July 15-21, 2012
Beyond Standard Model in Particle Physics
Quy Nhon, Vietnam

REVIEW ON BSM PHYSICS IN HEAVY FLAVORS -- CHARM SECTOR

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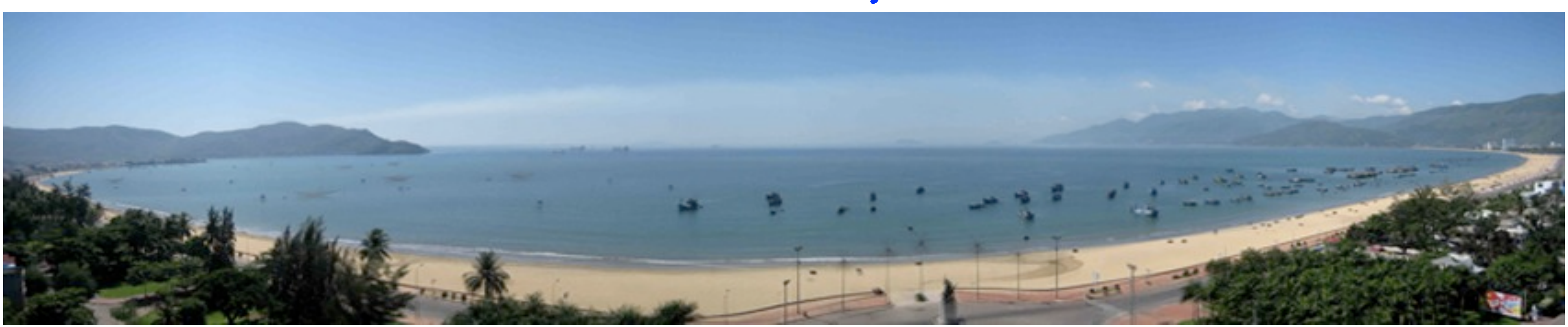

New Era of Particle Physics

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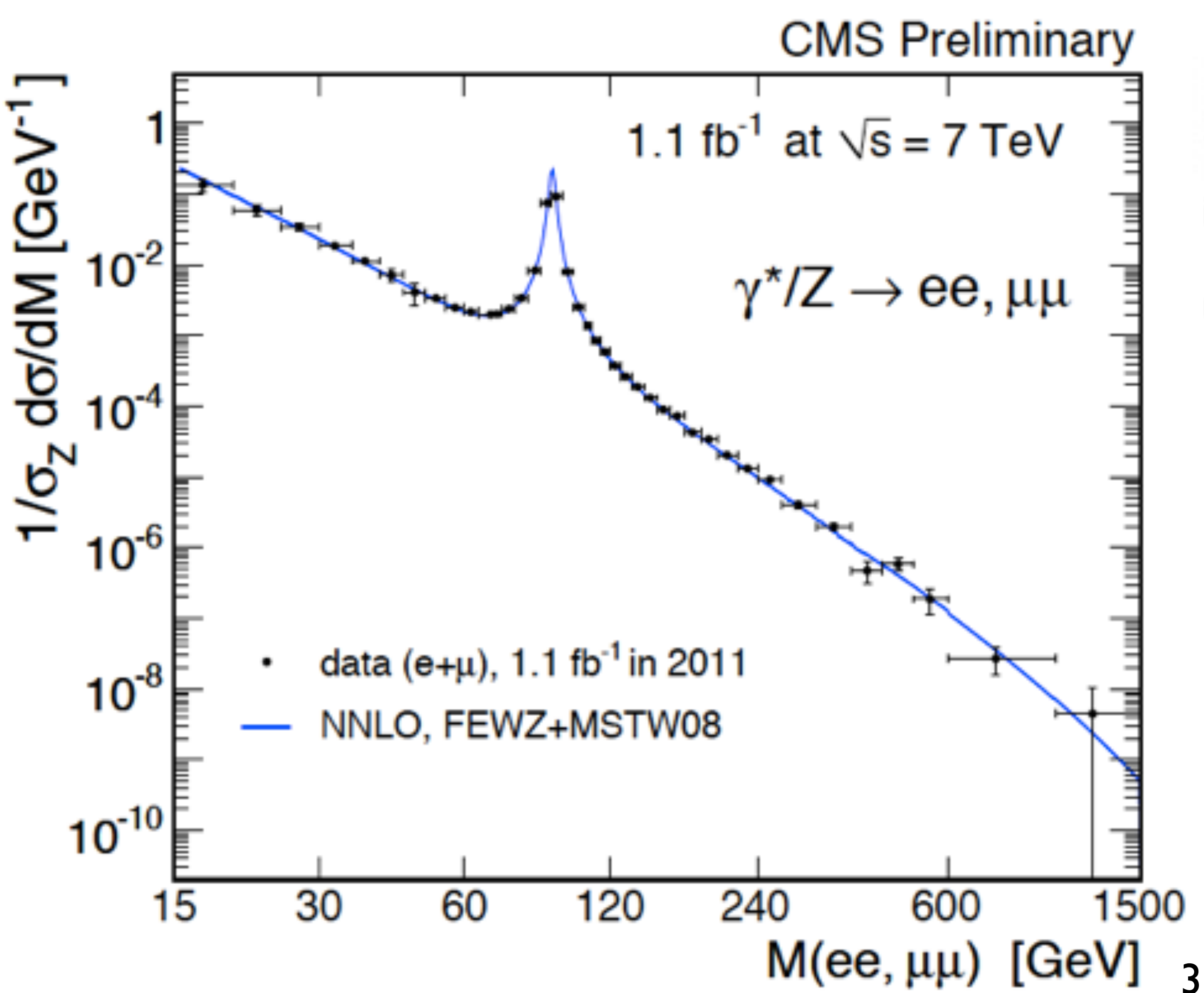
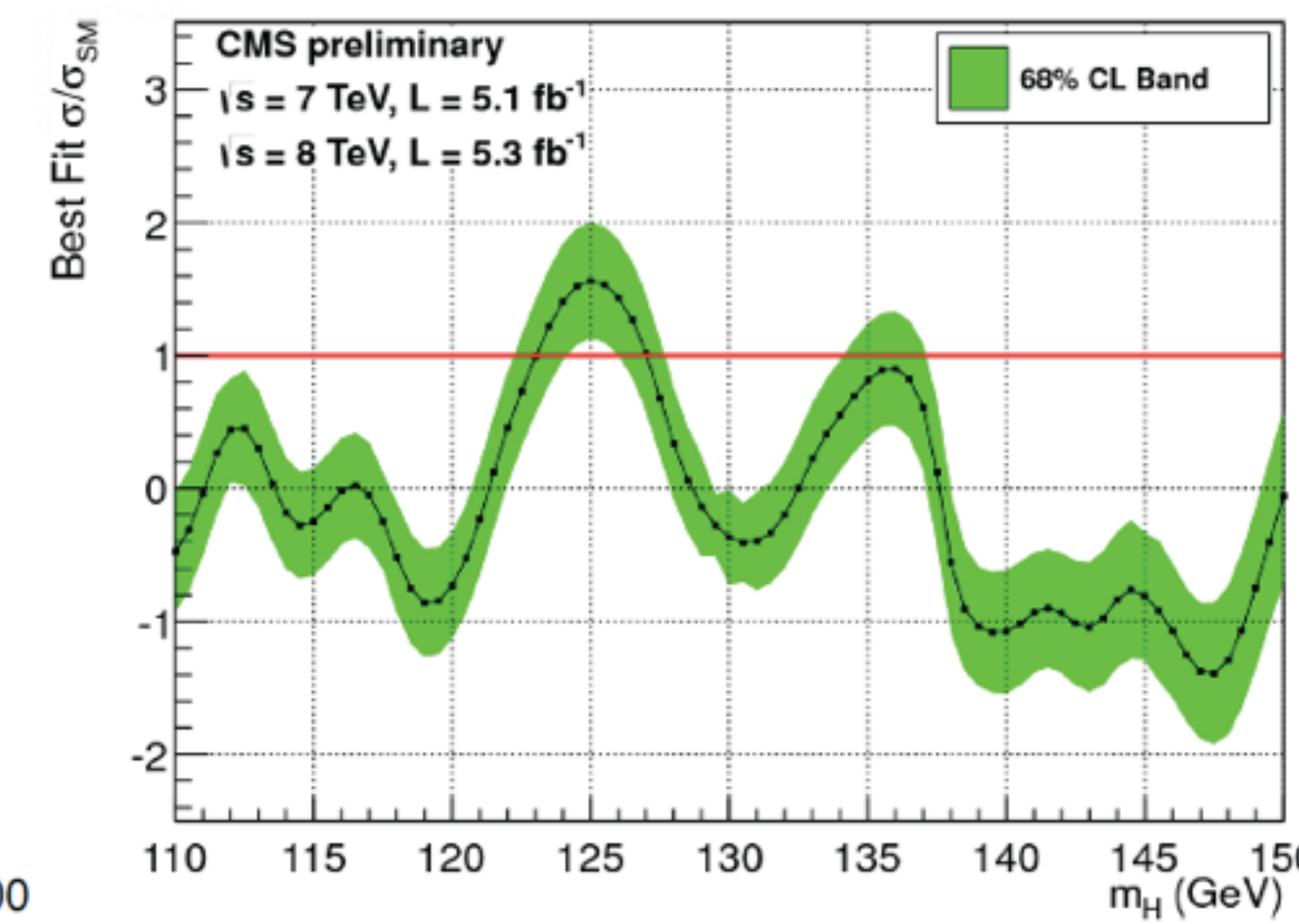
- Lots of high-precision data have been obtained and more to come. Have we really seen any of it?
- Probing NP in flavor physics = waiting for Godot?

Energy Frontiers

- LHC experiments have been probing particle physics at unprecedented energy frontier.
  - Up to now, no new particle from direct searches yet.
  - We even found a Higgs-like resonance at ~125 GeV. ➠ completing the SM





Precision Frontiers

- Flavor physics experiments have been probing particle physics at precision frontier.
- FCNC processes impose stringent constraints on new physics models. [as seen in previous talks]
  - Disappearing low-energy anomalies such as B_s meson mixing and FBA in $B \to K^* \mu\mu$.
  - Stronger bounds from $BR(B_{s,d} \to \mu^+\mu^-)$.
  - Some lingering problems such as $K\pi$ puzzle, tension between $B \to \tau\nu$ and $\sin 2\beta$ about $|V_{ub}|$, $R(D)$ and $R(D^*)$, and like-sign dimuon asymmetry.
- In general, current data point to contrived NP models if it has to show up at the TeV scale.

New Physics Phenomena

New Physics Phenomena

- Type I: ones that lead to new physics beyond SM
  - DM, neutrino mass, flavor pattern, gauge hierarchy, etc
    ➠ larger symmetry
  - recent collider experiment anomalies
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- Charm physics: Type I, Type II, or both?

Plan Of This Talk

- Brief review of charm system in general
- Hadronic D decays and direct CPV — see also Bachmann's talk
- D meson mixing — see also Arinstein's talk
- Puzzle about f_{Ds}
- Summary

Why Charm Physics Now?

- Being studied for about 4 decades, a lot of charm data (D meson mixing, decay BR's, A_{CP}'s) have been collected and analyzed (from BABAR, Belle, CLEO-c, BES-III, and LHCb).

  ➠ Consistent with SM expectations?
  ➠ A portal to NP as people suggest?

Peculiarities of Charm Quark

- Resides at an awkward place in mass spectrum ➠ no suitable effective theory to work with, particularly for hadronic decays
- Too light to grant reliable heavy-quark expansions
$$\Lambda_{QCD}/m_c \sim 0.3 \quad \text{vs} \quad \Lambda_{QCD}/m_b \sim 0.1$$
- Too heavy to use chiral perturbation theory
- Strong QCD coupling regime ➠ perturbative QCD calculations expected to fail
- Many resonances around ➠ nonperturbative rescattering effects kick in
- Flavor SU(3) symmetry for decays to light mesons
- Good realm to test various approaches

GIM Mechanism

- In hadronic charm decays, involved CKM matrix elements are essentially real and naively one does not expect CP violation.

Cabibbo 1963; Kobayashi, Maskawa 1973

$$\mathcal{L} \ni -\frac{g}{2}\overline{Q^I_{Li}}\gamma^\mu W^a_\mu \tau^a Q^I_{Li} + h.c.$$

$$= -\frac{g}{2}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W^+_\mu \left(V_{uL}V^\dagger_{dL}\right)\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + h.c.$$

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$= \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3[(1-\bar\rho) - i\bar\eta] & -A\lambda^2 & 1 \end{pmatrix}$$

(Upper-left 2×2 block) ~ real, antisymmetric

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$$
\begin{aligned}
\mathcal{L} \quad &\ni \quad -\frac{g}{2}\overline{Q^I_{Li}}\gamma^\mu W^a_\mu \tau^a Q^I_{Li} + h.c. \\
&= -\frac{g}{2}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W^+_\mu \left(V_{uL}V^\dagger_{dL}\right)\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + h.c.
\end{aligned}
$$

$$
\begin{aligned}
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&= \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3[(1-\bar{\rho}) - i\bar{\eta}] & -A\lambda^2 & 1 \end{pmatrix}
\end{aligned}
$$

CP-violating

Dominant Charm Decays

- D mesons decay dominantly (~84%) into hadronic final states, 3/4 of which goes to two-body modes.
  ➠ unlike B mesons.

Mode	BR
PP	$\sim 10\%$
VP	$\sim 28\%$
VV	$\sim 10\%$
SP	$\sim 4.2\%$
AP	$\sim 10\%$
TP	$\sim 0.3\%$
2-body	$\sim 63\%$
hadronic	$\sim 84\%$
semileptonic	$\sim 16\%$

P: pseudoscalar meson
V: vector meson
A: axial vector meson
T: tensor meson

Two-Body Hadronic Charm Decays

- Cabibbo-favored (CF):
  involving $V_{ud}^{*}V_{cs} \sim 1-\lambda^2 \sim 0.95$

- Singly Cabibbo-suppressed (SCS):
  involving $V_{us}^{*}V_{cs}$ and/or $V_{ud}^{*}V_{cd} \sim \lambda \sim 0.22$

- Doubly Cabibbo-suppressed (DCS):
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- Only SCS decays can possibly involve diagrams with different CKM phases and thus possibly have CPA.

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- Only SCS decays can possibly involve diagrams with different CKM phases and thus possibly have CPA.
- CP violation is expected only at 10^{-4} to 10^{-3} level
  ➠ NP if measured to be sizable

D Meson Mixing

- Assuming no CPV (comment on CPV later), D-$\bar{D}$ mixing can be characterized by two parameters

$$x \equiv \frac{\Delta m}{\Gamma} = \frac{m_+ - m_-}{\Gamma} \quad \text{and} \quad y \equiv \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_+ - \Gamma_-}{2\Gamma}$$

  where the subscripts (+,−) correspond to the CP eigenstates

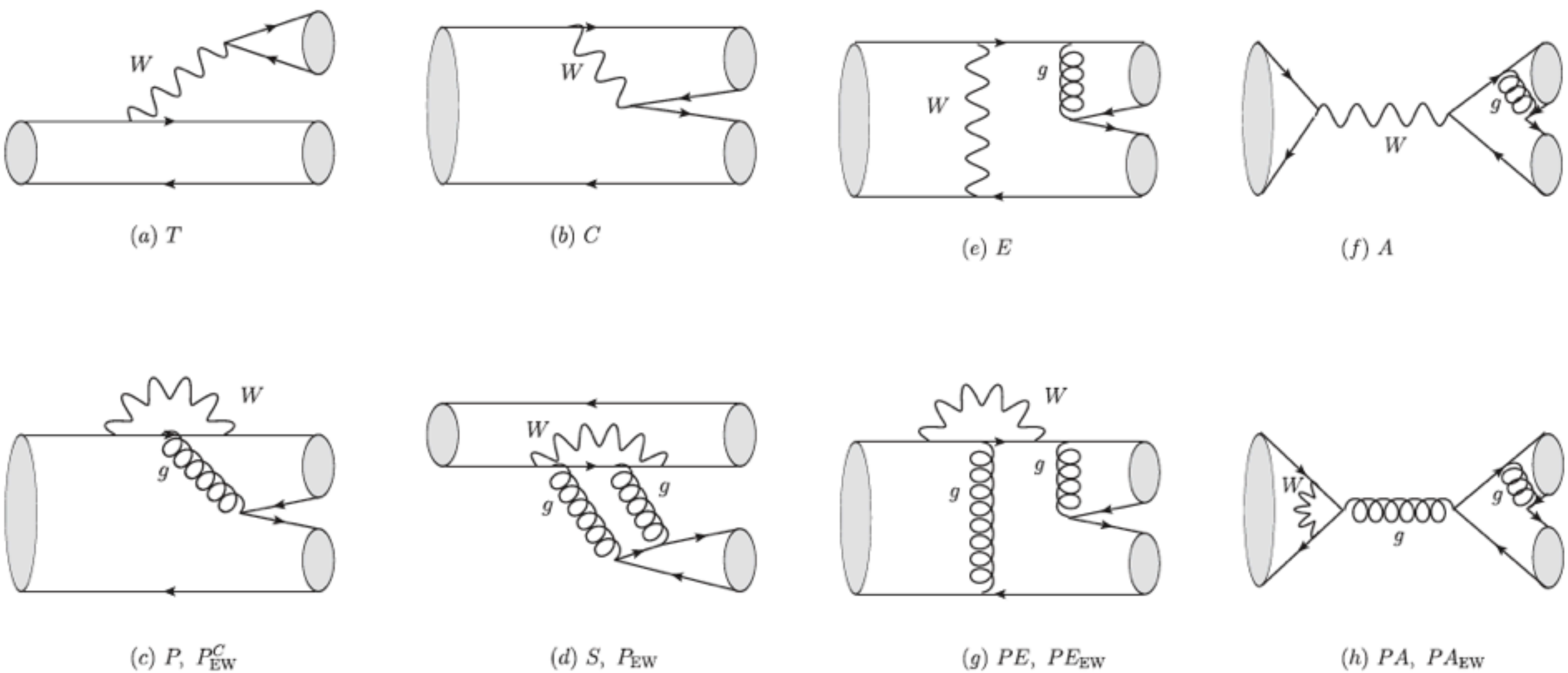
$$|D_\pm\rangle = \frac{1}{\sqrt{2}}(|D^0\rangle \pm |\bar{D}^0\rangle)$$

- In the SM, the short-distance contributions to these parameters are of order 10^{-6} due to GIM and double Cabibbo suppression. Cheng 1982; Datta and Kumbhakar 1985
  ➠ another good place to look for NP effects?

Flavor Diagrams

- Diagrams for 2-body hadronic D meson decays can be classified according to flavor topology into the tree- and loop-types:

Zeppenfeld 1981
Chau and Cheng 1986, 1987, 1991
Savage and Wise 1989
Grinstein and Lebed 1996
Gronau et. al. 1994, 1995, 1995
Cheng and Oh 2011



(a) T (b) C (e) E (f) A

(c) $P,\ P^C_{\rm EW}$ (d) $S,\ P_{\rm EW}$ (g) $PE,\ PE_{\rm EW}$ (h) $PA,\ PA_{\rm EW}$

CF D→PP Decays

TABLE I. Branching fractions and invariant amplitudes for Cabibbo-favored decays of charmed mesons to two pseudoscalar mesons. Data are taken from [4]. Predictions based on our best-fitted results in (7) are given in the last column.

Meson	Mode	Representation	$\mathcal{B}_{\rm exp}$ (%)	$\mathcal{B}_{\rm fit}$ (%)
D^0	$K^-\pi^+$	$V_{cs}^* V_{ud}(T+E)$	3.91 ± 0.08	3.91 ± 0.17
	$\bar{K}^0\pi^0$	$\frac{1}{\sqrt{2}} V_{cs}^* V_{ud}(C-E)$	2.38 ± 0.09	2.36 ± 0.08
	$\bar{K}^0\eta$	$V_{cs}^* V_{ud}[\frac{1}{\sqrt{2}}(C+E)\cos\phi - E\sin\phi]$	0.96 ± 0.06	0.98 ± 0.05
	$\bar{K}^0\eta'$	$V_{cs}^* V_{ud}[\frac{1}{\sqrt{2}}(C+E)\sin\phi + E\cos\phi]$	1.90 ± 0.11	1.91 ± 0.09
D^+	$\bar{K}^0\pi^+$	$V_{cs}^* V_{ud}(T+C)$	3.07 ± 0.10	3.08 ± 0.36
D_s^+	$\bar{K}^0K^+$	$V_{cs}^* V_{ud}(C+A)$	2.98 ± 0.17	2.97 ± 0.32
	$\pi^+\pi^0$	0	<0.037	0
	$\pi^+\eta$	$V_{cs}^* V_{ud}(\sqrt{2}A\cos\phi - T\sin\phi)$	1.84 ± 0.15	1.82 ± 0.32
	$\pi^+\eta'$	$V_{cs}^* V_{ud}(\sqrt{2}A\sin\phi + T\cos\phi)$	3.95 ± 0.34	3.82 ± 0.36

- η-η’ mixing (with $\phi = 40.4^\circ$):

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} \eta_q \\ \eta_s \end{pmatrix} \qquad \left[\eta_q = \frac{1}{\sqrt{2}}\left(u\bar{u} + d\bar{d}\right) \ , \ \eta_s = s\bar{s}\right]$$

Extracted Amplitudes

- The amplitudes extracted from Cabibbo-favored modes in units of 10^{-6} GeV are (χ^2/dof = 0.65):

$$T = 3.14 \pm 0.06 \ , \qquad C = (2.61 \pm 0.08) e^{-i(152 \pm 1)^\circ} \ ,$$

$$E = (1.53^{+0.07}_{-0.08}) e^{i(122 \pm 2)^\circ} \ , \qquad A = (0.39^{+0.13}_{-0.09}) e^{i(31^{+20}_{-33})^\circ} \ .$$

CKM factors extracted

Bhattacharya and Rosner 2008, 2010
Cheng and CWC 2010

- T and C almost opposite in phase, and C and E are quite sizable (unlike B decays)
  ➠ large final-state interaction effects
  ➠ failure of perturbative approaches

- Results are used to predict SCS and DCS decays.

SCS D→PP Decays -- SU(3) Limit

Decay Mode	$\mathcal{B}_{SU(3)}$	$\mathcal{B}_{expt}$
$D^0 \to \pi^+\pi^-$	2.26 ± 0.13	1.400 ± 0.026
$D^0 \to \pi^0\pi^0$	1.35 ± 0.08	0.80 ± 0.05
$D^0 \to \pi^0\eta$	0.75 ± 0.05	0.68 ± 0.07
$D^0 \to \pi^0\eta'$	0.75 ± 0.05	0.89 ± 0.14
$D^0 \to \eta\eta$	1.43 ± 0.09	1.67 ± 0.20
	1.43 ± 0.09	
$D^0 \to \eta\eta'$	1.20 ± 0.10	1.05 ± 0.26
	1.20 ± 0.10	
$D^0 \to K^+K^-$	1.89 ± 0.11	3.96 ± 0.08
	1.89 ± 0.11	
$D^0 \to K^0\overline{K}^0$	0	0.346 ± 0.058
	0	
$D^+ \to \pi^+\pi^0$	0.88 ± 0.06	1.19 ± 0.06
$D^+ \to \pi^+\eta$	1.49 ± 0.35	3.53 ± 0.21
$D^+ \to \pi^+\eta'$	3.77 ± 0.33	4.67 ± 0.29
$D^+ \to K^+\overline{K}^0$	5.32 ± 0.55	5.66 ± 0.32
$D_s^+ \to \pi^+K^0$	2.78 ± 0.28	2.42 ± 0.16
$D_s^+ \to \pi^0K^+$	0.69 ± 0.09	0.62 ± 0.21
$D_s^+ \to K^+\eta$	0.78 ± 0.08	1.75 ± 0.35
$D_s^+ \to K^+\eta'$	1.05 ± 0.17	1.8 ± 0.6

Problems With K^+K^- and $\pi^+\pi^-$ Modes

- These two modes are closely related and identical under SU(3) limit:

$$A_{\pi^+\pi^-} = \frac{1}{2}(\lambda_d - \lambda_s)(T + E + \Delta P)_{\pi\pi} - \frac{1}{2}\lambda_b(T + E + \Sigma P)_{\pi\pi}$$
$$\to \lambda_d(T + E) - \lambda_b \Sigma P \qquad [\mathrm{SU(3)\ limit}]$$
$$A_{K^+K^-} = \frac{1}{2}(\lambda_s - \lambda_d)(T + E - \Delta P)_{KK} - \frac{1}{2}\lambda_b(T + E + \Sigma P)_{KK}$$
$$\to \lambda_s(T + E) - \lambda_b \Sigma P \qquad [\mathrm{SU(3)\ limit}]$$

$$\Sigma P = (P + PE + PA)_d + (P + PE + PA)_s$$
$$\Delta P = (P + PE + PA)_d - (P + PE + PA)_s$$
$$\lambda_q = V^*_{cq} V_{uq}$$

quark involved in penguin loop

A Long-Standing Puzzle

- D → $\pi^+\pi^-$, K^+K^- modes are known to deviate from naive expectations for a long time.
- Empirically, the ratio of their decay rates

$$\frac{\Gamma(K^+K^-)}{\Gamma(\pi^+\pi^-)} \simeq 2.8$$

  is noticeably larger than 1 in the SU(3) limit, not to mention that K^+K^- has less phase space than $\pi^+\pi^-$.
- SU(3) breaking in factorizable part

$$\frac{T(K^+K^-)}{T(\pi^+\pi^-)} \simeq \frac{f_K}{f_\pi} \simeq 1.22$$

  is insufficient to account for data

Time-Integrated Asymmetry

- The time-integrated asymmetry

$$A_{CP}(f) \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}$$

$$\simeq a_{CP}^{\mathrm{dir}}(f) + \frac{\langle t \rangle}{\tau_D} a_{CP}^{\mathrm{ind}}$$

  to first order in the average decay time <t>.

- Consider

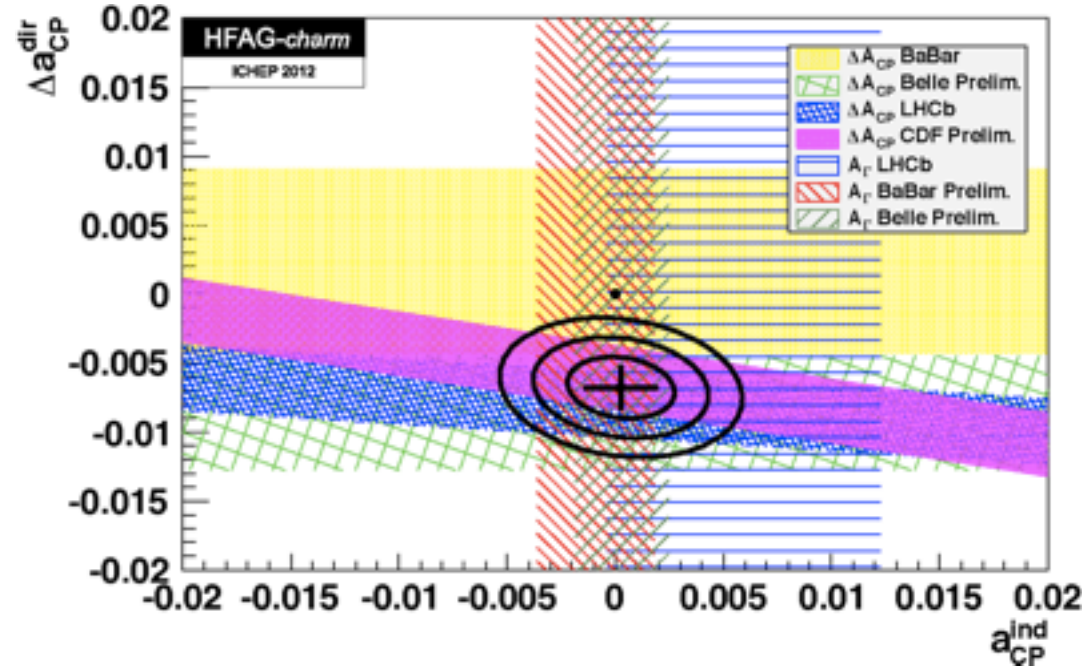
$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

  because
  (1) common systematic factor cancels out; and
  (2) SM and most NP models predict opposite signs.

CP Violation in K^+K^- and $\pi^+\pi^-$

HFAG ICHEP 2012

- Combination of the LHCb, CDF, BaBar and Belle measurements yields
  $a_{CP}^{ind} = -(0.027 \pm 0.163)\%$ and
  $\Delta a_{CP}^{dir} = -(0.678 \pm 0.147)\%$. 4.6σ



Experiment	$A_{CP}(K^+K^-)(\%)$	$A_{CP}(\pi^+\pi^-)(\%)$	$\Delta A_{CP}(\%)$
BaBar	$0.00 \pm 0.34 \pm 0.13$	$-0.24 \pm 0.52 \pm 0.22$	
LHCb			$-0.82 \pm 0.21 \pm 0.11$
CDF	$-0.24 \pm 0.22 \pm 0.09$	$0.22 \pm 0.24 \pm 0.11$	$-0.62 \pm 0.21 \pm 0.10$
Belle	$-0.32 \pm 0.21 \pm 0.09$	$0.55 \pm 0.36 \pm 0.09$	$-0.87 \pm 0.41 \pm 0.06$

Large Penguin Within SM -- I

Brod, Grossman, Kagan, Zupan 2012

- Assume different and large enhancements in d,s-quark penguin contractions $P_{d,s}$ relative to T.
- Require U-spin breaking in T+E:

$$(T+E)_{\pi\pi}=(T+E)(1+\varepsilon_T/2),\ (T+E)_{KK}=(T+E)(1-\varepsilon_T/2)$$

  with $|\varepsilon_T| \in (0,0.3)$.
- Large ΣP explains Δa_{CP}^{dir}, while large ΔP explains the large disparity in the rates of K^+K^- and $\pi^+\pi^-$.
  ➠ A fit to data shows $|(P_d-P_s)/T| \sim 0.5$!

Large Penguin Within SM -- II

Bhattacharya, Gronau, Rosner 2012

- Take nominal SU(3) breaking in T and assume a smaller ΔP:

$$\frac{T_{KK}}{T_{\pi\pi}} = \frac{a_1(KK)}{a_1(\pi\pi)} \frac{f_K}{f_\pi} \frac{F_0^{DK}(m_K^2)}{F_0^{D\pi}(m_\pi^2)} \frac{m_D^2 - m_K^2}{m_D^2 - m_\pi^2} \simeq 1.32$$

while assuming $E_{KK} = E_{\pi\pi}$.
➠ A fit to data shows $|(P_d - P_s)/T| \sim 0.15$
➠ requiring a P_b amplitude comparable to T (attributed to "unforseen QCD effects")

Our Explanation

- SU(3) symmetry must be broken in E:

$$A(D \to K^0 \underline{K}^0) = \lambda_d(E_d + 2PA_d) + \lambda_s(E_s + 2PA_s)$$

➠ vanishing in SU(3) limit, but measured to have a nonzero rate

- Neglect ΔP and fix E_d and E_s from K^+K^-, $\pi^+\pi^-$, $\pi^0\pi^0$, and $K^0\underline{K}^0$ to be

$$\text{(I)}\ E_d = 1.19\, e^{i15.0^\circ} E, \quad E_s = 0.58\, e^{-i14.7^\circ} E\ ,$$

$$\text{(II)}\ E_d = 1.19\, e^{i15.0^\circ} E, \quad E_s = 1.62\, e^{-i9.8^\circ} E\ .$$

- Accumulation of several small SU(3) breaking effects leads to apparently large SU(3) violation seen in the rates of K^+K^-, and $\pi^+\pi^-$.
- No attempt is made to fit Δa_{CP}^{dir} though.

SCS D→PP Decays

- Include SU(3) breaking in factorizable amplitudes:

	Mode	Representation
D^0	$\pi^+\pi^-$	$\lambda_d(0.96T+E_d)+\lambda_p(P_p+PE_p+PA_p)$
	$\pi^0\pi^0$	$\frac{1}{\sqrt{2}}\lambda_d(-0.79C+E_d)+\frac{1}{\sqrt{2}}\lambda_p(P_p+PE_p+PA_p)$
	$\pi^0\eta$	$-\lambda_d(E_d)\cos\phi-\frac{1}{\sqrt{2}}\lambda_s(1.25C)\sin\phi+\lambda_p(P_p+PE_p)\cos\phi$
	$\pi^0\eta'$	$-\lambda_d(E_d)\sin\phi+\frac{1}{\sqrt{2}}\lambda_s(1.25C)\cos\phi+\lambda_p(P_p+PE_p)\sin\phi$
	$\eta\eta$	$\frac{1}{\sqrt{2}}\lambda_d(0.79C+E_d)\cos^2\phi+\lambda_s(-\frac{1}{2}1.06C\sin 2\phi+\sqrt{2}\,E_s\sin^2\phi)+\frac{1}{\sqrt{2}}\lambda_p(P_p+PE_p+PA_p)\cos^2\phi$
	$\eta\eta'$	$\frac{1}{2}\lambda_d(0.79C+E_d)\sin 2\phi+\lambda_s(\frac{1}{\sqrt{2}}1.06C\cos 2\phi-E_s\sin 2\phi)+\frac{1}{2}\lambda_p(P_p+PE_p+PA_p)\sin 2\phi$
	K^+K^-	$\lambda_s(1.27T+E_s)+\lambda_p(P_p+PE_p+PA_p)$
	$K^0\overline{K}^0$	$\lambda_d(E_d)+\lambda_s(E_s)+2\lambda_p(PA_p)$
D^+	$\pi^+\pi^0$	$\frac{1}{\sqrt{2}}\lambda_d(0.96T+0.79C)$
	$\pi^+\eta$	$\frac{1}{\sqrt{2}}\lambda_d(0.82T+0.93C+1.15A)\cos\phi-\lambda_s(1.29C)\sin\phi+\sqrt{2}\lambda_p(P_p+PE_p)\cos\phi$
	$\pi^+\eta'$	$\frac{1}{\sqrt{2}}\lambda_d(0.82T+0.93C+1.56A)\sin\phi+\lambda_s(1.29C)\cos\phi+\sqrt{2}\lambda_p(P_p+PE_p)\sin\phi$
	$K^+\overline{K}^0$	$\lambda_d(0.86A)+\lambda_s(1.27T)+\lambda_p(P_p+PE_p)$
D_s^+	π^+K^0	$\lambda_d(1.12T)+\lambda_s(A)+\lambda_p(P_p+PE_p)$
	π^0K^+	$\frac{1}{\sqrt{2}}[-\lambda_d(0.91C)+\lambda_s(A)+\lambda_p(P_p+PE_p)]$
	$K^+\eta$	$\frac{1}{\sqrt{2}}\lambda_p[0.94C\delta_{pd}+A\delta_{ps}+P_p+PE_p]\cos\phi-\lambda_p[(1.28T+1.24C+A)\delta_{ps}+P_p+PE_p]\sin\phi$
	$K^+\eta'$	$\frac{1}{\sqrt{2}}\lambda_p[0.94C\delta_{pd}+A\delta_{ps}+P_p+PE_p]\sin\phi+\lambda_p[(1.28T+1.24C+A)\delta_{ps}+P_p+PE_p]\cos\phi$

SCS D→PP Decays -- SU(3) Breaking

Decay Mode	$\mathcal{B}_{\mathrm{SU(3)}}$	$\mathcal{B}_{\mathrm{SU(3)-breaking}}$	$\mathcal{B}_{\mathrm{expt}}$
$D^0 \to \pi^+\pi^-$	2.26 ± 0.13	1.40 ± 0.11	1.400 ± 0.026
$D^0 \to \pi^0\pi^0$	1.35 ± 0.08	0.78 ± 0.06	0.80 ± 0.05
$D^0 \to \pi^0\eta$	0.75 ± 0.05	0.83 ± 0.06	0.68 ± 0.07
$D^0 \to \pi^0\eta'$	0.75 ± 0.05	1.42 ± 0.08	0.89 ± 0.14
$D^0 \to \eta\eta$	1.43 ± 0.09	1.68 ± 0.09	1.67 ± 0.20
	1.43 ± 0.09	1.89 ± 0.10	
$D^0 \to \eta\eta'$	1.20 ± 0.10	0.68 ± 0.06	1.05 ± 0.26
	1.20 ± 0.10	2.11 ± 0.20	
$D^0 \to K^+K^-$	1.89 ± 0.11	3.89 ± 0.16	3.96 ± 0.08
	1.89 ± 0.11	3.90 ± 0.22	
$D^0 \to K^0\overline{K}^0$	0	0.346 ± 0.034	0.346 ± 0.058
	0	0.345 ± 0.034	
$D^+ \to \pi^+\pi^0$	0.88 ± 0.06	0.96 ± 0.07	1.19 ± 0.06
$D^+ \to \pi^+\eta$	1.49 ± 0.35	3.26 ± 0.39	3.53 ± 0.21
$D^+ \to \pi^+\eta'$	3.77 ± 0.33	4.70 ± 0.31	4.67 ± 0.29
$D^+ \to K^+\overline{K}^0$	5.32 ± 0.55	8.72 ± 0.85	5.66 ± 0.32
$D_s^+ \to \pi^+K^0$	2.78 ± 0.28	3.57 ± 0.33	2.42 ± 0.16
$D_s^+ \to \pi^0K^+$	0.69 ± 0.09	0.69 ± 0.09	0.62 ± 0.21
$D_s^+ \to K^+\eta$	0.78 ± 0.08	0.83 ± 0.08	1.75 ± 0.35
$D_s^+ \to K^+\eta'$	1.05 ± 0.17	1.28 ± 0.20	1.8 ± 0.6

Cheng and CWC 2012

Our A_{CP} Predictions

pQCD results

Cheng and CWC 2012

Decay Mode	$a_{dir}^{(tree)}$(this work)	$a_{dir}^{(tree)}$[22]	$a_{dir}^{(tot)}$(this work)	$a_{dir}^{(tot)}$[22]	Expt.
$D^0 \to \pi^+\pi^-$	0	0	0.96 ± 0.04	0.74	2.0 ± 2.2
$D^0 \to \pi^0\pi^0$	0	0	0.83 ± 0.04	0.26	1 ± 48
$D^0 \to \pi^0\eta$	0.82 ± 0.03	-0.29	0.06 ± 0.04	-0.61	
$D^0 \to \pi^0\eta'$	-0.39 ± 0.02	0.43	0.01 ± 0.02	1.67	
$D^0 \to \eta\eta$	-0.28 ± 0.01	0.29	-0.58 ± 0.02	0.18	
	-0.42 ± 0.02	0.29	-0.74 ± 0.02	0.18	
$D^0 \to \eta\eta'$	0.49 ± 0.02	-0.30	0.53 ± 0.03	0.97	
	0.38 ± 0.02	-0.30	0.33 ± 0.02	0.97	
$D^0 \to K^+K^-$	0	0	-0.42 ± 0.01	-0.54	-2.3 ± 1.7
	0	0	-0.54 ± 0.02	-0.54	
$D^0 \to K^0\overline{K}^0$	-0.73	0.69	-0.67 ± 0.01	0.90	
	-1.73	0.69	-1.90 ± 0.01	0.90	
$D^+ \to \pi^+\pi^0$	0	0	0	0	29 ± 29
$D^+ \to \pi^+\eta$	0.36 ± 0.06	-0.46	-0.78 ± 0.06	0.63	17.4 ± 11.5 [a]
$D^+ \to \pi^+\eta'$	-0.20 ± 0.04	0.30	0.34 ± 0.07	1.28	-1.2 ± 11.3 [a]
$D^+ \to K^+\overline{K}^0$	-0.08 ± 0.06	-0.08	-0.40 ± 0.04	-0.93	-1.0 ± 5.9
$D_s^+ \to \pi^+K^0$	0.08 ± 0.06	-0.01	0.46 ± 0.03	0.87	66 ± 24
$D_s^+ \to \pi^0K^+$	0.01 ± 0.11	0.17	0.98 ± 0.10	0.76	266 ± 228
$D_s^+ \to K^+\eta$	-0.70 ± 0.05	0.75	-0.61 ± 0.05	0.76	93 ± 152
$D_s^+ \to K^+\eta'$	0.35 ± 0.04	-0.48	-0.29 ± 0.12	1.83	60 ± 189

in units of 10^{-3}

- Use QCDF for an estimate of penguin amplitudes.

Our A_{CP} Predictions

pQCD results

Cheng and CWC 2012

Decay Mode	$a_{dir}^{(tree)}$(this work)	$a_{dir}^{(tree)}$[22]	$a_{dir}^{(tot)}$(this work)	$a_{dir}^{(tot)}$[22]	Expt.
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$D^0 \to K^0\overline{K}^0$	-0.73	0.69	-0.67 ± 0.01	0.90	
	-1.73	0.69	-1.90 ± 0.01	0.90	
$D^+ \to \pi^+\pi^0$	0	0	0	0	29 ± 29
[illegible]	[illegible]	46	-0.78 ± 0.06	0.63	17.4 ± 11.5 [a]
[illegible]	[illegible]	30	0.34 ± 0.07	1.28	-1.2 ± 11.3 [a]
[illegible]	[illegible]	08	-0.40 ± 0.04	-0.93	-1.0 ± 5.9
[illegible]	[illegible]	01	0.46 ± 0.03	0.87	66 ± 24
[illegible]	[illegible]	17	0.98 ± 0.10	0.76	266 ± 228
[illegible]	[illegible]	75	-0.61 ± 0.05	0.76	93 ± 152
$D_s^+ \to K^+\eta'$	0.35 ± 0.04	-0.48	-0.29 ± 0.12	1.83	60 ± 189

in units of 10^{-3}

$\Delta a_{CP}^{dir} = -(0.139 \pm 0.004)\%$ (I)

$-(0.151 \pm 0.004)\%$ (II)

~3.6σ from $-(0.739 \pm 0.154)\%$

- Use QCDF for an estimate of penguin amplitudes.

Our A_{CP} Predictions

pQCD results

Cheng and CWC 2012

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	-1.73	0.69	-1.90 ± 0.01	0.90	
$D^+ \to \pi^+\pi^0$	0	0	0	0	29 ± 29
[illegible]	[illegible]	...46	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	...30	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	...08	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	...01	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	...17	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	...75	[illegible]	[illegible]	[illegible]
$D_s^+ \to K^+\eta'$	0.35 ± 0.04	-0.48	-0.29 ± 0.12	1.83	60 ± 189

in units of 10^{-3}

$\Delta a_{CP}^{dir} = -(0.139 \pm 0.004)\%$ (I)
$-(0.151 \pm 0.004)\%$ (II)
~3.6σ from $-(0.739 \pm 0.154)\%$

even if PE~T, $\Delta a_{CP}^{dir} = -0.27\%$,
an upper bound in SM,
still ~2.8σ from data

- Use QCDF for an estimate of penguin amplitudes.

Other SM Explanations

- Pirtskhalava, Uttayarat 2011: SU(3) breaking with enhanced hadronic matrix element
  ➠ data plausible in SM
- Feldmann, Nandi, Soni 2012: large U-spin breaking with enhanced hadronic matrix element
  ➠ data plausible in SM
  ➠ SM4 not useful due to constrained data
- Franco, Mishima, Silvestrini 2012: SU(3) breaking, violation of naive $1/N_c$ counting and constrained I=0 rescattering
  ➠ data marginally accommodated by SM

New Physics Interpretations

- Before LHCb
  - Extra vector-like quarks, SUSY w/o R-parity, 2HDM, QCD dipole operator from SUSY — Grossman, Kagan, Nir 2007
  - Little Higgs with T-parity — Bigi, Paul, Rechsiegel 2011
- After LHCb
  - FCNC Z — Giudice, Isidori, Paradisi; Altmannshofer, Primulando, Yu, Yu
  - FCNC Z'; FCNC heavy gluon — Wang and Zhu; Altmannshofer et al
  - 2HDM (charged Higgs) — Altmannshofer et al
  - QCD dipole from SUSY — Hiller, Hochberg, Nir; Giudice, Isidori, Paradisi
  - Color-sextet scalar (diquark scalar) — Altmannshofer et al; Chen et al
  - Color-octet scalar — Altmannshofer et al
  - 4G — Rozanov and Vysotsky; Feldmann, Nandi, Soni

With Constraints

- Some models are ruled out by indirect CPV in D mixing, ε'/ε, etc: FCNC Z, FCNC Z', diquark scalar.
- Some others require fine-tuning in parameters: heavy FCNC gluon, 2HDM, color-octet scalar.
- 4G is not useful for data.
- The QCD dipole operator

Grossman, Kagan, Nir 2007
Giudice, Isidori, Paradisi 2012
Hiller, Hochberg, Nir 2012

$$O_{8g} = -\frac{g_s}{8\pi^2} m_c \bar{u} \sigma_{\mu\nu} (1+\gamma_5) G^{\mu\nu} c$$

is least constrained and can be enhanced.

- Example: left-right mixing of first two families in up sector, $(\delta^u_{12})_{LR} \sim 10^{-3}$, in SUSY
  ➠ usual chiral suppression for D mixing ($|\Delta C| = 2$)
  ➠ m_{SUSY}/m_c enhancement for D decays ($|\Delta C| = 1$)

Large Penguin / QCD Dipole

Cheng and CWC 2012

- Both made to accommodate Δa_{CP}^{dir} data
- Large QCD dipole predicts large CPA's for $D^0 \to \pi^0\pi^0, \pi^0\eta$, but small ones for $D^0 \to \pi^0\eta'$, $D^+ \to \pi^+\eta'$, $K^+\underline{K}^0$, $D_s^+ \to \pi^+K^0$, $K^+\eta'$
- The other way around for the large penguin scenario
- Discernible with more data

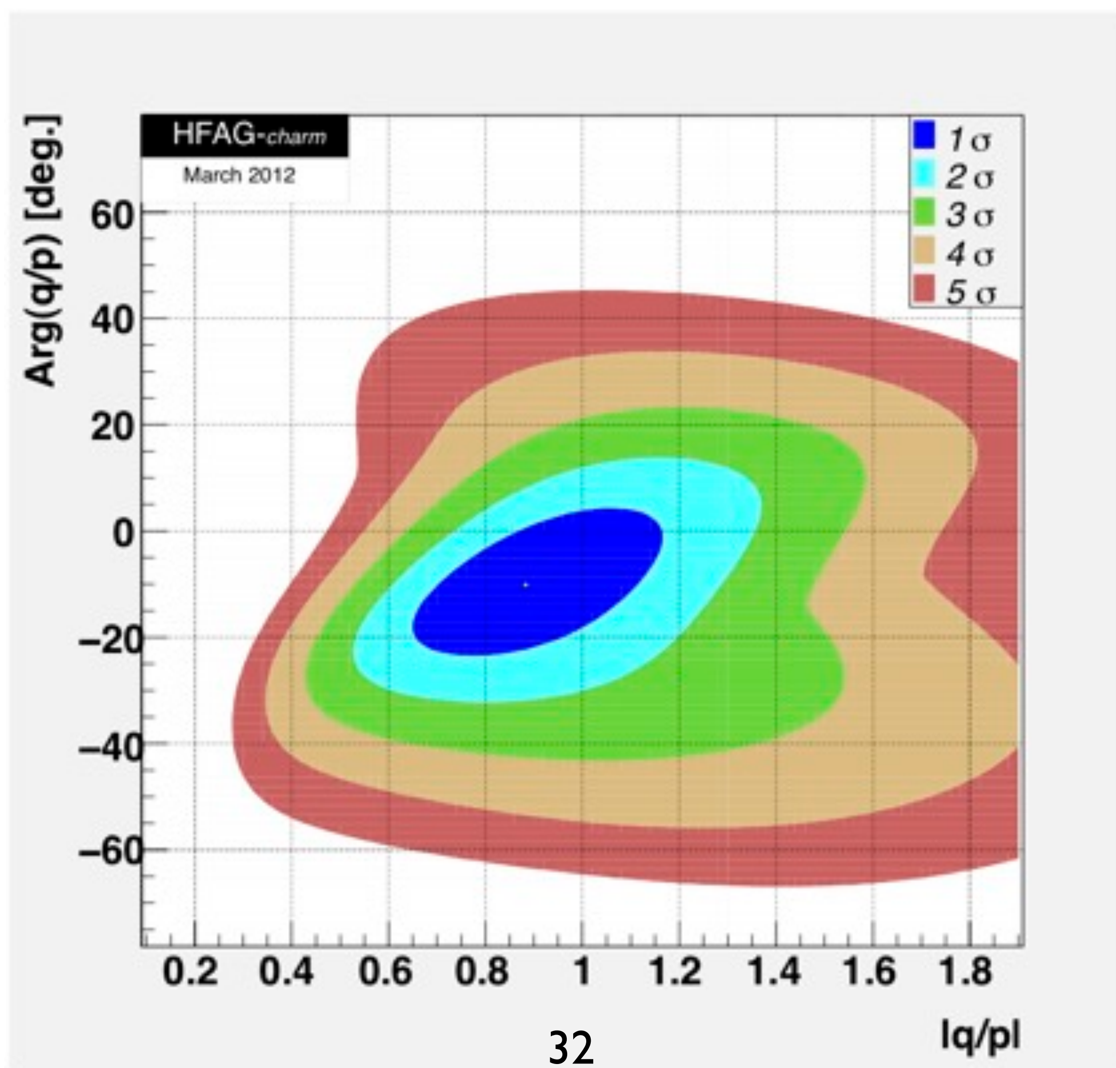
Decay Mode	Large penguins	Large c.d.o.
$D^0 \to \pi^+\pi^-$	4.38	3.72
$D^0 \to \pi^0\pi^0$	1.04	6.21
$D^0 \to \pi^0\eta$	0.28	−4.17
$D^0 \to \pi^0\eta'$	2.73	−0.44
$D^0 \to \eta\eta$	−1.96	−1.23
	−1.64	−2.01
$D^0 \to \eta\eta'$	2.90	−1.55
	1.49	−1.09
$D^0 \to K^+K^-$	−2.94	−1.01
	−2.37	−2.90
$D^0 \to K^0\overline{K}^0$	–	−0.67
	–	−1.90
$D^+ \to \pi^+\pi^0$	0	0
$D^+ \to \pi^+\eta$	−3.66	−3.69
$D^+ \to \pi^+\eta'$	3.34	0.59
$D^+ \to K^+\overline{K}^0$	−3.16	0.29
$D_s^+ \to \pi^+K^0$	4.14	−0.36
$D_s^+ \to \pi^0K^+$	4.55	3.15
$D_s^+ \to K^+\eta$	−0.57	0.95
$D_s^+ \to K^+\eta'$	−5.82	1.39
	Type II NP	Type I NP

CPV in D Meson Mixing

- Define mass eigenstates as

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

- No evidence of indirect CPV [either $|q/p| \neq 1$ or $\mathrm{Arg}(q/p) \neq 0$] from time-dependent Dalitz plot analysis of $D^0 \to K_S \pi^+ \pi^-$.



x and y Parameters

- Assuming no CPV, D-D̲ mixing can be characterized by two parameters

$$x \equiv \frac{\Delta m}{\Gamma} = \frac{m_+ - m_-}{\Gamma} \quad \text{and} \quad y \equiv \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_+ - \Gamma_-}{2\Gamma}$$

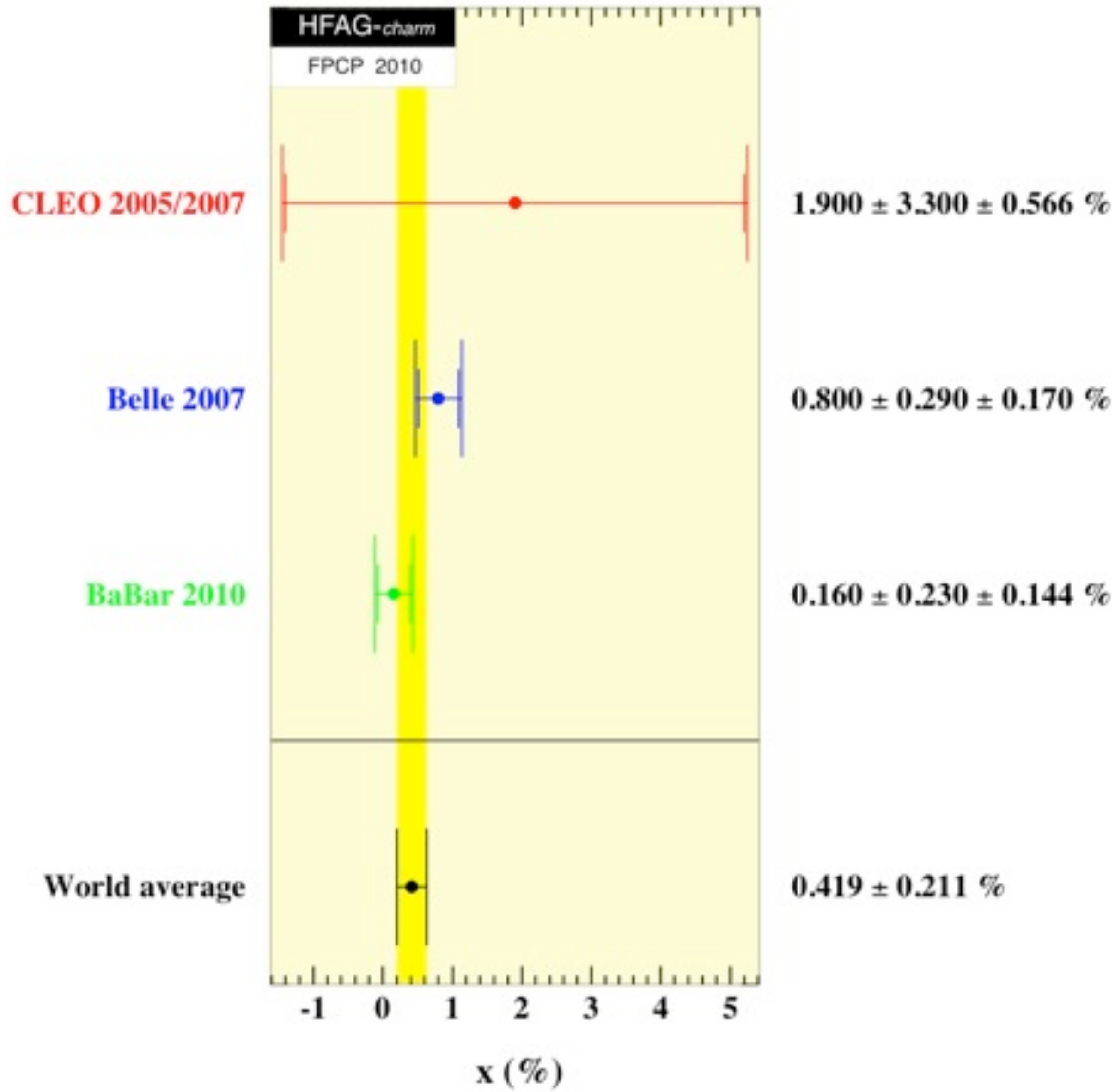
where the subscripts (+,−) correspond to the CP eigenstates

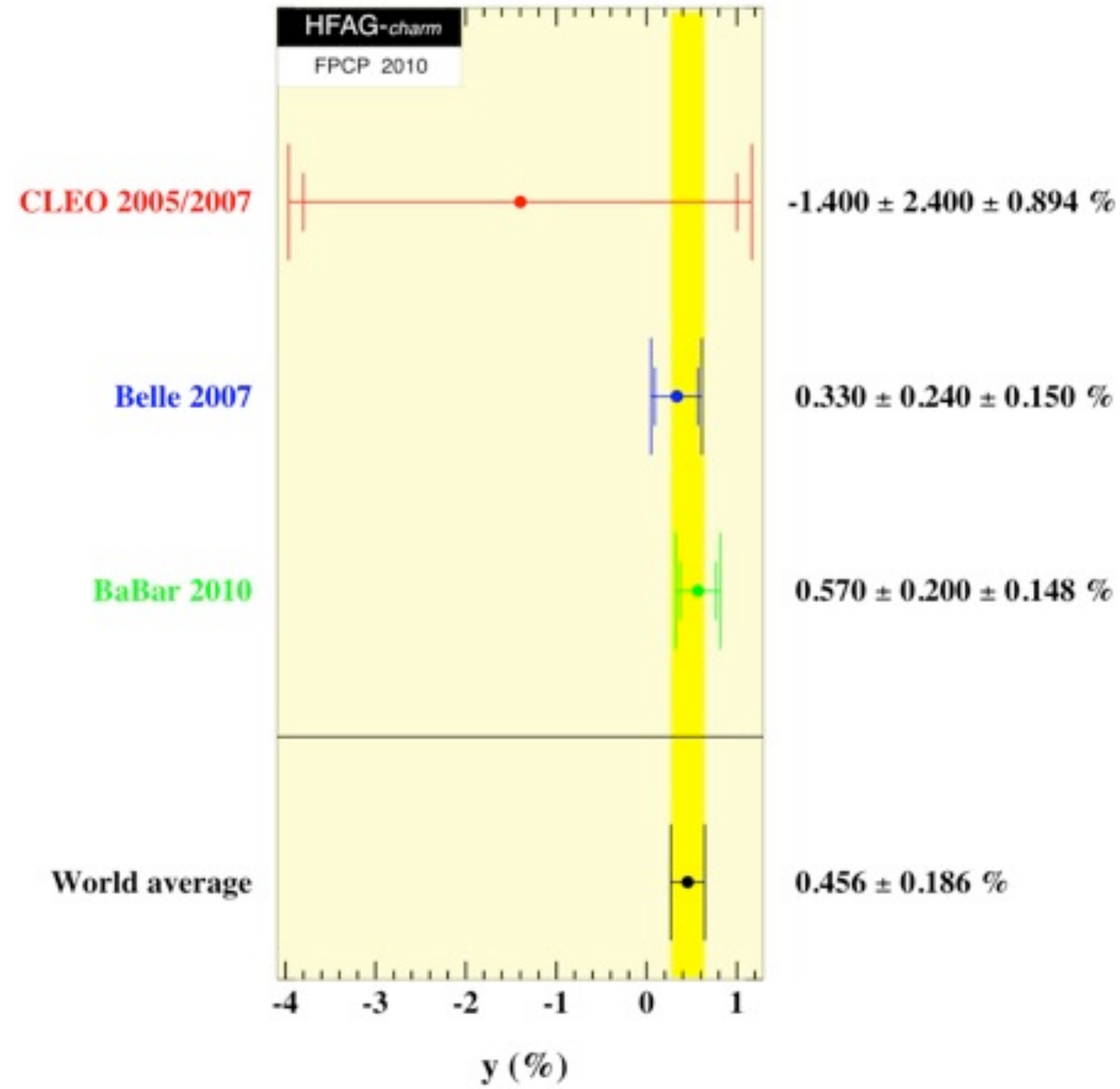
$$|D_\pm\rangle = \frac{1}{\sqrt{2}}(|D^0\rangle \pm |\bar{D}^0\rangle)$$

- In the SM, the short-distance contributions to these parameters are of order 10^{-6} due to GIM and double Cabibbo suppression. Cheng 1982; Datta and Kumbhakar 1985

➠ another good place to look for NP effects?

x and y Parameters





- They are orders of magnitudes larger than SM short-distance predictions.
  ➠ Type I or II new physics?

Mass and Width Differences

$$\Delta m = \frac{1}{m_D}\langle D^0|H_w|\overline{D}^0\rangle + \frac{1}{2m_D}\mathcal{P}\sum_n \frac{1}{\mathcal{N}}\frac{\langle D^0|H_w|n\rangle\langle n|H_w|\overline{D}^0\rangle + \langle\overline{D}^0|H_w|n\rangle\langle n|H_w|D^0\rangle}{m_D - E_n}$$

short-distance

long-distance

$$\Delta\Gamma = \frac{1}{2m_D}\sum_n \frac{1}{\mathcal{N}}\left[\langle D^0|H_w|n\rangle\langle n|H_w|\overline{D}^0\rangle + \langle\overline{D}^0|H_w|n\rangle\langle n|H_w|D^0\rangle\right](2\pi)\delta(m_D - E_n)$$

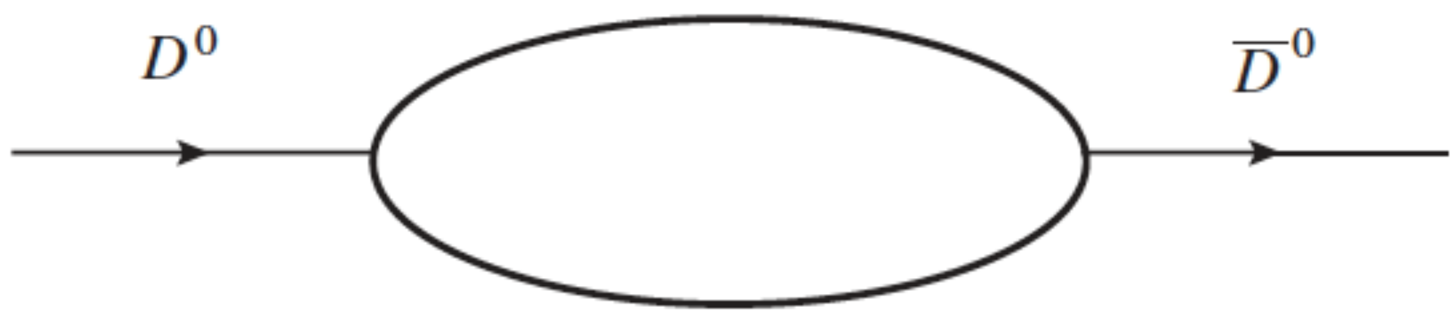


FIG. 1. Two-particle contribution to the neutral charmed meson mass difference.

General Properties

- Two approaches:
  - inclusive, depending on heavy-quark expansion;
  - exclusive, summing over all intermediate states.
- In SM, x and y are generated at 2nd order in SU(3) breaking: Falk et al 2002

$$x, y \sim \sin^2\theta_C \times [SU(3)\ \text{breaking}]^2$$

- Inclusive approach generally yields x ≥ y, while exclusive approach tends to have x < y.
- Possible SU(3) breaking:
  - phase space difference alone can produce y ~ 10^{-2}
  - amplitude difference, depending on model calculations

Master Formulas for x, y

$$x \approx \frac{m_D}{4\pi} \sum_n \eta_{\rm CKM}(n)\eta_{\rm CP}(n) \cos\delta_n \sqrt{\mathcal{B}(D^0 \to n)\mathcal{B}(D^0 \to \bar{n})} \frac{I(m_1, m_2, \Lambda)}{p_c(n)}$$

$$y \approx \sum_n \eta_{\rm CKM}(n)\eta_{\rm CP}(n) \cos\delta_n \sqrt{\mathcal{B}(D^0 \to n)\mathcal{B}(D^0 \to \bar{n})}$$

Falk et al 2002

- δ_n : relative strong phase between $A(D^0 \to n)$ and $A(\underline{D}^0 \to n)$.
- $\eta_{CKM} = \pm 1$, depending on # of s and $\underline{s}$ quarks in final state.
- η_{CP} : CP eignevalue of state n.

- x is smaller than y by about 4π because the rest factor $m_D\ I(m_1,m_2,\Lambda)/p_c$ is of order 1 (maximal for the ππ mode and about 2.5).
- Data are then employed to estimate x and y.

Summary of Experimental Results

Method	$x(\times 10^{-3})$	$y(\times 10^{-3})$	Source
Indirect	$9.8^{+2.4}_{-2.6}$	8.3 ± 1.6	WA 2008
Direct	$1.6 \pm 2.3 \pm 1.2 \pm 0.8$	$5.7 \pm 2.0 \pm 1.3 \pm 0.7$	BABAR 2010
Direct	$8.0 \pm 2.9^{+0.9+1.0}_{-0.7-1.4}$	$3.3 \pm 2.4^{+0.8+0.6}_{-1.2-0.8}$	Belle 2007
Direct	$5.6 \pm 1.9^{+0.3+0.6}_{-0.9-0.9}$	$3.0 \pm 1.5^{+0.4+0.3}_{-0.5-0.6}$	Belle 2012

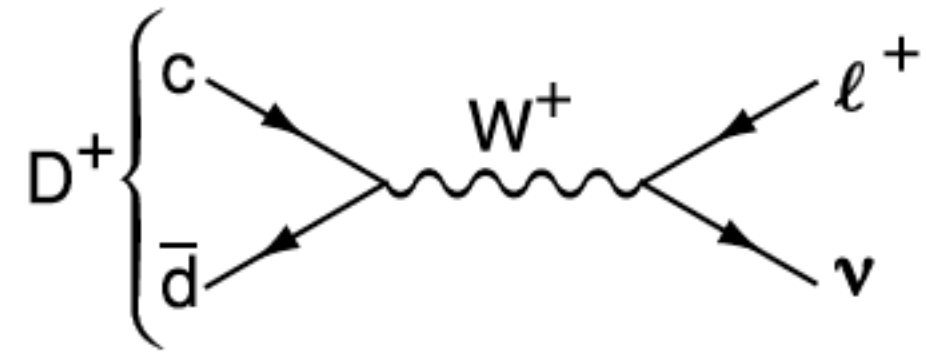
- BABAR favors x < y, while Belle favors the other way.
- Both of them have results smaller than previous world average from indirect measurements.

- Estimates based on flavor diagram approach give x ~ 0.1% and y ~ (0.5–0.7)%, in better agreement with the BABAR result. Cheng and CWC 2010
- No strong indication of new physics with current data.

Puzzle of f_{Ds}

$$\Gamma(P \to \ell\nu) = \frac{G_F^2}{8\pi} f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 |V_{q_1 q_2}|^2$$

- Experiments and unquenched HPQCD result used to have 4σ discrepancy (2008), now only 2σ.



- Most theory calculations are below data. Errors are sufficiently large to declare success.

Rosner and Stone 2012

Model	$f_{D_s^+}$(MeV)	f_{D^+}(MeV)	$f_{D_s^+}/f_{D^+}$
Experiment (our averages)	260.0 ± 5.4	206.7 ± 8.9	1.26 ± 0.06
Lattice (HPQCD) [21]	248.0 ± 2.5	213 ± 4	1.164 ± 0.018
Lattice (FNAL+MILC) [22]	260.1 ± 10.8		1.188 ± 0.025
PQL [23]	244 ± 8		1.24 ± 0.03
QCD sum rules [24]		177 ± 21	$1.16 \pm 0.01 \pm 0.03$
QCD sum rules [25]	$245.3 \pm 15.7 \pm 4.5$	$206.2 \pm 7.3 \pm 5.1$	$1.193 \pm 0.025 \pm 0.007$
Field correlators [26]	260 ± 10	210 ± 10	1.24 ± 0.03
Light front [27]	268.3 ± 19.1	206 (fixed)	1.30 ± 0.04

down by 1.3σ

up by 2.3σ

Summary

- Flavor diagram approach with major SU(3) symmetry breaking effects is combined with QCDF for penguin amplitudes to explain SCS $D \to PP$ data.
- Predictions of CPA's are made within SM, and Δa_{CP}^{dir} is around -0.15% and 3.6σ from data.
- Among various popular new physics models, those contributing mainly to the QCD dipole operator is least constrained by low-energy data.
  ➠ possible Type I NP if data stay roughly the same
  ➠ More CPA data are required to tell us which is right.
- While inclusive analyses generally render $x \geq y$, our exclusive calculations show that x ($\sim 10^{-3}$) is about one order of magnitude smaller than y [$(5\sim7)\times10^{-3}$].
  ➠ no Type I NP required
- Previous f_{D_s} puzzle between data and lattice is resolved.

Thank You!