Highlights on Charm Physics in Theory

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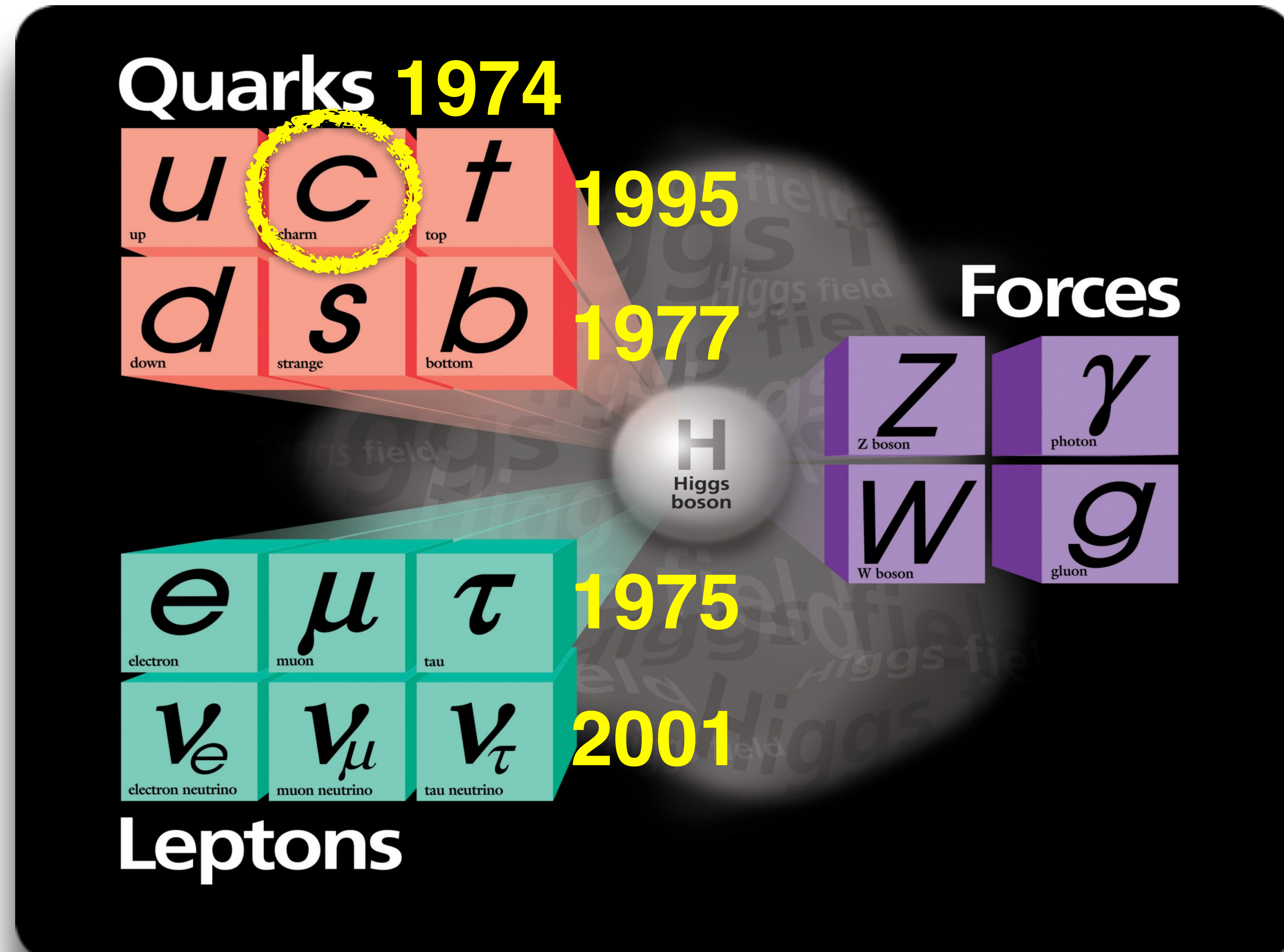
16th HFCPV @ Zhengzhou, 2018.10.26

Revolution: charm discovery

More and heavy flavors in particle zoo



Standard Model of particle physics

Why Charm Now?

1. New physics , up-type quark FCNC

GIM mechanism —> **small in SM, sensitive to NP**

2. QCD @ $\mu \lesssim m_c$, $\frac{\Lambda_{\rm QCD}}{m_c} \lesssim 1$

Margin of perturbative and non-perturbative QCD

3. Large data, higher precision

Outline

1. Charmed meson decays

- DDbar mixing — Hua-Yu Jiang
- CP Violation — Xian-Wei Kang

— — new CPV effect

2. Charmed baryon decays — Hai-Yang Cheng

- Single-charm baryon — Chao-Qiang Geng
- Double-charm baryon — Zhen-Xing Zhao, Li-Juan Jiang

— — discovery channel

CPV in charm

- CPV is required by baryogenesis, the matter-antimatter asymmetry in the Universe

- CPV has been well established in K and B systems, but never in charm

$$\Delta a_{CP}^{\text{dir}} = (-0.61 \pm 0.76) \times 10^{-3} \quad A_\Gamma = (-0.29 \pm 0.28) \times 10^{-3}$$

LHCb, '16 & '17

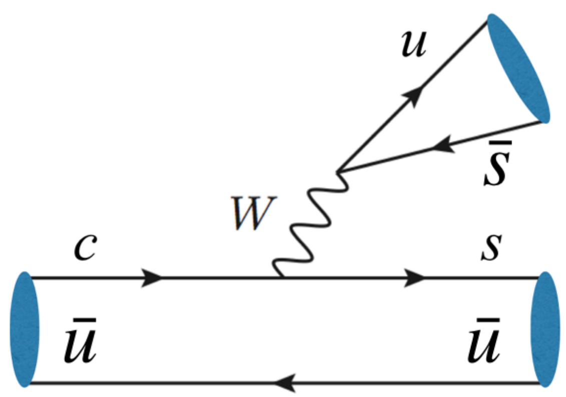
NO CPV, but precision is below 10^{-3}

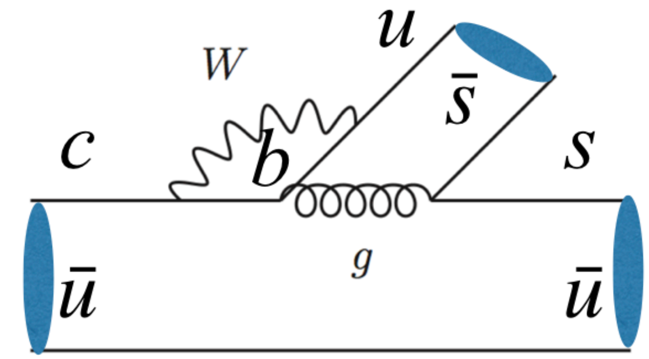
- CPV in charm decays plays an unique role in searching for new physics (NP) — up sector

Direct CPV in charm

Scenario 1 : SCS

tree v.s. **penguin**





$V_{cd}V_{ud}/V_{cs}V_{us}$ $\qquad$ $V_{cb}V_{ub}$

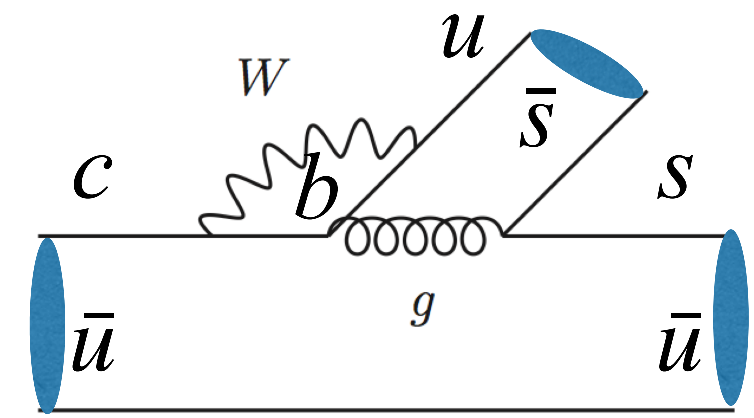
λ $\qquad$ $\lambda^5 + i\lambda^5$

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

See Xianwei Kang's talk

CPV in SCS decays: tree *v.s.* penguin

- **Ambiguity in penguins**
  - **heavy quark expansion $1/m_c$,** m_c =1.3GeV, **does not work** in exclusive processes



★ **$\Delta A_{CP}(K^+K^-, \pi^+\pi^-)$ predicted from 10^{-4} to 10^{-2}**

Grossman, Kagan, Nir, '07; Bigi, Paul, '11; Isidori, Kamenik, Ligeti, Perez, '11; Brod, Grossmann, Kagan, Zupan, '11, '12; Feldmann, Nandi, Soni, '12; Bhattarcharya, Gronau, Rosner, '12; Cheng, Chiang, '12; Li, Lu, **FSY**, '12; Franco, Mishima, Silvestrini, '12; Hiller, Jung, Schacht, '12; Khodjamirian, Petrov, '17.

$$\Delta a_{CP}^{\rm dir} = (-0.61 \pm 0.76) \times 10^{-3} \longrightarrow O(10^{-3})$$

★ **Even if CPV observed at 10^{-3} in individual mode, not distinguishable for NP or SM !!**

Tree amplitudes

- **Better understood, from data of BRs**

  - Topological diagrams in flavor SU(3) symmetry

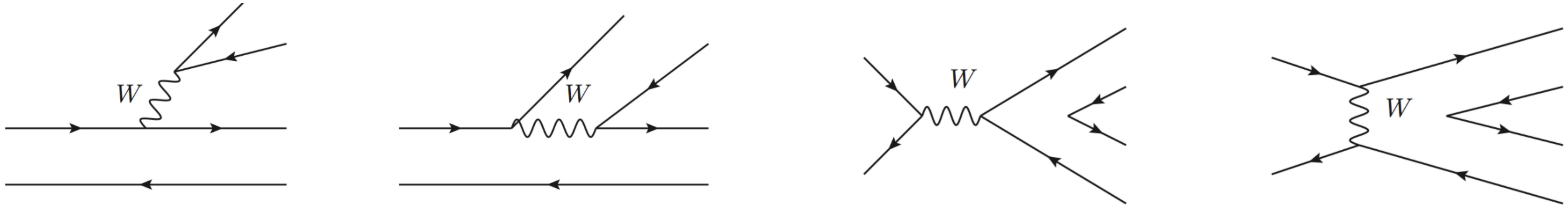
    Cheng, Chiang, ’10, ’16; Bhattarcharya, Rosner, ’09

  - Topological diagrams in SU(3) breaking

    Muller, Nierste, Schacht, ’15

  - Topological diagrams in factorization

    Li, Lu, Qin, **FSY**, ’12, ’14

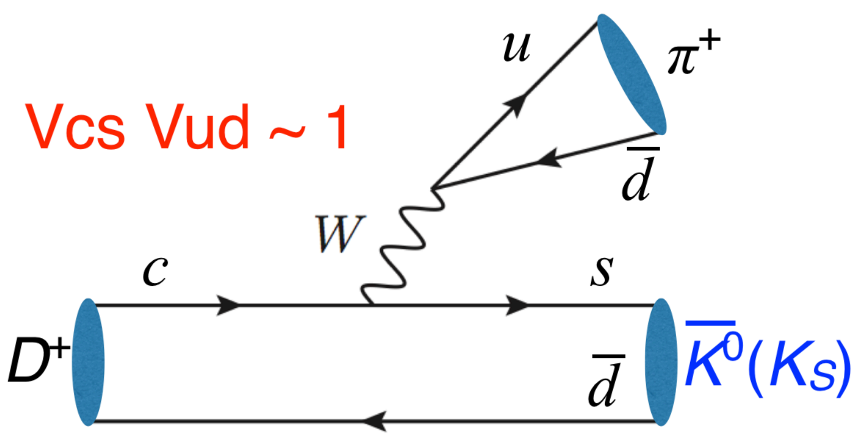


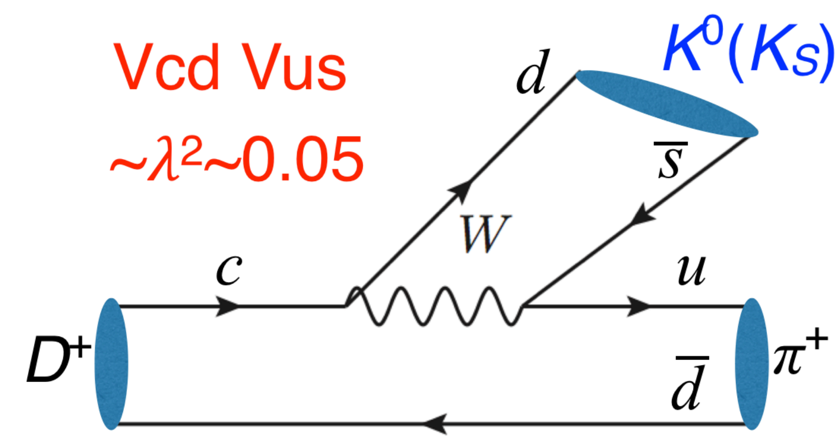
CPV in tree, would be better understood

Direct CPV in charm

Scenario 2 : CF with $K_S{}^0$

CF v.s. **DCS**





Tree ! $V_{cs}V_{ud}$

1

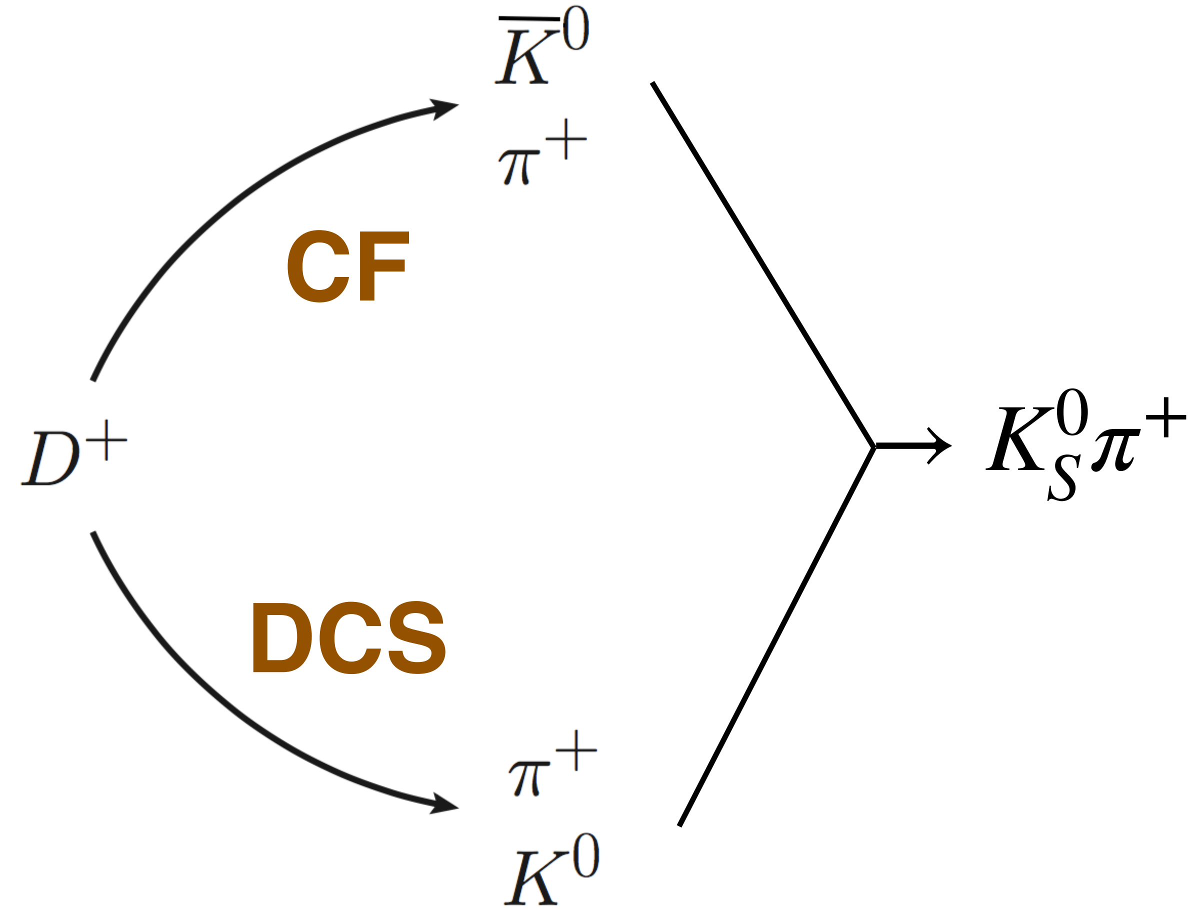
$V_{cd}V_{us}$ **Tree !**

$\lambda^2 + i\lambda^6$

$A_{CP}^{D^+\to K_S^0\pi^+} = (-0.363{\pm}0.094{\pm}0.067)\%$ Belle, '12

Postulated in literature:

deducting kaon mixing, data reveal direct CPV in charm



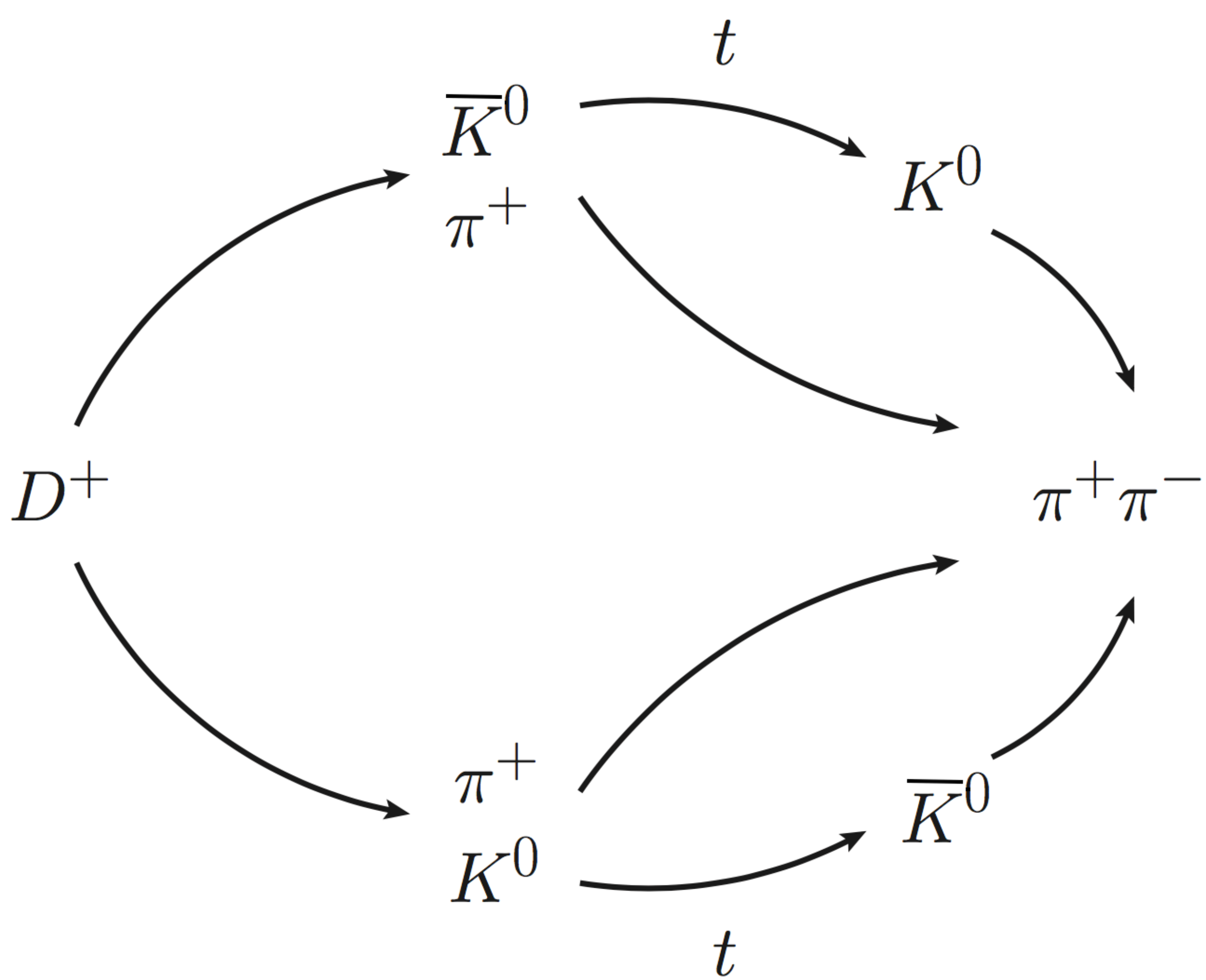
Lipkin, Xing, ’95; D’Ambrosio, Gao, ’01; Bianco, Fabbri, Benson, Bigi, ’03; Grossman, Nir, ’12; Belle, ’12

Due to the smallness of direct CPV, it can be used to search for new physics

However…

Full decay chain

$$D^+ \to \pi^+ K(t)(\to \pi^+ \pi^-)$$



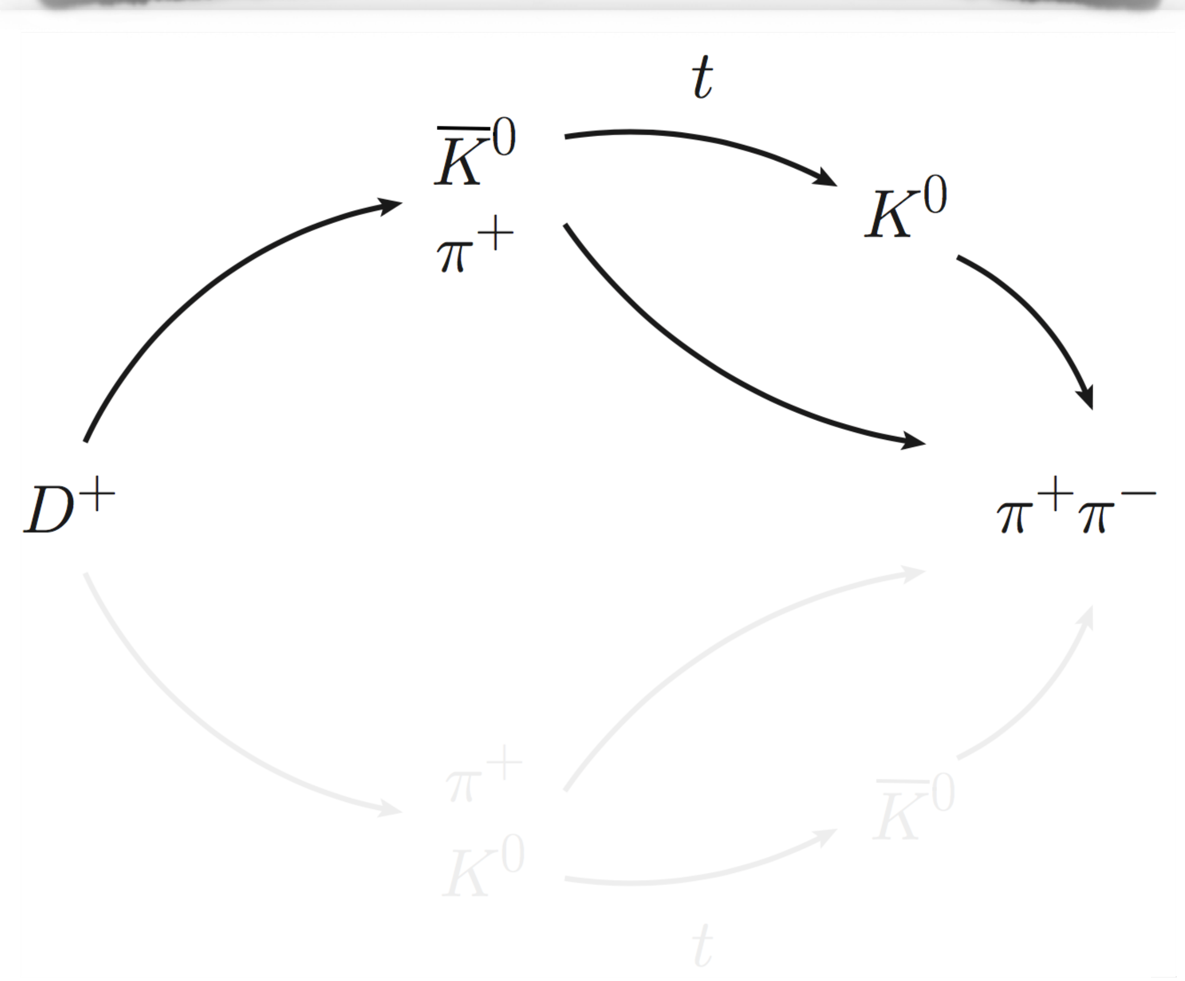
$$A_{CP}(t) = A_{CP}^{\overline{K}^0}(t) + A_{CP}^{\text{dir}}(t)$$

Indirect CPV in kaon mixing

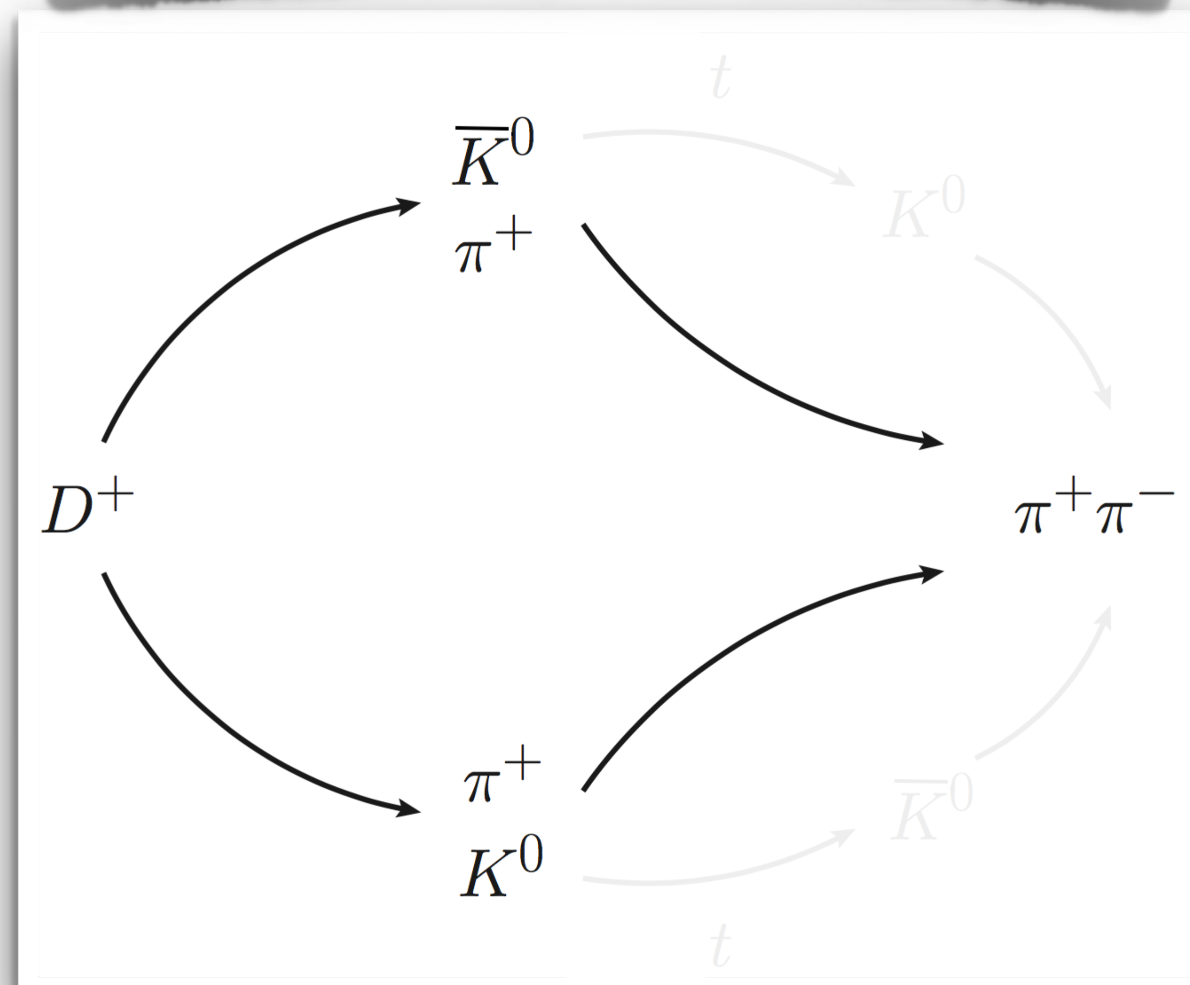
$\mathrm{Re}(\epsilon)=10^{-3}$

Direct CPV in charm decays

$\mathrm{Im}(V_{cd}V_{us}/V_{cs}V_{ud})=\lambda^6=10^{-5}$



Z.z. Xing, ’95



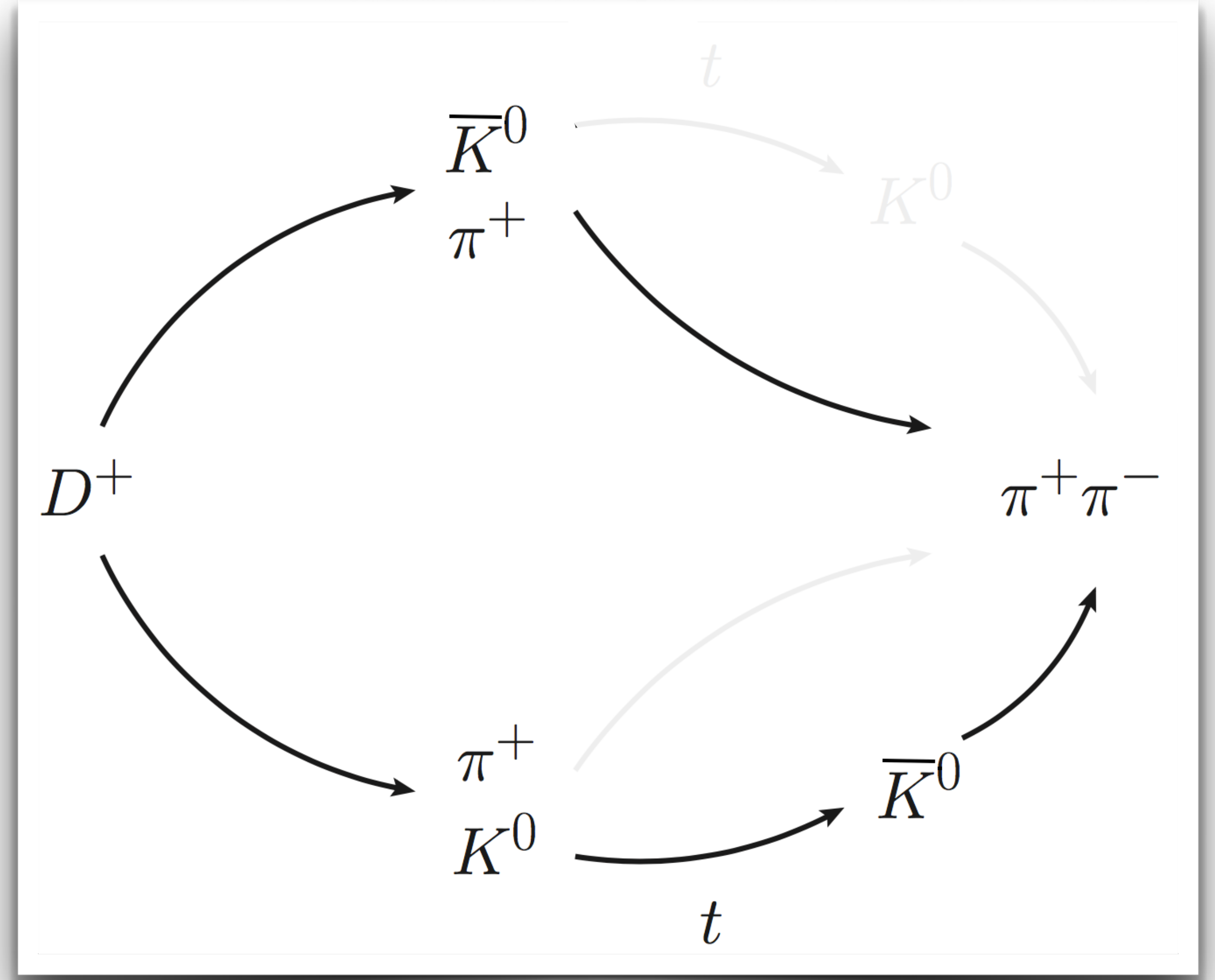
Bigi, Yamamoto, ’95

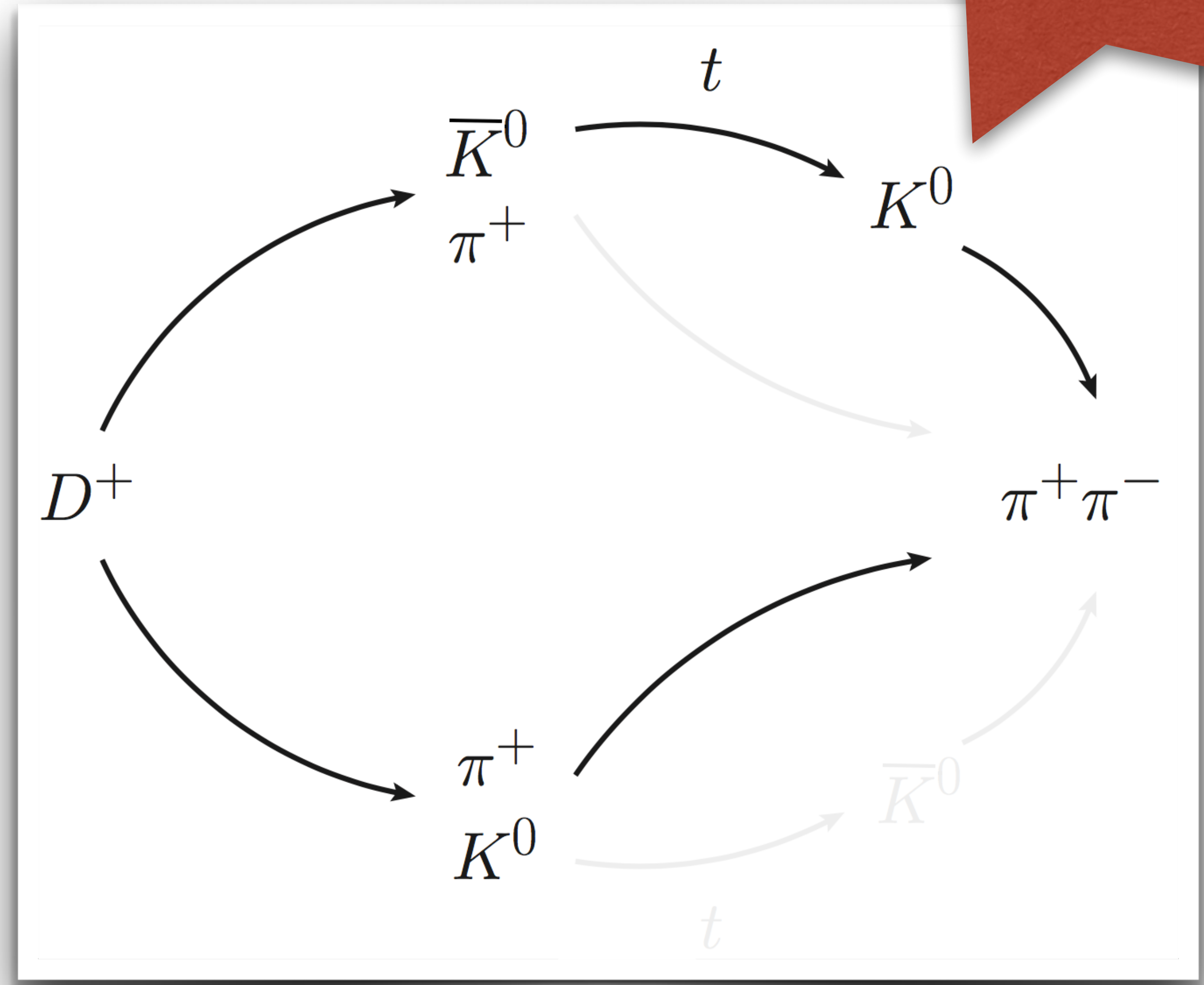
$$A_{CP}(t) = A_{CP}^{\overline{K}^0}(t) + A_{CP}^{\mathrm{dir}}(t) + A_{CP}^{\mathrm{int}}(t)$$

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



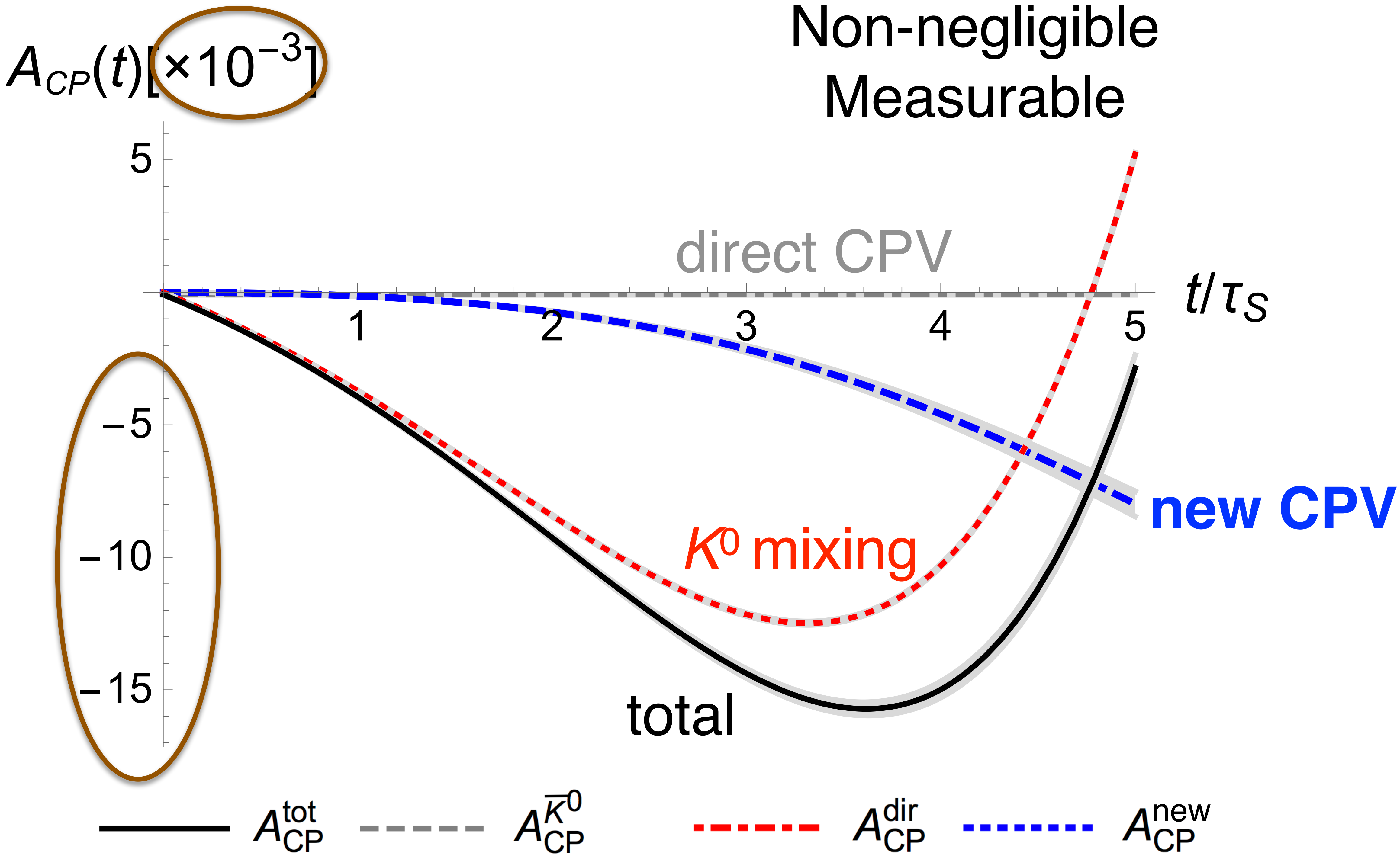


D.Wang, **FSY**, H.n.Li, Phys.Rev.Lett 119, 181802(2017)

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

Non-negligible
Measurable

$D^+ \to K_S^0 \pi^+$



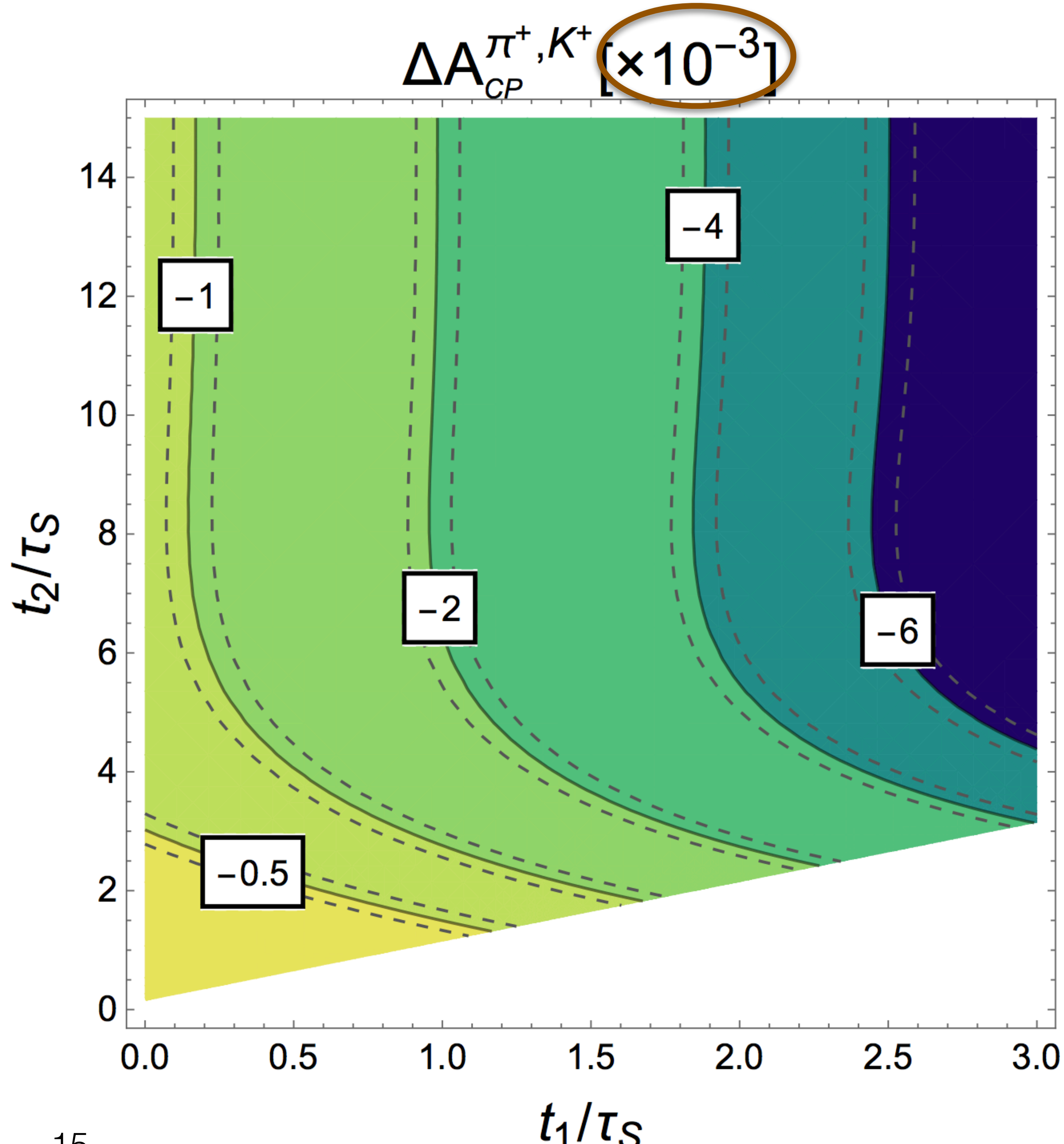
$$\Delta A_{CP} = A_{CP}(D^+ \to \pi^+ K_S^0) - A_{CP}(D_s^+ \to K^+ K_S^0)$$

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

New Physics in $D \to f K_S^0$

$$A_{CP}^{dir} \sim 2 r_f \sin\phi \sin\delta_f$$

SM: $\phi = O(10^{-4})$

NP: $\phi = O(1)$

Search for new physics at tree-level

CPV in charm -> neutral Kaon

- **New CPV effect** is found in CF $D \to K_S f$
  - mother decay and daughter mixing
  - Has to be subtracted to extract direct CPV
- **Accessible at Belle II and LHCb**
  - **An observable is proposed** to measure it.
  - Large branching fractions for measurements
- CPV stems from **TREE** amplitudes
  - Predictions better controlled by branching ratios
  - Promising for **NP**, compared to penguins

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

2. Charmed Baryon Decays

- Single-charm baryons
- Double-charm baryons

Charm-Baryon Renaissance

Cheng-Ping

1976
Observation
Λ_c^+

Yu Pan

Belle'14, BESIII'16
Absolute BR
$\Lambda_c^+ \to pK^-\pi^+$

Belle'18
Absolute BR
$\Xi_c^0 \to \Xi^-\pi^+$

No absolute BRs

Ji-bo

LHCb'17
Observation
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$

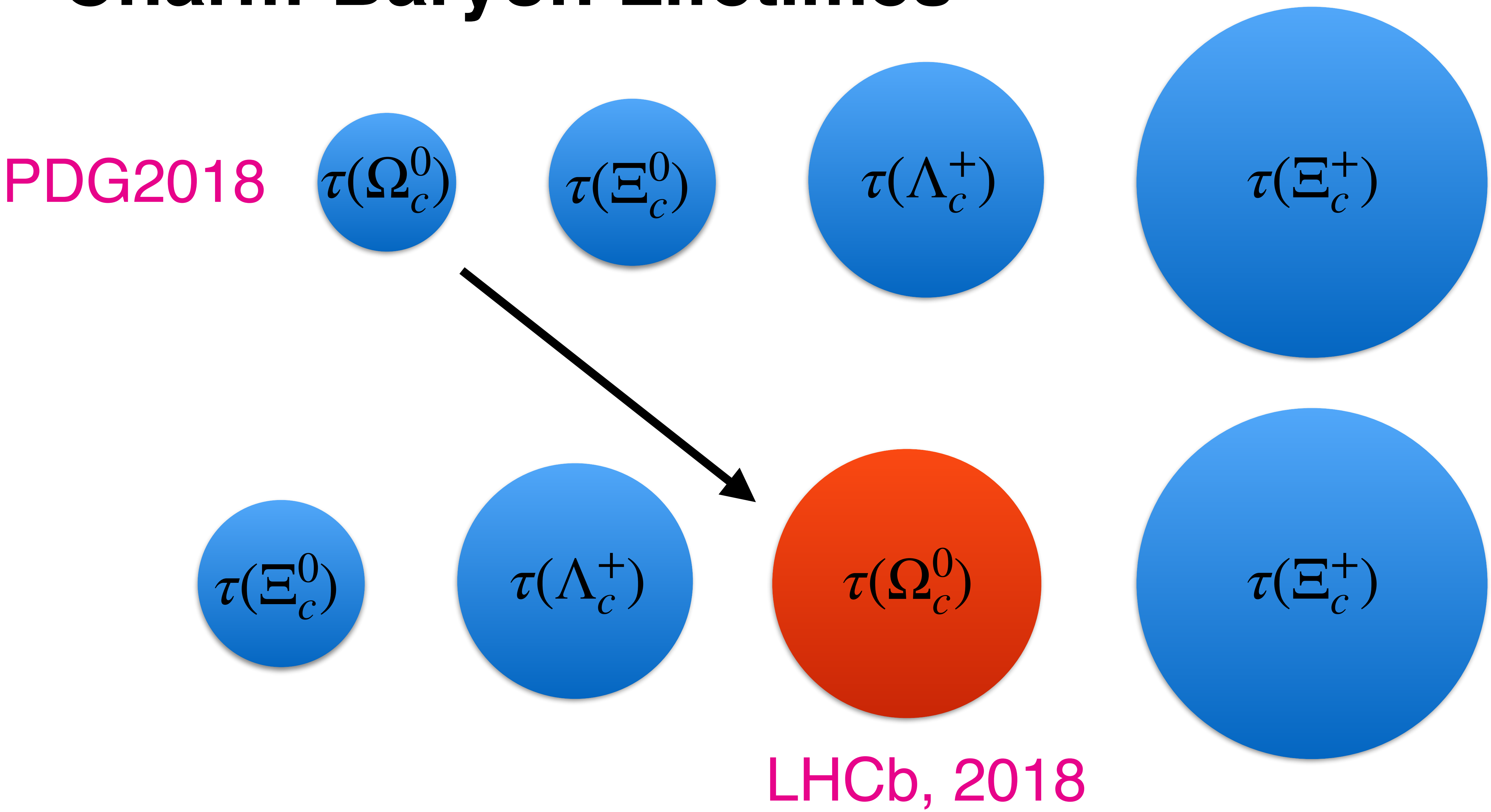
Theoretical studies
on nonleptonic decays

1990s
models

See Chao-Qiang's talk

Lu, Wang, **FSY**, '16
FSY,Jiang,Li,Lu,Wang,Zhao, '17
FSY,Wang,Zhao, '17
Wang,Xing,Xu, '17
Geng,Hsiao,Liu,Tsai, '17,'18
Cheng,Kang,Xu, '18
……

Charm-Baryon Lifetimes

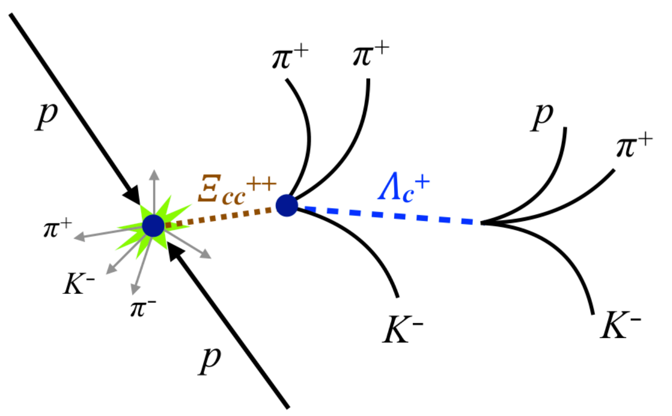


Hai-Yang Cheng, '18:

dimension-7 operators play a key role, $1/m_c$ correction

See Hai-Yang's talk

Double-Charm Baryons Lifetimes



Lifetime is important in pp collisions, to reject backgrounds

Large ambiguity in literature

Literatures	Ξ_{cc}^{++} (fs)	Ξ_{cc}^{+} (fs)
Karliner, Rosner, 2014	185	53
Kiselev, Likhoded, Onishchenko, 1998	430±100	110±10
Kiselev, Likhoded, 2002	460±50	160±50
Chang, Li, Li, Wang, 2007	670	250
Cheng, Shi, 2018	**300**	45

See Hai-Yang's talk

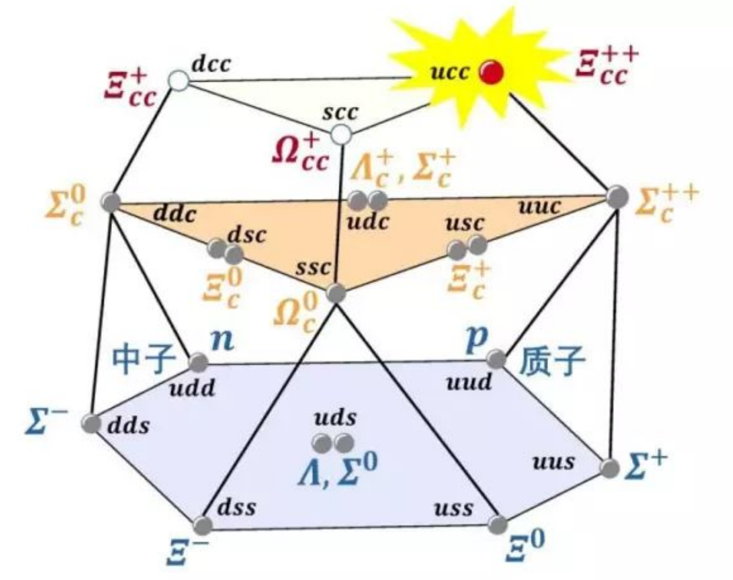
$$\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+})$$

$$\tau(\Xi_{cc}^{++}) = (2.56^{+0.24}_{-0.22} \pm 0.14) \times 10^{-13} s$$

LHCb, '18

Double-charm-baryon Searches

- **History** See Ji-bo's talk



Doubly charmed baryons exists in the quark model: SU(4)

- **Evidence**

$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ SELEX, '02 $\Xi_{cc}^+ \to p D^+ K^-$ SELEX, '04

- **But not confirmed**

$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ FOCUS, '02

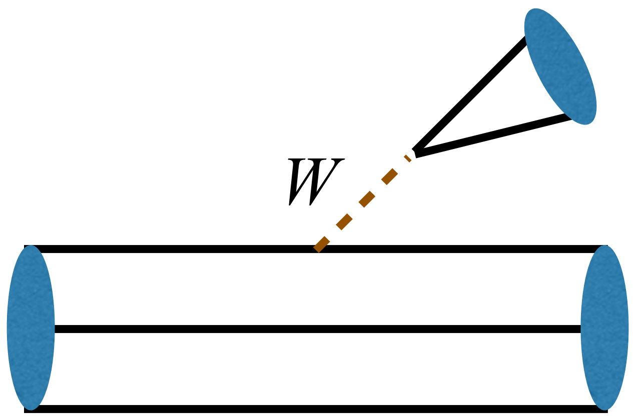
$\Xi_{cc}^{+(+)} \to \Xi_c^0 \pi^+ (\pi^+)$ and $\Lambda_c^+ K^- \pi^+ (\pi^+)$ Babar,'06; Belle, '06,'13

$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ LHCb, '13

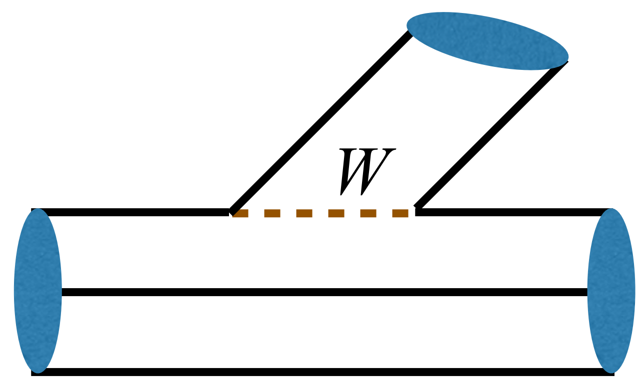
Misleading !!

2016, LHCb Run II, Jibo: What discovery channel?

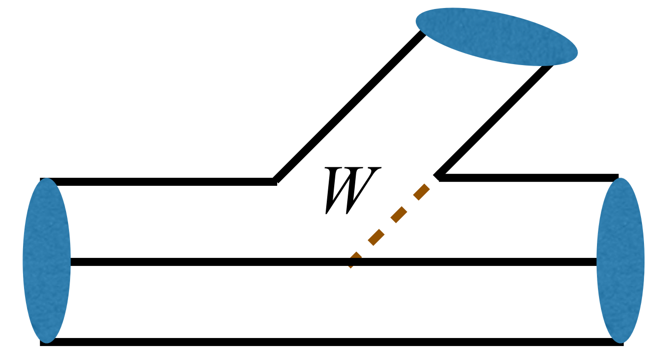
Topologies of two-body non-leptonic charmed baryon decays



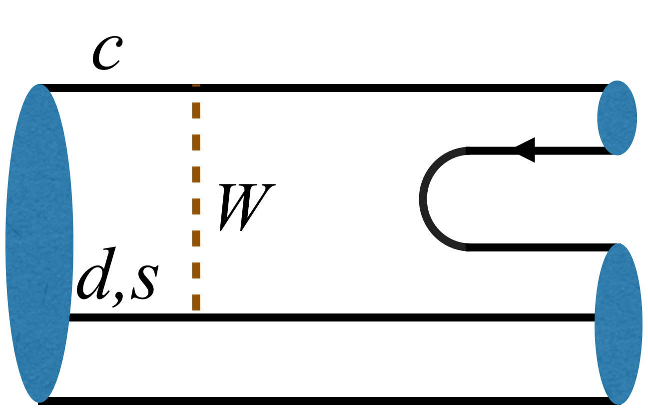
(T)
color-favored tree emitted



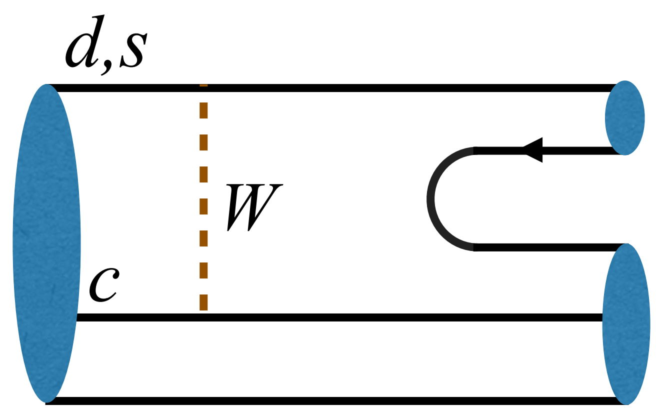
(C)
color-suppressed emitted



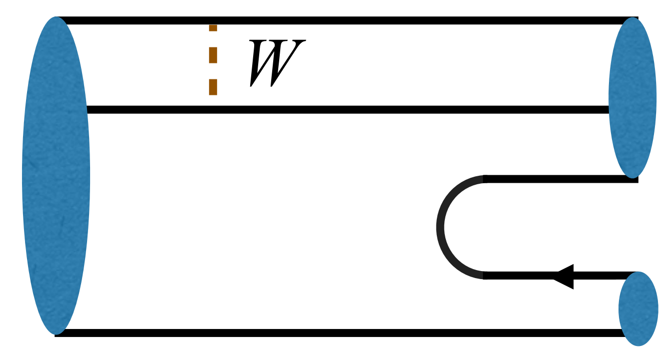
(C′)
color-commensurate



(E_1)
W-exchange 1



(E_2)
W-exchange 2



(B)
Bow tie

Hierarchy in heavy quark expansion

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

Leibovich, Ligeti, Stewart, Wise, ’04

b decay: $|C/T| \sim |C'/T| \sim |E/T| \sim |P/T| \sim O(\Lambda_{QCD}/m_Q) \sim 0.2$

$|B/E| \sim O(\Lambda_{QCD}/m_Q) \sim 0.2$

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

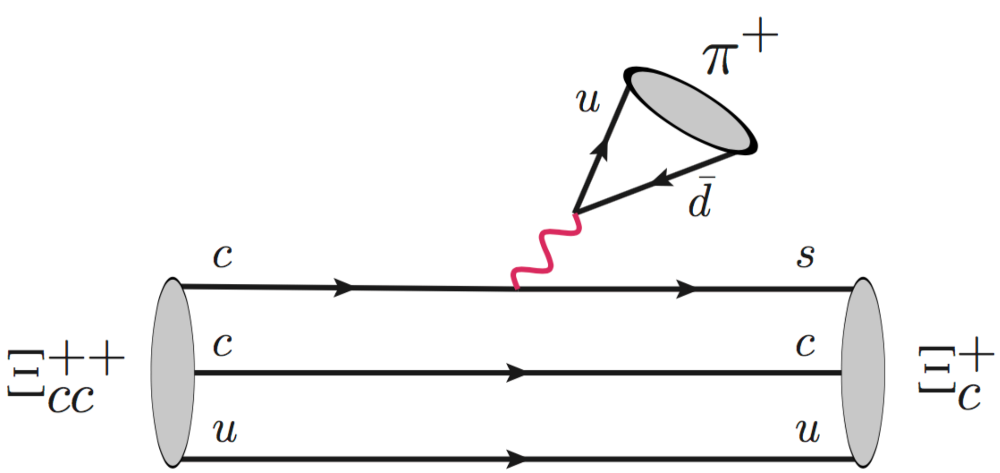
$|B/E| \sim O(\Lambda_{QCD}/m_Q) \sim 1$

$|P| \sim 0$

Short-distance effects

— external W-emission diagrams

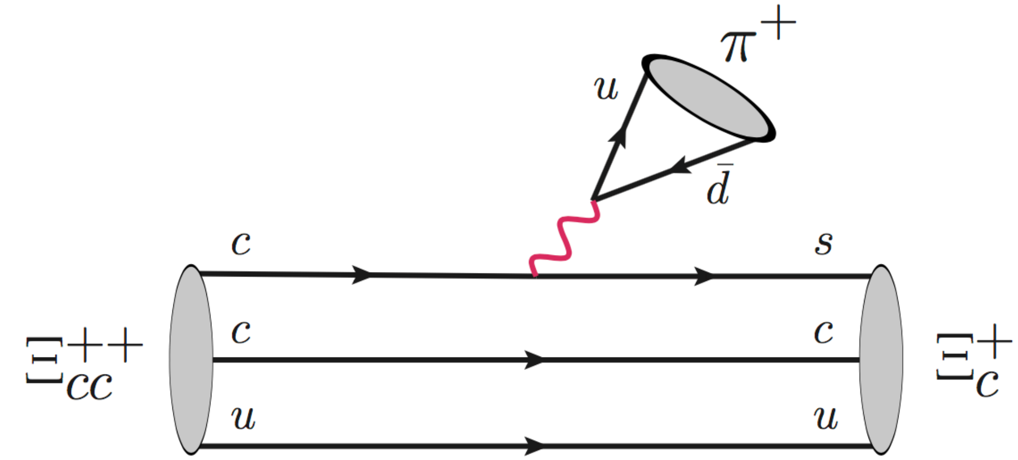
- Calculate form factors in light-front quark model
- Calculate amplitudes using factorization approach



	$\Xi_{cc} \to \Xi_c/\Xi_c'(0^+)$				$\Xi_{cc} \to \Xi_c/\Xi_c'(1^+)$			
	f_1	g_1	f_2	g_2	f_1	g_1	f_2	g_2^*
$F(0)$	0.75	0.62	−0.78	−0.08	0.74	−0.20	0.80	−0.02
$m_{\rm fit}$	1.84	2.16	1.67	1.29	1.58	2.10	1.62	1.62
δ	0.25	0.35	0.30	0.52	0.36	0.21	0.31	1.37
	$\Xi_{cc} \to \Lambda_c/\Sigma_c(0^+)$				$\Xi_{cc} \to \Lambda_c/\Sigma_c(1^+)$			
	f_1	g_1	f_2	g_2	f_1	g_1	f_2	g_2^*
$F(0)$	0.65	0.53	−0.74	−0.05	0.64	−0.17	0.73	−0.03
$m_{\rm fit}$	1.72	2.03	1.56	1.12	1.49	1.99	1.53	2.03
δ	0.27	0.38	0.32	1.10	0.37	0.23	0.32	2.62

- Form factors are the most important inputs and basis for the theoretical developments.
- Zhen-Xing Zhao's contributions are indispensable.

Short-Distance Effects



- External W-emission processes using factorization approach

$$A(\Xi_{cc} \to \mathcal{B}_c M)_{\rm SD}$$
$$= \frac{G_F}{\sqrt{2}} V_{cq'}^* V_{uq} a_1(a_2) \langle M|\bar{u}\gamma^\mu(1-\gamma_5)q|0\rangle \langle \mathcal{B}_c|\bar{q}'\gamma_\mu(1-\gamma_5)|\Xi_{cc}\rangle$$

- Relative branching fractions are reliable

$$\mathcal{B}(\Xi_{cc}^+ \to \Xi_c^0 \pi^+)/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = \mathcal{R}_\tau = 0.25 \sim 0.37,$$
$$\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ \pi^+)/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = 0.056,$$
$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \ell^+ \nu)/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = 0.71,$$

Uncertainties of form factors are mostly cancelled

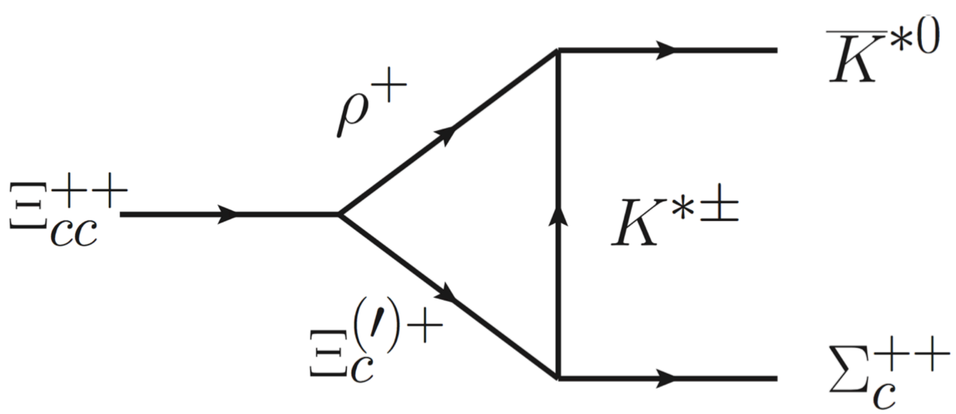
$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)$ **is the largest one**

Long-distance Effects

— final-state interacting (FSI) effects

— significantly large in charm decays

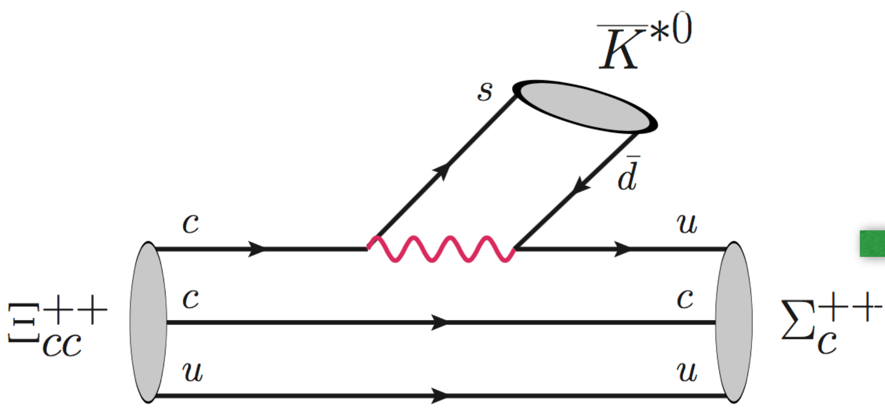
- Calculate rescattering effects



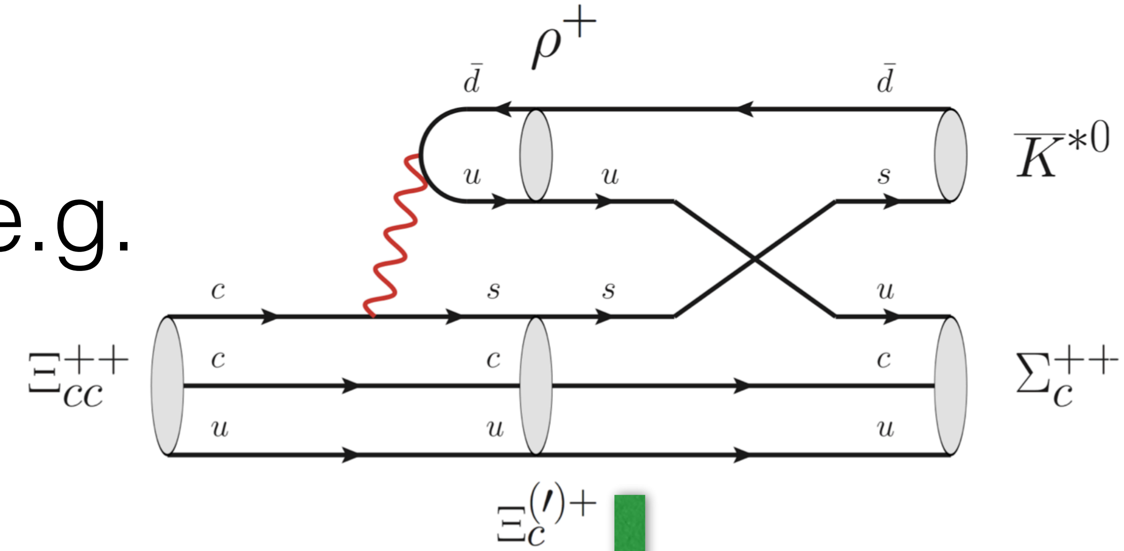
- It is the first work on the long-distance effects of doubly charmed baryon decays. The rescattering mechanism was firstly established in the doubly charmed baryon decays.
- Thanks to Hua-Yu Jiang’s and Run-Hui Li’s contribution.

Long-Distance Effects

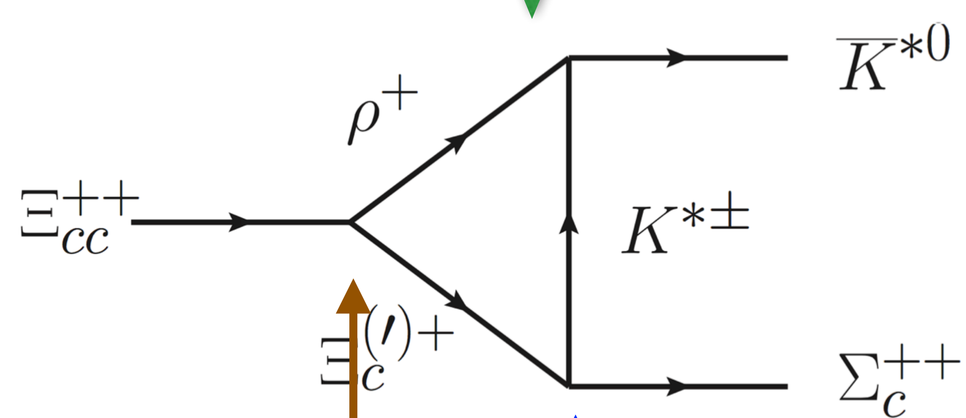
$$\Xi_{cc}^{++} \to \Sigma_c^{++} \overline{K}^{*0}$$



FSI e.g.



Rescattering mechanism of the final-state interacting effects



Absorptive part:

weak vertex

rescattering

$$\mathrm{Abs}\mathcal{M}(p_i \to p_f q) =$$

$$\frac{1}{2}\sum_j \left(\prod_{k=1}^{j}\int \frac{d^3 p_k}{(2\pi)^3 2E_k}\right)(2\pi)^4 \quad \times \delta^4\left(p_f + q - \sum_{k=1}^{j} p_k\right) M(p \to \{p_k\})\, T^*(p_f q \to \{p_k\})$$

Relative Branching Fractions with long-distance contributions

Baryons	Modes	$\mathcal{B}_{\rm LD}$
$\Xi_{cc}^{++}(ccu)$	$\Sigma_c^{++}(2455)\overline{K}^{*0}$	defined as 1
	pD^{*+}	0.04
	pD^{+}	0.0008
$\Xi_{cc}^{+}(ccd)$	$\Lambda_c^{+}\overline{K}^{*0}$	$(\mathcal{R}_\tau/0.3)\times 0.22$
	$\Sigma_c^{++}(2455)K^{-}$	$(\mathcal{R}_\tau/0.3)\times 0.008$
	$\Xi_c^{+}\rho^{0}$	$(\mathcal{R}_\tau/0.3)\times 0.04$
	ΛD^{+}	$(\mathcal{R}_\tau/0.3)\times 0.004$
	pD^{0}	$(\mathcal{R}_\tau/0.3)\times 0.002$

Largest

Theoretical uncertainties are still very large, but reduced in the relative branching fractions

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ **v.s.** $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$

SELEX's discovery channel,
LHCb measured

Baryons	Modes	$\mathcal{B}_{\rm LD}$
$\Xi_{cc}^{++}(ccu)$	$\Sigma_c^{++}(2455)\overline{K}^{*0}$	defined as 1
	pD^{*+}	0.04
	pD^+	0.0008
$\Xi_{cc}^{+}(ccd)$	$\Lambda_c^+\overline{K}^{*0}$	$(\mathcal{R}_\tau/0.3)\times 0.22$
	$\Sigma_c^{++}(2455)K^-$	$(\mathcal{R}_\tau/0.3)\times 0.008$
	$\Xi_c^+\rho^0$	$(\mathcal{R}_\tau/0.3)\times 0.04$
	ΛD^+	$(\mathcal{R}_\tau/0.3)\times 0.004$
	pD^0	$(\mathcal{R}_\tau/0.3)\times 0.002$

$\tau \times (\sim 3)$

Br × 5

$\Lambda_c^+ K^- \pi^+ \pi^+$

$\Lambda_c^+ K^- \pi^+$

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ has more signal yields around one more order than $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$

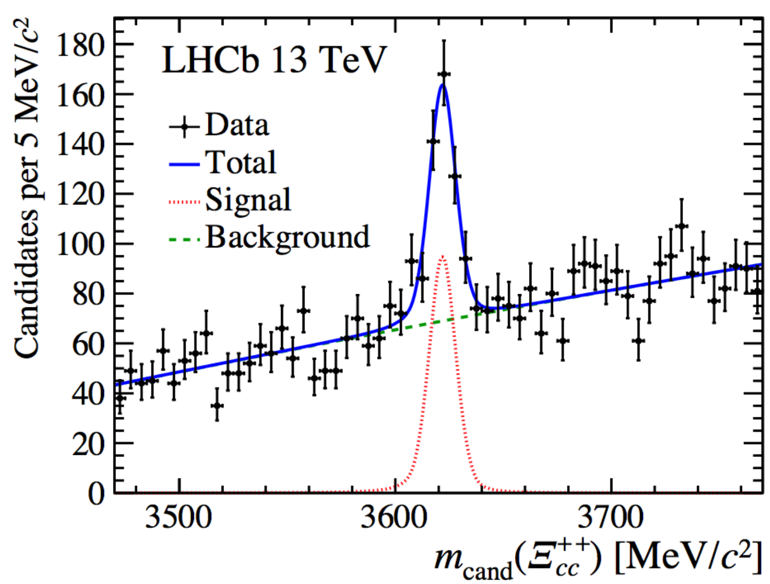
Discovery Potentials of Doubly Charmed Baryons

Abstract

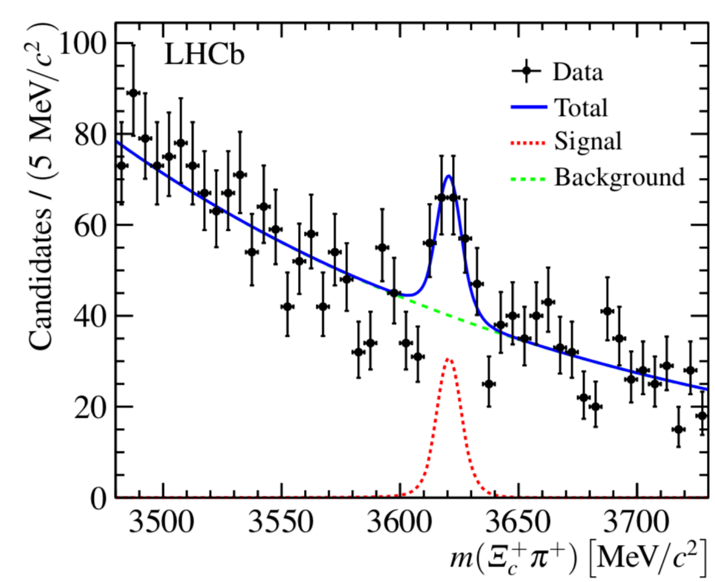
The existence of doubly heavy flavor baryons has not been well established experimentally so far. In this Letter we systematically investigate the weak decays of the doubly charmed baryons, Ξ_{cc}^{++} and Ξ_{cc}^{+}, which should be helpful for experimental searches for these particles. The long-distance 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



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

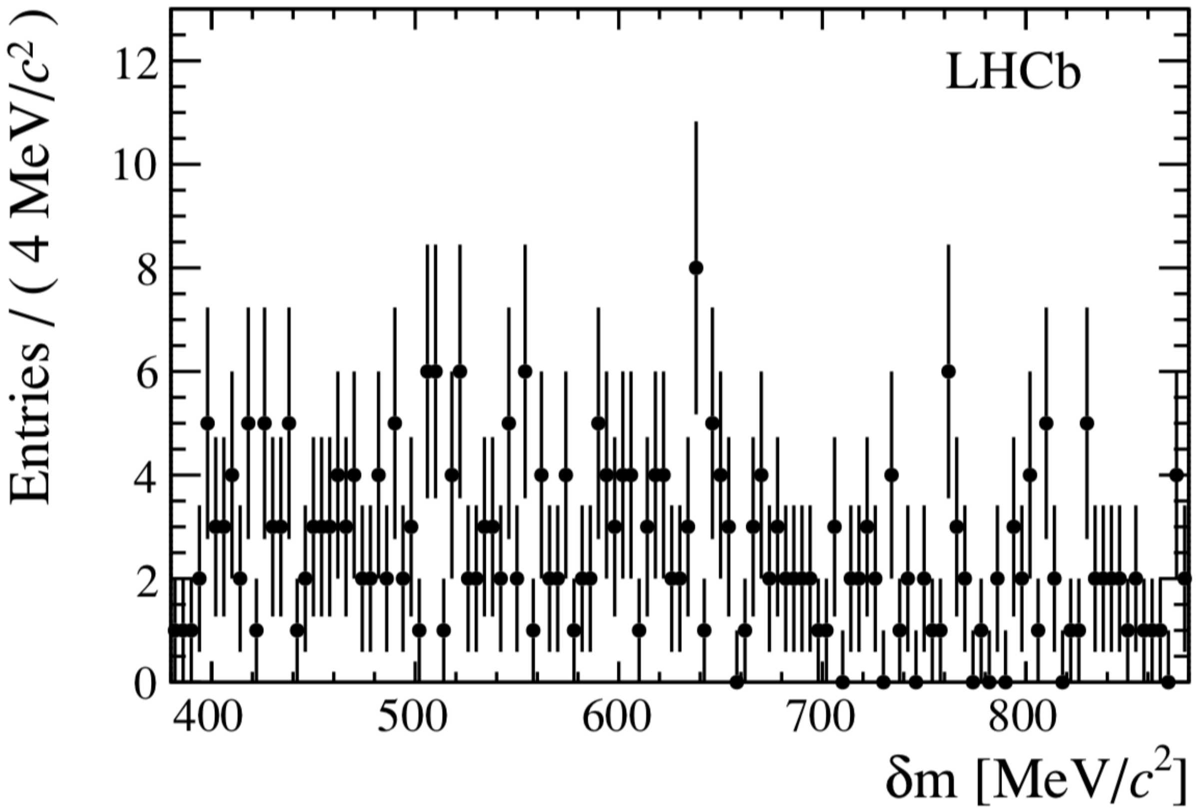


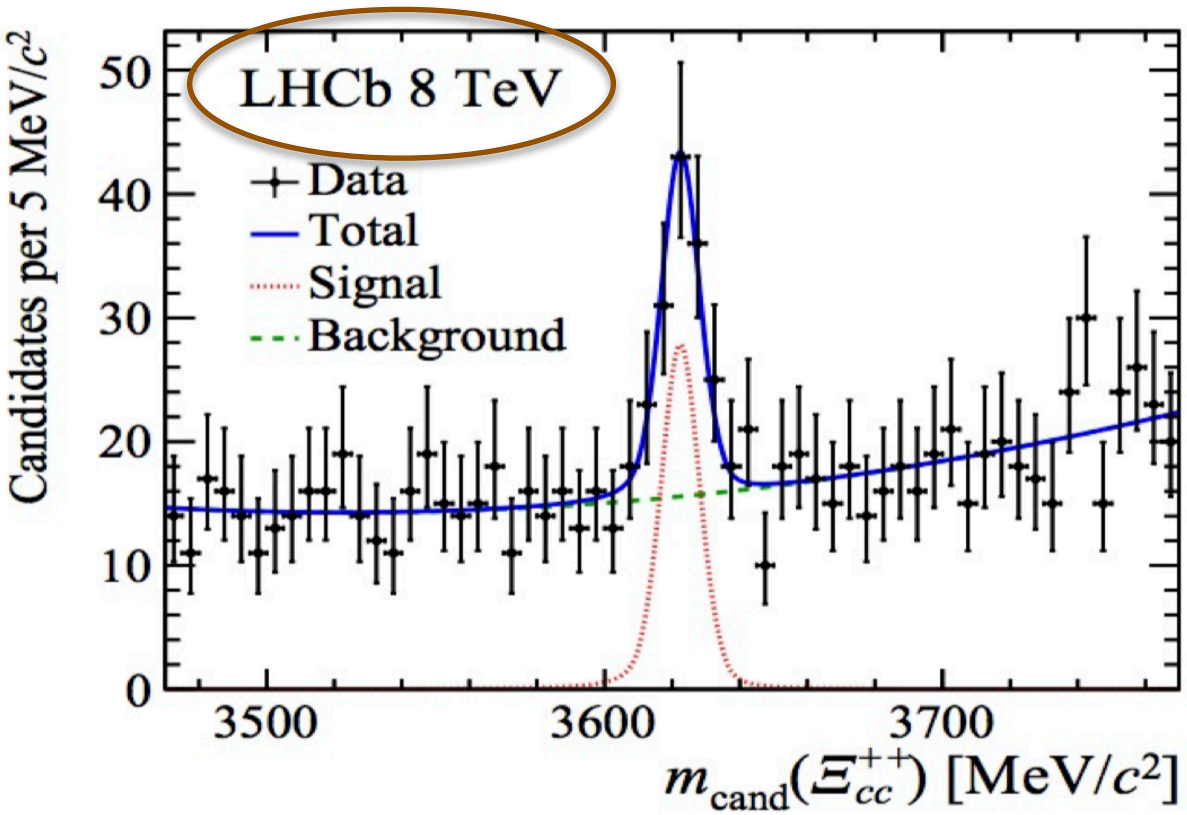
July 2018

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

LHCb observed Ξ_{cc}^{++}

LHCb Run-I Data Analysis





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

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

No signal

[LHCb, JHEP 12 (2013)090]

Observation

See Ji-bo's talks

It could be observed in 2013 if using the correct mode !!!

List of studies on weak decays

1. Doubly heavy baryon weak decays: $\Xi_{bc}^0 \to pK^-$, $\Xi_{cc}^+ \to \Sigma_c^{++}K^-$ 1701.03284
2. Discovery potentials of doubly charmed baryons 1703.09086
   $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\Xi_c^+ \pi^+$
3. Weak decays of doubly heavy baryons: the 1/2 → 1/2 case 1707.02834
4. Weak decays of doubly heavy baryons : SU(3) analysis 1707.06570
5. Weak decays of doubly heavy baryons : decay constant 1711.10289
6. Weak decays of doubly heavy baryons : Multi-body decays 1712.03830
7. Weak decays of doubly heavy baryons: the 1/2 → 3/2 case 1805.10878
8. Weak decays of doubly heavy baryons: $\mathcal{B}_{cc} \to \mathcal{B}_c V$ 1810.00541
9. Weak decays of triply heavy baryons 1803.01476

……

Hua-Yu Jiang, Run-Hui Li and Zhen-Xing Zhao are the pioneers and also contribute to a series of studies on the decays of doubly heavy baryons

Prospect of theoretical studies

1. Discovery potentials of Xi_cc^+, Omega_cc^+
2. Discovery potentials of Xi_bc, Omega_bc
3. Semileptonic decays
4. Effective theory of doubly heavy baryons
5. Lifetimes?
6. New physics and CPV?
7. Omega_ccc?

……

WG：兰州大学、高能所、上海交大、内蒙古大学、烟台大学、南京师大

Summary

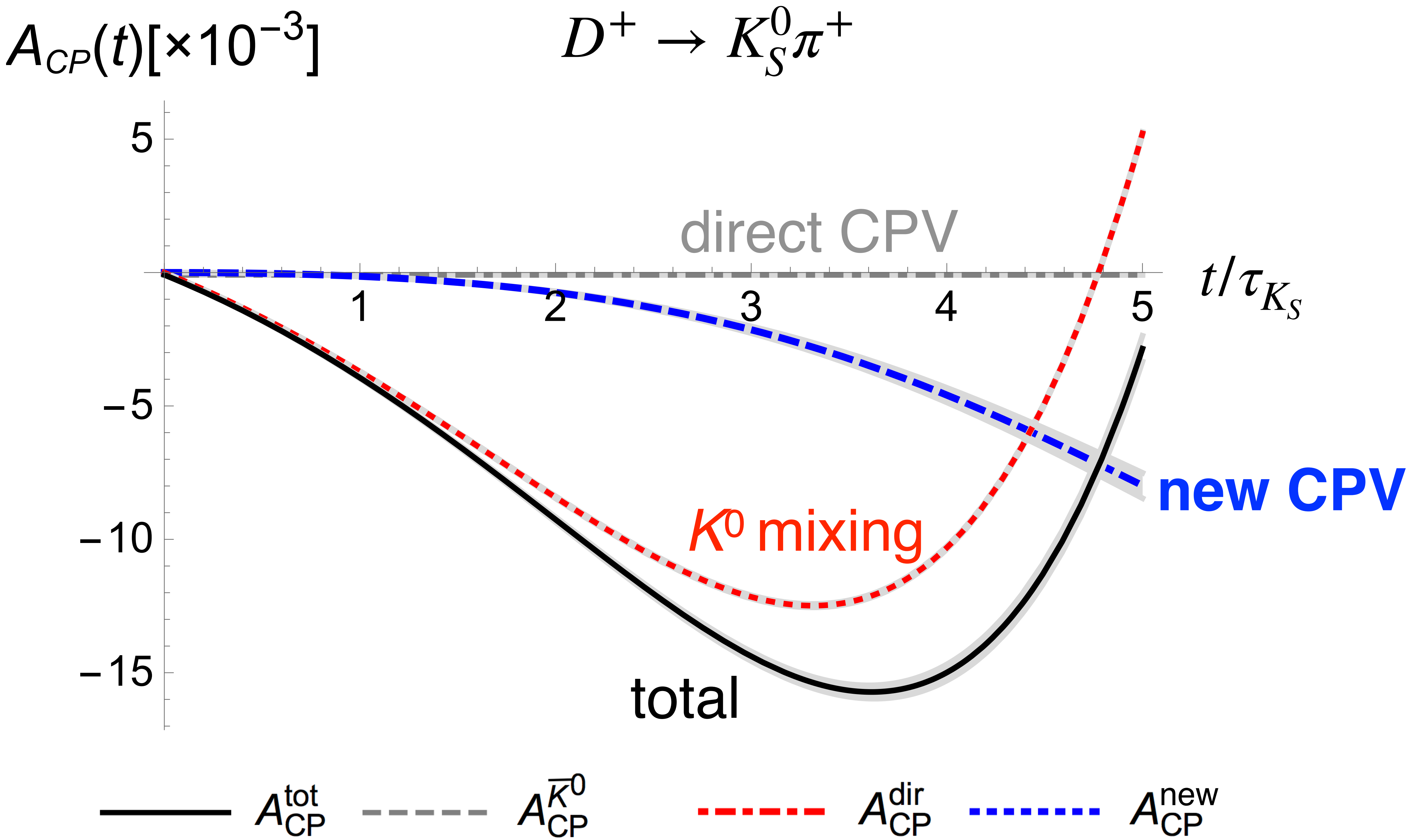
- **Charm physics is becoming more charming**
- **Highlights in theory:**

1. New CPV effect in charm

2. Predictions on the discovery channels of doubly charmed baryon

Welcome to play the charming games

Thanks!



$A_{CP}(t)[\times 10^{-3}]$
$D^+ \to K_S^0 \pi^+$
5
−5
−10
−15
1
2
3
4
5
t/τ_{K_S}
direct CPV
new CPV
K^0 mixing
total
A_{CP}^{tot}
$A_{CP}^{\overline{K}^0}$
A_{CP}^{dir}
A_{CP}^{new}