Charmed hadron hadronic decays at BESIII

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Recent charmed hadronic decsays in BESIII

- DataSet and Analysis method

1. Two body decays
    1. $D_s^+ \to K_S^0 K^+$ and $K_L^0 K^+$ based on 4178 data
    2. $D^+ \to K_{S/L}^0 K^+(\pi^0)$ based on the 3773 data
    3. $D_s^+ \to \omega\pi+$ and $D_s^+ \to \omega K^+$ based on the 4178 data
    4. $D_s^+ \to$ pnbar based on the 4178 data
2. Three body decays
    1. $D_s^+ \to \pi^+\pi^0\eta$ based on the 4178 data
    2. $D^0 \to K^-\pi^+\pi^0\pi^0$ based on the 3773 data
    3. $D^+ \to K_s\pi^+\pi^+\pi^-$ based on the 3773 data
3. Λ_c^+ decays
    1. $\Lambda_c^+ \to \Sigma^+(\eta/\eta')$ based on the 4600 data
    2. $\Lambda_c^+ \to \Lambda X$ at 4600 data

- Summary

Typical analysis method to measure BF

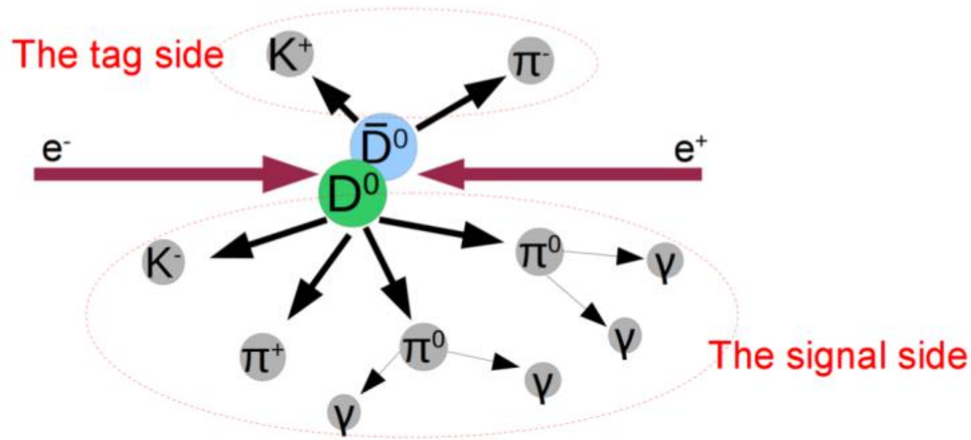
- In our sample, $D_{(s)}$ and Λ_c are produced in pair:

✓ @Ecm = 3773 MeV: $e^+e^- \to D\bar{D}$

✓ @Ecm = 4178 MeV: $e^+e^- \to D_s D_s^*$

$(D_s^* \to (\gamma/\pi^0 D_s))$

✓ @Ecm = 4600 MeV: $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$



- Reconstruct one of the D(s): ST
- There must be the other D(s): DT

✓ *allowing measurements of absolute BFs without the knowledge of data size (*

I.e., $BF(D_s \to KK\pi) = [B(D_s \to tag) \times BF(D_s \to KK\pi)]/BF(D_s \to tag)$

= [Double Tag yields]/[Single Tag yields].

✓ Systematics associated with ST also canceled in this ratio.

1. two body decay

$D_s^+ \to K_S^0 K^+$ and $K_L^0 K^+$ based on 4178 data

PRD 99, 112005 (2019)

- CF ($D \to \bar{K}^0 \pi$) and the DCS transition ($D \to K^0 \pi$) can interfere, and result in a K_S^0-K_L^0 asymmetry. (PLB 349, 363 (1986))

✓ So can the CF and DCS amplitudes in Ds decays: $D_s^+ \to K_S^0 K^+$ and $K_L^0 K^+$

- Such interference effect could also lead to CPV:

✓ **Acp~10^{-3},** predicted by F. S. Yu et, al (PRL 119, 181802 (2017))

- Provide information to explore D^0- $\bar{D}^0$ bar mixing, CPV and SU(3) breaking in charm sector. (PRD 55 196 (1997) & PLB 750, 338 (2015))

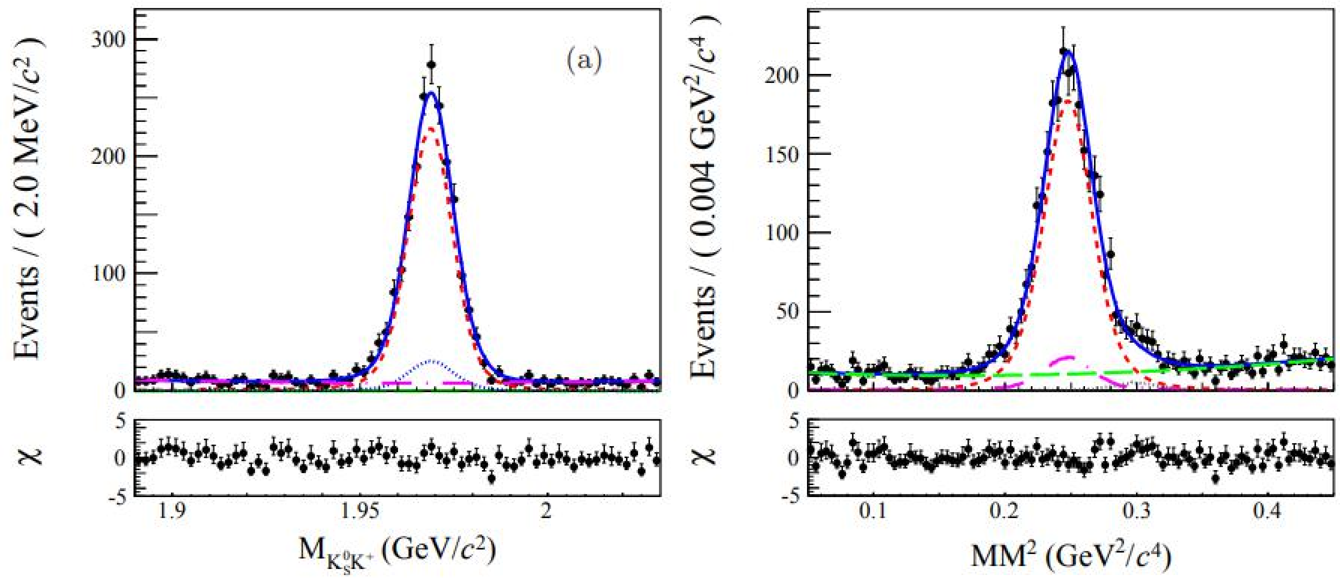
TABLE I: Predictions for K_S^0-K_L^0 asymmetries in charmed-meson decays from different phenomenological models and the CLEO measurements.

	DIAG [7]	DIAG [8]	QCDF [9]	SU(3)$_{FB}$ [10]	FAT [11]	CLEO [12]
$R(D^0 \to K_{S,L}^0 \pi^0)(\%)$	10.7	10.7	10.6	9_{-2}^{+4}	11.3 ± 0.1	$10.8 \pm 2.5_{\text{stat.}} \pm 2.4_{\text{syst.}}$
$R(D^+ \to K_{S,L}^0 \pi^+)(\%)$	-0.5 ± 1.3	-1.9 ± 1.6	-1.0 ± 2.6	-	2.5 ± 0.8	$2.2 \pm 1.6_{\text{stat.}} \pm 1.8_{\text{syst.}}$
$R(D_s^+ \to K_{S,L}^0 K^+)(\%)$	-0.22 ± 0.87	-0.8 ± 0.7	-0.8 ± 0.7	11_{-14}^{+4}	1.2 ± 0.6	-

$D_s^+ \to K_S^0 K^+$ and $K_L^0 K^+$

PRD 99, 112005 (2019)

1. Frist use 13 ST Ds- ST tag mode
2. For $K_S^0K^+$, reconstructed K_S^0 and K^+, 2D Fit to M(ST-tag) and M($K_S^0K^+$)
3. For $K_L^0K^+$, reconstuct gamma and K, Fit MissingMass^2.



BF($D_s^+ \to K_S^0K^+$)=(1.425±0.038±0.031)% consistent with the WA

BF($D_s^+ \to K_L^0K^+$)=(1.485±0.039±0.046)% 1st measurement

K_S/K_L: R= $\frac{\mathcal{B}(D_s^+ \to K_S^0 K^+) - \mathcal{B}(D_s^+ \to K_L^0 K^+)}{\mathcal{B}(D_s^+ \to K_S^0 K^+) + \mathcal{B}(D_s^+ \to K_L^0 K^+)}$ = (-2.1±1.9±1.6)%

$A_{CP}(D_S \to K_S K)$ =(0.6±2.8±0.6)% $A_{CP}(D_S \to K_L K)$ =(-1.1±2.6±0.6)%

$D^+ \to K_{S/L}^0 K^+(\pi^0)$ based on the 3773 data

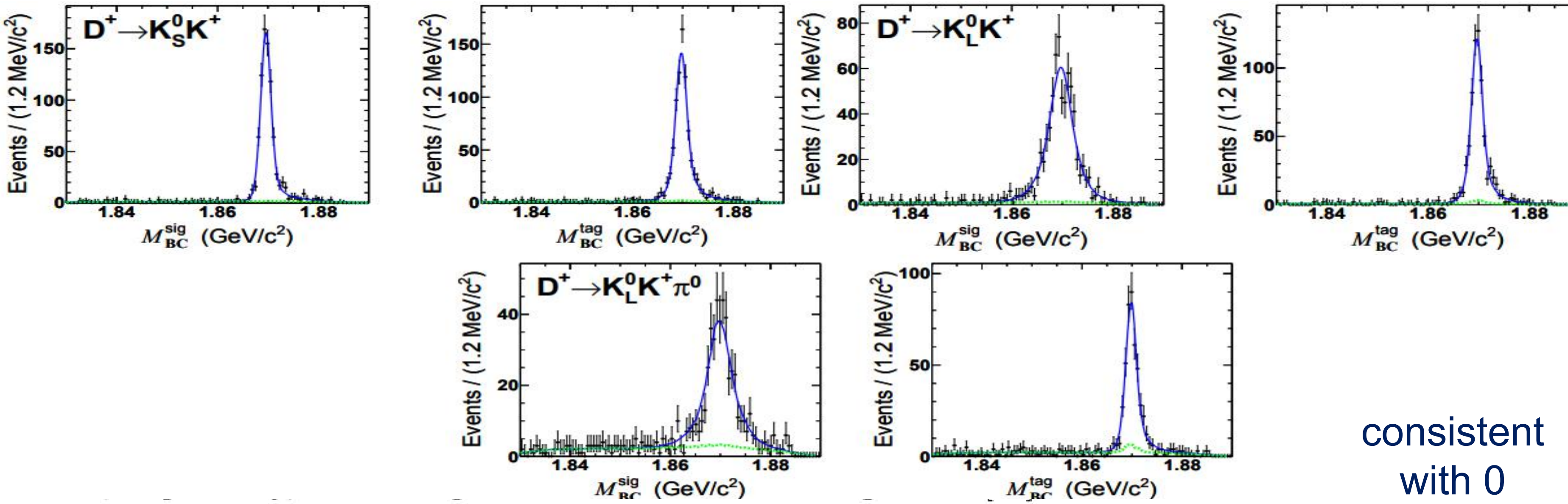
PRD 99, 032002 (2019)

- Also look for similar final states, but in D^+ decays
- Direct CPV in SCS arise from interference between tree-level and penguin.
- SCS D^+ meson hadronic decays are predicted to exhibit **CPV of 10^{-3}** (PLB 298,413 (1993))
- An CPV >O(10^{-3}) in SCS indicates new physics.
- Two-body decays can be calculated with in SU(3) flavor symmetry (PRD 86, 036012 (2012))
- Also added an additional π^0 (For this 3-body decay, MC was tuned based on $D \to KKp$) by CLEO (PRD 78, 072003 (2008))

$D^+ \to K_{S/L}{}^0 K^+ (\pi^0)$

1. 6 ST D- ST tag mode
2. For $K_S{}^0K^+$, reconstructed $K_S{}^0$ and K^+,
3. For $K_L{}^0K^+$, use the $K_L{}^0$ direction in the kinematic fit.
4. 2D fit to $M_{BC}{}^{sig}$ v.s. $M_{BC}{}^{tag}$.

PRD 99, 032002 (2019)

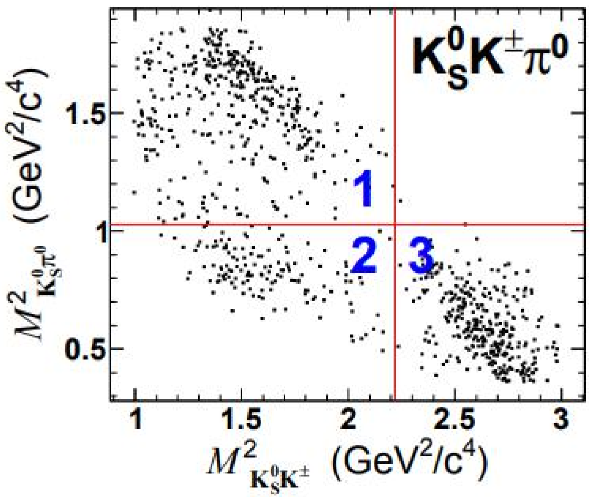


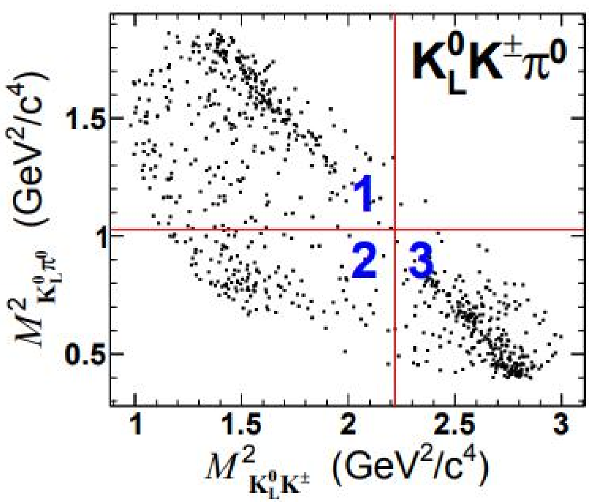
consistent with 0

Signal mode	$\mathcal{B}(D^+)$ $(\times 10^{-3})$	$\mathcal{B}(D^-)$ $(\times 10^{-3})$	$\overline{\mathcal{B}}$ $(\times 10^{-3})$	$\mathcal{B}$ (PDG) $(\times 10^{-3})$	$\mathcal{A}_{CP}$ (%)
$K_S^0 K^\pm$	$2.96 \pm 0.11 \pm 0.08$	$3.07 \pm 0.12 \pm 0.08$	$3.02 \pm 0.09 \pm 0.08$	2.95 ± 0.15	$-1.8 \pm 2.7 \pm 1.6$
$K_S^0 K^\pm \pi^0$	$5.14 \pm 0.27 \pm 0.24$	$5.00 \pm 0.26 \pm 0.22$	$5.07 \pm 0.19 \pm 0.23$	-	$1.4 \pm 3.7 \pm 2.4$
$K_L^0 K^\pm$	$3.07 \pm 0.14 \pm 0.10$	$3.34 \pm 0.15 \pm 0.11$	$3.21 \pm 0.11 \pm 0.11$	-	$-4.2 \pm 3.2 \pm 1.2$
$K_L^0 K^\pm \pi^0$	$5.21 \pm 0.30 \pm 0.22$	$5.27 \pm 0.30 \pm 0.22$	$5.24 \pm 0.22 \pm 0.22$	-	$-0.6 \pm 4.1 \pm 1.7$

1st measurent

$D^+ \to K_{S/L}^0 K^+ (\pi^0)$ Acp in Daliz bins





Region	$\mathcal{B}(D^+)$ ($\times 10^{-3}$)	$\mathcal{B}(D^-)$ ($\times 10^{-3}$)	$\mathcal{A}_{CP}$ (%)
	$K_S^0 K^+ \pi^0$	$K_S^0 K^- \pi^0$	
1	2.86 ± 0.22 ± 0.10	2.75 ± 0.21 ± 0.09	2.0 ± 5.4 ± 2.4
2	0.48 ± 0.08 ± 0.02	0.58 ± 0.09 ± 0.02	-9.4 ± 11.3 ± 2.7
3	1.85 ± 0.16 ± 0.05	1.65 ± 0.15 ± 0.04	-5.7 ± 6.3 ± 1.8
	$K_L^0 K^+ \pi^0$	$K_L^0 K^- \pi^0$	
1	2.89 ± 0.24 ± 0.08	2.83 ± 0.23 ± 0.06	1.0 ± 5.8 ± 1.7
2	0.51 ± 0.08 ± 0.01	0.50 ± 0.08 ± 0.01	1.0 ± 11.2 ± 1.4
3	1.90 ± 0.17 ± 0.03	2.12 ± 0.18 ± 0.03	-5.5 ± 6.1 ± 1.1

Determine the direct CP asymetries for SCS decays, also in Daliz plot regions.

No evidence for direct CPV found.

BF of two body decays in agreement with SU(3) calculation

W-Annihilation $D_s^+ \to \omega\pi^+$ and Evidce of $D_s^+ \to \omega K^+$ based on the 4178 data

PRD 99, 091101(R) (2019)

- In charm sector, Direct CPV can arise from SCS involving W-annihilation process.
- W-annihilation amplitude dominated by nonfactorizable long-distance & final-state interaction. The calculation is unreliable.
- Experimental BF measurement of W-annihilation is used as an input in theoretical calculations.
- We analyse the W-annihilation-only $D^+ \to \omega\pi^+$

$\omega\pi^+$: CF: Has seen by CLEO (PRD80, 051102): BF= $(2.1\pm0.9)\times10^{-3}$

ωK^+: SCS: CLEO (PRD80, 051102) UL = 2.4×10^{-3} @90% C.L

- Q. Qin et al. (PRD89, 054006) predicts (factorization):

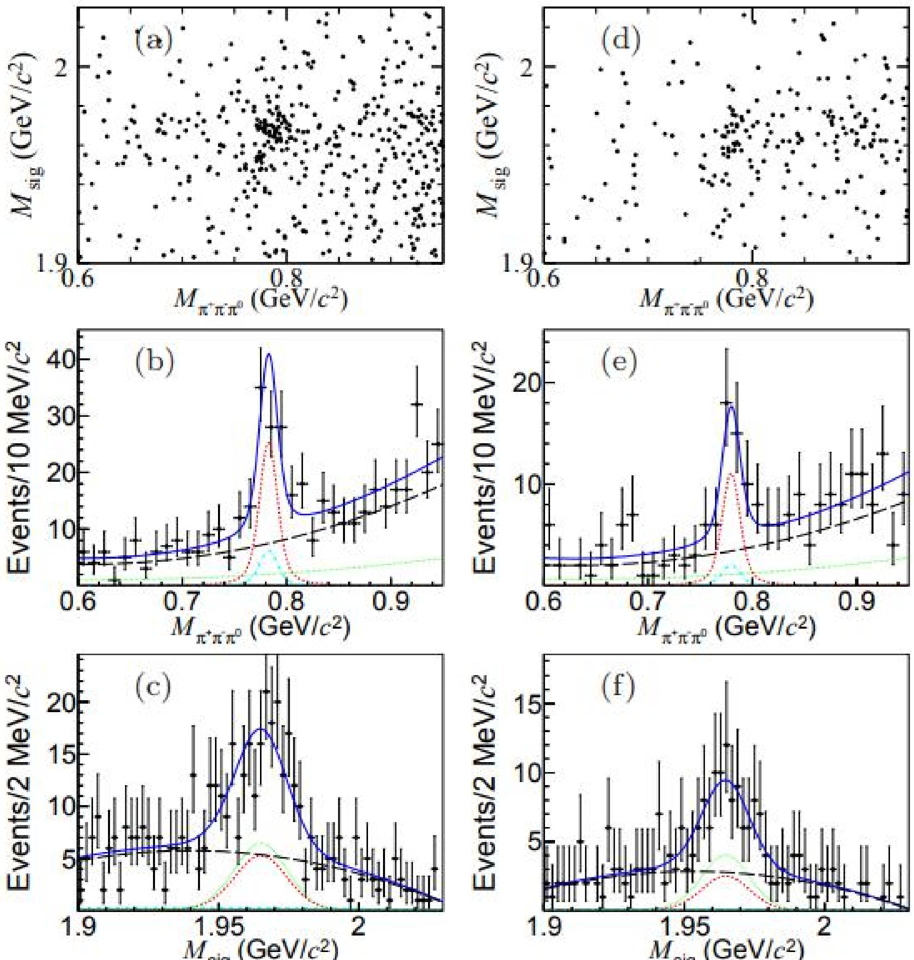
 - BF (ωK^+)**~0.6×10^{-3}** (with Acp**~$-0.6\omega K^+10^{-3}$**),

 - It could become **~0.07×10^{-4}** (with Acp**~2.3×10^{-3}**) if $\omega-\rho$ mix is considered

$D_s^+ \to \omega\pi^+$ and $D_s^+ \to \omega K^+$

1. ST: 2 higest purity decay modes
2. DT: reconstruct $\omega\pi^+/K^+$.
4. 2D fit to $M_{\pi+\pi-\pi0}$ v.s. M_{sig}.

PRD 99, 091101(R) (2019)



- BF($D_s^+ \to \omega\pi^+$) = $(1.77\pm0.32\pm0.13)10\times^{-3}$

Consistent with Cleo, more precise.

- BF($D_s^+ \to \omega K^+$)= $(0.87\pm0.24\pm0.08)\times10^{-3}$

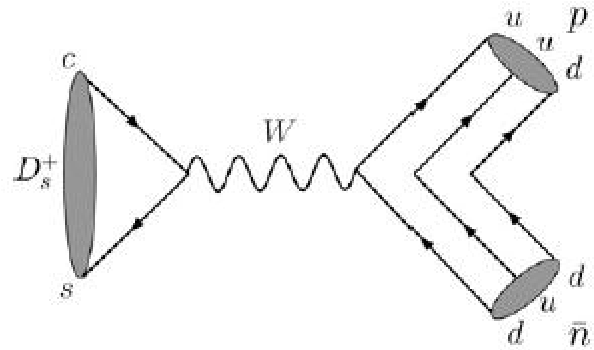
1st evidence

- According to Qin et al., this implies Acp ~ 0.6×10^{-3} and negligible effect from $\omega-\rho$ mixing

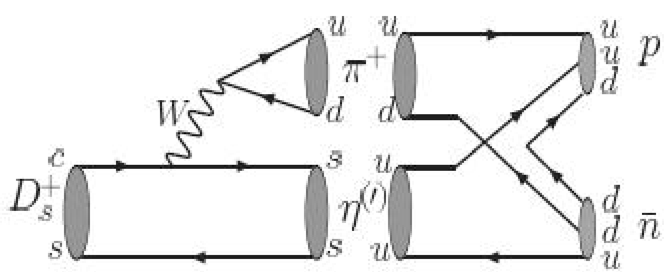
$D_s^+ \to p\bar{n}$ based on the 4178 data

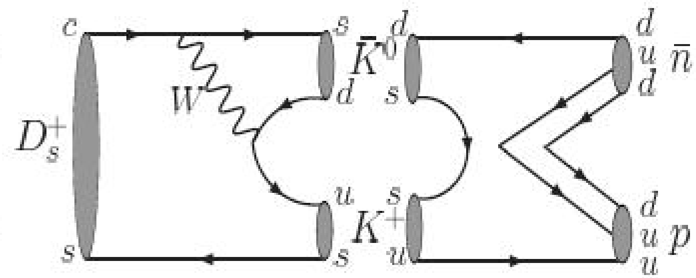
PRD 99, 031101(R) (2019)

- The only kinematically allowed hadronic decay, involving baryons.
- Short-distance contribution is expected to be small **BF~10^{-6}**
- due to the chiral suppression by a factor of $(m_\pi/m_{Ds})^4$



- But long-distance can enhance BF to **~10^{-3}** (C.H. Chen, et al. PLB663, 326)



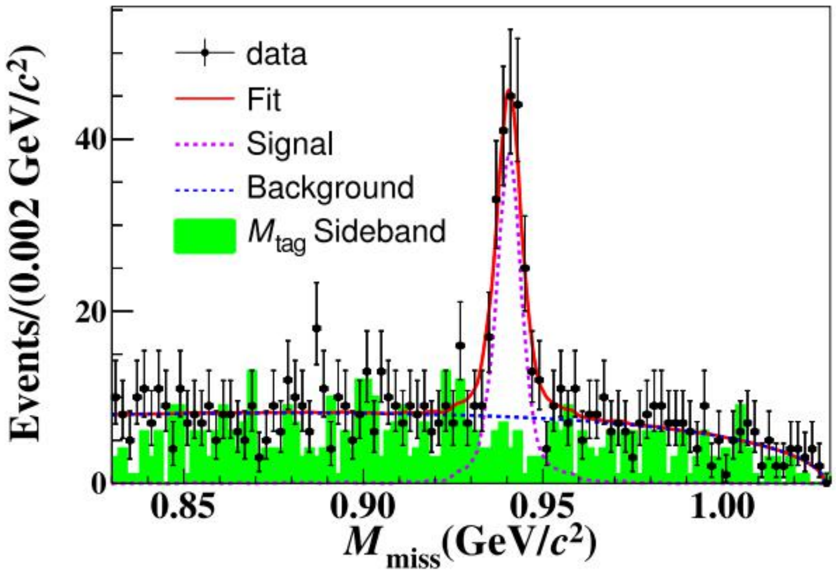


- First evidence was reported by CLEO with BF = $(1.30\pm0.36^{+0.12}_{-0.16})\times10^{-3}$ (PRL100, 181803)

$D_s^+ \to p\bar{n}$

1. 11 ST Ds- ST tag mode
2. DT, reconstruct a gamma and proton..
4. fit the miss mass

PRD 99, 031101(R) (2019)

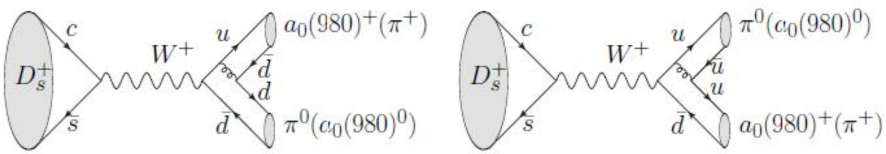


- BESIII confirms it is indeed large: BF = $(1.21 \pm 0.10 \pm 0.05) \times 10^{-3}$
- The short distance dynamics is not the driven mechanism.
- The hadronization process, driven by nonperturbative dynamics determines the underlying physics.

2. three body decay

$D_s^+ \to \pi^+\pi^0\eta$ based on the 4178 data

- Measurements of decays involving a W-annihilation is the best methld.
- Search for pure WA $D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)}$



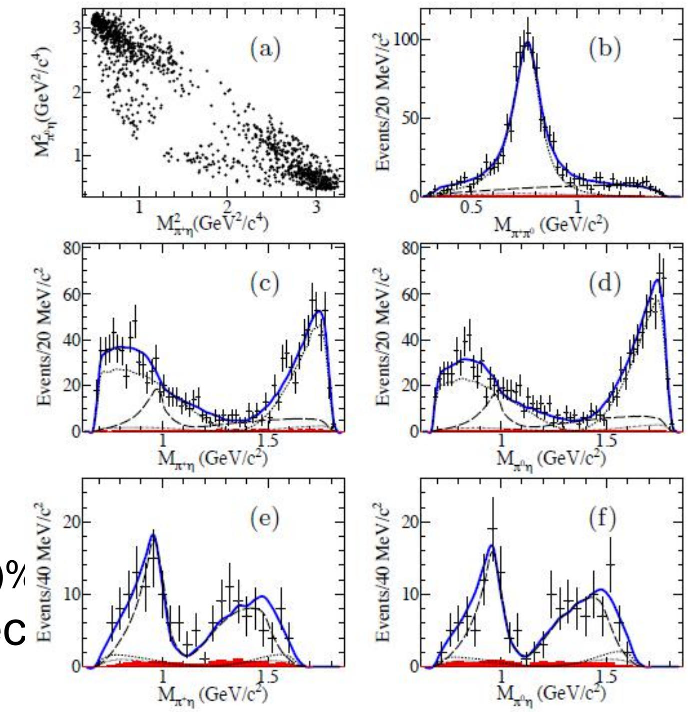
Amplitude	ϕ_n (rad)	FF$_n$
$D_s^+ \to \rho^+\eta$	0.0 (fixed)	$0.783 \pm 0.050 \pm 0.021$
$D_s^+ \to (\pi^+\pi^0)_V\eta$	$0.612 \pm 0.172 \pm 0.342$	$0.054 \pm 0.021 \pm 0.025$
$D_s^+ \to a_0(980)\pi$	$2.794 \pm 0.087 \pm 0.044$	$0.232 \pm 0.023 \pm 0.033$

- Improved precision:
  BF $(D_s^+ \to \pi^+\pi^0\eta) = (9.50 \pm 0.15 \pm 0.41)\%$
- First measurement (16.2 σ stat. significance)!
  BF$(D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)}, a_0(980)^{+(0)} \to \pi^{+(0)}\eta) = (1.46 \pm 0.15 \pm 0.23)\%$

Very large BF, compared to other W-annihilation dec
(e.g., $D_s^+ \to p\bar{n}/\omega\pi$ are all at 10^{-3} level).

Submitted to PRL
arXiv: 1903.04118

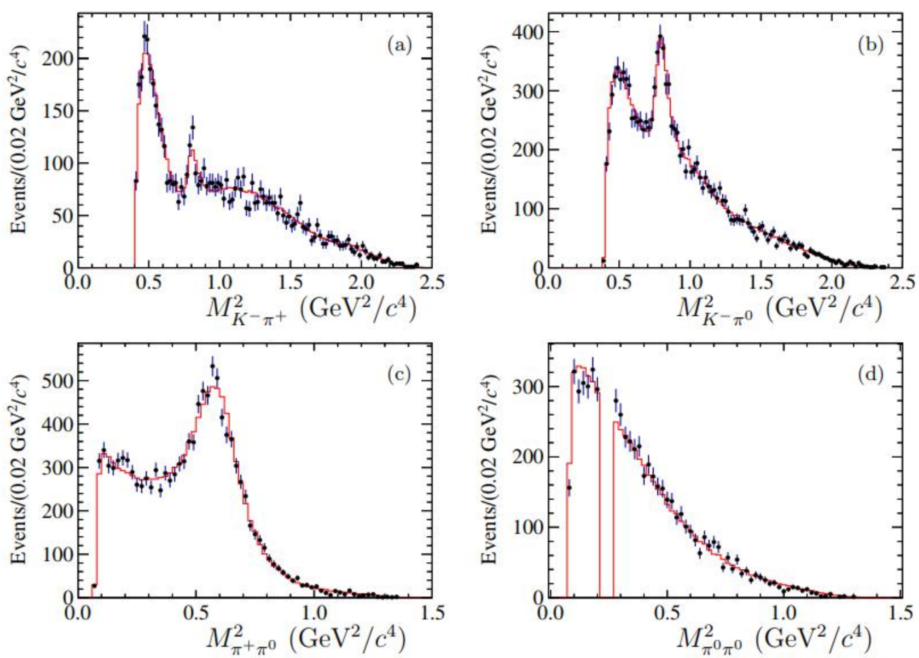
- Amplitude analysis based on DT-ed 1239 events (purity: 97.7%).
- 7 ST modes



$D^0 \to K^-\pi^+\pi^0\pi^0$ based on the 3773 data

- Amplitude analysis based on DT-ed 5950 events (purity: 98.9%)
- One of the largest BF in the neutral D decays. (contribute ~10% ST tag)
- First amplitude analysis on this decay mode

PRD 99, 092008 (2019)



Amplitude mode	I	II	III	IV	Total
$D \to SS$					
$D \to (K^-\pi^+)_S(\pi^0\pi^0)_S$	1.518	1.258	0.072	0.235	1.987
$D \to (K^-\pi^0)_S(\pi^+\pi^0)_S$	1.524	0.835	0.078	0.004	1.740
$D \to AP, A \to VP$					
$D \to K^-a_1(1260)^+, \rho^+\pi^0[S]$	1.293	0.436	0.030	0.363	1.412
$D \to K^-a_1(1260)^+, \rho^+\pi^0[D]$	0.938	0.368	0.024	0.284	1.046
$D \to K_1(1270)^-\pi^+, K^{*-}\pi^0[S]$	1.643	1.175	0.160	0.182	2.035
$D \to K_1(1270)^0\pi^0, K^{*0}\pi^0[S]$	1.562	0.567	0.034	0.036	1.662
$D \to K_1(1270)^0\pi^0, K^{*0}\pi^0[D]$	0.989	0.541	0.035	0.068	1.201
$D \to K_1(1270)^0\pi^0, K^-\rho^+[S]$	0.713	0.221	0.098	0.172	0.772
$D \to (K^{*-}\pi^0)_A\pi^+, K^{*-}\pi^0[S]$	1.253	1.254	0.076	0.237	1.790
$D \to (K^{*0}\pi^0)_A\pi^0, K^{*0}\pi^0[S]$	1.145	0.524	0.022	0.162	1.278
$D \to (K^{*0}\pi^0)_A\pi^0, K^{*0}\pi^0[D]$	0.865	1.468	0.052	0.106	1.708
$D \to (\rho^+K^-)_A\pi^0, K^-\rho^+[D]$	1.249	0.812	0.084	0.186	1.504
$D \to AP, A \to SP$					
$D \to ((K^-\pi^+)_S\pi^0)_A\pi^0$	1.377	0.372	0.102	0.164	1.439
$D \to VS$					
$D \to (K^-\pi^0)_S\rho^+$	1.308	0.252	0.070	0.476	1.416
$D \to K^{*-}(\pi^+\pi^0)_S$	0.381	0.549	0.023	0.166	0.689
$D \to K^{*0}(\pi^0\pi^0)_S$	0.880	0.417	0.078	0.232	1.005
$D \to VP, V \to VP$					
$D \to (K^{*-}\pi^+)_V\pi^0$	0.688	0.752	0.033	0.273	1.056
$D \to VV$					
$D \to K^{*-}\rho^+[S]$	0.980	1.354	0.059	0.371	1.713
$D \to K^{*-}\rho^+[P]$	0.425	0.506	0.031	0.348	0.747
$D \to K^{*-}\rho^+[D]$	1.365	0.598	0.049	0.398	1.543
$D \to (K^-\pi^0)_V\rho^+[P]$	0.695	1.223	0.027	0.140	1.414
$D \to (K^-\pi^0)_V\rho^+[D]$	1.335	0.848	0.237	0.401	1.649
$D \to K^{*-}(\pi^+\pi^0)_V[D]$	0.751	0.894	0.049	0.074	1.171
$D \to (K^-\pi^0)_V(\pi^+\pi^0)_V[S]$	0.818	0.443	0.046	0.211	0.955
$D \to TS$					
$D \to (K^-\pi^+)_S(\pi^0\pi^0)_T$	1.171	0.936	0.084	0.273	1.528
$D \to (K^-\pi^0)_S(\pi^+\pi^0)_T$	0.803	0.188	0.068	0.018	0.828

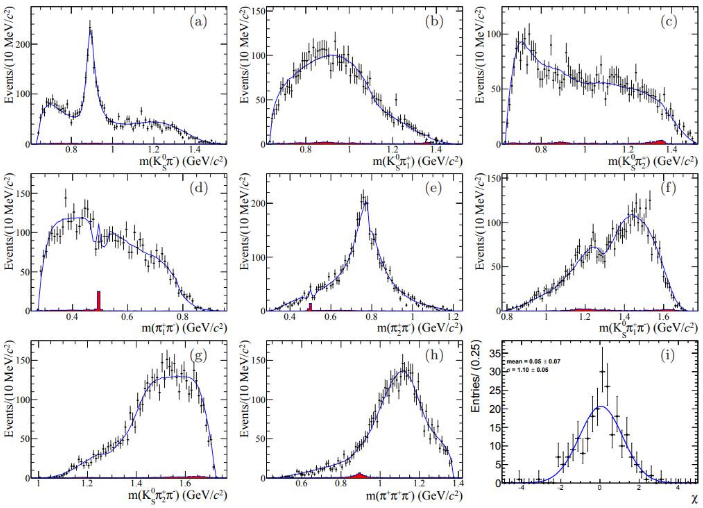
improved precision:
BF($D^0 \to K^-\pi^+\pi^0\pi^0$) = (8.86±0.13±0.19)%
led by $D^0 \to K^-a(1260)^+$

$D^+ \to K_s\pi^+\pi^+\pi^-$ based on the 3773 data

- Final-state interactions can cause significant changes in decay rates and shifts in the phases of decay amplitudes.
- Study more about D->AP decays.

Submitted to PRD
arXiv: 1901.05936

Amplitude analysis based on DT-ed 4559 events (purity: 97.5%)



1st measurement

Component	Branching fraction (%)
$D^+ \to K^0_S a_1(1260)^+(\rho^0\pi^+)$	$1.197 \pm 0.062 \pm 0.086 \pm 0.044$
$D^+ \to K^0_S a_1(1260)^+(f_0(500)\pi^+)$	$0.163 \pm 0.021 \pm 0.005 \pm 0.006$
$D^+ \to \bar{K}_1(1400)^0(K^{*-}\pi^+)\pi^+$	$0.642 \pm 0.036 \pm 0.033 \pm 0.024$
$D^+ \to \bar{K}_1(1270)^0(K^0_S\rho^0)\pi^+$	$0.071 \pm 0.009 \pm 0.021 \pm 0.003$
$D^+ \to \bar{K}(1460)^0(K^{*-}\pi^+)\pi^+$	$0.202 \pm 0.018 \pm 0.006 \pm 0.007$
$D^+ \to \bar{K}(1460)^0(K^0_S\rho^0)\pi^+$	$0.024 \pm 0.006 \pm 0.015 \pm 0.009$
$D^+ \to \bar{K}_1(1650)^0(K^{*-}\pi^+)\pi^+$	$0.048 \pm 0.012 \pm 0.027 \pm 0.002$
$D^+ \to K^0_S\pi^+\rho^0$	$0.190 \pm 0.021 \pm 0.089 \pm 0.007$
$D^+ \to K^0_S\pi^+\pi^+\pi^-$	$0.241 \pm 0.018 \pm 0.018 \pm 0.009$

- Improved precisions.
- Consistent with the previous measurements.
- Again, led by $D^+ \to K_s a_1(1260)^+$

(also consistent with our measurement in $D^0 \to K^-\pi^+\pi^+\pi^-$: PRD 95, 072010 (2017)).

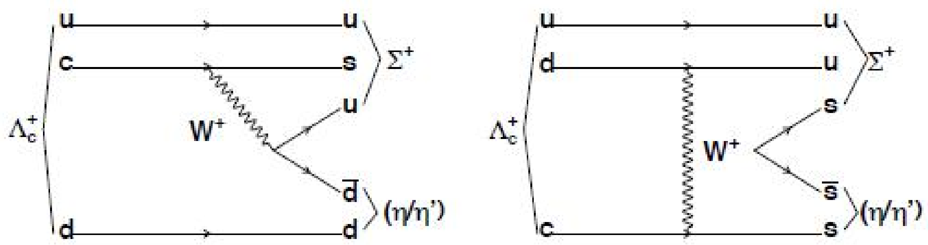
- But $D^+ \to K_1(1440)^0\pi^+$ is found to be larger, unlike what we saw in the two D^0 cases

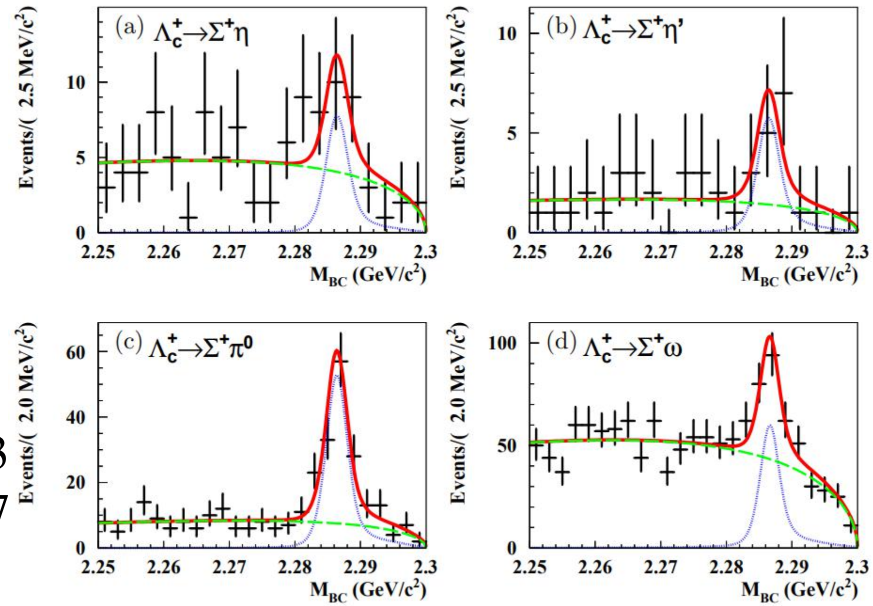
1. Λ^+_c decay

$\Lambda_c^+ \to \Sigma^+(\eta/\eta')$ based on the 4600 data

CPC 43, 083003 (2019)

CF decays, proceed through nonfactorizable internal W-mission/exchange
Large range of predicted BFs





- measured:

$BF(\Lambda_c^+\to\Sigma^+\eta)/BF(\Lambda_c^+\to\Sigma^+\pi^0) = 0.35\pm0.16\pm0.03$

$BF(\Lambda_c^+\to\Sigma^+\eta')/BF(\Lambda_c^+\to\Sigma^+\omega) = 0.86\pm0.34\pm0.07$

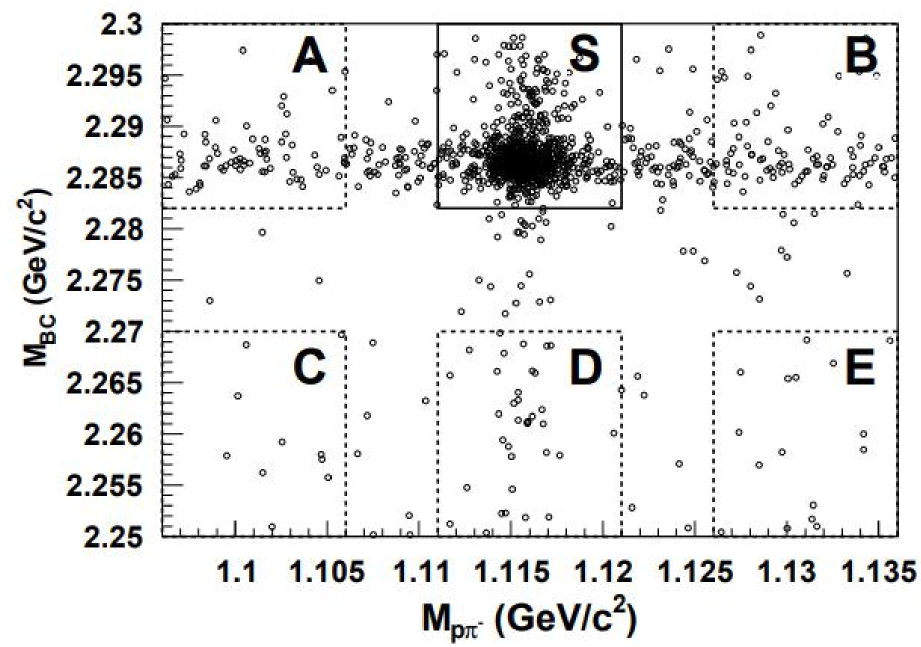
With the known $BF(\Lambda_c^+\to\Sigma^+\pi^0/\omega)$ from BESIII (PRL 116, 052001 (2016))

Decay mode	Körner [5]	Sharma [3]	Zenczykowski [4]	Ivanov [6]	CLEO [12]	This work
$\Lambda_c^+\to\Sigma^+\eta$	0.16	0.57	0.94	0.11	0.70±0.23	0.41±0.20 (<0.68)
$\Lambda_c^+\to\Sigma^+\eta'$	1.28	0.10	0.12	0.12	-	1.34±0.57 (<1.9)

$\Lambda_c^+ \to \Lambda X$ at 4600 data

PRL 121, 062003 (2018)

- Important to calibrate the amplitude of the CF transition.
- essential input in calculation of lifetimes of charmed baryons.



- ST tag mode: pKπ and pKs
- Extract yiels from 2D distribution in M_{BC}^{ST} and $M_{p\pi-}$

$$N^{\rm sig} = N^{\rm S} - \frac{N^{\rm A}+N^{\rm B}}{2} - f\cdot\left(N^{\rm D} - \frac{N^{\rm C}+N^{\rm E}}{2}\right),$$

BF($\Lambda_c^+ \to \Lambda X$)= (38.2+2.8-2.2±2.8)%

$$\mathcal{A}_{CP} \equiv \frac{\mathcal{B}(\Lambda_c^+\to\Lambda+X)-\mathcal{B}(\bar{\Lambda}_c^-\to\bar{\Lambda}+X)}{\mathcal{B}(\Lambda_c^+\to\Lambda+X)+\mathcal{B}(\bar{\Lambda}_c^-\to\bar{\Lambda}+X)} = (2.1^{+7.0}_{-6.6}\pm1.4)\%,$$

More Λ_c^+/XYZ data

- BESIII will take more data >4600 in the future
- BEPCII is ready for the energy up to 4.7GeV
- We have chance to improve the precisions of Λ_c^+ decay rates to the level of charmed mesons!
  - Hadronic decays
    - To explore as-yet-unmeasured channels and understand full picture
    - More semi-leptonic decays $\Sigma\pi l^+\nu$, $pK^-l+\nu$, $p\pi^-l^+\nu$, ...
    - CPV
    - Rare decays: LFV, BNV, FCNC,...

Summary

- Our result include new measurements, have confirmed and improved the precisions over the previous results.
- More measurements in D(s) hadronic decays are coming.
- Planning to take more data at/> Ecm~4.6GeV.
- Allow us to improve further precisions and rare/forbidden searches in Lc decays.

Thanks