Charm decay studies with threshold data

-some selected topics of (semi-)leptonic decays, hadronic structure and quantum correlation

Hailong Ma (IHEP&BESIII)

XXXVII International Symposium on Physics in Collision, Prague, Czech Republic, September 4-8 2017

Introduction

Leptonic and hadronic decays of charmed hadrons (D^0, D^+, D_s^+ and Λ_c^+) provide an ideal test-bed to explore weak and strong effects

- **D leptonic decays**

  $f_{D(s)+}$, $f^{K(\pi)}_+(0)$: better calibrate LQCD

  $|V_{cs(d)}|$: better test on CKM unitarity

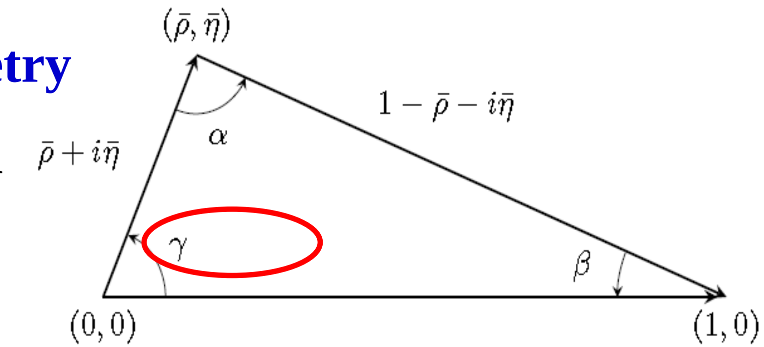
$$U = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & \boldsymbol{V_{cb}} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- **D hadronic decays**

  Hadronic decays: structure, SU(3) symmetry

  $D^0\bar{D}^0$ mixing parameters and CP violation

  Strong phase in D^0 decays: Constraint on γ/ϕ_3 measurement in B decays



- **D rare decays → Search for new physics**

- **Absolute BFs of Λ_c^+ decays**

  No absolute BF measurements of Λ_c^+ using near threshold data before BESIII

Contents

- Data at threshold
- (Semi-)leptonic $D_{(s)}$ decays

  $D_{(s)}^+ \rightarrow l^+ v$ & $K l^+ v$
- Hadronic $D_{(s)}$ decays

  structure & quantum correlation
- Λ_c^+ decays at BESIII
- Summary

Some selected topics at CLEO-c and BESIII

Experiments near threshold

- $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0, D^+D^-$ @~3.773 GeV from MARKIII, BESII, CLEO-c and BESIII
- $e^+e^- \rightarrow \psi(4030) \rightarrow D_s^+D_s^-$ @~4.03 GeV from BESI and BESIII
- $e^+e^- \rightarrow \psi(4170) \rightarrow D_s^{*+}D_s^- + c.c.$ @~4.17 GeV from MARKIII, CLEO-c and BESIII
- $e^+e^- \rightarrow \Lambda_c^+\bar{\Lambda}_c^- + c.c.$ @~4.6 GeV at BESIII

Absolute measurements

ST yield: $N_{\mathrm{ST}}^{i} = 2 \times N_{D\bar{D}} \times B_{\mathrm{ST}}^{i} \times \varepsilon_{\mathrm{ST}}^{i}$

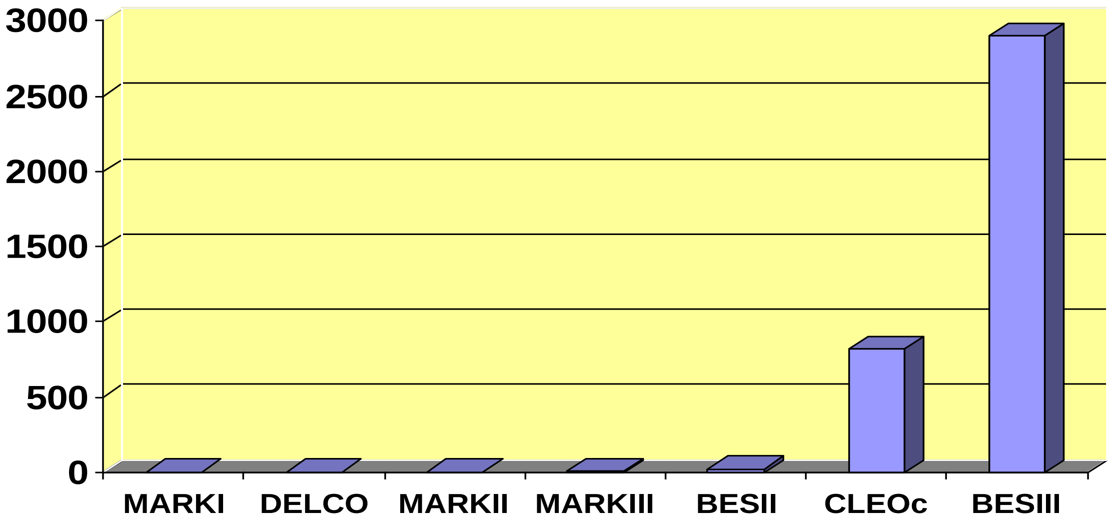
DT yield: $N_{\mathrm{DT}}^{i} = 2 \times N_{D\bar{D}} \times B_{\mathrm{ST}}^{i} \times B_{\mathrm{sig}} \times \varepsilon_{\mathrm{ST\ vs.sig}}^{i}$

Branching fraction: $B_{\mathrm{sig}} = \dfrac{N_{\mathrm{DT}}^{\mathrm{tot}}}{N_{\mathrm{ST}}^{\mathrm{tot}} \times \bar{\varepsilon}_{\mathrm{sig}}}$

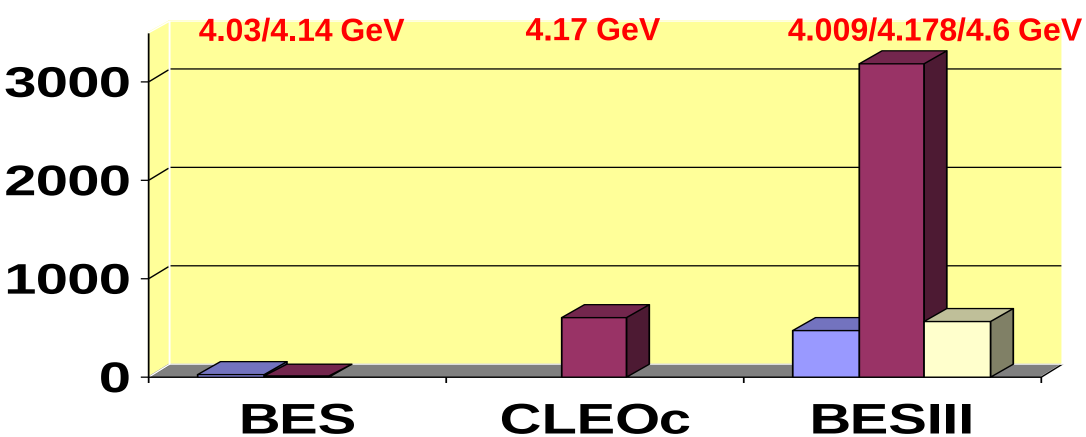
Average efficiency: $\bar{\varepsilon}_{\mathrm{sig}} = \sum_{i=1}^{N} (N_{\mathrm{ST}}^{i} \times \varepsilon_{\mathrm{ST\ vs.sig}}^{i} / \varepsilon_{\mathrm{ST}}^{i}) / \sum_{i=1}^{N} N_{\mathrm{ST}}^{i}$

$D^{0(+)}$, D_s^+, Λ_c^+ samples (pb^{-1}) at BESIII

- $D^{0(+)}$ samples



- $D_s^+/D_s^+/\Lambda_c^+$ samples

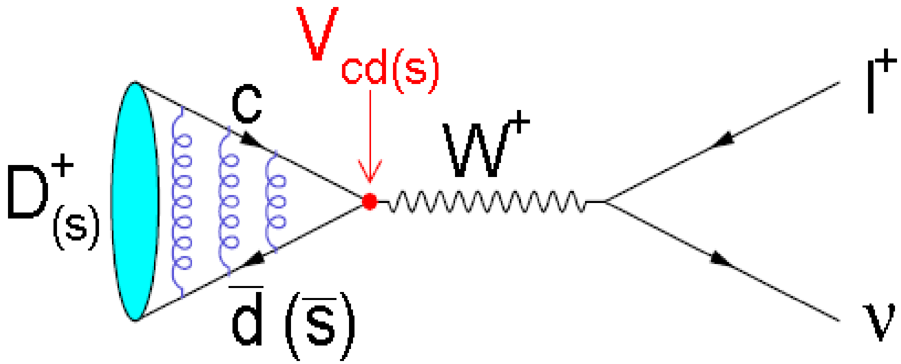


Focus on some selected topics from CLEO-c and BESIII

A series of results were published using a portion of data at CLEO-c. Final results are chosen

(Semi)leptonic $D_{(s)}$ decays

$D_{(s)}^+$ leptonic decays



In the SM:

$$\Gamma(D_{(s)}^+ \to \ell^+\nu_\ell) = \frac{G_F^2 f_{D_{(s)}^+}^2}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D_{(s)}^+} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}^+}^2}\right)^2$$

Bridge to precisely measure

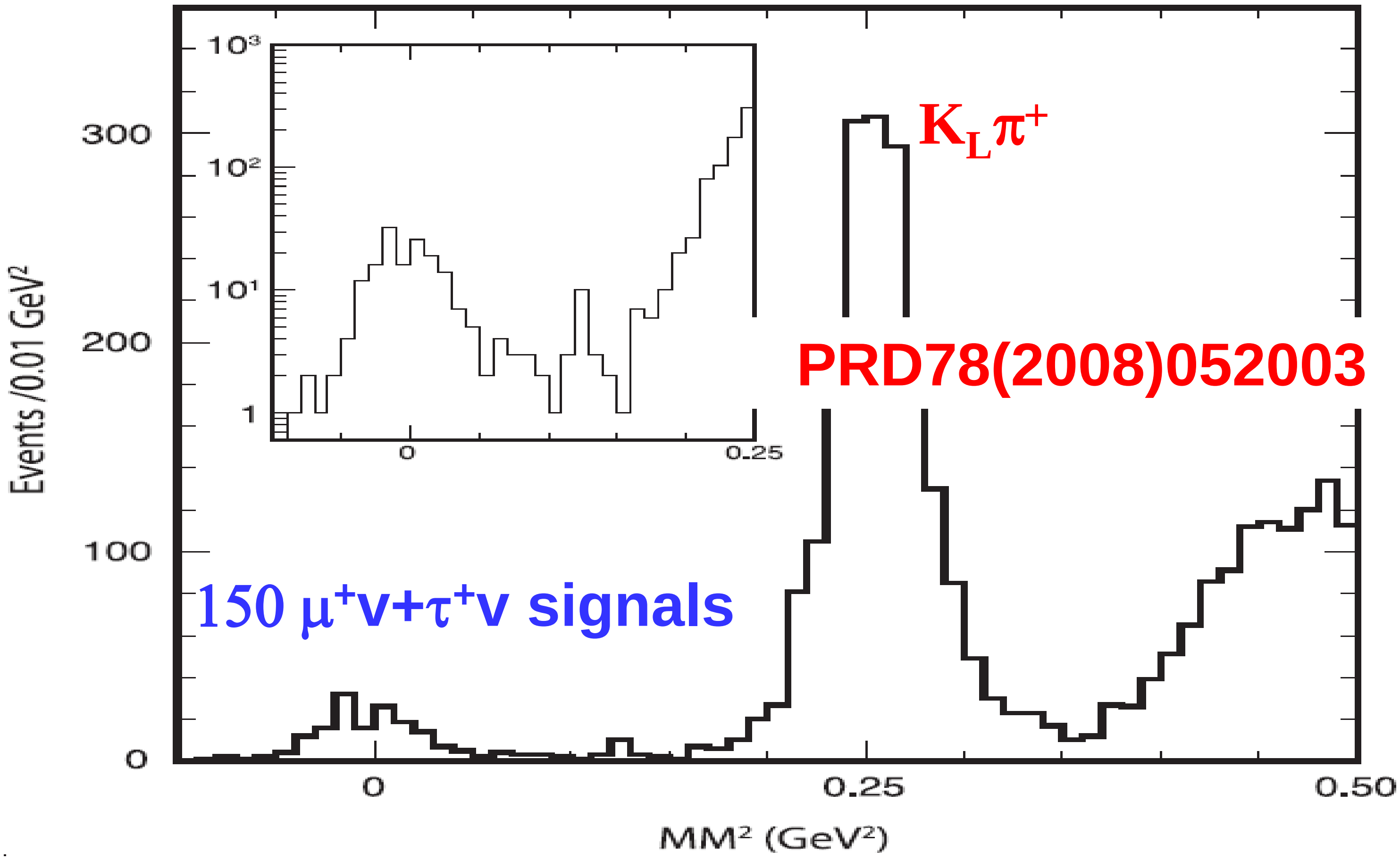
- **Decay constant $f_{D(s)+}$ with input $|V_{cd(s)}|^{CKMfitter}$**
- **CKM matrix element $|V_{cd(s)}|$ with input $f^{LQCD}_{D(s)+}$**

Measurement of f_{D+} at CLEO-c

818 pb^{-1} around $\psi(3770)$ (2004–2008)

$B[D^+ \rightarrow \mu^+\nu] = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$

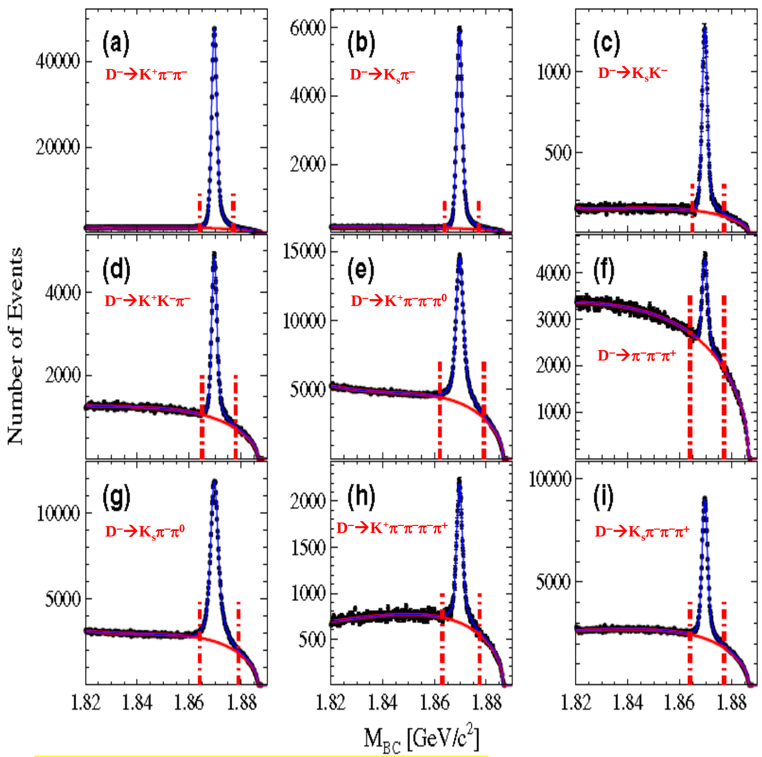
$f_{D+} = 205.8 \pm 7.5 \pm 2.5$ MeV

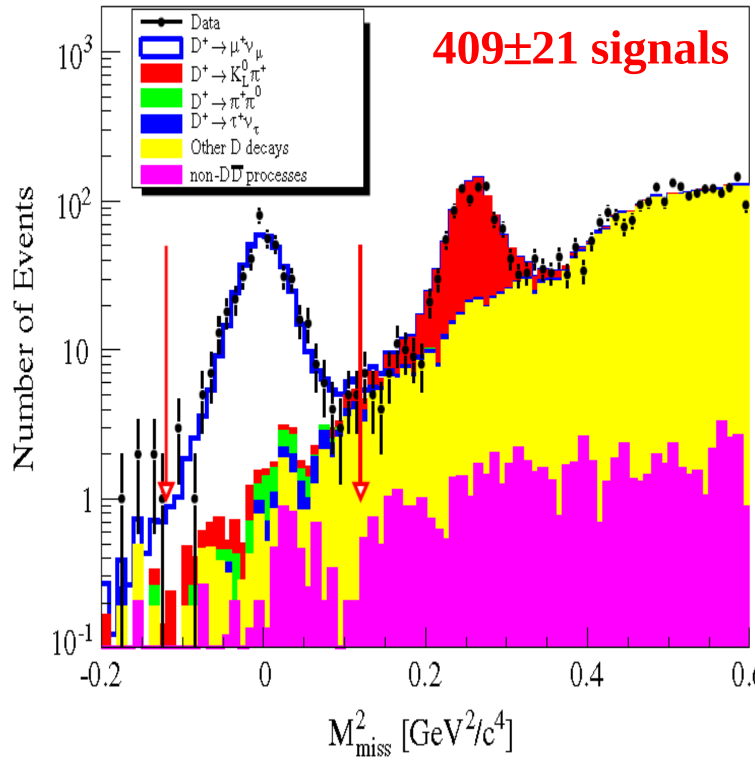


Improved $B[D^+ \rightarrow \mu^+ \nu]$, $f_{D+}|V_{cd}|$ at BESIII

$e^+e^- \rightarrow \psi(3770) \rightarrow D^+D^-$

2.93 fb^{-1} data@ 3.773 GeV
PRD89(2014)051104R





$N_{D^-_{tag}} = (170.31 \pm 0.34) \times 10^4$

$B[D^+ \rightarrow \mu^+ \nu] = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$

Input t_{D+}, m_{D+}, $m_{\mu+}$ on PDG and $|V_{cd}|$ of CKM-Fitter

Input t_{D+}, m_{D+}, $m_{\mu+}$ on PDG and LQCD calculated f_{D+}=207±4 MeV[PRL100(2008)062002]

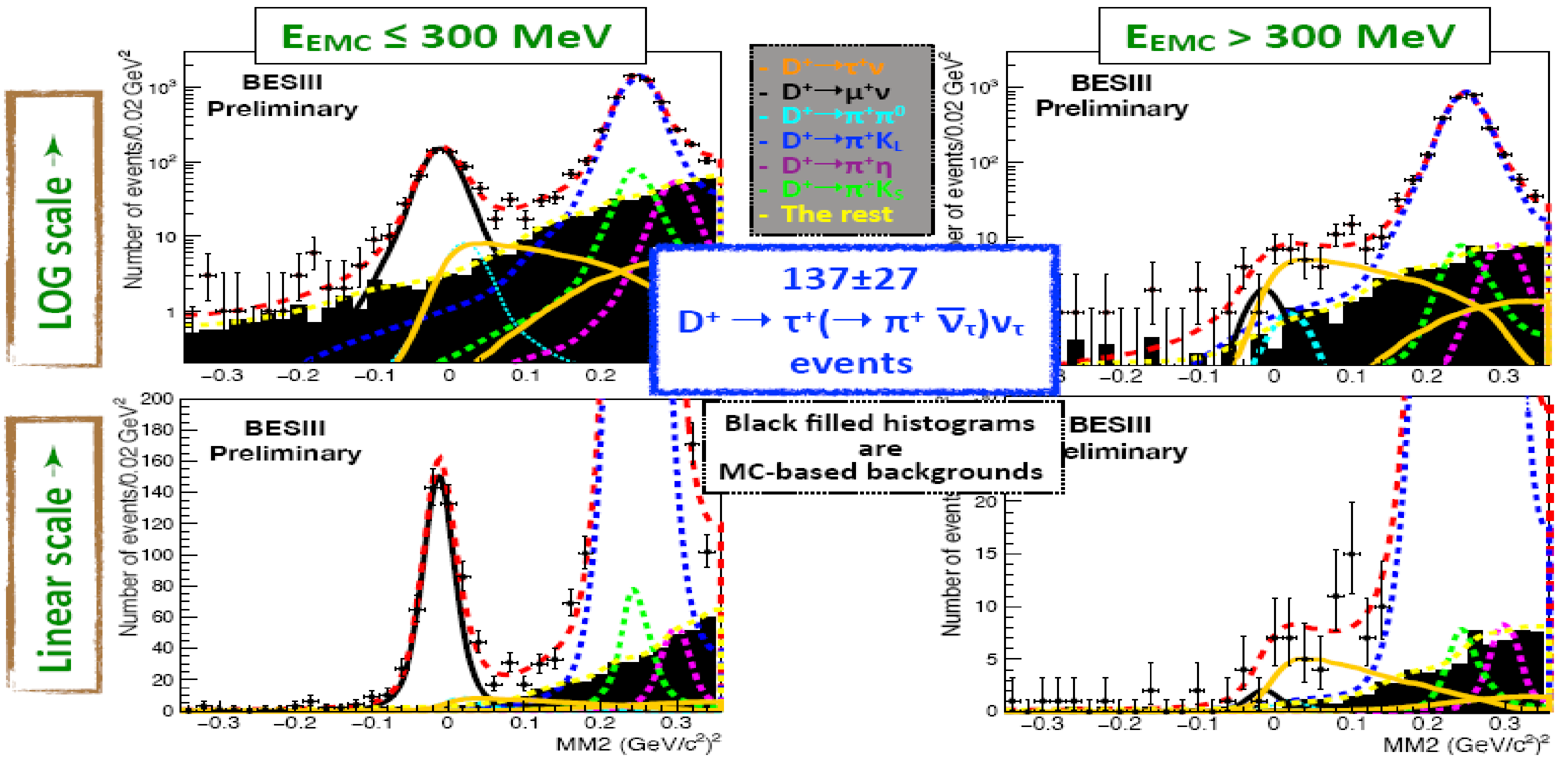
BESIII

$f_{D+} = (203.2 \pm 5.3 \pm 1.8)$ MeV

$|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$

Evidence for $D^+ \rightarrow \tau^+(\pi^+\nu)\nu$ (4σ) at BESIII

With 6 dominant D^- single tag Fitting to DATA



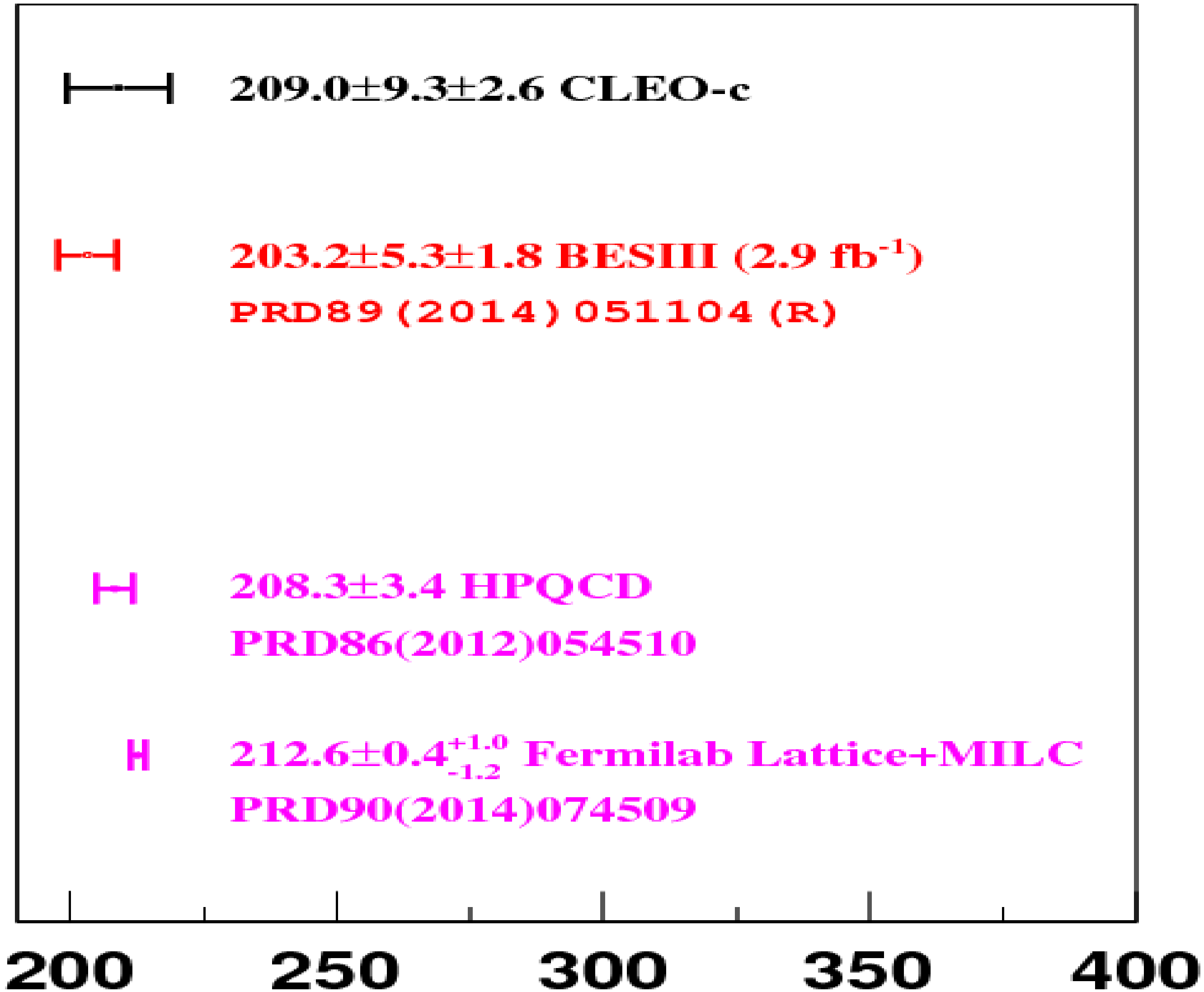
$$B[D^+ \rightarrow \tau^+\nu] = (1.20 \pm 0.24_{stat.}) \times 10^{-3}$$

$$R \equiv \frac{\Gamma(D^+ \to \tau^+\nu)}{\Gamma(D^+ \to \mu^+\nu)} = \frac{m_{\tau^+}^2 \left(1 - \frac{m_{\tau^+}^2}{M_{D^+}^2}\right)^2}{m_{\mu^+}^2 \left(1 - \frac{m_{\mu^+}^2}{M_{D^+}^2}\right)^2}$$

SM prediction: 2.66±0.01

BESIII: 3.21±0.64

Comparison of f_{D+}



f_{D+} [MeV]

Measurements of f_{D_s+} at CLEO-c

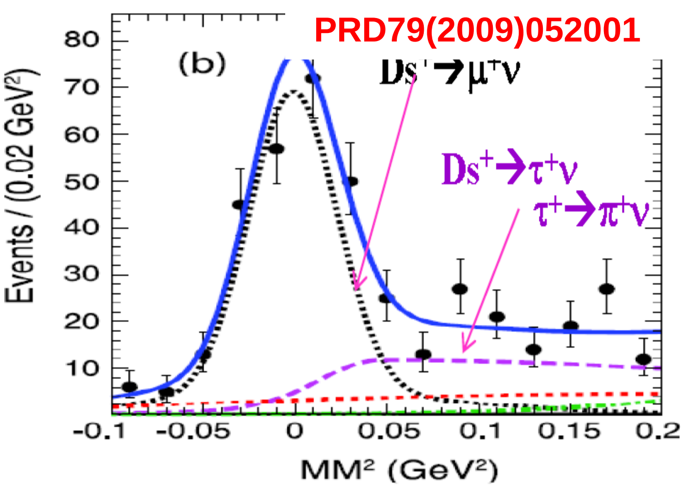
$D_s^{*+}D_s^-$, 600 pb^{-1} @ 4.17 GeV

Absolute measurement gives significantly improved statistical and systematic errors [697 signal]

235 ± 14 $D_s^+\to\mu^+\nu+\tau^+\nu$ signals

126 ± 16 $D_s^+\to\tau^+\nu$ signals

PRD79(2009)052001



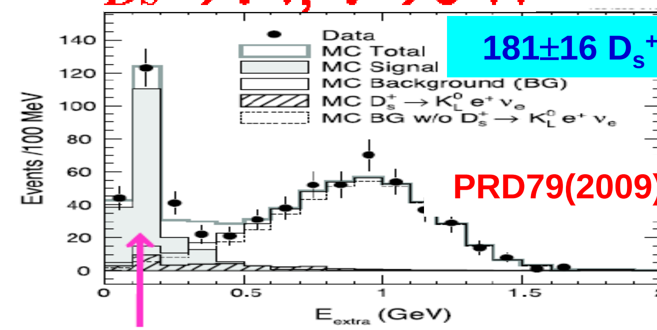
$B[D_s^+\to\mu^+\nu]=(5.65\pm0.45\pm0.17)\times10^{-3}$

$B[D_s^+\to\tau^+\nu]=(6.42\pm0.81\pm0.18)\%$

$f_{Ds+}=263.3\pm8.2\pm1.9$ MeV

$Ds^+\to\tau^+\nu,\ \tau^+\to e^+\nu\nu$

181 ± 16 $D_s^+\to\tau^+\nu$ signals



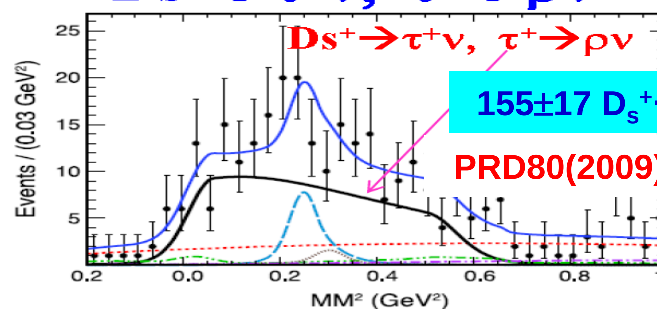
PRD79(2009)052002

Signal for $Ds^+\to\tau^+\nu$

$B[D_s^+\to\tau^+\nu]=(5.30\pm0.47\pm0.21)\%$

$f_{Ds+}=252.2\pm11.1\pm5.2$ MeV

$Ds^+\to\tau^+\nu,\ \tau^+\to\rho\nu$



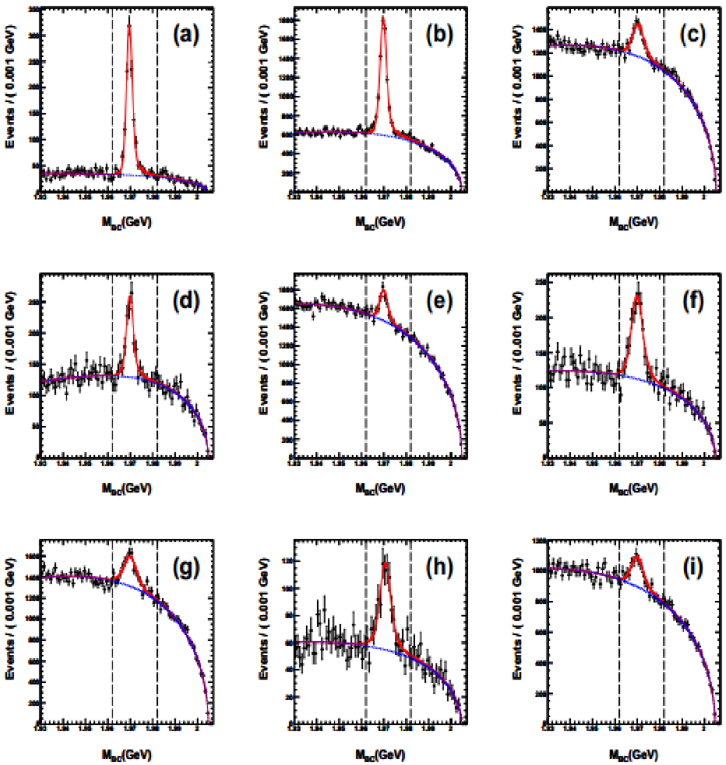
155 ± 17 $D_s^+\to\tau^+\nu$ signals

PRD80(2009)112004

$B[D_s^+\to\tau^+\nu]=(5.52\pm0.57\pm0.22)\%$

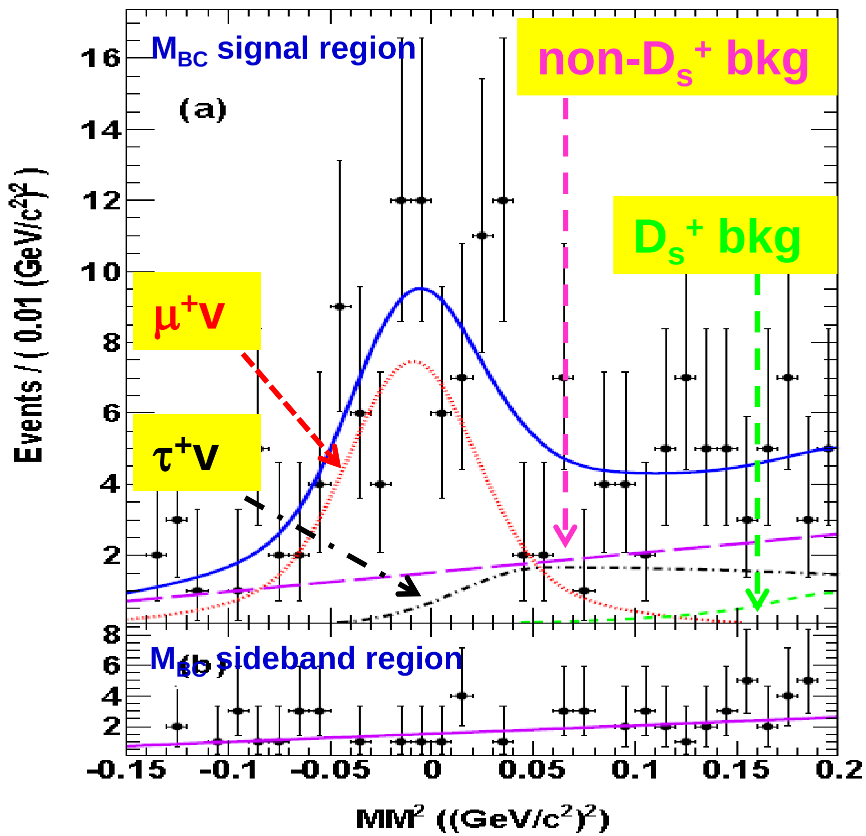
$f_{Ds+}=257.8\pm13.3\pm5.2$ MeV

f_{Ds+} at 4.009 GeV at BESIII



$N_{D_s^- tag} = 15127 \pm 312$

PRD94(2016)072004



$B[D_s^+ \rightarrow \mu^+ \nu] = (0.495 \pm 0.067 \pm 0.026)\%$

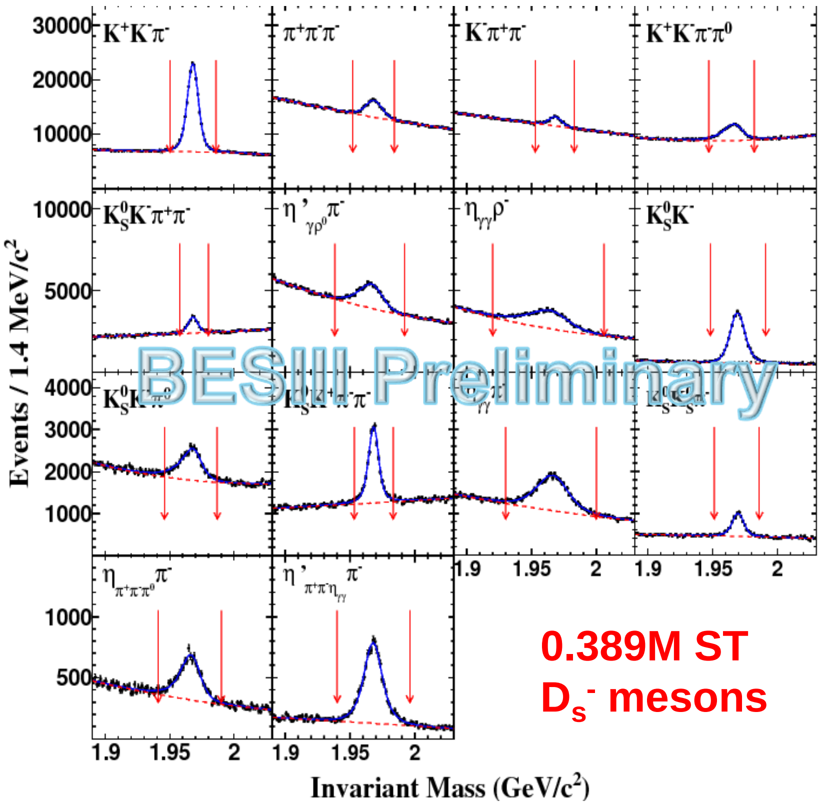
$B[D_s^+ \rightarrow \tau^+ \nu] = (4.83 \pm 0.65 \pm 0.26)\%$

$f_{Ds+} = (241.0 \pm 16.3 \pm 6.6)$ MeV

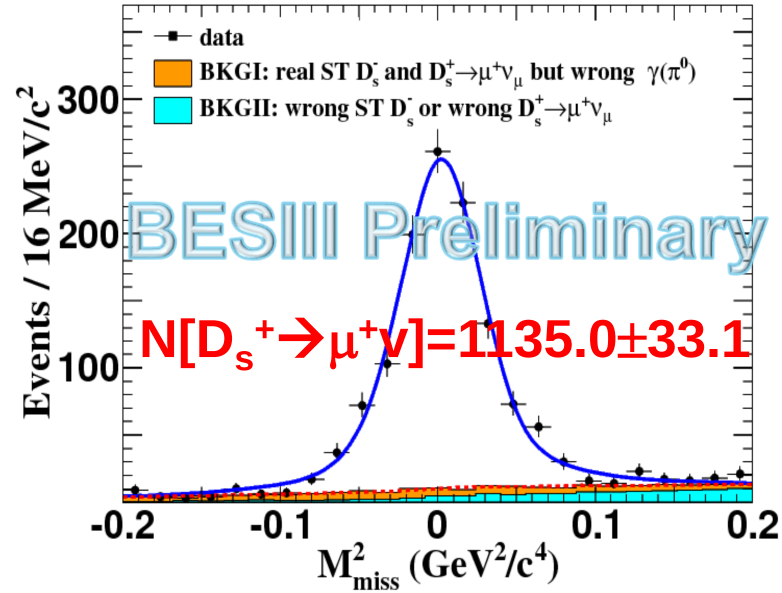
Improved $B[D_s^+ \to \mu^+ \nu]$, $f_{D_s^+}|V_{cs}|$ at BESIII

3.19 fb^{-1} data taken at 4.178 GeV in 2016

Use μ counter to suppress background



0.389M ST D_s^- mesons



1. Constraining signal/BKGI ratio via signal MC
2. Fixing BKGII via inclusive MC

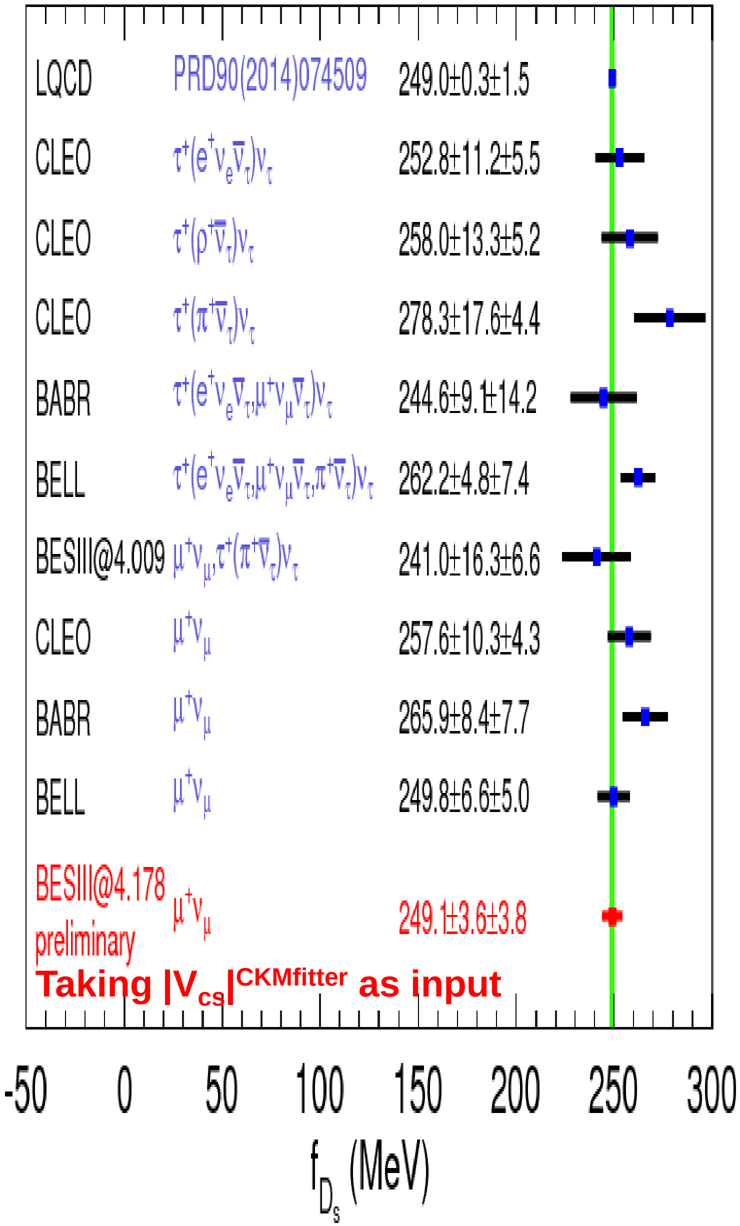
Source	Uncertainties(%)
Number of D_s^-	0.8
ΔE cut	0.5
$\gamma(\pi^0)$ match rate	1.1
$\gamma(\pi^0)$ efficiency	1.0
μ^+ tracking	0.5
μ^+ PID	0.8
$E^{\rm max}_{{\rm extra}\ \gamma}$ cut	0.3
$N^{\rm extra}_{\rm char} = 0$ cut	0.9
Signal shape	0.2
Fit range	0.6
Background estimation	0.6
MC statistics	0.4
BF($D_s^{*+} \to e^+e^-D_s^+$)	0.2
Radiative correction	1.0
Tag bias	0.6
Total	2.7

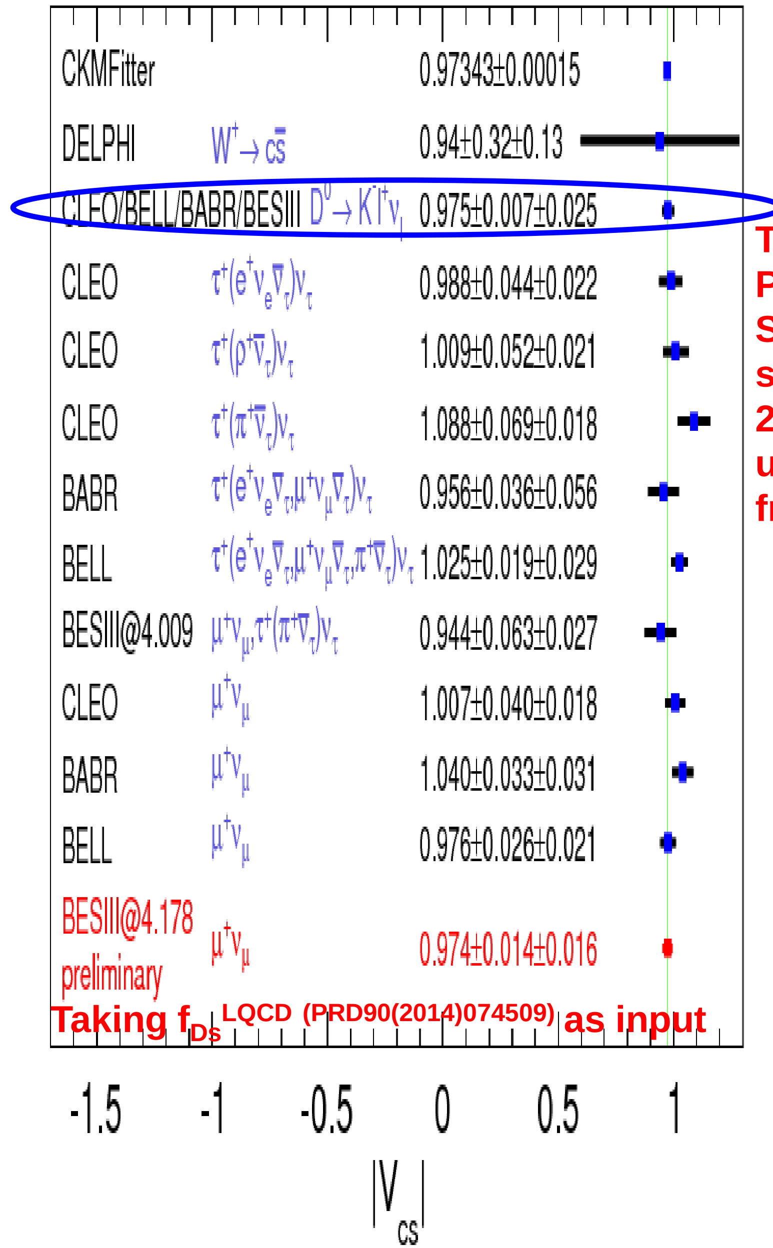
PRD51(1995)111

$B[D_s^+ \to \mu^+ v] = (5.28 \pm 0.15_{stat} \pm 0.14_{syst}) \times 10^{-3}$

$f_{D_s}|V_{cs}| = 242.5 \pm 3.5_{stat} \pm 3.7_{syst}$ MeV

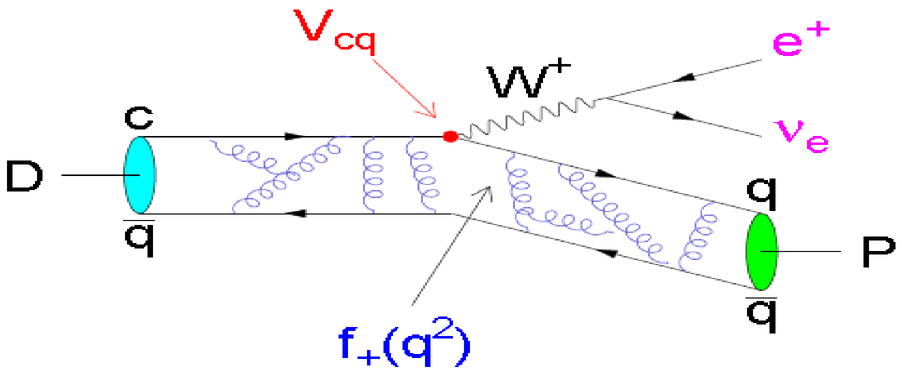
Comparisons of f_{Ds+} and $|V_{cs}|$





Taken from PDG, and the SL method suffers about 2.4% uncertainty from LQCD

Semi-leptonic decay $D \to K(\pi)e^+\nu$



Differential rates: $$\frac{d\Gamma}{dq^2} = X\frac{G_F^2|V_{cd(s)}|^2}{24\pi^3}p^3|f_+(q^2)|^2$$

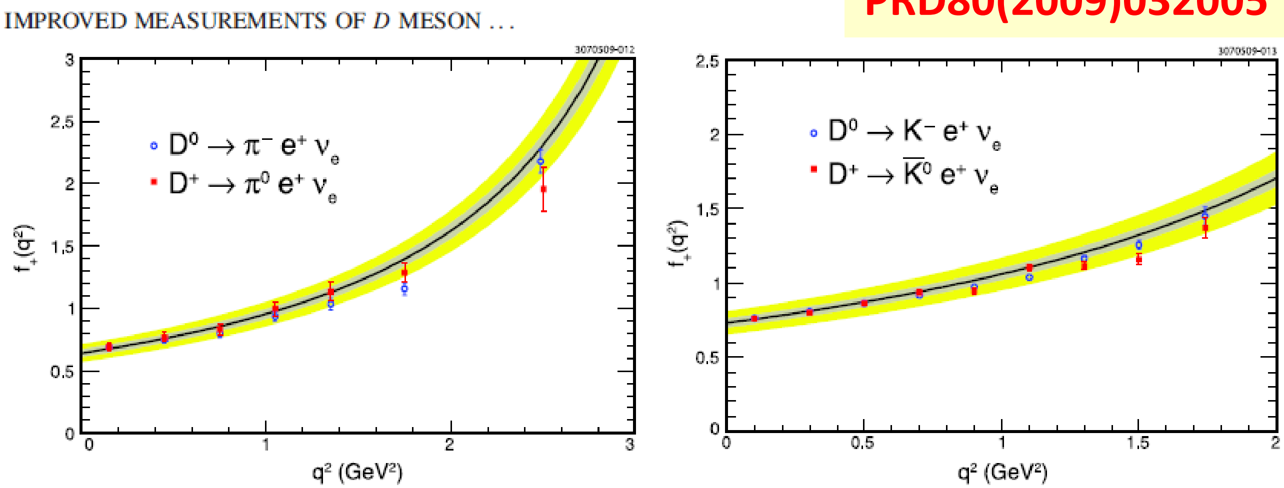
Bridge to precisely measure:

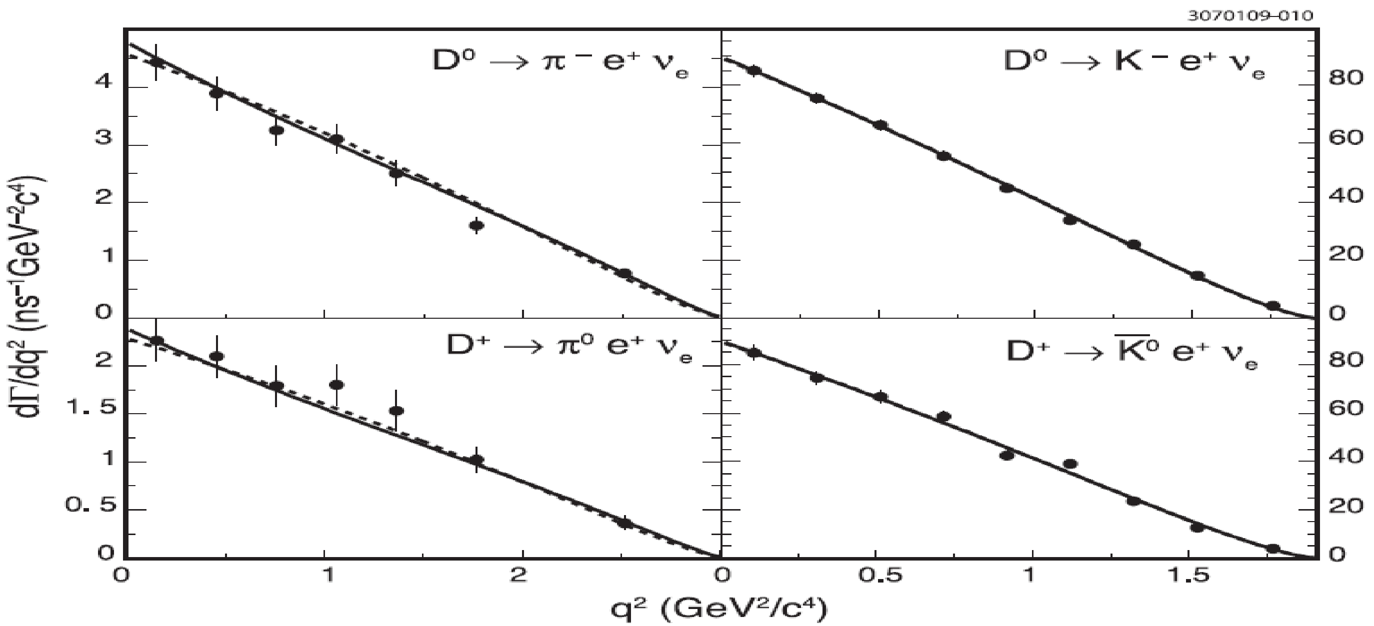
- **Form factors $f_+^{D\to K(\pi)}(0)$ with input $|V_{cd(s)}|^{CKMfitter}$**
  - **Single pole form**
    $$f_+(q^2) = \frac{f_+(0)}{1-\frac{q^2}{M^2_{\rm pole}}}$$
  - **Modified pole model**
    $$f_+(q^2) = \frac{f_+(0)}{(1-\frac{q^2}{M^2_{\rm pole}})(1-\alpha\frac{q^2}{M^2_{\rm pole}})}$$
  - **ISGW2 model**
    $$f_+(q^2) = f_+(q^2_{\rm max})\left(1+\frac{r^2_{\rm ISGW2}}{12}(q^2_{\rm max}-q^2)\right)^{-2}$$
  - **Series expansion model**
    $$f_+(t) = \frac{1}{P(t)\Phi(t,t_0)}a_0(t_0)\left(1+\sum_{k=1}^{\infty}r_k(t_0)[z(t,t_0)]^k\right)$$
- **CKM matrix element $|V_{cs(d)}|$ with input $f_+^{LQCD,D\to K(\pi)}(0)$**

Tagged analyses of D→K(π)e⁺ν at CLEO-c

818 pb^{-1} data at 3.773 GeV

PRD80(2009)032005

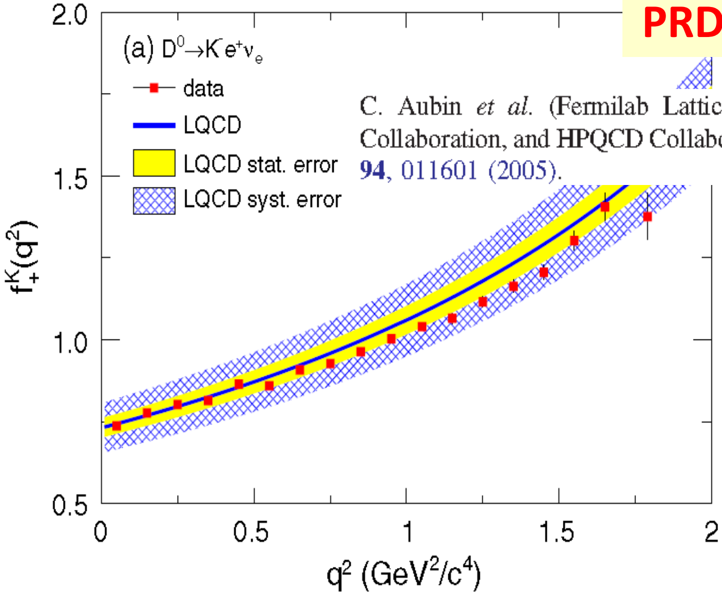


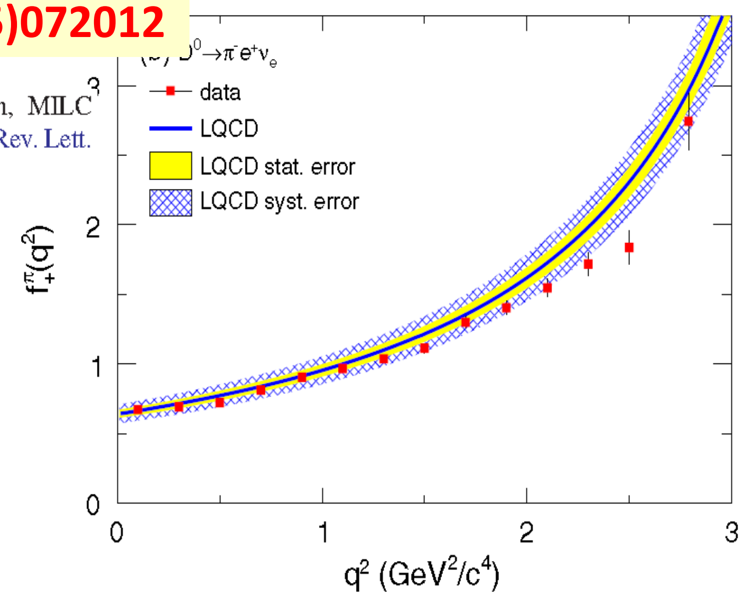


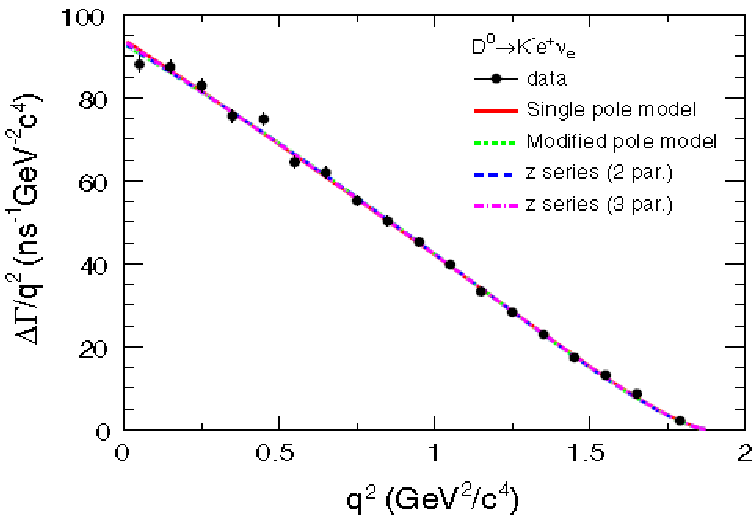
Analyses of D→K(π)e⁺ν dynamics at BESIII

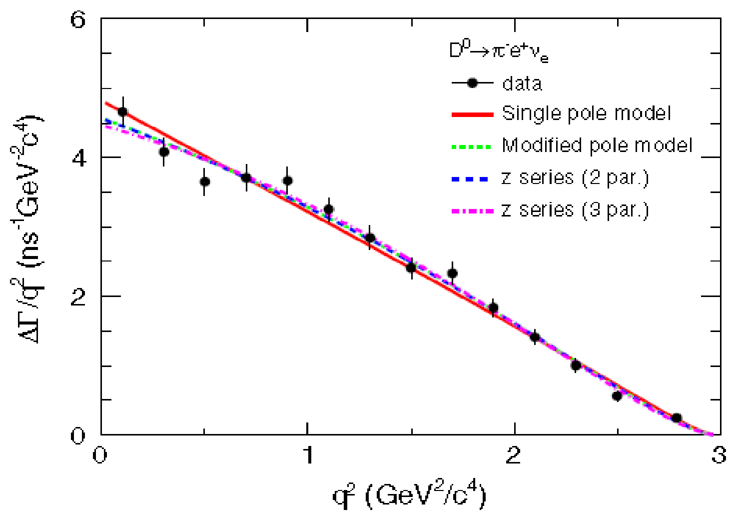
PRD92(2015)072012

C. Aubin *et al.* (Fermilab Lattice Collaboration, MILC Collaboration, and HPQCD Collaboration), Phys. Rev. Lett. **94**, 011601 (2005).



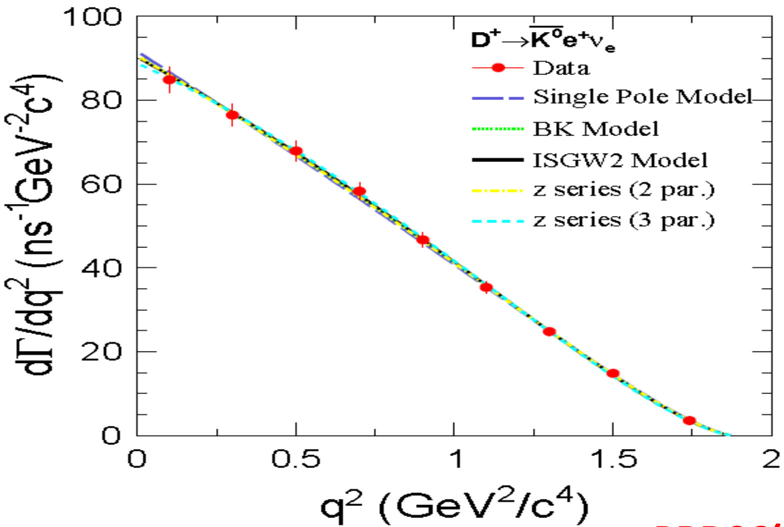


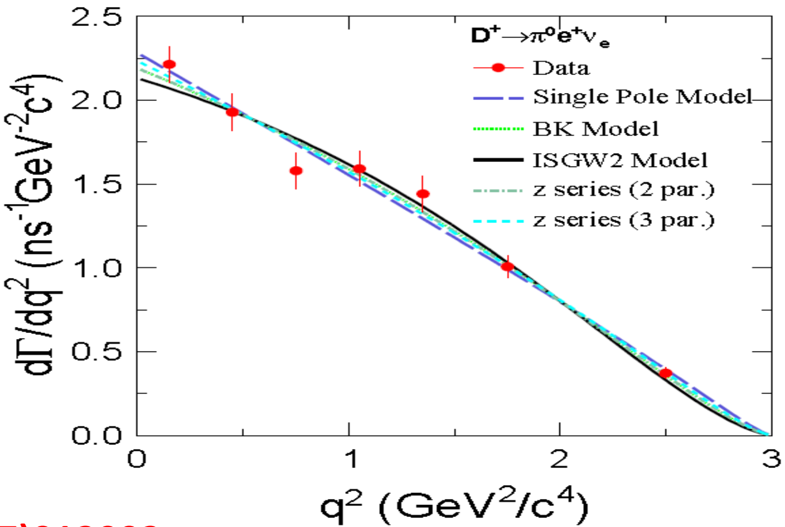




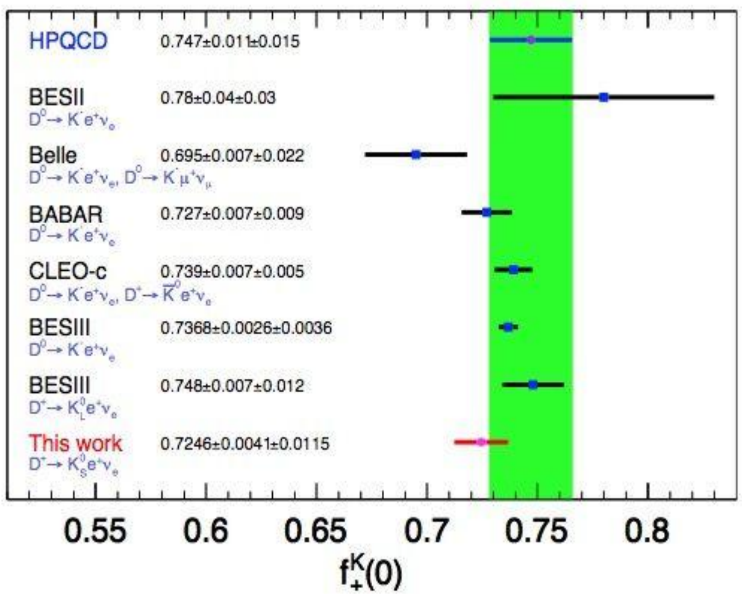
$D^0 \to K^- e^+ \nu$ **$D^0 \to \pi^- e^+ \nu$**

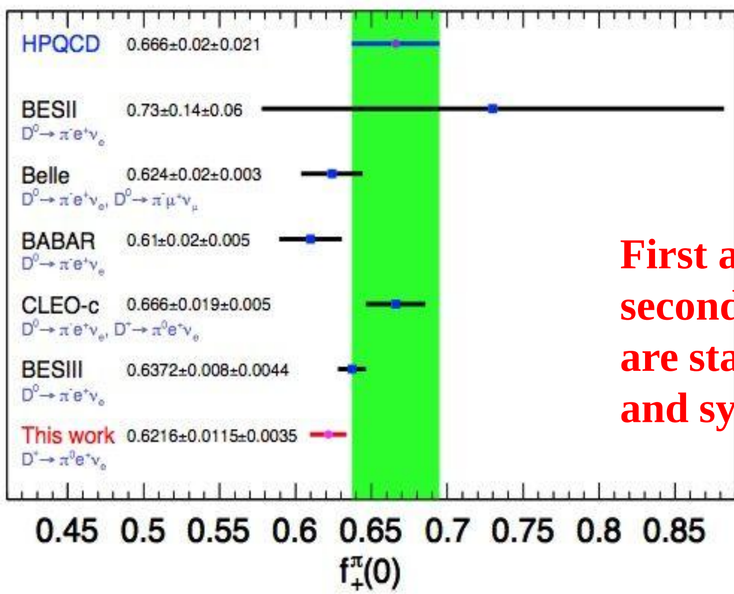
Comparisons of FFs by $D^+ \to \bar{K}^0(\pi^0)e^+v$





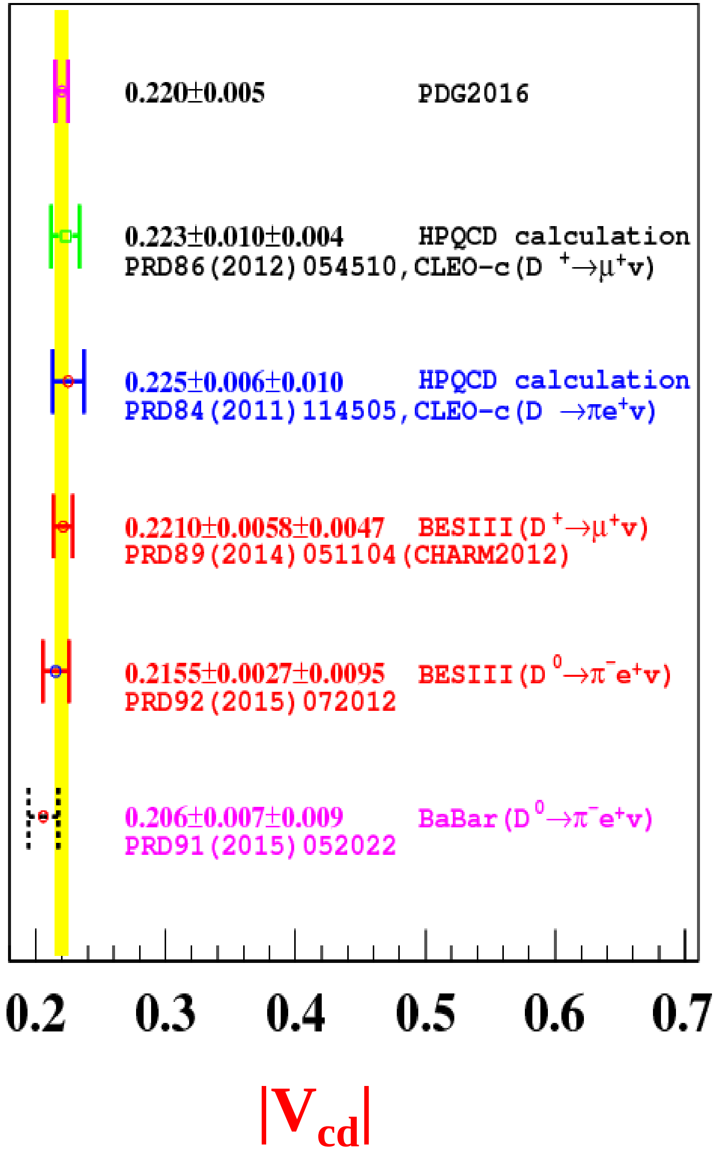
PRD96(2017)012002

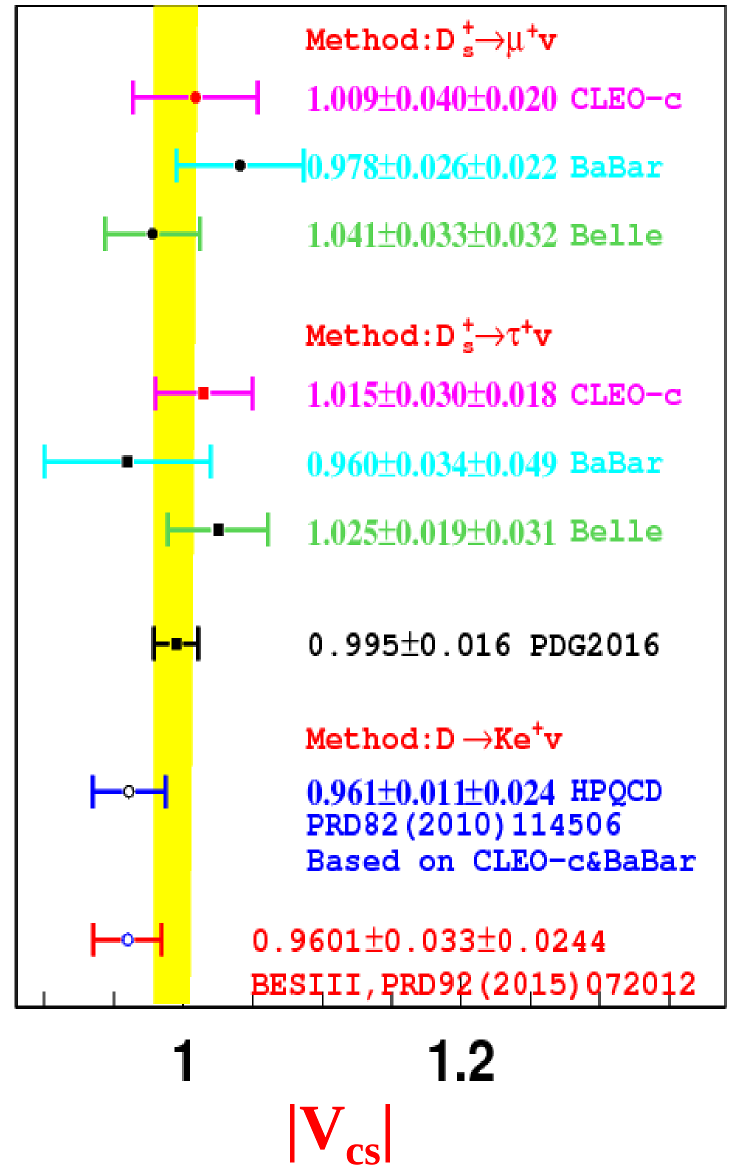




First and second errors are statistical and systematic

Comparison of $|V_{cd(s)}|$





Analysis of $D^+ \rightarrow K_L e^+ v$ at BESIII

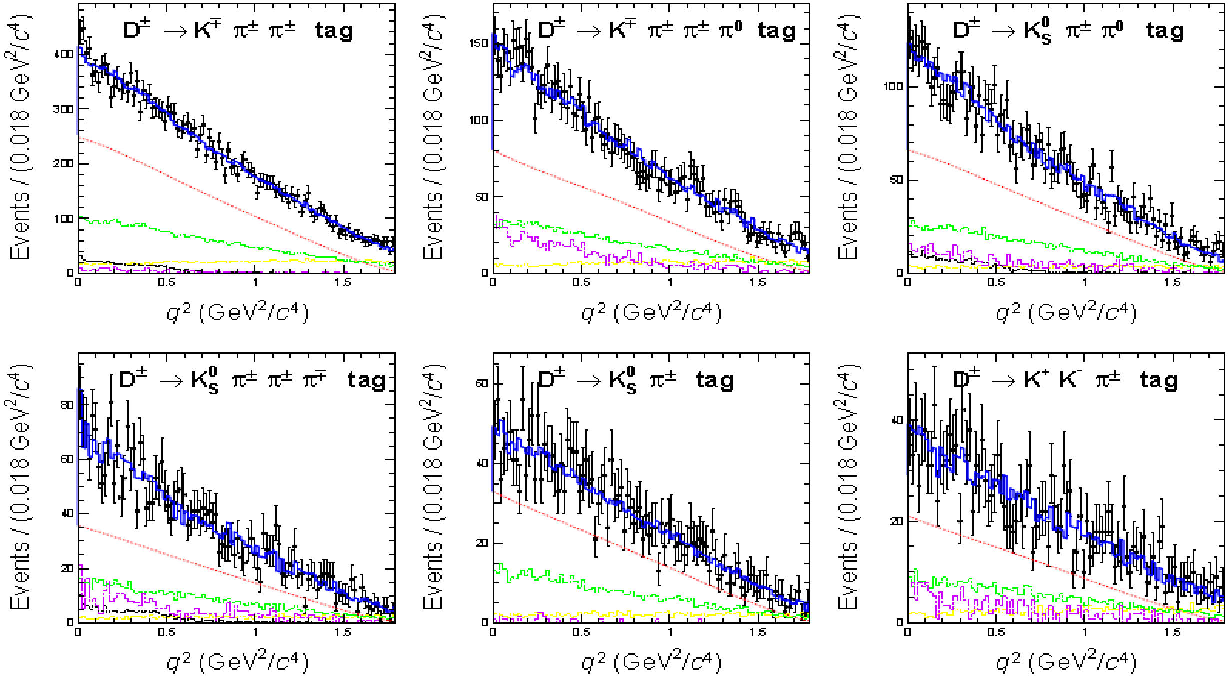
- Regardless of long flight distance, K_L interact with EMC and deposit part of energy, thus giving position information
- After reconstructing all other particles, K_L can be inferred with position information and constraint $U_{miss} \rightarrow 0$

$\bar{B}(D^+ \rightarrow K_L e^+ v) = (4.482 \pm 0.027 \pm 0.103)\%$

$$A_{CP} \equiv \frac{\mathcal{B}(D^+ \to K_L^0 e^+ \nu_e) - \mathcal{B}(D^- \to K_L^0 e^- \bar{\nu}_e)}{\mathcal{B}(D^+ \to K_L^0 e^+ \nu_e) + \mathcal{B}(D^- \to K_L^0 e^- \bar{\nu}_e)}$$

$A_{CP}^{D+ \rightarrow KLe+v} = (-0.59 \pm 0.60 \pm 1.50)\%$

Simultaneous fit to event density $I(q^2)$ with 2-par. series Form Factor



$D^+ \rightarrow K_L e+v$ is measured for the first time

PRD92(2015)112008

With 6 dominant D^- single tag

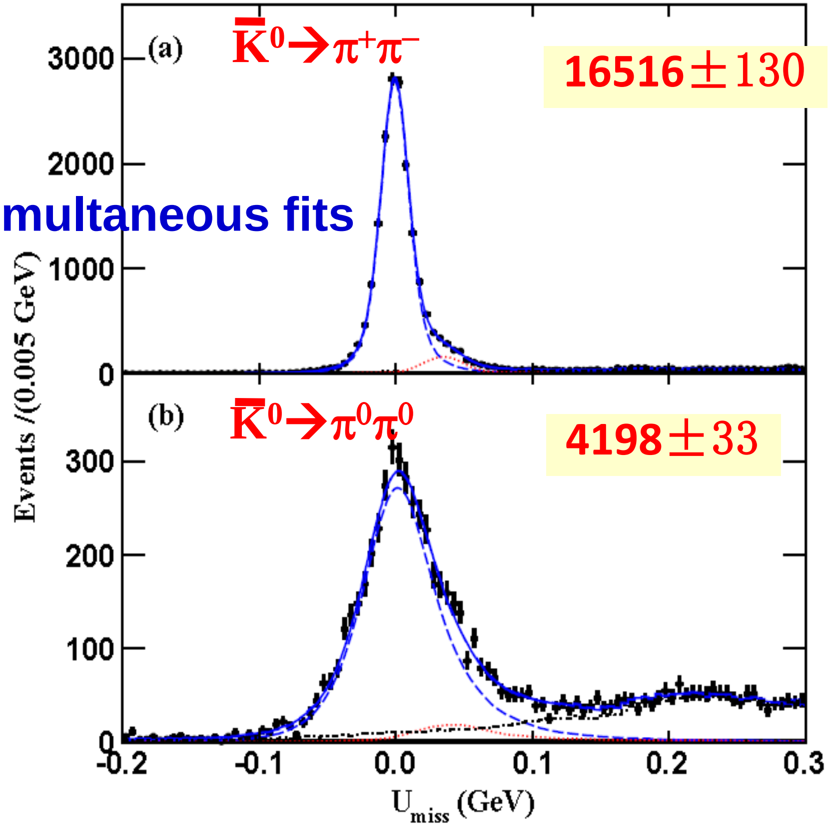
$f^K_+(0)|V_{cs}| = 0.728 \pm 0.006 \pm 0.011$

$r_1 = a_1/a_0 = -1.91 \pm 0.33 \pm 0.24$

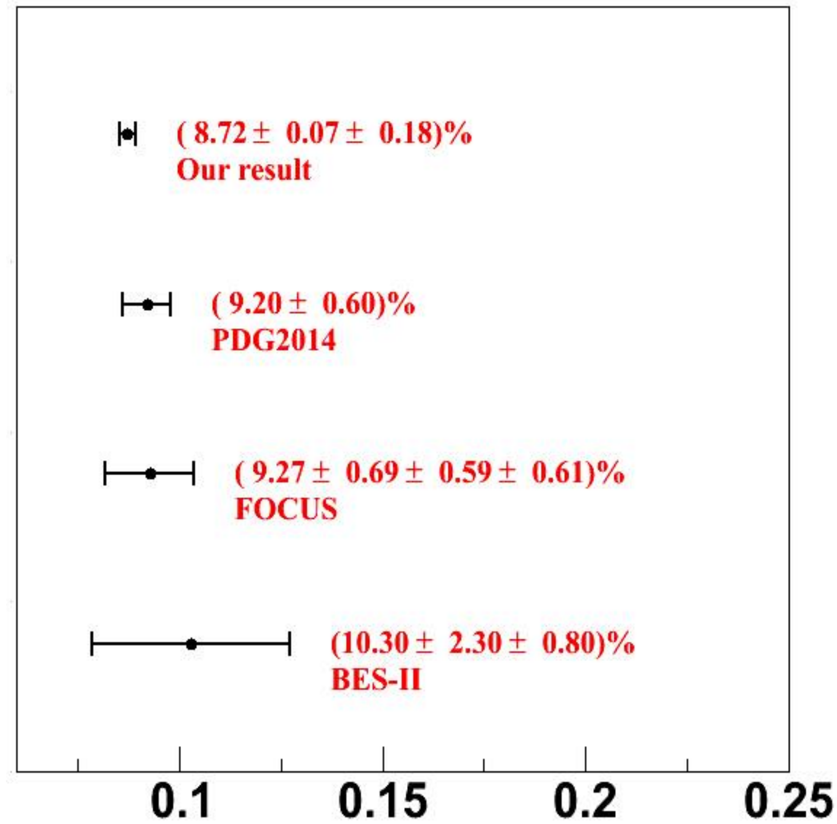
Improved BF for $D^+ \rightarrow \bar{K}^0 \mu^+ \nu$ at BESIII

With 6 dominant D^- single tag

Simultaneous fits



EPJC76(2016)369



Taking $B[D^0 \rightarrow K^- \mu^+ \nu]$ and $B[D^+ \rightarrow \bar{K}^0 e^+ \nu]$ from the PDG as input

$$\frac{\Gamma[D^0 \rightarrow K^- \mu^+ \nu]}{\Gamma[D^+ \rightarrow \bar{K}^0 \mu^+ \nu]} = 0.963 \pm 0.044$$

Support isospin conservation in these two decays within errors

$$\frac{\Gamma[D^+ \rightarrow \bar{K}^0 \mu^+ \nu]}{\Gamma[D^+ \rightarrow \bar{K}^0 e^+ \nu]} = 0.988 \pm 0.033$$

Consistent with theory prediction 0.97 within error

Lepton universality in $D^{0(+)} \rightarrow \pi^{-(0)} l^+ \nu$ at BESIII

- **Lepton universality (LU)**

$$R_{LU}^{0(+)} = \frac{B(D^{0(+)} \rightarrow \pi^{-(0)} \mu^+ \nu)}{B(D^{0(+)} \rightarrow \pi^{-(0)} e^+ \nu)} \sim 0.97$$

Expectations based on ZPC46 (1990)93, PRD69 (2004)074025, PLB633(2006)61 and PDG16

BFs on PDG16:

$$R_{LU}^{0} = 0.82 \pm 0.08 \quad (\sim 2.0\sigma)$$

$$B(D^0 \to \pi^- \mu^+ \nu) = (0.237 \pm 0.024)\%$$

Large error in $B[D^0 \rightarrow \pi^- \mu^+ \nu]$ and no measure of $B[D^+ \rightarrow \pi^0 \mu^+ \nu]$. Precision measurements are desired

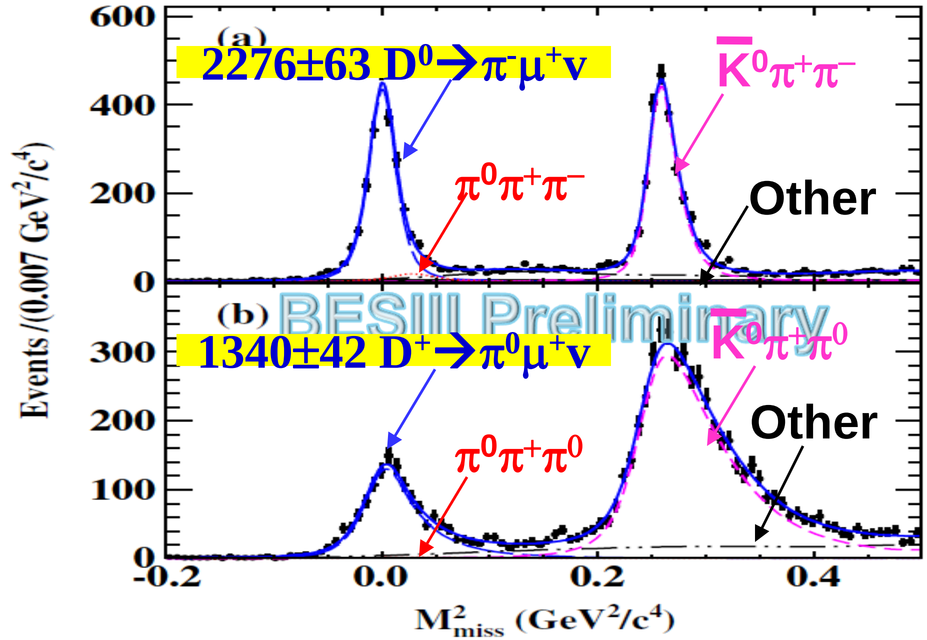
- **Isospin symmetry (IS)**

$$R_{IS}^{\ell} = \frac{\Gamma(D^0 \rightarrow \pi^- \ell^+ \nu)}{2\Gamma(D^+ \rightarrow \pi^0 \ell^+ \nu)} \sim 1$$

PDG16: $R_{IS}^{e} = 0.911 \pm 0.043 \quad (2.1\sigma)$

BESIII: $R_{IS}^{e} = 1.03 \pm 0.03 \pm 0.02$

With 3(6) dominant $D^{0(-)}$ single tag



BFs: $B(D^0 \to \pi^- \mu^+ \nu) = (0.267 \pm 0.007 \pm 0.007)\%$

agrees with PDG and with better precision

$B(D^+ \to \pi^0 \mu^+ \nu) = (0.342 \pm 0.011 \pm 0.010)\%$

measured for the first time

LU: $R_{LU}^{0} = 0.918 \pm 0.036$ $R_{LU}^{+} = 0.921 \pm 0.045$

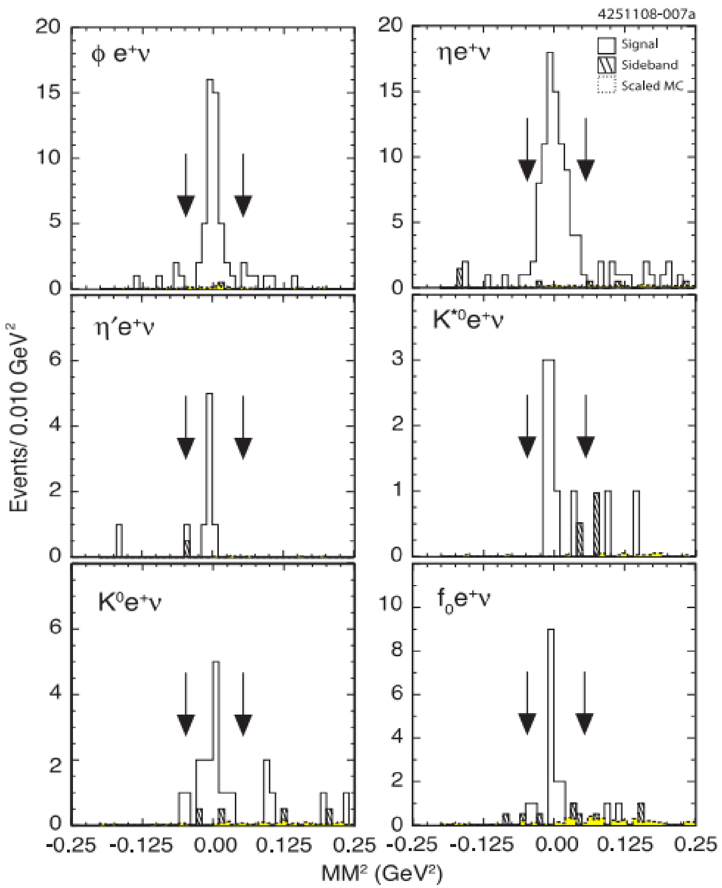
agree with expectation in 1.5(1.1) σ

IS: $R_{IS}^{\mu} = 0.990 \pm 0.054$

agree with IS prediction within uncertainty

Semileptonic D_s^+ decays at CLEO-c

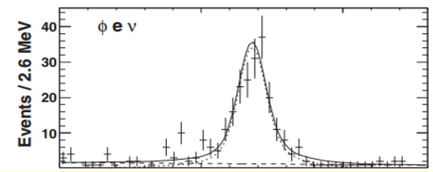
with 310 pb^{-1} data@4.17 GeV



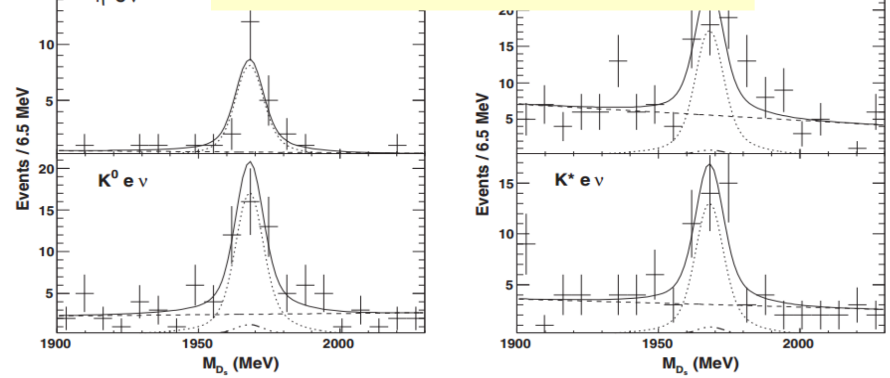
PRD80(2009)052007

J. Hietala,[1,*] D. Cronin-Hennessy,[1,†] T. Pedlar,[2] and I. Shipsey[3]

with 600 pb^{-1} data@4.17 GeV



PRD92(2015)112003



Signal mode	BABAR (%)	CLEO-c (%)	This analysis (%)
$D_s \to \phi e\nu$	$2.61 \pm 0.03 \pm 0.08 \pm 0.15$	$2.36 \pm 0.23 \pm 0.13$	$2.14 \pm 0.17 \pm 0.08$
$D_s \to \eta e\nu$	$\cdots$	$2.48 \pm 0.29 \pm 0.13$	$2.28 \pm 0.14 \pm 0.19$
$D_s \to \eta' e\nu$	$\cdots$	$0.91 \pm 0.33 \pm 0.05$	$0.68 \pm 0.15 \pm 0.06$
$D_s \to f_0 e\nu, f_0 \to \pi\pi$	Seen	$0.20 \pm 0.03 \pm 0.01$	$0.13 \pm 0.03 \pm 0.01$
$D_s \to K_S e\nu$	$\cdots$	$0.19 \pm 0.05 \pm 0.01$	$0.20 \pm 0.04 \pm 0.01$
$D_s \to K^* e\nu$	$\cdots$	$0.18 \pm 0.07 \pm 0.01$	$0.18 \pm 0.04 \pm 0.01$

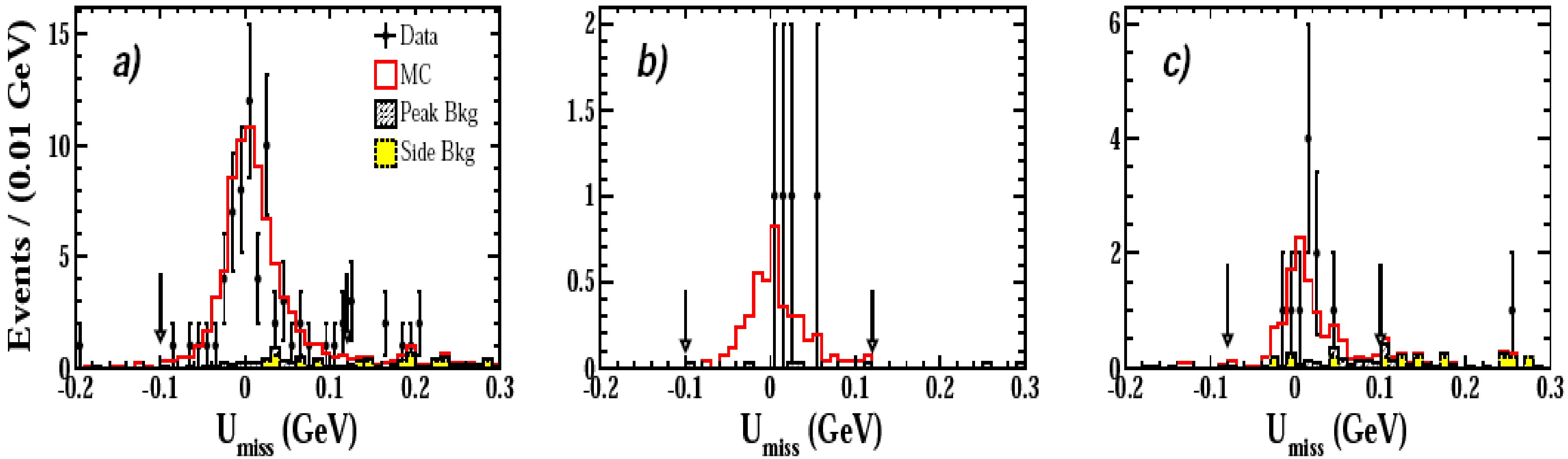
θ(η–η' mixing angle)=$(42\pm2\pm2)^0$

θ(f_0–ss mixing angle)=$(20^{+32}_{-20})^0$

Measurements of $D_s^+ \to \eta^{(\prime)} e^+ \nu$ at 4.009 GeV

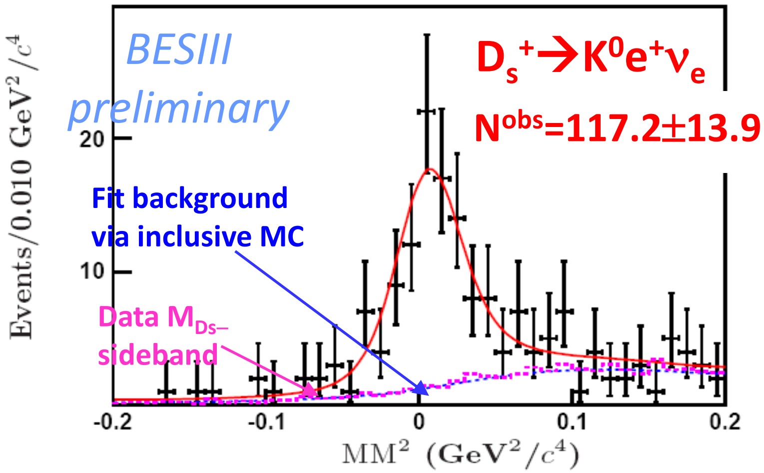
- Benefit the understanding of the source of difference of inclusive decay rates of $D^{0(+)}$ and D_s^+
- Complementary information to understand η–η' mixing

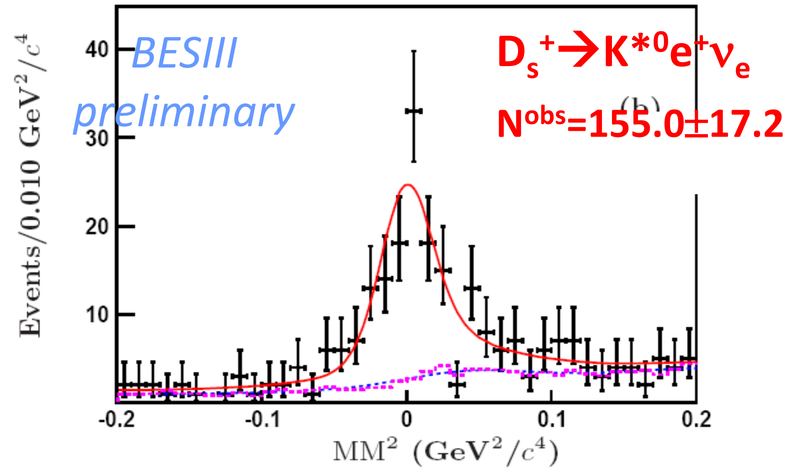
PRD94(2016)112003



	BESIII	CLEOII 95	CLEOc09	CLEOc15	PDG [4]
$B(D_s^+ \to \eta e^+ \nu_e)[\%]$	$2.30 \pm 0.31 \pm 0.08$	—	$2.48 \pm 0.29 \pm 0.13$	$2.28 \pm 0.14 \pm 0.20$	2.67 ± 0.29
$B(D_s^+ \to \eta' e^+ \nu_e)[\%]$	$0.93 \pm 0.30 \pm 0.05$	—	$0.91 \pm 0.33 \pm 0.05$	$0.68 \pm 0.15 \pm 0.06$	0.99 ± 0.23
$\frac{B(D_s^+ \to \eta' e^+ \nu_e)}{B(D_s^+ \to \eta e^+ \nu_e)}$	$0.40 \pm 0.14 \pm 0.02$	$0.35 \pm 0.09 \pm 0.07$	—	—	—

Studies of $D_s^+ \to K^{(*)0} e^+ \nu$ at 4.178 GeV



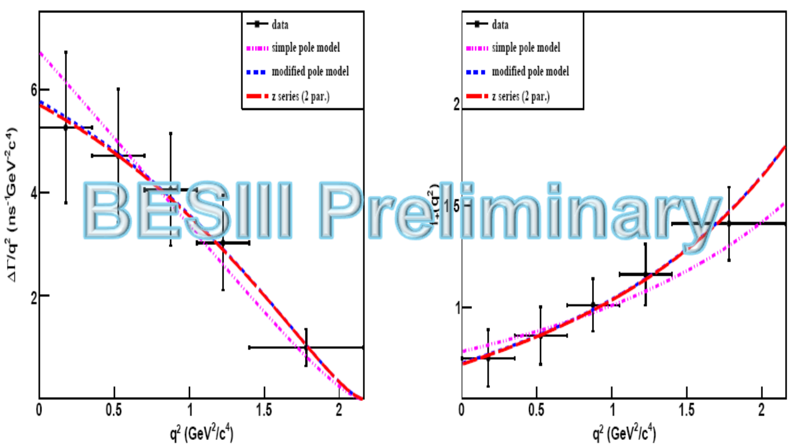


$B[D_s^+ \to K^0 e^+ \nu_e] = (3.25 \pm 0.38_{stat} \pm 0.14_{syst}) \times 10^{-3}$

$(3.9 \pm 0.9) \times 10^{-3}$ [PDG17]

$B[D_s^+ \to K^{*0} e^+ \nu_e] = (2.38 \pm 0.26_{stat} \pm 0.12_{syst}) \times 10^{-3}$

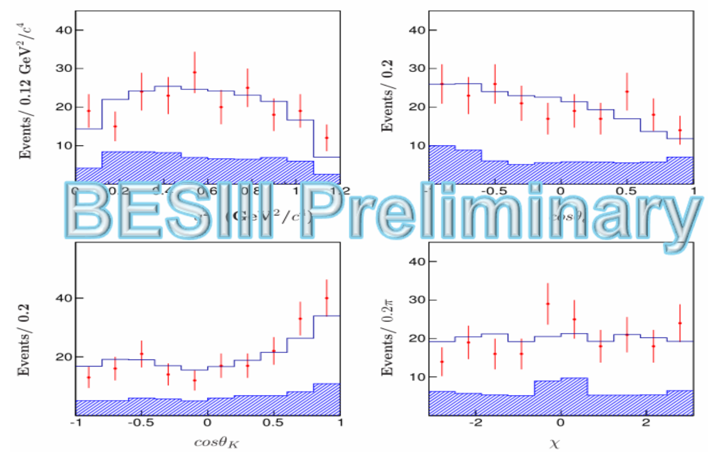
$(1.8 \pm 0.4) \times 10^{-3}$ [PDG17]



Model	Parameter	Value	$f_+(0)$
Simple pole	$f_+(0)\|V_{cd}\|$	$0.175 \pm 0.010 \pm 0.001$	$0.778 \pm 0.044 \pm 0.004$
Modified pole model	$f_+(0)\|V_{cd}\|$	$0.163 \pm 0.017 \pm 0.003$	$0.725 \pm 0.076 \pm 0.013$
	α	$0.45 \pm 0.44 \pm 0.02$	
Series two parameters	$f_+(0)\|V_{cd}\|$	$0.162 \pm 0.019 \pm 0.003$	$0.720 \pm 0.084 \pm 0.013$
	r_1	$-2.94 \pm 2.32 \pm 0.14$	

Taking $|V^{CKMfitter}_{cd}|$ as input

Four dimensional un-binned likelihood fit is performed. K* paramters are fixed



r_V=1.67±0.34±0.16

r_2=0.77±0.28±0.07

Hadronic structure and quantum correlation

D hadronic decays

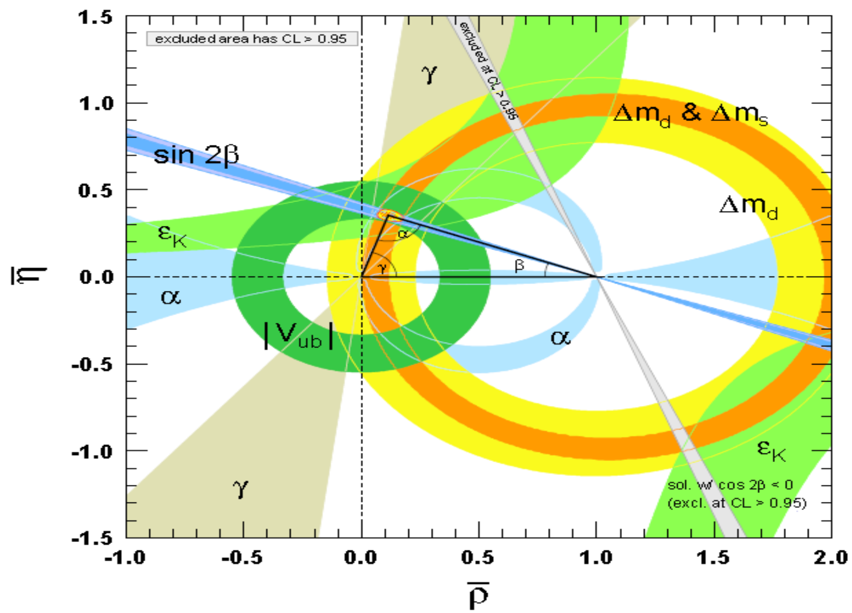
- **Better inputs for beauty physics**
- **Window into strong final-state interactions**
- **Quantum correlated $D^0\bar{D}^0$ decays:**
  - **CP asymmetry in mixing and decays**
  - **Interference → strong phase parameters c_i and s_i → Impact on γ/ϕ_3, which is important for CKM UT**

Direct measurement

$$\alpha/\phi_2 = \left(85.4^{+4.0}_{-3.9}\right)^\circ$$
$$\beta/\phi_1 = \left(21.38^{+0.79}_{-0.77}\right)^\circ$$
$$\gamma/\phi_3 = \left(68^{+8.0}_{-8.5}\right)^\circ$$

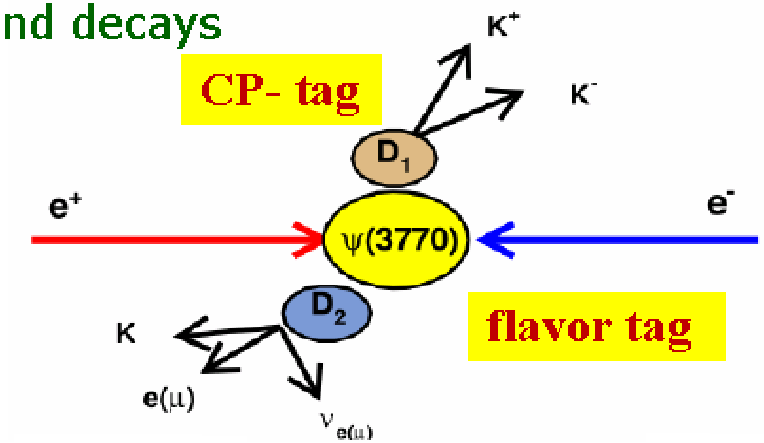
γ is the worst measured angle, mostly due to systematic error

Significant deviation from UT will imply NP beyond SM



$D^0\bar{D}^0$ mixing parameter y_{CP} at BESIII

We measure the y_{CP} using CP-tagged semi-leptonic D decays allow to access CP asymmetry in mixing and decays



For D decay to CP eigenstates:

$$R_{CP\pm} \propto |A_{CP\pm}|^2(1 \mp y_{CP})$$

$$y_{CP} = \frac{1}{2}[y\cos\phi(|\frac{q}{p}| + |\frac{p}{q}|) - x\sin\phi(|\frac{q}{p}| - |\frac{p}{q}|)]$$

For CP tagged semileptonic D decays:

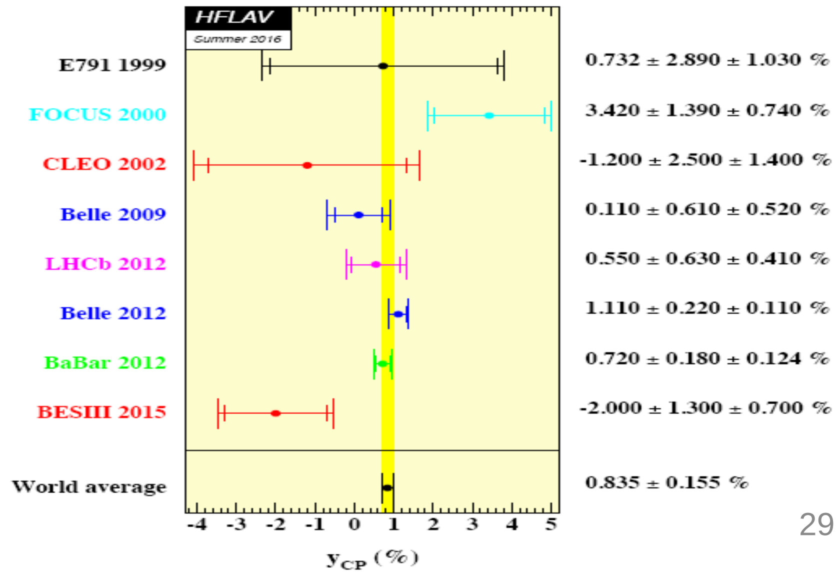
$$R_{l,CP\pm} \propto |A_l|^2|A_{CP\pm}|^2$$

$$y_{CP} \approx \frac{1}{4}(\frac{R_{l;CP+}R_{CP-}}{R_{l;CP-}R_{CP+}} - \frac{R_{l;CP-}R_{CP+}}{R_{l;CP+}R_{CP-}})$$

Type	Modes
CP^+	K^+K^-, $\pi^+\pi^-$, $K_S\pi^0\pi^0$
CP^-	$K_S^0\pi^0$, $K_S^0\omega$, $K_S^0\eta$
$l^\pm$	$Ke\nu$, $K\mu\nu$

$\boxed{y_{CP}=(-2.1\pm1.3\pm0.7)\%}$

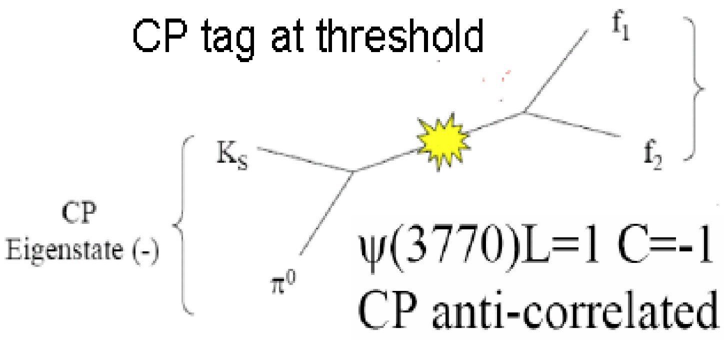
PLB 744(2015)339

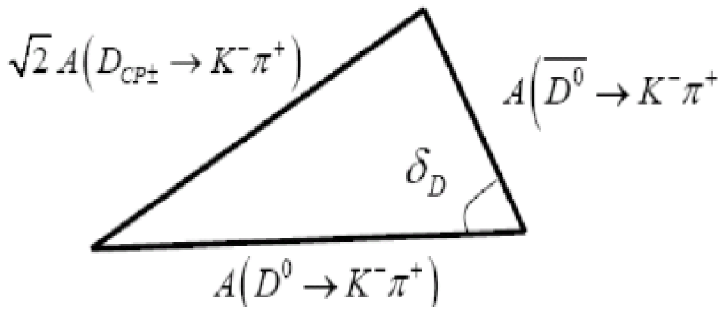


Strong phase difference $\delta_{K\pi}$ at BESIII

Quantum correlation → Interference → access strong phase!

If CP violation in charm is neglected: mass eigenstates = CP eigenstates





$$\mathcal{A}_{CP\to K\pi} = \frac{\mathcal{B}_{D_2\to K^-\pi^+} - \mathcal{B}_{D_1\to K^-\pi^+}}{\mathcal{B}_{D_2\to K^-\pi^+} + \mathcal{B}_{D_1\to K^-\pi^+}}.$$

$$2r\boxed{\cos\delta_{K\pi}} + y = (1 + R_{\mathrm{WS}}) \cdot \mathcal{A}_{CP\to K\pi},$$

$$|D_1\rangle \equiv \frac{|D^0\rangle + |\overline{D}^0\rangle}{\sqrt{2}} \quad |D_2\rangle \equiv \frac{|D^0\rangle - |\overline{D}^0\rangle}{\sqrt{2}}.$$

$A^{K\pi}_{CP}$=(12.7±1.3±0.7)%

$\delta_{K\pi}$ is important to relate to mixing parameters x and y from x' and y'

Type	Mode
Flavored	$K^-\pi^+, K^+\pi^-$
$CP+$	$K^+K^-, \pi^+\pi^-, K^0_S\pi^0\pi^0, \pi^0\pi^0, \rho^0\pi^0$
$CP-$	$K^0_S\pi^0, K^0_S\eta, K^0_S\omega$

With external inputs of the parameters in HFAG2013 and PDG

$R_{\mathrm{D}} = 3.47 \pm 0.06‰, \; y = 6.6 \pm 0.9‰ \quad R_{\mathrm{WS}} = 3.80 \pm 0.05‰$

$\cos\delta_{K\pi}$=1.02±0.11±0.06±0.01

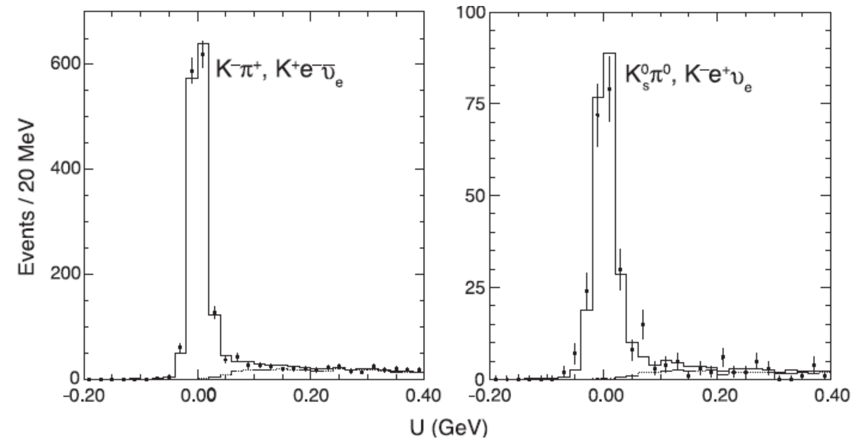
most precise to date

PLB734(2014)227

Strong phase difference $\delta_{K\pi}$ at CLEO-c

PRD86(2012)112001

Type	Reconstruction	Final states
f	Full	$K^-\pi^+$, $Y_0 - Y_7$
$\bar{f}$	Full	$K^+\pi^-$, $\bar{Y}_0 - \bar{Y}_7$
S_+	Full	K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$
S_+	Partial	$K_L^0\pi^0$, $K_L^0\eta$, $K_L^0\omega$
S_-	Full	$K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$
S_-	Partial	$K_L^0\pi^0\pi^0$
ℓ^+	Partial	$K^-e^+\nu_e$, $K^-\mu^+\nu_\mu$
ℓ^-	Partial	$K^+e^-\bar{\nu}_e$, $K^+\mu^-\bar{\nu}_\mu$



Mode	Correlated	Uncorrelated
$K^-\pi^+$	$1 + R_{WS}$	$1 + R_{WS}$
S_+	2	2
S_-	2	2
Y_k	$1 + Q_k$	$1 + Q_k$
$K^-\pi^+$, $K^-\pi^+$	$R_M[(1 + R_{WS})^2 - 4r\cos\delta(r\cos\delta + y)]$	R_{WS}
$K^-\pi^+$, $K^+\pi^-$	$(1 + R_{WS})^2 - 4r\cos\delta(r\cos\delta + y)$	$1 + R_{WS}^2$
$K^-\pi^+$, S_+	$1 + R_{WS} + 2r\cos\delta + y$	$1 + R_{WS}$
$K^-\pi^+$, S_-	$1 + R_{WS} - 2r\cos\delta - y$	$1 + R_{WS}$
$K^-\pi^+$, ℓ^-	$1 - ry\cos\delta - rx\sin\delta$	1
$K^-\pi^+$, ℓ^+	$r^2(1 - ry\cos\delta - rx\sin\delta)$	R_{WS}
$K^-\pi^+$, $\bar{Y}_i$	$(1 + R_{WS})(1 + Q_i) - r^2 - \rho_i^2 - 2(r\cos\delta + y)(\rho_i c_i + y) + 2r\sin\delta\rho_i s_i$	$1 + R_{WS}Q_i$
$K^-\pi^+$, Y_i	$(1 + R_{WS})(1 + Q_i) - 1 - r^2\rho_i^2 - 2(r\cos\delta + y)(\rho_i c_i + y) - 2r\sin\delta\rho_i s_i$	$R_{WS} + Q_i$
S_+, S_+	0	1
S_-, S_-	0	1
S_+, S_-	4	2
S_+, ℓ^-	$1 + y$	1
S_-, ℓ^-	$1 - y$	1
S_+, Y_i	$1 + Q_i + 2\rho_i c_i + y$	$1 + Q_i$
S_-, Y_i	$1 + Q_i - 2\rho_i c_i - y$	$1 + Q_i$
Y_i, ℓ^-	$1 - \rho_i y c_i - \rho_i x s_i$	1
Y_i, ℓ^+	$\rho_i^2(1 - \rho_i y c_i - \rho_i x s_i)$	Q_i
Y_i, $\bar{Y}_j$	$(1 + Q_i)(1 + Q_j) - \rho_i^2 - \rho_j^2 - 2(\rho_i c_i + y)(\rho_j c_j + y) + 2\rho_i s_i \rho_j s_j$	$1 + Q_i Q_j$
Y_i, Y_j	$(1 + Q_i)(1 + Q_j) - 1 - \rho_i^2\rho_j^2 - 2(\rho_i c_i + y)(\rho_j c_j + y) - 2\rho_i s_i \rho_j s_j$	$Q_i + Q_j$

$$\cos\delta = 0.81^{+0.22+0.07}_{-0.18-0.05}$$

$$\sin\delta = -0.01 \pm 0.41 \pm 0.04$$

$$\delta = (10^{+28+13}_{-53-0})^0$$

If including external inputs on mixing parameters in the fit,

$$\cos\delta = 1.15^{+0.19+0.00}_{-0.17-0.08}$$

$$\sin\delta = 0.56^{+0.32+0.21}_{-0.31-0.20}$$

$$\delta = (18^{+11}_{-17})^0$$

Strong phase difference $\delta_{K\pi\pi0/K3\pi}$ at CLEO-c

PRD80(2009)031105

Mode	$\mathcal{B}$
$D^0 \to CP$	$A_{CP}^2(1-\lambda_{\pm}y)$
$D^0 \to F$	A_F^2
$D^0 \to \bar{F}$	$A_{\bar{F}}^2[1-(y/r_D^F)R_F\cos\delta_D^F + (x/r_D^F)R_F\sin\delta_D^F + (y^2+x^2)/2(r_D^F)^2]$
$D^0 \to K^-\pi^+$	$A_{K^-\pi^+}^2$
$D^0 \to K^+\pi^-$	$A_{K^+\pi^-}^2[1-(y/r_D^{K\pi})\cos\delta_D^{K\pi} + (x/r_D^{K\pi})\times \sin\delta_D^{K\pi} + (y^2+x^2)/2(r_D^{K\pi})^2]$

Mode	$K^\pm\pi^\mp\pi^\mp\pi^\pm$	$K^\pm\pi^\mp\pi^0$	$K^\pm\pi^\mp$
$K^\mp\pi^\pm\pi^\pm\pi^\mp$	$4,044 \pm 64$		
$K^\pm\pi^\mp\pi^\mp\pi^\pm$	29.1 ± 5.9		
$K^\mp\pi^\pm\pi^0$	$9,594 \pm 99$	$7,342 \pm 87$	
$K^\pm\pi^\mp\pi^0$	63.6 ± 8.8	12.5 ± 4.1	
$K^\mp\pi^\pm$	$5,206 \pm 72$	$7,155 \pm 85$	
$K^\pm\pi^\mp$	35.6 ± 6.2	7.3 ± 3.3	
K^+K^-	536 ± 23	764 ± 28	
$\pi^+\pi^-$	246 ± 16	336 ± 18	
$K_S^0\pi^0\pi^0$	283 ± 18	406 ± 21	221 ± 15
$K_L^0\pi^0$	827 ± 30	$1,236 \pm 38$	689 ± 28
$K_L^0\omega$	296 ± 18	449 ± 22	251 ± 17
$K_S^0\pi^0$	705 ± 27	891 ± 30	473 ± 22
$K_S^0\omega$	319 ± 19	389 ± 21	183 ± 14
$K_S^0\phi$	53.0 ± 7.5	90.9 ± 9.9	42.8 ± 6.9
$K_S^0\eta(\gamma\gamma)$	128 ± 12	116 ± 11	65.5 ± 8.3
$K_S^0\eta(\pi^+\pi^-\pi^0)$	35.9 ± 6.5	36.3 ± 7.2	27.2 ± 5.4
$K_S^0\eta'$	35.7 ± 6.0	60.6 ± 7.8	30.0 ± 5.5

Significant coherence

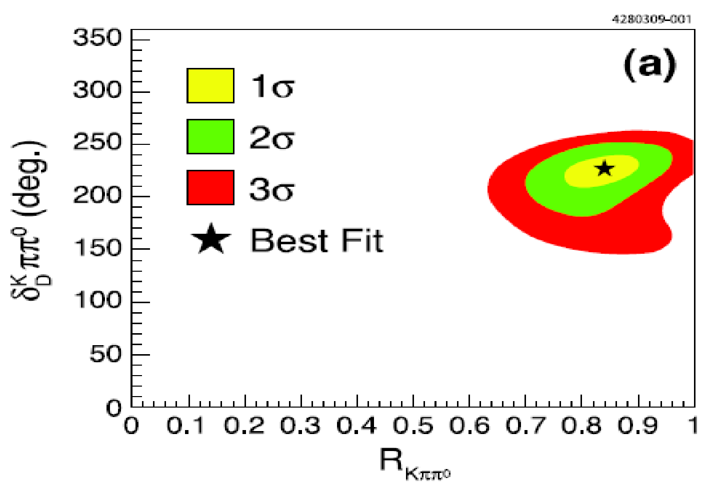
$$\cos_D^{K\pi\pi^0} = (227^{+14}_{-17})^0$$

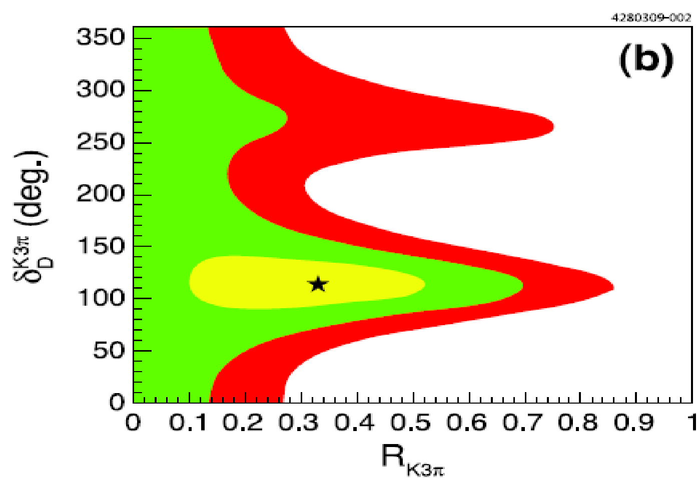
$$R_{K\pi\pi^0} = 0.84 \pm 0.07$$

Lower coherence

$$\cos_D^{K3\pi} = (114^{+26}_{-23})^0$$

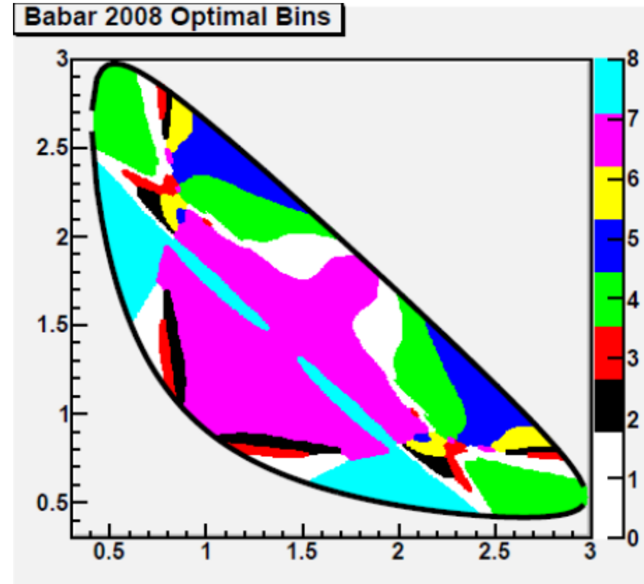
$$R_{K3\pi} = 0.33^{+0.20}_{-0.30}$$





Strong phase difference in $D^0/\bar{D}^0 \rightarrow K_S^0\pi^+\pi^-$

Help to reduce systematic/model uncertainty of CKM UT angle g/f_3 (GGSZ method **PRD68(2003)054018**)



Binned decay rate:

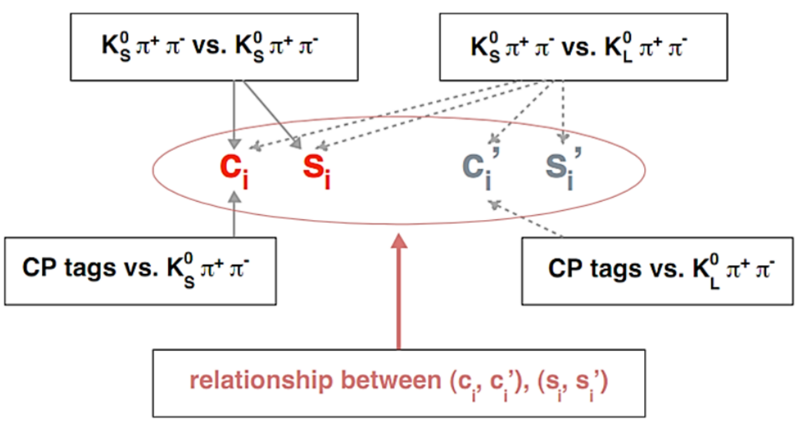
$$\Gamma_i^{\pm} \equiv \int_i d\Gamma(B^{\pm} \to (K_S^0\pi^-\pi^+)_D K^{\pm})$$
$$= T_i + r_B^2 T_{\bar{i}} \pm 2r_B\sqrt{T_i T_{\bar{i}}}[\cos(\delta_B+\gamma)c_i - \sin(\delta_B+\gamma)s_i]$$

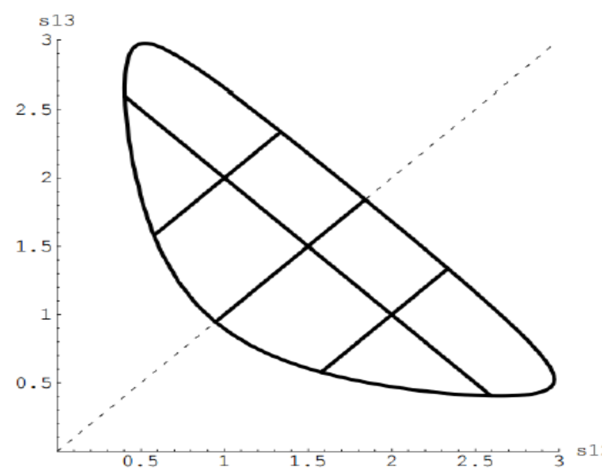
- T_i : Bin yield measured in flavor decays
- r_B : color suppression factor~0.1
- δ_B : strong phase of B decay
- c_i, s_i : weighted average of $\cos(\Delta\delta_D)$ and $\sin(\Delta\delta_D)$ respectively

  where $\Delta\delta_D$ is the difference between phase of D^0 and D^0

Measured at B-Factories

Through $D^0 \rightarrow K_S\pi^+\pi^-$ analysis





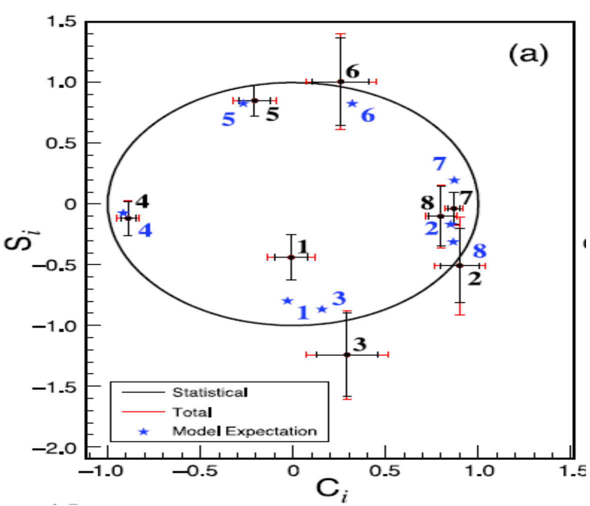
Mirrored binning over x=y makes it so $c_i=c_{-i}$ and $s_i=-s_{-i}$

Strong phase difference in $D^0/D^0 \rightarrow K_S^0h^+h^-$

PRD82(2010)112006

$K_S^0\pi^+\pi^-$

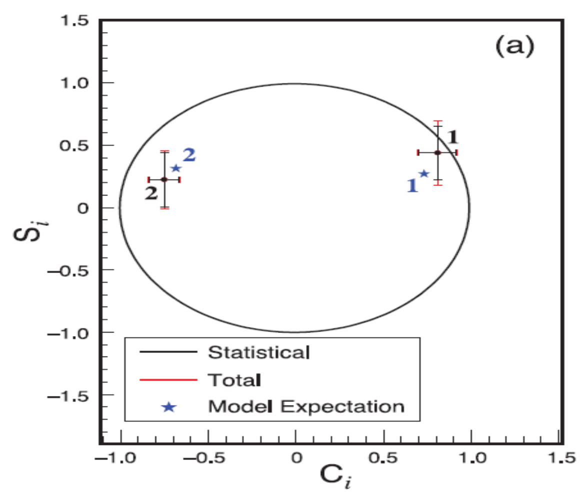
i	Optimal c_i	Optimal s_i
1	$-0.009 \pm 0.088 \pm 0.094$	$-0.438 \pm 0.184 \pm 0.045$
2	$0.900 \pm 0.106 \pm 0.082$	$-0.490 \pm 0.295 \pm 0.261$
3	$0.292 \pm 0.168 \pm 0.139$	$-1.243 \pm 0.341 \pm 0.123$
4	$-0.890 \pm 0.041 \pm 0.044$	$-0.119 \pm 0.141 \pm 0.038$
5	$-0.208 \pm 0.085 \pm 0.080$	$0.853 \pm 0.123 \pm 0.035$
6	$0.258 \pm 0.155 \pm 0.108$	$0.984 \pm 0.357 \pm 0.165$
7	$0.869 \pm 0.034 \pm 0.033$	$-0.041 \pm 0.132 \pm 0.034$
8	$0.798 \pm 0.070 \pm 0.047$	$-0.107 \pm 0.240 \pm 0.080$



Uncertainty in γ/ϕ_3 due to strong phase difference error is expected to be 1.7^0-3.9^0

$K_S^0K^+K^-$

i	c_i	s_i
	$\mathcal{N} = 2$ equal $\Delta\delta_D$ bins	
1	$0.818 \pm 0.107 \pm 0.037$	$0.445 \pm 0.215 \pm 0.143$
2	$-0.746 \pm 0.083 \pm 0.035$	$0.229 \pm 0.220 \pm 0.079$
	$\mathcal{N} = 3$ equal $\Delta\delta_D$ bins	
1	$0.793 \pm 0.063 \pm 0.038$	$0.431 \pm 0.222 \pm 0.142$
2	$-0.566 \pm 0.092 \pm 0.034$	$0.413 \pm 0.234 \pm 0.094$
3	$-0.096 \pm 0.329 \pm 0.131$	$-0.461 \pm 0.432 \pm 0.175$
	$\mathcal{N} = 4$ equal $\Delta\delta_D$ bins	
1	$0.858 \pm 0.059 \pm 0.034$	$0.309 \pm 0.248 \pm 0.180$
2	$0.176 \pm 0.223 \pm 0.091$	$0.992 \pm 0.473 \pm 0.403$
3	$-0.819 \pm 0.095 \pm 0.045$	$0.307 \pm 0.267 \pm 0.201$
4	$0.376 \pm 0.329 \pm 0.157$	$-0.133 \pm 0.659 \pm 0.323$



Uncertainty in γ/ϕ_3 due to strong phase difference error is expected to be 3.2^0-3.9^0

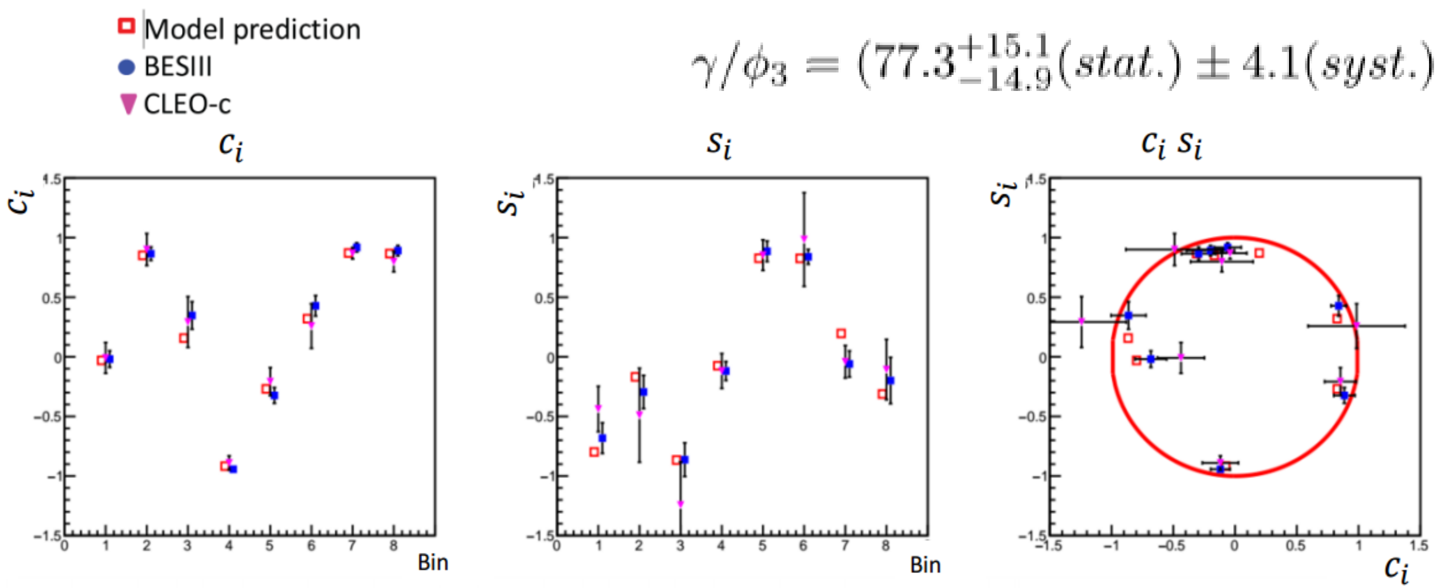
Improved measurement is expected at BESIII

BESIII preliminary

Bins	c_i BES-III	c_i CLEO-c	s_i BES-III	s_i CLEO-c
1	0.066 ± 0.066	-0.009 ± 0.088	-0.843 ± 0.119	-0.438 ± 0.184
2	0.796 ± 0.061	0.900 ± 0.106	-0.357 ± 0.148	-0.490 ± 0.295
3	0.361 ± 0.125	0.292 ± 0.168	-0.962 ± 0.258	-1.243 ± 0.341
4	-0.985 ± 0.017	-0.890 ± 0.041	-0.090 ± 0.093	-0.119 ± 0.141
5	-0.278 ± 0.056	-0.208 ± 0.085	0.778 ± 0.092	0.853 ± 0.123
6	0.267 ± 0.119	0.258 ± 0.155	0.635 ± 0.293	0.984 ± 0.357
7	0.902 ± 0.017	0.869 ± 0.034	-0.018 ± 0.103	-0.041 ± 0.132
8	0.888 ± 0.036	0.798 ± 0.070	-0.301 ± 0.140	-0.107 ± 0.240

BESIII only statistical error **CLEO-c PRD82,112006**

- Consistent with CLEOc, better stat. err
- Reduction of contribution to uncertainty of γ meas. of 40%(80% for 20fb^{-1})
- Improved stat. from B factories could place uncertainty from c_i,s_i contribution @1%



$$\gamma/\phi_3 = (77.3^{+15.1}_{-14.9}(stat.) \pm 4.1(syst.) \pm 4.3(c_i/s_i))^o$$

CLEO-c

$$\pm 2.5(0.9)(c_i/s_i)$$

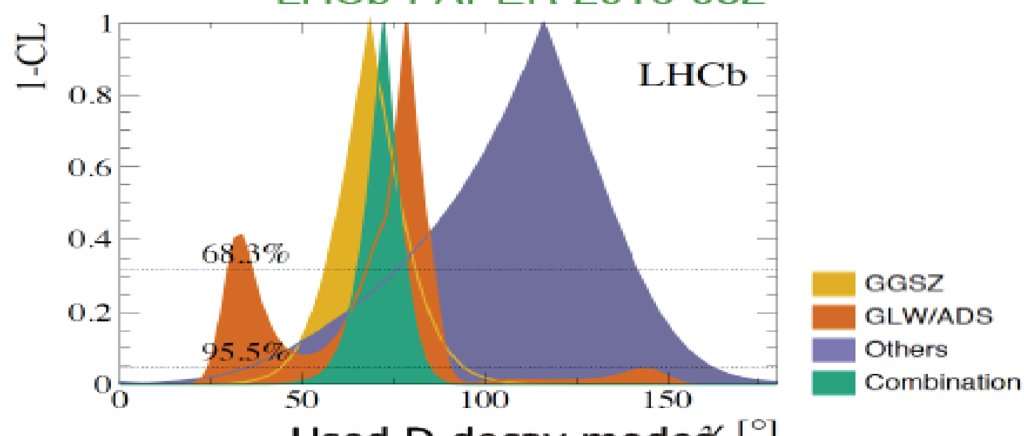
Constraint on γ/ϕ_3 measurement

taken from Liming Zhang's talk at FPCPV2016

γ combination at LHCb

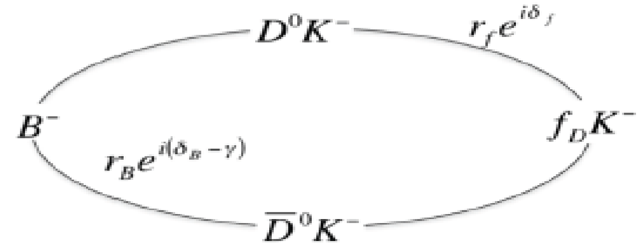
Determine γ from CPV measurements

LHCb-PAPER-2016-032



Used D decay modes

GLW: $D \to K^+K^-$, $\pi^+\pi^-$, $K_S\pi^0$
ADS: $D \to \pi^-K^+$
quasi-ADS $D \to \pi^-K^+\pi^+\pi^-$, $\pi^-K^+\pi^0$
quasi-GLW $D \to \pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^0$, $\pi^+\pi^-\pi^0$
GGSZ $D \to K_S\pi^+\pi^-$, $K_SK^+K^-$
GLS $D \to K_SK^-\pi^+$, $K_S\pi^-K^+$



$\gamma = \left(72.2^{+6.8}_{-7.3}\right)^\circ$ syst. included

BaBar: $\gamma = (70 \pm 18)^\circ$

Belle: $\gamma = (73^{+13}{}_{-15})^\circ$

Prospects

Sample	$\sigma_{stat}(\gamma)^\circ$
Run 1	8
Run 2	4
Upgrade	~ 1
Future upgrade	<0.5

- **Current one syst. ~2° from CLEO strong phase measurements**
- **15-20 fb^{-1} $\psi(3370)$ data from BESIII are desired to avoid syst. limitation for upgrade scenario**

More $\psi(3770)$ data at BESIII will better constrain on γ/ϕ_3

Amplitude analysis of $D^0 \to K^+K^-\pi^+\pi^-$ at CLEO-c

PRD85(2012)122002

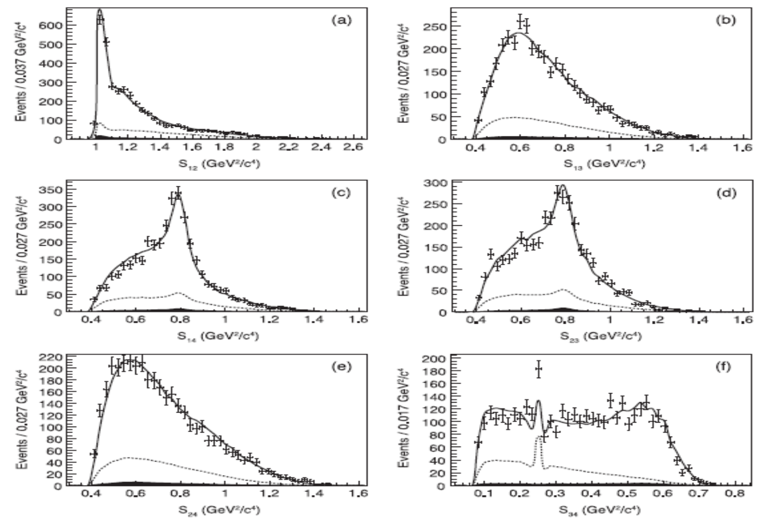
Previous analyses from E691 and FOCUS

Search for CPV in the SCS decay

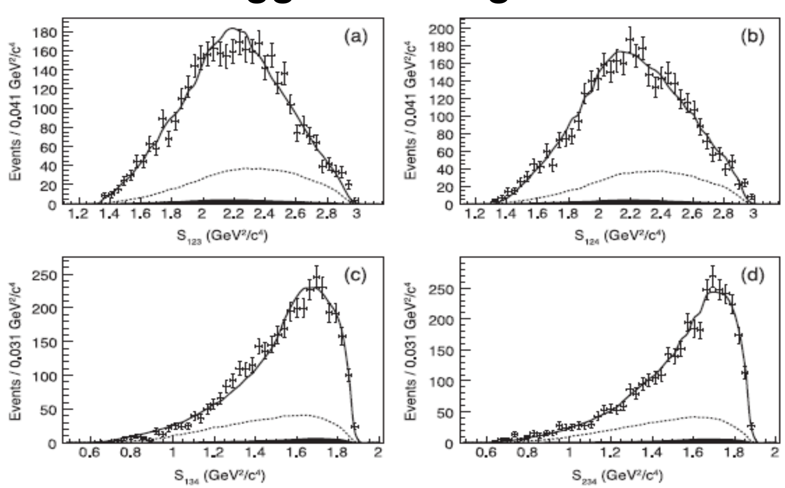
Strong phase to benefit γ/ϕ_3

818 pb^{-1} data@3.774 GeV
600 pb^{-1} data@4.17 GeV
9 fb^{-1} data@~10 GeV with CLEOII.V
15.3 fb^{-1} data@7-11.2 GeV with CLEOIII

Sample	Yield	Purity (%)	Mistag rate (%)
Flavor tags			
CLEO II.V	279	74 ± 3	0.64 ± 0.32
CLEO III	1225	89.2 ± 0.4	0.64 ± 0.05
CLEO-c 3770	1396	84.1 ± 0.6	4.5 ± 0.5
CLEO-c 4170	739	65.7 ± 1.1	7.5 ± 0.7
CP tags			
CP eigenstates	81	71.9 ± 3.1	...
Admixture	150	82.1 ± 1.5	...



2959 flavor-tagged and 181 CP-tagged true signals



Component	Fit fraction (%) CLEO II.V/III	CLEO-c	Difference (σ)
$K_1(1270)^+(K^{*0}\pi^-)K^-$	$4.4 \pm 0.9 \pm 0.8$	$9.8 \pm 1.2 \pm 4.6$	1.1
$K_1(1270)^-(\bar{K}^{*0}\pi^-)K^+$	$3.6 \pm 0.9 \pm 1.1$	$0.2 \pm 0.2 \pm 2.3$	1.2
$K_1(1270)^+(\rho^0 K^+)K^-$	$2.6 \pm 0.8 \pm 0.5$	$8.5 \pm 1.4 \pm 4.2$	1.3
$K_1(1270)^-(\rho^0 K^-)K^+$	$7.9 \pm 1.2 \pm 0.8$	$3.5 \pm 1.1 \pm 3.4$	1.2
$K^*(1410)^+(K^{*0}\pi^+)K^-$	$4.5 \pm 0.9 \pm 0.6$	$4.5 \pm 1.1 \pm 1.2$	0.0
$K^*(1410)^-(\bar{K}^{*0}\pi^-)K^+$	$5.5 \pm 1.0 \pm 0.8$	$4.6 \pm 0.9 \pm 1.1$	0.4
$K^{*0}\bar{K}^{*0}$ *S* wave	$7.5 \pm 1.8 \pm 1.8$	$5.2 \pm 1.0 \pm 2.0$	0.7
$\phi\rho^0$ *S* wave	$39.8 \pm 2.7 \pm 1.4$	$36.9 \pm 3.2 \pm 4.0$	0.5
$\phi\rho^0$ *D* wave	$4.7 \pm 1.0 \pm 1.1$	$1.7 \pm 0.8 \pm 2.3$	1.0
$\phi\{\pi^+\pi^-\}_S$	$8.3 \pm 1.2 \pm 0.5$	$10.9 \pm 1.7 \pm 3.0$	0.7
$\{K^-\pi^+\}_P\{K^+\pi^-\}_S$	$14.7 \pm 1.8 \pm 4.3$	$7.8 \pm 1.4 \pm 5.3$	1.1

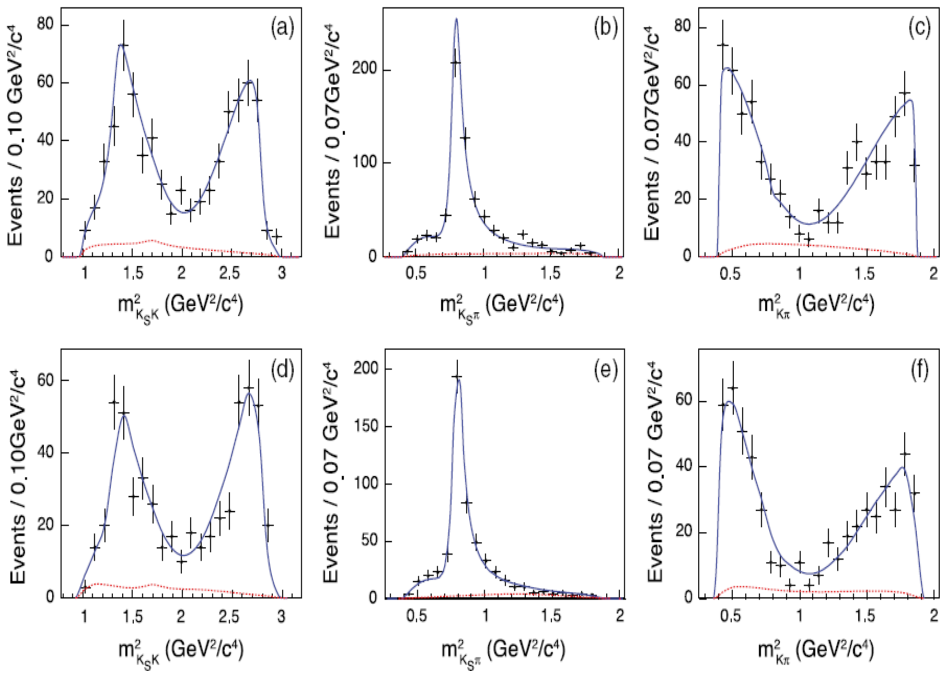
The sensitive to the CP-violating parameter γ/ϕ_3 from 2000 $B^+ \to D^0(K^+K^-\pi^+\pi^-)K^+$ decay is estimated to be $(11.3 \pm 0.3)^0$

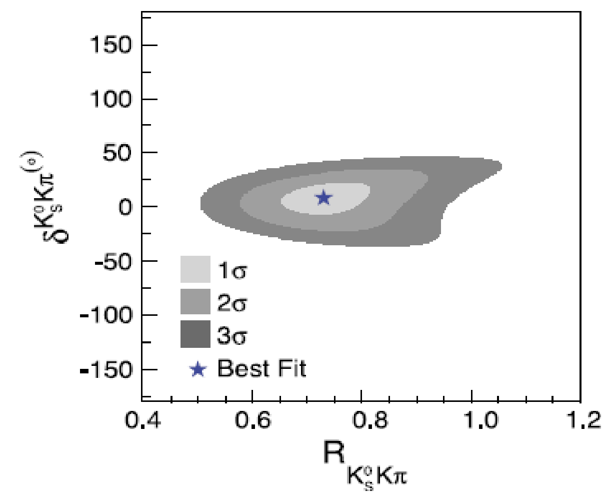
Amplitude analysis of $D^0 \to K_S K^- \pi^+ / K^+ \pi^-$ at CLEO-c

PRD89(2012)092016

818 pb^{-1} data@3.774 GeV
15.3 fb^{-1} data@7-11.2 GeV with CLEOIII

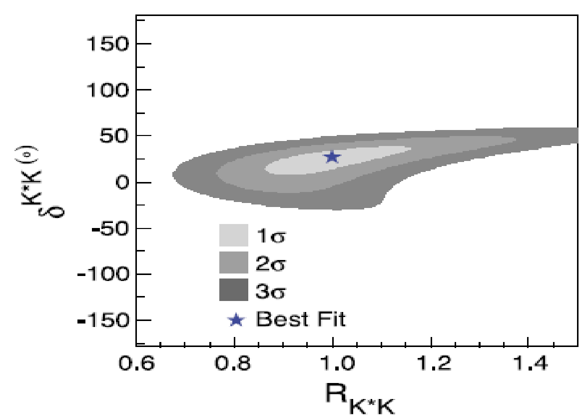
Tag	$D^0 \to K_S^0 K^- \pi^+$ Yield	$D^0 \to K_S^0 K^- \pi^+$ Purity %	$D^0 \to K_S^0 K^+ \pi^-$ Yield	$D^0 \to K_S^0 K^+ \pi^-$ Purity %
$K\pi$	122.0 ± 11.5	93.2 ± 0.5	80.6 ± 9.0	99.5 ± 0.1
$K\pi\pi\pi$	161.8 ± 13.4	89.8 ± 0.5	101.5 ± 10.2	97.6 ± 0.3
$K\pi\pi^0$	221.4 ± 15.6	91.0 ± 0.4	120.8 ± 11.1	97.4 ± 0.2





$R_{K_S K\pi} = 0.73 \pm 0.08$ $\delta_D^{K_S K\pi} = (8.3 \pm 15.2)^0$

$R_{K^*K} = 1.00 \pm 0.16$ $\delta_D^{K^*K} = (26.5 \pm 15.8)^0$



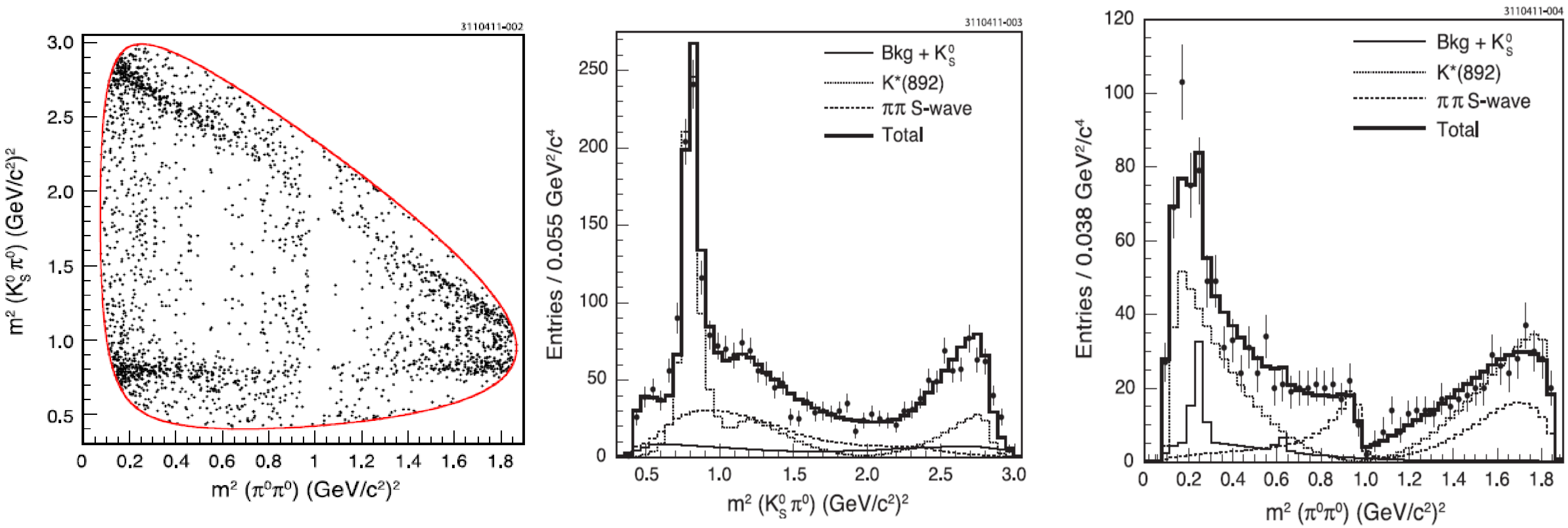
useful inputs for charm-mixing measurement

Amplitude analysis of $D^0 \rightarrow K_S\pi^0\pi^0$ at CLEO-c

PRD84(2011)092005

1259 tagged events with about 7.5% backgrounds

Ideal to study $\pi\pi$ S-wave contribution without ρ amplitude



Component	Fit fraction (%)
$\pi\pi$ S-wave	$28.9 \pm 6.3 \pm 3.1$
$K^*(892)$	65.6 ± 5.3
$K^*_2(1430)$	$0.49 \pm 0.45 \pm 2.5 \pm 0.23$
$K^*(1680)$	$11.2 \pm 2.7 \pm 2.5$
$f_2(1270)$	$2.48 \pm 0.91 \pm 0.78$
K^0_S	$3.46 \pm 0.92 \pm 0.66$

$$\alpha_\tau = 1 + 2r\cos\delta_\tau + R^\tau_{\mathrm{WS}} + y \equiv 1 + R^\tau_{\mathrm{WS}} + \Delta^\tau_{\mathrm{QC}}$$

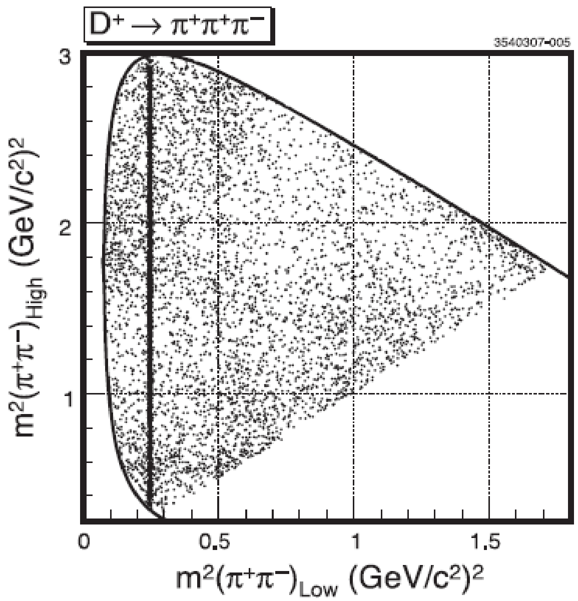
Tag Mode	$\mathcal{B}(D^0 \to K^0_S\pi^0\pi^0)$ (%)
$K^+\pi^0$	$1.030 \pm 0.069 \pm 0.094$
$K^+\pi^-\pi^0$	$1.061 \pm 0.054 \pm 0.110$
$K^+\pi^-\pi^+\pi^-$	$1.099 \pm 0.084 \pm 0.115$
Average	$1.058 \pm 0.038 \pm 0.073$

Dalitz plot analysis of $D^+ \rightarrow \pi^+\pi^-\pi^+$ at CLEO-c

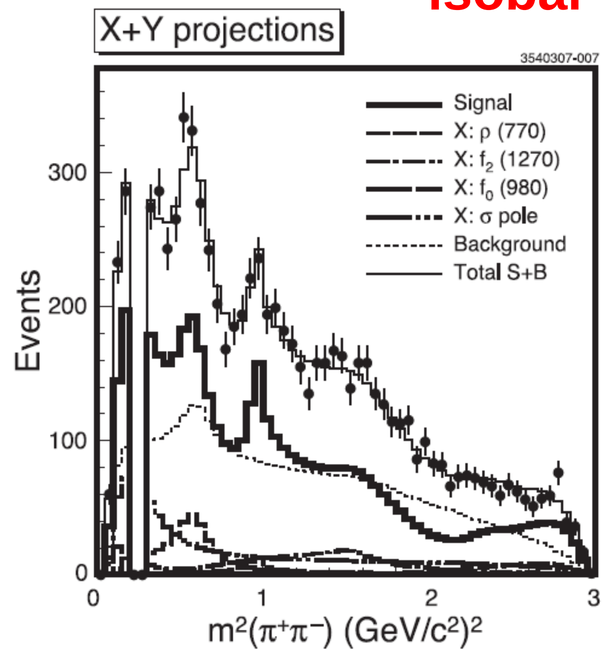
PRD86(2012)112001

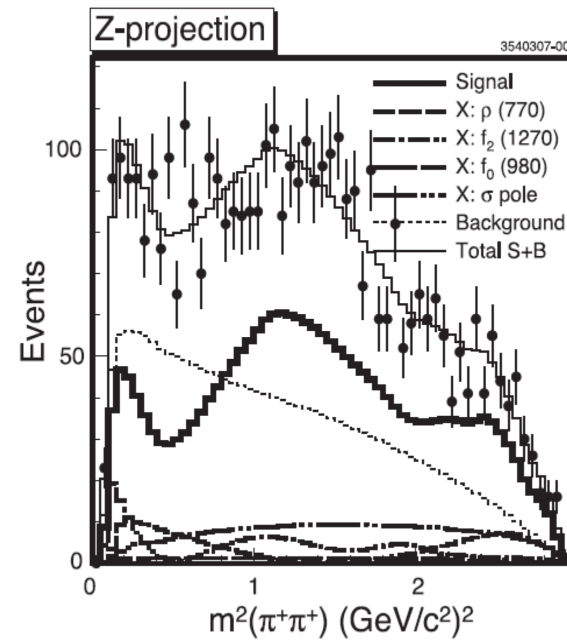
6991 candidates with 2159 backgrounds with single tag method from 281 pb^{-1} data

Dalitz plot



isobar model fit





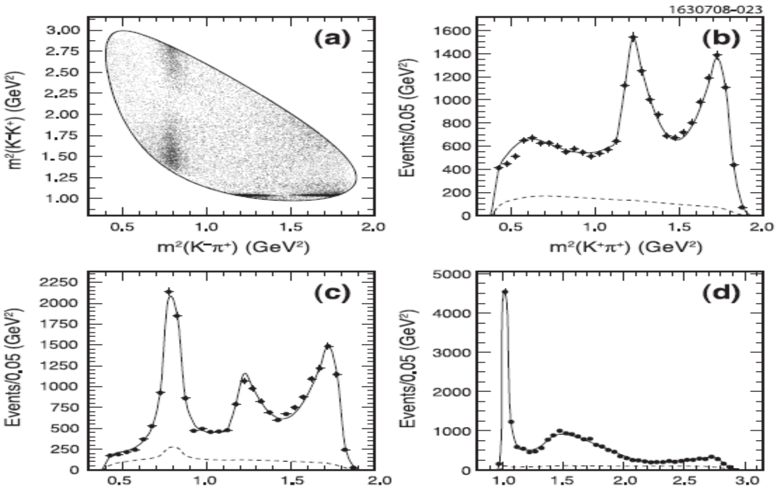
Mode	Amplitude (a.u.)	Phase (°)	Fit fraction (%)
$\rho(770)\pi^+$	1 (fixed)	0 (fixed)	$20.0 \pm 2.3 \pm 0.9$
$f_0(980)\pi^+$	$1.4 \pm 0.2 \pm 0.2$	$12 \pm 10 \pm 5$	$4.1 \pm 0.9 \pm 0.3$
$f_2(1270)\pi^+$	$2.1 \pm 0.2 \pm 0.1$	$-123 \pm 6 \pm 3$	$18.2 \pm 2.6 \pm 0.7$
$f_0(1370)\pi^+$	$1.3 \pm 0.4 \pm 0.2$	$-21 \pm 15 \pm 14$	$2.6 \pm 1.8 \pm 0.6$
$f_0(1500)\pi^+$	$1.1 \pm 0.3 \pm 0.2$	$-44 \pm 13 \pm 16$	$3.4 \pm 1.0 \pm 0.8$
σ pole	$3.7 \pm 0.3 \pm 0.2$	$-3 \pm 4 \pm 2$	$41.8 \pm 1.4 \pm 2.5$

Large S-wave contribution is found at low $\pi\pi$ mass

Dalitz plot analysis of $D^+ \to K^+K^-\pi^+$ at CLEO-c

PRD78(2008)072003

9757 D^+ and 9701 D^- signals



$$A_{CP} = (-0.03 \pm 0.84 \pm 0.29)\%$$

CPV is also searched in different amplitudes

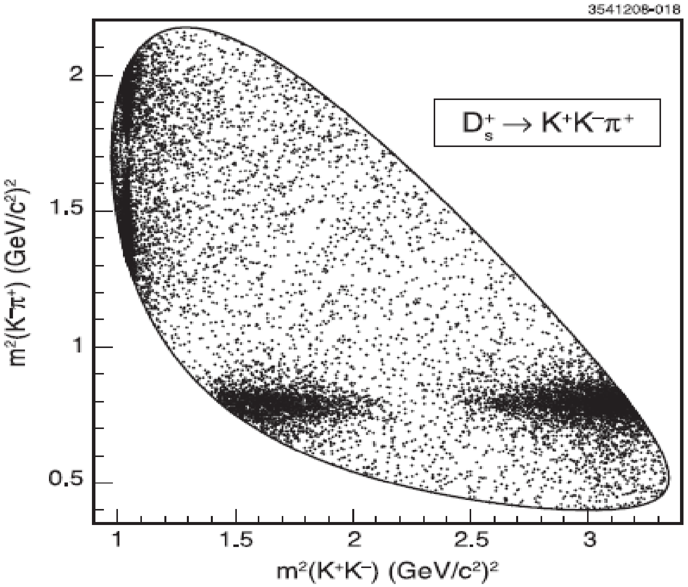
r	b/a (%)	ϕ (°)	FF asymmetry (%)
$\bar{K}^{*0}$	0(fixed)	0(fixed)	$-0.4 \pm 2.0^{+0.2+0.6}_{-0.5-0.3}$
$\bar{K}^*_0(1430)^0$	$4 \pm 3^{+1+2}_{-0-1}$	$-1 \pm 6^{+0+6}_{-3-1}$	$8 \pm 6^{+1+4}_{-1-1}$
ϕ	$-0.7 \pm 1.3^{+0.2+0.3}_{-0.1-0.2}$	$3 \pm 3^{+0+3}_{-1-1}$	$-1.8 \pm 1.6^{+0.0+0.2}_{-0.4-0.1}$
$a_0(1450)^0$	$-10 \pm 7 \pm 2^{+6}_{-3}$	$4 \pm 3^{+1+2}_{-2-1}$	$-19 \pm 12^{+5+6}_{-3-11}$
$\phi(1680)$	$-4 \pm 11^{+5+6}_{-4-4}$	$3 \pm 6 \pm 2^{+3}_{-2}$	$-9 \pm 22^{+10+9}_{-7-12}$
$\bar{K}^*_2(1430)^0$	$23^{+12+1+3}_{-11-7-7}$	5^{+5+1+3}_{-4-3-1}	$43 \pm 19^{+1+5}_{-13-12}$
$\kappa(800)$	$-6 \pm 6^{+3+1}_{-1-5}$	$3 \pm 6^{+4+1}_{-2-4}$	$-12 \pm 11^{+0+14}_{-6-2}$

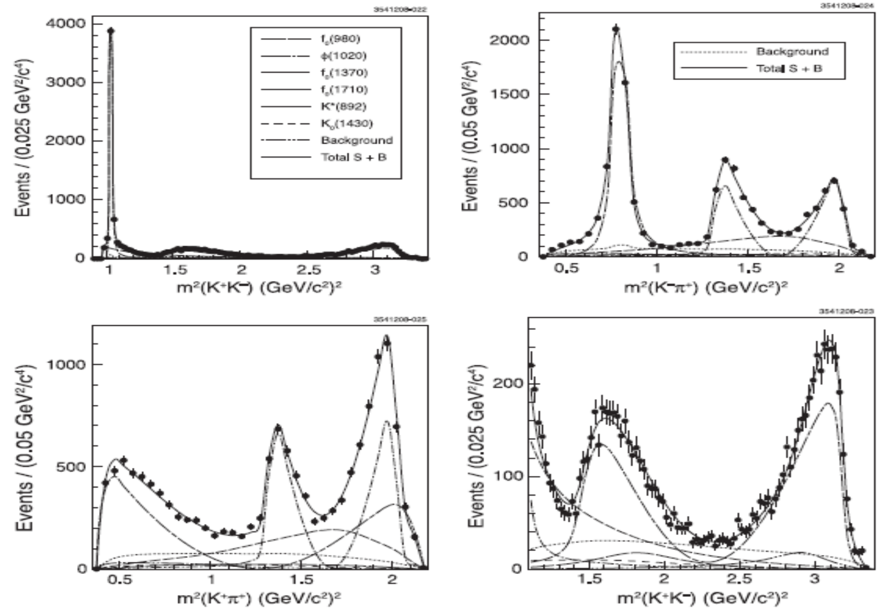
	Magnitude	Phase (°)	Fit fraction (%)
Fit A [χ^2/d.o.f. = 898/708]			
$\bar{K}^{*0}$	1(fixed)	0(fixed)	$25.0 \pm 0.6^{+0.4+0.2}_{-0.3-1.2}$
$\bar{K}^*_0(1430)^0$	$3.7 \pm 0.5^{+0.5+1.0}_{-0.1-1.0}$	$73 \pm 9^{+6+15}_{-6-38}$	$12.4 \pm 3.3^{+3.4+7.3}_{-0.7-5.8}$
ϕ	$1.189 \pm 0.015^{+0.000+0.028}_{-0.011-0.010}$	$-179 \pm 4^{+3+13}_{-1-5}$	$28.1 \pm 0.6^{+0.1+0.2}_{-0.3-0.4}$
$a_0(1450)^0$	$1.72 \pm 0.10^{+0.11+0.81}_{-0.11-0.28}$	$123 \pm 3^{+1+9}_{-1-15}$	$5.9 \pm 0.7^{+0.7+6.7}_{-0.6-1.8}$
$\phi(1680)$	$1.9 \pm 0.2^{+0.0+1.3}_{-0.1-0.7}$	$-52 \pm 8^{+0+10}_{-5-26}$	$0.51 \pm 0.11^{+0.02+0.85}_{-0.04-0.12}$
$\bar{K}^*_2(1430)^0$	$6.4 \pm 0.9^{+0.5+1.9}_{-0.4-3.6}$	$150 \pm 6^{+1+28}_{-0-13}$	$1.2 \pm 0.3^{+0.2+0.8}_{-0.1-0.6}$
NR	$5.1 \pm 0.3^{+0.0+0.6}_{-0.3-0.2}$	$53 \pm 7^{+1+18}_{-5-11}$	$14.7 \pm 1.8^{+0.2+3.9}_{-1.6-1.5}$
Total Fit Fraction = $(88.7 \pm 2.9)\%$			
Fit B [χ^2/d.o.f. = 895/708]			
$\bar{K}^{*0}$	1(fixed)	0(fixed)	$25.7 \pm 0.5^{+0.4+0.1}_{-0.3-1.2}$
$\bar{K}^*_0(1430)^0$	$4.56 \pm 0.13^{+0.10+0.42}_{-0.01-0.39}$	$70 \pm 6^{+1+16}_{-6-23}$	$18.8 \pm 1.2^{+0.6+3.2}_{-0.1-3.4}$
ϕ	$1.166 \pm 0.015^{+0.001+0.025}_{-0.009-0.009}$	$-163 \pm 3^{+1+14}_{-1-5}$	$27.8 \pm 0.4^{+0.1+0.2}_{-0.3-0.4}$
$a_0(1450)^0$	$1.50 \pm 0.10^{+0.09+0.92}_{-0.06-0.33}$	$116 \pm 2^{+1+7}_{-1-14}$	$4.6 \pm 0.6^{+0.5+7.2}_{-0.3-1.8}$
$\phi(1680)$	$1.86 \pm 0.20^{+0.02+0.62}_{-0.08-0.77}$	$-112 \pm 6^{+3+19}_{-4-12}$	$0.51 \pm 0.11^{+0.01+0.37}_{-0.04-0.15}$
$\bar{K}^*_2(1430)^0$	$7.6 \pm 0.8^{+0.5+2.4}_{-0.6-4.8}$	$171 \pm 4^{+0+24}_{-2-11}$	$1.7 \pm 0.4^{+0.3+1.2}_{-0.2-0.7}$
$\kappa(800)$	$2.30 \pm 0.13^{+0.01+0.52}_{-0.11-0.29}$	$-87 \pm 6^{+2+15}_{-3-10}$	$7.0 \pm 0.8^{+0.0+3.5}_{-0.6-1.9}$
Total Fit Fraction = $(86.1 \pm 1.1)\%$			
Fit C [χ^2/d.o.f. = 912/710]			
$\bar{K}^{*0}$	1(fixed)	0(fixed)	$25.3 \pm 0.5^{+0.2+0.2}_{-0.4-0.7}$
LASS	$3.81 \pm 0.06^{+0.05+0.13}_{-0.05-0.46}$	$25.1 \pm 2^{+1+6}_{-2-5}$	$40.6 \pm 0.8^{+0.4+1.6}_{-0.5-9.1}$
ϕ	$1.193 \pm 0.015^{+0.003+0.021}_{-0.010-0.011}$	$-176 \pm 2^{+0+8}_{-2-8}$	$28.6 \pm 0.4^{+0.2+0.2}_{-0.3-0.5}$
$a_0(1450)^0$	$1.73 \pm 0.07^{+0.14+0.68}_{-0.03-0.38}$	$122 \pm 2^{+1+8}_{-1-10}$	$6.0 \pm 0.4^{+0.9+5.5}_{-0.2-2.4}$
$\phi(1680)$	$1.71 \pm 0.16^{+0.02+0.41}_{-0.02-0.77}$	$-72 \pm 8^{+2+10}_{-2-22}$	$0.42 \pm 0.08^{+0.02+0.19}_{-0.01-0.16}$
$\bar{K}^*_2(1430)^0$	$4.9 \pm 0.7^{+0.1+2.2}_{-0.4-2.3}$	$146 \pm 9^{+0+34}_{-7-11}$	$0.7 \pm 0.2^{+0.0+0.7}_{-0.1-0.3}$
Total Fit Fraction = $(101.5 \pm 0.8)\%$			

Dalitz plot analysis of $D_s^+ \rightarrow K^+K^-\pi^+$ at CLEO-c

PRD79(2008)072008

14400 candidates with ~15% background method from 586 pb^{-1} data



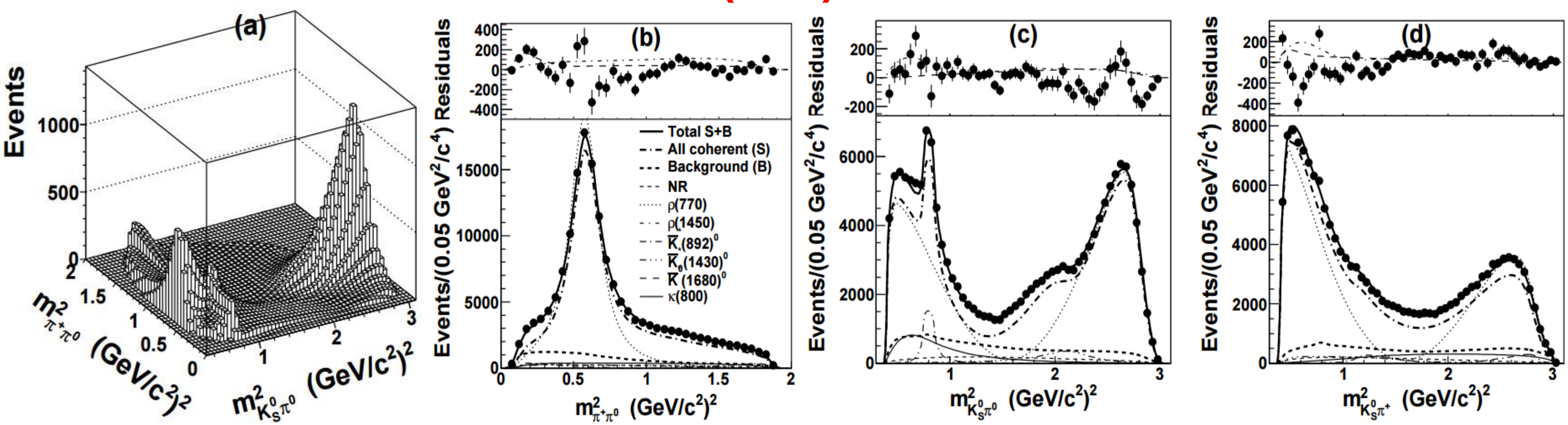


Parameter	E687 model	$f_2(1270)$	$a_2(1320)$	$f_0(1370)$	$f_0(1500)$	$f_2(1525)$	$a_0(1450)$	$\phi(1680)$
$m_{K^*(892)}$	895.8 ± 0.5	-0.4	-0.1	-0.9	-0.5	0.0	-0.8	0.1
$\Gamma_{K^*(892)}$	44.2 ± 1.0	2.3	2.4	1.5	0.6	0.6	1.0	1.2
$a_{K_0^*(1430)}$ (a.u.)	1.76 ± 0.12	0.11	0.08	-0.25	-0.03	-0.16	-0.22	-0.18
$\phi_{K_0^*(1430)}$ (°)	145 ± 8	-32	-28	1.0	-15	1.7	-15	18
$a_{f_0(980)}$ (a.u.)	3.67 ± 0.13	0.29	0.26	1.05	0.52	0.03	1.09	0.20
$\phi_{f_0(980)}$ (°)	156 ± 3	-2	-1.6	1.3	2.3	0.22	3.8	10.5
$a_{\phi(1020)}$ (a.u.)	1.15 ± 0.02	-0.03	-0.04	-0.02	-0.003	-0.02	-0.007	-0.012
$\phi_{\phi(1020)}$ (°)	-15 ± 4	-7	-6.3	7.2	-0.6	1.5	4.3	13.2
$a_{f_0(1710)}$ (a.u.)	1.27 ± 0.07	0.08	0.07	-0.16	0.17	-0.04	0.03	-0.018
$\phi_{f_0(1710)}$ (°)	102 ± 4	7	4.7	-13	-4.1	-3.8	-17	5.3
a_{add} (a.u.)		0.64 ± 0.09	0.45 ± 0.06	1.15 ± 0.09	0.50 ± 0.05	0.50 ± 0.07	1.32 ± 0.10	1.04 ± 0.17
ϕ_{add} (°)		17 ± 9	40 ± 8	53 ± 5	132 ± 7	173 ± 10	103 ± 5	-4 ± 11
χ^2/ν	278/119	237/117	237/117	178/117	229/117	249/117	192/117	256/117

Comparing to E687 model, involving an additional $f_0(1370)$ amplitude gives the best fit quality and involving other amplitude does not

Dalitz plot analysis of $D^+ \to K_S\pi^+\pi^0$ at BESIII

PRD89(2014)052001



Partial branching fractions calculated by combining fit fractions with PDG's $D^+ \to K_S\pi^+\pi^0$ branching ratio

Mode	Partial Branching Fraction (%)
$D^+ \to K_S^0\pi^+\pi^0$ Non Resonant	$0.32\pm0.05\pm0.25^{+0.28}_{-0.25}$
$D^+ \to \rho^+ K_S^0, \rho^+ \to \pi^+\pi^0$	$5.83\pm0.16\pm0.30^{+0.45}_{-0.15}$
$D^+ \to \rho(1450)^+ K_S^0, \rho(1450)^+ \to \pi^+\pi^0$	$0.15\pm0.02\pm0.09^{+0.07}_{-0.11}$
$D^+ \to \overline{K}^*(892)^0\pi^+, \overline{K}^*(892)^0 \to K_S^0\pi^0$	$0.250 \pm 0.012 \pm 0.015^{+0.025}_{-0.024}$
$D^+ \to \overline{K}_0^*(1430)^0\pi^+, \overline{K}_0^*(1430)^0 \to K_S^0\pi^0$	$0.26 \pm 0.04 \pm 0.05 \pm 0.06$
$D^+ \to \overline{K}^*(1680)^0\pi^+, \overline{K}^*(1680)^0 \to K_S^0\pi^0$	$0.09 \pm 0.01 \pm 0.05^{+0.04}_{-0.08}$
$D^+ \to \overline{\kappa}^0\pi^+, \overline{\kappa}^0 \to K_S^0\pi^0$	$0.54 \pm 0.09 \pm 0.28^{+0.36}_{-0.19}$
$NR+\overline{\kappa}^0\pi^+$	$1.30\pm0.12\pm0.12^{+0.12}_{-0.30}$
$K_S^0\pi^0$ S-wave	$1.21\pm0.10\pm0.16^{+0.19}_{-0.27}$

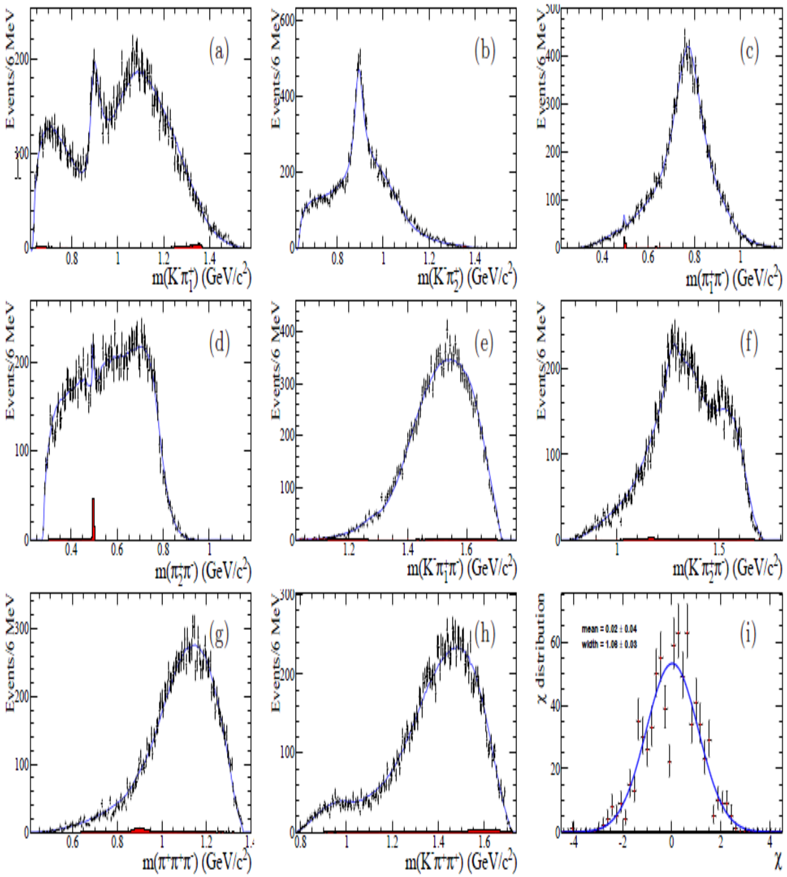
provide rich information about sub-resonance and strong phase

Amplitude analysis of $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ at BESIII

PRD95(2017)072010

Help to determine the absolute BF, strong phase, benefit γ/ϕ_3

Previous analyses only from MarkIII and E691

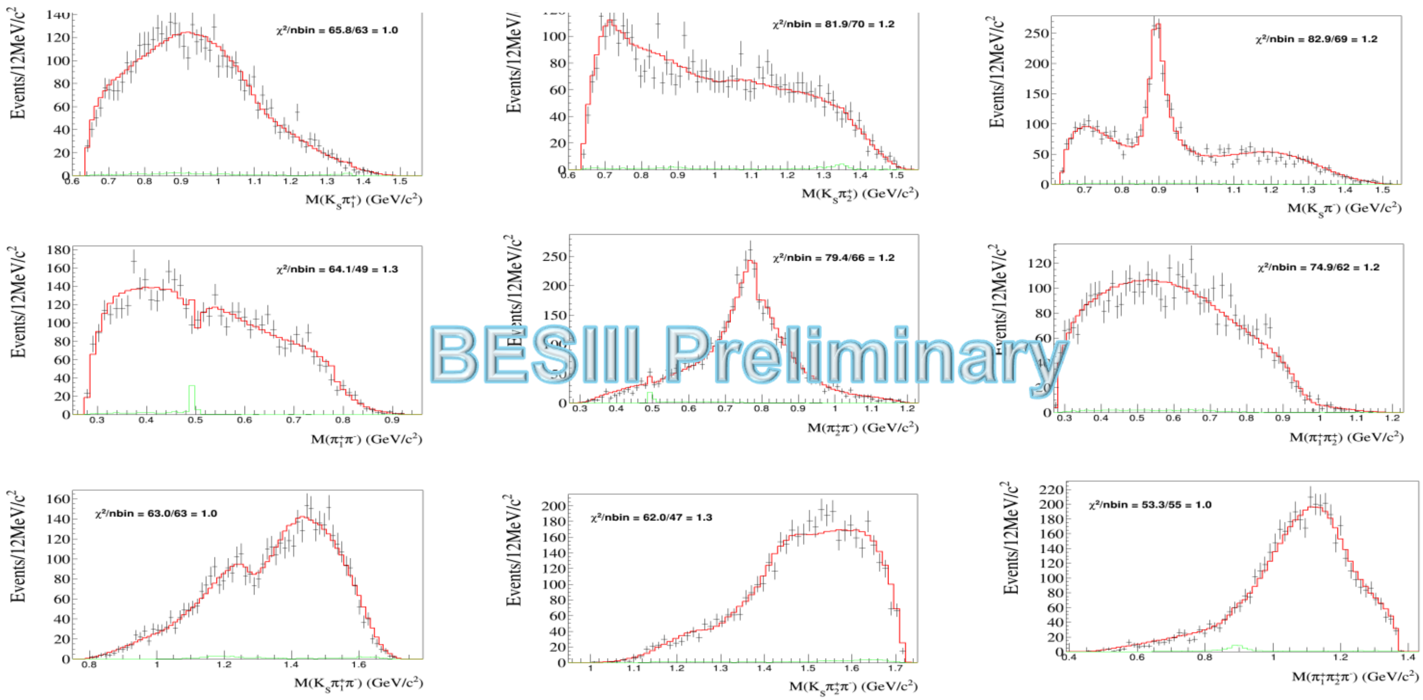


Amplitude	ϕ_i	Fit fraction (%)
$D^0[S] \to \bar{K}^*\rho^0$	$2.35 \pm 0.06 \pm 0.18$	$6.5 \pm 0.5 \pm 0.8$
$D^0[P] \to \bar{K}^*\rho^0$	$-2.25 \pm 0.08 \pm 0.15$	$2.3 \pm 0.2 \pm 0.1$
$D^0[D] \to \bar{K}^*\rho^0$	$2.49 \pm 0.06 \pm 0.11$	$7.9 \pm 0.4 \pm 0.7$
$D^0 \to K^-a_1^+(1260),\ a_1^+(1260)[S] \to \rho^0\pi^+$	0(fixed)	$53.2 \pm 2.8 \pm 4.0$
$D^0 \to K^-a_1^+(1260),\ a_1^+(1260)[D] \to \rho^0\pi^+$	$-2.11 \pm 0.15 \pm 0.21$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270)[S] \to \bar{K}^{*0}\pi^-$	$1.48 \pm 0.21 \pm 0.24$	$0.1 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270)[D] \to \bar{K}^{*0}\pi^-$	$3.00 \pm 0.09 \pm 0.15$	$0.7 \pm 0.2 \pm 0.2$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270) \to K^-\rho^0$	$-2.46 \pm 0.06 \pm 0.21$	$3.4 \pm 0.3 \pm 0.5$
$D^0 \to (\rho^0K^-)_A\pi^+,\ (\rho^0K^-)_A[D] \to K^-\rho^0$	$-0.43 \pm 0.09 \pm 0.12$	$1.1 \pm 0.2 \pm 0.3$
$D^0 \to (K^-\rho^0)_P\pi^+$	$-0.14 \pm 0.11 \pm 0.10$	$7.4 \pm 1.6 \pm 5.7$
$D^0 \to (K^-\pi^+)_S\rho^0$	$-2.45 \pm 0.19 \pm 0.47$	$2.0 \pm 0.7 \pm 1.9$
$D^0 \to (K^-\rho^0)_V\pi^+$	$-1.34 \pm 0.12 \pm 0.09$	$0.4 \pm 0.1 \pm 0.1$
$D^0 \to (\bar{K}^{*0}\pi^-)_P\pi^+$	$-2.09 \pm 0.12 \pm 0.22$	$2.4 \pm 0.5 \pm 0.5$
$D^0 \to \bar{K}^{*0}(\pi^+\pi^-)_S$	$-0.17 \pm 0.11 \pm 0.12$	$2.6 \pm 0.6 \pm 0.6$
$D^0 \to (\bar{K}^{*0}\pi^-)_V\pi^+$	$-2.13 \pm 0.10 \pm 0.11$	$0.8 \pm 0.1 \pm 0.1$
$D^0 \to ((K^-\pi^+)_S\pi^-)_A\pi^+$	$-1.36 \pm 0.08 \pm 0.37$	$5.6 \pm 0.9 \pm 2.7$
$D^0 \to K^-((\pi^+\pi^-)_S\pi^+)_A$	$-2.23 \pm 0.08 \pm 0.22$	$13.1 \pm 1.9 \pm 2.2$
$D^0 \to (K^-\pi^+)_S(\pi^+\pi^-)_S$	$-1.40 \pm 0.04 \pm 0.22$	$16.3 \pm 0.5 \pm 0.6$
$D^0[S] \to (K^-\pi^+)_V(\pi^+\pi^-)_V$	$1.59 \pm 0.13 \pm 0.41$	$5.4 \pm 1.2 \pm 1.9$
$D^0 \to (K^-\pi^+)_S(\pi^+\pi^-)_V$	$-0.16 \pm 0.17 \pm 0.43$	$1.9 \pm 0.6 \pm 1.2$
$D^0 \to (K^-\pi^+)_V(\pi^+\pi^-)_S$	$2.58 \pm 0.08 \pm 0.25$	$2.9 \pm 0.5 \pm 1.7$
$D^0 \to (K^-\pi^+)_T(\pi^+\pi^-)_S$	$-2.92 \pm 0.14 \pm 0.12$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to (K^-\pi^+)_S(\pi^+\pi^-)_T$	$2.45 \pm 0.12 \pm 0.37$	$0.5 \pm 0.1 \pm 0.1$

Component	Branching fraction (%)	PDG value (%)
$D^0 \to \bar{K}^{*0}\rho^0$	$0.99 \pm 0.04 \pm 0.04 \pm 0.03$	1.05 ± 0.23
$D^0 \to K^-a_1^+(1260)(\rho^0\pi^+)$	$4.41 \pm 0.22 \pm 0.30 \pm 0.13$	3.6 ± 0.6
$D^0 \to K_1^-(1270)(\bar{K}^{*0}\pi^-)\pi^+$	$0.07 \pm 0.01 \pm 0.02 \pm 0.00$	0.29 ± 0.03
$D^0 \to K_1^-(1270)(K^-\rho^0)\pi^+$	$0.27 \pm 0.02 \pm 0.04 \pm 0.01$	
$D^0 \to K^-\pi^+\rho^0$	$0.68 \pm 0.09 \pm 0.20 \pm 0.02$	0.51 ± 0.23
$D^0 \to \bar{K}^{*0}\pi^+\pi^-$	$0.57 \pm 0.03 \pm 0.04 \pm 0.02$	0.99 ± 0.23
$D^0 \to K^-\pi^+\pi^+\pi^-$	$1.77 \pm 0.05 \pm 0.04 \pm 0.05$	1.88 ± 0.26

Amplitude analysis of $D^+ \rightarrow K_S \pi^+ \pi^+ \pi^-$ at BESIII

Help to understand D→AP decay and the mixing between $K_1(1270)$ and $K_1(1400)$



Component	BESIII	Mark III	E691
$D^+ \to K_S^0 a_1(1260)^+(\rho^0\pi^+)$	$0.567 \pm 0.020 \pm 0.044$	$0.539 \pm 0.057 \pm 0.070$	$0.830 \pm 0.140 \pm 0.200$
$D^+ \to K_S^0 a_1(1260)^+(f_0(500)\pi^+)$	$0.050 \pm 0.006 \pm 0.007$		
$D^+ \to \bar{K}_1(1400)^0\pi^+$	$0.372 \pm 0.015 \pm 0.016$	$0.277 \pm 0.047 \pm 0.080$	
$D^+ \to \bar{K}_1(1270)^0\pi^+$	$0.036 \pm 0.004 \pm 0.002$		
$D^+ \to \bar{K}(1460)^0\pi^+$	$0.014 \pm 0.004 \pm 0.003$		
$D^+ \to K_S^0\pi^+\rho^0$	$0.044 \pm 0.005 \pm 0.005$		$0.070 \pm 0.040 \pm 0.060$
$D^+ \to K^{*-}\pi^+\pi^+$	$0.139 \pm 0.012 \pm 0.020$		$0.330 \pm 0.060 \pm 0.140$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$ nonresonant	$0.074 \pm 0.005 \pm 0.008$	$0.170 \pm 0.056 \pm 0.100$	$0.100 \pm 0.040 \pm 0.060$

Component	Branching fraction(%)
$D^+ \to K_S^0 a_1(1260)^+, a_1(1260)^+ \to \rho^0\pi^+$	$1.769 \pm 0.062 \pm 0.136 \pm 0.062$
$D^+ \to K_S^0 a_1(1260)^+, a_1(1260)^+ \to f_0(500)\pi^+$	$0.156 \pm 0.019 \pm 0.022 \pm 0.006$
$D^+ \to \bar{K}_1(1400)^0\pi^+, \bar{K}_1(1400)^0 \to K^{*-}\pi^+, K^{*-} \to K_S^0\pi^-$	$1.161 \pm 0.047 \pm 0.051 \pm 0.041$
$D^+ \to \bar{K}_1(1270)^0\pi^+, \bar{K}_1(1270)^0 \to K_S^0\rho^0$	$0.112 \pm 0.012 \pm 0.007 \pm 0.004$
$D^+ \to \bar{K}(1460)^0\pi^+, \bar{K}(1460)^0 \to K_S^0\rho^0$	$0.044 \pm 0.012 \pm 0.011 \pm 0.002$
$D^+ \to K_S^0\pi^+\rho^0$ three-body	$0.137 \pm 0.016 \pm 0.015 \pm 0.005$
$D^+ \to K^{*-}\pi^+\pi^+$ three-body, $K^{*-} \to K_S^0\pi^-$	$0.434 \pm 0.037 \pm 0.062 \pm 0.015$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$ nonresonant	$0.231 \pm 0.016 \pm 0.024 \pm 0.008$

Input $B^{PDG}[D^+ \rightarrow K_S\pi^+\pi^+\pi^-]$

Λ_c^+ decays at BESIII

Studies of Λ_c^+ decays before 2014

- Λ_c^+ was observed in 1979

- Before 2014, all decays of Λ_c^+ are measured relative to $\Lambda_c^+ \to pK^-\pi^+$, which suffer large error of 25%, with high energy data. No absolute measurement using data produced at Λ_c^+ pair threshold

- Sum of BFs of known decays Λ_c^+ is only about 60%

- In 2014, Belle reported improved measurement of $B[\Lambda_c^+ \to pK^-\pi^+]$, with a precision of ~5%

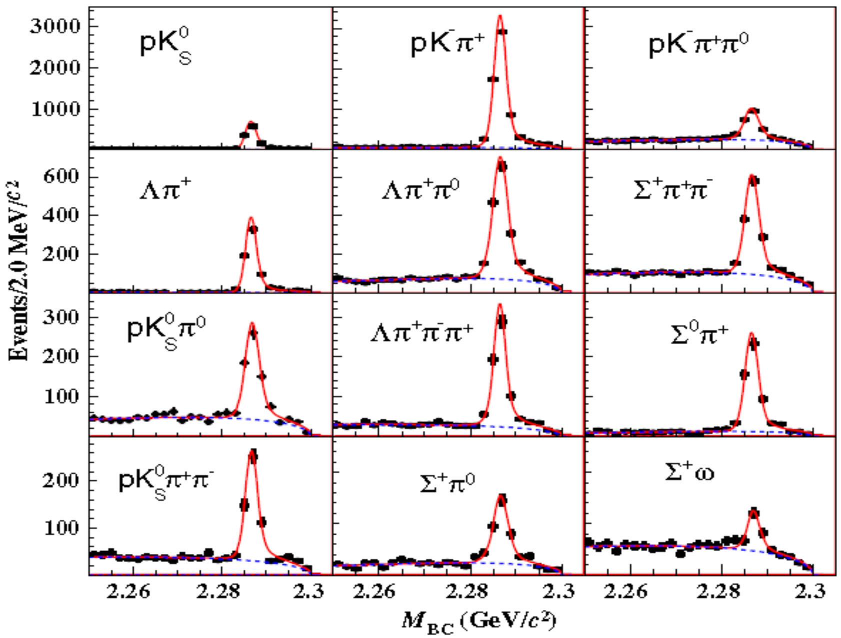
Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Hadronic modes with a p: $S = -1$ final states				
$p\overline{K}^0$		(2.3 ± 0.6) %		873
$pK^-\pi^+$	[a]	(5.0 ± 1.3) %		823
$p\overline{K}^*(892)^0$	[b]	(1.6 ± 0.5) %		685
$\Delta(1232)^{++}K^-$		(8.6 ± 3.0) × 10^{-3}		710
$\Lambda(1520)\pi^+$	[b]	(1.8 ± 0.6) %		627
$pK^-\pi^+$ nonresonant		(2.8 ± 0.8) %		823
$p\overline{K}^0\pi^0$		(3.3 ± 1.0) %		823
$p\overline{K}^0\eta$		(1.2 ± 0.4) %		568
Hadronic modes with a hyperon: $S = -1$ final states				
$\Lambda\pi^+$		(1.07 ± 0.28) %		864
$\Lambda\pi^+\pi^0$		(3.6 ± 1.3) %		844
$\Lambda\rho^+$		< 5 %	CL=95%	636
$\Lambda\pi^+\pi^+\pi^-$		(2.6 ± 0.7) %		807
$\Sigma(1385)^+\pi^+\pi^-$, $\Sigma^{*+} \to \Lambda\pi^+$		(7 ± 4) × 10^{-3}		688
$\Sigma(1385)^-\pi^+\pi^+$, $\Sigma^{*-} \to \Lambda\pi^-$		(5.5 ± 1.7) × 10^{-3}		688
$\Lambda\pi^+\rho^0$		(1.1 ± 0.5) %		524
$\Sigma(1385)^+\rho^0$, $\Sigma^{*+} \to \Lambda\pi^+$		(3.7 ± 3.1) × 10^{-3}		363
$\Lambda\pi^+\pi^+\pi^-$ nonresonant		< 8 × 10^{-3}	CL=90%	807
$\Lambda\pi^+\pi^+\pi^-\pi^0$ total		(1.8 ± 0.8) %		757
$\Lambda\pi^+\eta$	[b]	(1.8 ± 0.6) %		691
$\Sigma(1385)^+\eta$	[b]	(8.5 ± 3.3) × 10^{-3}		570
$\Lambda\pi^+\omega$	[b]	(1.2 ± 0.5) %		517
$\Lambda\pi^+\pi^+\pi^-\pi^0$, no η or ω		< 7 × 10^{-3}	CL=90%	757
$\Lambda K^+\overline{K}^0$		(4.7 ± 1.5) × 10^{-3}	S=1.2	443
$\Xi(1690)^0K^+$, $\Xi^{*0} \to \Lambda\overline{K}^0$		(1.3 ± 0.5) × 10^{-3}		286
$\Sigma^0\pi^+$		(1.05 ± 0.28) %		825
$\Sigma^+\pi^0$		(1.00 ± 0.34) %		827
$\Sigma^+\eta$		(5.5 ± 2.3) × 10^{-3}		713
$\Sigma^+\pi^+\pi^-$		(3.6 ± 1.0) %		804
$\Sigma^+\rho^0$		< 1.4 %	CL=95%	575
$\Sigma^-\pi^+\pi^+$		(1.7 ± 0.5) %		799
$\Sigma^0\pi^+\pi^0$		(1.8 ± 0.8) %		803
$\Sigma^0\pi^+\pi^+\pi^-$		(8.3 ± 3.1) × 10^{-3}		763
$\Sigma^+\pi^+\pi^-\pi^0$		—		767
$\Sigma^+\omega$	[b]	(2.7 ± 1.0) %		569
Semileptonic modes				
$\Lambda\ell^+\nu_\ell$	[c]	(2.0 ± 0.6) %		871
$\Lambda e^+\nu_e$		(2.1 ± 0.6) %		871
$\Lambda\mu^+\nu_\mu$		(2.0 ± 0.7) %		867
Inclusive modes				
e^+ anything		(4.5 ± 1.7) %		–
pe^+ anything		(1.8 ± 0.9) %		–
p anything		(50 ±16) %		–

Systematic studies of Λ_c^+, search for new decays, absolute BF measurements are important to fully explore the Λ_c^+ decay mechanisms

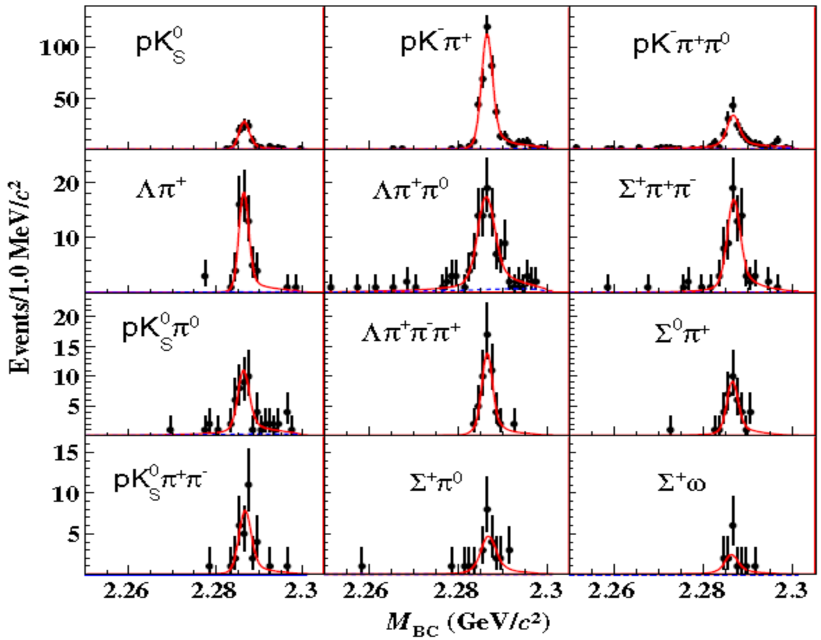
Improved BFs of $\Lambda_c^+ \rightarrow$ hadronic decays

PRL116(2016)052001

ST: ~15000



DT: ~1000



$$N_j^{\mathrm{ST}} = N_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}_j\varepsilon_j$$

$$N_{ij}^{\mathrm{DT}} = N_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}_i\mathcal{B}_j\varepsilon_{ij}$$

$$\mathcal{B}_i = \frac{N_{ij}^{\mathrm{DT}}}{N_j^{\mathrm{ST}}}\frac{\varepsilon_j}{\varepsilon_{ij}}$$

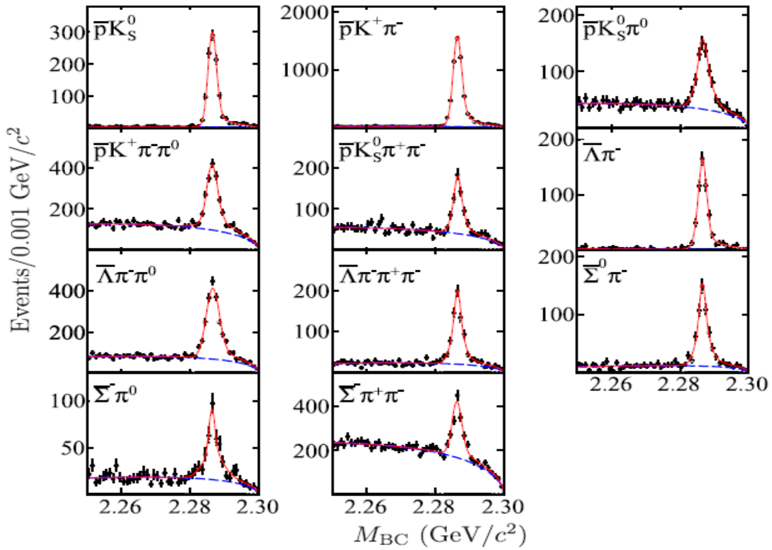
$$N_{i-}^{\mathrm{DT}} = N_{\Lambda_c^+\bar{\Lambda}_c^-}\sum_j \mathcal{B}_i\mathcal{B}_j\varepsilon_{i-}^{\mathrm{DT}}$$

$$\varepsilon_{i-}^{\mathrm{DT}} = [\textstyle\sum_j(\mathcal{B}_j\varepsilon_{ij})/\sum_j\mathcal{B}_j$$

Mode	This work (%)	PDG (%)
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0

Much better precision

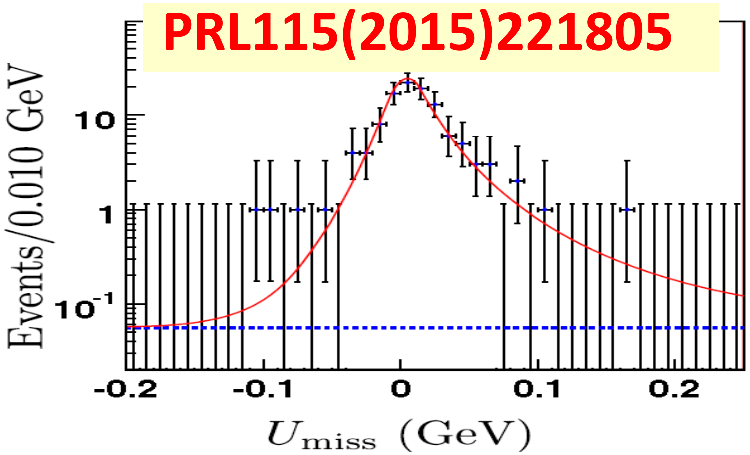
First absolute BFs of $\Lambda_c^+ \rightarrow \Lambda l^+ \nu$

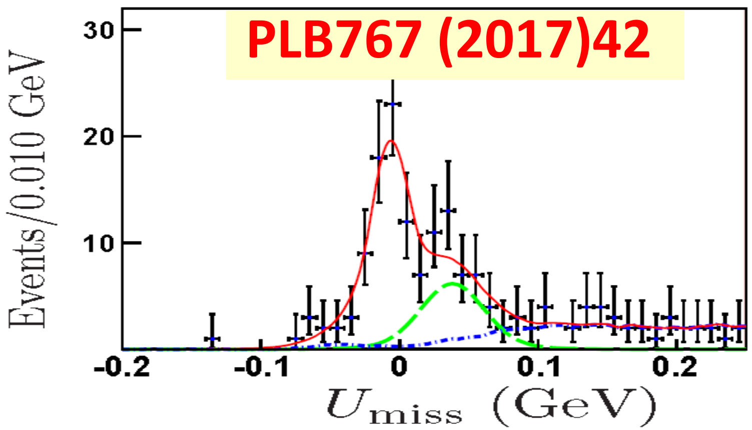


Theory: (1.4-9.2)%

Theoretical Models	predicated branching fraction for $\Lambda_c^+ \to \Lambda e^+ \nu_e$
MBM [1]	1.9%
NRQM [1]	2.6%
SU(4)-symmetry limit [2]	9.2%
RSQM [3]	4.4%
QCM [4]	5.62%
SQM [5]	1.96%
NRQM2 [6]	2.15%
NRQM3 [7]	1.42%
QCD SR1 [8]	$(3.0 \pm 0.9)\%$
QCD SR2 [9]	$(2.6 \pm 0.4)\%$
QCD SR3 [9]	$(5.8 \pm 1.5)\%$
STSR [10]	2.22% for $\Lambda_c^+ \to \Lambda l^+ \nu_l$
STNR [10]	1.58% for $\Lambda_c^+ \to \Lambda l^+ \nu_l$
HOSR [10]	4.72% for $\Lambda_c^+ \to \Lambda l^+ \nu_l$
HONR [10]	4.2% for $\Lambda_c^+ \to \Lambda l^+ \nu_l$
LCSRs [11]	$(3.0 \pm 0.3)\%$ for $\Lambda_c^+ \to \Lambda l^+ \nu_l$ (CZ-type)
PDG 2014 [14]	$(2.1 \pm 0.6)\%$
BESIII	$(3.63 \pm 0.38 \pm 0.20)\%$

3 fb^{-1} data help to explore FF studies





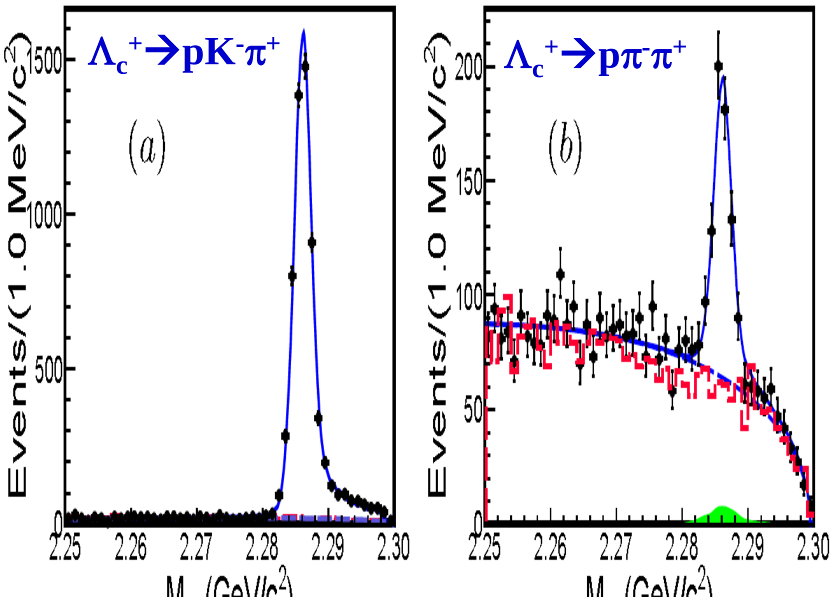
$B[\Lambda_c^+ \rightarrow \Lambda e^+ \nu] = (3.63 \pm 0.38 \pm 0.20)\%$

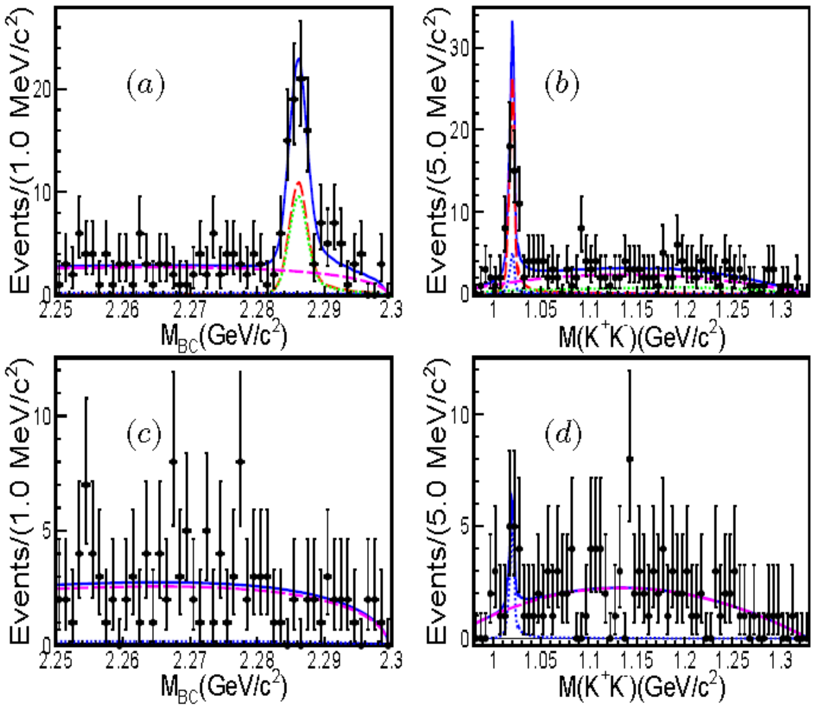
$B[\Lambda_c^+ \rightarrow \Lambda \mu^+ \nu_\mu] = (3.49 \pm 0.46 \pm 0.26)\%$

$\Gamma[\Lambda_c^+ \rightarrow \Lambda \mu^+ \nu_\mu] / \Gamma[\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e] = 0.96 \pm 0.16 \pm 0.04$

Measurements of SCS decays $\Lambda_c^+ \to pK^+K^- / \pi^+\pi^-$

PRL117(2016)232002



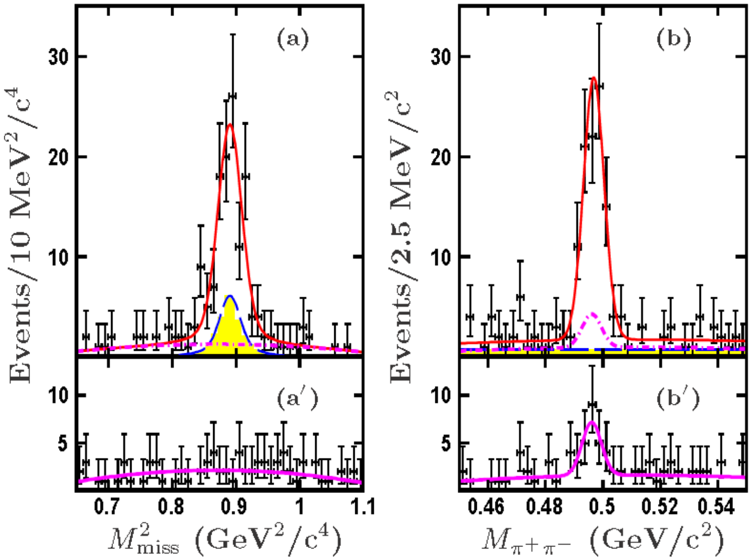


These help to distinguish predictions from different theoretical models and understand contributions from factorizable effects

Decay modes	$\mathcal{B}_{\rm mode}/\mathcal{B}_{\rm ref.}$	$\mathcal{B}_{\rm mode}$	$\mathcal{B}$(PDG)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(6.70 \pm 0.48 \pm 0.25) \times 10^{-2}$	$(3.91 \pm 0.28 \pm 0.15 \pm 0.24) \times 10^{-3}$	$(3.5 \pm 2.0) \times 10^{-3}$
$\Lambda_c^+ \to p\phi$	$(1.81 \pm 0.33 \pm 0.13) \times 10^{-2}$	$(1.06 \pm 0.19 \pm 0.08 \pm 0.06) \times 10^{-3}$	$(8.2 \pm 2.7) \times 10^{-4}$
$\Lambda_c^+ \to pK^+K^-$ (non-ϕ)	$(9.36 \pm 2.22 \pm 0.71) \times 10^{-3}$	$(5.47 \pm 1.30 \pm 0.41 \pm 0.33) \times 10^{-4}$	$(3.5 \pm 1.7) \times 10^{-4}$

Observation of $\Lambda_c^+ \to nK_S\pi^+$

PRL118(2017)112001



$B[\Lambda_c^+ \to nK_S\pi^+]=(1.82\pm0.23\pm0.11)\%$

$\Gamma[\Lambda_c^+ \to n\bar{K}^0\pi^+]/\Gamma[\Lambda_c^+ \to pK^-\pi^+]=0.62\pm0.09$

$\Gamma[\Lambda_c^+ \to n\bar{K}^0\pi^+]/\Gamma[\Lambda_c^+ \to p\bar{K}^0\pi^+]=0.97\pm0.16$

First measurement of BF of Λ_c^+ decay containing neutron

$$\cos\delta = -0.24 \pm 0.08$$

$$|I^{(1)}|/|I^{(0)}| \quad 1.14 \pm 0.11$$

Help to understand SU(3) and isospin symmetry and determine strong phase

Cai-Dian Lv et al, PRD93(2016)056008

$$\cos\delta = \frac{\mathcal{B}(n\bar{K}^0\pi^+) - \mathcal{B}(pK^-\pi^+)}{2\sqrt{\mathcal{B}(p\bar{K}^0\pi^0)(\mathcal{B}(pK^-\pi^+) + \mathcal{B}(n\bar{K}^0\pi^+) - \mathcal{B}(p\bar{K}^0\pi^0))}}$$

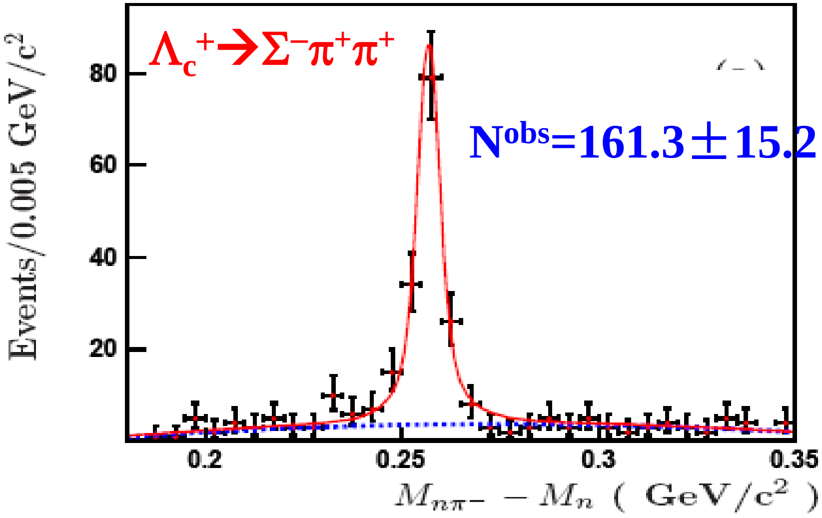
$$R_p = \frac{\mathcal{B}(\Lambda_c \to p\bar{K}^0\pi^0)}{\mathcal{B}(\Lambda_c \to pK^-\pi^+)}, \qquad R_n = \frac{\mathcal{B}(\Lambda_c \to n\bar{K}^0\pi^+)}{\mathcal{B}(\Lambda_c \to pK^-\pi^+)}$$

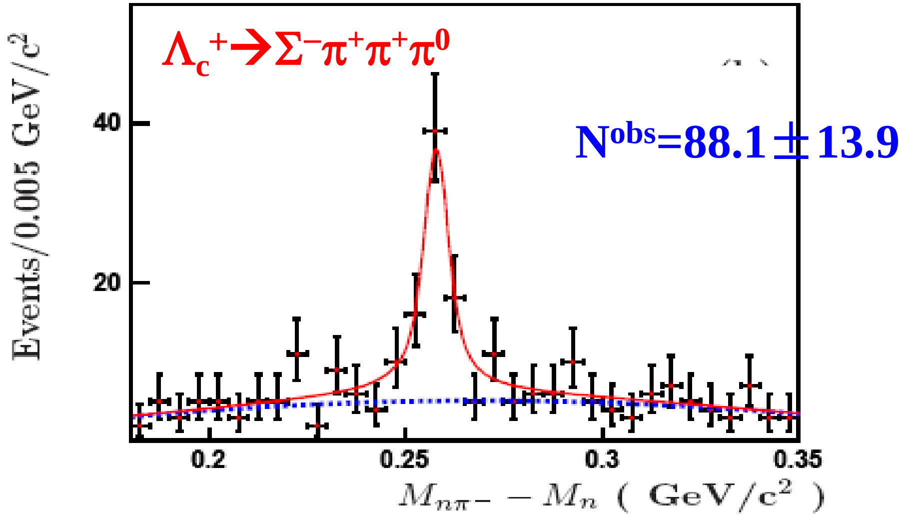
involving a neutron. Under the isospin symmetry, its amplitude is related to those of the most favored proton modes $\Lambda_c^+ \to pK^-\pi^+$ and $\Lambda_c^+ \to p\bar{K}^0\pi^0$ as $\mathcal{A}(n\bar{K}^0\pi^+) + \mathcal{A}(pK^-\pi^+) + \sqrt{2}\mathcal{A}(p\bar{K}^0\pi^0) = 0$. Hence, precise measure-

[2,3]. In the three-body Λ_c^+ decay to $N\bar{K}\pi$, the total decay amplitudes can be decomposed into two isospin amplitudes of the $N\bar{K}$ system as isosinglet ($I^{(0)}$) and isospin-one ($I^{(1)}$). In the factorization limit, the color-allowed tree diagram, in which the π^+ is emitted and the $N\bar{K}$ is an isosinglet, dominates $I^{(0)}$, and $I^{(1)}$ is expected to be small compared to $I^{(0)}$ as it can only proceed through the color-suppressed tree diagrams. Though the factorization scheme is spoiled in

Observation of $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$

PLB772(2017)388





Preliminary results :

$B[\Lambda_c^+ \to \Sigma^-\pi^+\pi^+] = (1.81\pm0.17\pm0.09)\%$

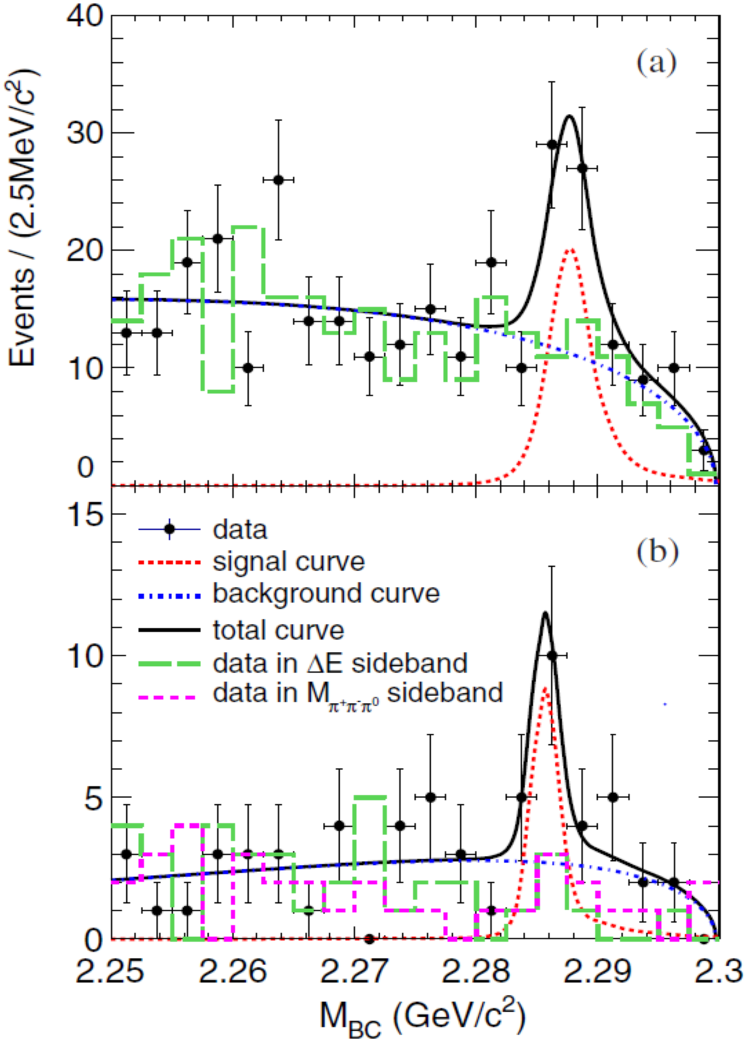
$B[\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0] = (2.11\pm0.33\pm0.14)\%$ **[First observation]**

The previous one is consistent with and more precise than the PDG value of $[\Lambda_c^+ \to \Sigma^-\pi^+\pi^+] = (2.3\pm0.4)\%$.

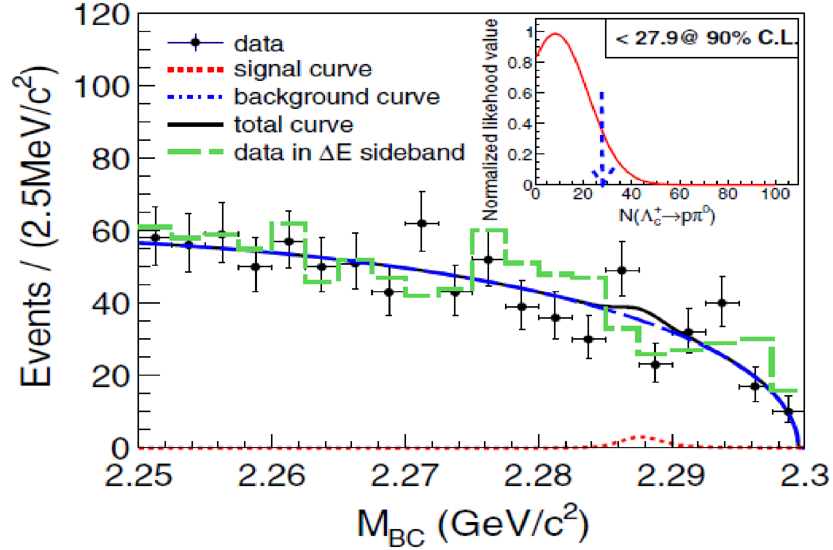
Evidence of $\Lambda_c^+ \to p\eta$ and search of $\Lambda_c^+ \to p\pi^0$

PRD95(2017)111102(RC)

4.2σ



$B[\Lambda_c^+ \to p\eta] = (1.24 \pm 0.28 \pm 0.10) \times 10^{-3}$

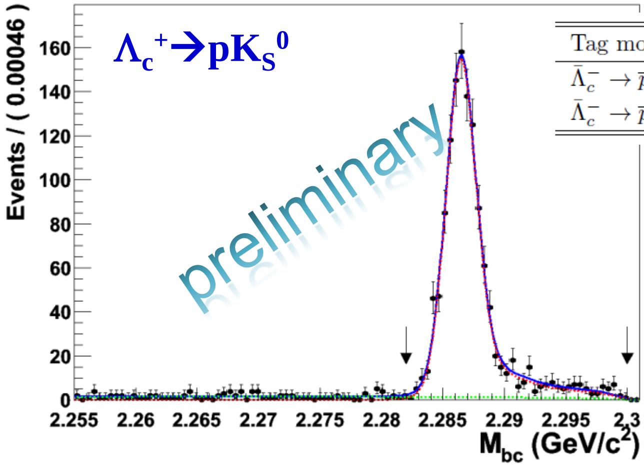


$B[\Lambda_c^+ \to p\pi^0] < 2.7 \times 10^{-4}$ 90%CL

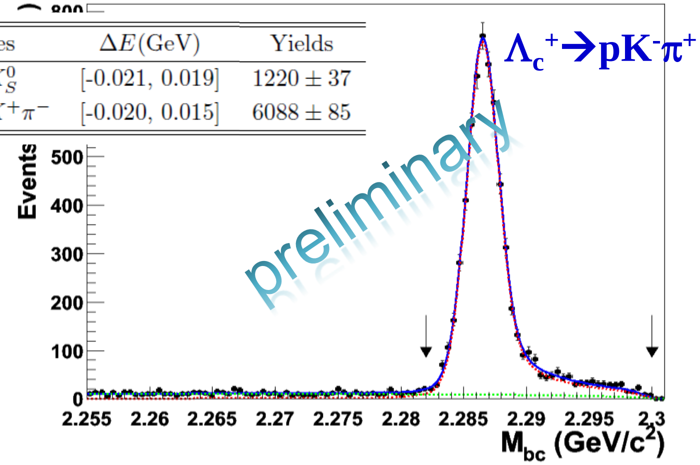
	$\Lambda_c^+ \to p\eta$	$\Lambda_c^+ \to p\pi^0$	$\frac{\mathcal{B}_{\Lambda_c^+ \to p\pi^0}}{\mathcal{B}_{\Lambda_c^+ \to p\eta}}$
BESIII	1.24 ± 0.29	<0.27	<0.24
Sharma *et al.* [3]	$0.2^a(1.7^b)$	0.2	$1.0^a(0.1^b)$
Uppal *et al.* [4]	0.3	0.1–0.2	0.3–0.7
S. L. Chen *et al.* [12]	...	$0.11–0.36^c$	...
Cai-Dian Lü *et al.* [13]	...	0.45	...

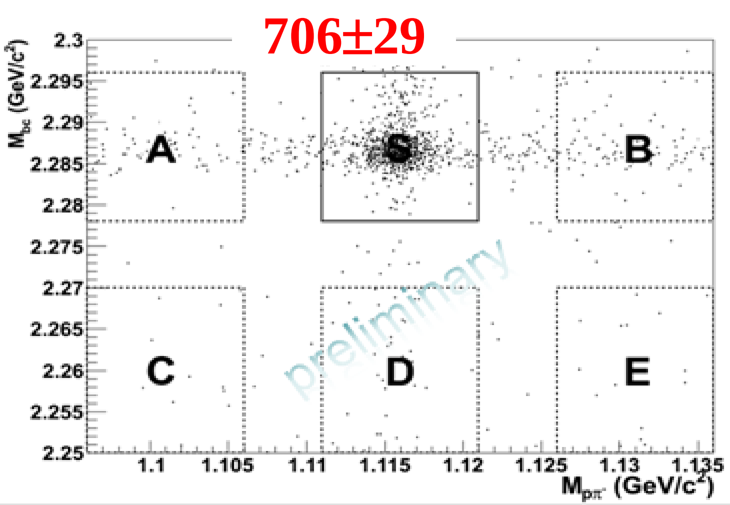
[a]Assumed to have a positive sign for the p-wave amplitude of $\Lambda_c^+ \to \Xi^0 K^+$.
[b]Assumed to have a negative sign for the p-wave amplitude of $\Lambda_c^+ \to \Xi^0 K^+$.
[c]Calculated relying on different values of parameters b and α.

Inclusive decay $\Lambda_c^+ \rightarrow \Lambda X$



Tag modes	ΔE(GeV)	Yields
$\bar{\Lambda}_c^- \to \bar{p}K_S^0$	[-0.021, 0.019]	1220 ± 37
$\bar{\Lambda}_c^- \to \bar{p}K^+\pi^-$	[-0.020, 0.015]	6088 ± 85





$$\mathcal{A}_{\rm CP} = \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) + \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}.$$

Help to explore the source of missing decays and search for new decay. Better input for charm baryon and B physics

$$N_{sig} = N_S - (N_A + N_B)/2 - r \cdot N_D + r \cdot (N_C + N_E)/2$$

$\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (36.98 \pm 2.18)\%$ **stat. only**

Agrees with PDG2015 value (35±11)%,

Decay mode	Branching fraction(%)	$\mathcal{A}_{\rm CP}$
$\Lambda_c^+ \to \Lambda + X$	38.02 ± 3.24	0.02 ± 0.06
$\bar{\Lambda}_c^- \to \bar{\Lambda} + X$	36.70 ± 3.04	

Summary

- In recent 10 years, rapid progress in charm hadron studies has been made with threshold data at CLEO-c and BESIII

- Studies of (semi-)leptonic D decays lead to improved decay constant f_{D+} and form factor $f_+^{D\to K(\pi)}(q^2)$, which are important to test and calibrate LQCD calculations, CKM matrix element $|V_{cs(d)}|$, which are important to test the CKM matrix unitarity

- Studies of hadronic structure and quantum correction in $\psi(3770)\to D^0\bar{D}^0$ have been performed in wide range

- Significantly improved measurements of Λ_c^+ decays with threshold data at 4.6 GeV have been made at BESIII

- Some preliminary results on D_s^+ decays with 3.19 fb^{-1} data@ 4.178 GeV at BESIII are coming

- More results with improved precision (with more data) are expected

Thank you!

56

Form factors in $D_s^+ \rightarrow K^{*0} e^+ \nu_e$

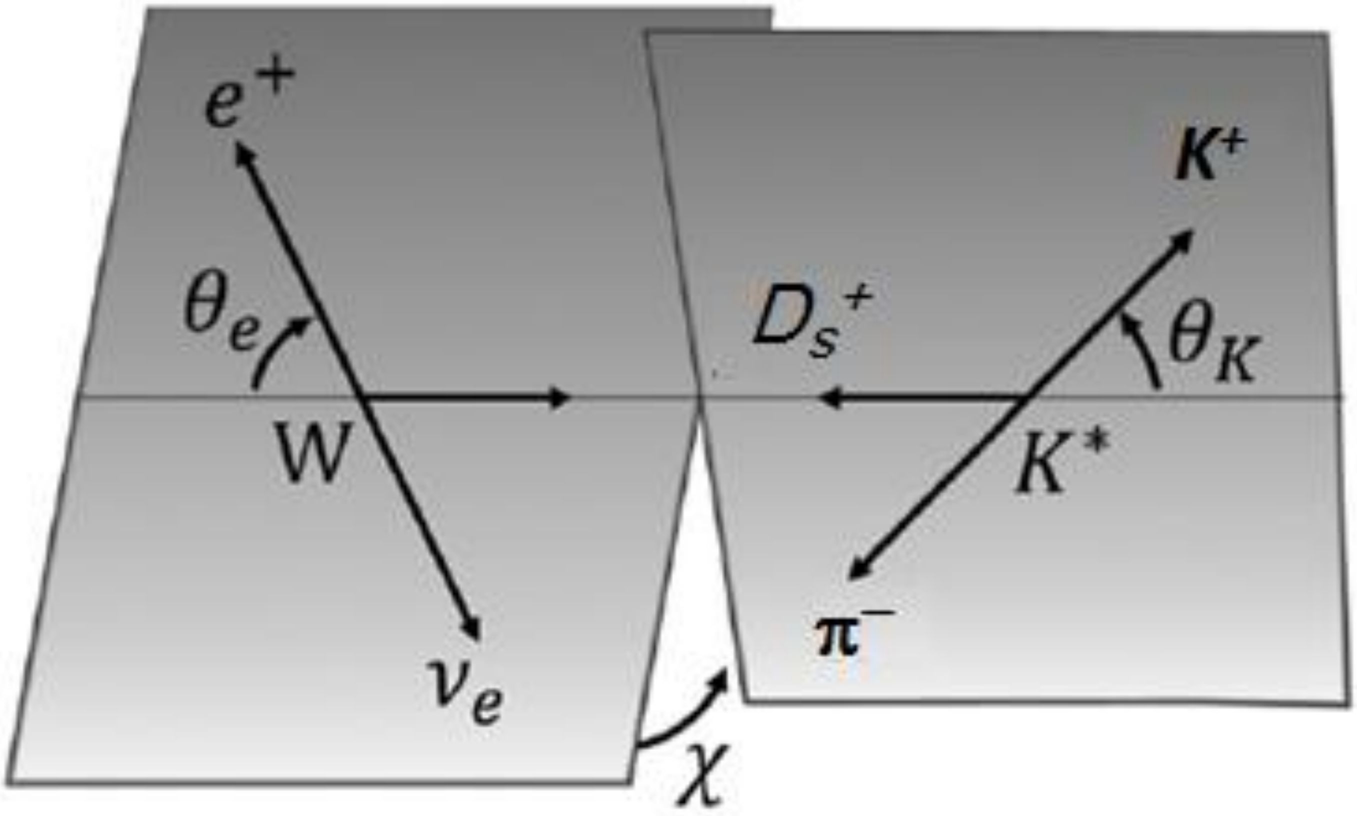
The differential decay rate for $D_s^+ \to K^{*0} e^+ \nu_e$ can be expressed in terms of three helicity amplitudes ($H_+(q^2)$, $H_-(q^2)$ and $H_0(q^2)$)

$$
\begin{aligned}
\frac{d^5\Gamma}{dm_{K\pi} dq^2 dcos\theta_K dcos\theta_e d\chi} &= \frac{3}{8(4\pi)^4} G_F^2 |V_{cd}|^2 \frac{p_{K\pi} q^2}{M_{D_s}^2} \mathcal{B}(K^{*0} \to K^+\pi^-) |\mathcal{BW}(m_{K\pi})|^2 \\
&\times \quad [(1+cos\theta_e)^2 sin^2\theta_K |H_+(q^2, m_{K\pi})|^2 \\
&+ \quad (1-cos\theta_e)^2 sin^2\theta_K |H_-(q^2, m_{K\pi})|^2 \\
&+ \quad 4sin^2\theta_e cos^2\theta_K |H_0(q^2, m_{K\pi})|^2 \\
&+ \quad 4sin\theta_e (1+cos\theta_e) sin\theta_K cos\theta_K cos\chi H_+(q^2, m_{K\pi}) H_0(q^2, m_{K\pi}) \\
&- \quad 4sin\theta_e (1-cos\theta_e) sin\theta_K cos\theta_K cos\chi H_-(q^2, m_{K\pi}) H_0(q^2, m_{K\pi}) \\
&- \quad 2sin^2\theta_e sin^2\theta_K cos2\chi H_+(q^2, m_{K\pi}) H_-(q^2, m_{K\pi})].
\end{aligned}
$$

The helicity amplitudes of $H_+(q^2)$, $H_-(q^2)$ and $H_0(q^2)$ take the form of
$H_\pm(q^2) = (M_{D_s} + m_{K\pi}) A_1(q^2) \mp \frac{2M_{D_s} P_{K\pi}}{M_{D_s}+M_{K\pi}} V(q^2)$ and

$H_0(q^2) = \frac{1}{2m_{K\pi} q}[(M_{D_s}^2 - m_{K\pi}^2 - q^2)(M_{D_s} + m_{K\pi}) A_1(q^2) - \frac{4M_{D_s}^2 p_{K\pi}^2}{M_{D_s}+M_{K\pi}} A_2(q^2)]$,
$A_i(q^2) = \frac{A_i(0)}{1-q^2/M_A^2}$ and $V(q^2) = \frac{V(0)}{1-q^2/M_V^2}$, $r_V = \frac{V(0)}{A_1(0)}$ and $r_2 = \frac{A_2(0)}{A_1(0)}$.
The Breit-Wigner function of K^{*0} line shape takes the form as
$\mathcal{BW}(M_{K\pi}) = \frac{\sqrt{m_0 \Gamma_0 (p/p_0)}}{m_0^2 - m_{K\pi}^2 - i m_0 \Gamma(m_{K\pi})} \frac{B(p)}{B(p_0)}$
where $B(p) = \frac{1}{\sqrt{1+R^2p^2}}$ with $R = 3$ GeV^{-1} and $\Gamma(m_{K\pi}) = \Gamma_0 (\frac{p}{p_0})^3 \frac{m_0}{m_{K\pi}} (\frac{B(p)}{B(p_0)})^2$.

Definition of the angular variables[1,2]



References:

[1] BESIII Collaboration, M. Ablikim, *et al*., Phys. Rev. D 94, 032001 (2016).

[1] CLEO Collaboration, S. Dobbs, *et al*., Phys. Rev. Lett. 110, 131802 (2013).