Weak Decays of Charmed Hadrons

—— Theoretical Progresses

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Outline

- Introduction
- DDbar mixing
- Charmed baryon decays
- K_S-K_L asymmetries
- Summary

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**, 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)
$\pi^0\overline{K}^0$	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, ‘18]

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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		
	$\mathscr{B}_{\rm exp}$	$\mathscr{B}_{\rm th}$	$\mathscr{B}_{\rm exp}$	$\mathscr{B}_{\rm th}$	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	
	PDG16		LHCb,'16		

Studies of the resonance structure in $D^0 \to K_S^0 K^\pm \pi^\mp$ decays

LHCb Collaboration (Roel Aaij (CERN) *et al.*) *Show all 726 authors*

Sep 22, 2015 - 35 pages

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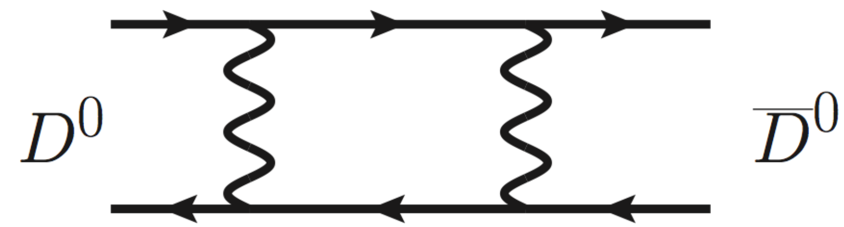
Let's see its impact on the prediction of DDbar mixing

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



- The time evolution

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

- Mass eigenstates in terms of weak eigenstates

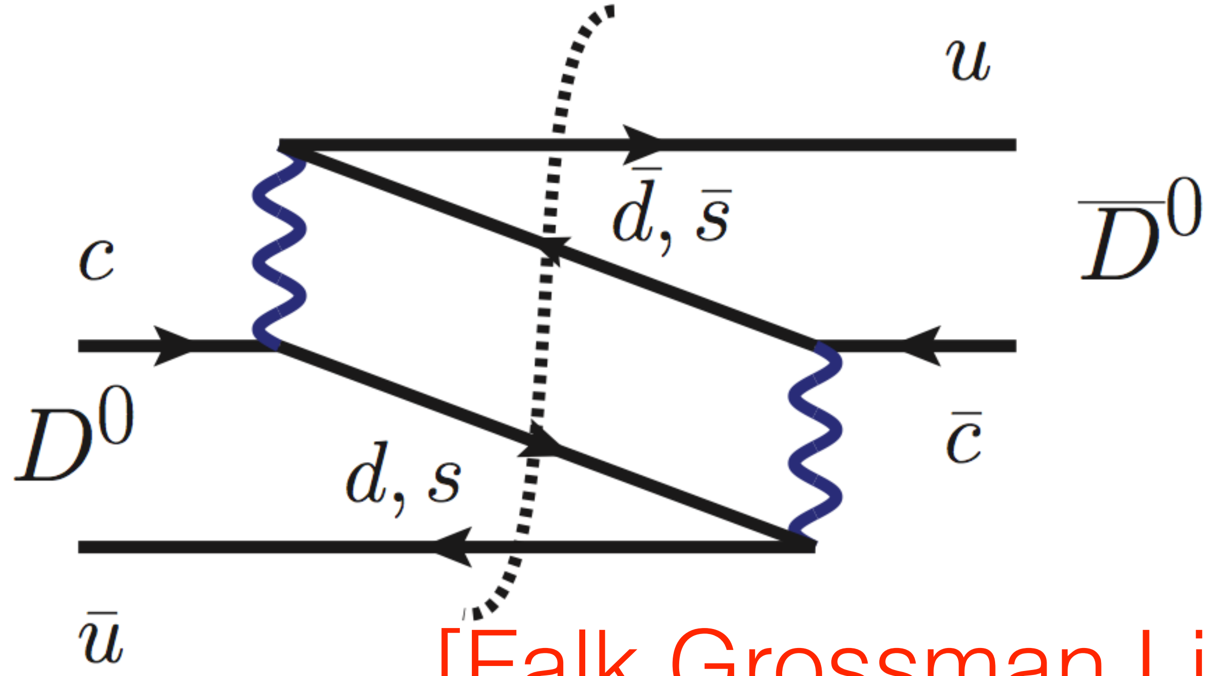
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

- Mass difference and Width difference

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

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

Exclusive Approach



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

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

Sum up all the intermediate states

Current most well known processes are **D→PP** and **PV**

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 $\quad y_{PV}$

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

More decay modes

[Qin, Li, Lu, FSY, PRD2014]

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

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

[H.Y.Jiang, **FSY**, Q.Qin, H.n.Li, C.D.Lü, ‘18]

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

Results before 2016

But now…

y_{PV}

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

$\cos\delta \sim 1$

	Before 2016		**After 2016**	
10^{-3}	$\mathcal{B}_{\rm exp}$	$\mathcal{B}_{\rm th}$	$\mathcal{B}_{\rm exp}$	$\mathcal{B}_{\rm th}$
$D^0 \to \overline{K}^{*0}K^0$	< 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}

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

Before2016 : 2.2×10^{-3}

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

After2016 : 0.38×10^{-3}

Before 2016 $y_{PV} = (0.32 \pm 0.07)\,\%$

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

But now, $y_{PV} = (0.11 \pm 0.07)\,\%$

[H.Y.Jiang, **FSY**, Q.Qin, H.n.Li, C.D.Lü, arXiv:1705.07335]

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

now

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

$$y_{PV} = (1.12 \pm 0.72) \times 10^{-3}$$

Before 2016

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

$$y_{PP+PV} = (0.21 \pm 0.07)\%$$

- Close to data

- PP and PV modes cannot help to understand:

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

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New measurements change our understanding !!

More measurements would be helpful as well

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$$y_{PP+PV} = (0.21 \pm 0.07)\%$$

- PP and PV modes cannot help to understand:

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

- **Uncertainty much better controlled than diagrammatic approach [Cheng, Chiang, '10]**

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

which can not tell anything.

2. BR of $\Xi_c{}^+ \rightarrow pK^-\pi^+$

$\Xi_c^+ \to pK^-\pi^+$

- **This process is always used to search for new particles and their properties**
  - ✦ New Ω_c states observed by LHCb [PRL118,182001(2017)
    - in $\Xi_c^+K^-$ with $\Xi_c^+ \to pK^-\pi^+$
  - ✦ Ξ_b' and Ξ_b^* states observed by LHCb [PRL114,062004(2014)]
    - in $\Xi_b^0\pi^-$ with $\Xi_b^0 \to \Xi_c^+\pi^-$, $\Xi_c^+ \to pK^-\pi^+$
  - ✦ Mass and lifetime of Ξ_b^0 by LHCb [PRL113,032001(2014)]
    - via $\Xi_b^0 \to \Xi_c^+\pi^-$, $\Xi_c^+ \to pK^-\pi^+$
  - ◉ Suggested to measure $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$ [1703.09086]
- **But its branching ratio not directly measured**

$\Xi_c^+ \to pK^-\pi^+$

- **This process is always used to search for new particles and their properties**
  - ✦ Fragmentation fraction $f_{\Xi_b^0}/f_{\Lambda_b^0}$ [LHCb, PRL113,032001(2014)]

$$b \to \Xi_b^0 \quad \textit{v.s.} \quad b \to \Lambda_b^0$$

$$\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \cdot \frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} \cdot \frac{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.88 \pm 0.04 \pm 0.03)\%$$

≈ 1 ≈ 0.1 assumption in [PRL113,032001]

$$\to \quad f_{\Xi_b^0}/f_{\Lambda_b^0} \approx 0.2$$

- **But its branching ratio not directly measured**

$\Xi_c^+ \to pK^-\pi^+$

- **This process is always used to search for new particles and their properties**
  - Fragmentation fraction $f_{\Xi_b^0}/f_{\Lambda_b^0}$ [LHCb, PRL113,032001(2014)]

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≈ 1 ✓ HQE $\qquad \approx 0.1$? assumption in [PRL113,032001]

$$\rightarrow \; f_{\Xi_b^0}/f_{\Lambda_b^0} \approx 0.2$$

- **But its branching ratio not directly measured**

$\Xi_c{}^+$

- has the longest lifetime of charmed baryons

$$\tau(\Lambda_c^+) = (200 \pm 6) \times 10^{-15} s, \qquad \tau(\Xi_c^+) = (442 \pm 26) \times 10^{-15} s,$$
$$\tau(\Xi_c^0) = (112^{+13}_{-10}) \times 10^{-15} s, \qquad \tau(\Omega_c^0) = (69 \pm 12) \times 10^{-15} s.$$

★ better for measurements @ LHCb

- Mass: m_{Ξ_c}=2467.87±0.30MeV

  $m_{\Lambda c}$=2286.46±0.14MeV

No Absolute Branching fraction of

$\Xi_c^+ \rightarrow pK^-\pi^+$

Ξ_c^+ No absolute branching fractions have been measured. The following are branching *ratios* relative to $\Xi^- 2\pi^+$.

PDG

$\Xi^- 2\pi^+$	DEFINED AS 1
$pK^-\pi^+$	0.21 $\pm$0.04

We should know the branching fraction for estimation on events

Branching Ratios of $\Xi_c^+ \to pK^-\pi^+$

- Absolute value not measured
- But compared to $\Xi_c^+ \to \Xi^-\pi^+\pi^+$

PDG

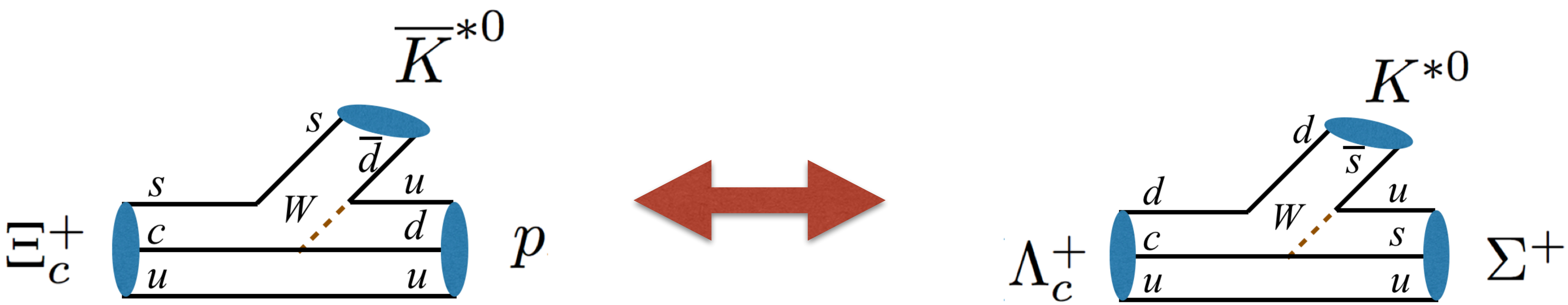
$\Gamma(\Xi_c^+ \to pK^-\pi^+)/\Gamma(\Xi_c^+ \to \Xi^- 2\pi^+)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.21 ± 0.04	**OUR AVERAGE**				
0.194 ±0.054	47 ±11	VAZQUEZ-JAURE..	2008	SELX	Σ^- nucleus, 600 GeV
0.234 ±0.047 ±0.022	202	LINK	2001B	FOCS	γ nucleus

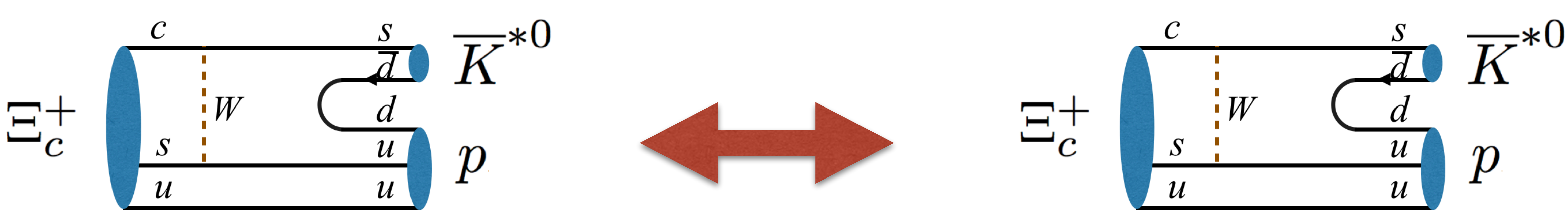
We should know the branching fraction for estimation on events

Under U-spin symmetry, $d \leftrightarrow s$

$$\mathcal{A}(\Xi_c^+ \to p\overline{K}^{*0}) = \mathcal{A}(\Lambda_c^+ \to \Sigma^+ K^{*0})$$



$d \leftrightarrow s$



Branching fraction in $\Xi_c^+ \to pK^-\pi^+$

Under U-spin symmetry, $d \leftrightarrow s$

$$\mathcal{A}(\Xi_c^+ \to p\overline{K}^{*0}) = \mathcal{A}(\Lambda_c^+ \to \Sigma^+ K^{*0})$$

$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K^{*0}) = (0.36 \pm 0.10)\%$$

[FOCUS, 01']

$$\mathcal{B}(\Xi_c^+ \to p\overline{K}^{*0})/\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = 0.54 \pm 0.10$$

[FOCUS, 02']

$$Br(\Xi_c^+ \to pK^-\pi^+) = (2.2 \pm 0.8)\%$$

[**FSY**, Jiang, Li, Lu, Wang, Zhao, 1703.09086]

$\Xi_c^+ \to pK^-\pi^+$

- **This process is always used to search for new particles and their properties**
  - ✦ Fragmentation fraction $f_{\Xi_b^0}/f_{\Lambda_b^0}$ [LHCb, PRL113,032001(2014)]

$$\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \cdot \frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} \cdot \frac{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.88 \pm 0.04 \pm 0.03)\%$$

≈ 1 ≈ 0.1 → **=0.35±0.13**

$$f_{\Xi_b^0}/f_{\Lambda_b^0} \approx 0.2$$ *v.s.* $$\boxed{f_{\Xi_b^0}/f_{\Lambda_b^0} = 0.05 \pm 0.02}$$

[LHCb, PRL113,032001]

[Jiang, **FSY**, 1802.02948]

Branching Ratio of $\Xi_c^+ \to pK^-\pi^+$

Precision improvements are required

LHCb

$$\mathcal{A}(\Xi_c^+ \to p\overline{K}^{*0}) = -\mathcal{A}(\Lambda_c^+ \to \Sigma^+ K^{*0})$$

BESIII

$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K^{*0}) = (0.36 \pm 0.10)\%$$

30% σ

$$\mathcal{B}(\Xi_c^+ \to p\overline{K}^{*0})/\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = 0.54 \pm 0.10$$

20% σ

$$Br(\Xi_c^+ \to pK^-\pi^+) = (2.2 \pm 0.8)\%$$

$$Br(\Xi_c^+ \to pK^-\pi^+) = (2.2 \pm 0.8)\%$$

Precision improvements are required

LHCb

$$\mathcal{A}(\Xi_c^+ \to p\overline{K}^{*0}) = -\mathcal{A}(\Lambda_c^+ \to \Sigma^+ K^{*0})$$

BESIII

$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K^{*0}) = (0.36 \pm 0.10)\%$$

30% σ

$$\mathcal{B}(\Xi_c^+ \to p\overline{K}^{*0})/\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = 0.54 \pm 0.10$$

20% σ

10^6 events $\Xi_c^+ \to pK^-\pi^+$ @ 3.3 fb^{-1}

[LHCb, PRL118(2017)182001]

PWA can be performed now

PWA calls for 2019 data

3. 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.
  - two-body decay is more interesting in theory
  - dynamics in charm baryon decays is not known, and DCS is important

Suggest to measure K_S-K_L asymmetry

to search for two-body DCS amplitude

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

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

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

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

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

If non-zero, signal of 2-body DCS

Numerical Results

Modes	Representation	$BR_{\rm exp}(\%)$	$BR_{\rm SU(3)}(\%)$
$\Lambda_c^+ \to \Lambda\pi^+$	$\frac{1}{\sqrt{6}}(-2e-2f-2g)$	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
$\Xi_c^+ \to \Xi^0\pi^+$	$-2g$		$0.01\sim 10.22$
$\Xi_c^+ \to \Sigma^+ K_S^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(-2e)-\frac{1}{\sqrt{2}}(2g)$		$0.06\sim 4.84$
$\Xi_c^+ \to \Sigma^+ K_L^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(-2e)+\frac{1}{\sqrt{2}}(2g)$		$0.00\sim 4.30$

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	$-0.113\sim 0.390$

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

K_S-K_L asymmetries in charm mesons

TABLE III. Results on $K_S^0 - K_L^0$ asymmetries in $D^0 \to K_{S,L}^0 \pi^0$, $D^+ \to K_{S,L}^0 \pi^+$ and $D_s^+ \to K_{S,L}^0 K^+$. Our results are compared to other approaches [7,10,13,24] and the experimental data [21].

	R [13]	R [7]	R [24]	R [10]	$R_{\rm exp}$ [21]	R(FAT)
$D^0 \to K_{S,L}^0 \pi^0$	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

Measurements could distinguish theoretical models

[Wang, **FSY**, Guo, Jiang, ’17]

Summary

- More measurements are helpful in theoretical understanding of DDbar mixing.
- Suggest to measure some processes to determine $\Xi_c^+ \to p K^- \pi^+$
- Suggest to measure KS-KL asymmetries

Thank you!