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Hadronic D Meson Decays

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New Era of Particle Physics

- In past two decades or so, many new physics (NP) models have been proposed to addresses such issues as:

neutrino mass | flavor pattern | dark matter physics | hierarchy problem | grand unification | fine-tuning problem

- Most of them are believed to leave detectable imprints in various low-energy flavor physics.
- Lots of high-precision data have been obtained and more to come. Have we really seen any of it?

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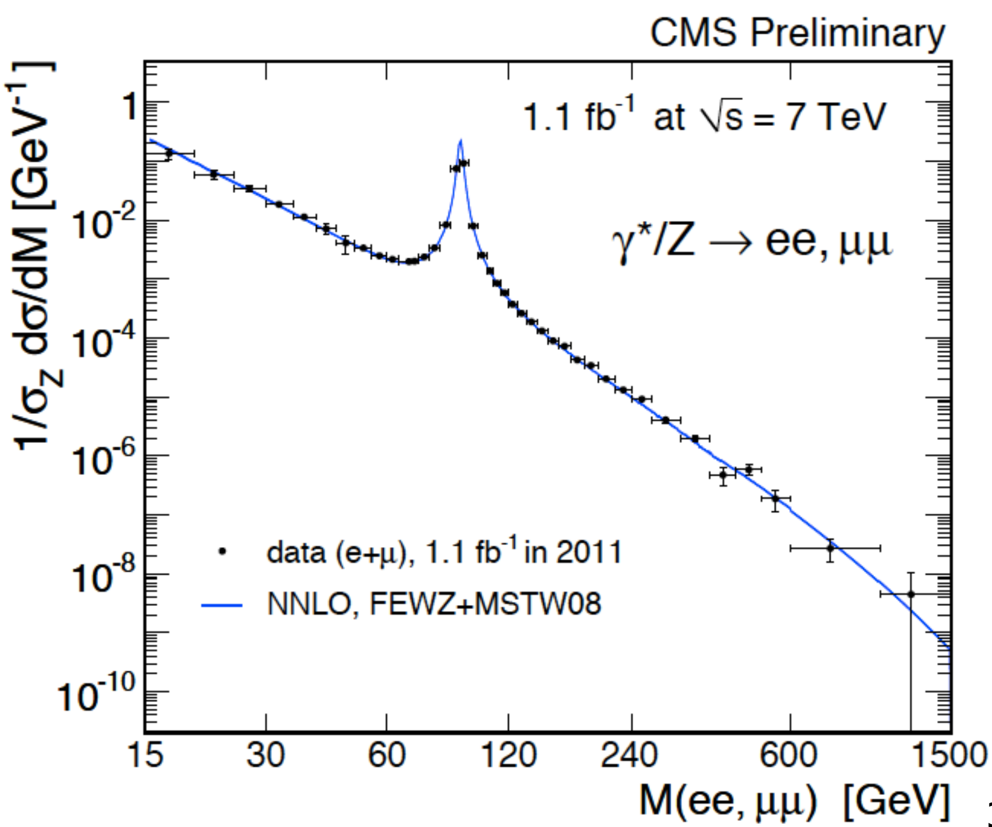
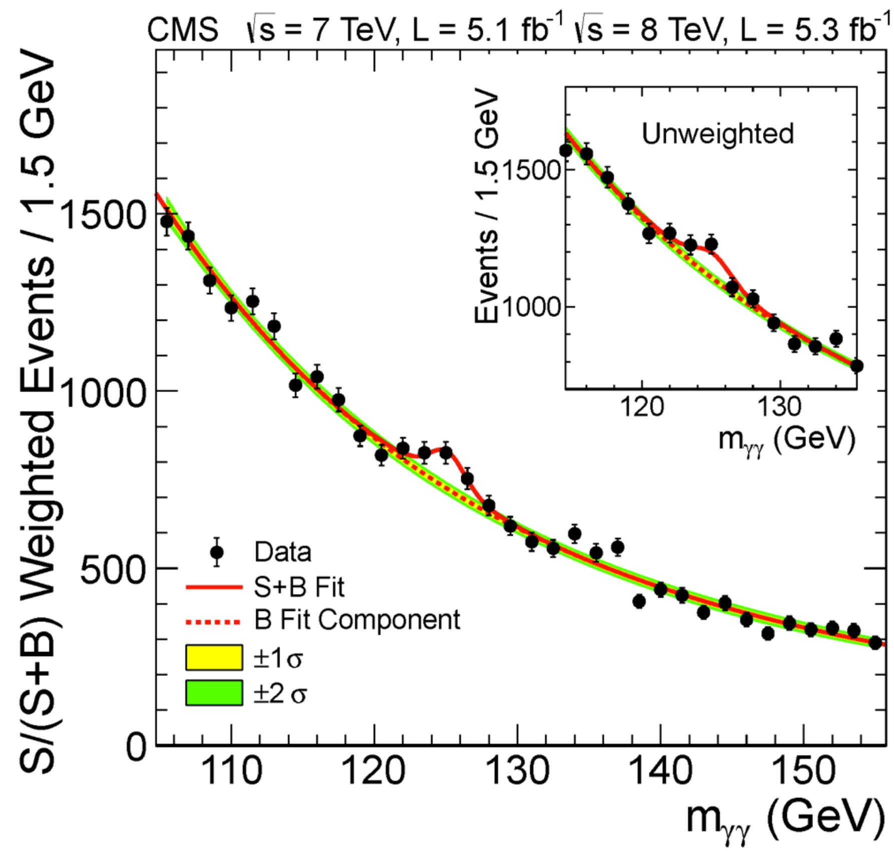
- Lots of high-precision data have been obtained and more to come. Have we really seen any of it?
- Probing NP in flavor physics = waiting for Godot?

Energy Frontiers

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





Precision Frontiers

- Flavor physics experiments have been probing particle physics at precision frontier.
- Many FCNC processes of B physics are used to impose stringent constraints on new physics models.
  - disappearing low-energy anomalies such as B_s meson mixing and FBA in $B \to K^* \mu\mu$
  - reduced tension between $B \to \tau\nu$ and $\sin 2\beta$ about $|V_{ub}|$.
  - stronger constraints / bounds from $BR(B_{s,d} \to \mu^+\mu^-)$.
  - some lingering problems such as $K\pi$ puzzle and like-sign dimuon asymmetry.

- In general, current data point to contrived NP models if it has to show up at the TeV scale.

What About Charm System?

- 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 good place to observe NP?

- Recent direct CPA difference in hadronic D decays
  ➡ indicating NP beyond the SM?
  ➡ demanding new understanding of SM?

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

Dominant Charm Decays

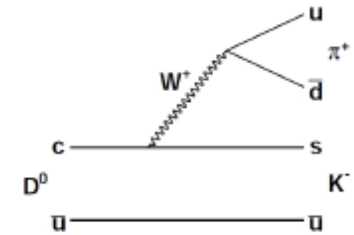
- D mesons decay dominantly (~84%) into hadronic final states, 3/4 of which are two-body modes.
  ➠ unlike B mesons

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	$\sim 16\%$

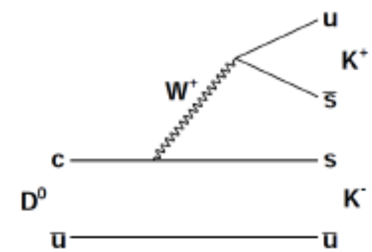
P: pseudoscalar meson
V: vector meson
A: axial vector meson
T: tensor meson

Two-Body Hadronic Charm Decays

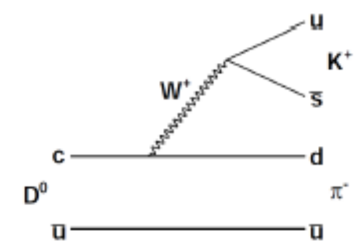
- Cabibbo-favored (CF):
  involving $V_{ud}^{*}V_{cs} \sim 1-\lambda^2 \sim 0.95$



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



- Doubly Cabibbo-suppressed (DCS):
  involving $V_{us}^{*}V_{cd} \sim \lambda^2 \sim 0.05$



Two-Body Hadronic Charm Decays

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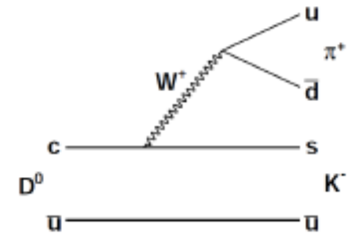

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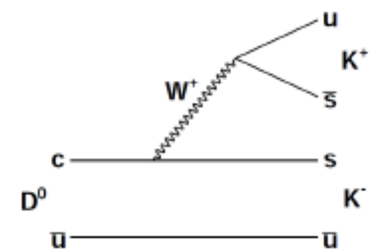
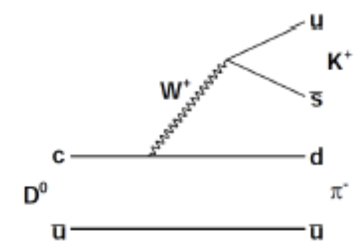


- Doubly Cabibbo-suppressed (DCS):
  involving $V_{us}^{*}V_{cd} \sim \lambda^2 \sim 0.05$



- Only SCS decays can possibly involve diagrams with different CKM phases and thus possibly have CPA's:

$$\text{Amp} = V_{cd}^{*}V_{ud}(\text{trees} + \text{penguins}) + V_{cs}^{*}V_{us}(\text{trees} + \text{penguins})$$

CP Violation in SCS Decays

- CPA's in SCS decay modes are expected only at 10^{-4} to 10^{-3} level

$$a_{CP}^{\rm dir} = \frac{2{\rm Im}(V_{cd}^* V_{ud} V_{cs} V_{us}^*)}{|V_{cd}^* V_{ud}|^2} \left|\frac{A_2}{A_1}\right| \sin\delta = 2\left|\frac{V_{cb}^* V_{ub}}{V_{cd}^* V_{ud}}\right| \sin\gamma \left|\frac{A_2}{A_1}\right| \sin\delta$$

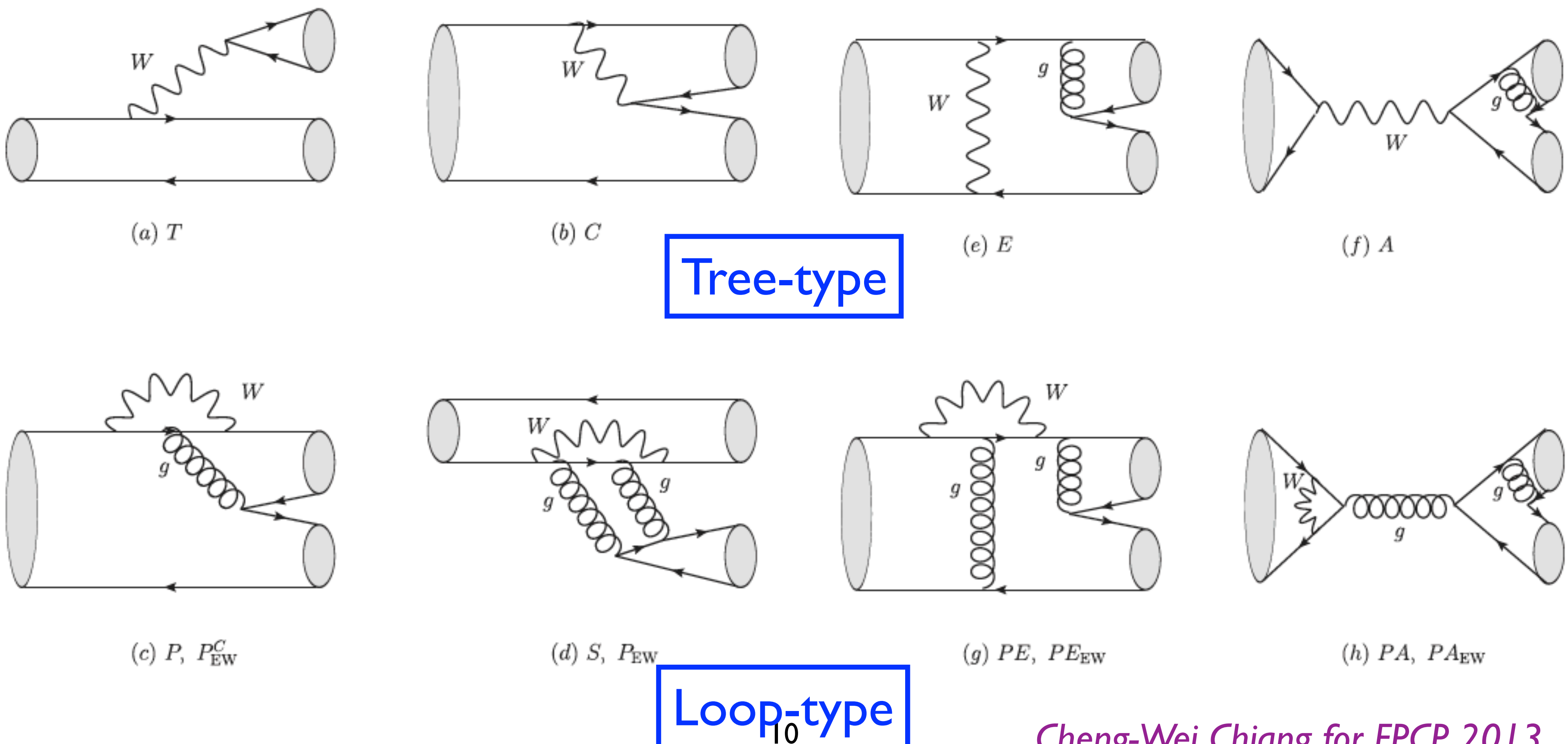
$$\sim 10^{-3} \left|\frac{A_2}{A_1}\right| \sin\delta \qquad (\delta = \text{relative strong phase})$$

➠ new physics, if measured to be sizable

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



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^+	$\bar{K}^0 K^+$	$V_{cs}^* V_{ud}(C+A)$	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

satisfactory fit

- η-η' mixing (with ϕ = 40.4°): KLOE 2009

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

Extracted Amplitudes

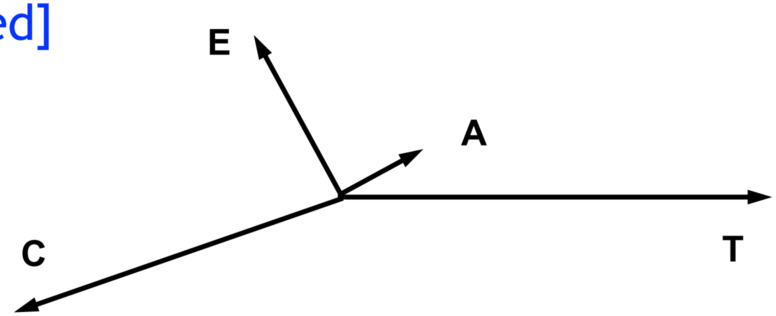
- The amplitudes extracted from Cabibbo-favored modes in units of 10^{-6} GeV are (χ^2/dof = 0.65):

CWC, Luo, Rosner 2002, 2003
Wu, Zhong, Zhou 2004
Bhattacharya and Rosner 2008, 2010
Cheng and CWC 2010

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

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

[CKM factors extracted]

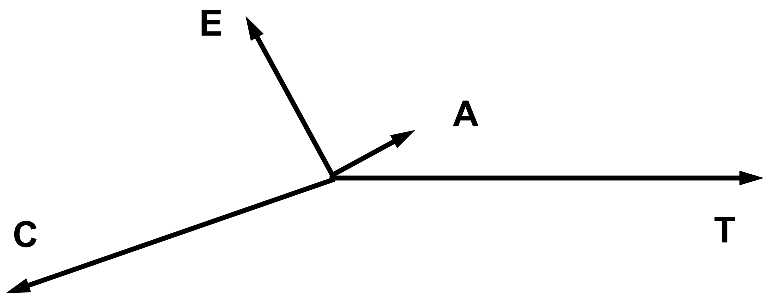


- Results are used to predict SCS and DCS decays utilizing the flavor SU(3) symmetry.

Implications

Cheng and CWC 2010

- T and C are almost opposite in phase, and C and E are quite sizable (*cf*. B decays)
  ➠ large final-state interaction effects
  ➠ result of rescattering via abundant resonances around D mesons
  ➠ failure of perturbative approaches



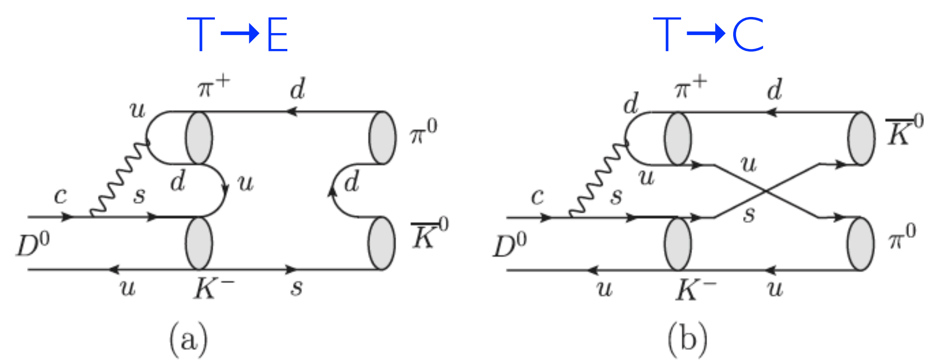


FIG. 1. Contributions to $D^0 \to \bar{K}^0\pi^0$ from the color-allowed weak decay $D^0 \to K^-\pi^+$ followed by a resonantlike rescattering (a) and quark exchange (b). While (a) has the same topology as the W-exchange graph, (b) mimics the color-suppressed internal W-emission graph.

SCS D→PP Decays -- SU(3) Limit

Decay Mode	$\mathcal{B}_{SU(3)}$	$\mathcal{B}_{SU(3)\text{-breaking}}$	$\mathcal{B}_{expt}$
$D^0 \to \pi^+\pi^-$	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

DCS D→PP Decays -- SU(3) Limit

- Predictions and measured data agree well.

Cheng and CWC 2010

TABLE III. Branching fractions and invariant amplitudes for doubly Cabibbo-suppressed decays of charmed mesons to two pseudoscalar mesons. Data are taken from [4]. Predictions based on our best-fitted results in (7) with exact flavor SU(3) symmetry are given in the last column.

Meson	Mode	Representation	$\mathcal{B}_{\rm exp}$ ($\times 10^{-4}$)	$\mathcal{B}_{\rm theory}$ ($\times 10^{-4}$)
D^0	$K^+\pi^-$	$V^*_{cd}V_{us}(T'' + E'')$	1.48 ± 0.07	1.12 ± 0.05
	$K^0\pi^0$	$\frac{1}{\sqrt{2}}V^*_{cd}V_{us}(C'' - E'')$		0.67 ± 0.02
	$K^0\eta$	$V^*_{cd}V_{us}[\frac{1}{\sqrt{2}}(C'' + E'')\cos\phi - E''\sin\phi]$		0.28 ± 0.02
	$K^0\eta'$	$V^*_{cd}V_{us}[\frac{1}{\sqrt{2}}(C'' + E'')\sin\phi + E''\cos\phi]$		0.55 ± 0.03
D^+	$K^0\pi^+$	$V^*_{cd}V_{us}(C'' + A'')$		1.98 ± 0.22
	$K^+\pi^0$	$\frac{1}{\sqrt{2}}V^*_{cd}V_{us}(T'' - A'')$	1.72 ± 0.19	1.59 ± 0.15
	$K^+\eta$	$V^*_{cd}V_{us}(\frac{1}{\sqrt{2}}(T'' + A'')\cos\phi - A''\sin\phi)$		0.98 ± 0.04
	$K^+\eta'$	$V^*_{cd}V_{us}(\frac{1}{\sqrt{2}}(T'' + A'')\sin\phi + A''\cos\phi)$		0.91 ± 0.17
D_s^+	K^0K^+	$V^*_{cd}V_{us}(T'' + C'')$		0.38 ± 0.04

to be checked against future data

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

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

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

$$
\begin{aligned}
\Sigma P &= (P + PE + PA)_d + (P + PE + PA)_s \\
\Delta P &= (P + PE + PA)_d - (P + PE + PA)_s \\
\lambda_q &= V_{cq}^* V_{uq}
\end{aligned}
$$

quark involved in penguin loop

A Long-Standing Puzzle

- $D \to \pi^+\pi^-$, 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 for the SU(3) limit, not to mention that K^+K^- has less phase space than $\pi^+\pi^-$.

- SU(3) breaking in factorizable part
$$\frac{T(K^+K^-)}{T(\pi^+\pi^-)} \simeq \frac{f_K}{f_\pi} \simeq 1.22 \text{ or } \frac{f_K}{f_\pi}\frac{F_+^{DK}(m_K^2)}{F_+^{D\pi}(m_\pi^2)} \simeq 1.38$$
is insufficient to account for data.

Direct CP Asymmetry Difference

- Time-integrated asymmetry to first order in the average decay time <t>:

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

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

- Consider

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

$$\simeq a_{CP}^{\rm dir}(K^+K^-) - a_{CP}^{\rm dir}(\pi^+\pi^-) + \frac{\Delta\langle t \rangle}{\tau_D} a_{CP}^{\rm ind}$$

(1) common systematic factors cancel out;
(2) insensitive to indirect CPV;
(3) SM and most NP models predict opposite signs.

ΔA_{CP} for K^+K^- and $\pi^+\pi^-$ circa 2012

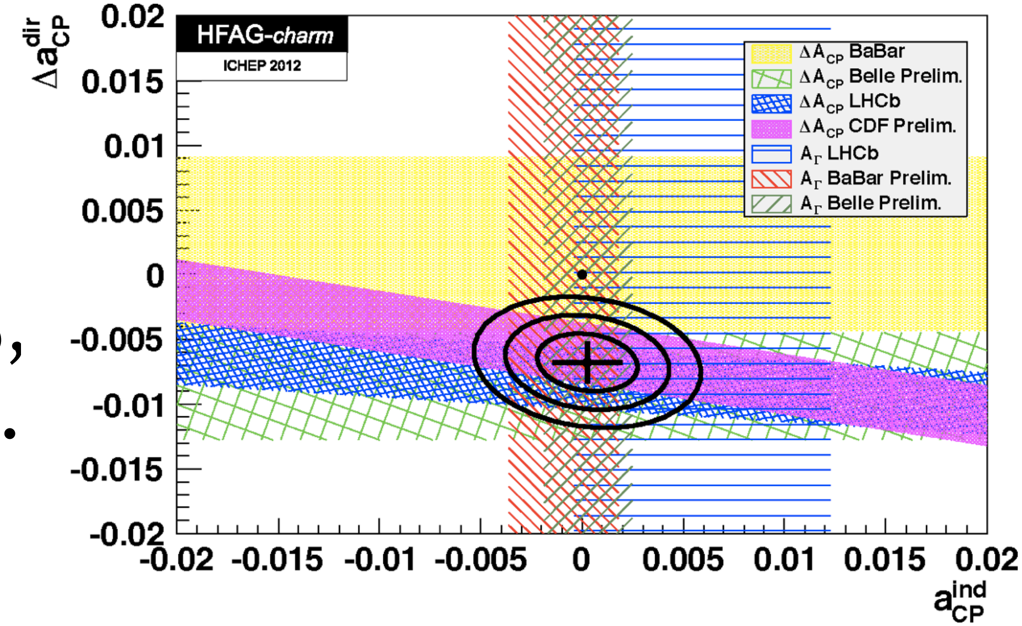
HFAG ICHEP 2012

- Combination of the LHCb, CDF, BaBar and Belle measurements yields

  $a_{CP}^{ind} = -(0.027\pm0.163)\%$,

  $\Delta a_{CP}^{dir} = -(0.678\pm0.147)\%$.

  4.6σ from no CPV



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	$-0.32 \pm 0.21 \pm 0.09$	$0.55 \pm 0.36 \pm 0.09$	$-0.87 \pm 0.41 \pm 0.06$

➠ ~30 theory papers followed

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 a complex ε_T and $|\varepsilon_T| \in (0,0.3)$.

- 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 SU(3) breaking in T by factorization

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

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

Our Analysis

- Significant SU(3) symmetry breaking 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
- Fix E_d and E_s from rates of K^+K^-, $\pi^+\pi^-$, $\pi^0\pi^0$, and $K^0\underline{K}^0$:

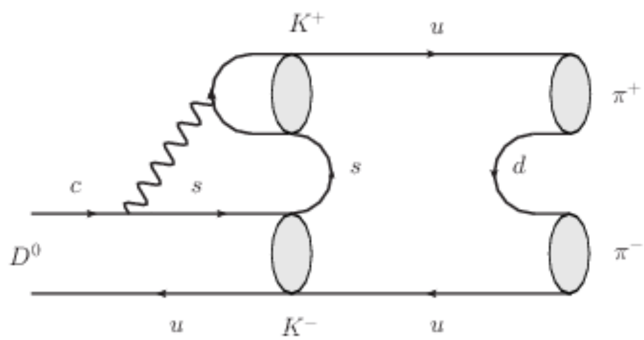
$$\text{(I)}\ E_d = 1.19\,e^{i15.0^\circ}E, \quad E_s = 0.58\,e^{-i14.7^\circ}E\ ,$$

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

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

Penguin Amplitudes

- Short-distance weak penguin exchange/annihilation diagrams are very small
  ➠ |PE/T| ~ 0.04 and |PA/T|~ 0.02
- Large long-distance contribution to PE can possibly arise from $D^0 \to K^+K^-$ followed by a resonance-like final-state rescattering, in the same fashion as for E



- It is possible to have PE ~ E, just to maximize CPV.
- Use QCDF to estimate other penguin amplitudes.
  ➠ negligible ΔP

SCS D→PP Decays -- SU(3) Breaking

Decay Mode	$\mathcal{B}_{SU(3)}$	$\mathcal{B}_{SU(3)-breaking}$	$\mathcal{B}_{expt}$
$D^0 \to \pi^+\pi^-$	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

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

Cheng and CWC 2012

in units of 10^{-3}

Our A_{CP} Predictions

pQCD results

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	
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$D^+ \to \pi^+\pi^0$	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
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Cheng and CWC 2012

$\Delta a_{CP}^{dir} = -(0.139 \pm 0.004)\%$ (I)
$-(0.151 \pm 0.004)\%$ (II)
$\sim 3.6\sigma$ from $-(0.678 \pm 0.147)\%$

in units of 10^{-3}

Our A_{CP} Predictions

pQCD results

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

Cheng and CWC 2012

$\Delta a_{CP}^{dir} = -(0.139 \pm 0.004)\%$ (I)
$-(0.151 \pm 0.004)\%$ (II)
~3.6σ from $-(0.678 \pm 0.147)\%$

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

in units of 10^{-3}

New Physics Interpretations

- Before LHCb result:
  - 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 result:
  - 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
  - non-MFV 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.

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

- The QCD dipole operator

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

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 fit Δa_{CP}^{dir}
- 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 using more data

TABLE IV. Direct CP asymmetries (in units of 10^{-3}) of SCS $D \to PP$ decays estimated in the scenarios with large penguin contributions and large chromomagnetic dipole operator (c.d.o.). The parameters ΣP and c_{8g}^{NP} are chosen to fit the data of Δa_{CP}^{dir}: $\frac{1}{2}\Sigma P = 2.9Te^{i85°}$ and $c_{8g}^{NP} = 0.017e^{i14°}$ for Solution I, $\frac{1}{2}\Sigma P = 3.2Te^{i85°}$ and $c_{8g}^{NP} = 0.012e^{i14°}$ for Solution II. The number in parentheses is for Solution II of E_d and E_s [Eq. (17)].

Decay mode	Large penguins	Large c.d.o.
$D^0 \to \pi^+\pi^-$	3.96 (4.40)	5.18 (3.70)
$D^0 \to \pi^0\pi^0$	0.93 (1.01)	8.63 (6.19)
$D^0 \to \pi^0\eta$	0.09 (0.03)	−6.12 (−4.15)
$D^0 \to \pi^0\eta'$	2.36 (2.67)	−0.44 (−0.44)
$D^0 \to \eta\eta$	−1.79 (−1.64)	−1.63 (−2.00)
$D^0 \to \eta\eta'$	2.65 (1.49)	−2.30 (−1.08)
$D^0 \to K^+K^-$	−2.63 (−2.36)	−1.46 (−2.88)
$D^+ \to \pi^+\pi^0$	0 (0)	0 (0)
$D^+ \to \pi^+\eta$	−3.24 (−3.62)	−5.35 (−3.67)
$D^+ \to \pi^+\eta'$	2.97 (3.34)	0.93 (0.59)
$D^+ \to K^+\bar{K}^0$	−2.95 (−3.28)	0.37 (0.29)
$D_s^+ \to \pi^+K^0$	3.29 (3.66)	−0.47 (−0.35)
$D_s^+ \to \pi^0K^+$	4.57 (5.08)	4.40 (3.14)
$D_s^+ \to K^+\eta$	−0.58 (−0.57)	1.59 (0.94)
$D_s^+ \to K^+\eta'$	−5.16 (−5.79)	1.76 (1.39)

New LHCb data

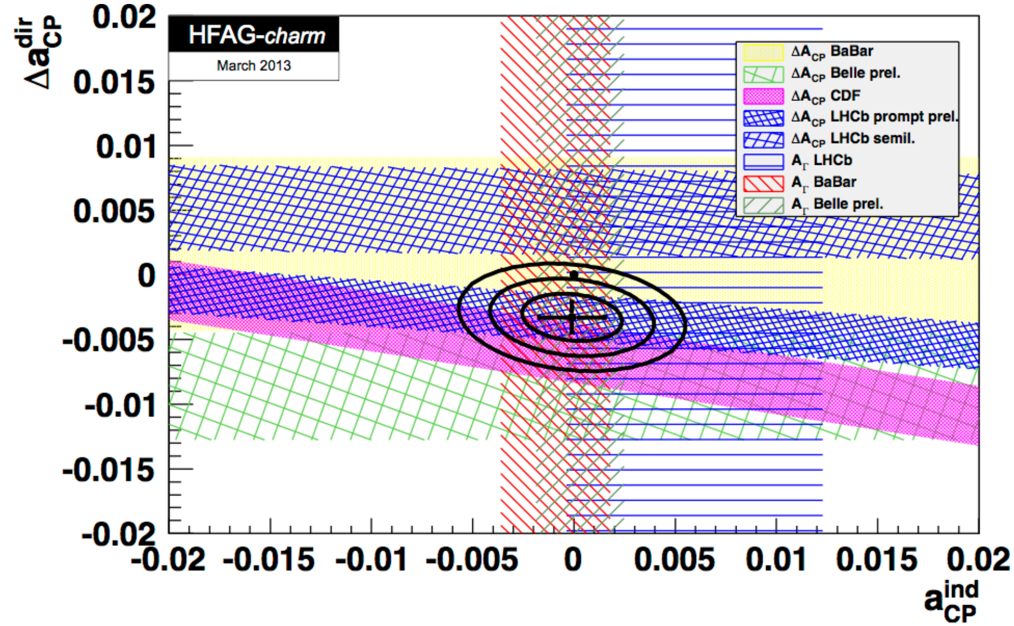
- Use 1.0 fb^{-1} of data collected in 2011. LHCb 2013
- Include two datasets: prompt (update) and secondary (new as a crosscheck), with little overlap in between.
  Prompt: $\Delta A_{CP} = -(0.34 \pm 0.15 \pm 0.10)\%$
  Secondary: $\Delta A_{CP} = +(0.49 \pm 0.30 \pm 0.14)\%$

HFAG 2013

- New world average:
  $a_{CP}^{ind} = -(0.010 \pm 0.162)\%$,
  $\Delta a_{CP}^{dir} = -(0.329 \pm 0.121)\%$.

  2.7σ from no CPV
  1.5σ from our estimate

➠ more SM-like now



x and y Parameters

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

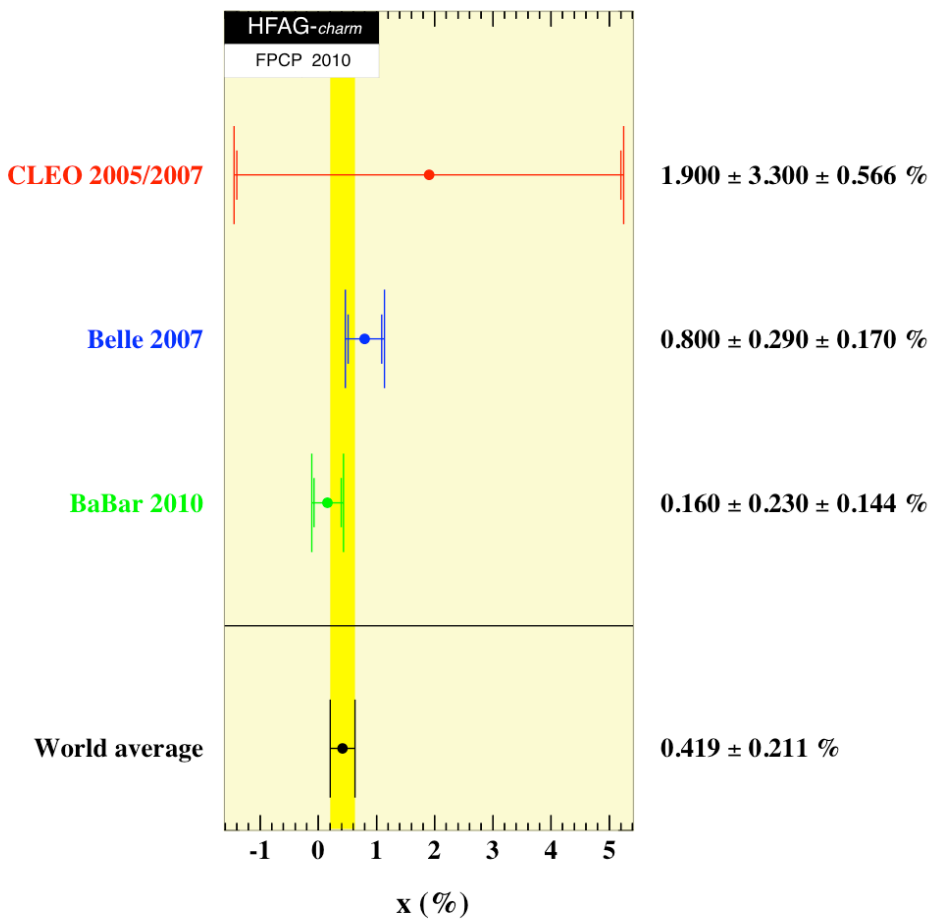
$$x \equiv \frac{\Delta m}{\Gamma} = \frac{m_+ - m_-}{\Gamma} \quad \text{and} \quad y \equiv \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_+ - \Gamma_-}{2\Gamma}$$

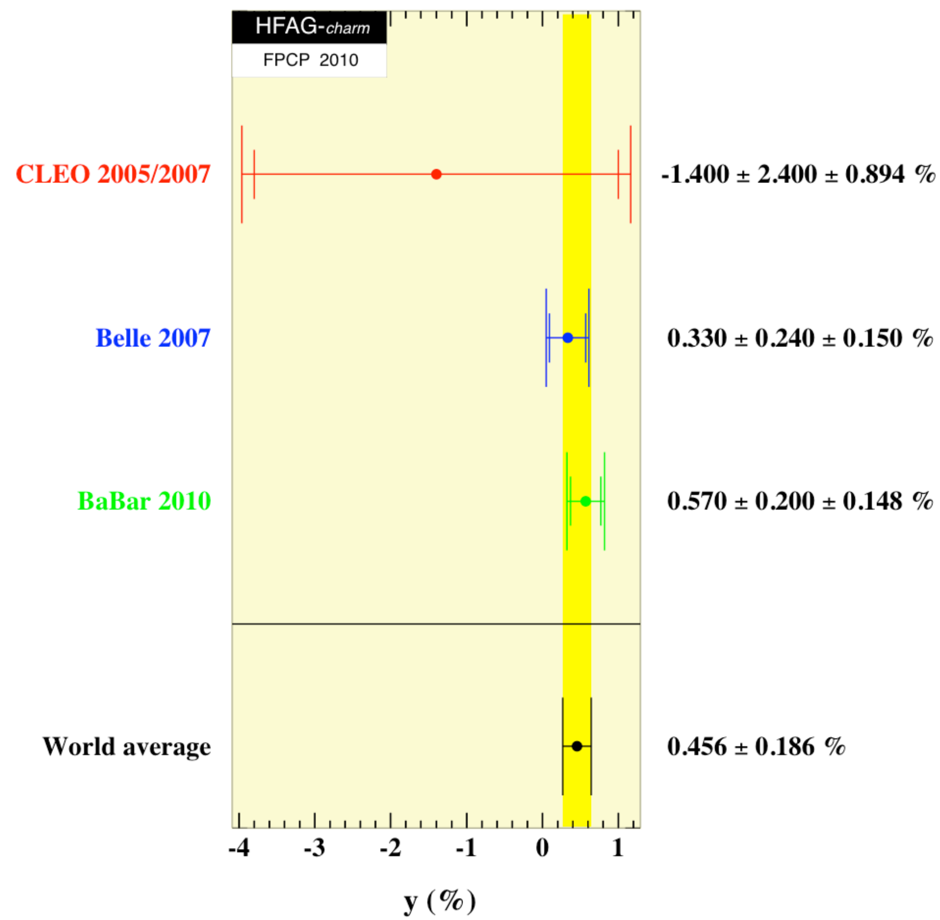
where the subscripts (+,−) correspond to the CP eigenstates

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

- 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?

x and y from Dalitz Analysis





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

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 $y \sim 10^{-2}$
  - 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 and predictions based on the flavor symmetry approach 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.

Summary

- Flavor diagram approach with SU(3) symmetry breaking effects is useful to explain BR's of SCS $D \to PP$ decays.
- Large final-state rescattering effects and thus failure of purely perturbative approach are seen in data.
- Predictions of CPA's are made within SM, and Δa_{CP}^{dir} is around −0.15%, 3.6σ from 2012 data but only 1.5σ from new world average.
  ➠ tension between data and SM predictions is alleviated
- Measurements of other CPA's will help discriminating among different analyses (within and beyond SM).
- Long-distance contributions dominate in the D mixing parameters. Current data do not call for NP.

Thank You!