D0-D0bar Mixing in an exclusive approach

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in progress

CHARM @ WSU

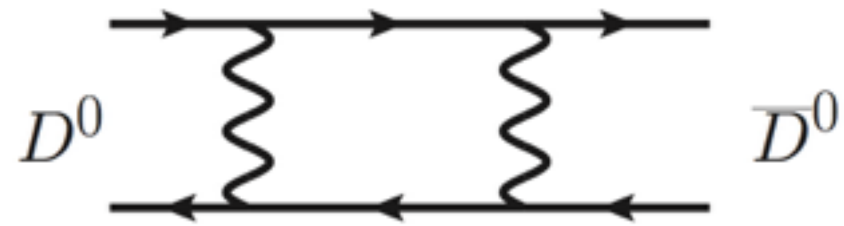
20.05.2015

Outline

A.Kagan's talk tomorrow

- Motivation
  - DDbar mixing misunderstood in theory
- D-Dbar Mixing in an exclusive approach
  - Large flavor SU(3) breaking effect in factorization-assisted topological-amplitude approach
- Conclusions

$D^0 - \overline{D}^0$ Mixing



- The time evolution

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

- Mass eigenstates in terms of weak eigenstates

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

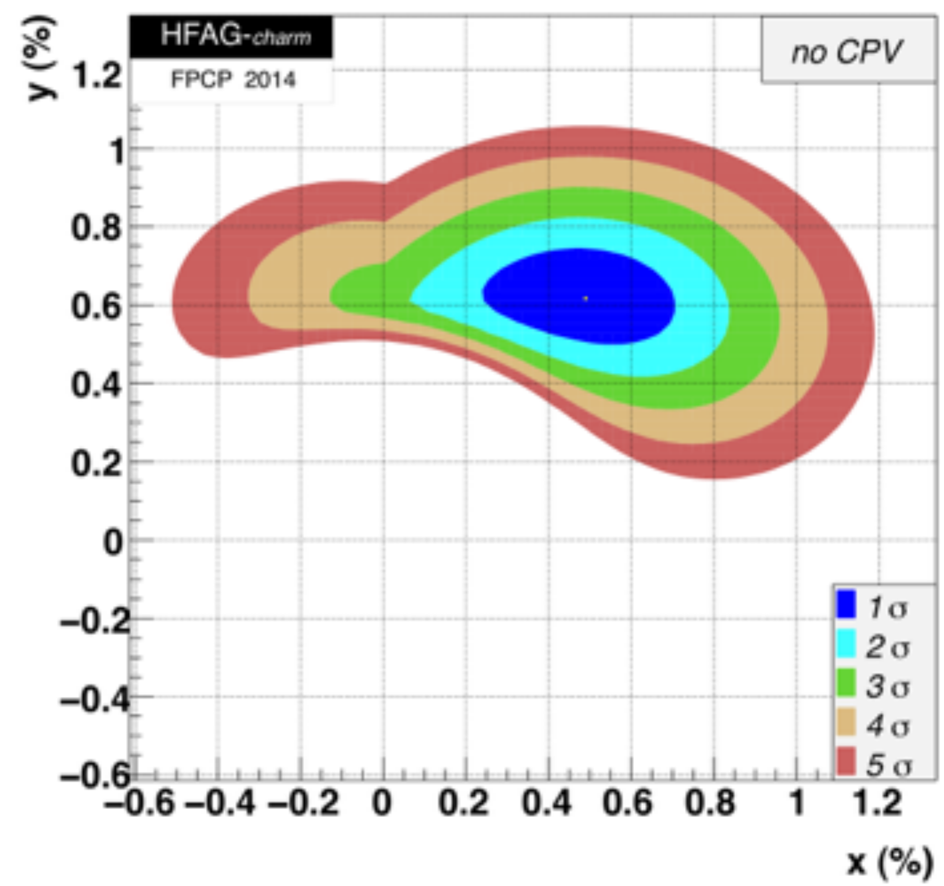
- Mass difference and Width difference

$$\boxed{x \equiv \frac{\Delta m}{\Gamma} = \frac{m_1 - m_2}{\Gamma}} \qquad \boxed{y \equiv \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}}$$

Experiment vs. Theory

- Current world average results

[HFAG, 2014]



  - ✳ If CP is conserved

$$x = (0.49^{+0.14}_{-0.15})\%, \quad y = (0.62 \pm 0.08)\%$$

  - ✳ If CP violation is allowed

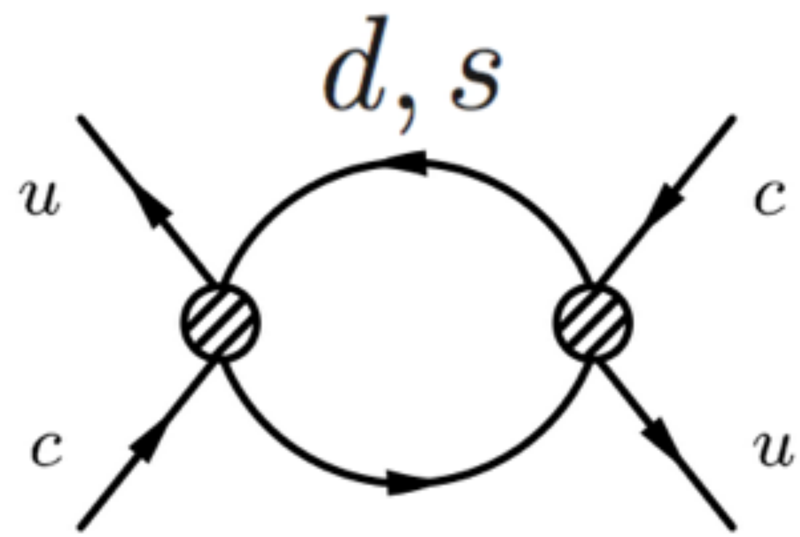
$$x = (0.41^{+0.14}_{-0.15})\%, \quad y = (0.63^{+0.07}_{-0.08})\%$$

- So far, **quantitatively** theoretical calculation can just reach to the order of x~y~0.1%

[Bigi et al, 00'; Lenz et al, 10'; Cheng et al, 10']

Inclusive approach:

quark level **Heavy Quark Expansion**



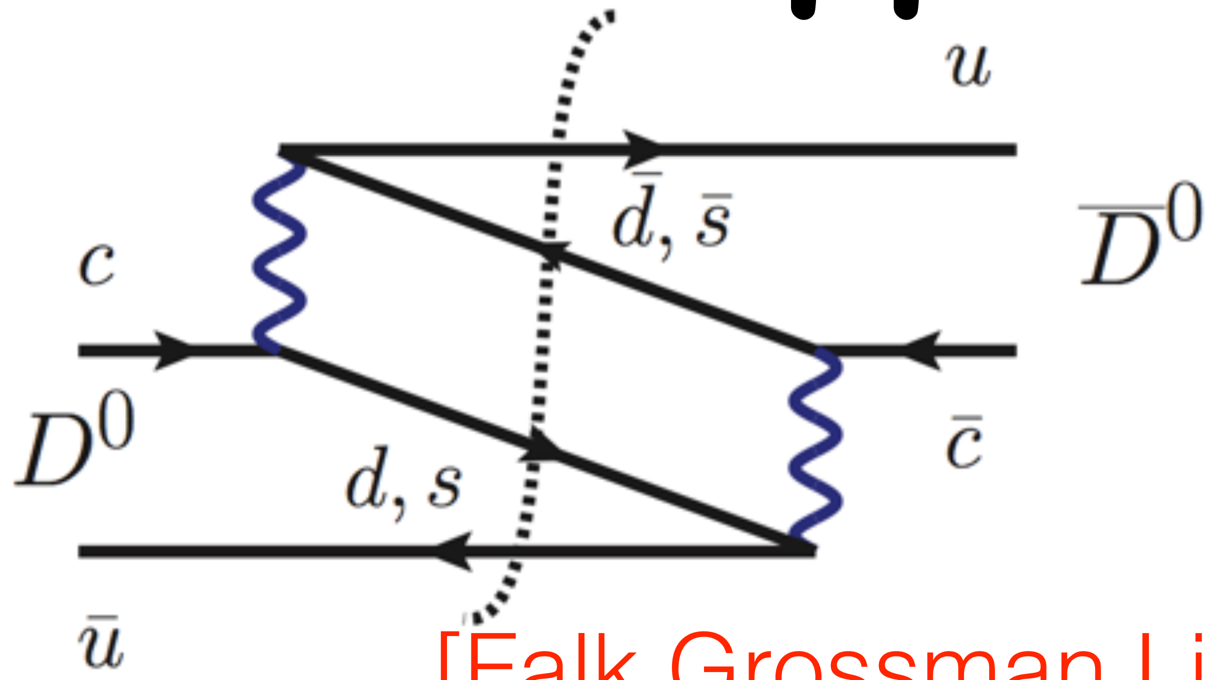
$x \sim (m_s/m_c)^4$ $y \sim (m_s/m_c)^6$

$x \sim 10^{-6}$ $y \lesssim 0.9 \times 10^{-5}$ [Bobrowski, Lenz, 09']

[Lenz,et al, 10']

$\boxed{\text{Short-distance contributions are small}}$

Exclusive Approach



[Falk,Grossman,Ligeti,Petrov, 02']

$$y = \frac{1}{2\Gamma}\sum_n \rho_n \eta_{\rm CP}(n)\left(\langle D^0|H_w|n\rangle\langle\bar{n}|H_w|D^0\rangle + \langle D^0|H_w|\bar{n}\rangle\langle n|H_w|D^0\rangle\right)$$
$$= \sum_n \eta_{\rm CKM}(n)\eta_{\rm CP}(n)\cos\delta_n\sqrt{Br(D^0\to n)Br(D^0\to\bar{n})}\,,$$

Sum up all the intermediate states

➩ **To predict Branching fractions well**

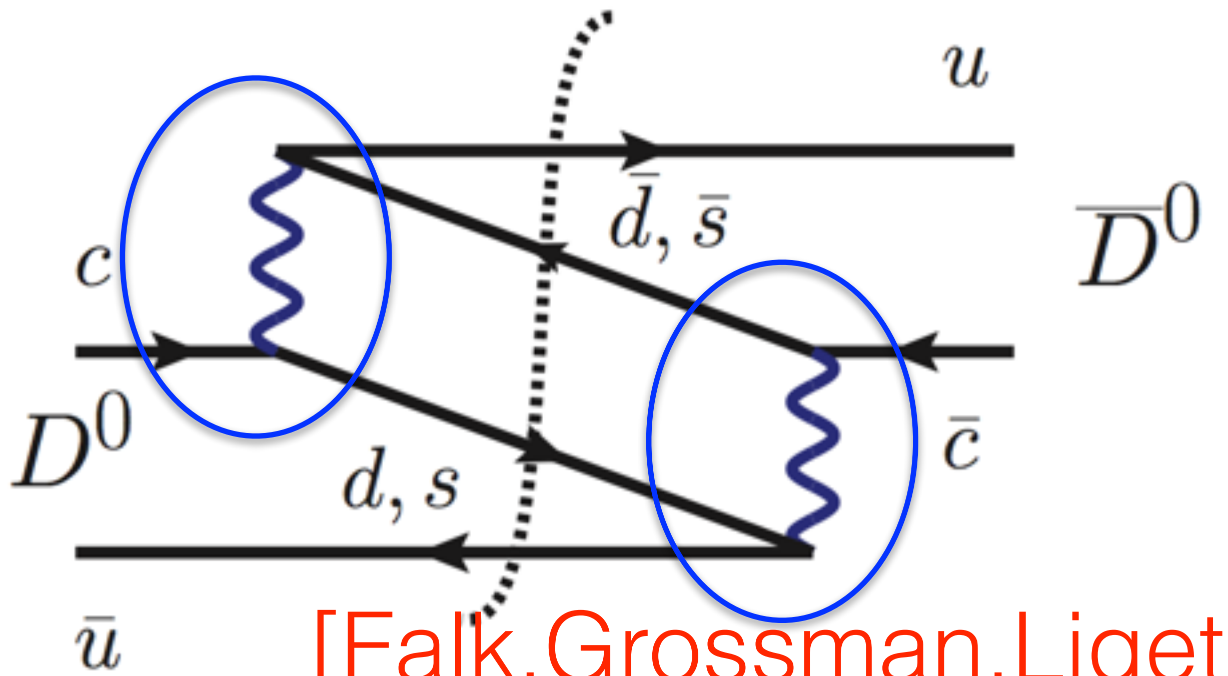
Exclusive Approach

Sum up all the intermediate states

$$
\begin{aligned}
y &= \frac{1}{2\Gamma}\sum_n \rho_n \eta_{\mathrm{CP}}(n)(\langle D^0|H_w|n\rangle\langle\bar{n}|H_w|D^0\rangle + \langle D^0|H_w|\bar{n}\rangle\langle n|H_w|D^0\rangle) \\
&= \sum_n \eta_{\mathrm{CKM}}(n)\eta_{\mathrm{CP}}(n)\cos\delta_n \sqrt{Br(D^0\to n)Br(D^0\to\bar{n})}\ ,
\end{aligned}
$$

- SU(3) breaking effect from phase space [Falk,Grossman,Ligeti,Petrov, 02'] $\pi\pi\pi\pi$ $v.s.$ $KKKK$
- Topological diagrammatic approach [Cheng,Chiang, 10']
- U-spin breaking effect [Gronau, Rosner, 12']

Naive Expectation



[Falk,Grossman,Ligeti,Petrov,2002]

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

$$0.2^2 \times 0.3^2 \sim \boxed{0.4\%}$$

Exp: $x = (0.49^{+0.14}_{-0.15})\%, \quad y = (0.62 \pm 0.08)\%$

- **Well description of SU(3) breaking is a central issue**

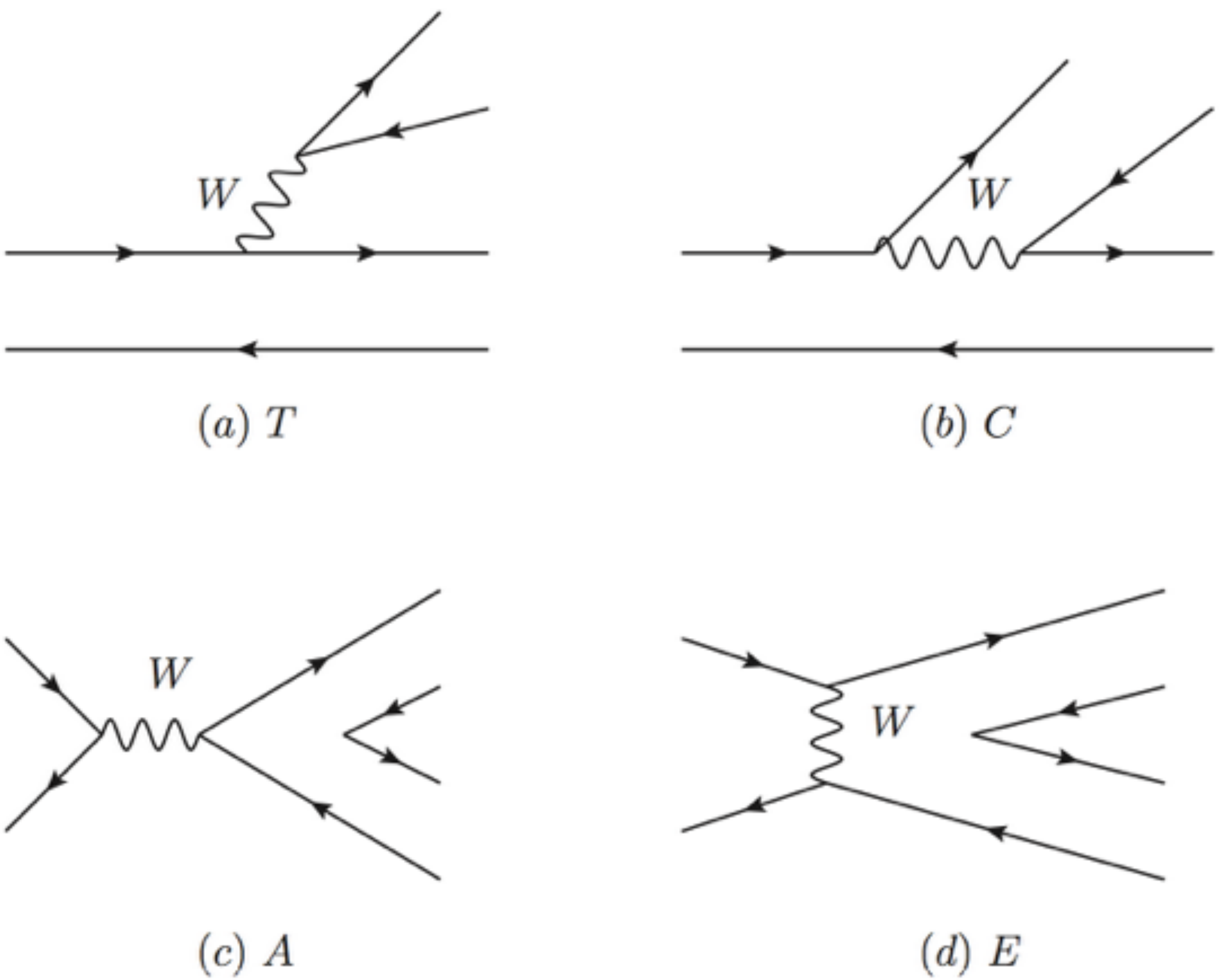
[Paul's talk yesterday]

Problem on dynamics

- $m_c \sim 1.3\text{GeV}$
  - Neither heavy enough for heavy quark expansion, 1/mc
  - Nor light enough for chiral perturbation theory
- QCD-inspired methods do not work: HQET, QCDF, PQCD, SCET.

Large nonperturbative contributions

Topological-Amplitude Approach

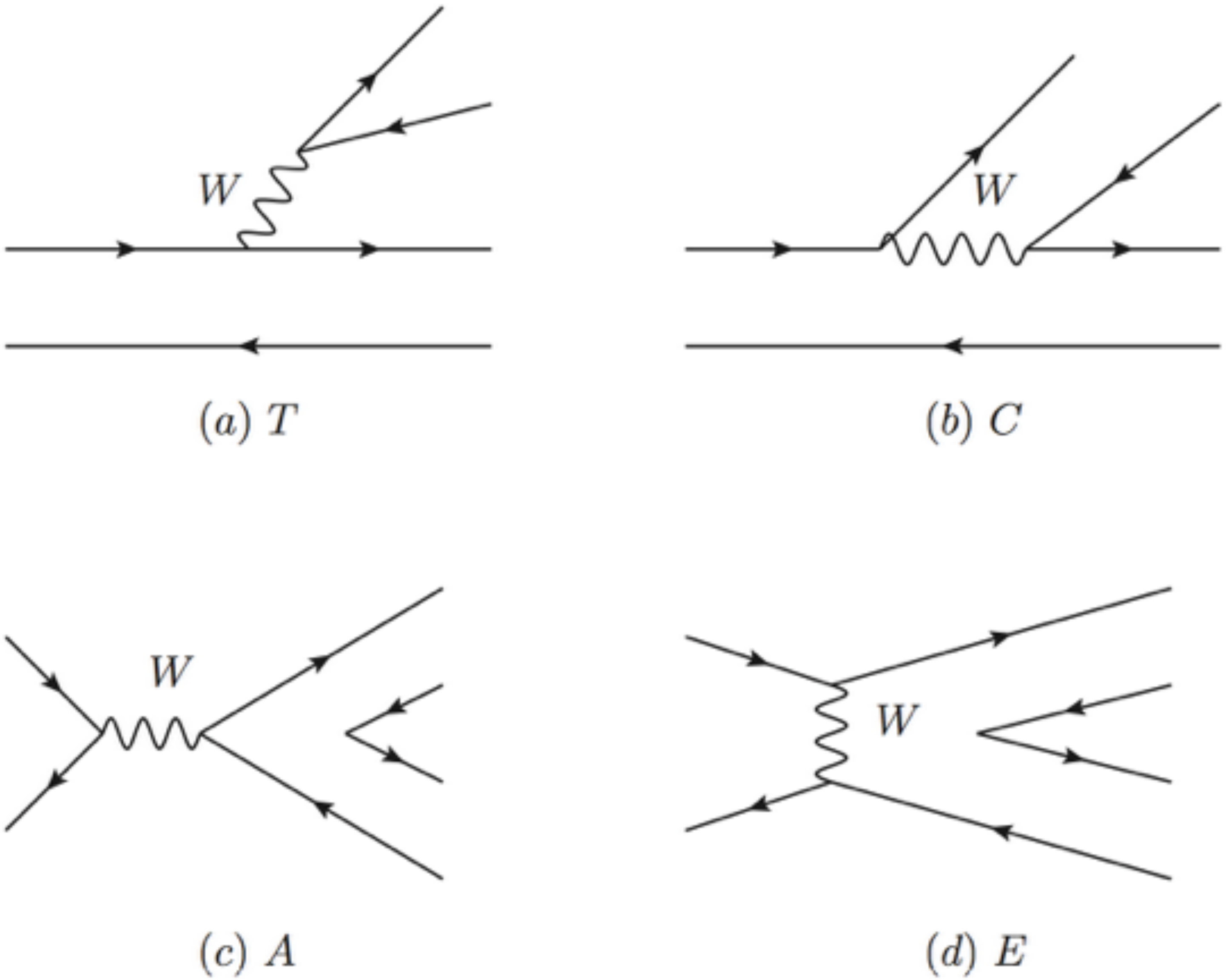


[Bhattacharya, Rosner, 08',10']

[Cheng, Chiang, 10']

[Schacht's talk tomorrow]

Factorization-Assisted Topological-Amplitude Approach



[Bhattacharya, Rosner, 08',10']

[Cheng, Chiang, 10']

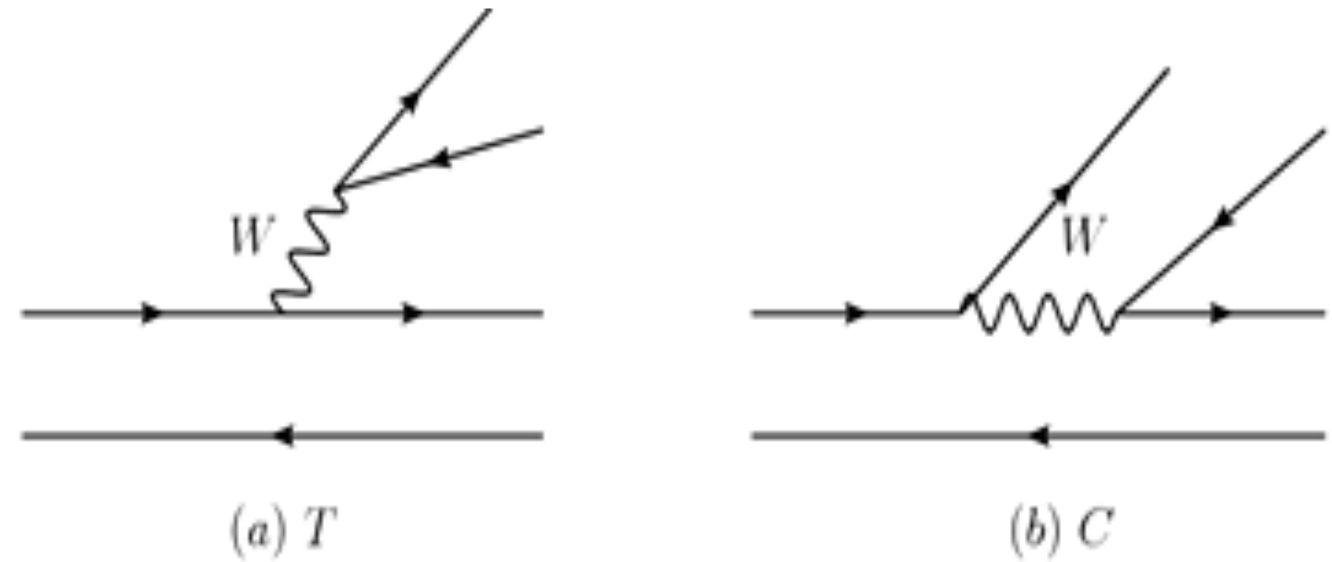
[Schacht's talk tomorrow]

- Calculate each topological amplitude in factorization:
- Short-distance dynamics: Wilson coefficients
- Long-distance dynamics: hadronic matrix elements

[Li, Lu, FSY, 1203.3120]

Emission Amplitudes

- Color-favored Tree (T)
- Color-suppressed (C)



$$\boxed{\langle P_1 P_2 | \mathcal{H}_{eff} | D \rangle_{T,C} \;=\; \frac{G_F}{\sqrt{2}} V_{CKM} a_{1,2}(\mu) f_{P_2} (m_D^2 - m_{P_1}^2) F_0^{DP_1}(m_{P_2}^2)}$$

$$a_1(\mu) = C_2(\mu) + \frac{C_1(\mu)}{N_c},$$

Non-factorizable

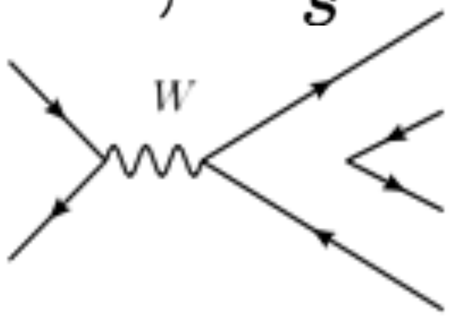
$$a_2(\mu) = C_1(\mu) + C_2(\mu)\left[\frac{1}{N_c} + \chi_{nf} e^{i\phi}\right],$$

$$\mu = \sqrt{\Lambda m_D (1 - r_2^2)}, \quad r_2 = m_{P_2}^2 / m_D^2$$

SU(3) breaking effects

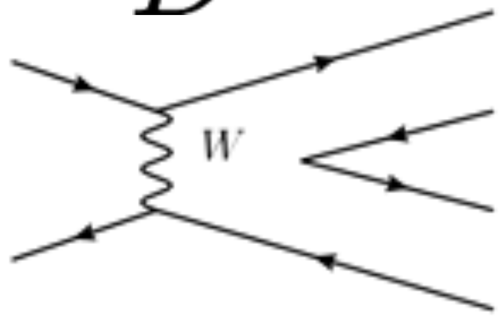
[Li, Lu, FSY, 1203.3120]

$D^{\pm}, D_s^{\pm}$



(c) A

D^0



(d) E

[Li, Lu, FSY, 12']

W-annihilation (A)
W-exchange (E)

$$\langle P_1 P_2 | \mathcal{H}_{\rm eff} | D \rangle_{E,A} = \frac{G_F}{\sqrt{2}} V_{\rm CKM} b_{q,s}^{E,A}(\mu) f_D m_D^2 \left(\frac{f_{P_1} f_{P_2}}{f_\pi^2} \right)$$

Dominated by **non-factorizable** contribution

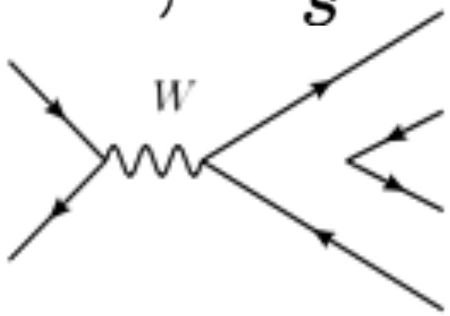
$$\text{A:}\quad b_{q,s}^{A}(\mu) = C_1(\mu)\,\boxed{\chi_{q,s}^{A}}\, e^{i\phi_{q,s}^{A}}$$

$$\text{E:}\quad b_{q,s}^{E}(\mu) = C_2(\mu)\,\boxed{\chi_{q,s}^{E}}\, e^{i\phi_{q,s}^{E}},$$

Factorization-Assisted Topological Approach

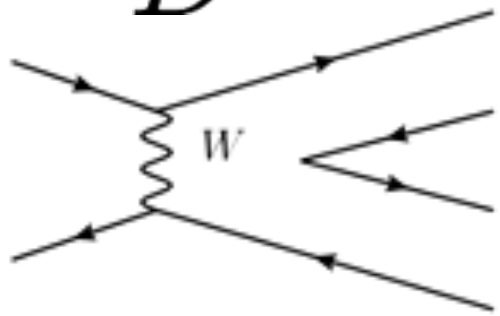
nonperturbative contributions

$D^{\pm}, D_s^{\pm}$



(c) A

D^0



(d) E

[Li, Lu, FSY, 12']

W-annihilation (A)
W-exchange (E)

$$\boxed{\langle P_1 P_2 | \mathcal{H}_{\text{eff}} | D \rangle_{E,A} = \frac{G_F}{\sqrt{2}} V_{\text{CKM}} b_{q,s}^{E,A}(\mu) f_D m_D^2 \left(\frac{f_{P_1} f_{P_2}}{f_\pi^2} \right)}$$

Dominated by **non-factorizable** contribution

SU(3) breaking effects

A: $b_{q,s}^{A}(\mu) = C_1(\mu) \chi_{q,s}^{A} e^{i\phi_{q,s}^{A}}$

E: $b_{q,s}^{E}(\mu) = C_2(\mu) \chi_{q,s}^{E} e^{i\phi_{q,s}^{E}}$

$\boxed{\chi^A \sim \chi^E}$

$$\chi_q^E = 0.11, \quad \chi_q^A = 0.12,$$
$$\chi_s^E = 0.18, \quad \chi_s^A = 0.17.$$

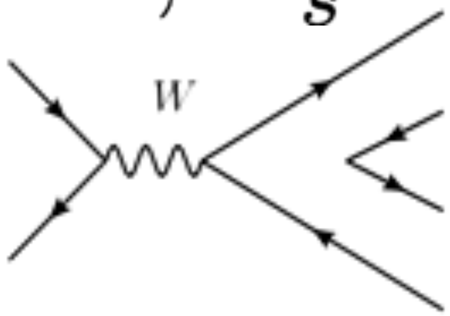
$\boxed{\chi_q \neq \chi_s}$

subscripts: quark pairs produced from vacuum

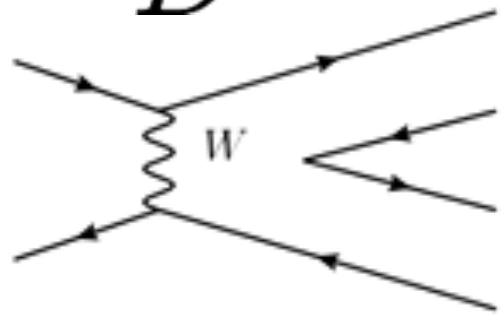
$D^{\pm}, D_s^{\pm}$ D^0

[Li, Lu, FSY, 12']

W-annihilation (A)
W-exchange (E)



(c) A



(d) E

$$\langle P_1 P_2 | \mathcal{H}_{\rm eff} | D \rangle_{E,A} = \frac{G_F}{\sqrt{2}} V_{\rm CKM} b^{E,A}_{q,s}(\mu) f_D m_D^2 \left(\frac{f_{P_1} f_{P_2}}{f_\pi^2} \right)$$

Dominated by **non-factorizable** contribution

SU(3) breaking effects

A: $b^A_{q,s}(\mu) = C_1(\mu) \chi^A_{q,s} e^{i\phi^A_{q,s}} + S_\pi$

E: $b^E_{q,s}(\mu) = C_2(\mu) \chi^E_{q,s} e^{i\phi^E_{q,s}} + S_\pi$

Glauber strong phase for pions

$\chi_q \neq \chi_s$

pion=> Goldstone boson?
qqbar bound state?

Much and precise experimental data

To extract nonperturbative parameters from data

PP: 12 parameters for 28 data
PV: 14 parameters for 33 data

more dynamics
more predictive

Singly Cabibbo-suppressed modes

agree well with experiments

More SU(3) breaking effects included

($\times 10^{-3}$)

Modes	Br(FSI)	Br(diagram)	Br(pole)	Br(exp)	Br(this work)
$D^0 \to \pi^+\pi^-$	1.59	2.24 ± 0.10	2.2 ± 0.5	1.45 ± 0.05	1.43
$D^0 \to K^+K^-$	4.56	1.92 ± 0.08	3.0 ± 0.8	4.07 ± 0.10	4.19
$D^0 \to K^0\bar{K}^0$	0.93	0	0.3 ± 0.1	0.320 ± 0.038	0.36
$D^0 \to \pi^0\pi^0$	1.16	1.35 ± 0.05	0.8 ± 0.2	0.81 ± 0.05	0.57
$D^0 \to \pi^0\eta$	0.58	0.75 ± 0.02	1.1 ± 0.3	0.68 ± 0.07	0.94
$D^0 \to \pi^0\eta'$	1.7	0.74 ± 0.02	0.6 ± 0.2	0.91 ± 0.13	0.65
$D^0 \to \eta\eta$	1.0	1.44 ± 0.08	1.3 ± 0.4	1.67 ± 0.18	1.48
$D^0 \to \eta\eta'$	2.2	1.19 ± 0.07	1.1 ± 0.1	1.05 ± 0.26	1.54
$D^+ \to \pi^+\pi^0$	1.7	0.88 ± 0.10	1.0 ± 0.5	1.18 ± 0.07	0.89
$D^+ \to K^+\bar{K}^0$	8.6	5.46 ± 0.53	8.4 ± 1.6	6.12 ± 0.22	5.95
$D^+ \to \pi^+\eta$	3.6	1.48 ± 0.26	1.6 ± 1.0	3.54 ± 0.21	3.39
$D^+ \to \pi^+\eta'$	7.9	3.70 ± 0.37	5.5 ± 0.8	4.68 ± 0.29	4.58
$D_S^+ \to \pi^0 K^+$	1.6	0.86 ± 0.09	0.5 ± 0.2	0.62 ± 0.23	0.67
$D_S^+ \to \pi^+ K^0$	4.3	2.73 ± 0.26	2.8 ± 0.6	2.52 ± 0.27	2.21
$D_S^+ \to K^+\eta$	2.7	0.78 ± 0.09	0.8 ± 0.5	1.76 ± 0.36	1.00
$D_S^+ \to K^+\eta'$	5.2	1.07 ± 0.17	1.4 ± 0.4	1.8 ± 0.5	1.92

[Li, Lu, FSY, 1203.3120]

Back to our topic in the end

D-Dbar Mixing in an exclusive approach

$$
\boxed{\begin{aligned} y &= \frac{1}{2\Gamma}\sum_n \rho_n \eta_{\rm CP}(n)\left(\langle D^0|H_w|n\rangle\langle\bar{n}|H_w|D^0\rangle + \langle D^0|H_w|\bar{n}\rangle\langle n|H_w|D^0\rangle\right) \\ &= \sum_n \eta_{\rm CKM}(n)\eta_{\rm CP}(n)\cos\delta_n\sqrt{Br(D^0\to n)Br(D^0\to\bar{n})}\ , \end{aligned}}
$$

$$
CP|M_1M_2\rangle = \eta_{\rm CP}(M_1)\eta_{\rm CP}(M_2)(-1)^L|M_1M_2\rangle = \eta_{\rm CP}(M_1M_2)|M_1M_2\rangle
$$

$$y_{PP}$$

vanish in the SU(3) symmetry limit

$$\boxed{\mathcal{B}(\pi^+\pi^-) + \mathcal{B}(K^+K^-) - 2\cos\delta_{K^+\pi^-}\sqrt{\mathcal{B}(K^-\pi^+)\mathcal{B}(K^+\pi^-)}}$$

$$+\mathcal{B}(\pi^0\pi^0) + \mathcal{B}(K^0\bar{K}^0) - 2\cos\delta_{K^0\pi^0}\sqrt{\mathcal{B}(\bar{K}^0\pi^0)\mathcal{B}(K^0\pi^0)}$$

$$+\mathcal{B}(\pi^0\eta) + \mathcal{B}(\pi^0\eta') + \mathcal{B}(\eta\eta) + \mathcal{B}(\eta\eta')$$

$$-2\cos\delta_{K^0\eta}\sqrt{\mathcal{B}(\bar{K}^0\eta)\mathcal{B}(K^0\eta)} - 2\cos\delta_{K^0\eta'}\sqrt{\mathcal{B}(\bar{K}^0\eta')\mathcal{B}(K^0\eta')}$$

y_{PV}

$$
\begin{aligned}
& Br(\pi^0\rho^0) + Br(\pi^0\omega) + Br(\pi^0\phi) + Br(\eta\omega) + Br(\eta'\omega) + Br(\eta\phi) + Br(\eta\rho^0) + Br(\eta'\rho^0) \\
& -2\cos\delta_{K^{*-}\pi^+}\sqrt{Br(K^{*-}\pi^+)Br(K^{*+}\pi^-)} - 2\cos\delta_{K^{*0}\pi^0}\sqrt{Br(K^{*0}\pi^0)Br(\bar{K}^{*0}\pi^0)} \\
& -2\cos\delta_{K^-\rho^+}\sqrt{Br(K^-\rho^+)Br(K^+\rho^-)} - 2\cos\delta_{K^0\rho^0}\sqrt{Br(K^0\rho^0)Br(\bar{K}^0\rho^0)} \\
& -2\cos\delta_{K^{*0}\eta}\sqrt{Br(K^{*0}\eta)Br(\bar{K}^{*0}\eta)} - 2\cos\delta_{K^{*0}\eta'}\sqrt{Br(K^{*0}\eta')Br(\bar{K}^{*0}\eta')} \\
& -2\cos\delta_{K^0\omega}\sqrt{Br(K^0\omega)Br(\bar{K}^0\omega)} - 2\cos\delta_{K^0\phi}\sqrt{Br(K^0\phi)Br(\bar{K}^0\phi)} \\
& +2\cos\delta_{K^+K^{*-}}\sqrt{Br(K^+K^{*-})Br(K^-K^{*+})} + 2\cos\delta_{K^0\bar{K}^{*0}}\sqrt{Br(K^0\bar{K}^{*0})Br(\bar{K}^0K^{*0})} \\
& +2\cos\delta_{\pi^+\rho^-}\sqrt{Br(\pi^+\rho^-)Br(\pi^-\rho^+)}
\end{aligned}
$$

More decay modes

[Qin, Li, Lu, FSY, 14']

Our results

$$y_{PP} = 0.08\%$$
$$y_{PV} = 0.29\%$$

preliminary

$$\boxed{y_{PP+PV} = 0.37\%}$$

- Experimental data

Exp: $y_D = (0.62 \pm 0.08)\%$ [HFAG]

Outlook 1: uncertainties to be studied

Outlook 2: contributions from other modes

D^0 decay branching fractions
two-body decays dominated

PP	PV	VV	PA	PS	PT	semilep
10%	30 %	10 %	10 %	5 %	0.2%	15%

[PDG]

η_{CP} : + + +, S,D + -

-, P wave

Estimation: $y_{VV} = 0.10\%$ Longitudinal

$$y_{PP+PV+VV} = 0.47\%$$

Exp: $y_D = (0.62 \pm 0.08)\%$

More efforts required for experimentalists

to measure VV, PA, PS modes

x from dispersion relation

$$Ref(s) = \frac{1}{\pi} P \int_0^\infty \frac{ds'}{s'-s} Imf(s')$$

In the heavy quark limit

$$\Delta m = -\frac{1}{2\pi} \mathrm{P} \int_{2m_\pi}^{\infty} \mathrm{d}E \left[\frac{\Delta\Gamma(E)}{E - m_D} + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{E} \right) \right]$$

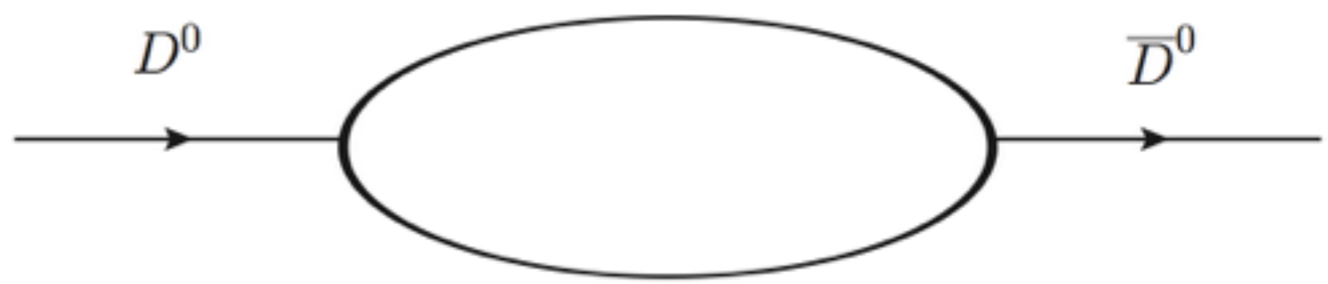
[Falk,Grossman,Ligeti,Nir,Petrov,2004]

x from dispersion relation

$$Ref(s) = \frac{1}{\pi} P \int_0^\infty \frac{ds'}{s'-s} Imf(s')$$

$$\Delta m = 2M_{12} = 2Re[\Pi(m_D^2)]$$

$$\Delta\Gamma = 2\Gamma_{12} = 2Im[\Pi(m_D^2)]$$



$$\Delta m(m_D^2) = \frac{2}{\pi} P \int_{(2m_\pi^2)^2}^\infty \frac{\Delta\Gamma(s)}{s - m_D^2} ds$$

x from dispersion relation

$$\Delta m(m_D^2) = \frac{2}{\pi} P \int_{(2m_\pi^2)^2}^{\infty} \frac{\Delta\Gamma(s)}{s - m_D^2} ds$$

$\sqrt{s}$

m_B vanishes due to SU(3) symmetry

m_D $y(m_D^2)$ Simulate nearby m_D

dynamics required

0 $y(4m_\pi^2) = 0$

Summary

- Two-body D meson decays are well studied in Factorization-Assisted Topological-amplitude approach. SU(3) breaking effects are well described.
- D-Dbar mixing parameter **y** can be understood in an exclusive approach.
- More efforts for experimentalist are required to measure VV, PA and PS modes
- More efforts on dynamics are required for mixing parameter **x**

Thank you for your attention!

Backup

$D^0 \to \pi^+\pi^- \quad v.s. \quad D^0 \to K^+K^-$

$$\mathcal{A}(D^0 \to \pi^+\pi^-) = \frac{G_F}{\sqrt{2}}\lambda_d\,(T^{\pi\pi} + E^{\pi\pi})$$

Glauber phase

$$= \frac{G_F}{\sqrt{2}}V_{cd}^*V_{ud}\left[a_1(\mu)(m_D^2 - m_\pi^2)f_\pi F_0^{D\pi}(m_\pi^2) + C_2(\mu)e^{i(\phi_q^E + 2S_\pi)}\chi_q^E f_D m_D^2\right]$$

Main difference

$$\mathcal{A}(D^0 \to K^+K^-) = \frac{G_F}{\sqrt{2}}\lambda_s\,(T^{KK} + E^{KK})$$

$$= \frac{G_F}{\sqrt{2}}V_{cs}^*V_{us}\left[a_1(\mu)(m_D^2 - m_K^2)f_K F_0^{DK}(m_K^2) + C_2(\mu)e^{i\phi_q^E}\chi_q^E f_D m_D^2 \frac{f_K^2}{f_\pi^2}\right]$$

Modes	Br(FSI)	Br(diagram)	Br(pole)	Br(exp)	Br(this work)
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$$T^{\pi\pi} = 2.73, \qquad E^{\pi\pi} = 0.82e^{-i142^\circ},$$

$$T^{KK} = 3.65, \qquad E^{KK} = 1.2e^{-i85^\circ},$$

Result of CP asymmetries

- Difference of CPV in D->KK and D-> pipi

$$\Delta A_{CP}^{\rm dir} = A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+)$$

- Our prediction:

$$\boxed{\Delta A_{CP} = (-0.57 \sim -1.87) \times 10^{-3}}$$ [Li, Lu, FSY,12']

- After our prediction, the world average value is lowered down by the LHCb results

Exp: $\Delta A_{CP} = (-2.53 \pm 1.04) \times 10^{-3}$ [HFAG2014]