Charm potentials at BESIII

Fu-Sheng Yu

Lanzhou University

BESIII粲物理研讨会 @ WuhanU
2018.11.11

Thank Hai-Long for the invitation every year!

Nonleptonic decays of charmed mesons

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Charm Workshop @ IHEP, 2015.12.17

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Nonleptonic decays of charmed hadrons

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Theoretical Progress on Charm Weak Decays

Fu-Sheng Yu

Lanzhou University

2017.09.23 @ NankaiU

Joint workshop on charmed hadron decays @ BESIII, Belle, LHCb

# of charmed hadrons

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... charmed hadrons

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... charmed mesons

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Charm Workshop @ IHEP, 2015.12.17

2015

- Theoretical status of nonleptonic charmed meson decays
  - Factorization-assisted Topological-amplitude approach (FAT)
- DDbar mixing
  - to measure $D \rightarrow VV$, PS, PA modes

2015

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2016

1. K_S-K_L asymmetries in charm decays
2. CP violation in charm — New type CPV
3. Annihilation processes
4. D->K_1 M
5. Λ_c decays

2017

1. **Theories in charm decays**
2. **To search for new physics — CP violation**
3. **To search for exotic states — weak decay is a new tool**

2016

1. K_S-K_L asymmetries in charm decays
2. CP violation in charm — New type CPV
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2015

- Theoretical status of nonleptonic ch meson decays
  - Factorization-assisted Topologica amplitude approach (FAT)
- DDbar mixing
  - to measure D→VV, PS, PA modes

2018

- Interplay between theory and experiment
- Measurements change the understanding of DDbar mixing
- K_S-K_L asymmetries in charmed meson and baryon decays

2017

decays

physics — CP violation

c states — weak decay is a new tool

2016

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BF($D_s^+ \to \eta' X$) and BF($D_s^+ \to \eta' \rho^+$)

- The situation is rather interesting
  Sum[BF($D_s^+ \to \eta'$ + exclusive in PDG)] = (18.6±2.3)%, while
  BF($D_s^+ \to \eta' X$) = (11.7±1.8)% (CLEO-c @ E_{cm}~4.170 GeV PRD79, 112008).
- In the exclusives, the single largest BF is
  BF($D_s^+ \to \eta' \rho^+$) = (12.5±2.2)% (CLEO2 @ E_{cm}~$M_{\Upsilon(4S)}$,PRD58, 052002(1998))
  However, CLEO-c reports (@ E_{cm}~4.170 GeV; PRD88,032009(2013))
  BF($D_s^+ \to \eta' \pi^+\pi^0$;inclusive) = (5.6±0.5±0.6)%.
- A factorization method predicts
  BF($D_s^+ \to \eta' \rho^+$) = (3.0±0.5)% (F.S. Yu, et al, PRD84, 074019 (2011)).

BESIII

BF($D_s^+ \to \eta' \rho^+$) = (5.8±1.4±0.4)%

Observation of $\Lambda_c^+ \to nK_S^0\pi^+$
BESIII Collaboration (Medina Ablikim (Beijing, Inst. High
Published in **Phys.Rev.Lett. 118 (2017) no.11, 112001**
DOI: 10.1103/PhysRevLett.118.112001
e-Print: **arXiv:1611.02797 [hep-ex]** | **PDF**

Measurement of absolute branching fraction of the inclusive decay $\Lambda_c^+ \to \Lambda + X$
BESIII Collaboration (Medina Ablikim (Beijing, Inst. High Energy Phys.) *et al.*). Mar 15, 2018. 8 pp.
Published in **Phys.Rev.Lett. 121 (2018) no.6, 062003**
DOI: 10.1103/PhysRevLett.121.062003
e-Print: **arXiv:1803.05706 [hep-ex]** | **PDF**

Observation of $D^{0(+)} \to K_S^0\pi^{0(+)}\eta'$ and improved measurement of $D^0 \to K^-\pi^+\eta'$
BESIII Collaboration (Medina Ablikim (Beijing, Inst. High Energy Phys.) *et al.*). Sep 11, 2018.
e-Print: **arXiv:1809.03750 [hep-ex]** | **PDF**

Observation of the W-Annihilation Decay $D_s^+ \to \omega\pi^+$ and Evidence for $D_s^+ \to \omega K^+$
BESIII Collaboration (M. Ablikim *et al.*). Nov 1, 2018.
e-Print: **arXiv:1811.00392 [hep-ex]** | **PDF**

Observation of $D_s^+ \to p\bar{n}$ and confirmation of its large branching fraction
BESIII Collaboration (M. Ablikim *et al.*). Nov 2, 2018.
e-Print: **arXiv:1811.00752 [hep-ex]** | **PDF**

感 谢 致 谢 ！

国家自然科学基金委员会

资助项目计划书

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亚类说明：培育项目

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项目名称：BESIII上关于粲物理的唯象研究

直接费用：50万元　　执行年限：2018.01-2020.12

负 责 人：于福升

感 谢 经 费 支 持 ！

Charm physics

if of highly connection

between experiments and theories

More data and more precision

is very important for the progress in theory

and in turn for the progress in experiment

Theories of heavy flavor decays

- Amplitudes are described by effective Hamiltonian based on OPE in the **heavy-quark limit**

- **QCD-inspired methods at the leading $1/m_Q$**
  - PQCD, QCDF, SCET
  - **NLO, NNLO effects by α_s**
  - perturbative, successful in B decays

- **Big Problem in charm : $1/m_c$ power corrections**
  - **Non-perturbative**
  - **Long-distance contributions** are important around 1GeV and below, final-state interaction or resonance.

- **In phenomenology**
  - some data to be explained
  - some important observables to be predicted
- **Basic ideas:**
  - Calculate what we can — HQET and factorization
  - Parametrize what we cannot — $1/m_Q$ corrections
  - Include important information — SU(3) breaking
  - Non-perturbations/corrections — extracted from data
  - Predict some observables to be tested

Factorization-Assisted Topological-amplitude (FAT) approach works well for *D* decays

H.n.Li, C.D.Lü, **FSY**, ’12; Q.Qin, H.n.Li, C.D.Lü, **FSY**, ’14

Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)	Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)	Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)
$\pi^0\overline{K}^0$	24.0 ± 0.8	24.2 ± 0.8	$\pi^0\overline{K}^{*0}$	37.5 ± 2.9	35.9 ± 2.2	$\overline{K}^0\rho^0$	$12.8^{+1.4}_{-1.6}$	13.5 ± 1.4
π^+K^-	39.3 ± 0.4	39.2 ± 0.4	π^+K^{*-}	54.3 ± 4.4	62.5 ± 2.7	$K^-\rho^+$	111.0 ± 9.0	105.0 ± 5.2
$\eta\overline{K}^0$	9.70 ± 0.6	9.6 ± 0.6	$\eta\overline{K}^{*0}$	9.6 ± 3.0	6.1 ± 1.0	$\overline{K}^0\omega$	22.2 ± 1.2	22.3 ± 1.1
$\eta'\overline{K}^0$	19.0 ± 1.0	19.5 ± 1.0	$\eta'\overline{K}^{*0}$	< 1.10	0.19 ± 0.01	$\overline{K}^0\phi$	$8.47^{+0.66}_{-0.34}$	8.2 ± 0.6
$\pi^+\pi^-$	1.421 ± 0.025	1.44 ± 0.02	$\pi^+\rho^-$	5.09 ± 0.34	4.5 ± 0.2	$\pi^-\rho^+$	10.0 ± 0.6	9.2 ± 0.3
K^+K^-	4.01 ± 0.07	4.05 ± 0.07	K^+K^{*-}	1.62 ± 0.15	1.8 ± 0.1	K^-K^{*+}	4.50 ± 0.30	4.3 ± 0.2
$K^0\overline{K}^0$	0.36 ± 0.08	0.29 ± 0.07	$K^0\overline{K}^{*0}$	0.18 ± 0.04	0.19 ± 0.03	$\overline{K}^0K^{*0}$	0.21 ± 0.04	0.19 ± 0.03
$\pi^0\eta$	0.69 ± 0.07	0.74 ± 0.03	$\eta\rho^0$		1.4 ± 0.2	$\pi^0\omega$	0.117 ± 0.035	0.10 ± 0.03
$\pi^0\eta'$	0.91 ± 0.14	1.08 ± 0.05	$\eta'\rho^0$		0.25 ± 0.01	$\pi^0\phi$	1.35 ± 0.10	1.4 ± 0.1
$\eta\eta$	1.70 ± 0.20	1.86 ± 0.06	$\eta\omega$	2.21 ± 0.23	2.0 ± 0.1	$\eta\phi$	0.14 ± 0.05	0.18 ± 0.04
$\eta\eta'$	1.07 ± 0.26	1.05 ± 0.08	$\eta'\omega$		0.044 ± 0.004			
$\pi^0\pi^0$	0.826 ± 0.035	0.78 ± 0.03	$\pi^0\rho^0$	3.82 ± 0.29	4.1 ± 0.2			
π^0K^0		0.069 ± 0.002	π^0K^{*0}		0.103 ± 0.006	$K^0\rho^0$		0.039 ± 0.004
π^-K^+	0.133 ± 0.009	0.133 ± 0.001	π^-K^{*+}	$0.345^{+0.180}_{-0.102}$	0.40 ± 0.02	$K^+\rho^-$		0.144 ± 0.009
ηK^0		0.027 ± 0.002	ηK^{*0}		0.017 ± 0.003	$K^0\omega$		0.064 ± 0.003
$\eta'K^0$		0.056 ± 0.003	$\eta'K^{*0}$		0.00055 ± 0.00004	$K^0\phi$		0.024 ± 0.002

D0 decays. [H.Y.Jiang, **FSY**, Q.Qin, H.n.Li, C.D.Lü, ’17]

Factorization-Assisted Topological-amplitude (FAT) approach works well for *D* decays

[H.n.Li, C.D.Lü, **FSY**, PRD2012][Q.Qin, H.n.Li, C.D.Lü, **FSY**, PRD2014]

Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)	Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)	Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)
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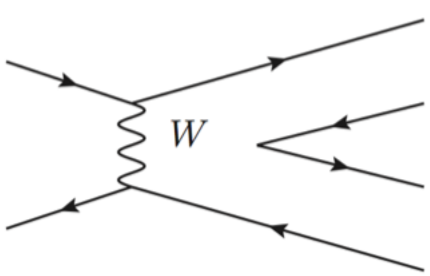
1. **Enough data is required to extract non-perturbative parameters**
2. **Theoretical results must be consistent with data**
3. **Understanding all the data is the first step for predictions**

	Before 2016		After 2016		
	$\mathscr{B}_{\rm exp}$	$\mathscr{B}_{\rm th}$	$\mathscr{B}_{\rm exp}$	$\mathscr{B}_{\rm th}$	$(\times 10^{-3})$
$D^0 \to \overline{K}^{*0} K^0$	< 1	1.1	0.18 ± 0.04	0.19 ± 0.03	
$D^0 \to K^{*0} \overline{K}^0$	< 0.56	1.1	0.21 ± 0.04	0.19 ± 0.03	
	PDG,'16	Qin, Li, Lü, **FSY**, '14	LHCb,'16	Jiang, **FSY**, Qin, Li, Lü, '17	

Pure W-exchange

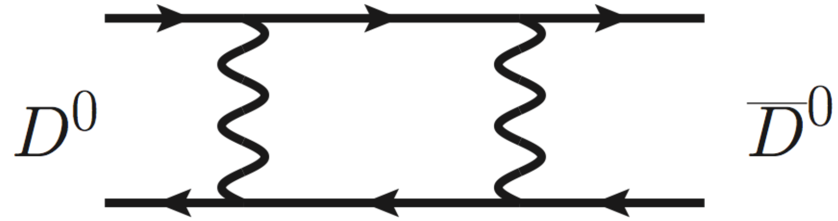
$E_V - E_P$



told by Yu Lu @ BESIII charm workshop in 2016

Let's see its impact on the prediction of DDbar mixing

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



- The time evolution

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

- Mixing parameters: Mass and Width differences

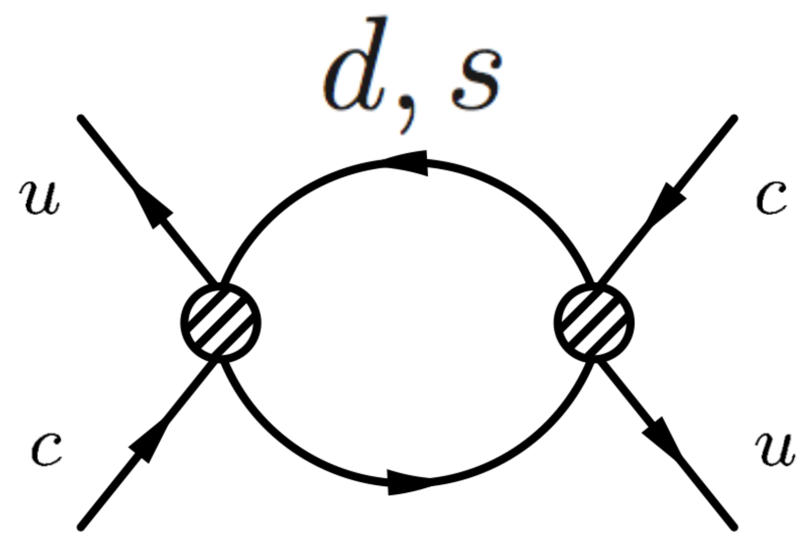
$$x \equiv \frac{\Delta m}{\Gamma} = \frac{m_1 - m_2}{\Gamma}$$

$$y \equiv \frac{\Delta \Gamma}{2\Gamma} = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

- Useful to search for new physics,
- but less understood in the Standard Model

Inclusive approach

quark level **Heavy Quark Expansion**

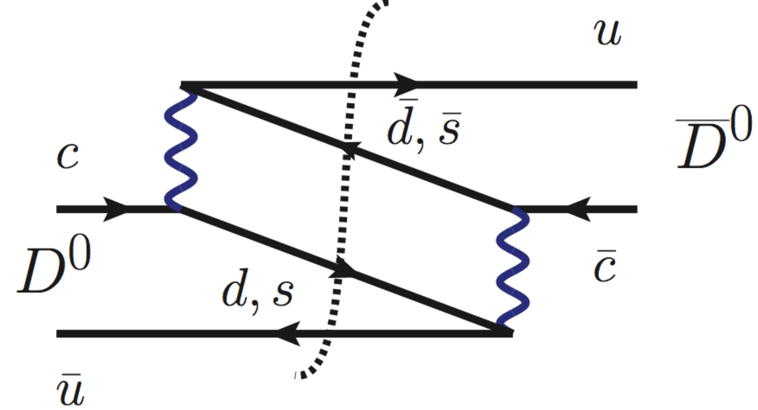


$x \sim (m_s/m_c)^4$ $y \sim (m_s/m_c)^6$

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

Inclusive approach is three-orders smaller

Exclusive Approach



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

Sum up all the intermediate states

- Falk,Grossman,Ligeti,Petrov, '02 — Only qualitative
- Cheng, Chiang '10 — $y_{PP+VP} = (0.36 \pm 0.26)\%$ Large error

During the past decade, exclusive approach is almost the only hopeful approach.

D→PP and **PV**: precise data + FAT approach

D→PP modes y_{PP}

vanish in the SU(3) symmetry limit

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

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

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

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

D→PV modes $\quad y_{PV}$

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

More decay modes

Qin, Li, Lü, **FSY**, ’14

All $D^0 \to$PP and PV modes

Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)	Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)	Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)
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$K^0\overline{K}^0$	0.36 ± 0.08	0.29 ± 0.07	$K^0\overline{K}^{*0}$	0.18 ± 0.04	0.19 ± 0.03	$\overline{K}^0K^{*0}$	0.21 ± 0.04	0.19 ± 0.03
$\pi^0\eta$	0.69 ± 0.07	0.74 ± 0.03	$\eta\rho^0$		1.4 ± 0.2	$\pi^0\omega$	0.117 ± 0.035	0.10 ± 0.03
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$\eta\eta$	1.70 ± 0.20	1.86 ± 0.06	$\eta\omega$	2.21 ± 0.23	2.0 ± 0.1	$\eta\phi$	0.14 ± 0.05	0.18 ± 0.04
$\eta\eta'$	1.07 ± 0.26	1.05 ± 0.08	$\eta'\omega$		0.044 ± 0.004			
$\pi^0\pi^0$	0.826 ± 0.035	0.78 ± 0.03	$\pi^0\rho^0$	3.82 ± 0.29	4.1 ± 0.2			
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π^-K^+	0.133 ± 0.009	0.133 ± 0.001	π^-K^{*+}	$0.345^{+0.180}_{-0.102}$	0.40 ± 0.02	$K^+\rho^-$		0.144 ± 0.009
ηK^0		0.027 ± 0.002	ηK^{*0}		0.017 ± 0.003	$K^0\omega$		0.064 ± 0.003
$\eta' K^0$		0.056 ± 0.003	$\eta' K^{*0}$		0.00055 ± 0.00004	$K^0\phi$		0.024 ± 0.002

- All the measured data are understood in theory
- Unmeasured processes are predicted

Jiang, **FSY**, Qin, Li, Lü, ’17

Results before 2016

Our results

$$y_{PP} = (0.063 \pm 0.008)\%$$
$$y_{PV} = (0.32 \pm 0.07)\%$$

preliminary

$$y_{PP+PV} = (0.38 \pm 0.07)\%$$

- Close to experimental data

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

- Compared to Diagrammatic approach [Cheng, Chiang, 10']

$$y_{PP+VP} = (0.36 \pm 0.26)\% \text{ or } (0.24 \pm 0.22)\%$$

No other theoretical calculation at the experimental level

But now…

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

$\cos\delta \sim 1$

10^{-3}	Before 2016 $\mathcal{B}_{exp}$	Before 2016 $\mathcal{B}_{th}$	After 2016 $\mathcal{B}_{exp}$	After 2016 $\mathcal{B}_{th}$
$D^0 \to \overline{K}^{*0}K^0$	< 1	1.1	0.18 ± 0.04	0.19 ± 0.03
$D^0 \to K^{*0}\overline{K}^0$	< 0.56	1.1	0.21 ± 0.04	0.19 ± 0.03

Before2016 : 2.2×10^{-3}

After2016 : 0.38×10^{-3}

y_{PV}

reduced by $\sim 2 \times 10^{-3}$

Before 2016 $y_{PV} = (3.2 \pm 0.7) \times 10^{-3}$

↓

reduced by $\sim 2 \times 10^{-3}$

But now, $y_{PV} = (1.1 \pm 0.7) \times 10^{-3}$

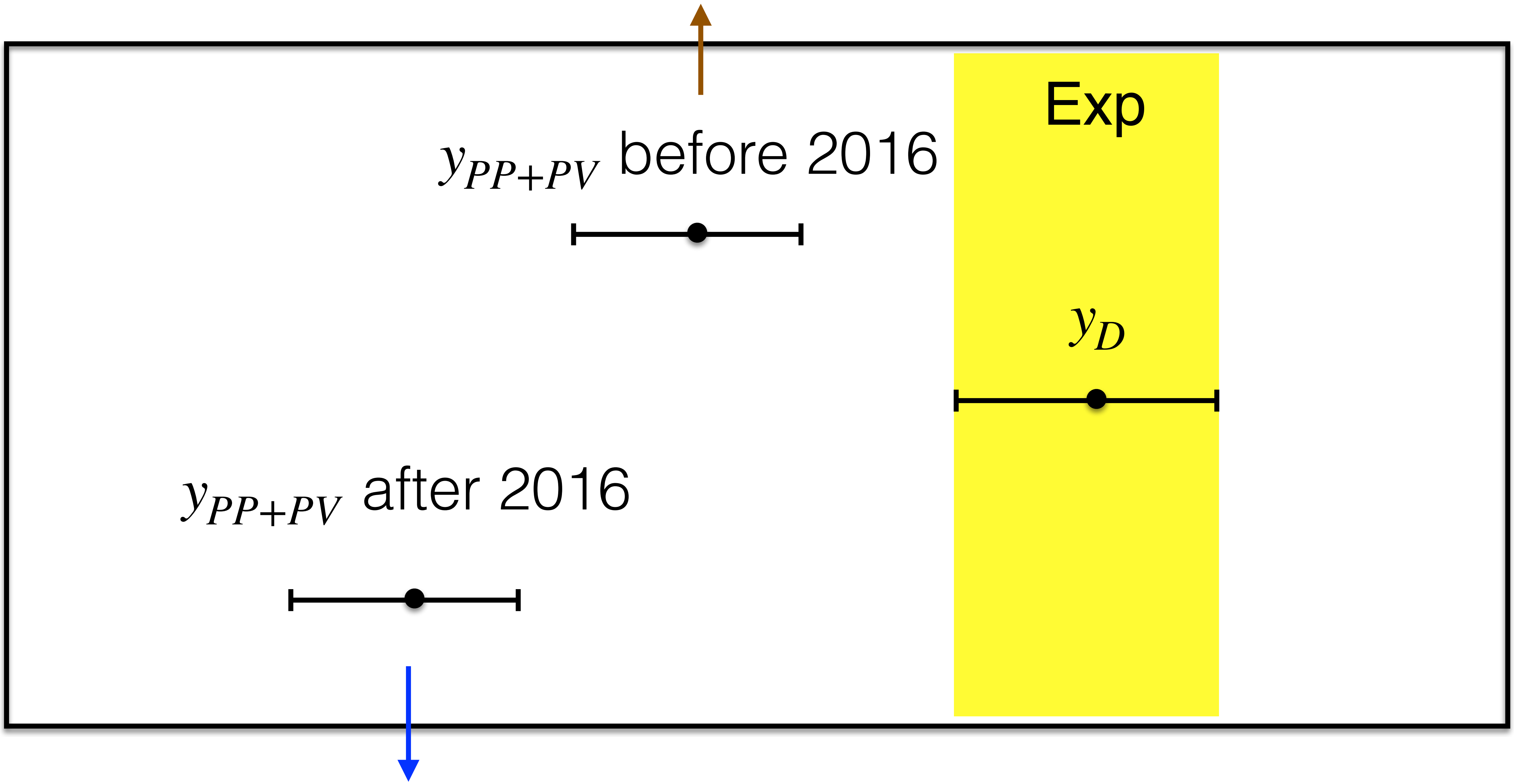
Jiang, **FSY**, Qin, Li, Lü, ’17

Measurements on $D^0 \to \overline{K}^{*0} K^0$ $D^0 \to K^{*0} \overline{K}^0$

change the predictions on DDbar mixing y_D

$y_{PP} = (1.00 \pm 0.19) \times 10^{-3}$

- **Before 2016, exclusive approach is hopeful**



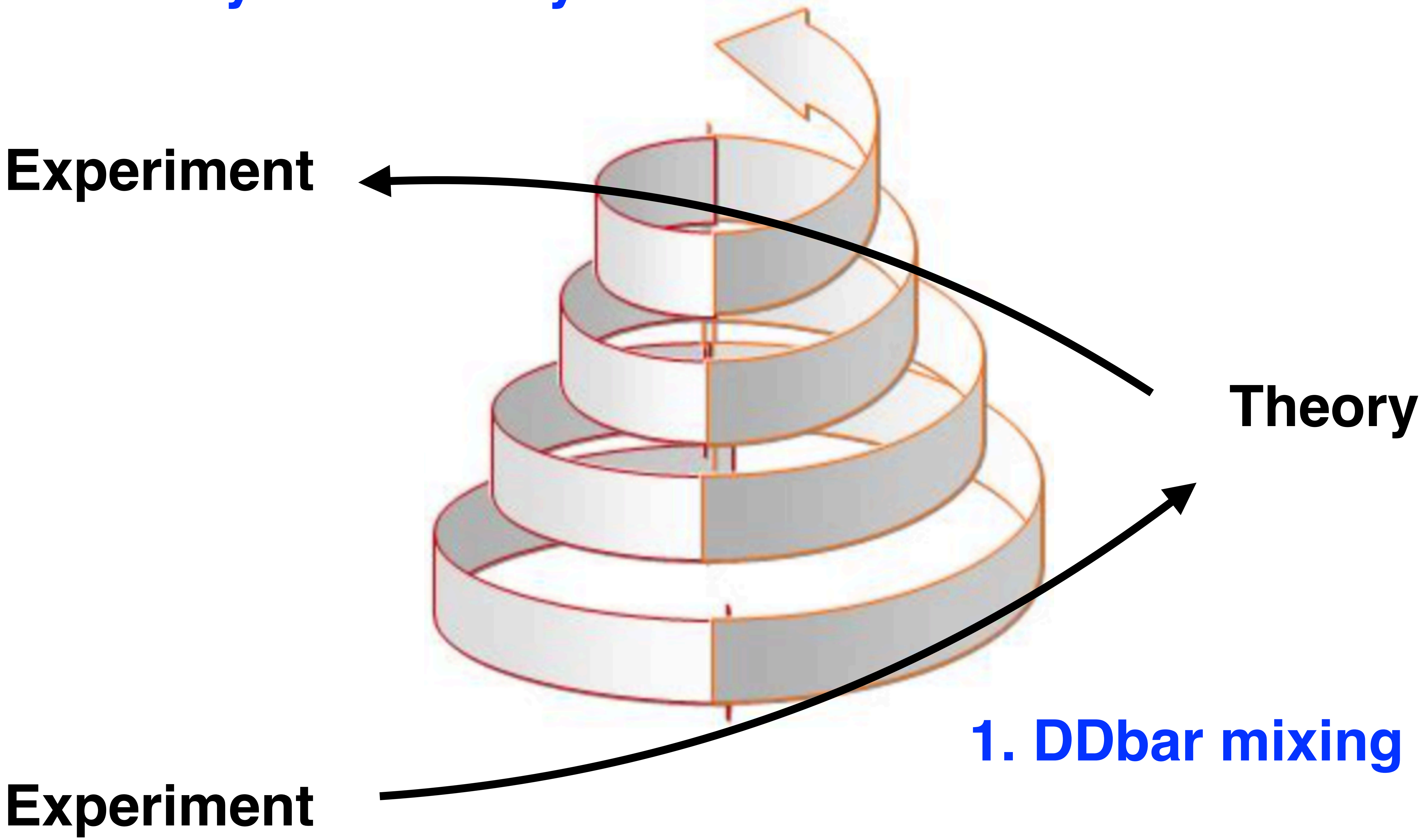
- **After 2016, exclusive approach is dying**

New measurements change our understanding !!

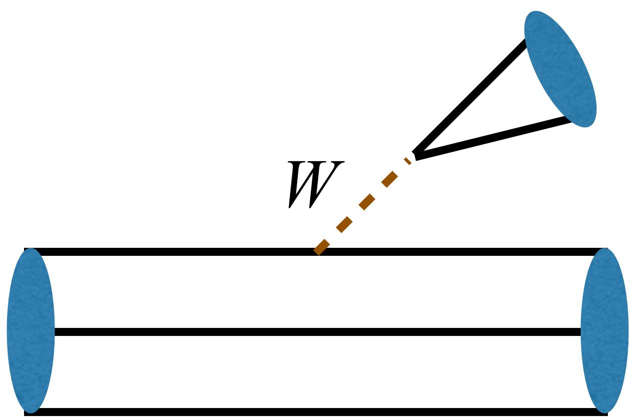
More measurements on all possible D decays would be helpful as well

Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)	Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)	Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)
$\pi^0\overline{K}^0$	24.0 ± 0.8	24.2 ± 0.8	$\pi^0\overline{K}^{*0}$	37.5 ± 2.9	35.9 ± 2.2	$\overline{K}^0\rho^0$	$12.8^{+1.4}_{-1.6}$	13.5 ± 1.4
π^+K^-	39.3 ± 0.4	39.2 ± 0.4	π^+K^{*-}	54.3 ± 4.4	62.5 ± 2.7	$K^-\rho^+$	111.0 ± 9.0	105.0 ± 5.2
$\eta\overline{K}^0$	9.70 ± 0.6	9.6 ± 0.6	$\eta\overline{K}^{*0}$	9.6 ± 3.0	6.1 ± 1.0	$\overline{K}^0\omega$	22.2 ± 1.2	22.3 ± 1.1
$\eta'\overline{K}^0$	19.0 ± 1.0	19.5 ± 1.0	$\eta'\overline{K}^{*0}$	<1.10	0.19 ± 0.01	$\overline{K}^0\phi$	$8.47^{+0.66}_{-0.34}$	8.2 ± 0.6
$\pi^+\pi^-$	1.421 ± 0.025	1.44 ± 0.02	$\pi^+\rho^-$	5.09 ± 0.34	4.5 ± 0.2	$\pi^-\rho^+$	10.0 ± 0.6	9.2 ± 0.3
K^+K^-	4.01 ± 0.07	4.05 ± 0.07	K^+K^{*-}	1.62 ± 0.15	1.8 ± 0.1	K^-K^{*+}	4.50 ± 0.30	4.3 ± 0.2
$K^0\overline{K}^0$	0.36 ± 0.08	0.29 ± 0.07	$K^0\overline{K}^{*0}$	0.18 ± 0.04	0.19 ± 0.03	$\overline{K}^0K^{*0}$	0.21 ± 0.04	0.19 ± 0.03
$\pi^0\eta$	0.69 ± 0.07	0.74 ± 0.03	$\eta\rho^0$		1.4 ± 0.2	$\pi^0\omega$	0.117 ± 0.035	0.10 ± 0.03
$\pi^0\eta'$	0.91 ± 0.14	1.08 ± 0.05	$\eta'\rho^0$		0.25 ± 0.01	$\pi^0\phi$	1.35 ± 0.10	1.4 ± 0.1
$\eta\eta$	1.70 ± 0.20	1.86 ± 0.06	$\eta\omega$	2.21 ± 0.23	2.0 ± 0.1	$\eta\phi$	0.14 ± 0.05	0.18 ± 0.04
$\eta\eta'$	1.07 ± 0.26	1.05 ± 0.08	$\eta'\omega$		0.044 ± 0.004			
$\pi^0\pi^0$	0.826 ± 0.035	0.78 ± 0.03	$\pi^0\rho^0$	3.82 ± 0.29	4.1 ± 0.2			
π^0K^0		0.069 ± 0.002	π^0K^{*0}		0.103 ± 0.006	$K^0\rho^0$		0.039 ± 0.004
π^-K^+	0.133 ± 0.009	0.133 ± 0.001	π^-K^{*+}	$0.345^{+0.180}_{-0.102}$	0.40 ± 0.02	$K^+\rho^-$		0.144 ± 0.009
ηK^0		0.027 ± 0.002	ηK^{*0}		0.017 ± 0.003	$K^0\omega$		0.064 ± 0.003
$\eta'K^0$		0.056 ± 0.003	$\eta'K^{*0}$		0.00055 ± 0.00004	$K^0\phi$		0.024 ± 0.002

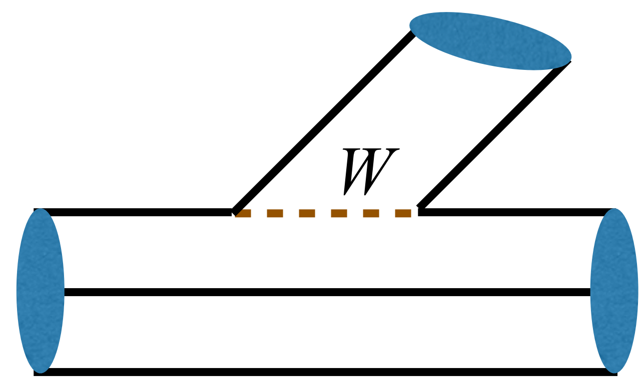
2. Prediction and discovery of doubly charm baryon



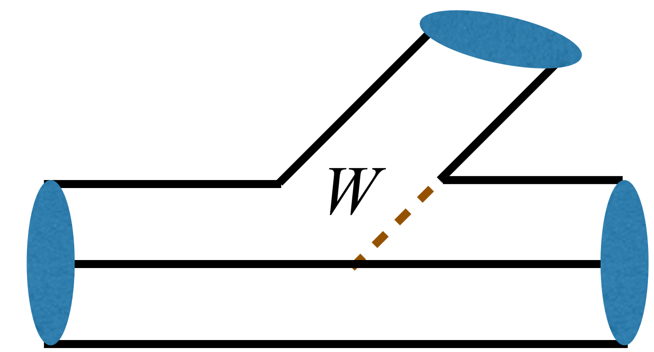
Topologies of two-body non-leptonic charmed baryon decays



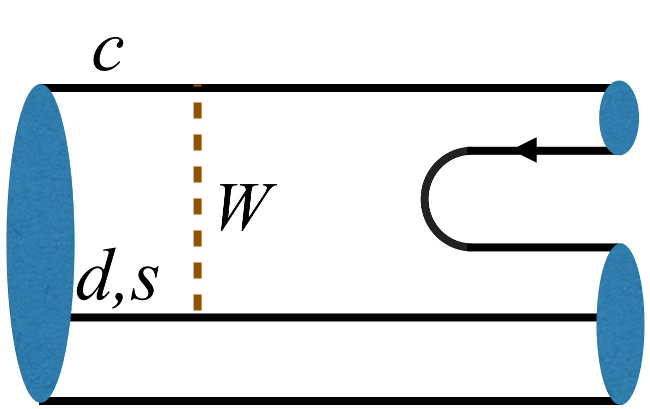
(T)
color-favored tree emitted



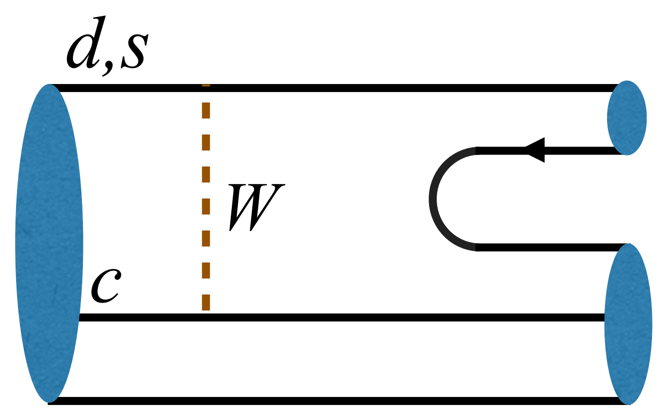
(C)
color-suppressed emitted



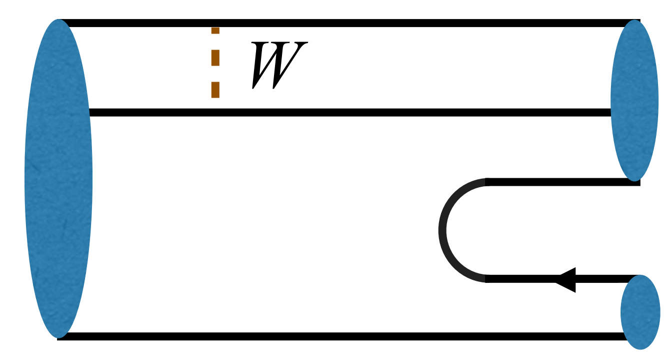
(C′)
color-commensurate



(E_1)
W-exchange 1



(E_2)
W-exchange 2



(B)
Bow tie

Hierarchy in heavy quark expansion

SCET: |C/T|~|C'/T|~|E/T|~$O(\Lambda_{QCD}/m_Q)$, |B/E|~$O(\Lambda_{QCD}/m_Q)$,

[Leibovich, Ligeti, Stewart, Wise, '04]

c decay: |C/T|~|C'/T|~|E/T|~$O(\Lambda_{QCD}/m_Q)\sim 1$

|B/E|~$O(\Lambda_{QCD}/m_Q)\sim 1$

|P|~0

$$\lambda_{sd} \equiv V_{cs}^* V_{ud}$$

	Modes	Representation	$\mathcal{B}_{\rm exp}$
Λ_c^+	$p\overline{K}^0$	$\lambda_{sd}(C+E)$	$(3.04 \pm 0.17)\%$
	$\Lambda^0\pi^+$	$\lambda_{sd}(T - C' + B - E)/\sqrt{2}$	$(1.24 \pm 0.08)\%$
	$\Delta^{++}K^-$	$\lambda_{sd}E$	$(1.18 \pm 0.27)\%$

Λ_c decay would help to understand dynamics

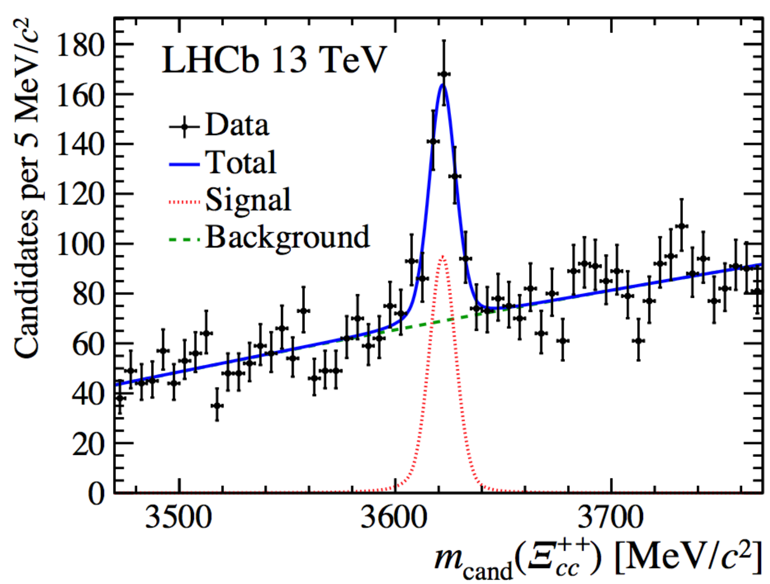
Discovery Potentials of Doubly Charmed Baryons

Abstract

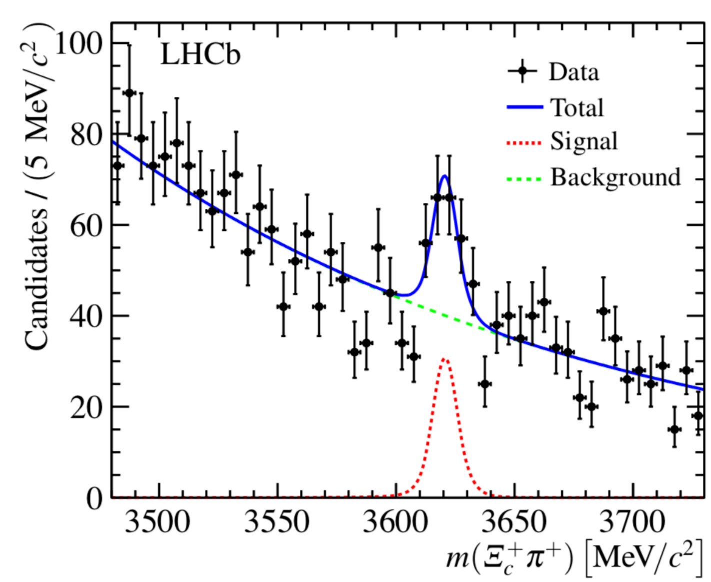
The existence of doubly heavy flavor baryons has not been well established experimentally so far. In this Letter we systematically investigate the weak decays of the doubly charmed baryons, Ξ_{cc}^{++} and Ξ_{cc}^{+}, which should be helpful for experimental searches for these particles. The long-distance contributions are first studied in the doubly heavy baryon decays, and found to be significantly enhanced. Comparing all the processes, $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ are the most favorable decay modes for experiments to search for doubly heavy baryons.

FSY, Jiang, Li, Lü, Wang, Zhao, 1703.09086

July 2017



$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$



July 2018

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

LHCb observed Ξ_{cc}^{++}

Mode	HFAG 2016 (%)	BESIII (%)	PDG 2014 (%)	BELLE (%)
pK_S^0	1.59 ± 0.07	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	6.46 ± 0.24	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S^0\pi^0$	2.03 ± 0.12	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50	
$pK_S^0\pi^+\pi^-$	1.69 ± 0.11	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	5.05 ± 0.29	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0	
$\Lambda\pi^+$	1.28 ± 0.06	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28	
$\Lambda\pi^+\pi^0$	7.09 ± 0.36	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3	
$\Lambda\pi^+\pi^-\pi^+$	3.73 ± 0.21	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7	
$\Sigma^0\pi^+$	1.31 ± 0.07	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28	
$\Sigma^+\pi^0$	1.25 ± 0.09	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34	
$\Sigma^+\pi^+\pi^-$	4.64 ± 0.24	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0	
$\Sigma^+\omega$	1.77 ± 0.21	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0	
$\Lambda e^+\nu_e$	3.18 ± 0.32	$3.63 \pm 0.38 \pm 0.20$	2.1 ± 0.6	

See Pei-Rong's talk

More measurements on Λ_c decays
will be helpful to understand dynamics
and predict doubly heavy baryon decays


Disney's
Charming Dance
Theory
Experiment

3. K_L-involved decay modes

K_S-K_L asymmetry

$$R(f) \equiv \frac{\Gamma(D \to K_S^0 f) - \Gamma(D \to K_L^0 f)}{\Gamma(D \to K_S^0 f) + \Gamma(D \to K_L^0 f)}$$

$$|K_S^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K}^0\rangle\right), \qquad |K_L^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K}^0\rangle\right)$$

- amplitudes $A(K_S^0) = A_{CF} - A_{DCS}$ $\qquad A(K_S^0) = A_{CF} + A_{DCS}$

$$\frac{A_{DCS}}{A_{CF}} \equiv re^{i\delta}$$

$$R(f) = -2r_f \cos \delta_f$$

K_S-K_L asymmetries in charm mesons

Bhattacharya, Rosner, '10
Cheng, C.W.Chiang, '10
Gao, '15
Muller, Nierste, Schacht, '15
PDG
Wang, **FSY**, Guo,Jiang, '17

	R [13]	R [7]	R [24]	R [10]	R_{exp} [21]	R(FAT)
$D^0 \to K^0_{S,L}\pi^0$	0.107	0.107	0.106	$0.09^{+0.04}_{-0.02}$	0.108 ± 0.035	0.113 ± 0.001
$D^+ \to K^0_{S,L}\pi^+$	-0.005 ± 0.013	-0.019 ± 0.016	-0.010 ± 0.026		0.022 ± 0.024	0.025 ± 0.008
$D_s^+ \to K^0_{S,L}K^+$	-0.002 ± 0.009	-0.008 ± 0.007	-0.008 ± 0.007	$0.11^{+0.04}_{-0.14}$		0.012 ± 0.006

Sifan Zhang's talk:

BESIII preliminary

$$R(D^0) = 0.1077 \pm 0.0125$$

$$R(D^+) = 0.001 \pm 0.009 \pm 0.009$$

$$R(D_s^+) = -0.021 \pm 0.019 \pm 0.016$$

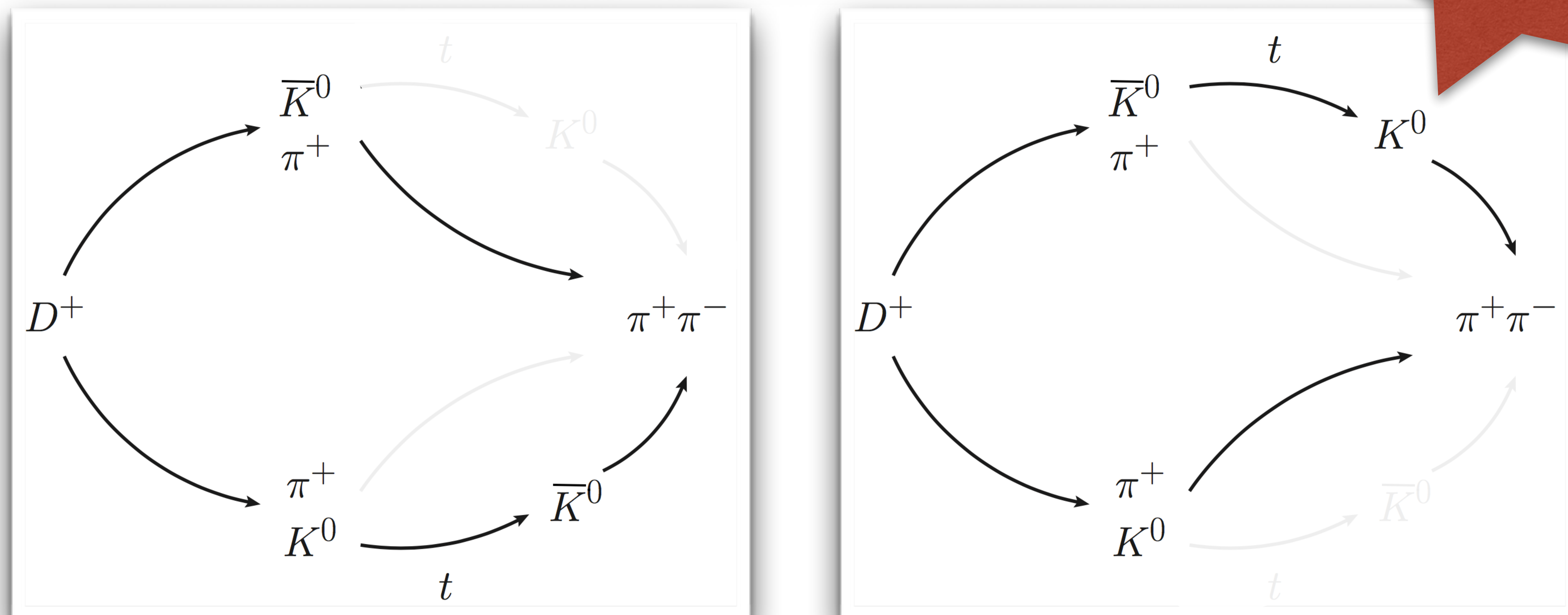
Measurements distinguish models, and what's more…

$$A_{CP}(t) = A_{CP}^{\overline{K}^0}(t) + A_{CP}^{\rm dir}(t) + A_{CP}^{\rm int}(t)$$

CPV induced by mother decay and daughter mixing

$\mathrm{Im}(\epsilon)\ \mathrm{Re}(V_{cd}^{*}V_{us}/V_{cs}^{*}V_{ud})=10^{-4\sim-3}$

NEW



D.Wang, **FSY**, H.n.Li, Phys.Rev.Lett 119, 181802(2017)

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

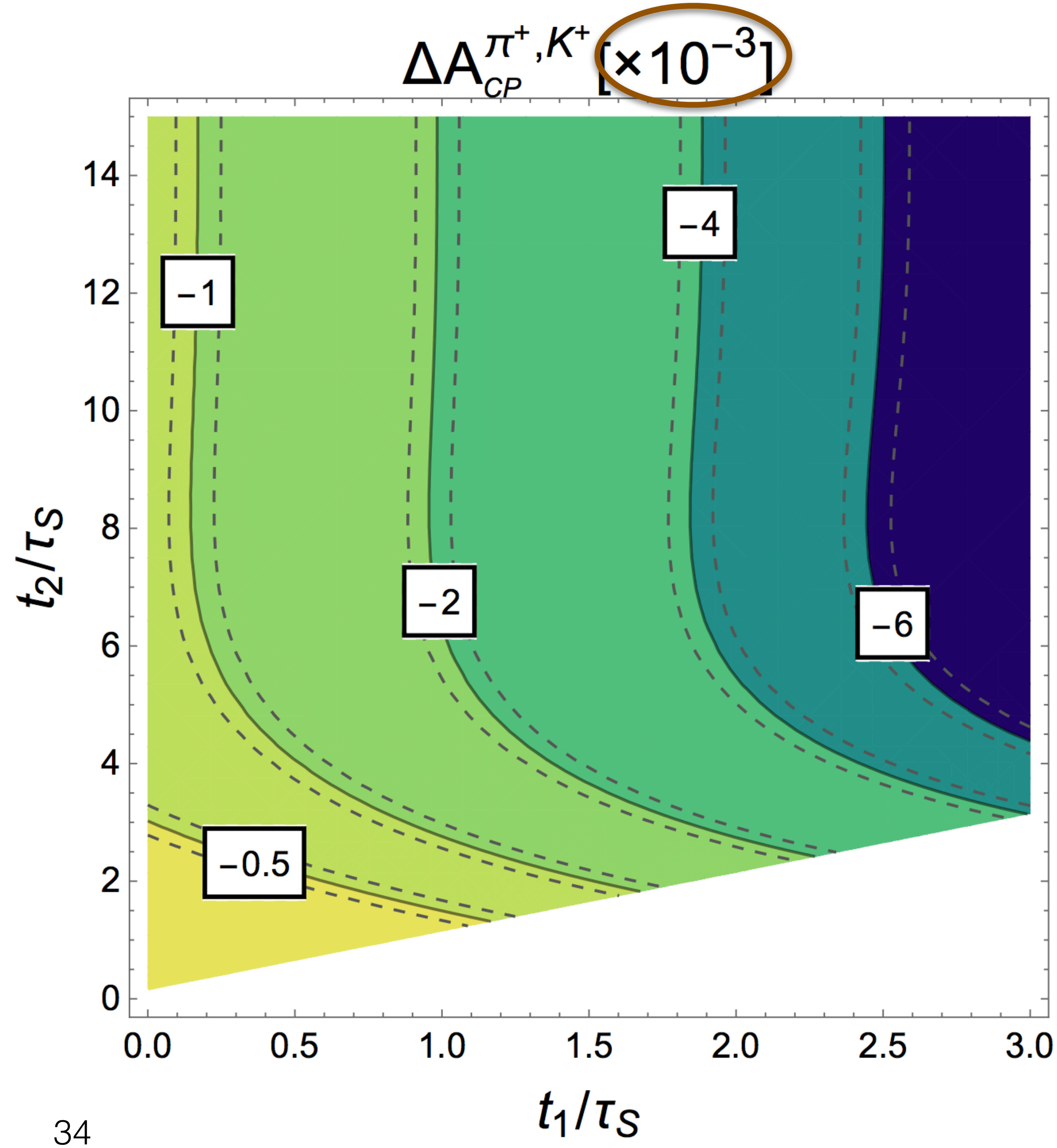
Wang, **FSY**, Li, PRL'17

New Observable

revealing

new CPV effect

$$A_{CP}(t) \simeq \left[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{dir}(t) + A_{CP}^{int}(t) \right]$$



Measurement @ LHCb

See Liang Sun's talk

K_S-K_L asymmetries

$$R \equiv \frac{\Gamma(D \to f K_S^0) - \Gamma(D \to f K_L^0)}{\Gamma(D \to f K_S^0) + \Gamma(D \to f K_L^0)}$$
$$= -2r_f \cos(\phi + \delta_f) \approx -2r_f \cos\phi \cos\delta_f$$

$$A_{CP}^{int} \propto r_f \sin\delta_f$$

	R [1]	R [2]	R [3]	R [4]	$R_{\rm exp}$ [5]	R [6]
$D^0 \to K_{S,L}^0 \pi^0$	0.107	0.107	0.106	$0.09^{+0.04}_{-0.02}$	0.108 ± 0.035	0.113 ± 0.001
$D^+ \to K_{S,L}^0 \pi^+$	-0.005 ± 0.013	-0.019 ± 0.016	-0.010 ± 0.026		0.022 ± 0.024	0.025 ± 0.008
$D_s^+ \to K_{S,L}^0 K^+$	-0.002 ± 0.009	-0.008 ± 0.007	-0.008 ± 0.007	$0.11^{+0.04}_{-0.14}$		0.012 ± 0.006

$D^+ \to \pi^+ K_S^0$ $\quad r_{\pi^+} = -0.073 \pm 0.004,\quad \delta_{\pi^+} = -1.39 \pm 0.05,$

$D_s^+ \to K^+ K_S^0$ $\quad r_{K^+} = -0.055 \pm 0.002,\quad \delta_{K^+} = +1.45 \pm 0.05$

Sifan Zhang's talk: $\quad R(D^+) = 0.001 \pm 0.009 \pm 0.009$

BESIII preliminary $\quad R(D_s^+) = -0.021 \pm 0.019 \pm 0.016$

K_S-K_L asymmetries in charmed baryon decays

- First doubly Cabibbo-suppressed (DCS) process measured is

$$BR(\Lambda_c^+ \to pK^+\pi^-)/BR(\Lambda_c^+ \to pK^-\pi^+) = (2.35 \pm 0.27 \pm 0.21) \times 10^{-3}$$

Belle, ’15

- But no two-body DCS decay is measured.

1. two-body decay is more interesting in theory
2. dynamics in charm baryon decays is not known, and DCS is important
3. DCS amplitude is required in the new CPV effect in neutral Kaon involved modes

K_S-K_L asymmetry to search for two-body DCS amplitude

$$R(\Lambda_c \to pK^0_{S,L}) \equiv \frac{\Gamma(\Lambda_c \to pK^0_S) - \Gamma(\Lambda_c \to pK^0_L)}{\Gamma(\Lambda_c \to pK^0_S) + \Gamma(\Lambda_c \to pK^0_L)}$$

$$\frac{A_{DCS}}{A_{CF}} \equiv re^{i\delta}$$

$$R(\Lambda_c \to pK^0_{S,L}) \approx -2r\cos\delta$$

If non-zero, signal of 2-body DCS

Two-body DCS Lambda_c decays

$$\frac{A_{DCS}}{A_{CF}} \equiv re^{i\delta} \qquad R(\Lambda_c \to pK^0_{S,L}) \approx -2r\cos\delta$$

$$\Lambda_c^+ \to pK^0 \longrightarrow R(pK^0_{S,L}) \propto r = |A_{DCS}/A_{CF}| = \lambda^2$$

$$\Lambda_c^+ \to nK^+ \longrightarrow \mathscr{B}(nK^+) \propto |A_{DCS}/A_{CF}|^2 \mathscr{B}_{CF} = \lambda^4 \mathscr{B}_{CF}$$

$$\Lambda_c^+ \to pK^{*0} \; (\to pK^+\pi^-)$$

$$\Lambda_c^+ \to nK^{*+} \; (\to nK^0_S\pi^+, nK^+\pi^0)$$

$$\Lambda_c^+ \to \Delta^+K^0 \; (\to p\pi^0K^0)$$

$$\Lambda_c^+ \to \Delta^0K^+ \; (\to p\pi^-K^+)$$

Numerical Results

Modes	Representation	$BR_{\text{exp}}(\%)$	$BR_{\text{SU(3)}}(\%)$
$\Lambda_c^+ \to \Lambda\pi^+$	$\frac{1}{\sqrt{6}}(-2e-2f-2g)$	1.30±0.07	1.30±0.17
$\Lambda_c^+ \to \Sigma^0\pi^+$	$\frac{1}{\sqrt{2}}(-2e+2f+2g)$	1.29±0.07	1.27±0.17
$\Lambda_c^+ \to \Sigma^+\pi^0$	$\frac{1}{\sqrt{2}}(2e-2f-2g)$	1.24±0.10	1.27±0.17
$\Lambda_c^+ \to pK_S^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(2g) - \frac{1}{\sqrt{2}}(-2e)$	1.58±0.08	$1.36 \sim 1.80$
$\Lambda_c^+ \to pK_L^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(2g) + \frac{1}{\sqrt{2}}(-2e)$		$1.24 \sim 1.67$
$\Lambda_c^+ \to \Xi^0 K^+$	$-2f$	0.50±0.12	0.50±0.12
$\Xi_c^0 \to \Xi^-\pi^+$	$2e$		2.24±0.34
$\Xi_c^0 \to \Xi^0\pi^0$	$\frac{1}{\sqrt{2}}(-2e+2g)$		$0.07 \sim 1.81$
$\Xi_c^0 \to \Lambda K_S^0$	$\frac{1}{\sqrt{12}}\tan^2\theta_C(-2e+4f+4g) - \frac{1}{\sqrt{12}}(-4e+2f+2g)$		0.47±0.08
$\Xi_c^0 \to \Lambda K_L^0$	$\frac{1}{\sqrt{12}}\tan^2\theta_C(-2e+4f+4g) + \frac{1}{\sqrt{12}}(-4e+2f+2g)$		0.50±0.09
$\Xi_c^0 \to \Sigma^+ K^-$	$2f$		0.31±0.09
$\Xi_c^0 \to \Sigma^0 K_S^0$	$\frac{1}{2}\tan^2\theta_C(2e) - \frac{1}{2}(-2f-2g)$		0.23±0.07
$\Xi_c^0 \to \Sigma^0 K_L^0$	$\frac{1}{2}\tan^2\theta_C(2e) + \frac{1}{2}(-2f-2g)$		0.20±0.06
$\Xi_c^+ \to \Xi^0\pi^+$	$-2g$		$0.01 \sim 10.22$
$\Xi_c^+ \to \Sigma^+ K_S^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(-2e) - \frac{1}{\sqrt{2}}(2g)$		$0.06 \sim 4.84$
$\Xi_c^+ \to \Sigma^+ K_L^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(-2e) + \frac{1}{\sqrt{2}}(2g)$		$0.00 \sim 4.30$

Wang, Guo, Long, **FSY**, '17

TABLE II: $K_S^0 - K_L^0$ asymmetries in $\mathcal{B}_c \to \mathcal{B}K_{S,L}^0$ decays.

$R(\Lambda_c^+ \to pK_{S,L}^0)$	$R(\Xi_c^0 \to \Lambda K_{S,L}^0)$	$R(\Xi_c^0 \to \Sigma^0 K_{S,L}^0)$	$R(\Xi_c^+ \to \Sigma^+ K_{S,L}^0)$
$-0.010 \sim 0.087$	-0.037 ± 0.004	0.091 ± 0.016	$-0.113 \sim 0.390$

	$A_{CP}(\Lambda_c^+ \to pK_S^0)$	$A_{CP}(\Xi_c^0 \to \Lambda K_S^0)$	$A_{CP}(\Xi_c^0 \to \Sigma^0 K_S^0)$	$A_{CP}(\Xi_c^+ \to \Sigma^+ K_S^0)$
$S1$	$-3.15 \sim -2.67$	-3.13 ± 0.05	-3.42 ± 0.05	$-4.57 \sim -2.60$
$S2$	$-3.55 \sim -3.09$	-3.58 ± 0.04	-2.50 ± 0.10	$-2.91 \sim -1.39$

Summary

- Theory and experiment interplay in charm physics
- More measurements on D meson decays are helpful for understanding of DDbar mixing.
- More measurements on charm baryon decays are helpful to understand dynamics and predict doubly charmed baryon decays
- Measure KS-KL asymmetries to distinguish models, benchmark for how large the new CPV are, and search for first two-body DCS charmed baryon decays
- Charming potentials are expected at BESIII


Disney's
Charming Dance
Theory
Experiment

Thank you!