec. IV to the case of a three body decay. First of all, we can consider the three body decay as consisting of a number of quasi-two-body channels which we can regard as distinct modes and find a solution for $b(k)$ and γ. A second approach is to regard each point of the Dalitz plot as a distinct mode. We can then apply the inequalities Eqs. (30),(33) at each point. Since all of these inequalities must be true simultaneously, a very stringent bound can generally be placed on γ and $b(k)$. In fact we will argue that for at least some points this inequality is an equality so the limit given by such an argument should in fact give γ and $b(k)$.

As an example we will consider in particular the case of D^0, $\overline{D^0}\to K^+\pi^-\pi^0$. In this case the CBA decay $\overline{D^0}\to K^+\pi^-\pi^0$ has been experimentally studied by the E687 Collaboration [15]. The data they obtain are fit to an amplitude to a general multi-channel 3-body decay form:

$$\mathcal{M}(\overline{D^0}\to K^+\pi^-\pi^0)=a_0e^{i\delta_0}+\sum_i a_i\exp(i\delta_i)B(a,b,c|r)$$

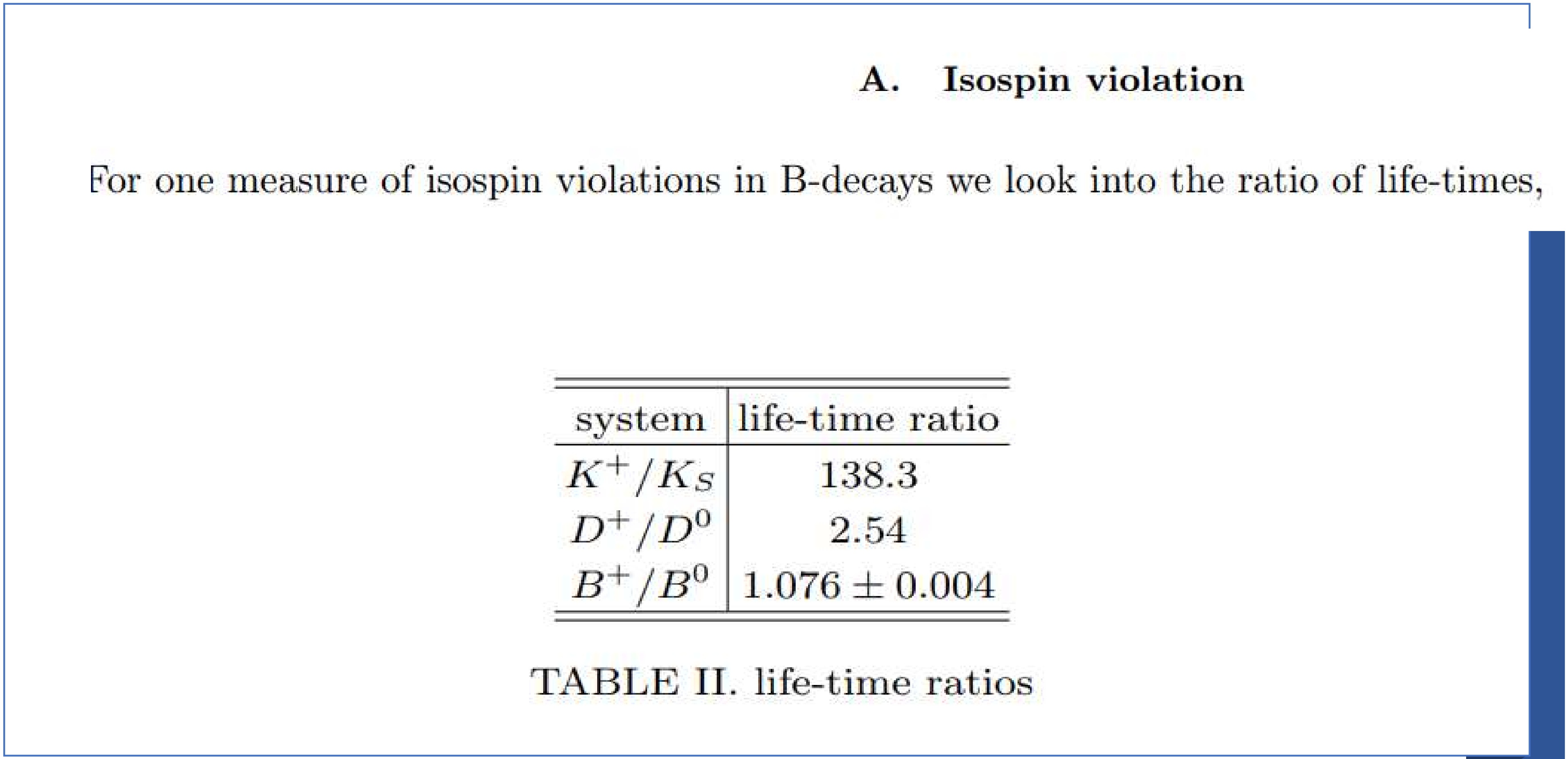
$D, \bar{D}^0 \to K^+K^-\pi^0$

FNAL E687



B-decay mode	Br	Dir-CP asymm (ΔA_{CP})	Ref
$\bar{B}^0 \to K^+\pi^-$	$(1.96 \pm 0.05) \times 10^{-5}$	-0.083 ± 0.004	
$\bar{B}^0 \to K^0\pi^0$	$(9.9 \pm 0.5) \times 10^{-6}$	0.00 ± 0.013	
$B^+ \to K^0\pi^+$	$(2.37 \pm 0.08) \times 10^{-5}$	0.031 ± 0.013	
$B^+ \to K_S^0\pi^+$	$(1.29 \pm 0.05) \times 10^{-5}$	-0.017 ± 0.016	

TABLE I. Experimental information on $B \to K\pi$ modes taken from PDG 2021 [?]



A. Isospin violation

For one measure of isospin violations in B-decays we look into the ratio of life-times,

system	life-time ratio
K^+/K_S	138.3
D^+/D^0	2.54
B^+/B^0	1.076 ± 0.004

TABLE II. life-time ratios

Summary

- **Significant progress in K=> pi pi , Delta I=1/2 Rule and eps' , 1st principles lattice calculations**

For eps' current accuracy is around 35% ….Major effort underway to improve this calculation…May take 2-3 years

For D0 decays, nearby scalar resonances f0(1710) and f0(1790) have significant influence and it appears observed Delta ACP is consistent with the SM; unfortunately need better expt info esp on f0(1790)

- **Effort underway to tackle dir CP puzzles in B=>K pi**