Charm hadronic and semi-leptonic Decays

-- "Charm" ≡ "$D^{\pm,0}$, D_s, Λ_c"

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XXXVI Physics In Collison

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Interesting topics from Charm decays

- CP violation & mixing in Charm sector
- Rare/Forbidden decays: searching for new physics (Not suppose to see them in SM)

Covered by Dr. Brodizicka Jolanta

- Test CKM Unitarity / Calibrate Lattice QCD (complementary to B physics)
  - (Semi-)Leptonic and Hadronic decays
- Studying the impact of non-pQCD dynamics
  - Branching fractions measurements
- Light Hadron Spectroscopy & FSI
  - Weak Multi-body decays (Hadronic & Semileptonic) : Amplitude analysis ⇒ precision measurements of low-energy QCD
- …

QCD related

Outline

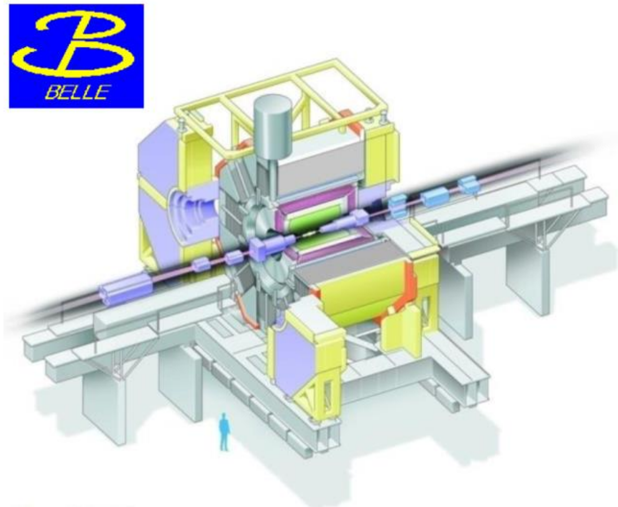
- Introduction
- Selected recent results in
  - (Semi-)Leptonic decays
  - Hadronic decays
    } Charmed Mesons
  - Charmed baryon Λ_c decays
    - BESIII results can be found in Xiaozhong Huang's talk in Sept. 17th.
- Summary

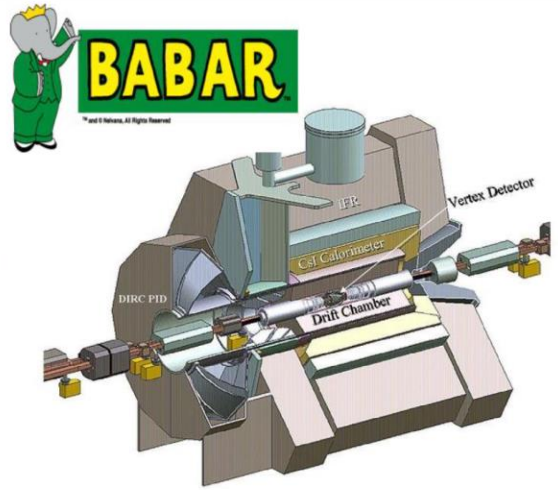
I will briefly go through some high lights of the recent experimental results today.

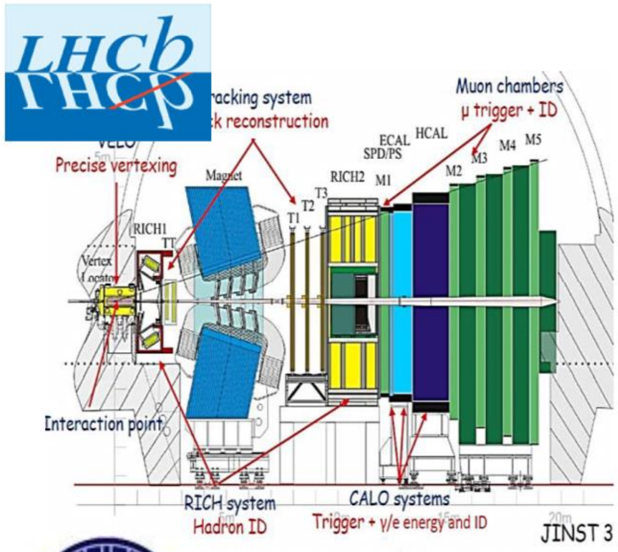
Charm facilities

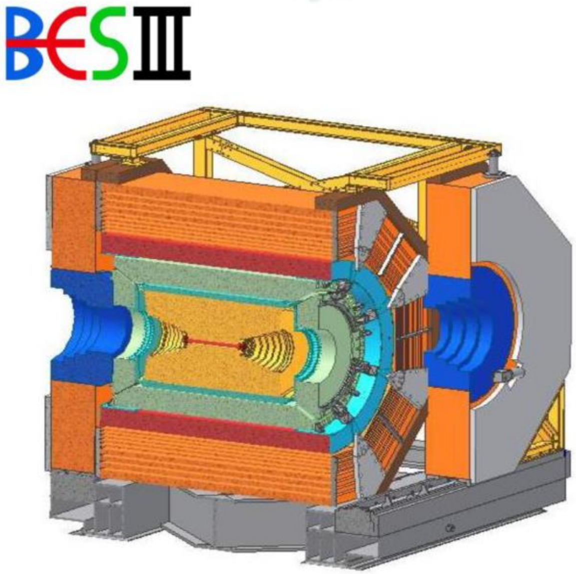
- Hadron colliders (Huge cross-section, energy boost)
  - Tevetron (CDF, D0)
  - LHC (LHCb, CMS, ATLAS)
- e^+e^- Colliders (more kinematic constrains, clean environment, ~100% trigger efficiency)
  - B-factories (Belle, BaBar)
    - Prompt D* decays & B decays
    - High Luminosity ⇒ double tag technique possible
  - Threshold production (CLEOc, BESIII)
    - Can not compete in statistics with Hadron colliders & B-factories!
    - Only Charm hadron pairs, no extra CM Energy for pions
    - Quantum Correlations (QC) and CP-tagging are unique
    - Systematic uncertainties cancellations while applying double tag technique

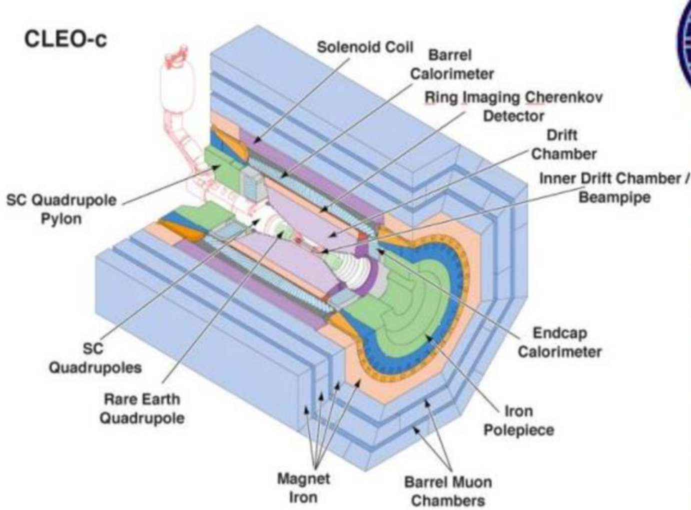
Experiments ⇒ Charm results

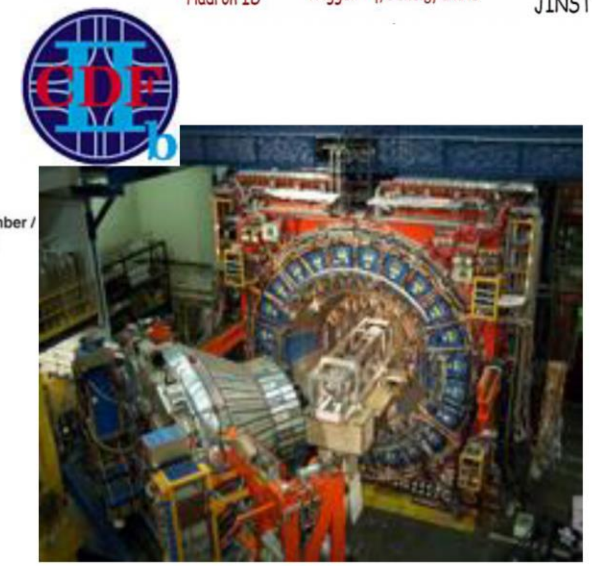








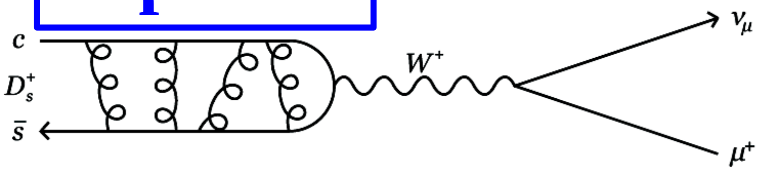




(Semi-)Leptonic decays

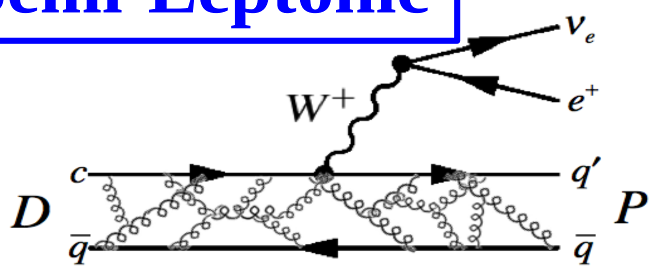
(Semi-)Leptonic decays ⇒ $f_{D(s)}$, $f_+(q^2)$

Leptonic



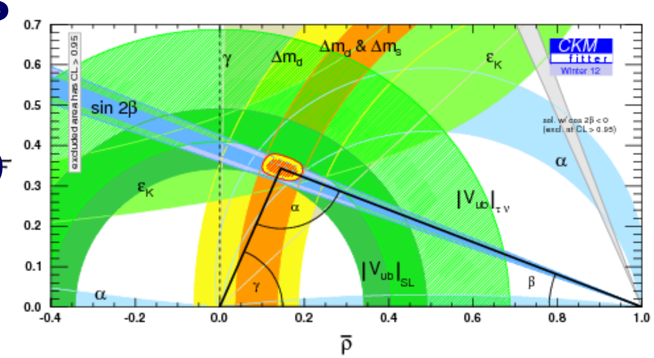
$$\Gamma\left(D^+ \to \ell^+\nu_\ell\right) = f_D^2\left|V_{cd}\right|^2 \frac{G_F^2}{8\pi} m_D m_\ell^2 \left(1 - \frac{m_\ell^2}{m_D^2}\right)^2$$

Semi-Leptonic



$$\frac{d\Gamma\left(D \to K(\pi)e\nu\right)}{dq^2} = \frac{G_F^2\left|V_{cs(d)}\right|^2 P_{K(\pi)}^3}{24\pi^3}\left|f_+\left(q^2\right)\right|^2$$

- Windows on weak and strong physics
- Weak decay ⇒ **theoretically clean**
- Strong interaction ⇒ test Lattice QCD
- Over-constrain CKM and search for New Physics

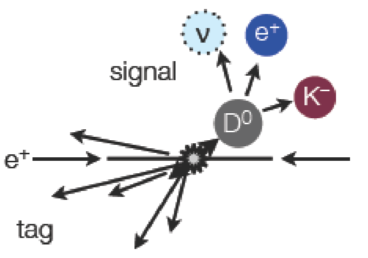


ν Recon. (Experimental challenges)

Commonly used techniques (Partial reconstruction)

- Hadron Machines (FOCUS, LHCb)
  - Applied for semileptonic decays
  - Secondary vertex ⇒ D direction
  - 4-momenta of charged decay product(s)
- B-factories (BaBar, Belle)
  - Get direction of the signal D from momentum conservation (sum of momentums of the rest decay products)

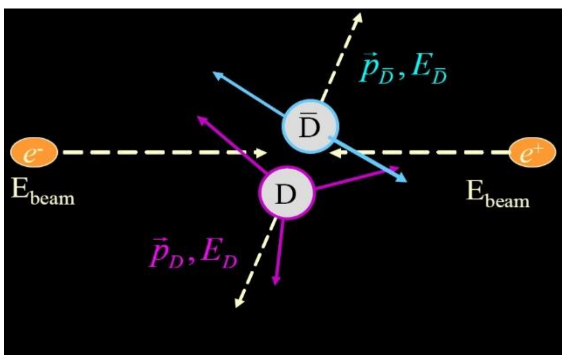
$$\vec{p}_D \propto - \sum \vec{p}_i$$



  - Fully reconstruct the tag side as D*X (better resolution but less statistics)
- Charm @ threshold (see next slide)

ν Recon. @charm threshold

- CLEO-c, BESIII
- 100% of beam energy converted to D pair (Clean environment, kinematic constrains ν Recon.)
- *D* generated in pair ⇒ absolute Branching fractions
- At ψ(3770) charm production is $D^0\bar{D}^0$ and D^+D^-
- Fully reconstruct about 15% of *D* decays



$$\Delta E = E_D - E_{\mathrm{Beam}}$$

$$M_{\mathrm{BC}} = \sqrt{E_{\mathrm{Beam}}^2 - p_D^2}$$

- **Double tag** techniques: Hadronic tag on one side, on the other side for leptonic/semileptonic studies. Neutrino is reconstructed from missing energy and momentum (Double tag efficiency is high.)

f_{Ds} : Theoretical/Experimental status

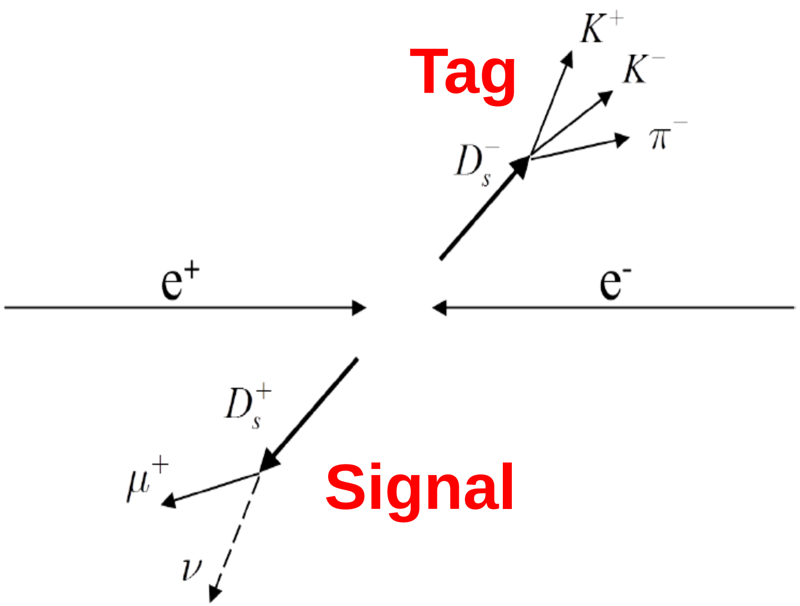
Model	f_{Ds} (MeV)
Experimental average of $\mu\nu + \tau\nu$	257.5 ± 4.6
Lattice (HPQCD) (PRD86, 054510 (2012))	$246.0 \pm 0.7 \pm 3.5$
Lattice (FNAL + MILC) (PRD85, 114506 (2012))	$246.4 \pm 0.5 \pm 3.6$

[1] PRD82,114504(2010); [2] arXiv:1112.3051; [3] JHEP0907,043(2009); [4] JHEP0511,014(2005); [5] PLB701,82(2011); [6] PRD75,116001(2007); [7] PRD81,054022(2010)

- **~2σ discrepancy between experimental measurement and unquenched lattice calculation, which may indicate the possible presence of new physics**
- **Experimental results**
  - **Ds → l ν : WA75, E653, L3, ALEPH, OPAL, CLEOII, BESI, CLEOc, Belle, BaBar, Belle (919 fb-1) for Ds →μ(τ) ν , new BESIII (@4.009GeV) results**

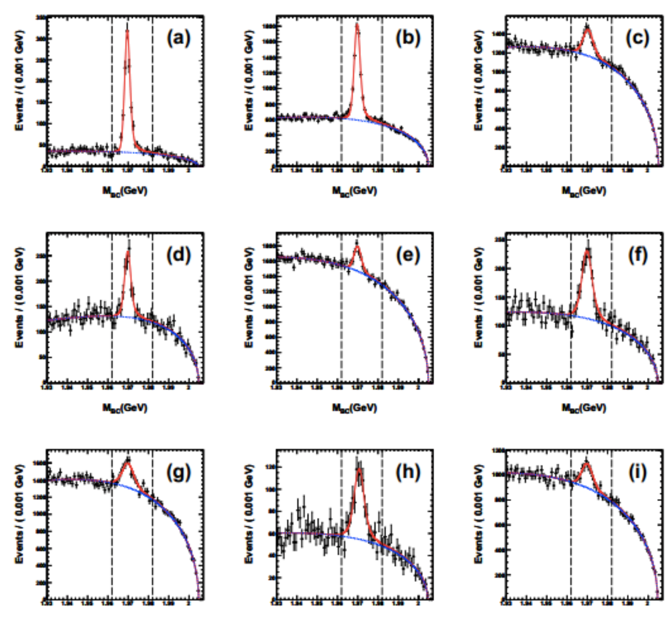
$D_s \to \mu\nu$ and $D_s \to \tau\nu$

- **Submitted to PRD (arXiv:1608.06732)**
- **Measure f_{D_s} using 482 pb^{-1} @4.009 GeV**
  - **Clean sample: below the DsDs* production threshold**
  - **Small D_sD_s cross section, ~1/3 of DsDs*'s at 4.17 GeV**
- **Double Tag method (Tag + Signal)**



(or $D_s^+ \to \tau^+\nu; \tau^+ \to \pi^+\bar{\nu}$)

Tag side: 15127 $\pm$ 312
D_s events in total

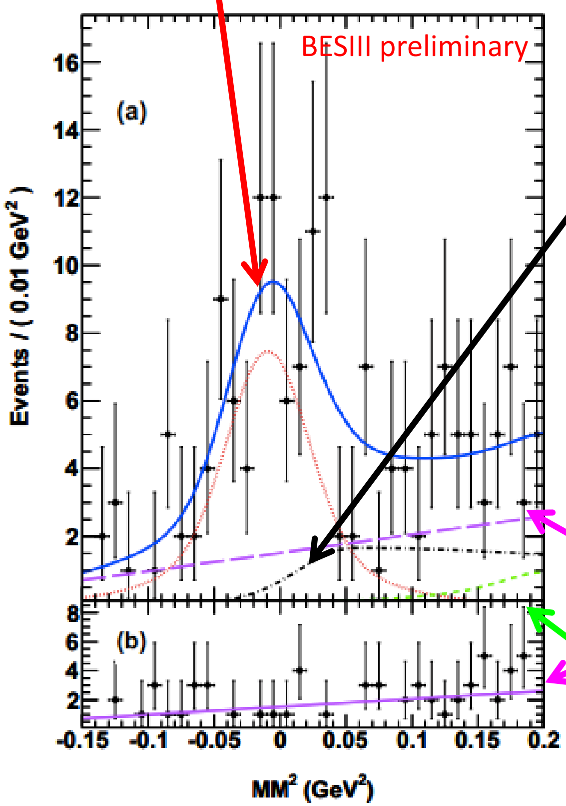


Mode
$K_S^0 K^-$
$K^+K^-\pi^-$
$K^+K^-\pi^-\pi^0$
$K_S^0K^+\pi^-\pi^-$
$\pi^+\pi^-\pi^-$
$\pi^-\eta$
$\pi^-\pi^0\eta$
$\pi^-\eta'(\eta' \to \pi^+\pi^-\eta)$
$\pi^-\eta'(\eta' \to \pi^+\pi^-\gamma)$

$D_s \to \mu\nu$ and $D_s \to \tau\nu$

Unbinned likelihood fit

$\mu\nu$



$\tau\nu$

Non-D_s bkg (by M_{BC} sideband)

D_s bkg (by MC simulation)

$$MM^2 = (E_{beam} - E_{\mu^+})^2 - (-p_{D_s^-} - p_{\mu^+})^2$$

⇧

Constrain $\tau\nu/\mu\nu$ to the SM prediction (9.76)

Signals ($\mu\nu$ + $\tau\nu$): 101.8±10.2

Mode	Branching fractions (%)
$D_s^+ \to \mu^+\nu$	$0.495 \pm 0.067 \pm 0.026$
$D_s^+ \to \tau^+\nu$	$4.83 \pm 0.65 \pm 0.26$

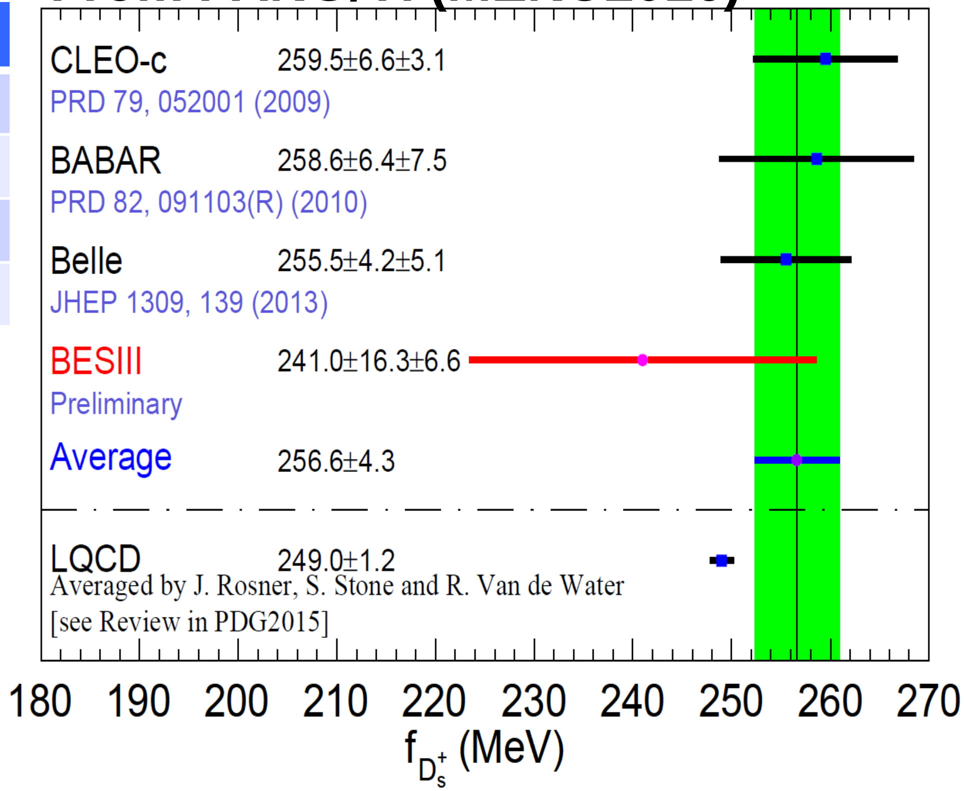
Input τ_{Ds}, M_{Ds}, M_μ and $|V_{cs}|=|V_{ud}|$ from PDG
⇒ f_{Ds} = (241.0 ± 16.3 ± 6.6) MeV

Comparison of Decay constant f_{Ds}

Experiment	Mode	$f_{D_s^+}$ (MeV)
CLEO-c *	μν	259 ± 6.2 ± 3.0
BaBar **	μν	258.4 ± 6.4 ± 7.5
Belle ***	μν	257.8 ± 4.2 ± 4.8
This work (preliminary)	μν	241.0 ± 16.3 ± 6.6

* PRD79, 052001 (2009)
** PRD82, 091103 (2010)
*** JHEP09, 139 (2013)

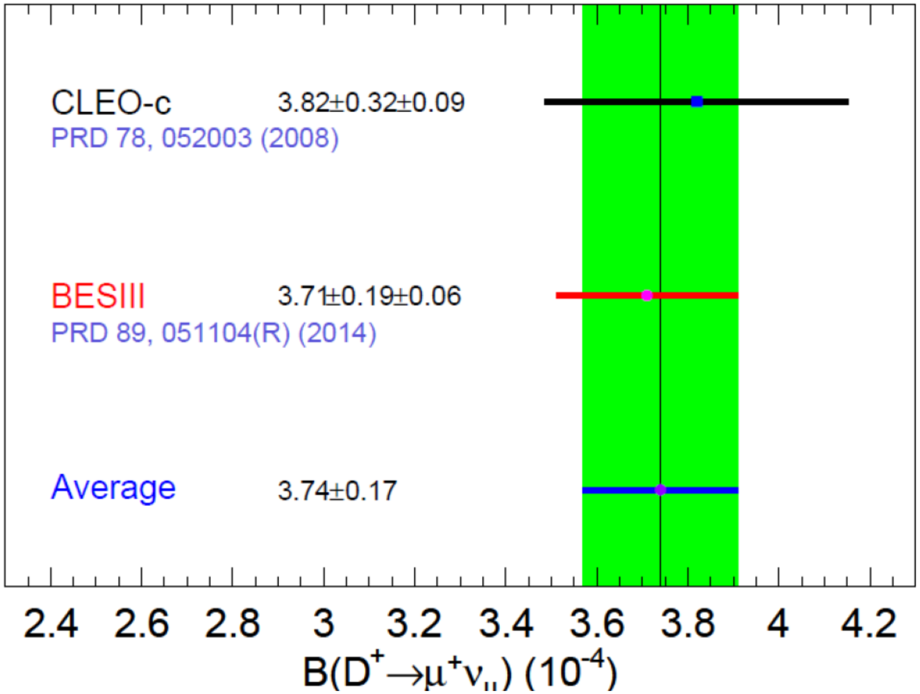
From FANG/Yi (MENU2016)

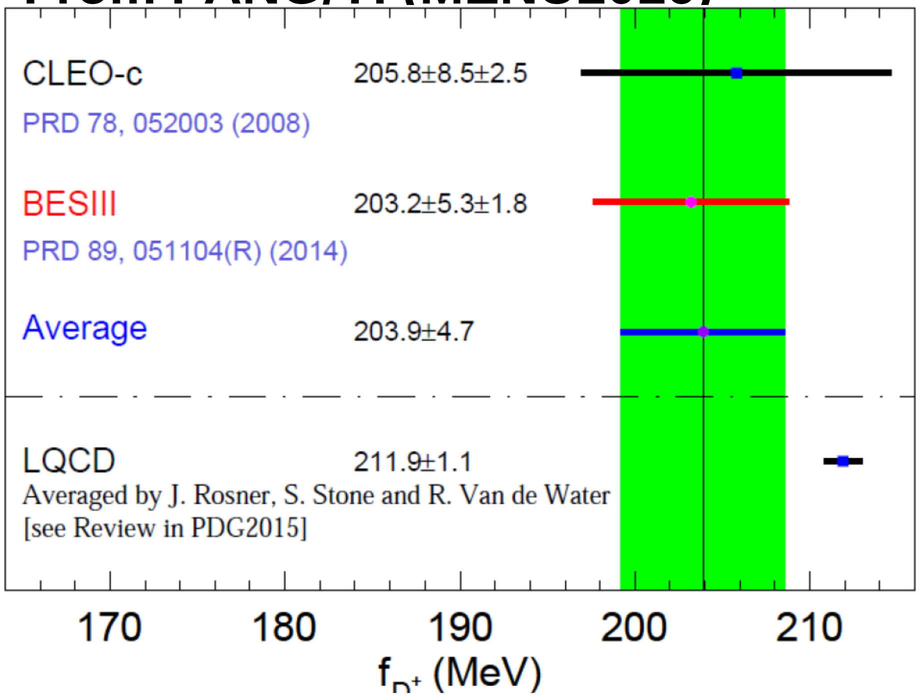


- In 2013, Belle made the most precise measurement
- Precision：experimental average ~1.7%, LQCD calculation ~0.5%
- BESIII has collected 3 fb^{-1} $D_sD_s^*$ data at 4.18 GeV
  - ~15× D_s statistics to the BESIII 4.009 GeV data
  - ~5× D_s statistics to the CLEO-c 4.17 GeV data

What about B($D^+ \to \mu^+\nu$) and f_{D^+}?

From FANG/Yi (MENU2016)





- **BESIII made the most precise measurement (PRD89, 051104(R) (2014)). The error is still dominated by statistics.**
  - **Measure f_{D+} using 2930 pb^{-1} @3.773 GeV**
  - **Similar analysis technique as f_{Ds} measurement**
- **For f_{D+}, the experimental average is lower than the theoretical calculation by ~1.7σ.**

$D^0 \to Pe^+\nu$ (P= K/π)

BESIII

Motivation

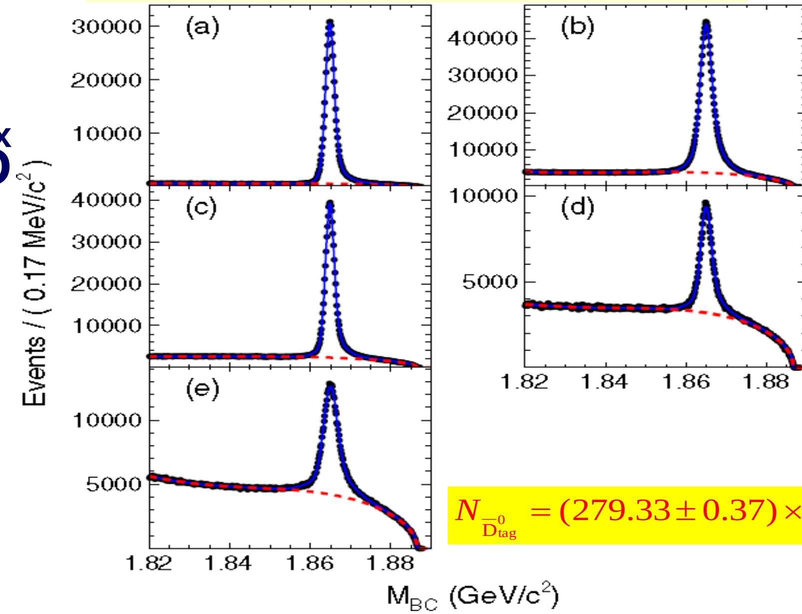
- BR ⇒ Measure $|V_{cx}|$ x FF
- Charm physics: CKM-unitarity ⇒ $|V_{cx}|$ extract FF, test LQCD; Or input LQCD FF to test CKM-unitarity
- *B* physics: Validate LQCD for form factor, extract $|V_{ub}|$ to test CKM-unitarity
  - Example: $B \to \pi l \nu \Rightarrow |V_{ub}| = 3.92 \pm 0.09 \pm 0.45$(Theory) rely on LQCD Form Factor calculations (provide perfect calibration)

Data analysis

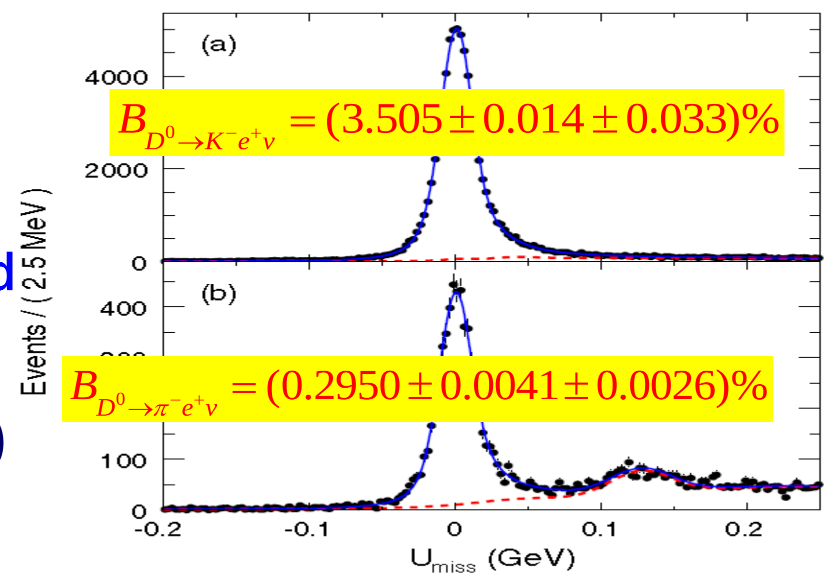
- Full data samples: 2.93fb^{-1} @3.773GeV
- Kinematic variable: U_{miss}
- Most precise measurements on FF and $|V_{cx}|$

BABAR: analysis of $D^0 \to \pi^- e^+ \nu$ decays (347.2 fb^{-1} @Υ(4S) PRD 91 (2015), 052022)

PRD92(2015)072012



$N_{\bar{D}^0_{tag}} = (279.33 \pm 0.37) \times 10^4$



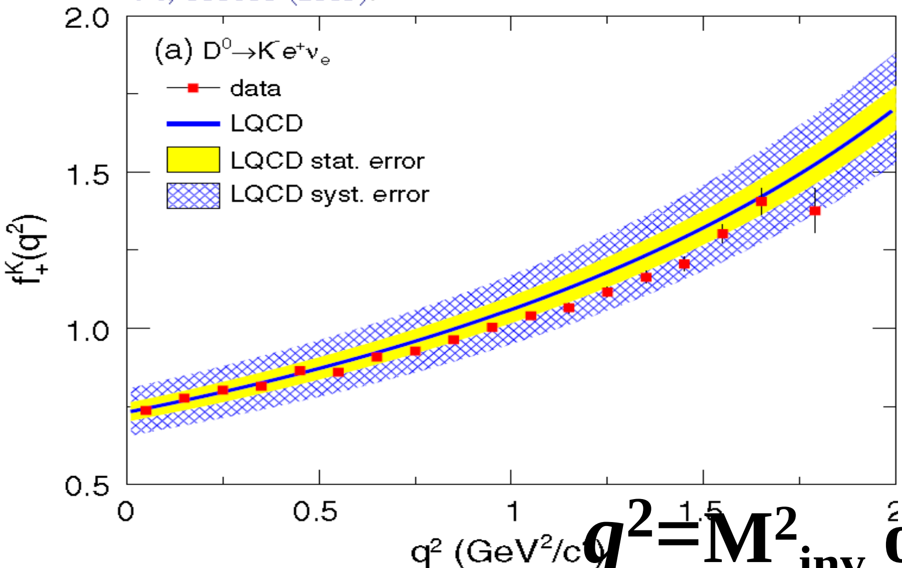
$B_{D^0 \to K^- e^+ \nu} = (3.505 \pm 0.014 \pm 0.033)\%$

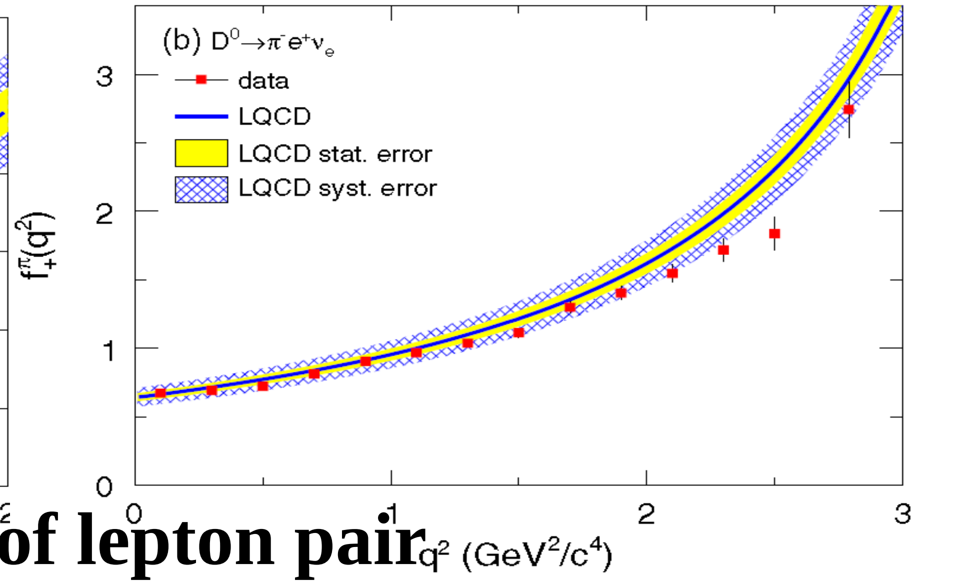
$B_{D^0 \to \pi^- e^+ \nu} = (0.2950 \pm 0.0041 \pm 0.0026)\%$

Measurement of Form Factors $f_+^{K(\pi)}(q^2)$

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

PRD92(2015)072012





$q^2 = M^2_{inv}$ of lepton pair

- The solid lines are the best fit to LQCD with modified pole model
  - Inner band is statistical uncertainty of the LQCD calculation
  - Outer band is stat.+syst. uncertainties of the LQCD calculation
- Slight tension between measurements and LQCD calculation at higher q^2 bins.

The precision of these form factors is higher than that of the LQCD calculations by a factor of 3~4.

$f_+^{\pi}(0)/f_+^{K}(0)$ and $|V_{cd}|/|V_{cs}|$

PRD92(2015)072012

- **Experimentally**
  - $f_+^{\pi}(0)/f_+^{K}(0) = 0.8649 \pm 0.0112 \pm 0.0073$
- **Theoretically**
  - $f_+^{\pi}(0)/f_+^{K}(0) = 0.84 \pm 0.04$
  - LCSR: P. Ball, PLB 641, 50 (2006)

The ratio is in excellent agreement with the LCSR calculation.

- **BESIII**
  - $|V_{cd}|/|V_{cs}| = 0.238 \pm 0.004_{stat} \pm 0.002_{sys} \pm 0.011_{LCSR}$
- **Comparison of $|V_{cd}|/|V_{cs}|$ measurements**

Experiment	$\vert V_{cd}\vert/\vert V_{cs}\vert$	Note
PDG2014 [6]	0.228 ± 0.009	Using $\vert V_{cd}\vert = 0.225 \pm 0.008$ and $\vert V_{cs}\vert = 0.986 \pm 0.016$
CLEO-c [23]	$0.242 \pm 0.011 \pm 0.004 \pm 0.012$	Using $D \to \pi e^+ \nu_e$ and $D \to K e^+ \nu_e$
BESIII (this work)	$0.238 \pm 0.004 \pm 0.002 \pm 0.011$	Using $D^0 \to \pi^- e^+ \nu_e$ and $D^0 \to K^- e^+ \nu_e$

For the BES-III and CLEO-c results of $|V_{cd}|/|V_{cs}|$, the first error is statistical, second systematic, and the third is theoretical uncertainty

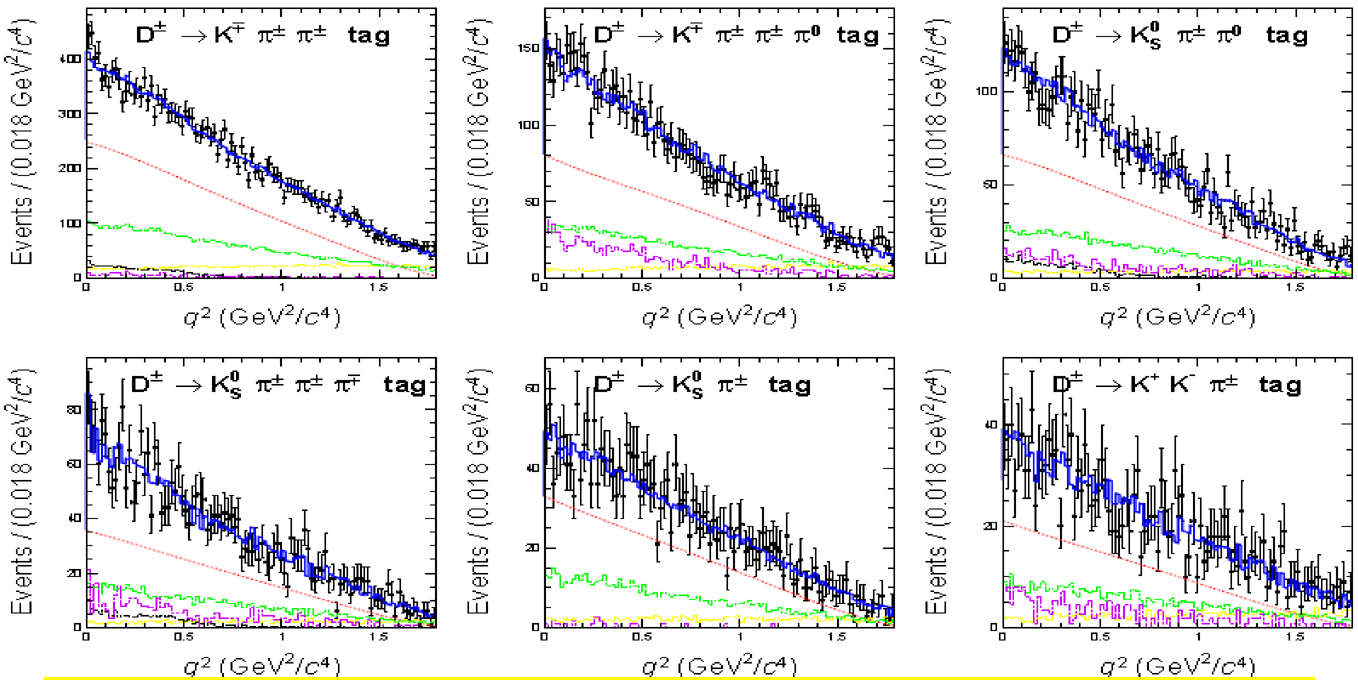
$D^+ \to K_L e^+ \nu$

PRD92(2015)112008

- K_L reconstruction (Partial recon.)
  - EMC neutral cluster $\Rightarrow K_L$ position
  - Fix $U_{miss}=0 \Rightarrow K_L$ momentum
- $D^+ \to K_L e^+ \nu$ is measured for the first time
- This result is consistent with theoretical prediction (-3.3×10^{-3}) [Z.Z. Xing, PLB353, 313(1995); PLB363, 266(1996)]

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

$A_{CP}^{D^+\to K_L e^+ \nu} = (-0.59 \pm 0.60 \pm 1.50)\%$



Simultaneous Fit to observed DT yields, red dash is signal

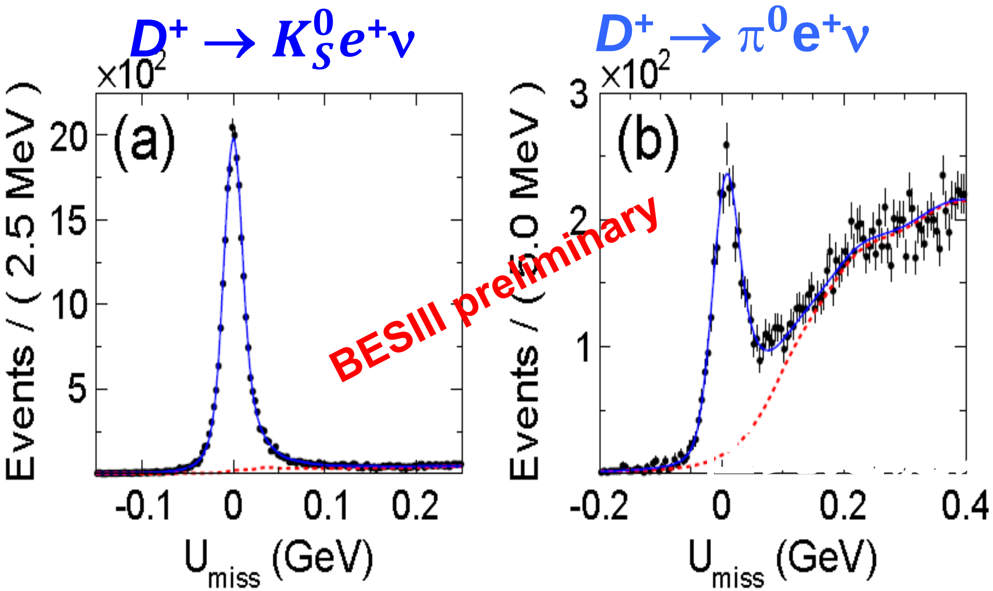
$f^K_+(0)|V_{cs}| = 0.728 \pm 0.006 \pm 0.011$

Direct measurement

$f^K_+(0) = 0.748 \pm 0.007 \pm 0.012 \Leftarrow$ [with $|V_{cs}|$ from SM constraint fit]

$|V_{cs}| = 0.975 \pm 0.008_{stat} \pm 0.015_{sys} \pm 0.025_{LQCD} \Leftarrow$ [with fK+(0)=0.747$\pm$0.019 (PRD82, 114506(2010)]

$D^+ \to K^0_S e^+\nu$ and $D^+ \to \pi^0 e^+\nu$

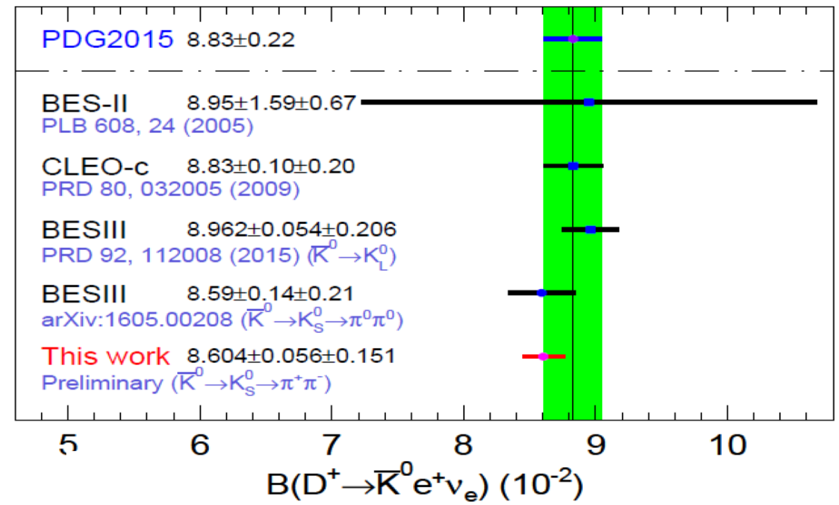


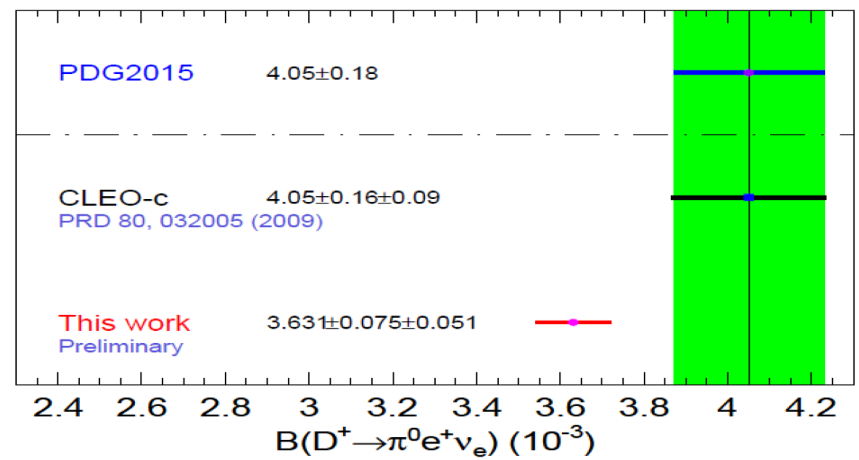
$N_{D^- \to \overline{K}^0 e^+\nu} = 26008 \pm 168$

$N_{D^+ \to \pi^- e^+\nu} = 3402 \pm 70$

$B[D^+ \to \overline{K}^0 e^+\nu] = (8.604 \pm 0.056 \pm 0.151)\%$

$B[D^+ \to \pi^0 e^+\nu] = (3.631 \pm 0.075 \pm 0.051) \times 10^{-3}$



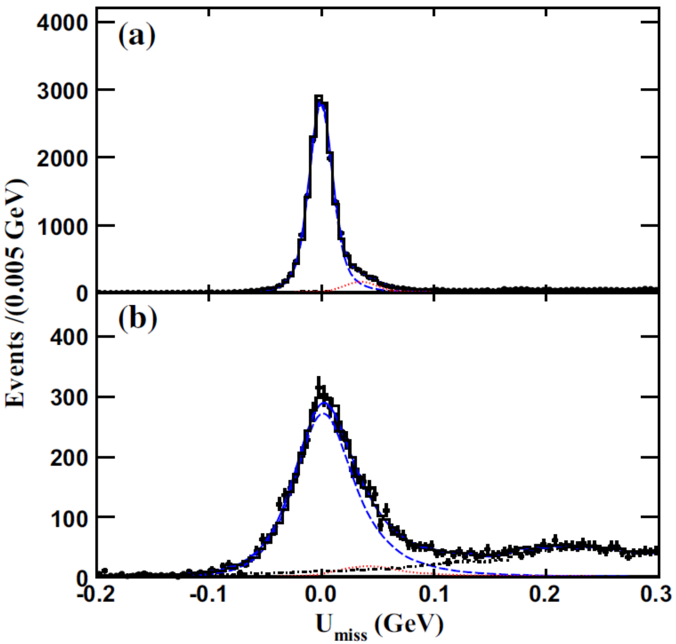


- **Full data set: 2.93 fb^{-1} data@ 3.773 GeV**
- **BESIII's BR for $D^+ \to \pi^0 e^+\nu$ is lower than CLEOc's.**
- **Form Factors are also measured.**

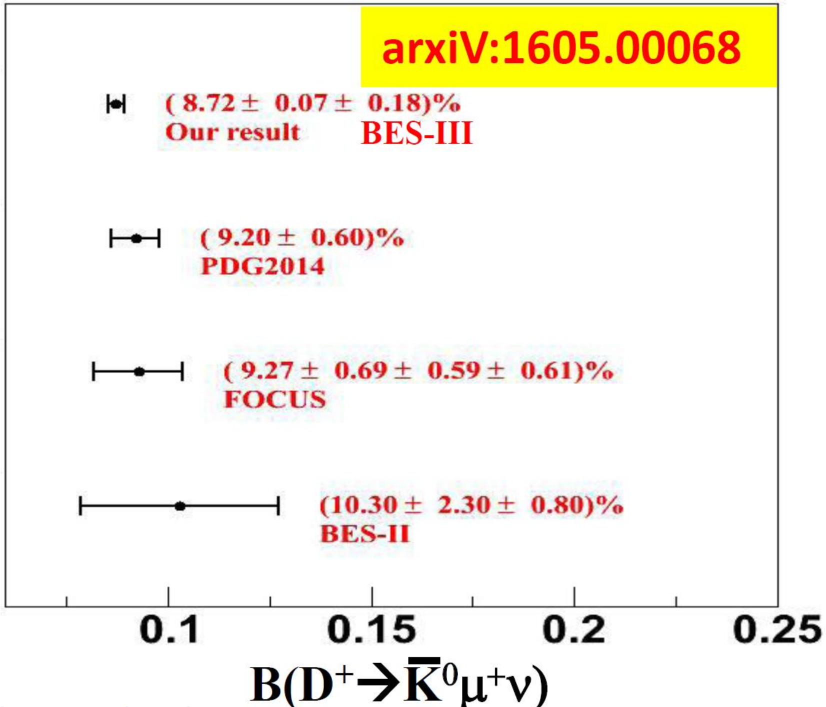
$D^+ \to K_S^0 \mu^+ \nu$

BESIII

Eur. Phys. J. C 76 (2016) 369



From Rong/Gang at CHARM2016

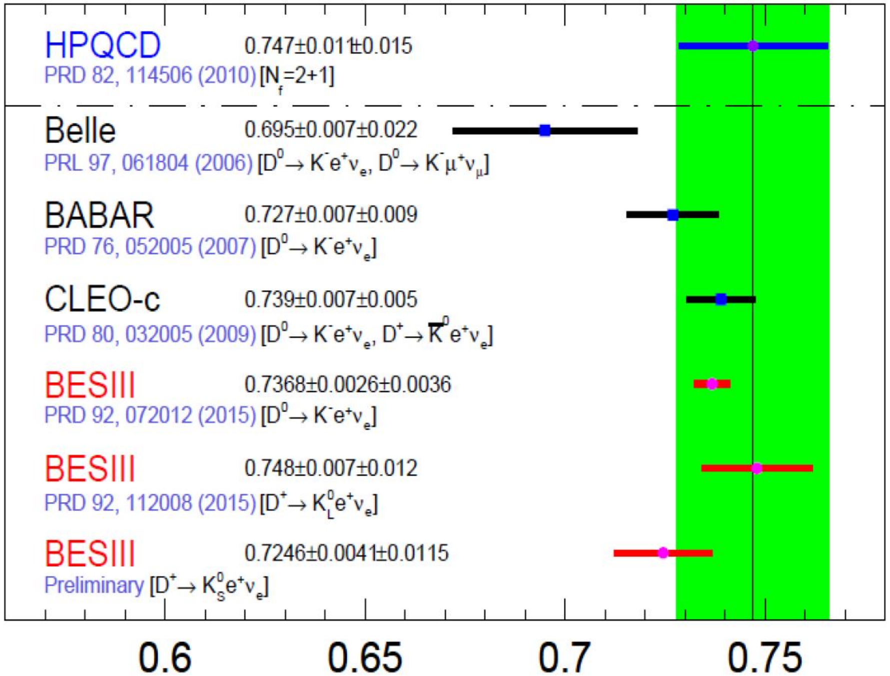


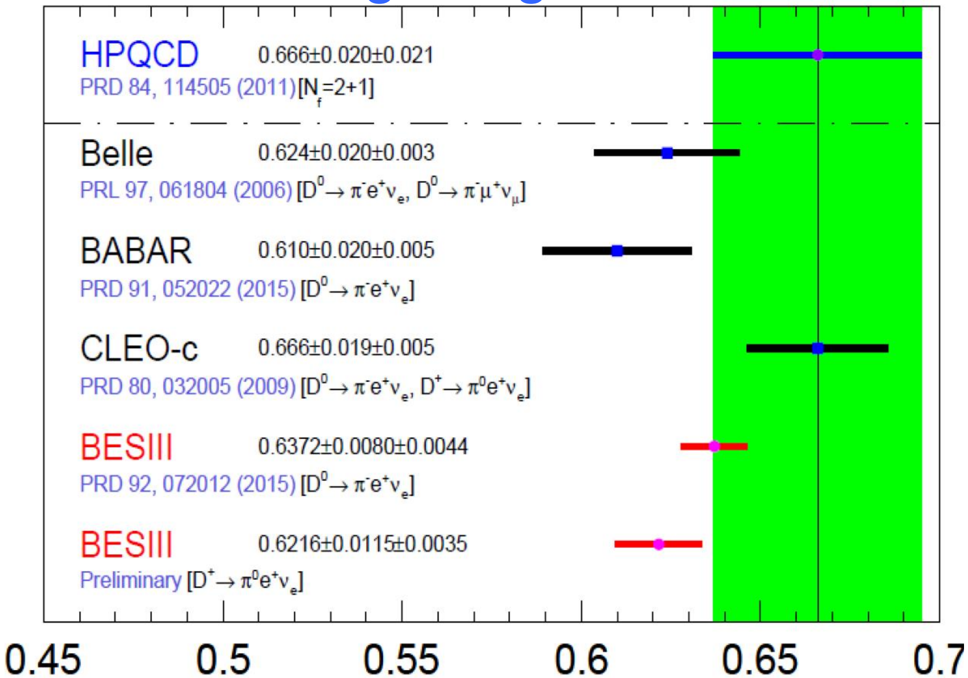
- **Full data set: 2.93 fb^{-1} data@ 3.773 GeV**
- **6 hadronic modes, 1.52×10^6 D^- tags**
- **Comparing this measured BF with PDG:**
  - $\frac{\Gamma[D^0 \to K^- \mu^+ \nu]}{\Gamma[D^+ \to \bar{K}^0 \mu^+ \nu]} = 0.963 \pm 0.044$ $\Rightarrow$ **Supporting isospin conservation.**
  - $\frac{\Gamma[D^+ \to \bar{K}^0 \mu^+ \nu]}{\Gamma[D^+ \to \bar{K}^0 e^+ \nu]} = 0.988 \pm 0.033$ $\Rightarrow$ **consistent with theoretical prediction.**

Status of Form Factors $f_+^{D\to K(\pi)}(0)$

$f_+^{D\to K(\pi)}(0)$ determined from $f_+^{D\to K(\pi)}(0)\,|V_{cs(d)}|$ combining with $|V_{cs(d)}|$ from the SM global fit

From Rong/Gang at CHARM2016





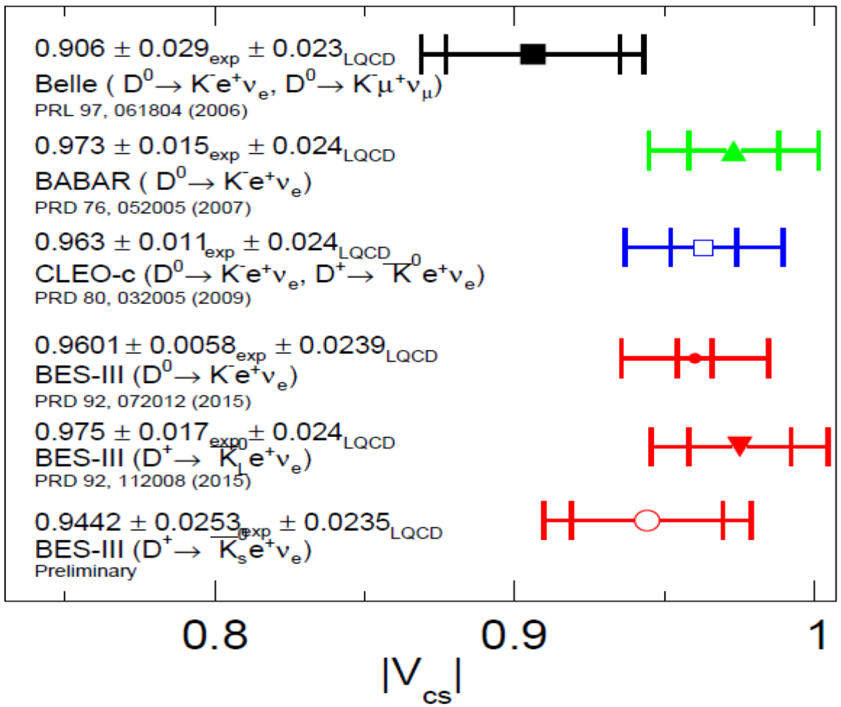
$f_+^{D\to K}(0)$ $\qquad$ $f_+^{D\to\pi}(0)$

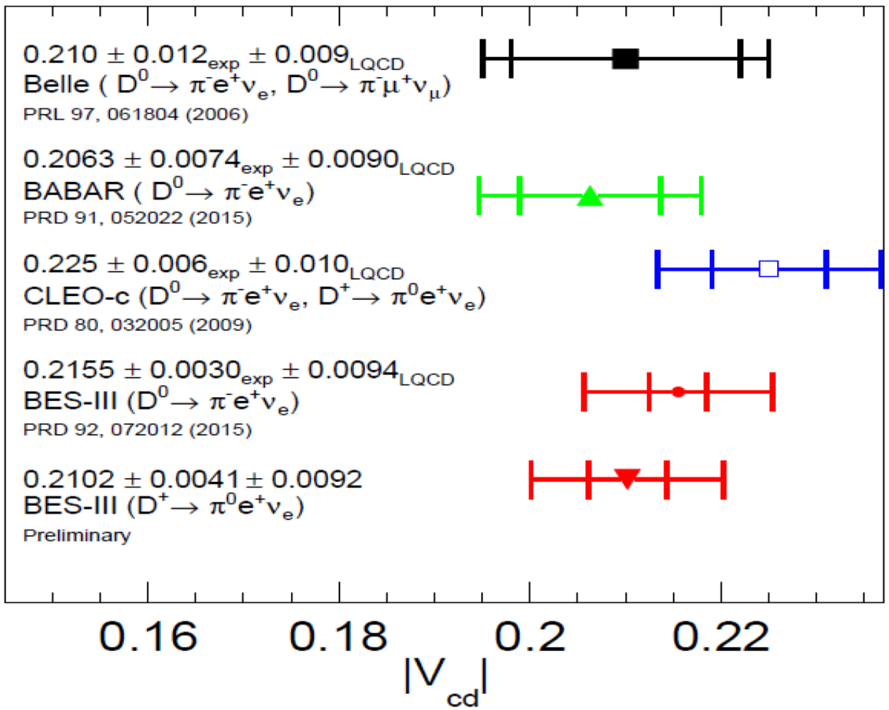
- $D^0 \to \pi^- e^+\nu$ and $D^0 \to K^- e^+\nu$ from BESIII $\Rightarrow$ most precise measurements
- Experimental accuracy is better than the LQCD calculation.

Status of $|V_{cs}|$ and $|V_{cd}|$

$|V_{cs(d)}|$ extracted from $f_+^{D\to K(\pi)}(0)$ $|V_{cs(d)}|$ combining with $f_+^{D\to K(\pi)}(0)$ from LQCD calculation.

From Rong/Gang at CHARM2016

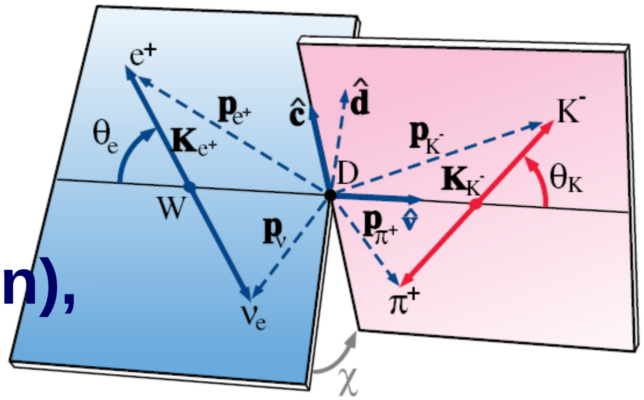




- **The inner uncertainties are experimental; the outer uncertainties are due to uncertainties of LQCD calculations**

$D \to V\, l\, \nu$

- **Kinematics** ($K^* \to K\pi$ as Vector decay example): 5 degree of freedom (m^2 in K^* system, q^2 in $l\nu$ system, $\cos(\theta_K)$, $\cos(\theta_e)$ and χ
- For massless l (e: good approximation), need 3 form factors: 2 axial and a vector. Uaually parameterized with simple pole.
- Usually measure r_V and r_A
- Combined with $D\to\rho e\nu$, $D\to K^* e\nu$ and $B\to V\, l^+ l^-$, to extract $|V_{ub}|$ from $B\to\rho e\nu$ (PRD 70, 114005 (2004))
- Measure $D\to\{K\pi$ -S wave$\}e\nu$ component
  - fist observed: FOCUS, PLB535 (2002) 43-51
  - CLEOc confirmed evidence for S-wave with: 818 pb^{-1} PRD81 (2010) 112001
  - BaBar(348 fb^{-1}):PRD 83 (2011) 072001



Simple pole parameterization:

$$V(q^2) = \frac{V(0)}{1 - \frac{q^2}{m_V^2}}, \qquad r_V \equiv \frac{V(0)}{A_1(0)}$$

$$A_1(q^2) = \frac{A_1(0)}{1 - \frac{q^2}{m_A^2}}, \qquad r_A \equiv \frac{A_2(0)}{A_1(0)}$$

$$A_2(q^2) = \frac{A_2(0)}{1 - \frac{q^2}{m_A^2}},$$

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

BESIII

PRD94(2016)032001

- **Fractions with >5σ significance**

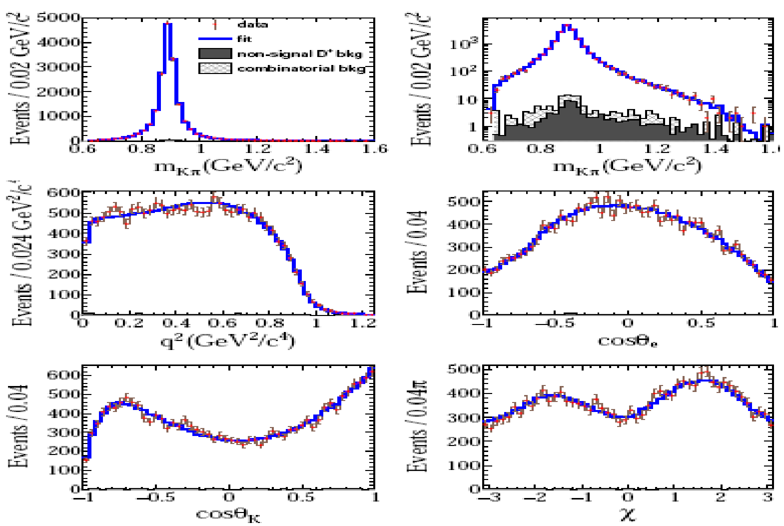
$$f(D^+\to(K^-\pi^+)_{K^{*0}(892)}\,e^+\nu_e)=(93.93\pm0.22\pm0.18)\%$$

$$f(D^+\to(K^-\pi^+)_{S-wave}\,e^+\nu_e)=(6.05\pm0.22\pm0.18)\%$$

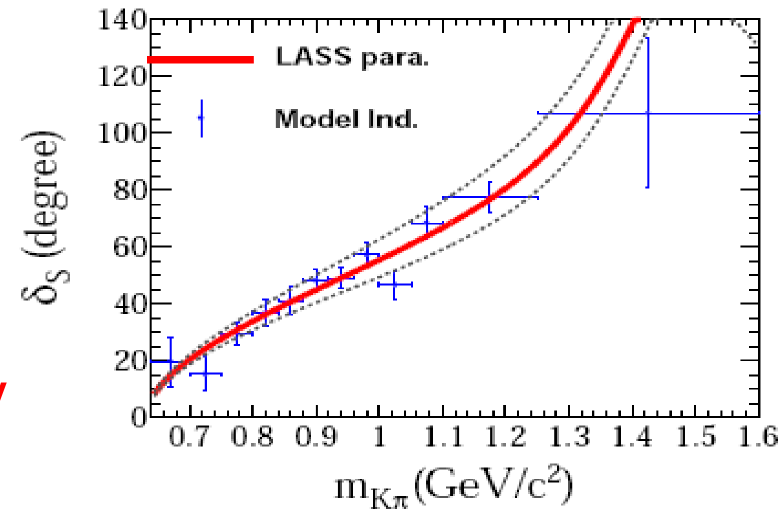
- **Properties of different Kπ (non-) resonant amplitudes**

$$m_{K^{*0}(892)}=(894.60\pm0.25\pm0.08)\ \mathrm{MeV}/c^2$$
$$\Gamma_{K^{*0}(892)}=(46.42\pm0.56\pm0.15)\ \mathrm{MeV}/c^2$$
$$r_{BW}=(3.07\pm0.26\pm0.11)\ (\mathrm{GeV}/c)^{-1}$$

- **q^2 dependent form factors in $D^+\to\overline{K}^{*0}(892)e^+\nu$**



Model independent S-wave phase measurement



$M_{V/A}$ is expected to $M_{D^*(1^-/^+)}$

$$m_V=(1.81^{+0.25}_{-0.17}\pm0.02)\ \mathrm{GeV}/c^2$$
$$m_A=(2.61^{+0.22}_{-0.17}\pm0.03)\ \mathrm{GeV}/c^2$$
$$A_1(0)=0.573\pm0.011\pm0.020$$
$$r_V=V(0)/A_1(0)=1.411\pm0.058\pm0.007$$
$$r_2=A_2(0)/A_1(0)=0.788\pm0.042\pm0.008$$

Model independent form factors

the dominate K*(892)0 component is accompanied by S-wave contribution（~6% of total）and that other component are negligible.

$D \to \omega e \nu$ and $D \to \phi e \nu$

BESIII

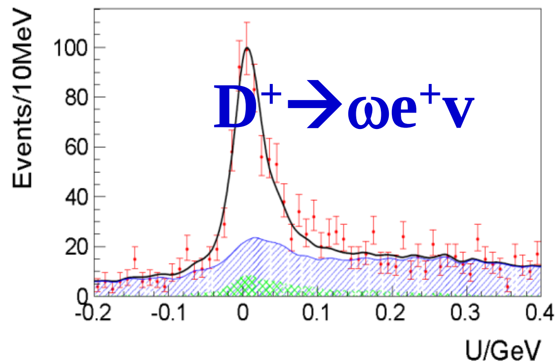
PRD92(2015)071101(R)

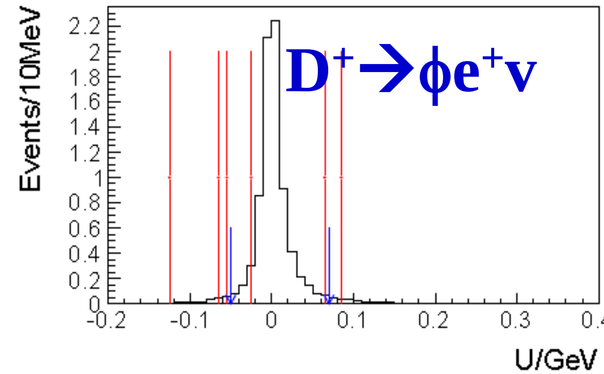
- **CLEOc: $D \to \rho e \nu$ and $D \to \omega e \nu$**
  - **Measured FF for $D \to \rho e \nu$ for the first time.**
  - **PRL110, 131802 (2013)**
- **BESIII**
  - **Most precise BR for $D \to \omega e \nu$**
  - **Amplitude analysis of $D^+ \to \omega e^+ \nu$ is performed for the first time**
  - **Form Factor ratio**

$r_V = V(0)/A_1(0) = 1.24 \pm 0.09 \pm 0.06$

$r_2 = A_2(0)/A_1(0) = 1.06 \pm 0.15 \pm 0.05$

- **BFs are consistent with FK predictions (Fajfer and Kamenik, Phys. Rev. D 72, 034029 (2005))**

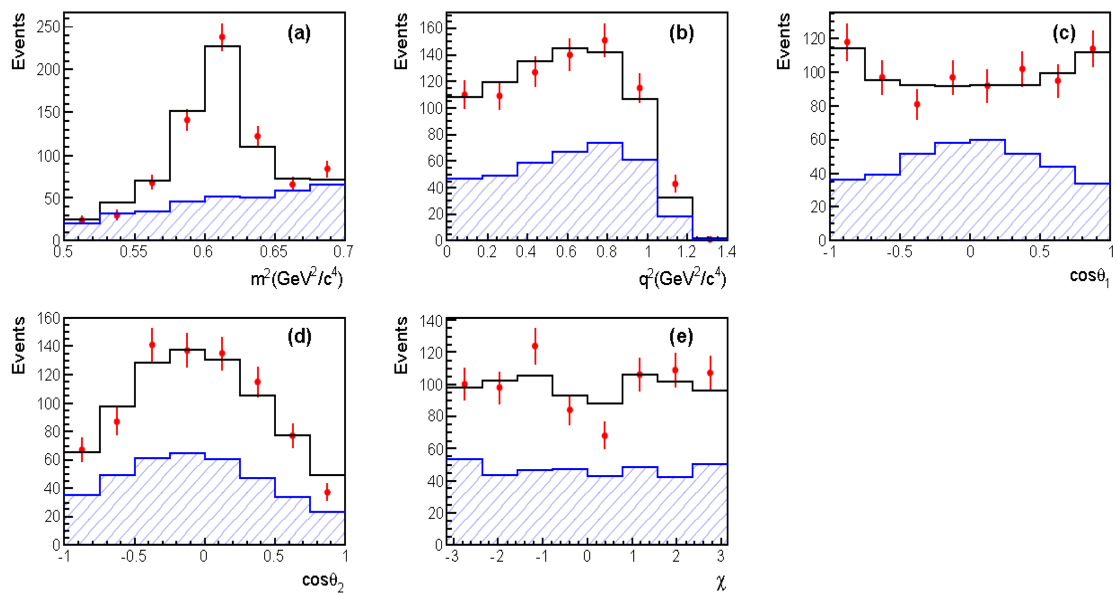




$B[D^+ \to \omega e^+ \nu] = (1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$

$B[D^+ \to \phi e^+ \nu] < 1.3 \times 10^{-5}$ at 90% C.L.

Better precision or sensitivity

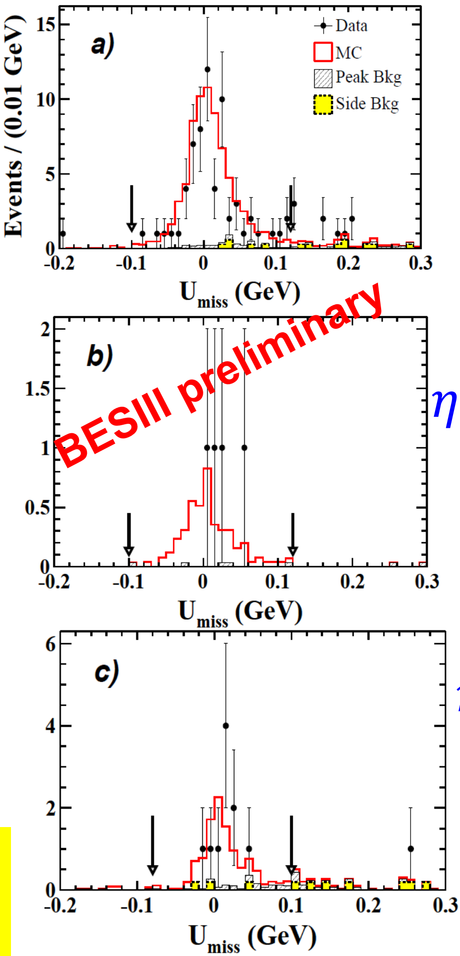


$D_s^+ \to \eta^{(\prime)} e^+ \nu$

BESIII

Submitted to PRD arXiv 1608.06484

- **ISGW2 model (PRD 52, 2783 (1995))**
  - **Predict a difference between the *D* and D_s^+ inclusive semileptonic rates**
- **BRs measurements**
  - **Data sample: 482 pb^{-1} @4.009 GeV**
  - **Agree to previous experimental measurements.**
  - **Can be used to determine the η−η' mixing angle.(PLB 404, 166 (1997))**
  - **Improve upon the Ds+ semileptonic branching ratio precision.**



Ref. [7]: PRL 75, 3804 (1995) (CLEO II)
Ref. [8]: PRD 80, 052007 (2009) (CLEO-c)
Ref. [9]: PRD 92, 012009 (2015)

	BESIII	Ref. [7]	Ref. [8]	Ref. [9]	PDG [4]
$B(D_s^+ \to \eta e^+ \nu_e)[\%]$	$2.30 \pm 0.31 \pm 0.09$	—	$2.48 \pm 0.29 \pm 0.13$	$2.28 \pm 0.14 \pm 0.20$	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
$\frac{B(D_s^+ \to \eta' e^+ \nu_e)}{B(D_s^+ \to \eta e^+ \nu_e)}$	$0.40 \pm 0.14 \pm 0.02$	$0.35 \pm 0.09 \pm 0.07$	—	—	—

BESIII preliminary

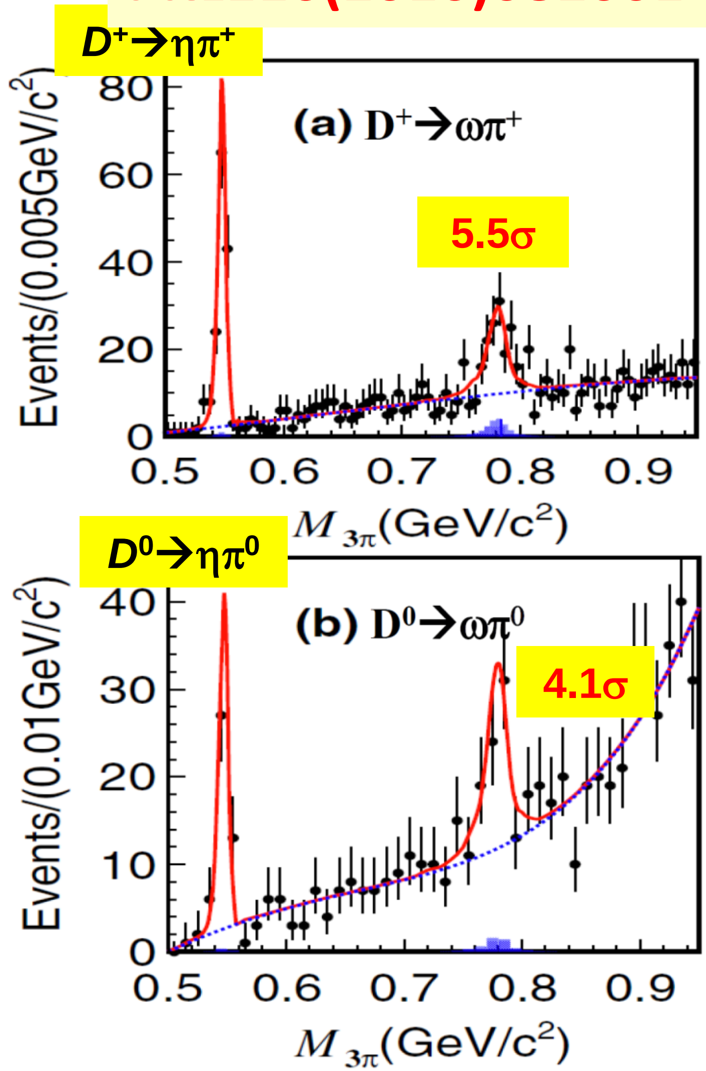
Hadronic decays

Observation/Evidence of $D \to \omega\pi$

BESIII

- Theoretical prediction for BR : ~1.0×10^{-4}
  - Neglect the W-annihilation contribution
  - H. Y. Cheng and C. W. Chiang, PRD 81, 074021 (2010)
- Single Cabibbo-Suppressed D decays
- Full data samples: $2.93 fb^{-1}$ @3.773GeV
- Double tag method: $D^{+,0} \to \omega\pi^{+,0}$, $\omega \to \pi^+\pi^-\pi^0$
- First observation: $D^+ \to \omega\pi^+$ with statistical significance of 5.5σ.

PRL116(2016)082001

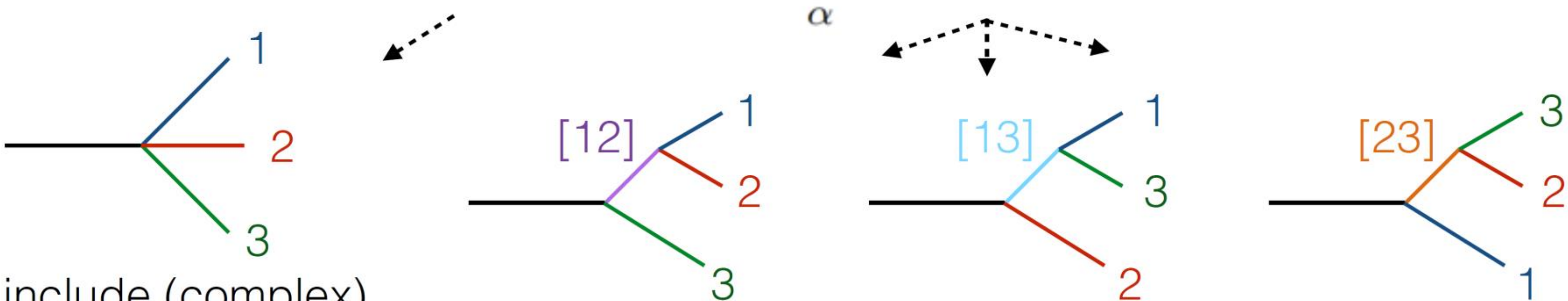


Mode	This work	Previous measurements
$D^+ \to \omega\pi^+$	$(2.79 \pm 0.57 \pm 0.16) \times 10^{-4}$	$< 3.4 \times 10^{-4}$ at 90% C.L.
$D^0 \to \omega\pi^0$	$(1.17 \pm 0.34 \pm 0.07) \times 10^{-4}$	$< 2.6 \times 10^{-4}$ at 90% C.L.
$D^+ \to \eta\pi^+$	$(3.07 \pm 0.22 \pm 0.13) \times 10^{-3}$	$(3.53 \pm 0.21) \times 10^{-3}$
$D^0 \to \eta\pi^0$	$(0.65 \pm 0.09 \pm 0.04) \times 10^{-3}$	$(0.68 \pm 0.07) \times 10^{-3}$

Amplitude analysis of *D* decays

- **Weak multi-body decays platform ⇒ study interference between intermediate resonances(hadrons)**
  - **Many applications: CP and T violation, mixing, new Physics**
  - **More kinematic freedom than two-body final states**
  - **Intermediate resonances dominate and cause non-uniform distribution of events in Dalitz plot**
  - **Unique features to study the ππ, *K*π and $K\bar{K}$ S-wave amplitudes**
- **Total amplitude : a coherent sum of quasi-two-body contributions (most commonly using isobar model)**

$$\mathcal{A}_{D^0}(\vec{a},\vec{x}) = a_0\mathcal{A}_0 + \sum_\alpha a_\alpha \mathcal{A}_\alpha(\vec{x})$$

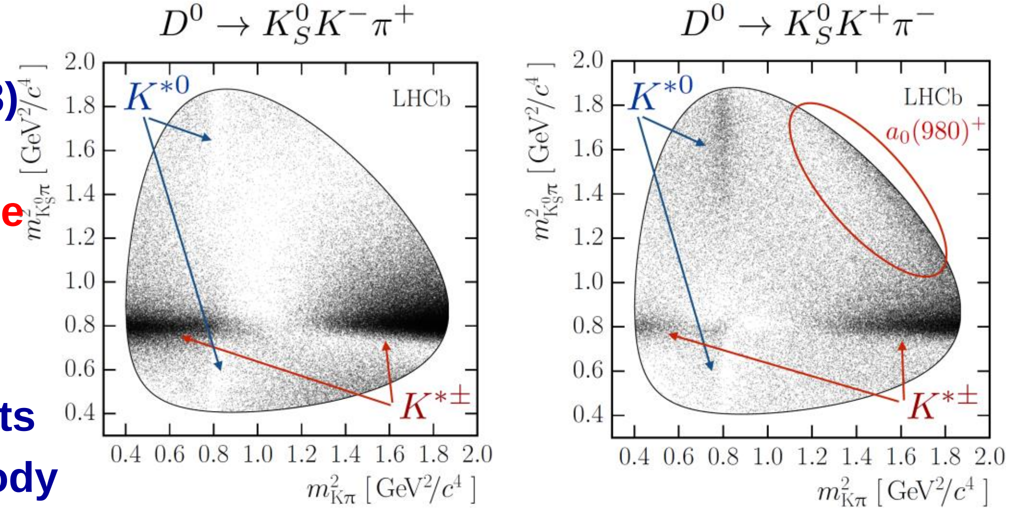


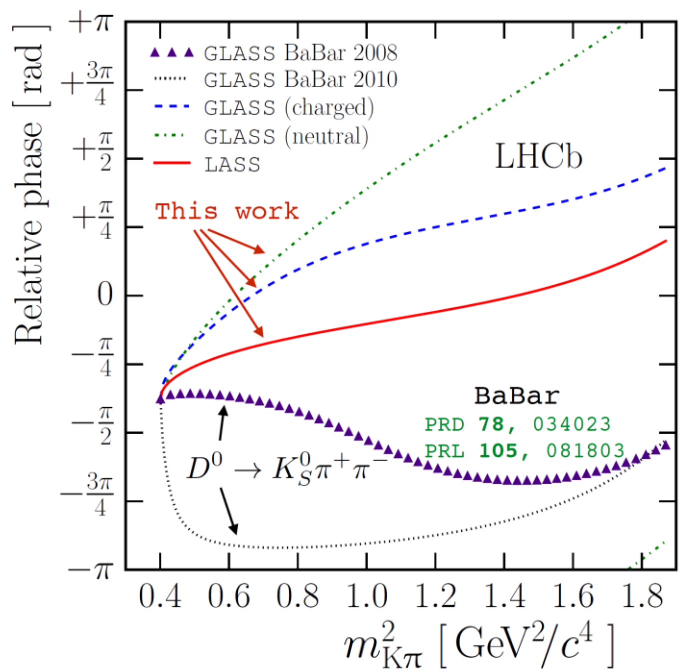
Often include (complex) non-resonant term

Amplitude analysis of $D^0 \to K_S^0 K^\pm \pi^\mp$

PRD93(2016)052018

- **Twin CS decays**
  - Combine with $B^- \to D^0 K^- \Rightarrow$ CKM γ
  - Resonant structure $\Rightarrow$ tests of SU(3) flavor symmetry
  - Studies of $(K\pi)^{0,\pm}$ *S*-wave amplitude
- **Data analysis (3fb^{-1})**
  - $D^{*+} \to D^0 \pi_s^+, D^0 \to K_S^0 K^\pm \pi^\mp$
  - Fit Δm of D^{*+} to extract signal events
  - Possible contributions in all two-body systems: $K^*(892, 1410)^{0,\pm}$, $(K\pi)^{0,\pm}_{S-wave}$, $a_0(980, 1450)^\pm$, $\rho(1450, 1700)^\pm$, $a_2(1320)^\pm, K_2^*(1430)^{0,\pm}$ $\Rightarrow$ Fit fractions for the dominant contributions
- **Conclusions**
  - Good fits are obtained with GLASS and LASS models
  - GLASS phases are different for neutral and charged amplitudes
  - very different GLASS phases depending on the decay mode.

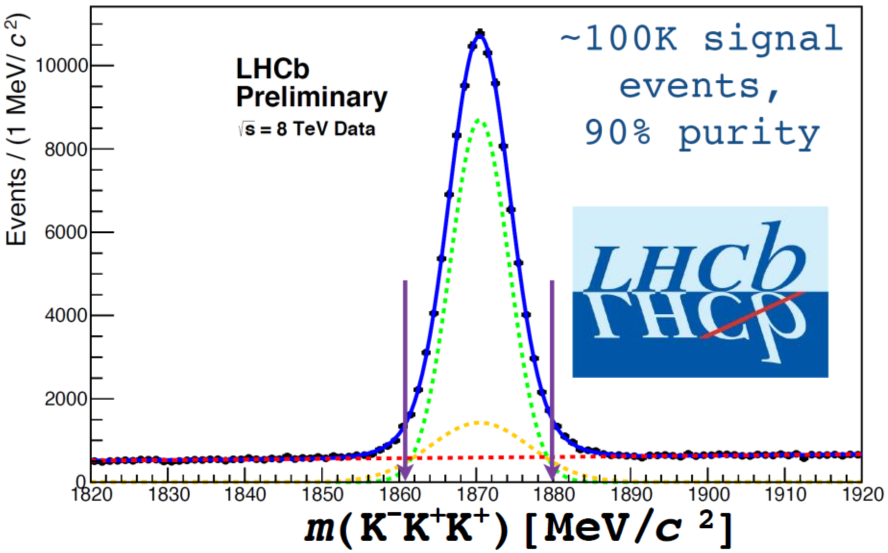


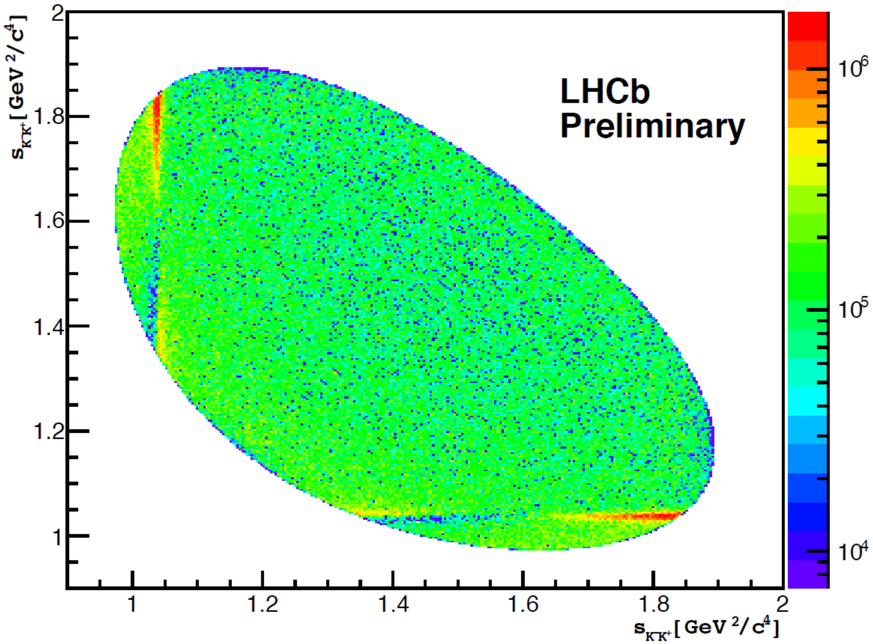


Amplitude analysis of $D^+ \to K^- K^+ K^+$

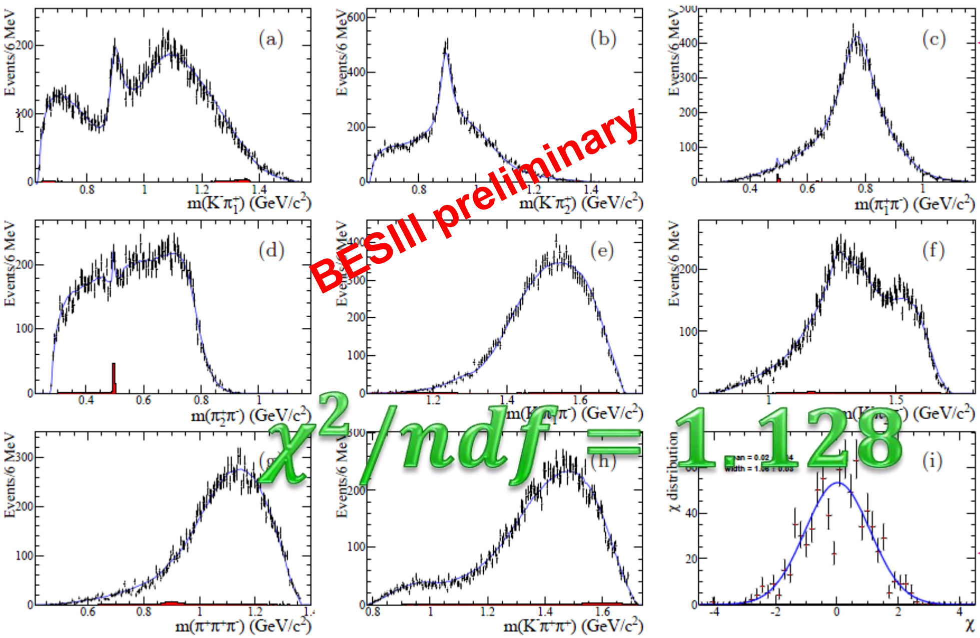
- **First study of the resonant structure of this decay**
  - **Excellent place for a direct measurement of K^+K^- S-wave amplitude**
- **Data analysis (3fb^{-1})**
  - $D^{*+} \to D^0 \pi_s^+, D^+ \to K^- K^+ K^+$
  - **Fit Δm of D^{*+} to extract signal events**
  - **Possible contributions: $\phi(1020)$, $a_0(980)$, $f_0(980)$, $f_0(1370)$, $a_0(1450)$, K^+K^- S-wave, Non Resonance ⇒ Fit fractions for the dominant contributions**
- **Conclusions**
  - **The S-wave accounts for ~90% of the decay rate**
  - **The $f_0(980)$ is the dominant contribution, with a stable fit fraction for the $\phi(1020)$ amplitude (~7%)**
  - **Large interference between S-wave components.**
  - **A direct measurement of the K^+K^- S-wave will follow**

LHCb-CONF-2016-008,in preparation

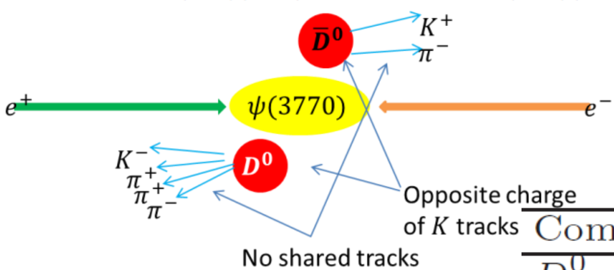




Amplitude analysis of $D^0 \to K^-\pi^+\pi^+\pi^-$



- Knowledge of intermediate process can be widely used:
  - Branching ratio measurement,
  - Strong phase measurement,
  - CKM unitary triangle $\gamma(\phi_3)$ measurement.
- BESIII: 2.93fb^{-1} @3.773GeV
  - Double Tag technique applied
  - Amplitude Analysis



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
$D^0 \to K_1^-(1270)(K^-\rho^0)\pi^+$	$0.27 \pm 0.02 \pm 0.02 \pm 0.01$	
$D^0 \to K^-\pi^+\rho^0$	$0.68 \pm 0.09 \pm 0.18 \pm 0.02$	0.51 ± 0.23
$D^0 \to \bar{K}^{*0}\pi^+\pi^-$	$0.57 \pm 0.03 \pm 0.03 \pm 0.02$	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

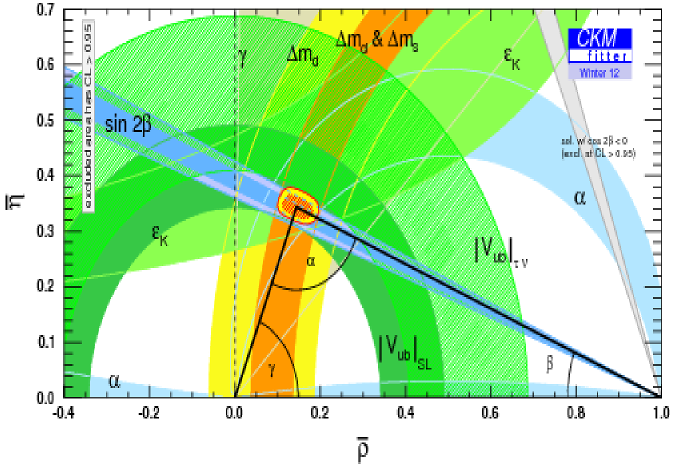
BESIII

Quantum Correlations at the $\psi(3770)$

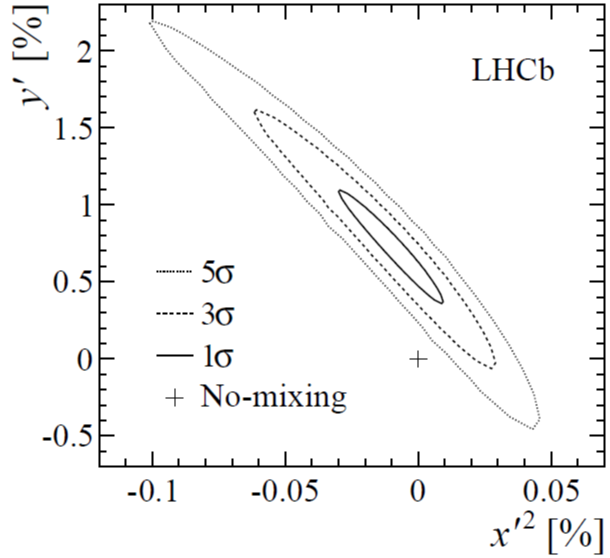
- $e^+e^- \to \psi(3770) \to D\bar{D}$: Pure $J^{PC} = 1^{--}$ initial state
- A typical entangled 2-state system
  - $L=1$ and Bose statistics $\Rightarrow D\bar{D}$ state anti-symmetric
  - $|\alpha\rangle = \frac{1}{\sqrt{2}}\left(|D^0(p)\rangle|\overline{D^0}(-p)\rangle - |\overline{D^0}(p)\rangle|D^0(-p)\rangle\right)$

    $\Rightarrow D^0D^0$ and $\overline{D^0D^0}$ are prohibited
  - At any time until one D decays : one D^0 and one $\overline{D^0}$
- Similar to CP eigenstates $|D_{CP\pm}\rangle = \left(|D^0\rangle \pm |\overline{D^0}\rangle\right)/\sqrt{2}$, assuming no CPV:
  - $|\alpha\rangle = \frac{1}{\sqrt{2}}(|D_{CP+}(p)\rangle|D_{CP-}(-p)\rangle - |D_{CP-}(p)\rangle|D_{CP+}(-p)\rangle)$
  - At any time one D_{CP+} , one D_{CP-} $\Rightarrow$ "CP eigenstates filter" $\Rightarrow$ Clear differences in Dalitz plots for CP+ and CP- tags

QC inputs for Charm Physics



Precision CKM test



Charm Mixing & CP violation

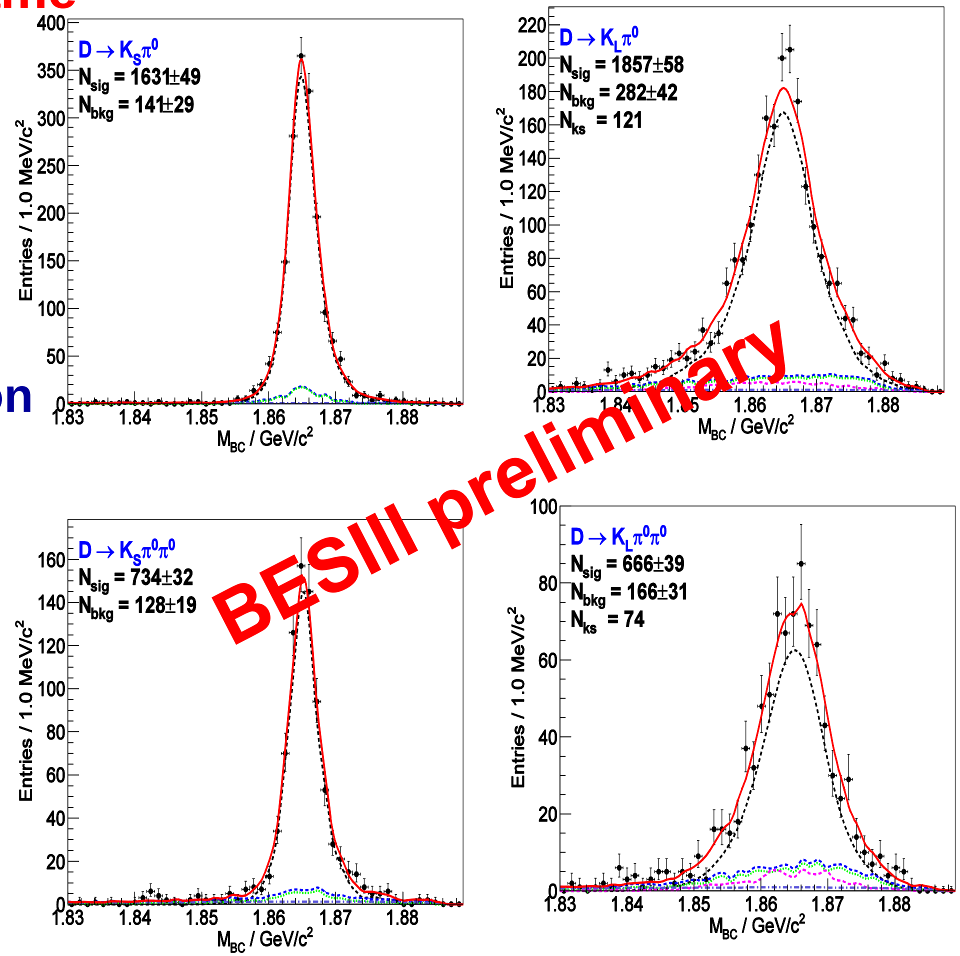
- inputs from Quantum Correlated (QC) $\psi(3770)\to D\bar{D}$ decays
  - (Averaged)Strong phase difference: δ_D （i.e. BESIII: PLB 734 (2014) 227, CLEOc: PRD86,112001(2012) $\Rightarrow$ $\cos\delta_{K\pi}$)
  - Coherent factors: R_D
  - (Averaged)Strong phase in Dalitz bins: c_i, s_i $\Leftarrow$ CLEOc : PRD82,112006(2010), BESIII preliminary results with 2.93 fb^{-1}
- *B* factories, LHCb, Super *B* factories are the customers

Absolute BR of $D^0 \to K_S/K_L\pi^0(\pi^0)$

- Interference $D \to K^0\pi$'s with (DCS) $D \to \bar{K}^0\pi$'s component ⇒ Br($D \to K_S\pi$) and Br($D \to K_L\pi$): Not same
- absolute branching fractions decays $D^0 \to K_S\pi^0$, $D^0 \to K_S\pi^0\pi^0$, $D^0 \to K_L\pi^0$ and $D^0 \to K_L\pi^0\pi^0$ are measured.
- K_L reconstruction
  - EMC neutral cluster ⇒ K_L position
  - Fix $\Delta E=0$ ⇒ K_L momentum

$D \to K^0_{S,L}\pi^0$			
	$BR_{K_S\pi^0}(\%)$	$BR_{K_L\pi^0}(\%)$	$R(D \to K_{S,L}\pi^0)$
$K\pi$	1.209±0.041	1.044±0.038	0.0731±0.0245
$K3\pi$	1.205±0.035	0.946±0.033	0.1207±0.0225
$K\pi\pi^0$	1.237±0.028	0.939±0.028	0.1373±0.0184
All	1.221±0.019	0.967±0.019	0.1163±0.0123
$D \to K^0_{S,L}\pi^0\pi^0$			
	$BR_{K_S2\pi^0}(\%)$	$BR_{K_L2\pi^0}(\%)$	$R(D \to K_{S,L}2\pi^0)$
$K\pi$	1.028±0.048	1.257±0.075	-0.1001±0.0374
$K3\pi$	0.873±0.040	1.002±0.060	-0.0689±0.0376
$K\pi\pi^0$	1.004±0.036	1.156±0.062	-0.0703±0.0320
All	0.965±0.023	1.123±0.037	-0.0755±0.0204

BESIII preliminary

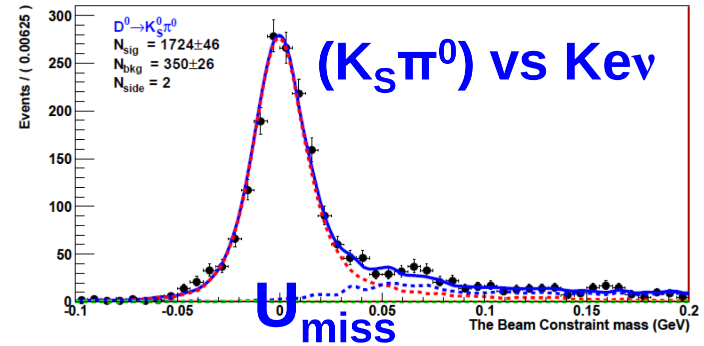


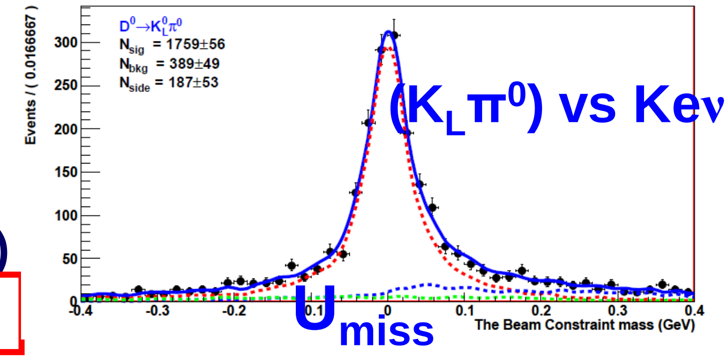
y_{CP} Measurement from $D^0 \to K_S/K_L\pi^0$

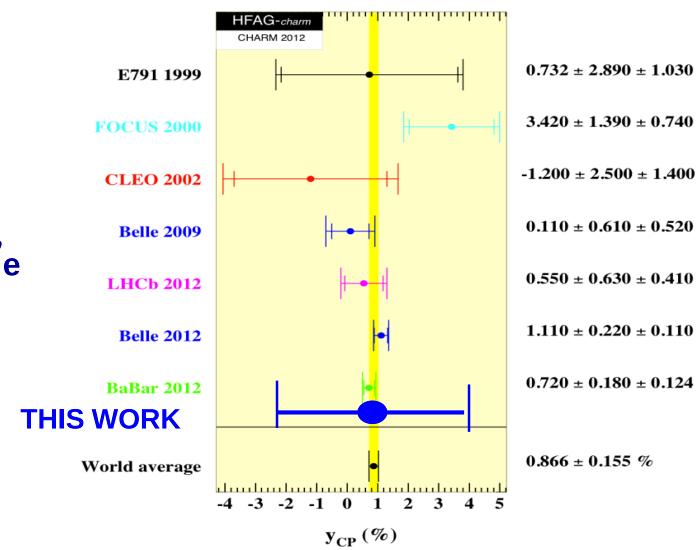
- Single Tag decay rate (CP tags)
  - $\Gamma_{CP\pm} \propto 2|A_{CP\pm}|^2(1 \mp y)$
- Double Tag decay rate (Flavor tags + CP tags)
  - $\Gamma_{l;CP\pm} \propto |A_l|^2 |A_{CP\pm}|^2$
- Neglect term y^2 or higher order
  - $y_{CP} \approx \frac{1}{4}\left(\frac{\Gamma_{l;CP+}\Gamma_{CP-}}{\Gamma_{l;CP-}\Gamma_{CP+}} - \frac{\Gamma_{l;CP-}\Gamma_{CP+}}{\Gamma_{l;CP+}\Gamma_{CP-}}\right)$
- BESIII Previous measurement: (PLB 744(2015)339)
  - Flavor tags: $Ke\nu_e$, $K\mu\nu_\mu$
  - CP+ tags (3 modes): K^-K^+, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$,
  - CP- tags (3 modes): $K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$

y_{CP}=(-2.0±1.3±0.7)%

- For this analysis
  - CP+ tag: $K^0_L\pi^0$; CP- tag: $K^0_S\pi^0$; Flavor tag: $Ke\nu_e$
  - Double-Tag yields are from U_{miss} fit
  - y_{CP} = (0.98±2.43)% (Statistical error only)





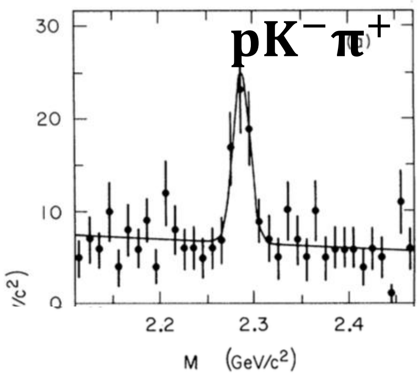


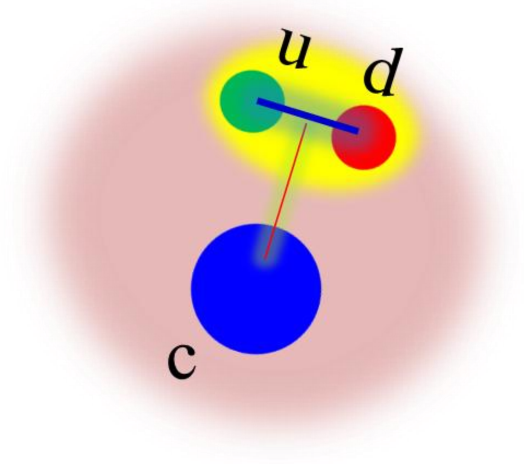
Λ_c decays

More Details of BESIII analysis can be found in Xiaozhong's talk tomorrow.

Introduction to Λ_c

- Λ_c : First evidence Fermi Lab (PRL37, 882 (1976)) and Established at Mark II (PRL44, 10 (1980))
- The lightest charmed baryon: 2286.48MeV
- Most of the charmed baryons will eventually decay to Λ_c^+
- Charm quark is heavy: (1500 MeV) > u,d,s quarks (300-500 MeV)
- spin-spin interaction $\propto$ $1/m_1m_2$
- Di-quark correlation in light quarks (more simple!)

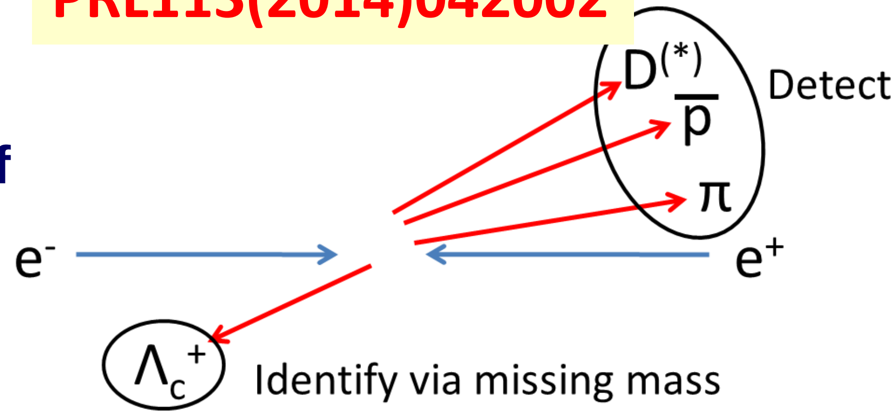


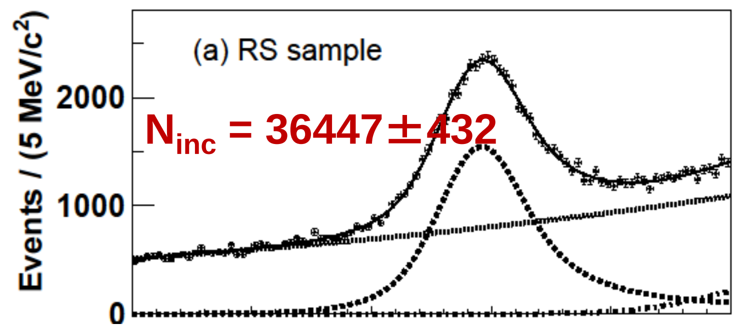


Absolute BR of $\Lambda_c^+ \rightarrow pK^-\pi^+$

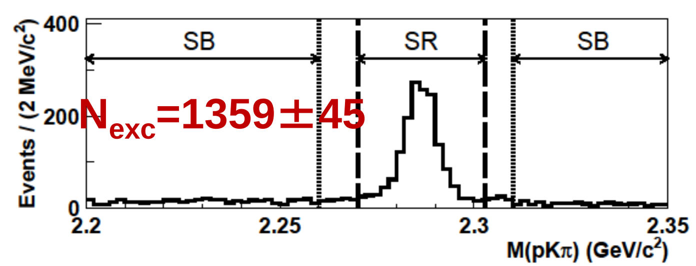
PRL113(2014)042002

- **Br($\Lambda_c^+ \rightarrow pK\pi^-$) important for the measurements related to charmed baryons (ex:branching fraction of $B \rightarrow \Lambda_c X$, baryon cross section).**
- **The accuracy had not been good (5.0±1.3)% :26%. Existing measurements are model dependent.**
- **Model independent measurement. Detect $D^{(*)}p\pi$ and reconstruct Λ_c^+ using the missing mass technique, which does not need specific decay mode.**
- **BR measurements**
  - **$6.84 \pm 0.24^{+0.21}_{-0.27}\% \Leftrightarrow 5.0 \pm 1.3\%$**
  - **Factor 5 improvement!**
  - **Slight tension with BES III (see next slides)**





Missing mass of $D^{(*)}p\pi$



$M(pK\pi^-)$. Require exactly 3 remaining particles

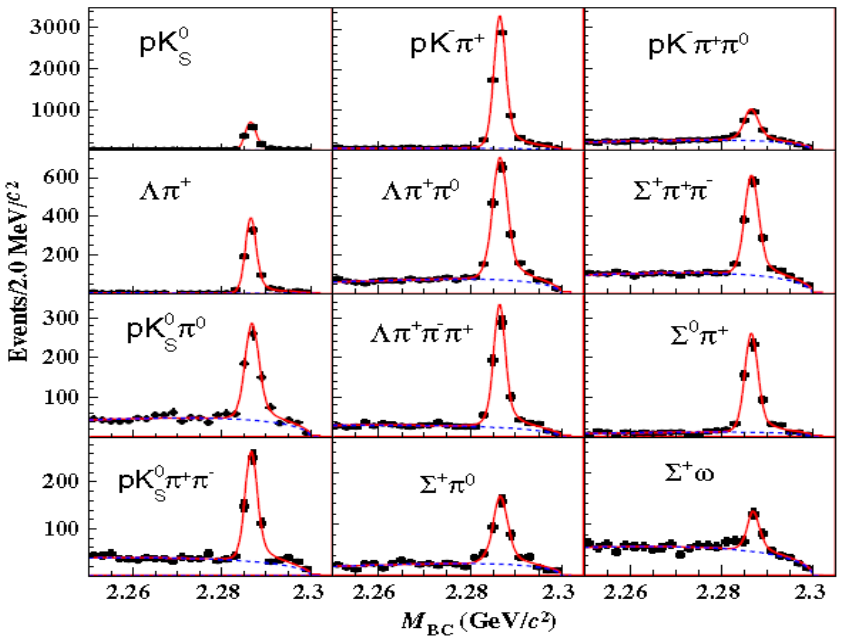
Absolute BRs of Λ_c decays

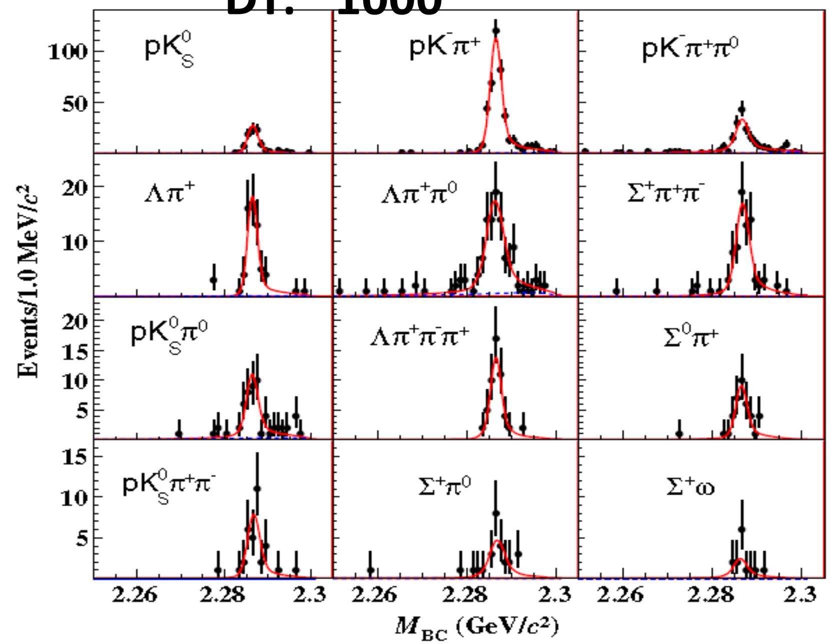
BESIII

PRL116(2016)052001

ST: ~15000 $N_{\Lambda_c^+\bar{\Lambda}_c^-} = (105.9 \pm 4.8 \pm 0.5) \times 10^3$

DT: ~1000





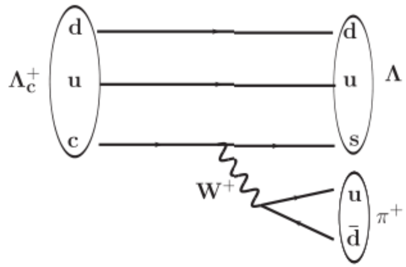
- **Threshold pair-productions: technique is simple and straightforward.**
- **Absolute BFs are improved significantly.**
- **BESIII BF for $\Lambda_c^+ \to pK^-p^+$ is smaller.**
- **Improved absolute BF of $pK^-\pi^+$ together with BELLE's result are key to calibrate other decays.**

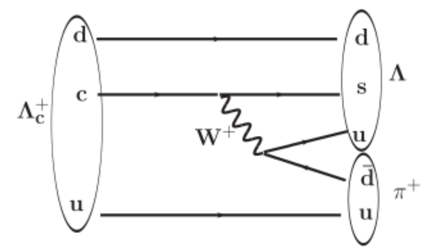
Mode	This work (%)	PDG (%)	BELLE $\mathcal{B}$
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50	
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	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	

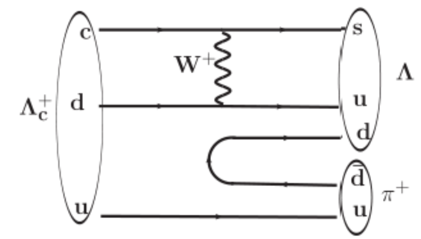
A conflict: $B(\Lambda_c^+ \to p\overline{K^0})$ v.s. $B(\Lambda_c^+ \to \Lambda\pi^+)$

T: external W-emission | **C: internal W-emission** | **W: W-exchange**

$\Lambda_c^+ \to \Lambda\pi^+$:

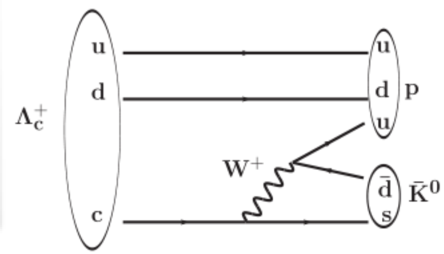


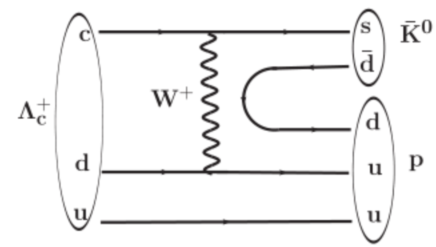




$\Lambda_c^+ \to p\overline{K^0}$

X





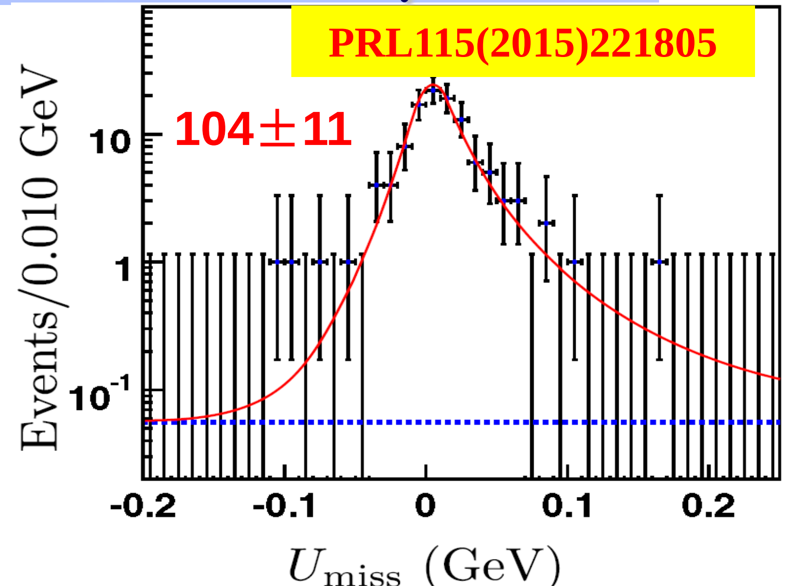
factorizable | non-factorizable

- **In naïve quark-diquark model, C- and W-diagram are suppressed, hence $B(\Lambda_c^+ \to p\overline{K^0}) << B(\Lambda_c^+ \to \Lambda\pi^+)$**
- **But BESIII measures: $B(\Lambda_c^+ \to p\overline{K^0})$ =(3.04±0.18)%; $B(\Lambda_c^+ \to \Lambda\pi^+)$=(1.24±0.08)%**
- **The non-factorizable C- and W-diagram are not trivial.**
- **Experimental studies on the non-factorizable C- and W-diagrams is critical in understanding the Λ_c^+ internal dynamics.**

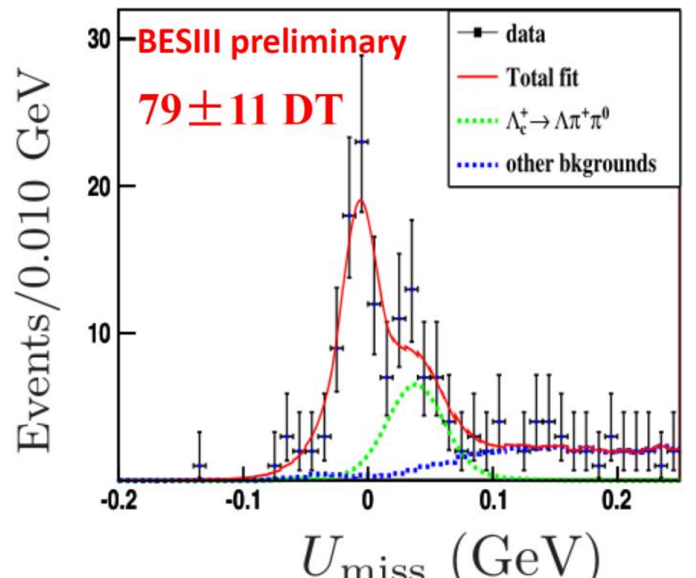
$\Lambda_c^+ \to \Lambda e^+ \nu_e$ and $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$

- Theoretical calculations on the BF ranges from 1.4% to 9.2%
- Experimentally:
  - ARGUS reported the first measurement (PLB269, 234 (1991))
  - CLEO : (PLB 323, 219 (1994))
  - No direct measurement!
- First absolute measurement
- Important for test and calibrate the LQCD calculations.
- Useful for determining CKM matrix elements

$$\frac{\Gamma[\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu]}{\Gamma[\Lambda_c^+ \to \Lambda e^+ \nu_e]} = 0.96 \pm 0.16 \pm 0.04$$



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



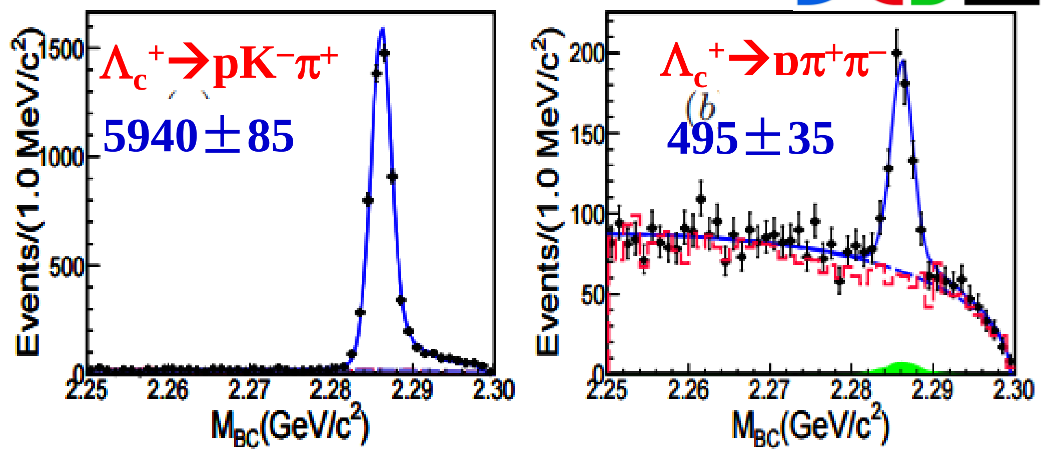
$B[\Lambda_c^+ \to \Lambda \mu^+ \nu] = (3.49 \pm 0.46 \pm 0.26)\%$

SCS Decays: $\Lambda_c^+ \to p\pi^+\pi^-$, $\Lambda_c^+ \to pK^+K^-$

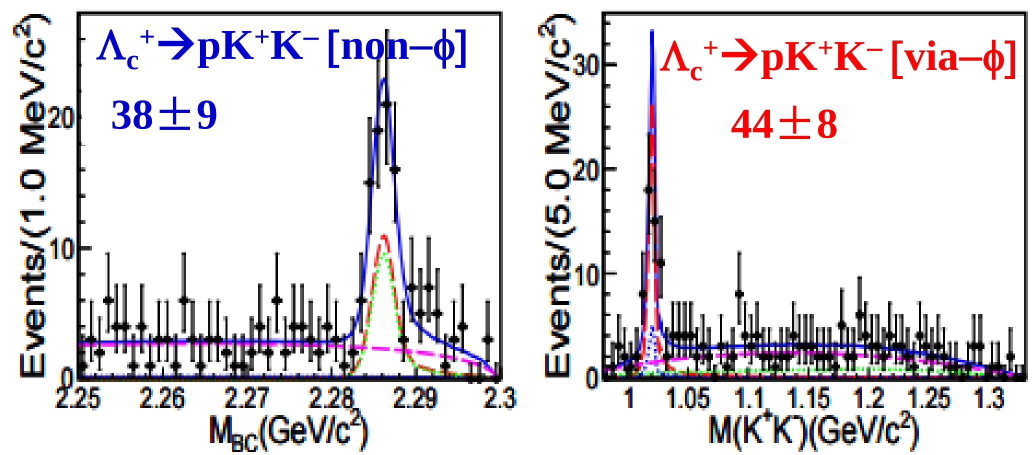
Submitted to PRL arXiv:1608.00407

- **Study of SCS - Singly Cabibbo Suppressed decays can shed light on dynamics of Λ_c^+ decays**
- **B[$\Lambda_c^+ \to p\phi$] is of particular interest since it proceeds Internal W-emission only, which is essential to validate the theoretical models and test the application of large-N_c factorization in charmed baryon.**
- **ST study, relative BFs to $\Lambda_c^+ \to pK^-\pi^+$ is measured.**
- **Input BESIII measurement:**

B[$\Lambda_c^+ \to pK^-\pi^+$]=(5.84±0.27±0.23)%



Two-dimensional unbinned maximum likelihood fit

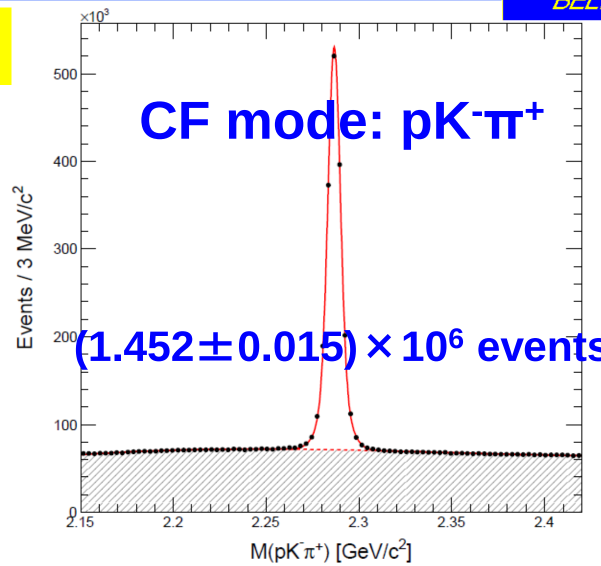


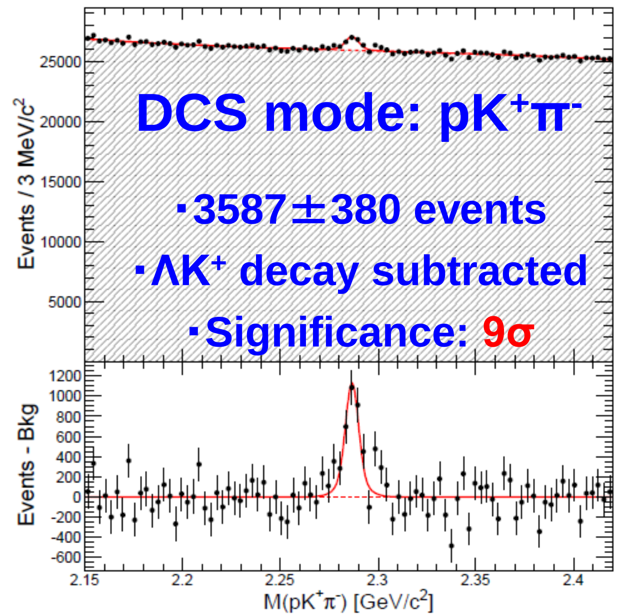
−	$\mathcal{B}_{\rm mode}$	$\mathcal{B}$(PDG)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(3.91 \pm 0.28 \pm 0.15 \pm 0.24) \times 10^{-3}$	$(3.5 \pm 2.0) \times 10^{-3}$
$\Lambda_c^+ \to p\phi$	$(1.06 \pm 0.19 \pm 0.08 \pm 0.06) \times 10^{-3}$	$(8.2 \pm 2.7) \times 10^{-4}$
$\Lambda_c^+ \to pK^+K^-$ (non-ϕ)	$(5.47 \pm 1.30 \pm 0.41 \pm 0.33) \times 10^{-4}$	$(3.5 \pm 1.7) \times 10^{-4}$

Observation of DCS Decays: $\Lambda_c^+ \to pK^+\pi^-$

PRL117(2016)011801

- Baryon sector: Doubly Cabbibo Suppressed (DCS) decay has **NEVER been observed**.
- Naively, ratio to CF decay, $pK^-\pi^+$ is expected to be $\frac{B(\Lambda_c^+ \to pK^+\pi^-)}{B(\Lambda_c^+ \to pK^-\pi^+)} \simeq \tan^4\theta_c$
- In the CF Λ_c^+ decay, the W exchange diagram may contribute.
- Belle results:
  - ratio to CF decay: $(1.10\pm0.17)\times\tan^4\Theta$
  - W exchange diagram contribution in DCS $\Lambda_c^+ \to pK^+\pi^-$ decay is small.
  - BR(DCS) = $1.61\pm0.23\,^{+0.07}_{-0.08}\times10^{-4}$ if BR(CF) = $(6.84\,^{+0.32}_{-0.40})\times10^{-2}$ (PRL, 113, 042002) is used.





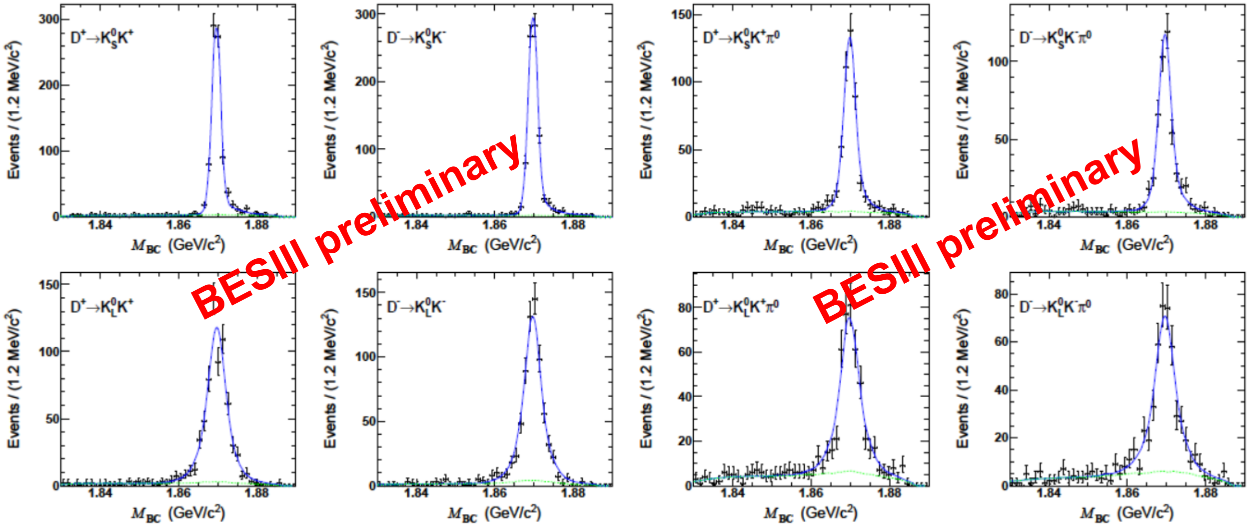
Summary and future perspective

- (Semi-)Leptonic decays
  - Many new and improved form factor measurements (Exist Lattice QCD calculations generally in good agreement with data)
- Hadronic decays
  - Entered the precision era for amplitude analysis
  - The large ψ(3770) sample of BESIII allows to make measurements with improved precisions
- Charmed baryon
  - precision measurements in Λ_c decays
  - fill the unknown charts in the PDG
  - observe doubly Cabibbo-suppressed decays
- In future
  - BESIII has collected 3 fb^{-1} 'D_S' data around Ecm ~ 4180 MeV, expect new results on DS decays in the near future.
  - More Λ_c data taking proposed at BESIII ⇒ push the precisions to the level as we have in D/DS
  - LHCb & Belle II (will turn on soon): Large inclusive samples of all charmed hadrons ⇒ two challenges: control of systematics & better theoretical tools

Thank you

Backup slides

$D^+ \to K_S K^+(\pi^0)$ and $D^+ \to K_L K^+(\pi^0)$



$$\mathcal{A}_{CP} = \frac{\mathcal{B}(D^+) - \mathcal{B}(D^-)}{\mathcal{B}(D^+) + \mathcal{B}(D^-)}$$

Mode	$\mathcal{B}(D^+)$ $(\times 10^{-3})$	$\mathcal{B}(D^-)$ $(\times 10^{-3})$	$\overline{\mathcal{B}}$ $(\times 10^{-3})$	$\mathcal{A}_{CP}$ (%)
$K_S^0 K^\pm$	$3.01 \pm 0.12 \pm 0.10$	$3.10 \pm 0.12 \pm 0.10$	$3.06 \pm 0.09 \pm 0.10$	$-1.5 \pm 2.8 \pm 1.6$
$K_S^0 K^\pm \pi^0$	$5.23 \pm 0.28 \pm 0.24$	$5.09 \pm 0.29 \pm 0.22$	$5.16 \pm 0.21 \pm 0.23$	$1.4 \pm 4.0 \pm 2.4$
$K_L^0 K^\pm$	$3.13 \pm 0.14 \pm 0.13$	$3.32 \pm 0.15 \pm 0.13$	$3.23 \pm 0.11 \pm 0.13$	$-3.0 \pm 3.2 \pm 1.2$
$K_L^0 K^\pm \pi^0$	$5.17 \pm 0.30 \pm 0.21$	$5.26 \pm 0.30 \pm 0.20$	$5.22 \pm 0.22 \pm 0.21$	$-0.9 \pm 4.1 \pm 1.6$

- **The branching fraction of $D^+ \to K_S K^+$ agrees with the CLEO result.**

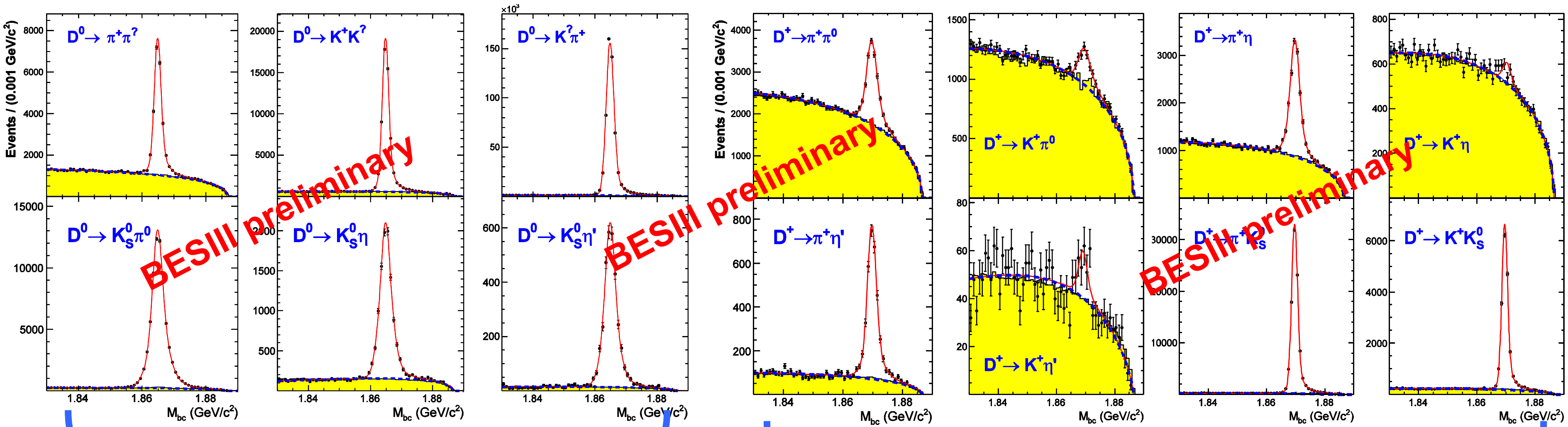
	$\mathcal{B}(D^+ \to K_S^0 K^+)$
CLEO	$(3.14 \pm 0.09 \pm 0.08) \times 10^{-3}$

Phys. Rev. D77, 091106(R) (2008)

Single tag method

- **The branching fractions of $D^+ \to K_S K^+ \pi^0$, $D^+ \to K_L K^+$ and $D^+ \to K_L K^+ \pi^0$ are measured for the first time.**
- **No evidence for CP asymmetry in the four SCS decays.**

D^0 (D^+) $\rightarrow PP$ (P= pseudoscalar)



6 D^0 modes

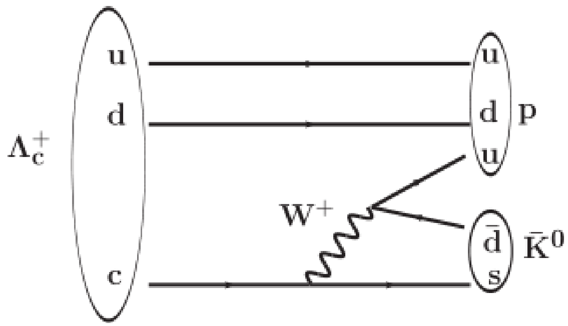
8 D^+ modes

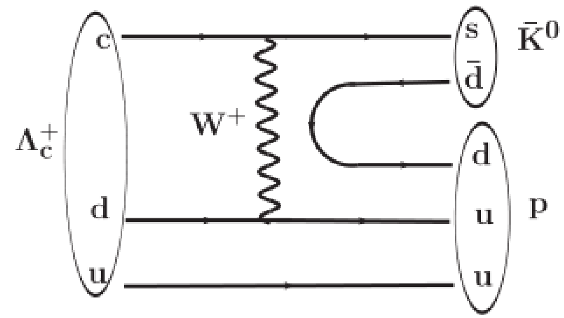
Mode	$N^{\rm net}_{\rm signal}$	ε (%)	$\mathcal{B}\pm$(stat)$\pm$(sys)	$\mathcal{B}_{\rm P}$
$\pi^+\pi^-$	21105 ± 249	66.03 ± 0.25	$(1.505 \pm 0.018 \pm 0.031) \times 10^{-3}$	$(1.421 \pm 0.025) \times 10^{-3}$
K^+K^-	56438 ± 273	62.82 ± 0.32	$(4.229 \pm 0.020 \pm 0.087) \times 10^{-3}$	$(4.01 \pm 0.07) \times 10^{-3}$
$K^-\pi^+$	537745 ± 767	64.98 ± 0.09	$(3.896 \pm 0.006 \pm 0.073)$ %	(3.93 ± 0.04) %
$K^0_S\pi^0$	66539 ± 302	38.06 ± 0.17	$(1.236 \pm 0.006 \pm 0.032)$ %	(1.20 ± 0.04) %
$K^0_S\eta$	9532 ± 126	31.96 ± 0.14	$(5.149 \pm 0.068 \pm 0.134) \times 10^{-3}$	$(4.85 \pm 0.30) \times 10^{-3}$
$K^0_S\eta'$	3007 ± 61	12.66 ± 0.08	$(9.562 \pm 0.197 \pm 0.379) \times 10^{-3}$	$(9.5 \pm 0.5) \times 10^{-3}$
$\pi^0\pi^+$	10108 ± 267	48.98 ± 0.34	$(1.259 \pm 0.033 \pm 0.025) \times 10^{-3}$	$(1.24 \pm 0.06) \times 10^{-3}$
π^0K^+	1834 ± 168	51.52 ± 0.42	$(2.171 \pm 0.198 \pm 0.060) \times 10^{-4}$	$(1.89 \pm 0.25) \times 10^{-4}$
$\eta\pi^+$	11636 ± 215	46.96 ± 0.25	$(3.790 \pm 0.070 \pm 0.075) \times 10^{-3}$	$(3.66 \pm 0.22) \times 10^{-3}$
ηK^+	439 ± 72	48.21 ± 0.31	$(1.393 \pm 0.228 \pm 0.124) \times 10^{-4}$	$(1.12 \pm 0.18) \times 10^{-4}$
$\eta'\pi^+$	3088 ± 83	21.49 ± 0.18	$(5.122 \pm 0.140 \pm 0.210) \times 10^{-3}$	$(4.84 \pm 0.31) \times 10^{-3}$
$\eta'K^+$	87 ± 25	22.39 ± 0.22	$(1.377 \pm 0.428 \pm 0.202) \times 10^{-4}$	$(1.83 \pm 0.23) \times 10^{-4}$
$K^0_S\pi^+$	93884 ± 352	51.38 ± 0.18	$(1.591 \pm 0.006 \pm 0.033) \times 10^{-2}$	$(1.53 \pm 0.06) \times 10^{-2}$
$K^0_SK^+$	17704 ± 151	48.45 ± 0.14	$(3.183 \pm 0.028 \pm 0.065) \times 10^{-3}$	$(2.95 \pm 0.15) \times 10^{-3}$

BR results Consistent with other measurements and have similar precisions with the existing best measurements.

W-exchange contribution in Λ_c^+ weak decays

$\Lambda_c^+ \to p\overline{K^0}$



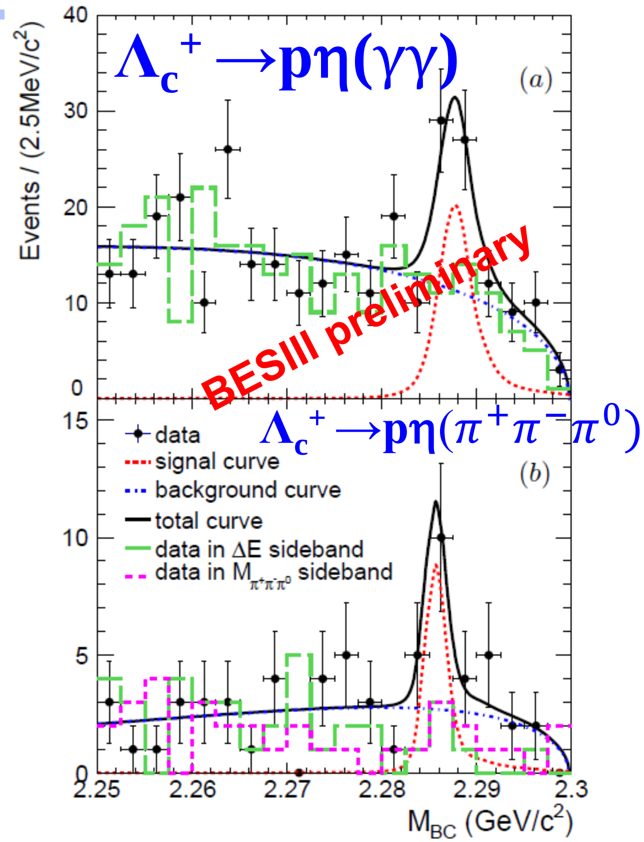


- **References:**
- **Experimental measurement of $B(\Lambda_c^+ \to p\overline{K^0})$ are not consistent with theoretically factorization approach at tree level.**
- **Contrary to charmed meson, W-exchange contribution is important.**
- **W-exchange are non-factorizable. There contribution can be only determined by experiment measurement.**
- **Search for process happened only through W-exchange process to extract their contribution are key to factorization approach**

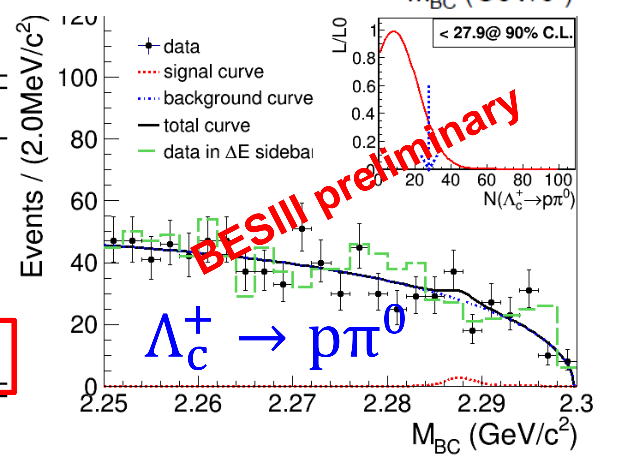
$$\Lambda_c^+ \to \Xi^0 K^+, \Xi^{*0} K^+, \Delta^{++} K^-, \Sigma^+ K^+ K^-$$

$\Lambda_c^+ \to p^+\eta^0$ and $\Lambda_c^+ \to p^+\pi^0$

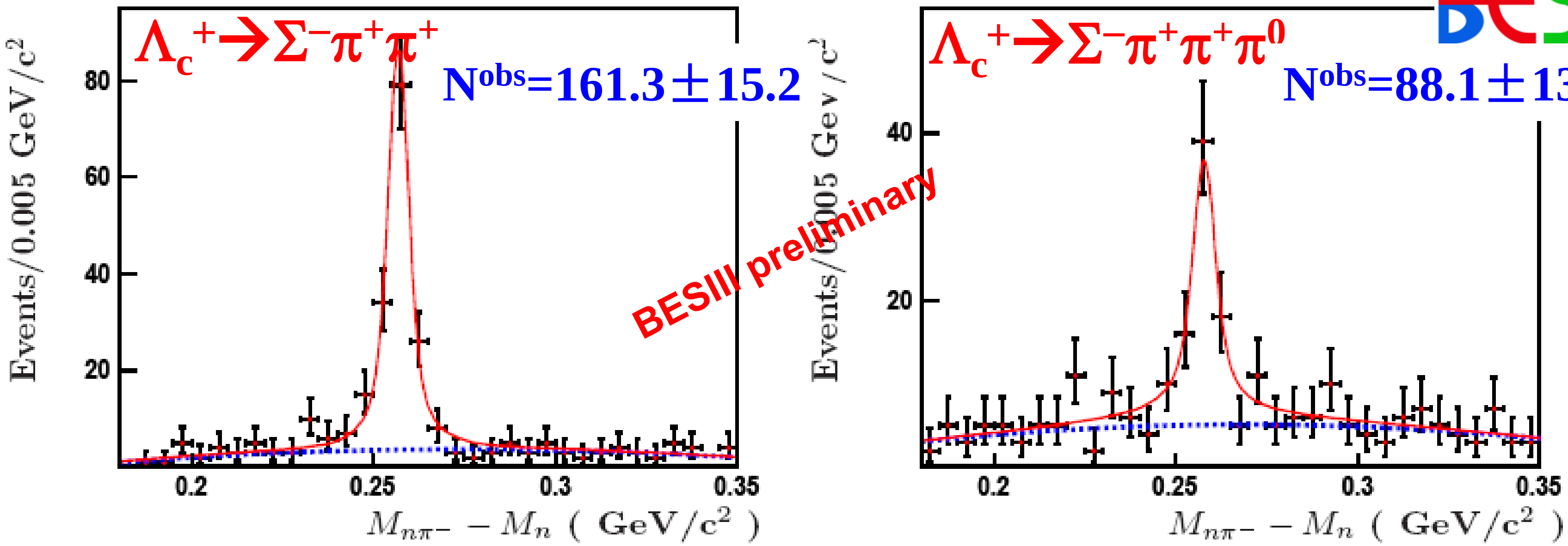
- SU(3) flavor symmetry $\Rightarrow$ $Br(\Lambda_c^+ \to p\eta)$ >> $Br(\Lambda_c^+ \to p\pi^0)$
- Signal Tag method and un-binned maximum likelihood fit on the M_{BC} is performed
- First measurement of absolute BF of $\Lambda_c^+ \to p\eta$
- No obvious signal is observed for $\Lambda_c^+ \to p\pi^0$
- **Preliminary results:**



	$p\eta_{\gamma\gamma}$	$p\eta_{\pi^+\pi^-\pi^0}$	$p\pi^0$
ΔE (GeV)	$[-0.034, 0.030]$	$[-0.027, 0.018]$	$[-0.056, 0.029]$
$N_{\rm sig}$	38 ± 11	14 ± 5	< 27.9
Significance	3.2σ	2.7σ	–
$\varepsilon(\%)$	39.8	20.3	49.0
$\mathcal{B}(\times 10^{-3})$	$1.15 \pm 0.33 \pm 0.09$	$1.45 \pm 0.52 \pm 0.15$	< 0.27



$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ and $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$



- **The total measured Λ_c^+ decays BR < 65%.**
- **PDG2015 : $B[\Lambda_c^+ \to \Sigma^-\pi^+\pi^+]$ =(2.3±0.4)% (Large error)**
- **Prelininary results (statistical errors only):**

  $B[\Lambda_c^+ \to \Sigma^-\pi^+\pi^+]$ =(1.81±0.17)%

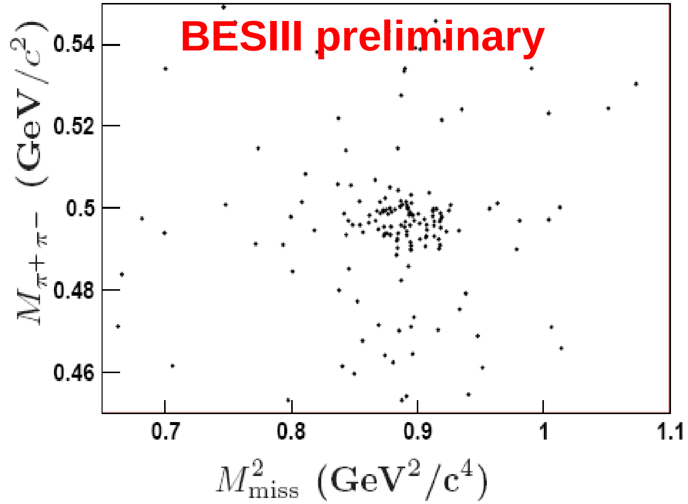
  $B[\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0]$=(2.11 ±0.33)% [First observation]

- **Consistent with PDG15 with better precision.**

Observation of $\Lambda_c^+ \to nK_S^0\pi^+$

- The relative BF of neutron-involved mode to proton-involved mode is essential to test the isospin symmetry for Λ_c^+ decays. [arXiv:1601.04241]
- The missing **neutron** is detected by:

$$M^2_{\rm miss} = (p_{\Lambda_c^+} - p_{K_S^0} - p_{\pi^+})^2 = E^2_{\rm miss} - c^2|\overrightarrow{p}_{\rm miss}|^2$$

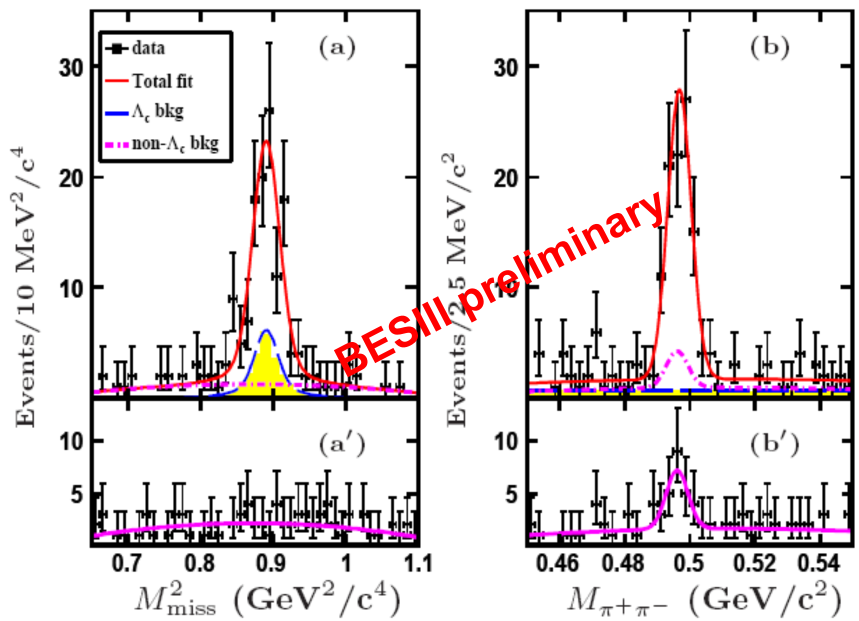


- Fit to $M^2_{\rm miss}$ and $M_{\pi+\pi}$ spectra in (a,b) Λ_c^- signal region and (a',b') Λ_c^- sideband region simultaneously.

83±11 net signal events observed

- BESIII Preliminary results:

$$B[\Lambda_c^+ \to nK_S^0\pi^+] = (1.82 \pm 0.23 \pm 0.11)\%$$



 First observation of Λ_C^+ decays to final states involving the neutron.

Amplitude analysis of $D^0 \to K_S^0 K^\pm \pi^\mp$

Fit fractions (%) for the dominant contributions.

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

Resonance	LASS	GLASS
$K^*(892)^+$	$56.9 \pm 0.6 \pm 1.1$	$57.0 \pm 0.8 \pm 2.6$
$K^*(1410)^+$	$9.6 \pm 1.1 \pm 2.9$	$5 \pm 1 \pm 4$
$(K_S^0\pi)^+_{S-\text{wave}}$	$11.7 \pm 1.0 \pm 2.3$	$12 \pm 2 \pm 9$
$K^*(892)^0$	$2.5 \pm 0.2 \pm 0.2$	$2.5 \pm 0.25 \pm 0.4$
$\overline{K}^*(1410)^0$	$3.8 \pm 0.5 \pm 2.0$	$9 \pm 1 \pm 4$
$(K_S^0\pi)^0_{S-\text{wave}}$	$18 \pm 2 \pm 4$	$11 \pm 2 \pm 10$
$a_0(980)^-$	$4.0 \pm 0.7 \pm 1.1$	–

All parameters but $a_R e^{i\phi_R}$ are common to the two decay modes.

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

Resonance	LASS	GLASS
$K^*(892)^-$	$28.8 \pm 0.4 \pm 1.3$	$29.5 \pm 0.6 \pm 1.6$
$K^*(1410)^-$	$11.9 \pm 1.5 \pm 2.2$	$3.1 \pm 0.6 \pm 1.6$
$(K_S^0\pi)^-_{S-\text{wave}}$	$6.3 \pm 0.9 \pm 2.1$	$5.4 \pm 0.9 \pm 1.7$
$K^*(892)^0$	$4.8 \pm 0.2 \pm 0.4$	$5.2 \pm 0.2 \pm 0.3$
$\overline{K}^*(1410)^0$	$2.2 \pm 0.6 \pm 2.1$	$9 \pm 1 \pm 4$
$(K_S^0\pi)^0_{S-\text{wave}}$	$17 \pm 2 \pm 6$	$12 \pm 1 \pm 8$
$a_0(980)^+$	$26 \pm 2 \pm 10$	$11 \pm 1 \pm 6$

Complete tables in supplemental slides.

y_{CP}: Analysis Technique

- To get y_{CP}, the following double tag modes are used.
  Single tag:
  - ✓ CP+: $K_L\pi^0$;
  - ✓ CP-: $K_S\pi^0$;

  Double tag:
  - ✓ CP+ ($K_L\pi^0$) VS Kev;
  - ✓ CP- ($K_S\pi^0$) VS Kev ;
- The relation of single tag and double tag yield forms as:

$$N_{ST(CP\pm)} = (1 \mp y_{CP})2N_{D^0\bar{D}^0} Br_{CP\pm} \cdot \varepsilon_{CP\pm}$$

$$N_{DT(Kev,CP\pm)} = 2N_{D^0\bar{D}^0} Br_{Kev} Br_{CP\pm} \cdot \varepsilon_{CP\pm,Kev}$$

- where $K_L\pi^0$ single tag yield can be got from the other CP+ modes:

$$\frac{N_{K_L\pi^0}}{\varepsilon_{K_L\pi^0}} = \frac{N_{CP+}}{\varepsilon_{CP+}} \frac{N_{K_L\pi^0,CF} / \varepsilon_{K_L\pi^0,CF}}{N_{CP+,CF} / \varepsilon_{CP+,CF}}$$

- So,

$$y_{CP} = \frac{\frac{N_{CP-,Kev} / \varepsilon_{CP-,Kev}}{N_{CP-} / \varepsilon_{CP-}} - \frac{N_{CP+,Kev} / \varepsilon_{CP+,Kev}}{N_{CP+} / \varepsilon_{CP+}}}{\frac{N_{CP-,Kev} / \varepsilon_{CP-,Kev}}{N_{CP-} / \varepsilon_{CP-}} + \frac{N_{CP+,Kev} / \varepsilon_{CP+,Kev}}{N_{CP+} / \varepsilon_{CP+}}}$$