Understanding charm CP

Amarjit Soni
HET-BNL

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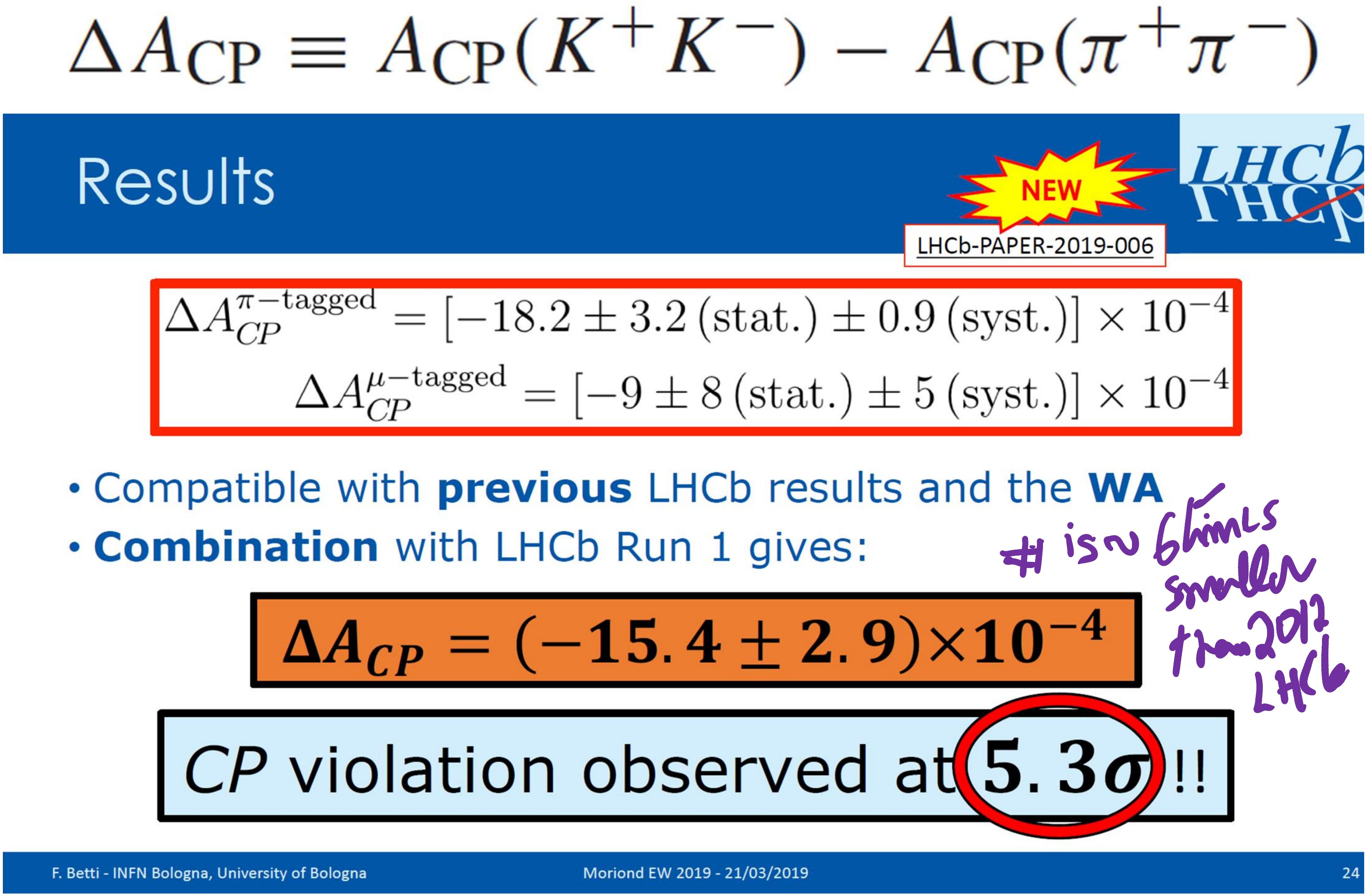
Outline

- Recently, LHCb exciting obs of ΔACP EW Moriond March 2019
- Naturalness reasoning strongly suggests other BSM-CP phase(s) must exist. To discern computations essential
- CPV represents an imp. avenue for searching new pheno but precise calculations are highly desirable
- Crude estimate of ΔACP → 1905.00907
- Propose a specific mechanism for understanding ΔACP
- Many testable implications
- This mechanism points to new difficulties for first priciples (lattice) calculations addressing ΔACP
- Suggest mode(s) for precision testing the SM-CKM
- Lattice feasibility
- Summary + Outlook



$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

Results

NEW

LHCb-PAPER-2019-006

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

- Compatible with **previous** LHCb results and the **WA**
- **Combination** with LHCb Run 1 gives:

$$\boxed{\boldsymbol{\Delta A_{CP} = (-15.4 \pm 2.9)\times 10^{-4}}}$$

CP violation observed at **5.3σ** !!

is ~ 6 times smaller than 2012 LHCb

F. Betti - INFN Bologna, University of Bologna Moriond EW 2019 - 21/03/2019 24

CP violation history

BNL-COLUMBIA

1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
***CP* violation in K**
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

BNL
Indirect CP
$\sim 10^{-3}$

ϵ'_K Direct $\sim 10^{-6}$
CERN/FNAL

1973
The CKM matrix
M. Kobayashi and
T. Maskawa

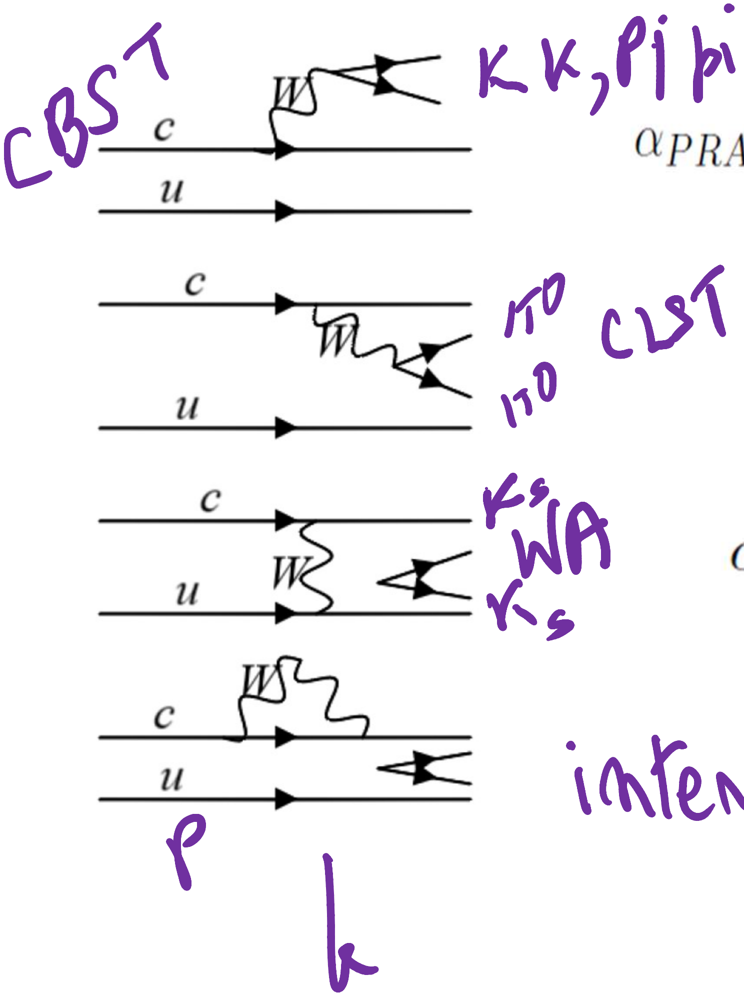
2001
Beauty particle
***CP* violation in**
meson decays
BaBar and Bell
collaborations

2019
Charm partic
***CP* violation**
meson decay
LHCb collabo

Alas, we cannot compute!

- **Sadly calculations of Direct CP remain a challenge for theory; we are not able to calculate with any precision [eps' an exception as a result of over 3 decades of concerted lattice effort]. As a rule, we can just give crude (QCD) model-dependent estimates..**
- **Essential ingredient is CP-conserving scattering phases & usually complicated non-perturbative effect on weak decays….difficult for the lattice in general**

BASICS of DIRECT CP Asy



$$\alpha_{PRA} = \mathcal{B}[\mathcal{I} \to \mathcal{F}] - \mathcal{B}[\bar{\mathcal{I}} \to \bar{\mathcal{F}}]/\mathcal{B}[\mathcal{I} \to \mathcal{F}] + \mathcal{B}[\bar{\mathcal{I}} \to \bar{\mathcal{F}}]$$

$$A_{hh} = \lambda T_{hh} + \lambda^5 P_{hh} e^{i[\overset{+}{\delta_{st}} + \overset{-}{\eta_{wk}}]}$$ due CPT

$\to$ PRA

$$\alpha_{hh} = 2\lambda^4 P_{hh} \sin(\delta_{st}) \sin(\gamma)/\underset{\downarrow \sqrt{Br}}{T_{hh}}$$

interferes with CBST

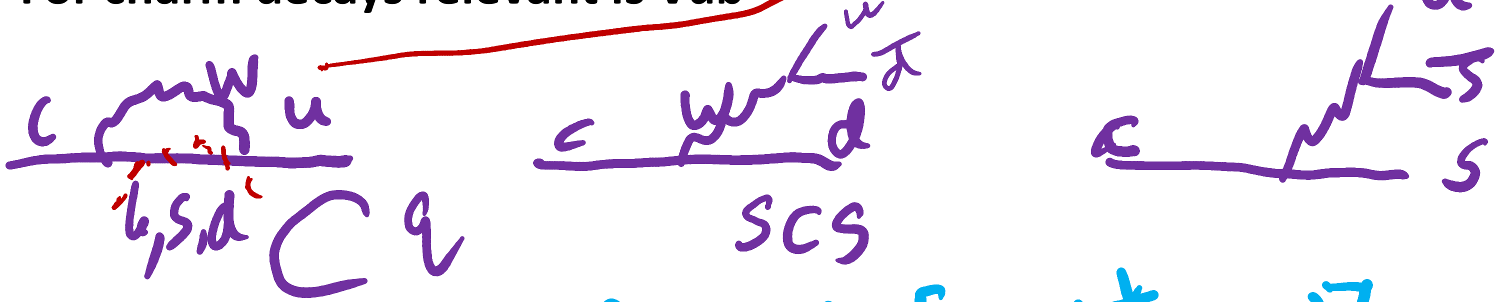
$V_{cb}V^*_{ub}$ CP-odd phase

CRUDE ESTIMATE

ASeCKM 2018

SM expectation…DCP

- Dir CP….. See Bander, Silverman + AS, PRL 1979 for DCP when → non-perturbative mq >> lamda_QCD…anticipate large corrections for charm from s-quark[K-decays]
- Key points: Penguin-Tree interference; SCS modes……Hall mark of BSS'79
- Need suitable simple changes
- SM-dominant CKM phase either in Vub or in Vtd → $m_c^2 > 4[m_s^2, m_d^2]$
- For charm decays relevant is Vub



4CLA → $\mathrm{DCP} \sim \dfrac{\mathrm{Im}[V_{cb} V_{ub}^{*} * \lambda]}{\lambda^2} \sim \lambda^4 \sim 10^{-3}$

→ $K^+K^-, \pi^+\pi^-$

may be enhanced a lot by CLS e.g. $K_S K_S$

$< N \times 10^{-3} \lesssim 10^{-2}$!!

↑ Very DIFFICULT to reach in SM

Lattice difficulties for ΔACP

- **mD~1.865 GeV; Br [D=> K^+ K^-] ~0.4%**

much larger Br to multiparticle states…difficult on the lattice….see Hansen and Sharpe, PRD'12.

- **However, strictly speaking ΔACP requires only difference between KK and pipi states.**
- **Therefore, optimistically, one may hope for appreciable cancellation between multiparticle states; i.e U-spin or SU(3) may provide a basis for such a cancellation.**
- **But unlikely to be viable as will be explained.**

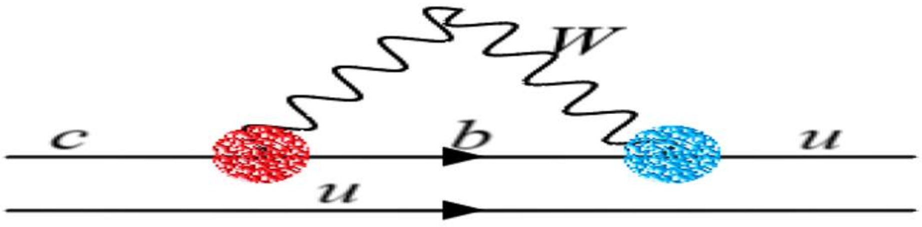
Interplay with resonances

- Charm region has many resonances

- Resonances that have appreciable Br to KK & pi pi are relevant
- In particular (ps) scalar resonances
- These can enter the weak decay dynamics via the penguin H_eff

b-penguin

- b-penguin fig



Penguin Hamiltonian

- Since mb>>Lambda_QCD, we can integrate it out along with W and get the familiar, H_eff:
- Heff = Ci Oi

$$O_3=(\bar{c}_\alpha u_\alpha)_{V-A}[(\bar{u}_\beta u_\beta)_{V-A}+(\bar{d}_\beta d_\beta)_{V-A}+(\bar{s}_\beta s_\beta)_{V-A}+(\bar{c}_\beta c_\beta)_{V-A}]\ ,$$

$$O_4=(\bar{c}_\alpha u_\beta)_{V-A}[(\bar{u}_\beta u_\alpha)_{V-A}+(\bar{d}_\beta d_\alpha)_{V-A}+(\bar{s}_\beta s_\alpha)_{V-A}+(\bar{c}_\beta c_\alpha)_{V-A}]\ ,$$

$$O_5=(\bar{c}_\alpha u_\alpha)_{V-A}[(\bar{u}_\beta u_\beta)_{V-A}+(\bar{d}_\beta d_\beta)_{V+A}+(\bar{s}_\beta s_\beta)_{V+A}+(\bar{c}_\beta c_\beta)_{V+A}]\ ,$$

$$O_6=(\bar{c}_\alpha u_\beta)_{V-A}[(\bar{u}_\beta u_\alpha)_{V+A}+(\bar{d}_\beta d_\alpha)_{V+A}+(\bar{s}_\beta s_\alpha)_{V+A}+(\bar{c}_\beta c_\alpha)_{V+A}]\ ,$$

See Abbott, Sikivie, Wise '80; Goldman+Grinstein '89

Buchalla, Buras, Lautenbacher '96

A.S. 1905.00907 Penguin Ops & Resonance Coupling

O_5 & O_6 are LXR $\Rightarrow -2[S+P]\times[S-P]$

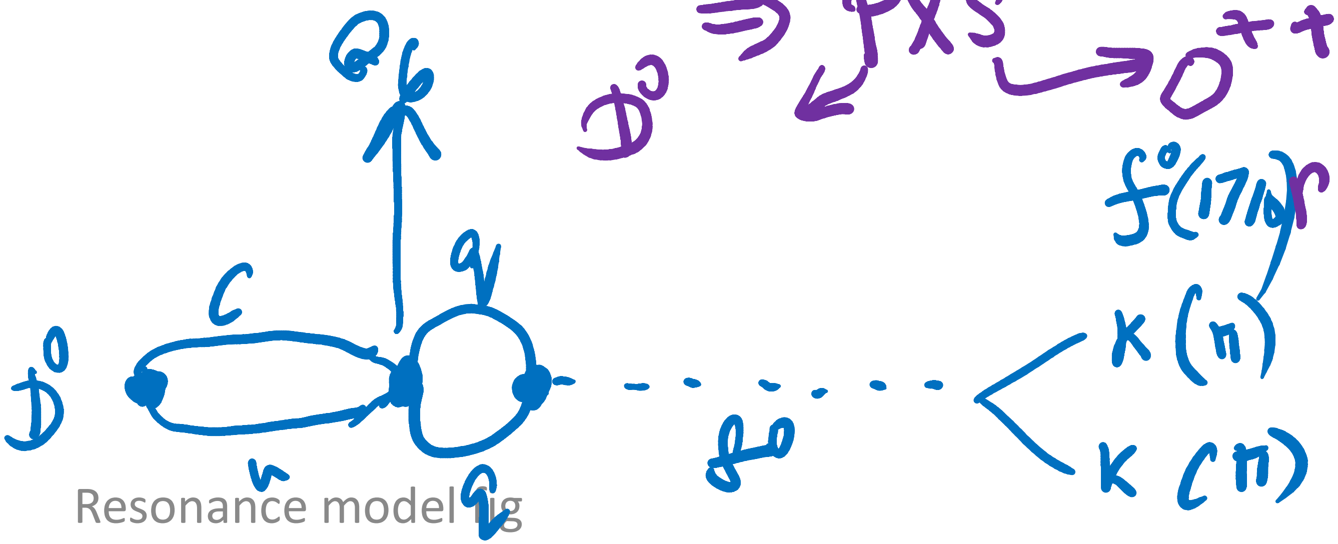
$\Rightarrow P \times S \rightarrow 0^{++}$ $m_{f_0} = 1723$ MeV

D^0

$f^0(1710)$ $\Gamma \sim 150$ MeV

$\Rightarrow K\bar{K}$

$\pi\pi$



Resonance model fig

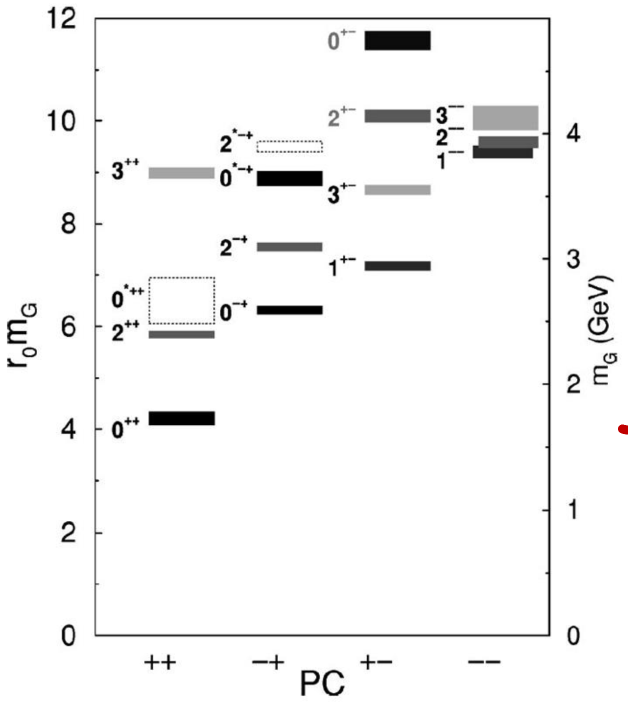
See PDG Live

BR $f_0 \rightarrow K\bar{K} \sim 40\%$

$\frac{(f_0 \rightarrow \pi\pi)}{(f_0 \rightarrow KK)} \sim 0.4$

S,P Glueballs & their SU3 breakings

Morningstar
+
Peardon,
Review'99



← P

← S ~1.7GeV

FIG. 8. The mass spectrum of glueballs in the pure SU(3) gauge theory. The masses are given in terms of the hadronic scale r_0 along the left vertical axis and in terms of GeV along the right vertical axis (assuming $r_0^{-1} = 410$ MeV). The mass uncertainties indicated by the vertical extents of the boxes do *not* include the uncertainty in setting r_0. The locations of states whose interpretation requires further study are indicated by the dashed open boxes.

PDG gives Br's of D0

K^+K^-	$(3.97 \pm 0.07) \times 10^{-3}$
$\pi^+\pi^-$	$(1.407 \pm 0.025) \times 10^{-3}$

Ratio of $\frac{Br(D^0 \to K^+K^-)}{Br(D^0 \to \pi^+\pi^-)} \simeq 2.82$

Large SU3 breaking known for long

Mystery for long

$(f_K/f_\pi)^2 \approx 1.7$ explains a part

New understanding of an old issue

Cornwall + AS, PRD '84; c also Cheng + Chiang 1001.0487

$$\mathscr{L}_{\rm eff}=-\bar{\psi}(G_S S+i\gamma_5 G_P P)\psi+\cdots , \qquad (3.2)$$

$$G_S=\frac{M_Q}{2\langle S\rangle}$$

$$\langle S\rangle\simeq 130\ \mathrm{MeV}\ . \qquad (1.3)$$

Couplings to quarks are proportional to quark mass

S, P are low lying gluonia 0^{++} & 0^{-+}

f0 decay to KK & pi pi

- **PDG live gives**
- **Br [f0 => pi+ + pi-]/Br[f0 => K+ + K-] ~ 0.4**

enhancing the SU3 breaking decays of the D0

Imp implication of Resonances for CP

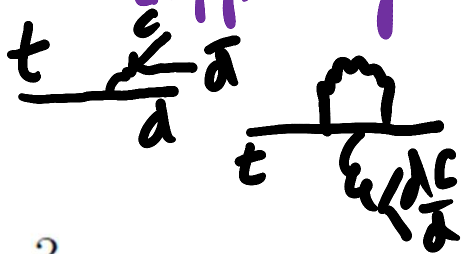
WHEN DEALING WITH FINAL STATES THAT ARE DOMINATED BY RESONANCES, THEN THE WIDTH OF THE RESONANCE PROVIDES THE "STRONG"-CP-EVEN PHASE NEEDED FOR COMPUTING PRA…1ST ILLUSTRATED BY EILAM, HEWETT + AS, PRL'91

Resonance idea

For basic idea See Eilam, Hewett + AS PRL 1991

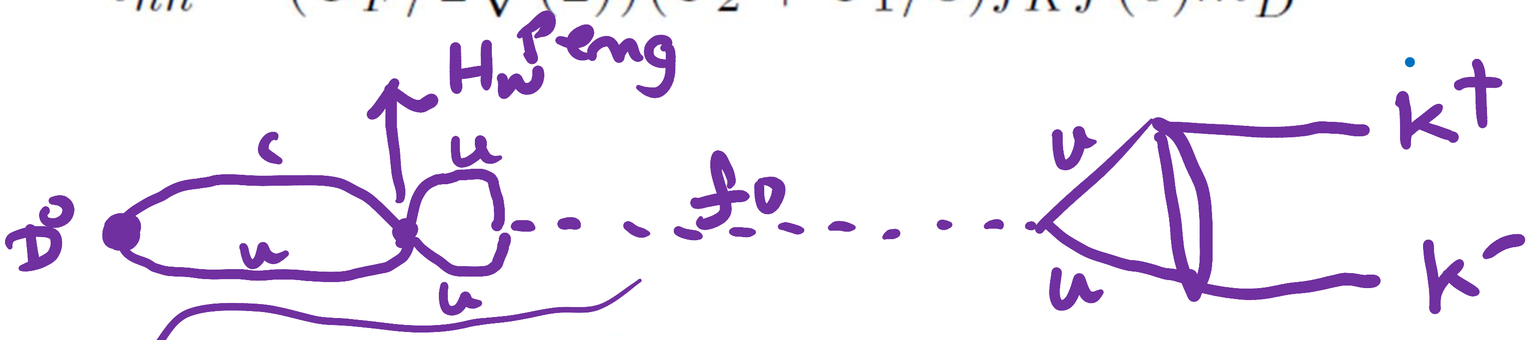
[Appld to top decays]

See also Atwood + AS ZP 1994



For $D^0 \to KK$

$$t_{hh} = (G_F/2\sqrt(2))(C_2 + C_1/3) f_K f(0) m_D^2$$



$$P_{hh} = (G_F/2\sqrt(2)) C_6 A^2 \sqrt(\rho^2 + \eta^2)$$

$$(f_D m_D/m_c) K_f m_f^2 \qquad (7)$$

$[m_D^2 - m_f^2 + i m_f \Gamma_f]$

$K_f \sim 3.7$

$$\alpha_{K^+K^-} \approx 5.5 \times 10^{-4}$$

Nice paper!!

$\alpha_{\pi^+\pi^-} = -1.06 * \alpha_{K^+K^-}$; $\Delta A_{CP} \simeq 12 \times 10^{-4}$

CahOH-N Li, C.D Lu + Fu-S Yu PRD86, 2012

Interplay of CPT & resonant CP

Because of the CPT constraint that life-time of particle must equal to that of its antiparticle, we must have,

$$\sum_X \Delta\Gamma(X) = 0 \tag{9}$$

where X are the various final states that emerge from the decays of D^0 and

$\Delta\Gamma(X) = \Gamma(D^0 \to X) - \Gamma(\overline{D}^0 \to \overline{X})$

Since at the quark level in charm decays there are only two channels, $c \to u\bar{d}d$ and $c \to u\bar{s}s$, this means because of CPT we must have [20, 21],

$$\Delta\Gamma(c \to u\bar{d}d) = -\Delta\Gamma(c \to u\bar{s}s) \tag{10}$$

At the meson level, it is suggested [20] that this materializes into,

$$\Delta\Gamma(\pi^+\pi^-) = -\Delta\Gamma(K^+K^-) \tag{11}$$

Using the tree dominance, as emphasized above, one then arrives at the relation,

$$\alpha_{K^+K^-} \propto -\alpha_{\pi^+\pi^-}/\sqrt{2.8} \tag{12}$$

where, we have taken for simplicity that the two Brs differ by about $\sqrt{2.8}$ [18].

However, f-dominance of the penguin amplitude, in the h h channel that is our central focus, appearing in the numerator of (4) modifies this expectation appreciably. This is because, it appears that [5].

$$Br(f_0 \to \pi\pi)/Br(f_0 \to KK) \approx 0.4 \tag{13}$$

- See ATWOOD+AS PTEP 2013

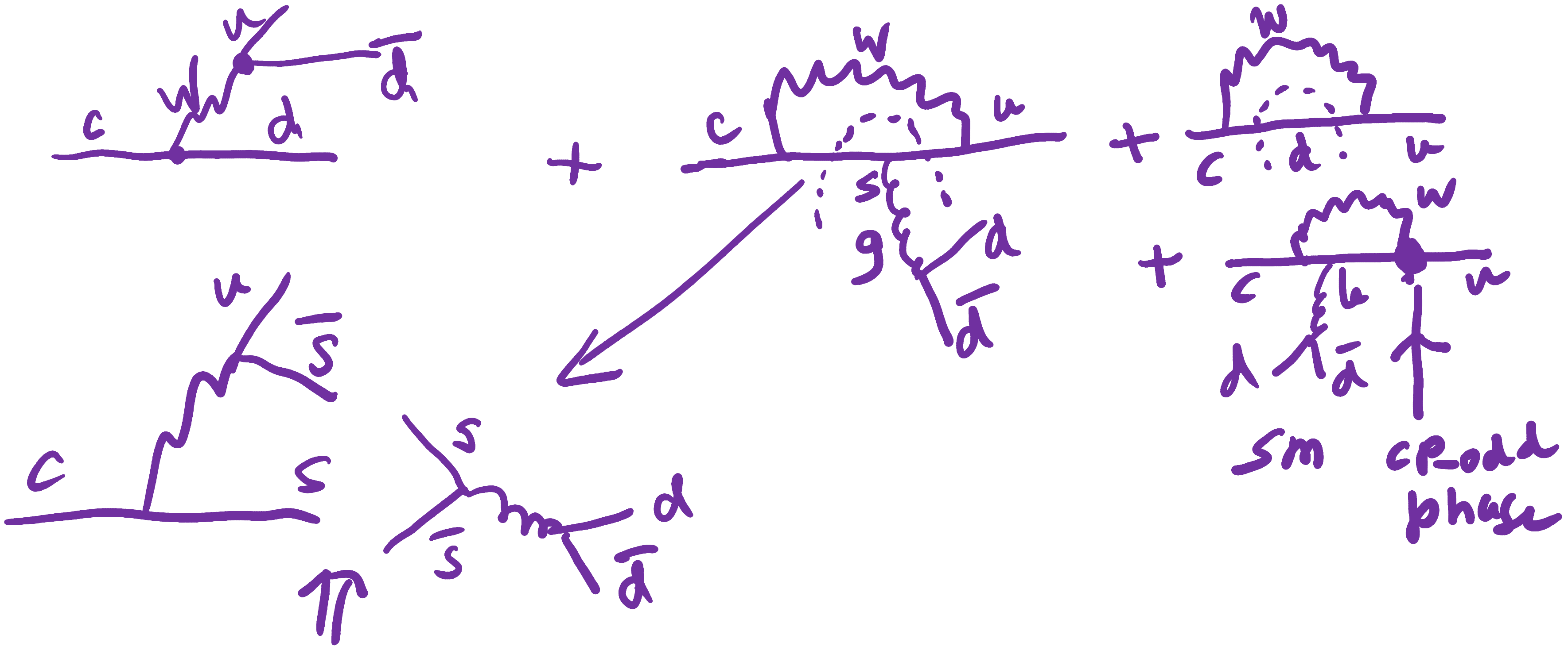
$c \to u\bar{d}d,\ u\bar{s}s$

$\Leftarrow$

In charm decays $T >> P \Rightarrow$

$\alpha_{PRA} \propto \frac{1}{\sqrt{Br}}$

PDG LIVE



On-shell rescattering phase
CP-even phase $\Rightarrow$ Total amplitude for $c \to u d \bar{d}$ is complex

central value

$$-\alpha_{\pi^+\pi^-}/\alpha_{K^+K^-} = \sqrt{(0.4 \times 2.8)} \approx 1.06$$

I

Large uncertainty (PDG)

Mode	BR (10^{-3})	Current PRA bound (10^{-2})
K^+K^-	$3.97 \pm .07$	-0.07 ± 0.11
K_sK_s	0.17 ± 0.012	-0.4 ± 1.5
$\pi^+\pi^-$	1.407 ± 0.025	0.13 ± 0.14
$\pi^0\pi^0$	0.822 ± 0.025	0.0 ± 0.6

outdated

outdated

$$\alpha_{K_sK_s}/\alpha_{K^+K^-} \approx \sqrt{(23/4)}$$
$$\approx 2.4$$

II

$$\alpha_{\pi^0\pi^0} = 1.3\ \alpha_{\pi^+\pi^-}$$

III

CANDIDATES FOR PRECISION TEST: NEEDS TO BE EXPERIMENTALLY ACCESSIBLE AND BE ALSO AMENABLE TO PRECISE LATTICE CALCULATIONS

Candidate for precision test: CPV in D0=> gamma + [phi => K^+ K^-]

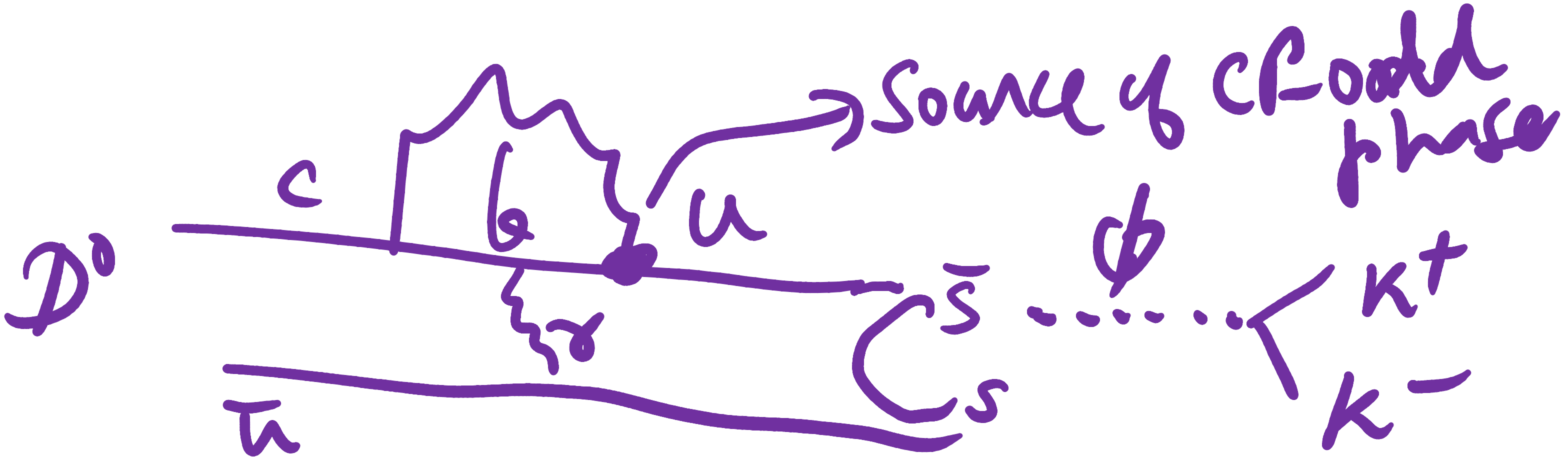
- **Requires KK scattering phases for CM energy below around 1 GeV**

- **Dfferential photon energy spectrum can be used for precision test**
- **Integrated BR ~ 2.74 pm 0.19 X10^-5 well measured**
- **Belle-II expected ~10^10 D's/yr …precise measurement of differential spectrum is clearly feasible**

Production mechanisms

- Dominant production: Tree ~ Lambda

- Interfering penguin ~Lamda^5



Feasibility of lattice extraction of KK phases in ~ 1 GeV energy region

- Good reason to expect that this is doable: see works of JLAB [Briceno et al PRL 2017], RBC-UKQCD [Tainle Wang, Chris Kelly, Aaron Meyer, Mattia Bruno, Dan Hoying, David Murphy et al, Lat2018 & 2019 presentations] paper(s) in preparation; see also G. Rendon et al Lat2018
- At ~ 1 GeV or below, relevant to radiative D0 decays, error due to KKpipi, 4 pi contamination likely small

If needs be can focus on higher E_γ so as to reduce contamination from 4 pi's

BRIEF REMARKS ON RADIATIVE CHARM DECAYS

- **New class of radiative decays…interesting nearby resonances relevant for radiative transitions: [see PDGLive]:would be useful to target these to confirm role of resonances**

$\phi(1680)$, $\Gamma \sim 150$ mev $\Rightarrow K\bar{K}^*(892)$

$\rho(1702)$, $\Gamma \sim 250$ mev $\to \rho\pi\pi$, 4π ….

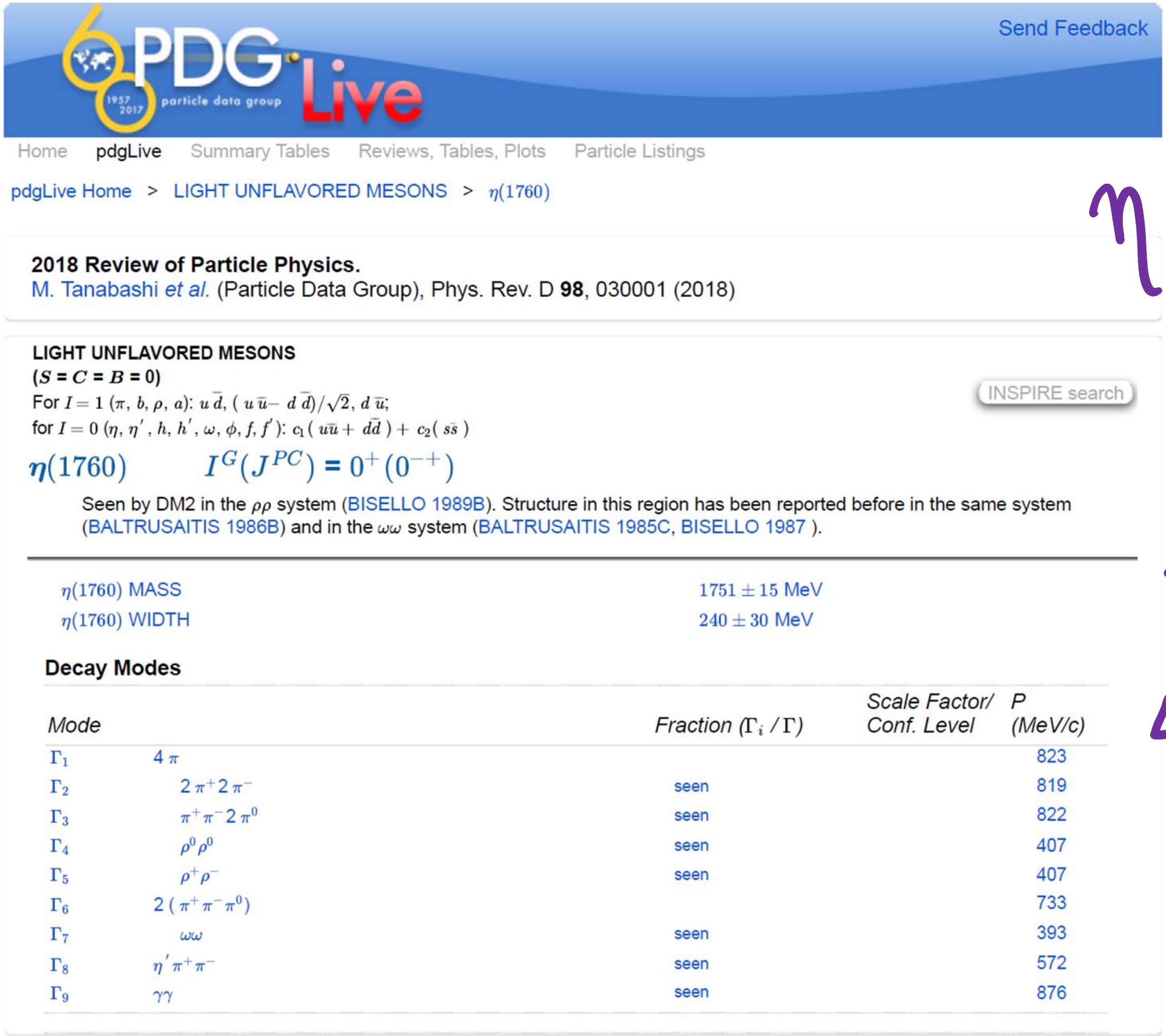
$D^0 \to \gamma\,\rho(1702)$, $\gamma\,\phi(1680)$ $E_\gamma \lesssim 300$ MeV ⇐

- Best candidates for precision tests of the SM

$D^0 \to \gamma\,\rho(770)$, $\gamma\,\phi(1020)$ $BR \sim 10^{-4} - 10^{-5}$

$\gamma_\mu(1-\gamma_5) \times \gamma_\mu(1+\gamma_5) \xrightarrow[FT]{} P \times P$

Another important resonance nearby



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2018 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

LIGHT UNFLAVORED MESONS
($S = C = B = 0$)
For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ ($\eta, \eta', h, h', \omega, \phi, f, f'$): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

INSPIRE search

$\eta(1760)$ $I^G(J^{PC}) = 0^+(0^{-+})$

Seen by DM2 in the $\rho\rho$ system (BISELLO 1989B). Structure in this region has been reported before in the same system (BALTRUSAITIS 1986B) and in the $\omega\omega$ system (BALTRUSAITIS 1985C, BISELLO 1987).

$\eta(1760)$ MASS	1751 ± 15 MeV
$\eta(1760)$ WIDTH	240 ± 30 MeV

Decay Modes

	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P (MeV/c)
Γ_1	4π			823
Γ_2	$2\pi^+ 2\pi^-$	seen		819
Γ_3	$\pi^+\pi^- 2\pi^0$	seen		822
Γ_4	$\rho^0\rho^0$	seen		407
Γ_5	$\rho^+\rho^-$	seen		407
Γ_6	$2(\pi^+\pi^-\pi^0)$			733
Γ_7	$\omega\omega$	seen		393
Γ_8	$\eta'\pi^+\pi^-$	seen		572
Γ_9	$\gamma\gamma$	seen		876

$\eta(1760)$

0^-

Eng Asy

TCA

4π, $\eta'\pi\pi$

$\rho^0\rho^0$ ....

$R_D(*)$ ANOMALY AND NEW PHYSICS IN B-PENGUIN CONTRIBUTION TO CHARM DECAYS [18]

b c $\Rightarrow R_{D(*)}$

Another reason fa precision test

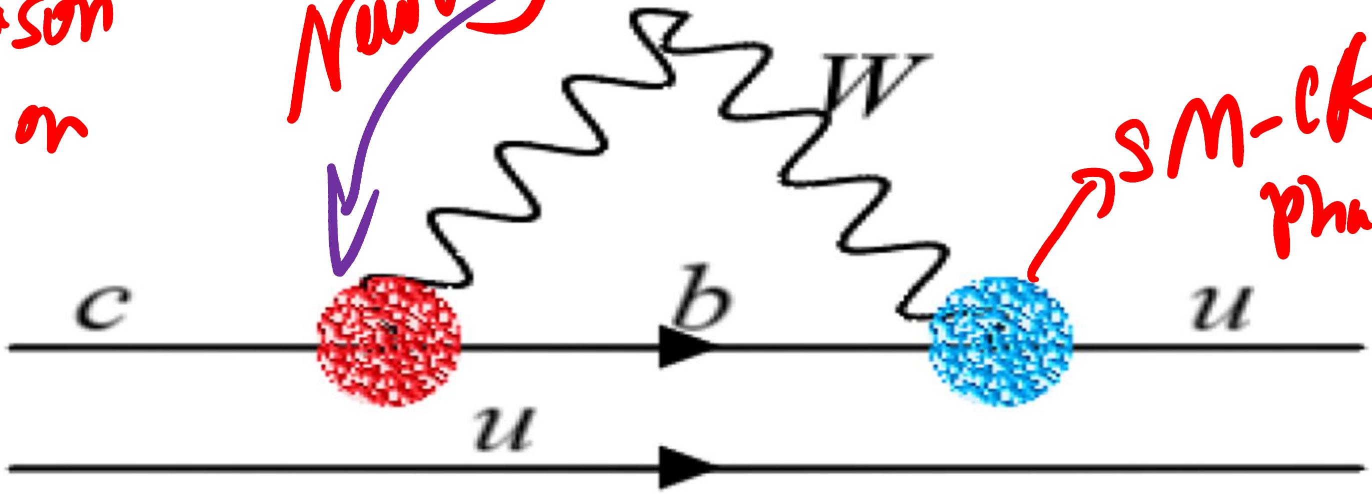


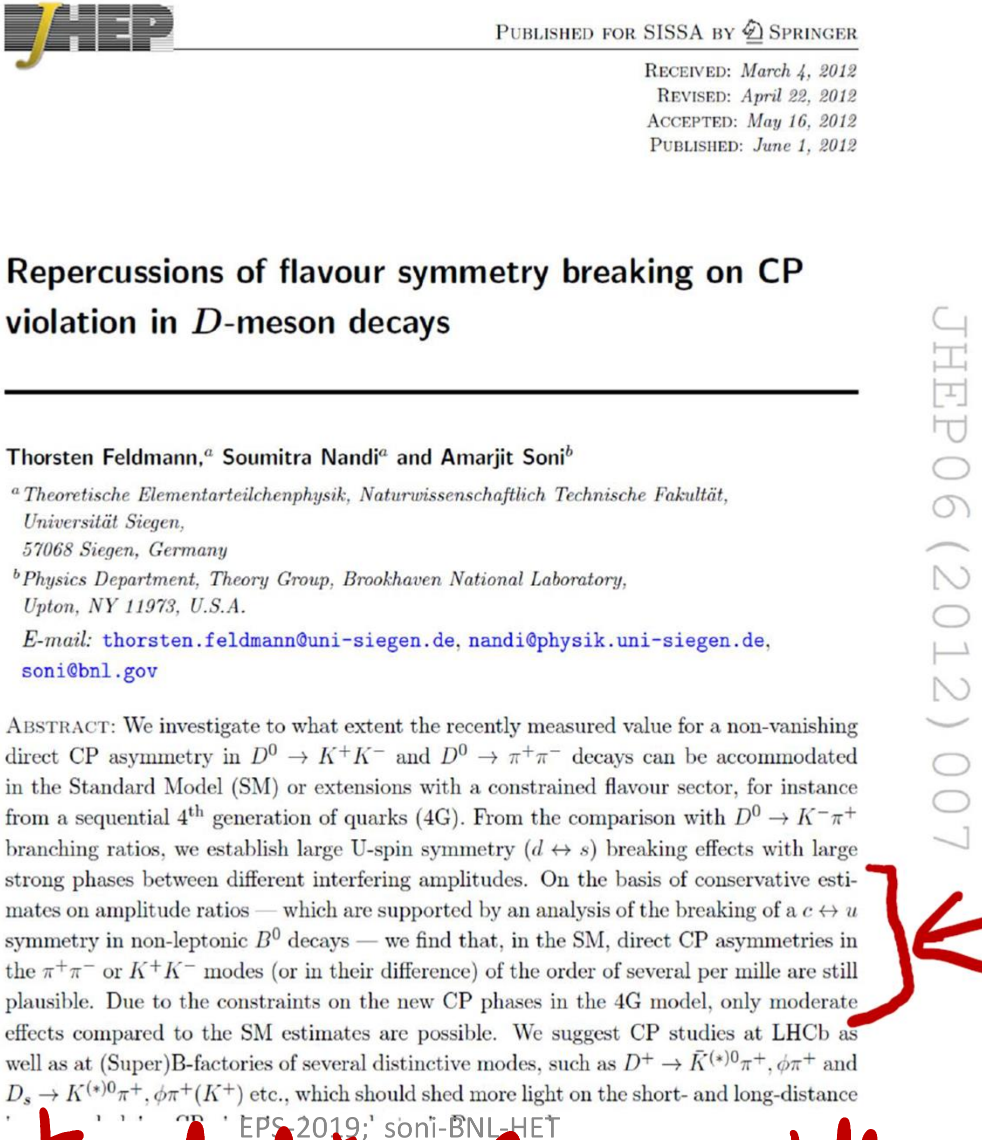
FIG. 2. b-penguin in charm decay; left c-b (red) vertex may have a CP-odd phase endowed by new physics affecting $R_{D(*)}$ whereas the right b-u (blue) vertex contains the SM-CKM phase.

Summary + outlook

- **Charm region is rich with resonances**
- **Some of these are expected to play an important role in driving CP asymmetries, PRA, energy (3 or more particle FS), TCA (4 or more spin-less)**
- **New class of radiative decays with photon energy < ~300 MeV to resonances which cascade down to several diff FS, such as KK, pi pi, eta’(eta, pi0) pi pi….**
- **Resonant mechanism leads to predictions relating PRA’s in 2Ks, pi^+pi^-, and 2 pi0 to that in K^+ K^-**
- **Mixing of D0 weak decays with f0 accounts roughly for the observed size of ΔACP & large SU3 breaking seen for long. Resonances complicate addressing of ΔACP by lattice methods.**
- **Important target should be precise CP-tests for SM-CKM. For this purpose, it is suggested that the best candidate for precision test are CPV asymmetries (~O .1%), Br ~10^-5: D0=>γϕ with ϕ => K+ K-**

PRA as well as energy(γ) asy are expected

XTRAS



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Repercussions of flavour symmetry breaking on CP violation in D-meson decays

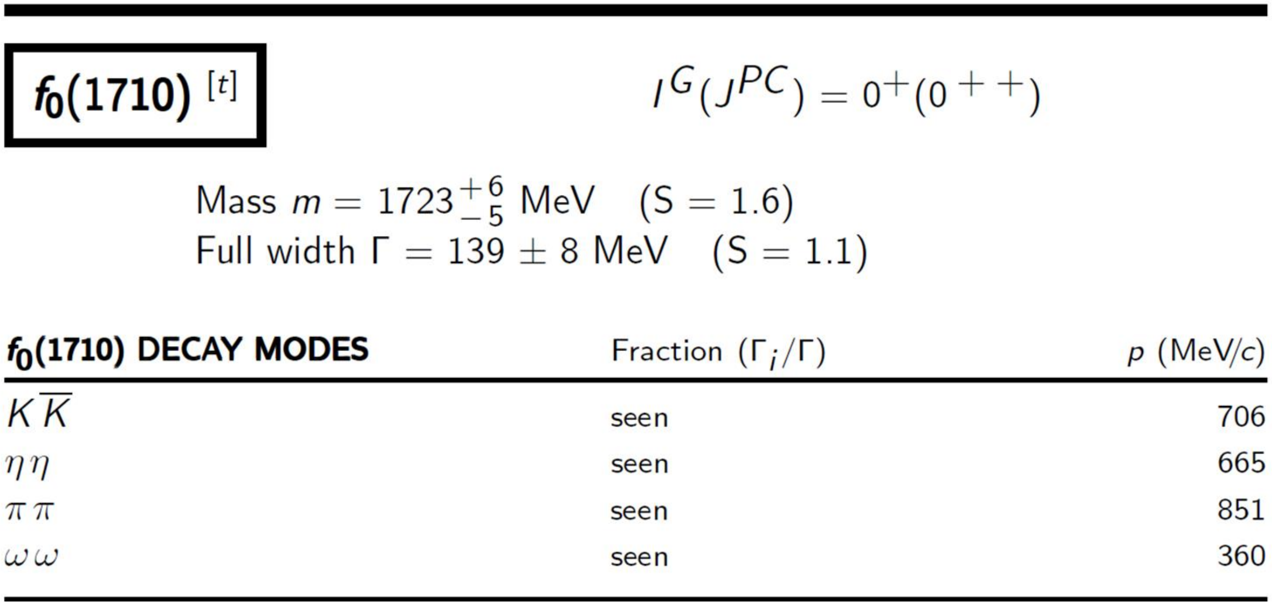
Thorsten Feldmann,[a] Soumitra Nandi[a] and Amarjit Soni[b]

[a] *Theoretische Elementarteilchenphysik, Naturwissenschaftlich Technische Fakultät, Universität Siegen,*
57068 Siegen, Germany
[b] *Physics Department, Theory Group, Brookhaven National Laboratory,*
Upton, NY 11973, U.S.A.

E-mail: thorsten.feldmann@uni-siegen.de, nandi@physik.uni-siegen.de, soni@bnl.gov

Abstract: We investigate to what extent the recently measured value for a non-vanishing direct CP asymmetry in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays can be accommodated in the Standard Model (SM) or extensions with a constrained flavour sector, for instance from a sequential 4th generation of quarks (4G). From the comparison with $D^0 \to K^-\pi^+$ branching ratios, we establish large U-spin symmetry ($d \leftrightarrow s$) breaking effects with large strong phases between different interfering amplitudes. On the basis of conservative estimates on amplitude ratios — which are supported by an analysis of the breaking of a $c \leftrightarrow u$ symmetry in non-leptonic B^0 decays — we find that, in the SM, direct CP asymmetries in the $\pi^+\pi^-$ or K^+K^- modes (or in their difference) of the order of several per mille are still plausible. Due to the constraints on the new CP phases in the 4G model, only moderate effects compared to the SM estimates are possible. We suggest CP studies at LHCb as well as at (Super)B-factories of several distinctive modes, such as $D^+ \to \bar{K}^{(*)0}\pi^+, \phi\pi^+$ and $D_s \to K^{(*)0}\pi^+, \phi\pi^+(K^+)$ etc., which should shed more light on the short- and long-distance

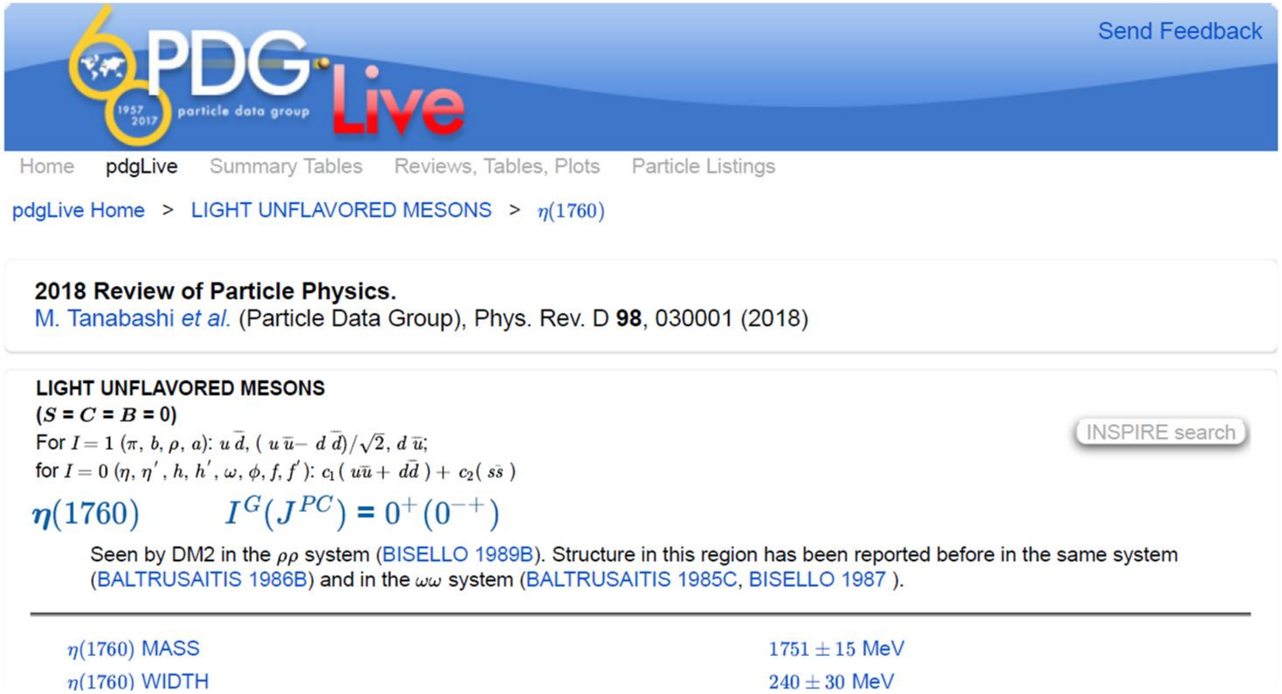
Reliable + accurate calculation Remains challenge for Theorists!



$f_0(1710)$ [t] $I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 1723^{+6}_{-5}$ MeV (S = 1.6)
Full width $\Gamma = 139 \pm 8$ MeV (S = 1.1)

$f_0(1710)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}$	seen	706
$\eta\eta$	seen	665
$\pi\pi$	seen	851
$\omega\omega$	seen	360



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for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

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