Charmed hadron decays at BESIII and future

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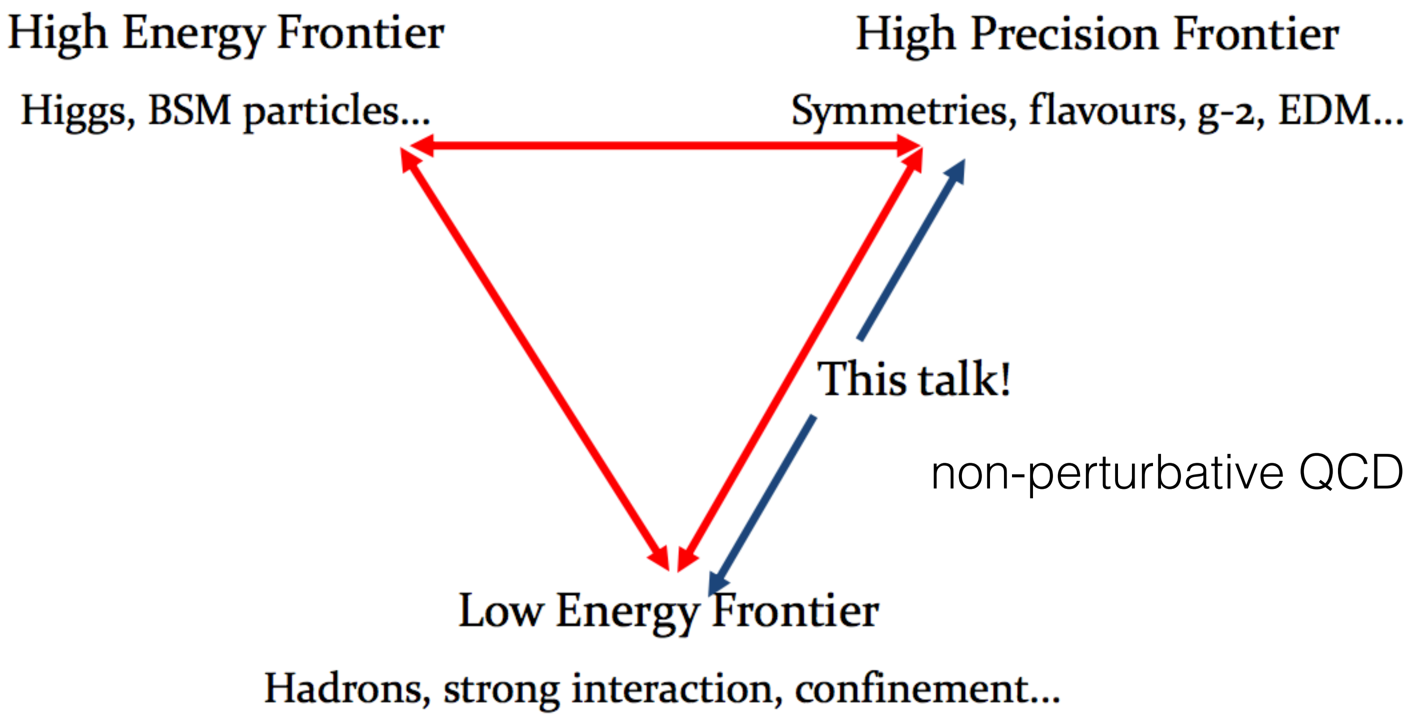
(On behalf of the BESIII collaboration)

Outline

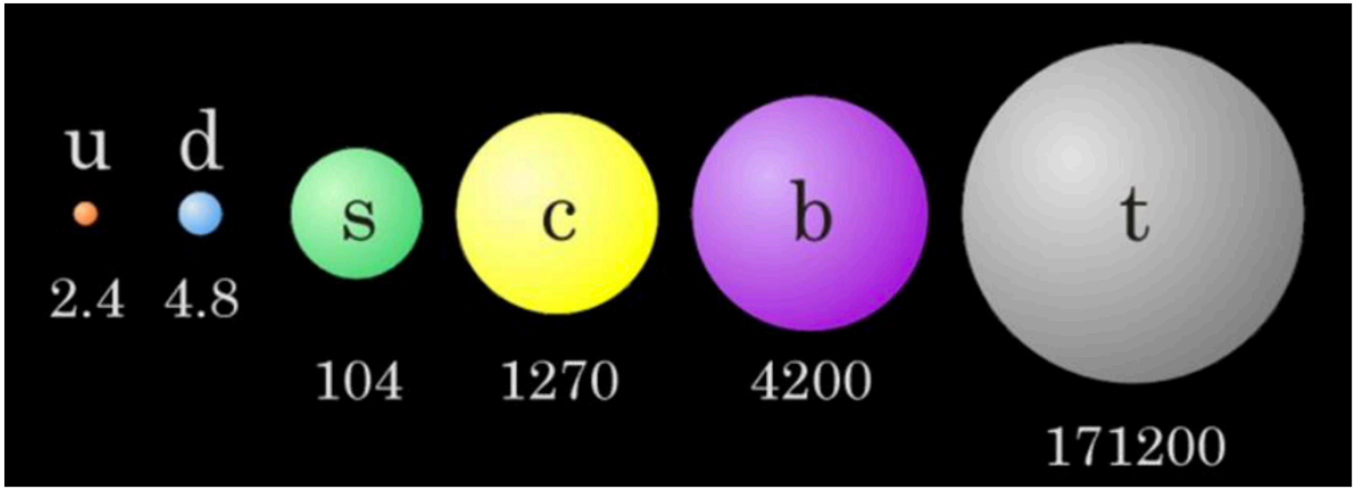
- Introduction
- BEPCII/BESIII
- Charmed hadron decays at BESIII
- Future prospects at STCF
- Summary and Outlook

Frontiers of the Standard Model

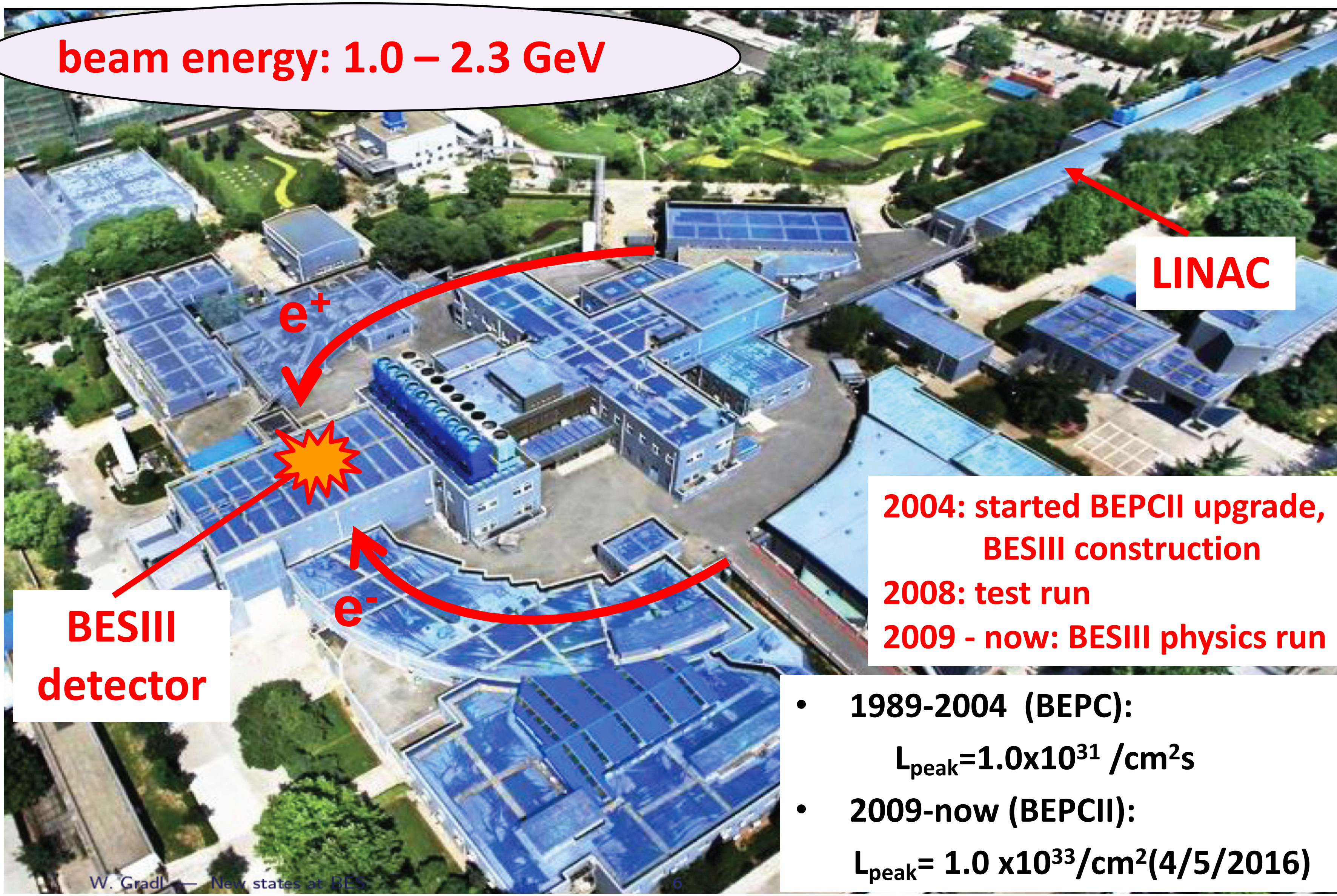


Charmed hadron
– key to the strong interaction

- Systems with strangeness
  - Scale: $m_s \approx 100$ MeV ~ $\Lambda_{QCD} \approx 200$ MeV: Relevant degrees of freedom?
  - **Probes QCD in the confinement domain.**
- Systems with charm
  - Scale: $m_c \approx 1300$ MeV: Quarks and gluons more relevant.
  - **Probes QCD just below pQCD.**



Beijing Electron Positron Collider (BEPC)



2004: started BEPCII upgrade, BESIII construction

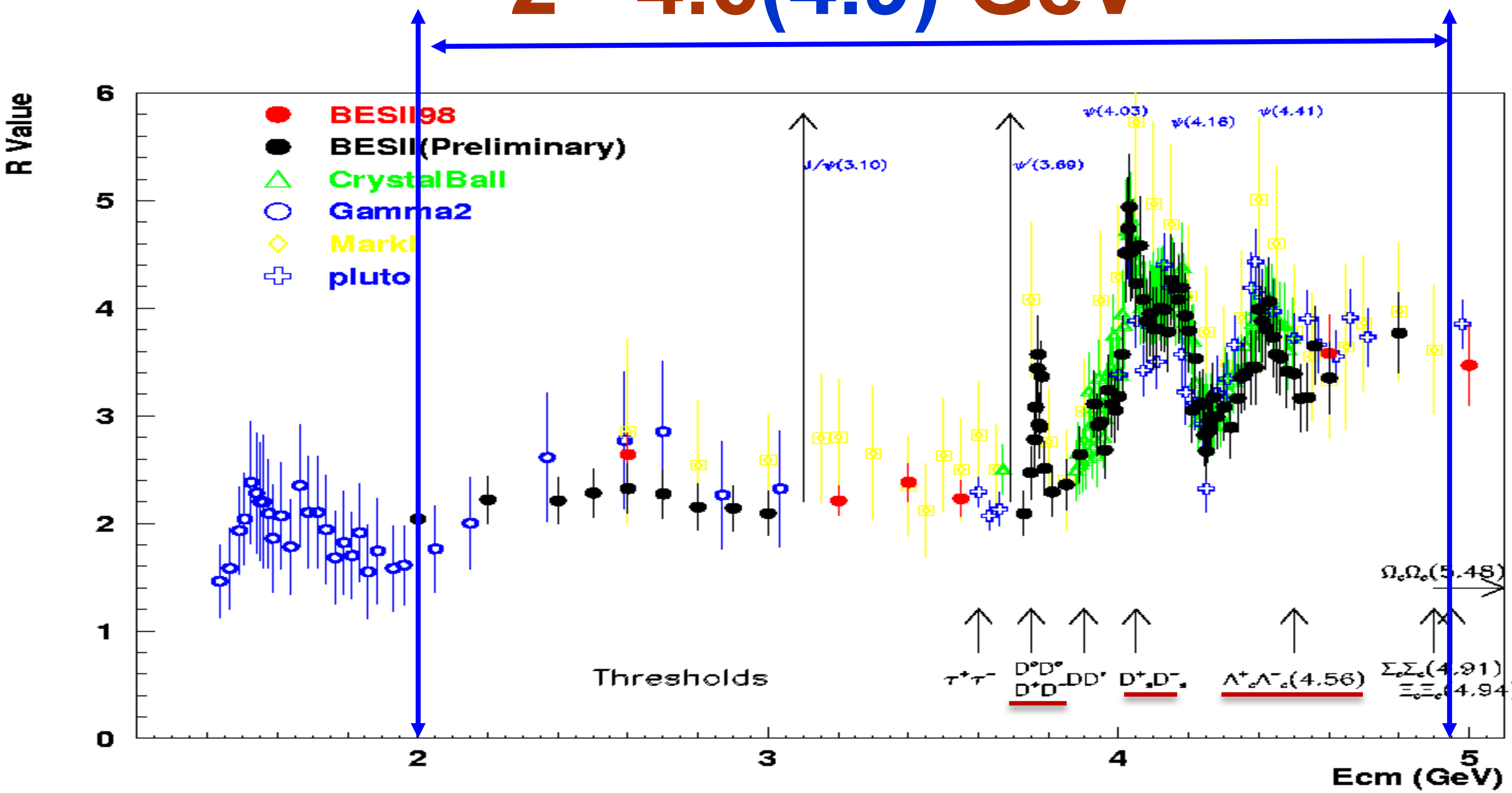
2008: test run

2009 - now: BESIII physics run

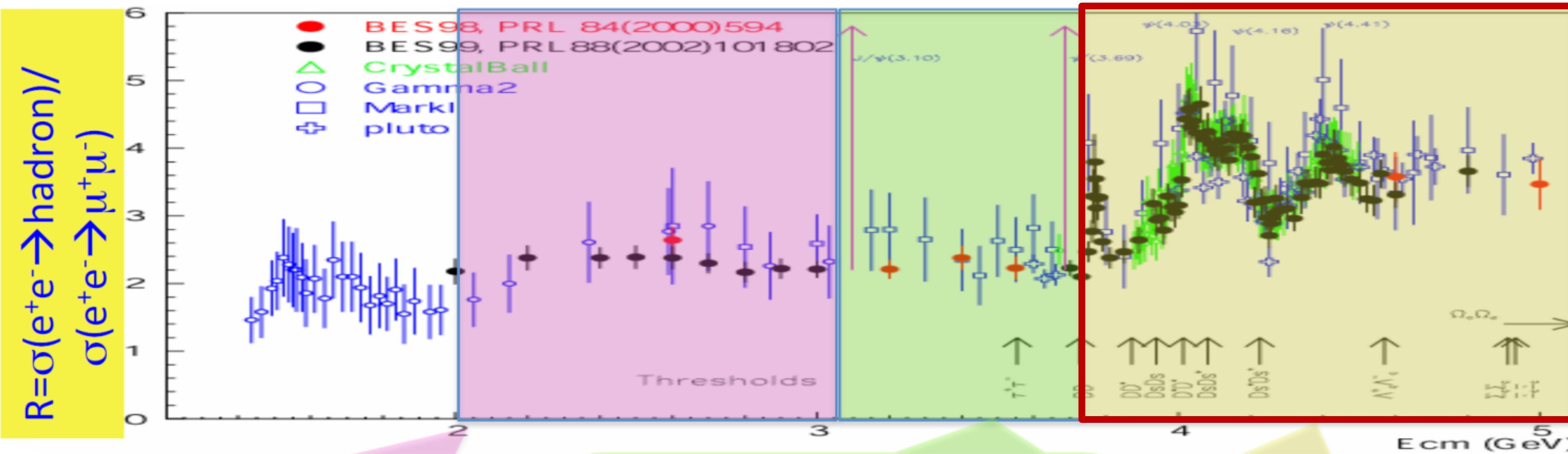
- 1989-2004 (BEPC):
  L_{peak}=1.0x10^{31} /cm^{2}s
- 2009-now (BEPCII):
  L_{peak}= 1.0 x10^{33}/cm^2(4/5/2016)

Energies of the BEPCII Collider

2 ~4.6(4.9) GeV



Physics at tau-charm Energy Region



- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

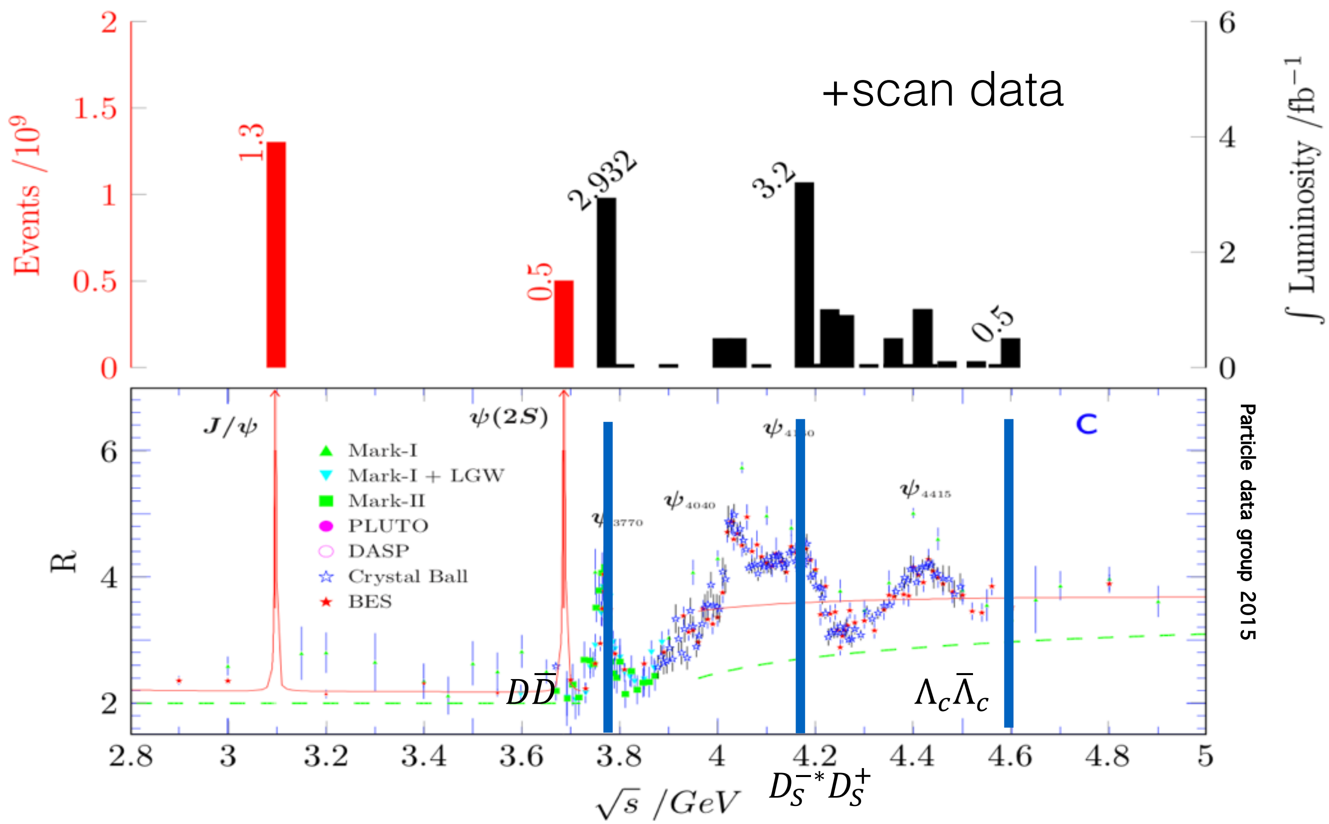
- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- D mesons
- f_D and f_{Ds}
- D_0-D_0 mixing
- Charm baryons

Data for studying charmed hadron decays

$D_{(s)}$ & Λ_c decays:

- (semi-)leptonic decays
- hadronic decays



Precision measurement of CKM elements -- Test EW theory

CKM matrix elements are fundamental SM parameters that describe the mixing of quark fields due to weak interaction.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM matrix

BESIII + B factories + LQCD

Three generations of quark?

Unitary matrix?

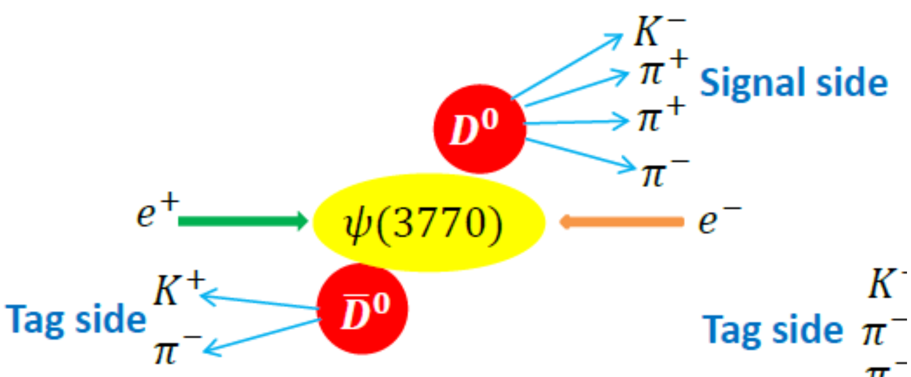
Expected precision < 2% at BESIII

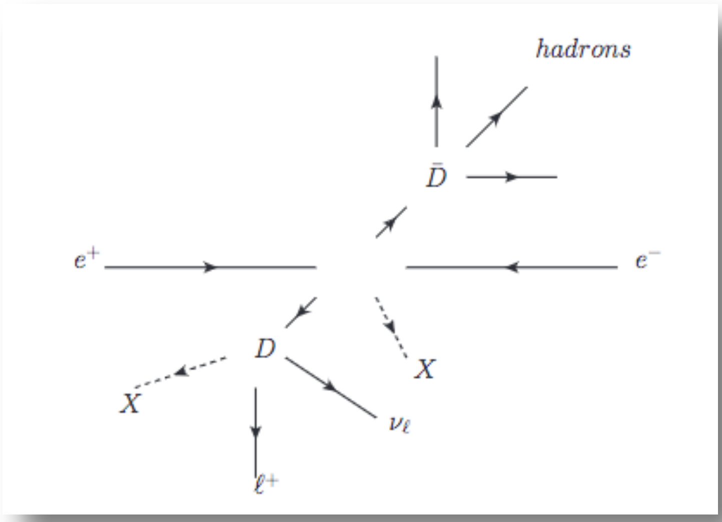
BESIII + B factories + LHCb + LQCD

- **Precision measurement of CKM matrix elements**
- **A precise test of SM model**
- **New physics beyond SM?**

Double Tag (DT) techniques

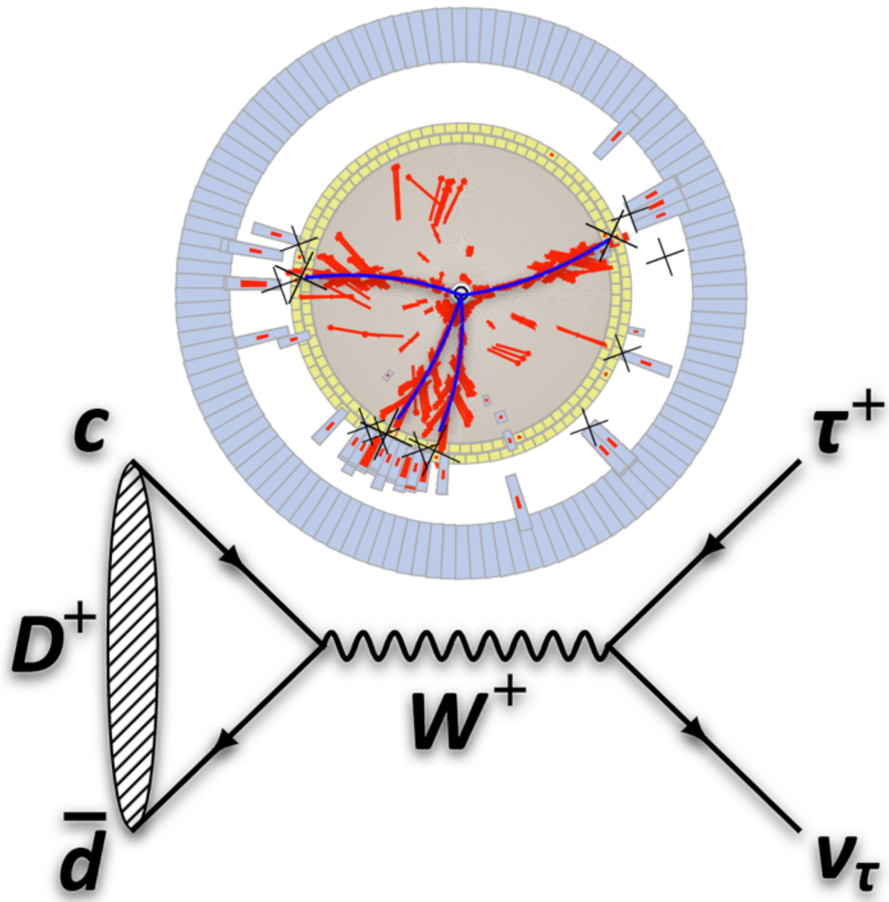
- 100% of beam energy converted to D pair (Clean environment, kinematic constrains ν Recon.)
- $D_{(S)}$ generated in pair ⇒ absolute Branching fractions
- Fully reconstruct about 15% of $D_{(S)}$ decays





◆ **Double tag techniques: Hadronic tag on one side, on the other side for missing-mass studies (Double tag efficiency is high.)**

Charmed meson decays



$D_{(S)}$ Leptonic decays

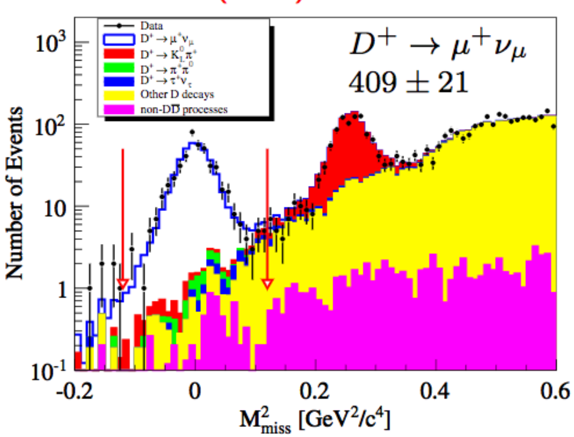
Purely Leptonic:

- Extract decay constant $f_{D(s)}$ incorporates the strong interaction effects (wave function at the origin)
- To validate Lattice QCD calculation of $f_{D(s)}$ and provide constrain of CKM-unitarity

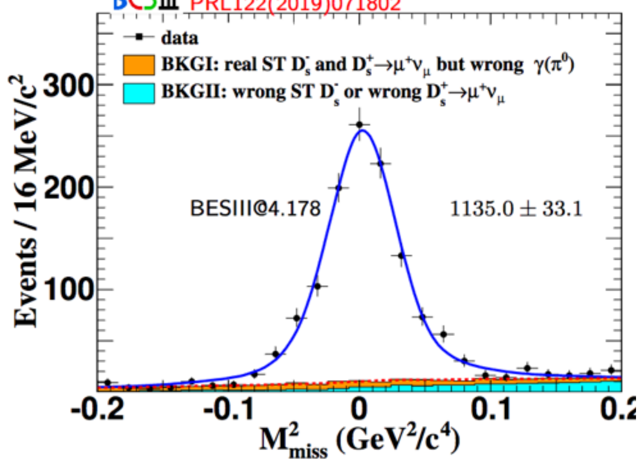
$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} \mid V_{cd(s)} \mid^2 m_\ell^2 m_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

BESIII PRD94(2016)072004

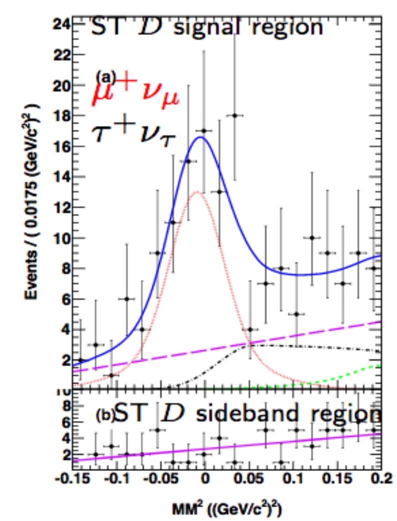
BESIII PRD89(2014)051104



BESIII PRL122(2019)071802



BESIII@4.009

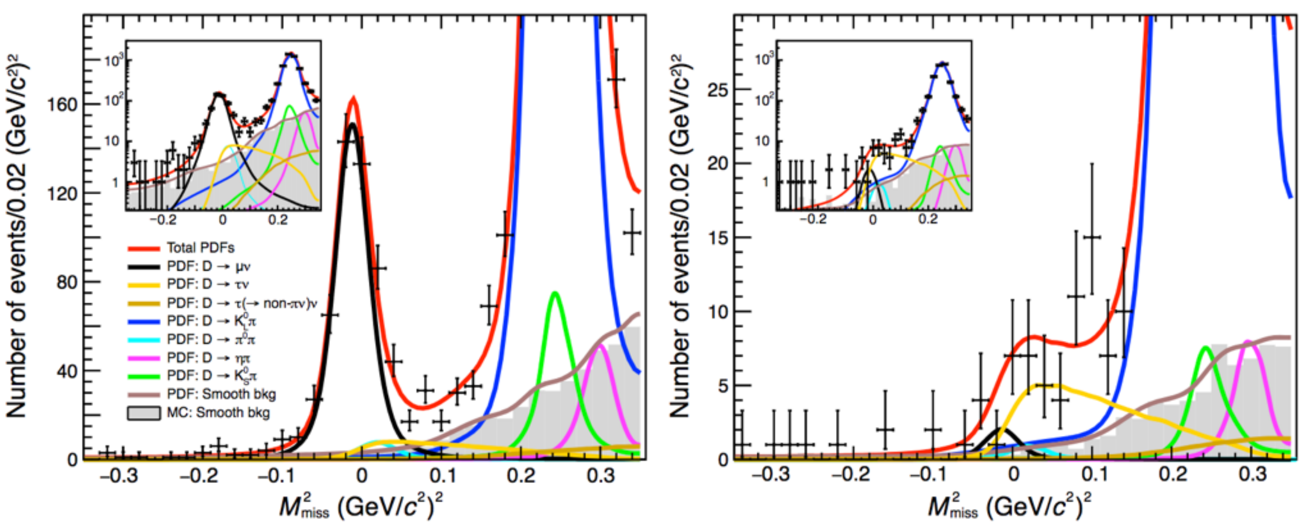


Will be updated using 4178 MeV data

Observation of $D^+ \to \tau^+\nu, \tau^+ \to \pi^+\bar{\nu}$

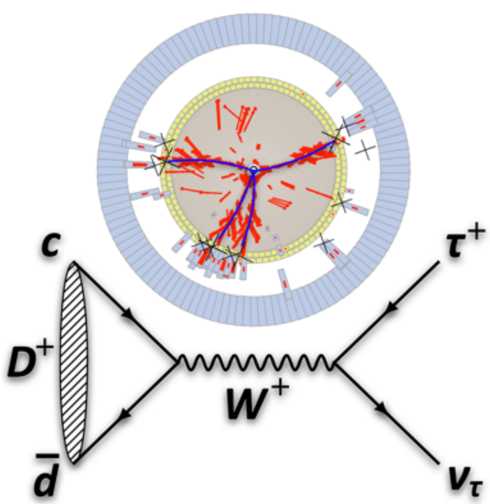
arXiv:1908.08877 [hep-ex]
accepted by PRL

μ-like tracks ($E_{\rm EMC} \leq 300$ MeV) π-like tracks ($E_{\rm EMC} > 300$ MeV).



137±27 signals

5.1σ significance



$$\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$$

$$R_{D^+} = \frac{\Gamma(D^+ \to \tau^+\nu_\tau)}{\Gamma(D^+ \to \mu^+\nu_\mu)} = 3.21 \pm 0.64 \pm 0.43$$

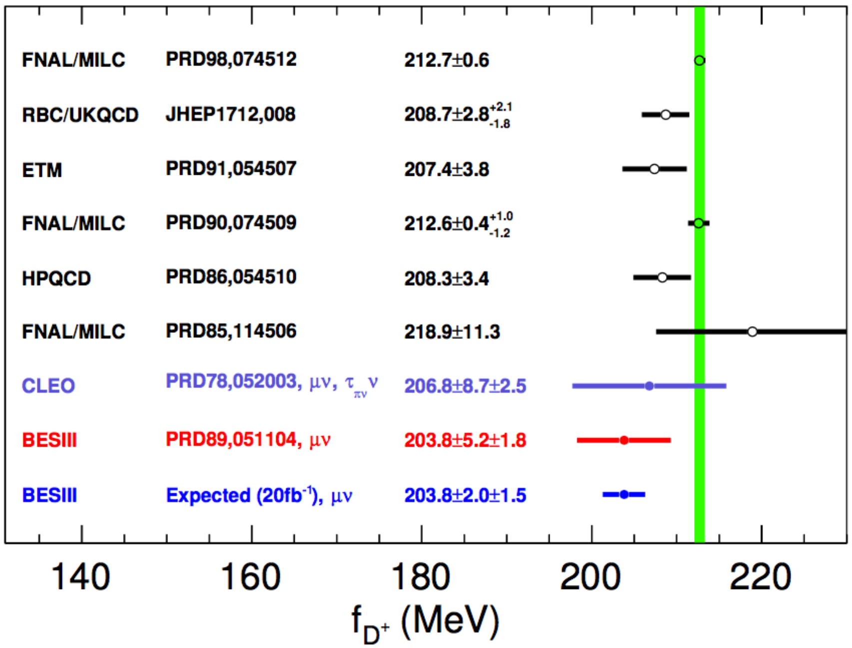
SM prediction 2.67 ± 0.01.

Decay constant $f_{D(s)}$

Inputs:

PDG2018 from CKM unitarity:

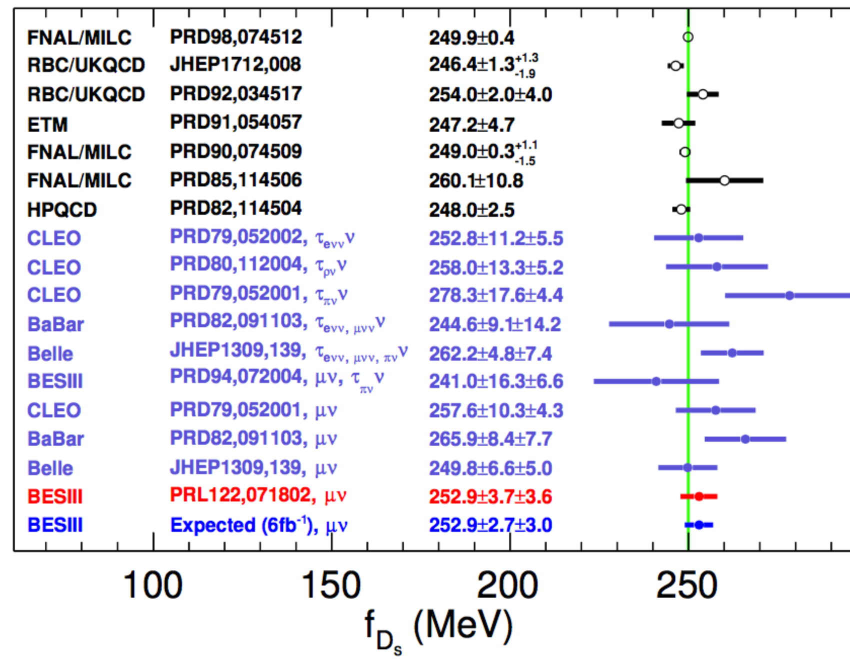
$$|V_{cd}| = 0.22438 \pm 0.00044$$



Inputs:

PDG2018 from CKM unitarity:

$$|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$$

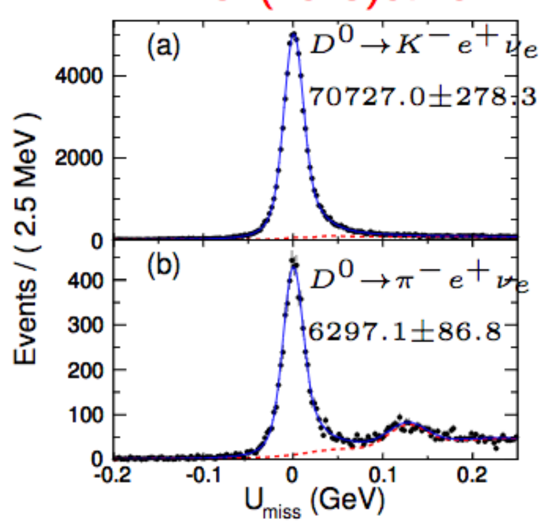


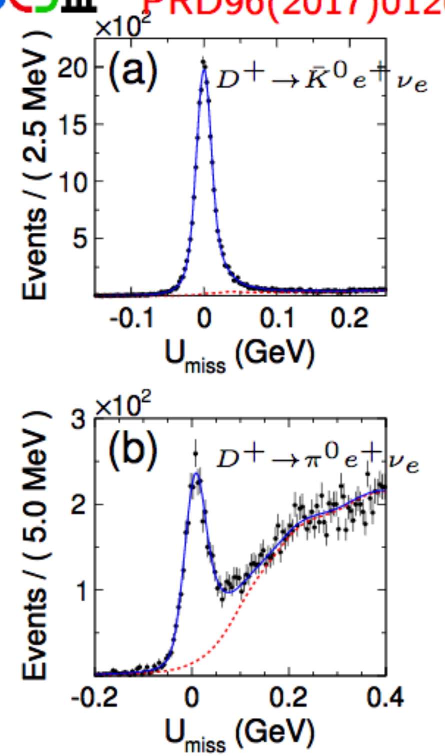
- Precisions of LQCD results are superior to experimental ones
- Hint of slight tension between exp. & LQCD results

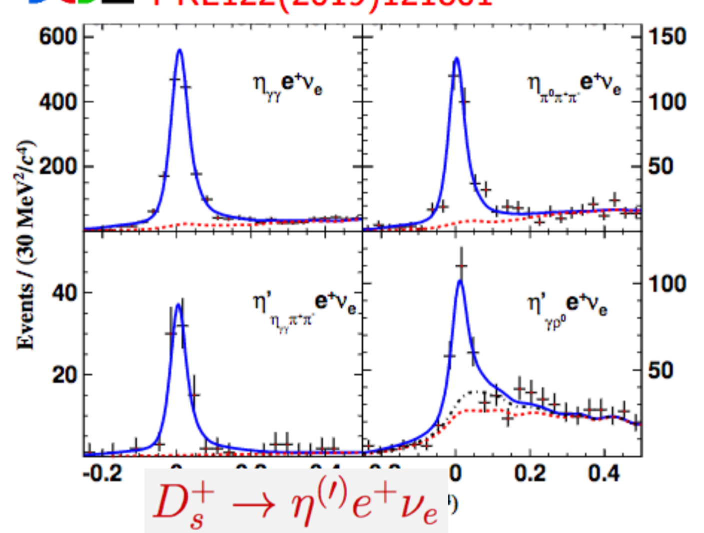
$D_{(S)}$ Semi-Leptonic decays: *e*-mode

Semi-leptonic: form factor (FF)

- Measure $|V_{cx}|$ x FF
- Charm physics:
  - CKM-unitarity ⇒ $|V_{cx}|$, extract FF, test LQCD
  - Input LQCD FF to test CKM-unitarity

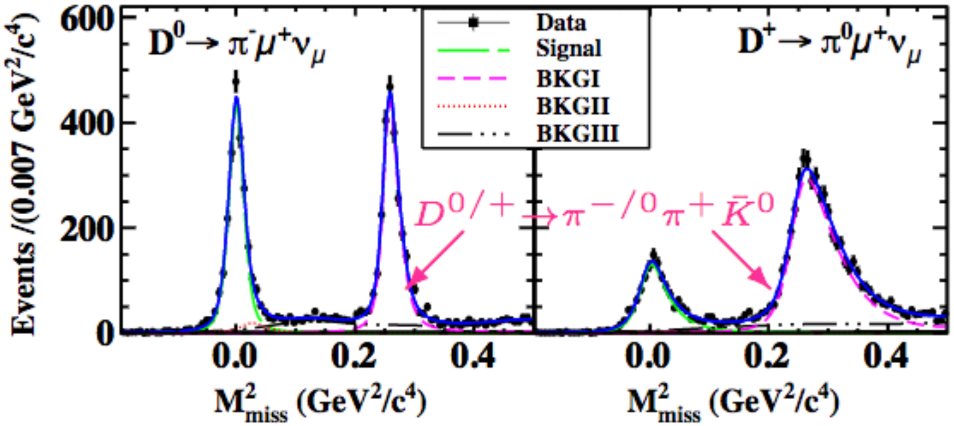




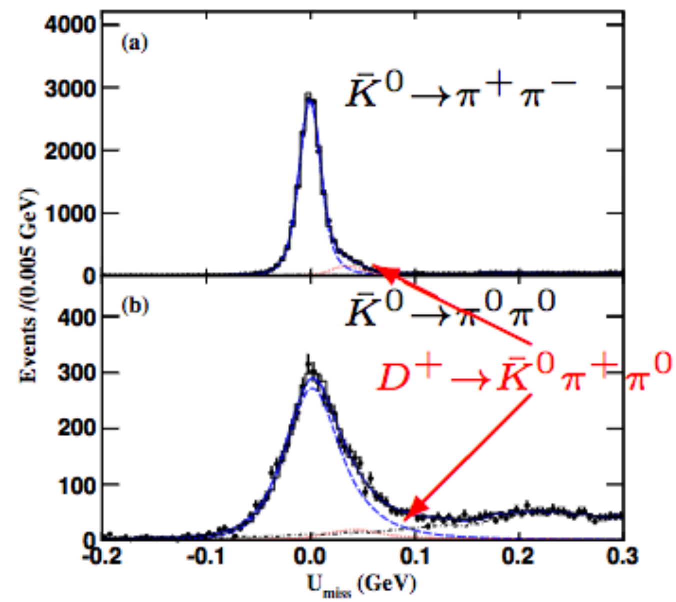


$D_{(S)}$ Semi-Leptonic decays: μ-mode

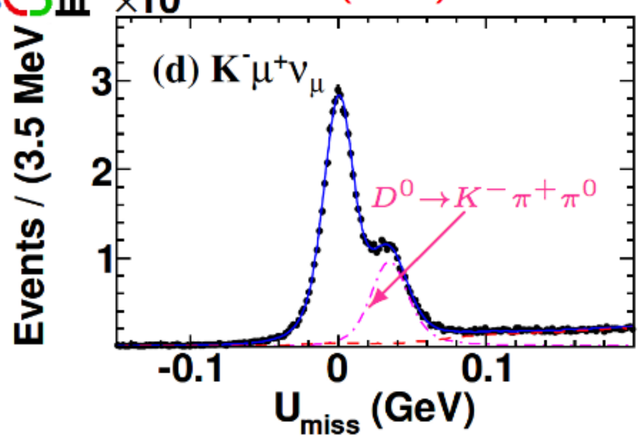
BESIII PRL121(2018)171803



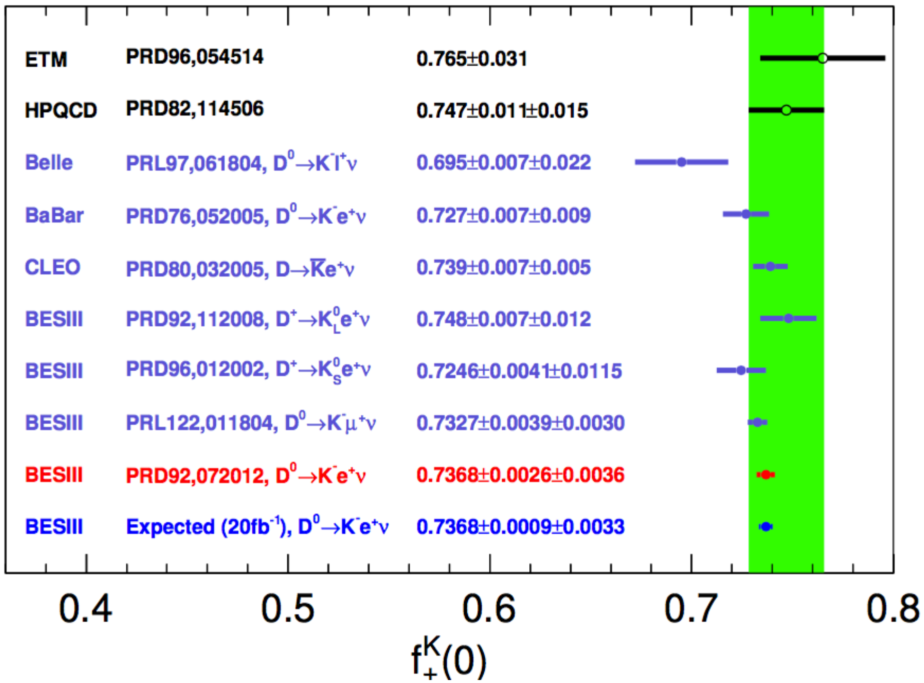
BESIII EPJC76(2016)369

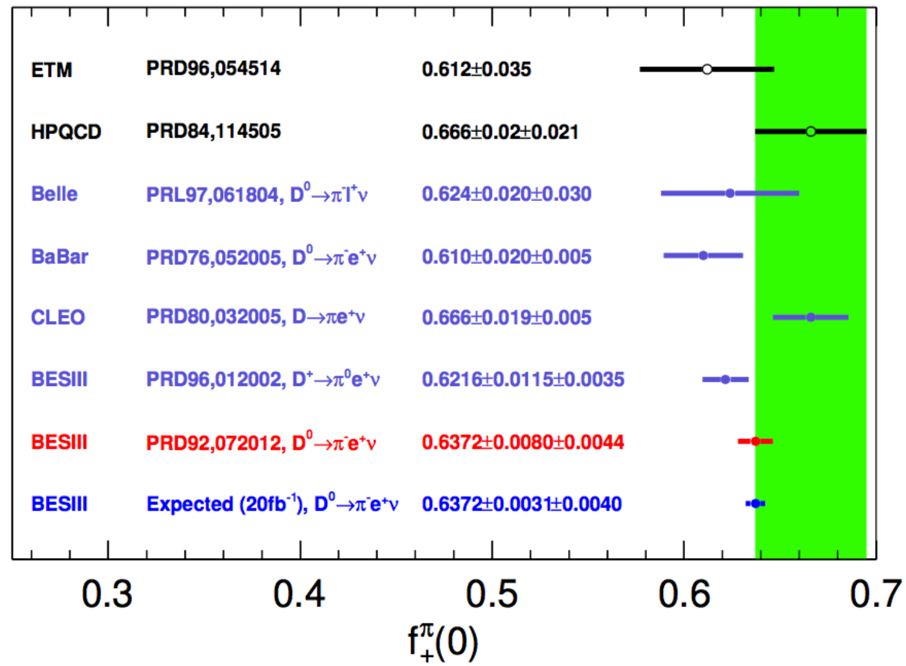


BESIII PRL122(2019)011804



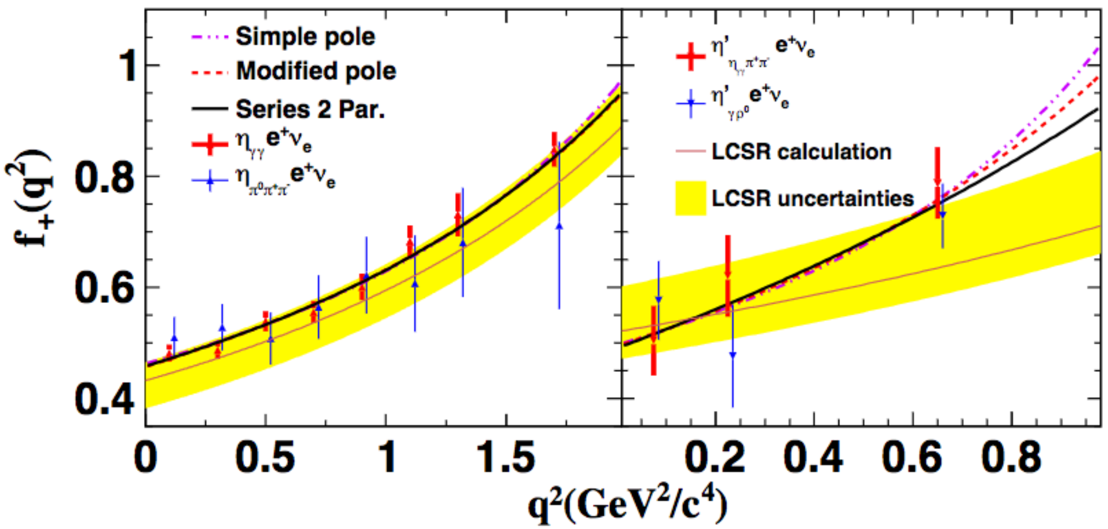
Form factors $f_+^{D\to h}$

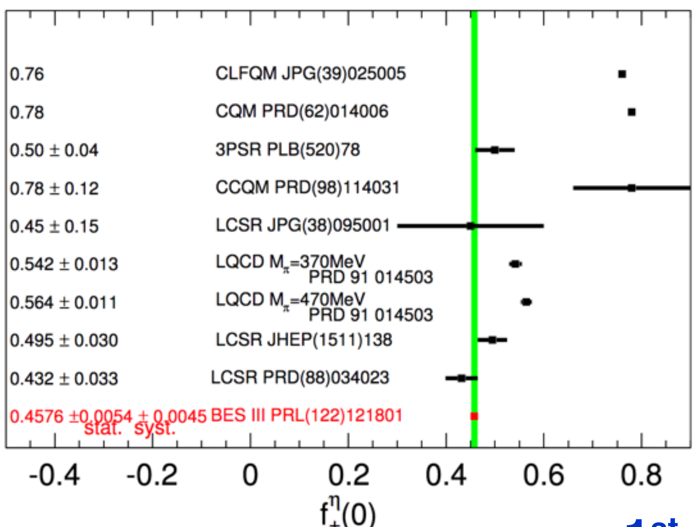




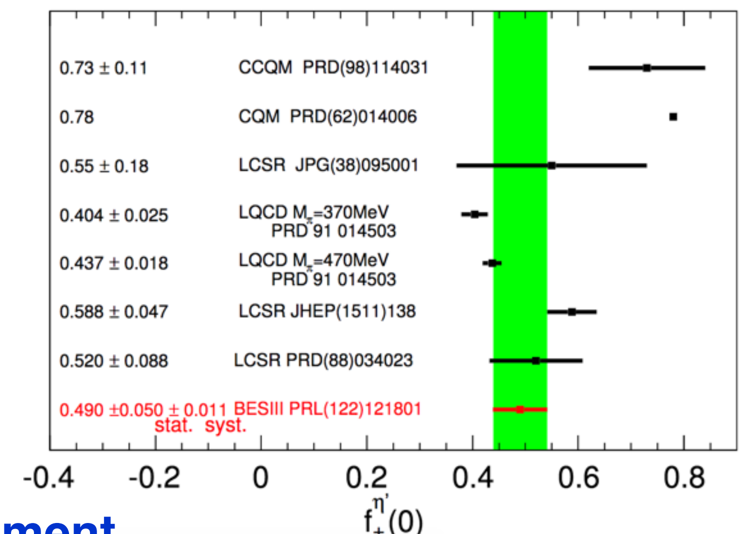
Precisions better than those of LQCD results

Form factors $f_+^{D_s \to \eta^{(\prime)}}$

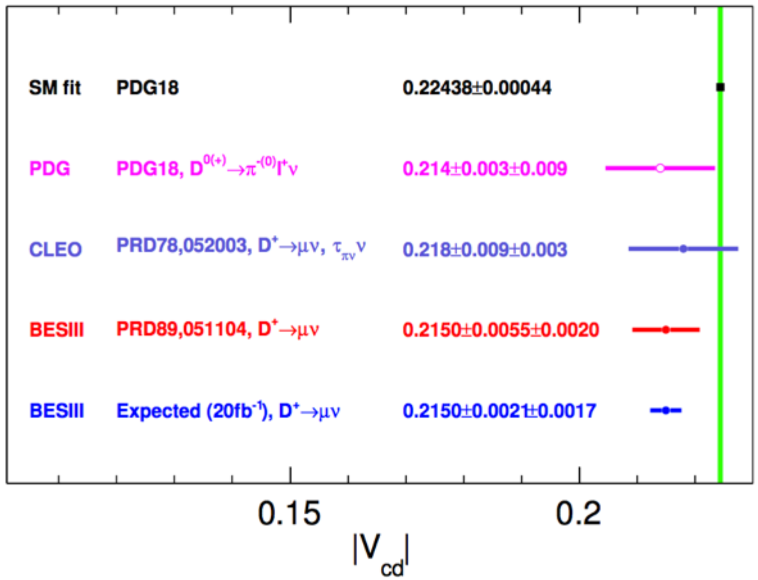




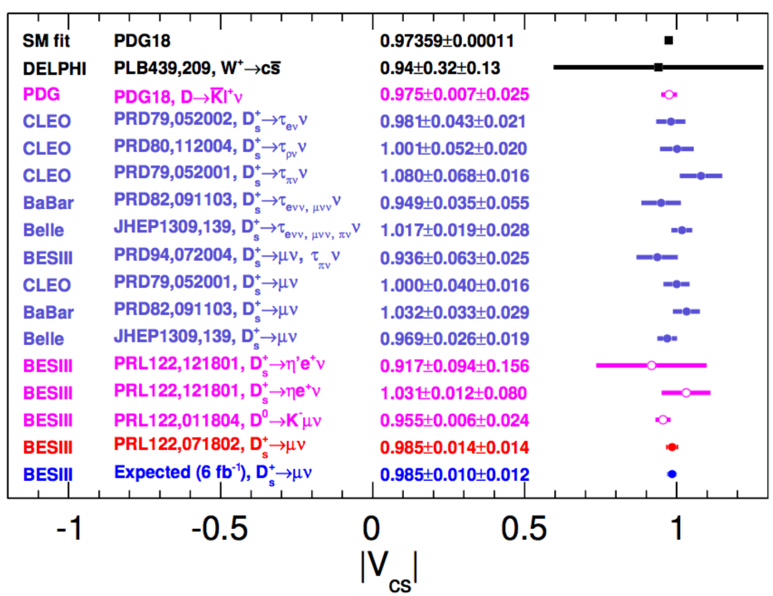
1st measurement

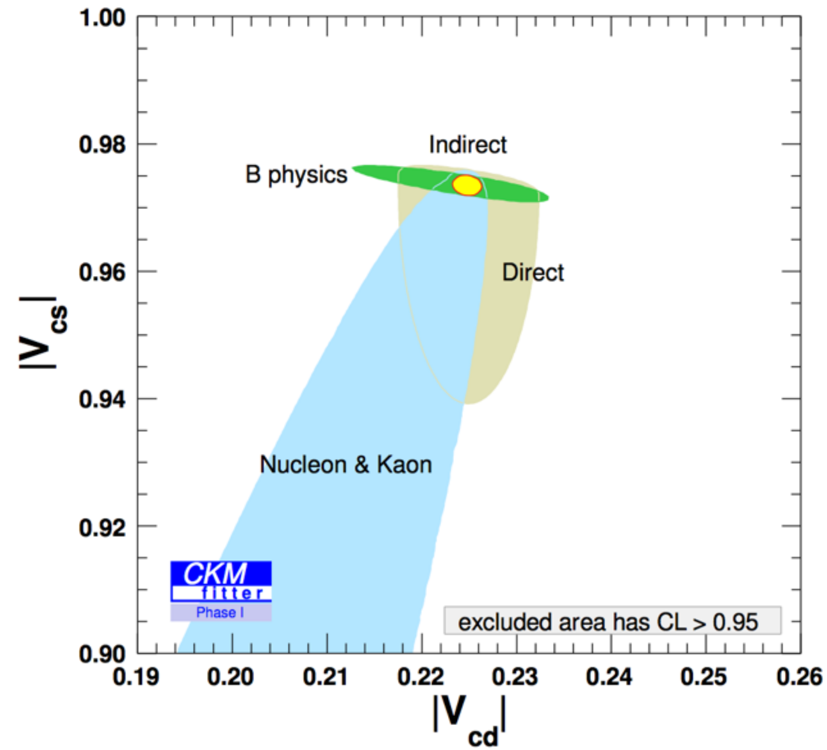


Vcs and Vcd



BESIII: best precision and systematic dominant





Tests of lepton flavor universality

$$R_{D^+_{(s)}} = \frac{\Gamma(D^+_{(s)} \to \tau^+\nu_\tau)}{\Gamma(D^+_{(s)} \to \mu^+\nu_\mu)} = \frac{m^2_{\tau^+}\left(1 - \frac{m^2_{\tau^+}}{m^2_{D^+_{(s)}}}\right)^2}{m^2_{\mu^+}\left(1 - \frac{m^2_{\mu^+}}{m^2_{D^+_{(s)}}}\right)^2}.$$

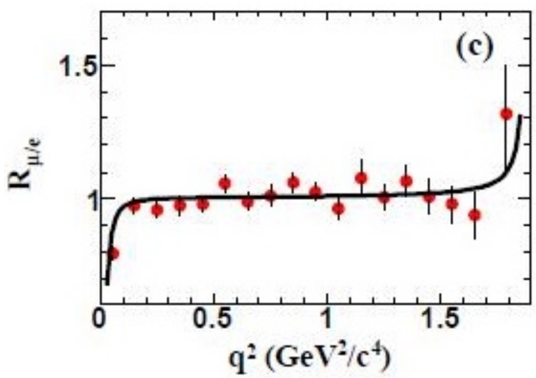
SM prediction: R_D =2.67±0.01

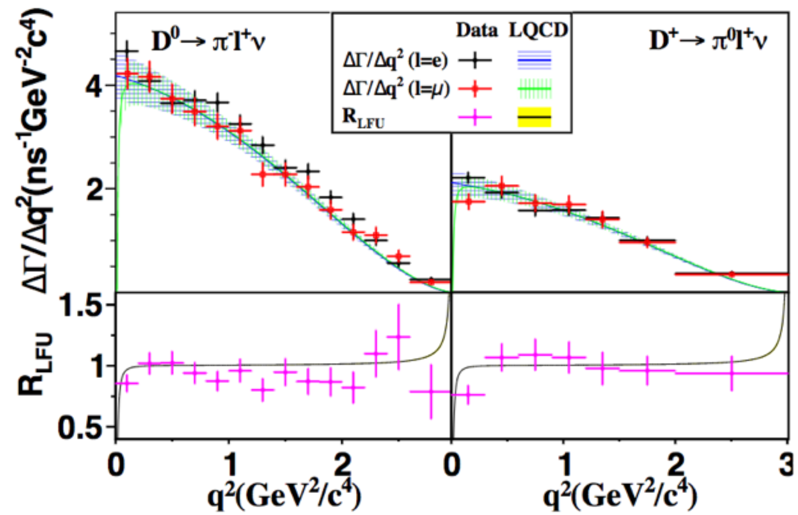
BESIII: R_D =3.21±0.64 ±0.43

1σ difference?

Semi-leptonic modes

$$R_{\mu/e} = \Gamma_{D^0\to K^-\mu^+\nu_\mu}/\Gamma_{D^0\to K^-e^+\nu_e}$$





2.93/fb@3773MeV;
3.19/fb @
4178MeV

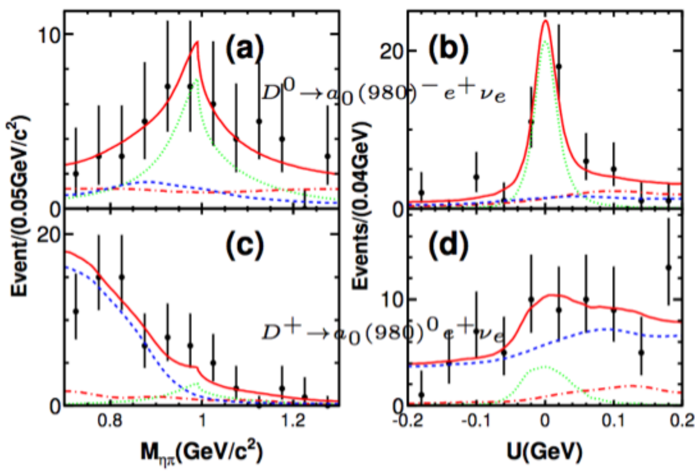
	$R(D_s^+)$	$R(D^+)$	$R(K^-)$	$R(\bar{K}^0)$	$R(\pi^-)$	$R(\pi^0)$
SM	9.74(1)	2.66(1)	0.975(1)	0.975(1)	0.985(2)	0.985(2)
BESIII	10.19(52)	3.21(64)	0.974(14)	1.013(29)	0.922(37)	0.964(45)

2σ difference?

Future 20/fb @3773MeV data will improve these test.

SL decays for spectroscopy study

$D \to a_0(980)e^+\nu_e$ PRL121(2018)081802



A model-independent way to study the nature of light scalar mesons proposed by PRD82(2016)034016

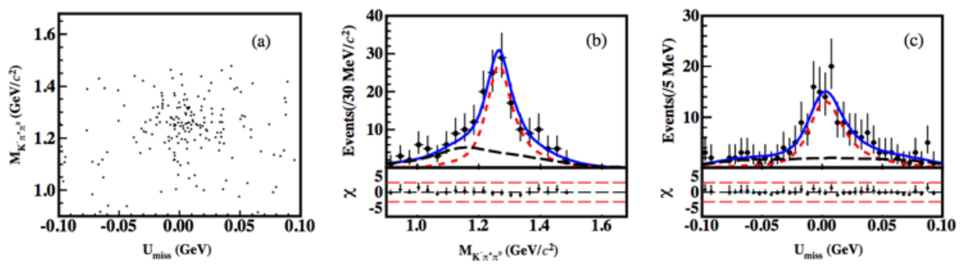
$$R = \frac{\mathcal{B}(D^+ \to f_0(980)e^+\nu_e) + \mathcal{B}(D^+ \to f_0(500)e^+\nu_e)}{\mathcal{B}(D^+ \to a_0(980)^0 e^+\nu_e)}$$

$R = 1.0 \pm 0.3$ for two-quark description;
$R = 3.0 \pm 0.9$ for tetraquark description.

We have $R > 2.7$ @90% C.L. at BESIII
Which favors the tetraquark description.

$D^+ \to \bar{K}_1(1270)^0 e^+\nu_e$

BESIII arXiv:1907.11370, accepted by PRL



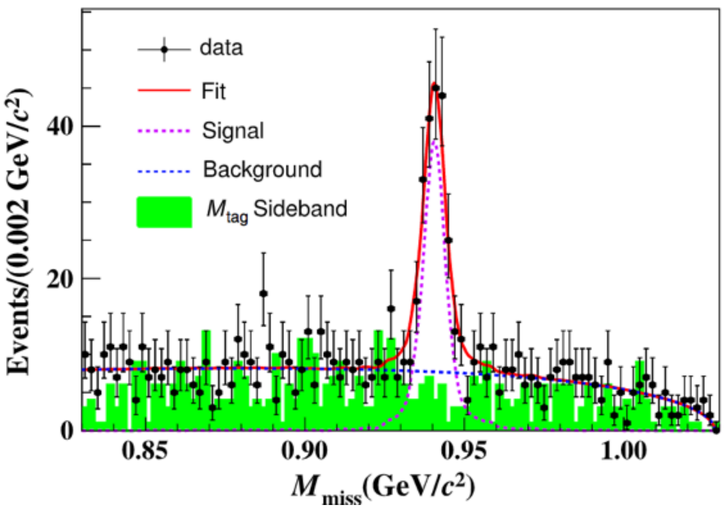
$$\mathcal{B}(D^+ \to \bar{K}_1(1270)^0 e^+\nu_e) = (2.30 \pm 0.26 \pm 0.18 \pm 0.25) \times 10^{-3}$$

Studies on $D_s^+ \to p\,\bar{n}$ and $\omega\pi^+$

3.19 fb^{-1} @E_{cm} = 4.178 GeV

- understanding the dynamical enhancement of W-annihilation
  - Short-distance vs Long-distance

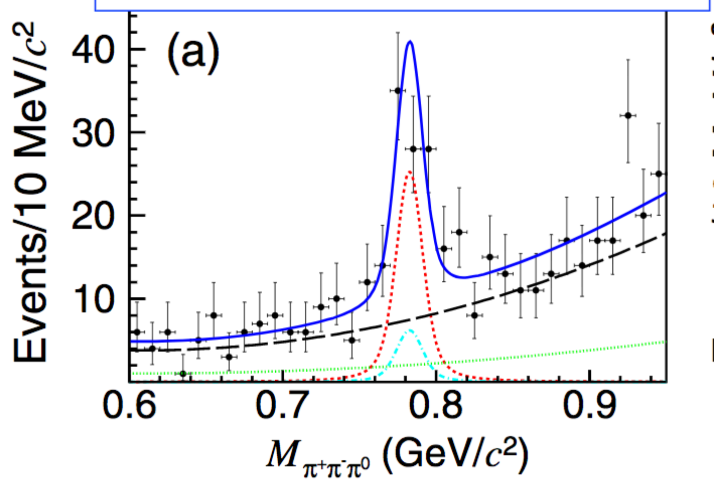
PRD99, 031101(R) (2019)



BF = (1.21±0.10±0.05)×10^{-3}

PRD 99, 091101 (R) (2019)

ωπ:65.0±11.6 evts (6.7σ)

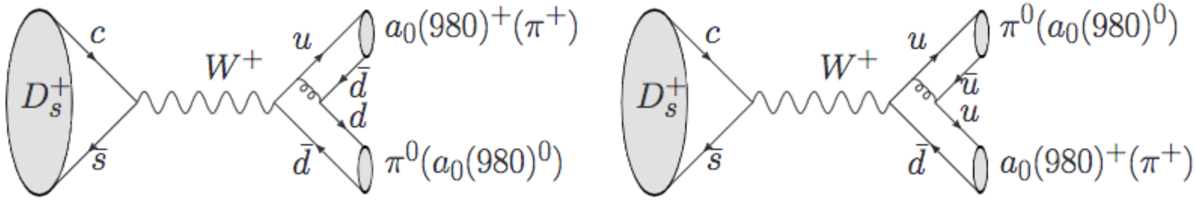


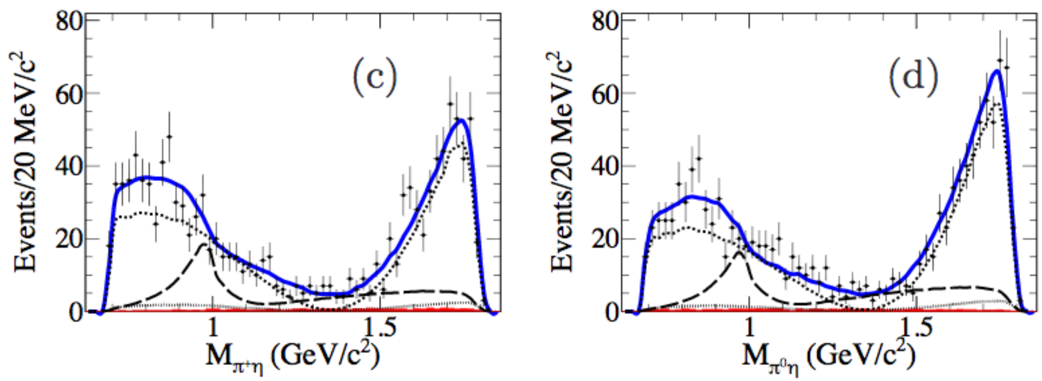
= (1.77±0.32±0.13)×10^{-3}

BF enhanced BR due to long-distance effect via hadronic loop

Dalitz analysis of $D_s^+ \to \pi^+\pi^0\eta$

PRL 123, 112001 (2019)





- First measurement (16.2σ stat. significance)!

  BF($D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)}$, $a_0(980)^{+(0)} \to \pi^{+(0)}\eta$) = $(1.46\pm0.15\pm0.23)\%$

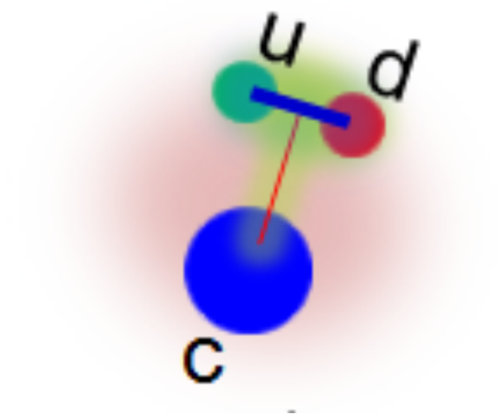
  Very large BF, compared to other W-annihilation decays

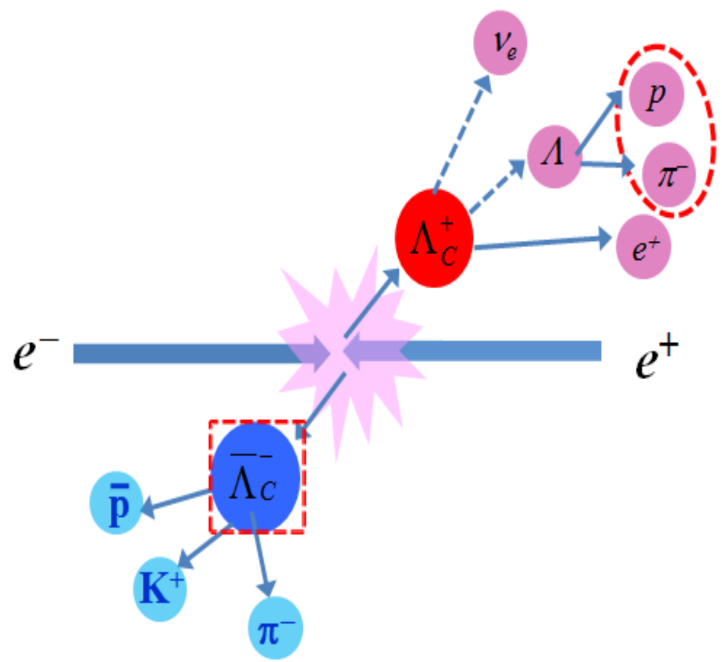
  (e.g., $D_s \to p\bar{n}/\omega\pi$ are all at 10^{-3} level).

One interpretation by Yu-Kuo Hsiao et al, arXiv:1909.07327

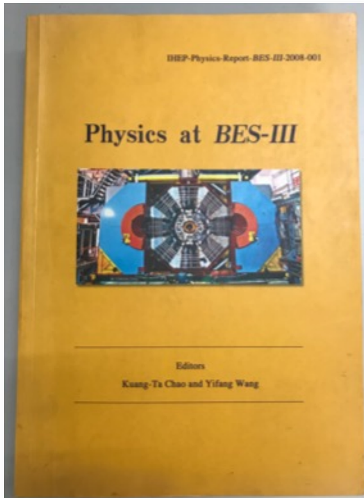
Evidence for $a_0(980)$ as tetraquark

The Λ_c^+ decays





北京谱仪III粲重子物理



Chapter 24

Charm baryon production and decays[1]

24.1 Introduction

In the past years many new excited charmed baryon states have been discovered by BaBar, Belle and CLEO. In particular, B factories have provided a very rich source of charmed baryons both from B decays and from the continuum $e^+e^- \to c\bar{c}$. A new chapter for the charmed baryon spectroscopy is opened by the rich mass spectrum and the relatively narrow widths of the excited states. Experimentally and theoretically, it is important to identify the quantum numbers of these new states and understand their properties. Since the pseudoscalar mesons involved in the strong decays of charmed baryons are soft, the charmed baryon system offers an excellent ground for testing the ideas and predictions of heavy quark symmetry of the heavy quark and chiral symmetry of the light quarks.

The observation of the lifetime differences among the charmed mesons D^+, D^0 and charmed baryons is very interesting since it was realized very early that the naive parton model gives the same lifetimes for all heavy particles containing a heavy quark Q, while experimentally, the lifetimes of Ξ_c^+ and Ω_c^0 differ by a factor of six ! This implies the importance of the underlying mechanisms such as W-exchange and Pauli interference due to the identical quarks produced in the heavy quark decay and in the wavefunction of the charmed baryons. With the advent of heavy quark effective theory, it was recognized in early nineties that nonperturbative corrections to the parton picture can be systematically expanded in powers of $1/m_Q$. Within the QCD-based heavy quark expansion framework, some phenomenological assumptions can be turned into some coherent and quantitative statements and nonperturbative effects can be systematically studied.

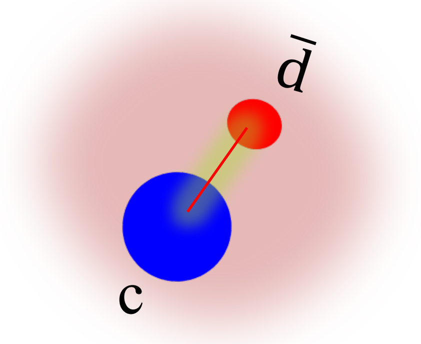
Contrary to the significant progress made over the last 20 years or so in the studies of the heavy meson weak decay, advancement in the arena of heavy baryons is relatively slow. Nevertheless, the experimental measurements of the charmed baryon hadronic weak decays have been pushed to the Cabibbo-suppressed level. Many new data emerged can be used to test a handful of phenomenological models available in the literature. Apart from the complication due to the presence of three quarks in the baryon, a major

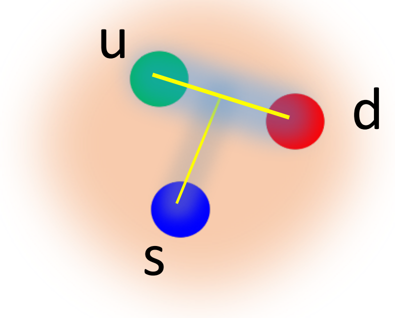
[1] By Hai-Yang Cheng

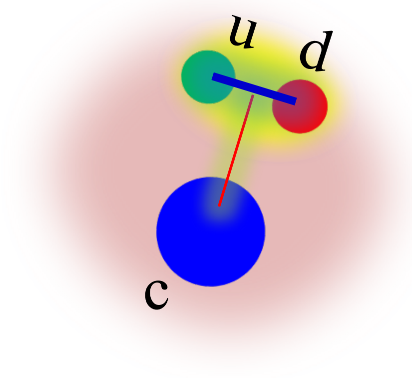
Quark model picture

a heavy quark (*c*) with an unexcited spin-zero diquark (*u*-*d*)

→ *diquark correlation is enhanced by weak Color Magnetic Interaction with a heavy quark.*







→ Charmed meson ($D^+[c\bar{d}]$)
$m_d << m_c$ → **quark + heavy quark**
(q) (Q)

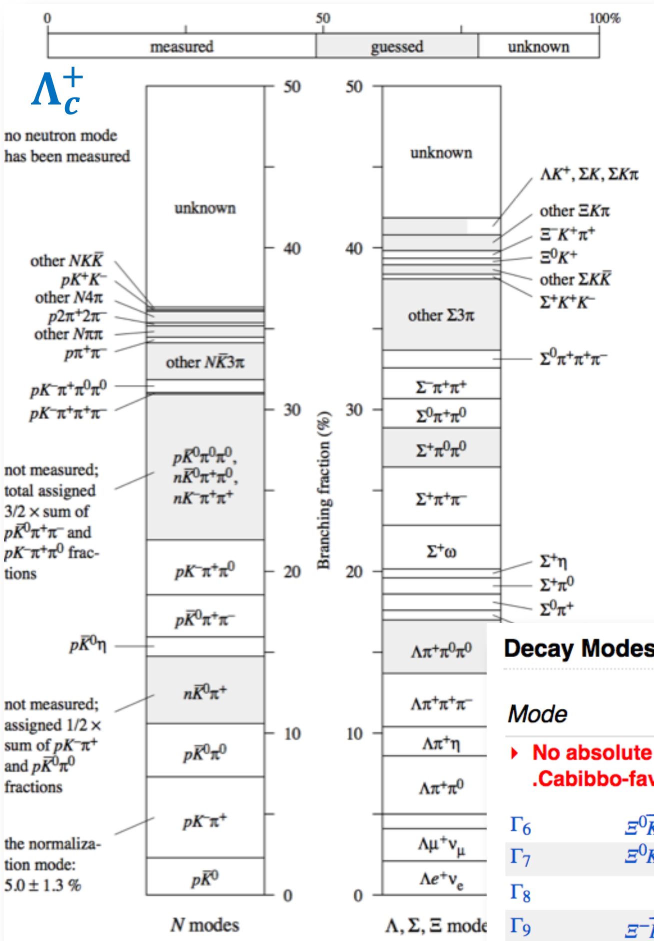
→ Strange baryons ($\Lambda[uds]$)
$m_u, m_d \approx m_s$ → **(qqq)** uniform

→ Charmed baryon ($\Lambda_c[udc]$)
$m_u, m_d << m_c$ → **diquark + quark**
(qq) (Q)

In some sense, more reliable prediction of heavy-light quark transition without dealing with light degrees of freedom that have net spin or isospin.

Λ_c^+ may provide complementary powerful test on internal dynamics to D/Ds does

2015年之前的粲重子衰变信息



Ξ_c^+: relative to the decay of $\Xi^- 2\pi^+$

	Mode	Fraction (Γ_i/Γ)
	No absolute branching fractions have been measured. The following are branching to $\Xi^-\pi^+$. Cabibbo-favored ($S=-2$) decays — relative to $\Xi^-\pi^+$	
Γ_1	$p2K_S^0$	0.087 ± 0.021
Γ_2	$\Lambda\bar{K}^0\pi^+$	
Γ_3	$\Sigma(1385)^+\bar{K}^0$	1.0 ± 0.5
Γ_4	$\Lambda K^-2\pi^+$	0.323 ± 0.033
Γ_5	$\Lambda\bar{K}^*(892)^0\pi^+$	< 0.16
Γ_6	$\Sigma(1385)^+K^-\pi^+$	< 0.23
Γ_7	$\Sigma^+K^-\pi^+$	0.94 ± 0.10
Γ_8	$\Sigma^+\bar{K}^*(892)^0$	0.81 ± 0.15
Γ_9	$\Sigma^0K^-2\pi^+$	0.27 ± 0.12
Γ_{10}	$\Xi^0\pi^+$	0.55 ± 0.16
Γ_{11}	$\Xi^-2\pi^+$	DEFINEDAS1
		< 0.10
		2.3 ± 0.7
		1.7 ± 0.5
		$2.3^{+0.7}_{-0.8}$
		0.07 ± 0.04
	…ative to $\Xi^-\pi^+$	
		0.21 ± 0.04
		0.116 ± 0.030
		0.48 ± 0.20
		0.18 ± 0.09
		0.15 ± 0.06

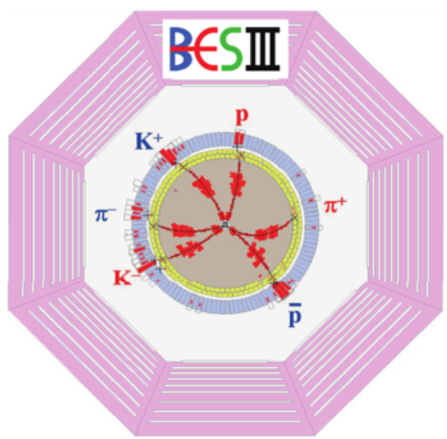
Decay Modes Ω_c^0

	Mode	Fraction (Γ_i/Γ)
	No absolute branching fractions have been measured. The following are branching ra… Cabibbo-favored ($S=-3$) decays – relative to $\Omega^-\pi^+$	
Γ_6	$\Xi^0\bar{K}^0$	1.64 ± 0.29
Γ_7	$\Xi^0K^-\pi^+$	1.20 ± 0.18
Γ_8	$\Xi^0\bar{K}^{*0}$, $\bar{K}^{*0}\to K^-\pi^+$	0.68 ± 0.16
Γ_9	$\Xi^-\bar{K}^0\pi^+$	2.12 ± 0.28
Γ_{10}	$\Xi^-K^-2\pi^+$	0.63 ± 0.09
Γ_{11}	$\Xi(1530)^0K^-\pi^+$, $\Xi^{*0}\to\Xi^-\pi^+$	0.21 ± 0.06
Γ_{12}	$\Xi^-\bar{K}^{*0}\pi^+$	0.34 ± 0.11
Γ_{13}	$\Sigma^+K^-K^-\pi^+$	< 0.32
Γ_{14}	$\Lambda\bar{K}^0\bar{K}^0$	1.72 ± 0.35

Λ_c threshold production at BESIII

In 2014, BESIII took data above Λ_c pair threshold and run machine at 4.6GeV with excellent performance.

Energy(GeV)	lum.(1/pb)
4.575	47.67
4.580	8.54
4.590	8.16
4.600	567.93



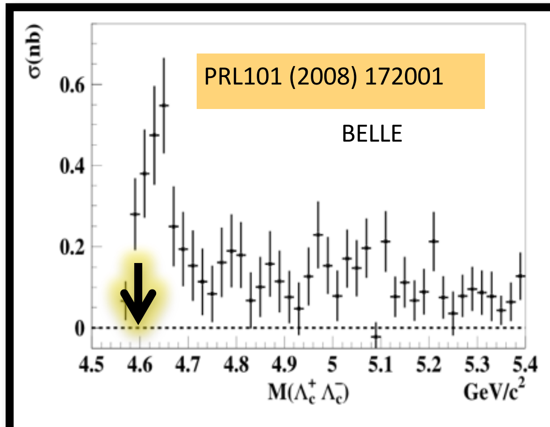


FIG. 4: The cross section for the exclusive process $e^+e^- \to \Lambda_c^+\Lambda_c^-$.

Measurement using the threshold pair-productions via e^+e^- annihilations is unique: *the most simple and straightforward*

First time to systematically study charmed baryon at threshold!

Physics output on the Λ_c^+

- Published 17 papers (7 **PRLs**)
- … more will be coming

Hadronic decay

$\Lambda_c^+ \to pK^-\pi^+$ + 11 CF hadronic modes	PRL 116, 052001 (2016)
$\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-$	PRL 117, 232002 (2016)
$\Lambda_c^+ \to nK_S\pi^+$	PRL 118, 12001 (2017)
$\Lambda_c^+ \to p\eta, p\pi^0$	PRD 95, 111102(R) (2017)
$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$	PLB 772, 388 (2017)
$\Lambda_c^+ \to \Xi^{0(*)}K^+$	PLB783, 200 (2018)
Λ_c^+ …	PRD99, 032010 (2019)
Λ_c^+ …	
Λ_c^+ …	

New gateway to charmed baryon for BESIII
One of the highlight BESIII results!

Semi-leptonic decay

$\Lambda_c^+ \to \Lambda e^+\nu_e$	PRL 115, 221805(2015)
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	PLB 767, 42 (2017)

Inclusive decay

$\Lambda_c^+ \to \Lambda X$	PRL121, 062003 (2018)
$\Lambda_c^+ \to e^+X$	PRL 121 251801(2018)

Production

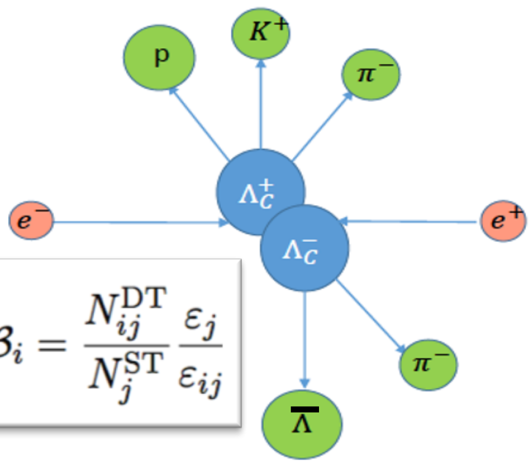
$\Lambda_c^+\Lambda_c^-$ cross section	PRL 120,132001(2018)

BESIII Absolute BFs of Λ_c^+ hadronic decays

- Absolute BF of Λ_c^+ decays are still not well determined since its discovery 30 years ago. PDG2014: δB/B ~25%; BELLE2014: δB/B ~4.7%
- Tagging technique @BESIII will provide *the most simple and straightforward measurement*

567/pb @ 4.6 GeV

PRL 116, 052001 (2016)



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

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	

- The absolute BF can be obtained by the ratio of double tag yields to single tag yields.
- a global least square fit to 12 hadronic modes [Chin. Phys. C37(2013)106201]

✓ **First direct measurement on Λc BFs at threshold**

✓ **$B(pK^-\pi^+)$: BESIII precision comparable with Belle's**

✓ **Improved precisions of the other 11 modes significantly**

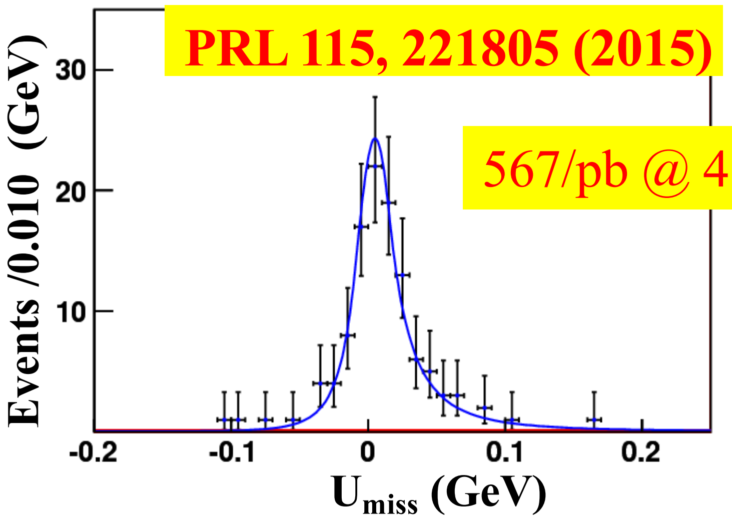
BF for $\Lambda_c^+ \to \Lambda e^+ \nu_e$

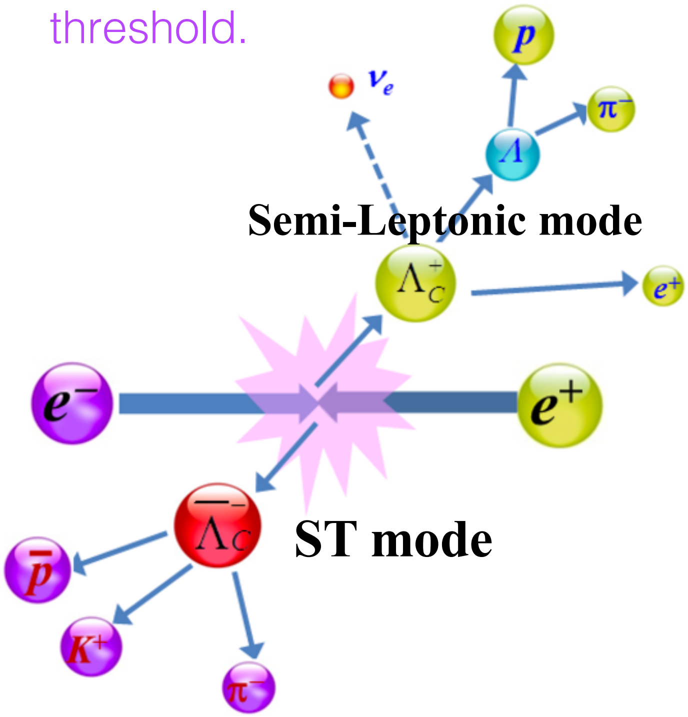
- $\Lambda_c^+ \to \Lambda e^+ \nu_e$ is a $c \to s l^+ \nu_l$ dominated process.
- Urgently needed for LQCD calculations.
- No direct absolute measurement for $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ available.

$$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (2.1 \pm 0.6)\% \qquad \text{PDG 2014}$$

The tagging method and missing-mass technique at threshold.

11 hadronic single tag modes are used





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

- ➢ First absolute measurement of the semi-leptonic decay
- ➢ Statistics limited
- ➢ Best precision to date: twofold improvement
- ➢ We also measure the muonic mode [PLB 767, 42 (2017)]

The first Lattice calculation on Λ_c^+ SL decays

PRL **118,** 082001 (2017) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2017

$\Lambda_c \to \Lambda l^+ \nu_l$ Form Factors and Decay Rates from Lattice QCD with Physical Quark Masses

Stefan Meinel
Department of Physics, University of Arizona, Tucson, Arizona 85721, USA and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA
(Received 1 December 2016; published 21 February 2017)

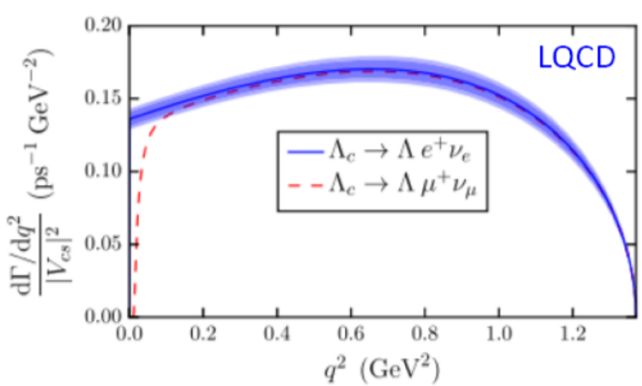
- Input the measured BFs from BESIII

$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell) = \begin{cases} 0.0363(38)(20), & \ell = e, \\ 0.0349(46)(27), & \ell = \mu. \end{cases}$$

Triggered by BESIII

- The first LQCD calculations on BFs and form factors

$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell) = \begin{cases} 0.0380(19)_{\rm LQCD}(11)_{\tau_{\Lambda_c}}, & \ell = e, \\ 0.0369(19)_{\rm LQCD}(11)_{\tau_{\Lambda_c}}, & \ell = \mu, \end{cases}$$



✓ The first determination of $|V_{cs}|$ based on BFs of $\Lambda_c^+ \to \Lambda l^+ \nu_l$ measured by BESIII

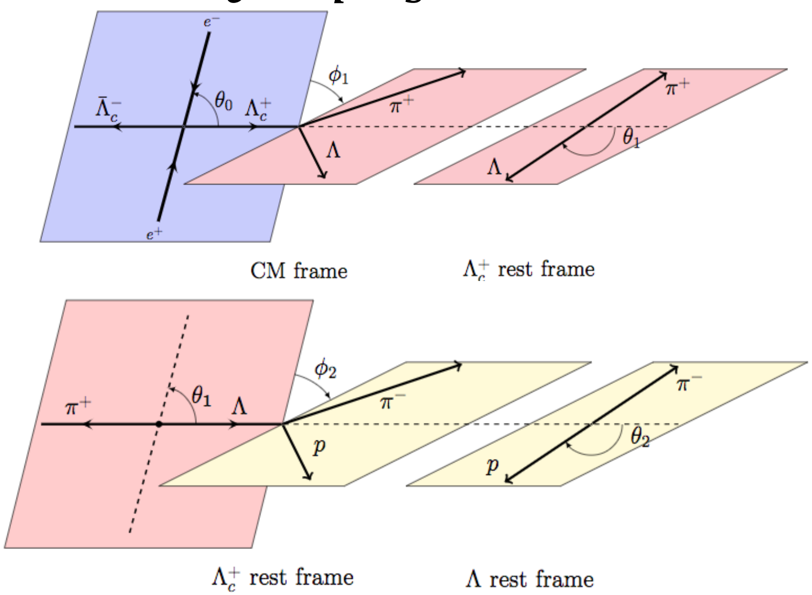
$$|V_{cs}| = \begin{cases} 0.951(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(56)_{\mathcal{B}}, & \ell = e, \\ 0.947(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(72)_{\mathcal{B}}, & \ell = \mu, \\ 0.949(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(49)_{\mathcal{B}}, & \ell = e, \mu, \end{cases}$$

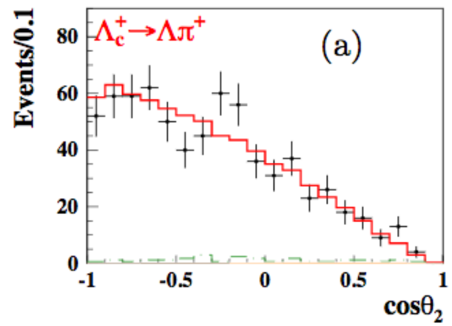
✓ More data on Λ_c^+ will be collected at BESIII

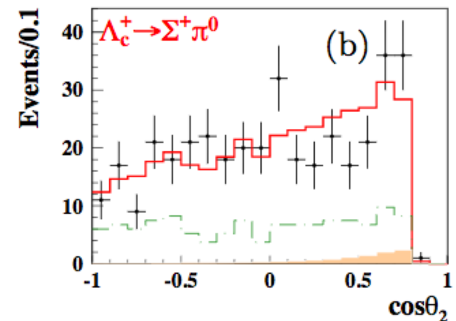
Λ_c decay asymmetries

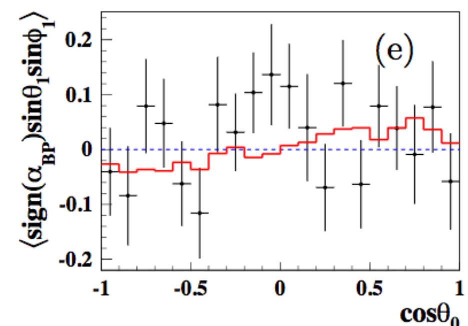
PRD100, 072004 (2019)

- 4(6)-fold angular analysis of the cascade decays of $\Lambda_c \to pK_s, \Lambda\pi^+, \Sigma^+\pi^0$ and $\Sigma^0\pi^+$ based on 567/pb data









$\Lambda_c^+ \to$		pK_S^0	$\Lambda\pi^+$	$\Sigma^+\pi^0$	$\Sigma^0\pi^+$
$\alpha_{BP}^{\Lambda_c^+}$	Predicted	−1.0 [16], 0.51 [11]	−0.70 [16], −0.67 [11]	0.71 [16], 0.92 [11]	0.70 [16], 0.92 [11]
		−0.49 [10], −0.90 [10]	−0.95 [10], −0.99 [10]	0.79 [10] −0.49 [10]	0.78 [10], −0.49 [10]
		−0.49 [17], −0.97 [18]	−0.96 [17], −0.95 [18]	0.83 [17], 0.43 [18]	0.83 [17], 0.43 [18]
		−0.66 [19], −0.90 [30]	−0.99 [19], −0.86 [30]	0.39 [19], −0.76 [30]	0.39 [19], −0.76 [30]
		−0.99 [20], −0.91 [31]	−0.99 [20], −0.94 [31]	−0.31 [20], −0.47 [31]	−0.31 [20], −0.47 [31]
	PDG [2]		-0.91 ± 0.15	-0.45 ± 0.32	
	This work	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.57 \pm 0.10 \pm 0.07$	$-0.73 \pm 0.17 \pm 0.07$

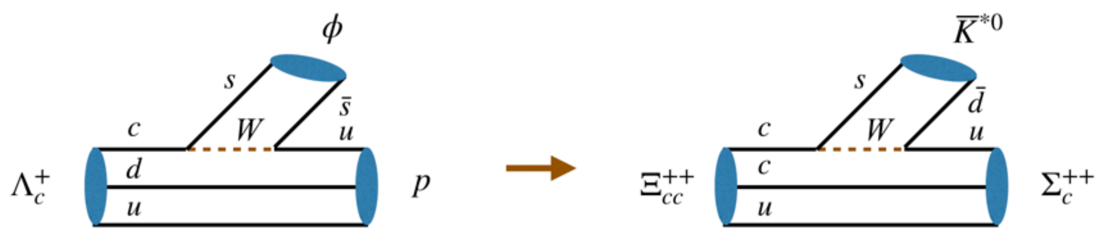
$\sin\Delta_0 = -0.28 \pm 0.13 \pm 0.03$

- Best precisions on the hadronic weak decay asymmetries
- The transverse polarization is firstly studied and found to be non-zero with 2.1σ

A theoretical Framework for Charmed Hadrons

from Fu-Sheng Yu

- Topological diagrams + Symmetries + Experimental inputs $\Rightarrow$ to understand the decaying dynamics, predicting double-charm baryon decays, CPV, etc. (predictive power)
  - Λ_c^+ branching fractions used for global analysis
    $\Rightarrow$ $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ are large enough for observation.



$Br(\Lambda_c^+ \to p\phi)/|V_{us}|^2 = 2\ \%$ → $Br\left(\Xi_{cc}^{++} \to \Sigma_c^{++} \bar{K}^{*0}\right) = O(\%)$

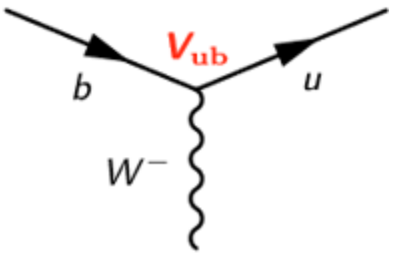
[PRL 117, 232002 (2016)]

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

Large enough for observation

Λ_c^+ BFs from BESIII → Stronger predictive power

CKM matrix element V_{ub}



$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \quad \frac{\sigma(V_{\rm CKM})}{V_{\rm CKM}}^{\text{PDG 2014}} \sim \begin{pmatrix} 0.02\% & 0.3\% & 12\% \\ 4\% & 2\% & 2\% \\ 7\% & 7\% & 3\% \end{pmatrix}$$

$$\underbrace{\frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)}}_{\text{Measure this experimentally}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \underbrace{\frac{G(\Lambda_b \to p\mu^-\nu_\mu)}{G(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)}}_{\text{Get this from theory}}$$

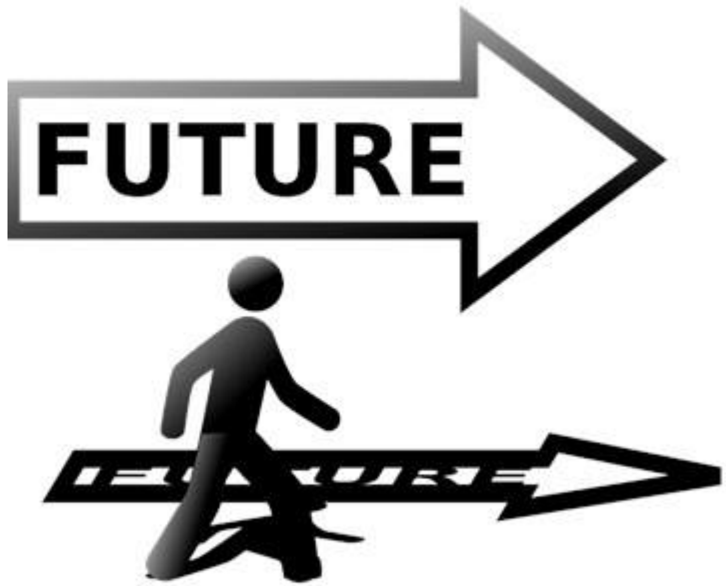
Nature Physics 11, 743 (2015)

Source	Relative u[illegible]%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	[illegible]
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

- $B(pK^-\pi^+)$ quoted BELLE's result
- 10x Λ_c data ➔ < 2%

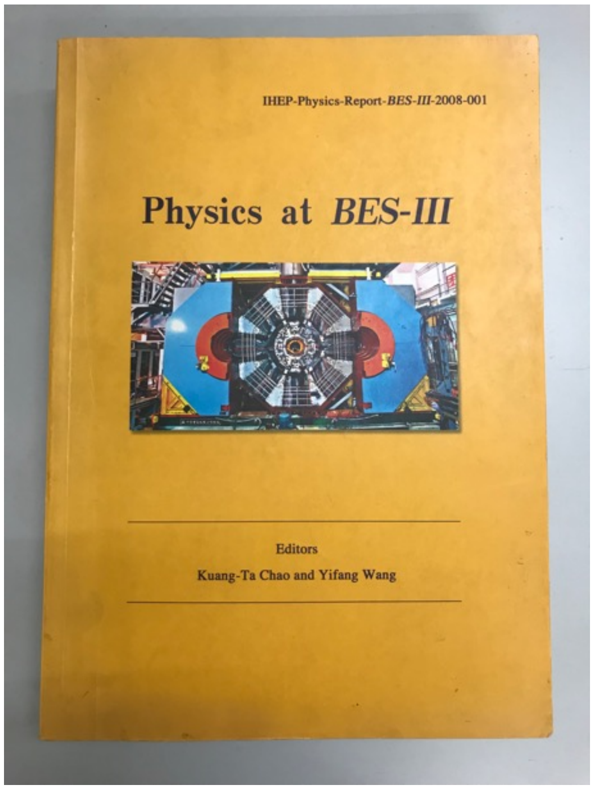
Yet unknowns

- Many of the following modes are not measured (~40%)
  - most of the semileptonic (SL) modes
  - the singly Cabibbo-Suppressed (CS) and doubly CS hadronic modes
  - the neutron- and K_L-involved channels
- Amplitude analysis of the three- and four-body decays
  - important to study the excited hyperons
  - to study the decay types of $B\left(\frac{1}{2}^{+}\right)V$ and $B(\frac{3}{2}^{+})P$
  - not much have been done yet


FUTURE

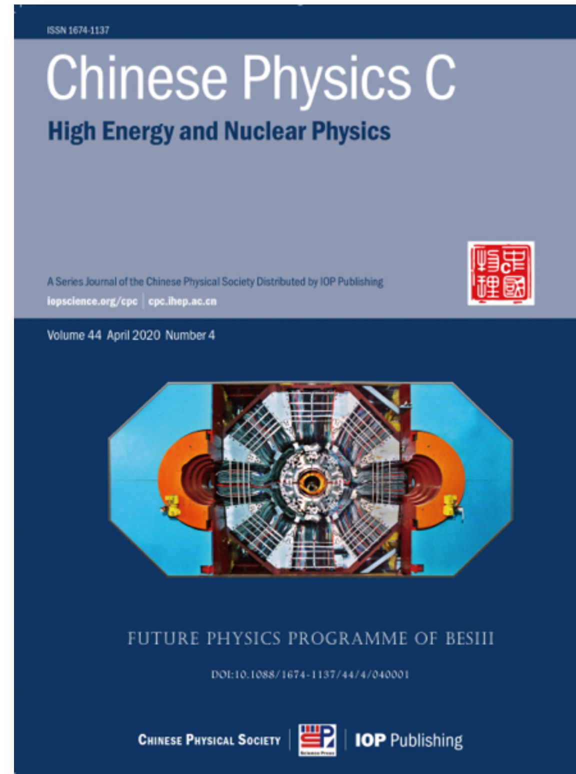
From BESIII physics (yellow) book to BESIII white paper

2008



D. Asner et al, Int. J. Mod. Phys. A 24, S1 (2009)

2020



M. Ablikim et al, Chin. Phys. C 44 040001 (2020)
DOI: [10.1088/1674-1137/44/4/040001](10.1088/1674-1137/44/4/040001)

High precision charm physics at thresholds

Observables	Exp. measure	BESIII	Belle-II	LHCb
$B(D^+ \to l\nu)$	$f_D\|V_{cd}\|$	1.1%	1.4%	N/A
$B(D_S^+ \to l\nu)$	$f_{Ds}\|V_{cs}\|$	1.0%	1.0%	N/A
$\frac{B(D^+ \to l\nu)}{B(D_S^+ \to l\nu)}$	$\frac{f_D\|V_{cd}\|}{f_{Ds}\|V_{cs}\|}$	1.0%	1.4%	N/A
$d\Gamma(D \to \pi l\nu)/dq^2$	$f_{D\to\pi}(0)\|V_{cd}\|$	0.6%	1.0%	N/A
$d\Gamma(D \to K l\nu)/dq^2$	$f_{D\to K}(0)\|V_{cs}\|$	0.5%	0.9%	N/A
$d\Gamma(D_S \to K l\nu)/dq^2$	$f_{Ds\to K}(0)\|V_{cd}\|$	1.3%	N/A	N/A
$d\Gamma(D_S \to \phi l\nu)dq^2$	$f_{Ds\to\phi}(0)\|V_{cs}\|$	1.0%	N/A	N/A

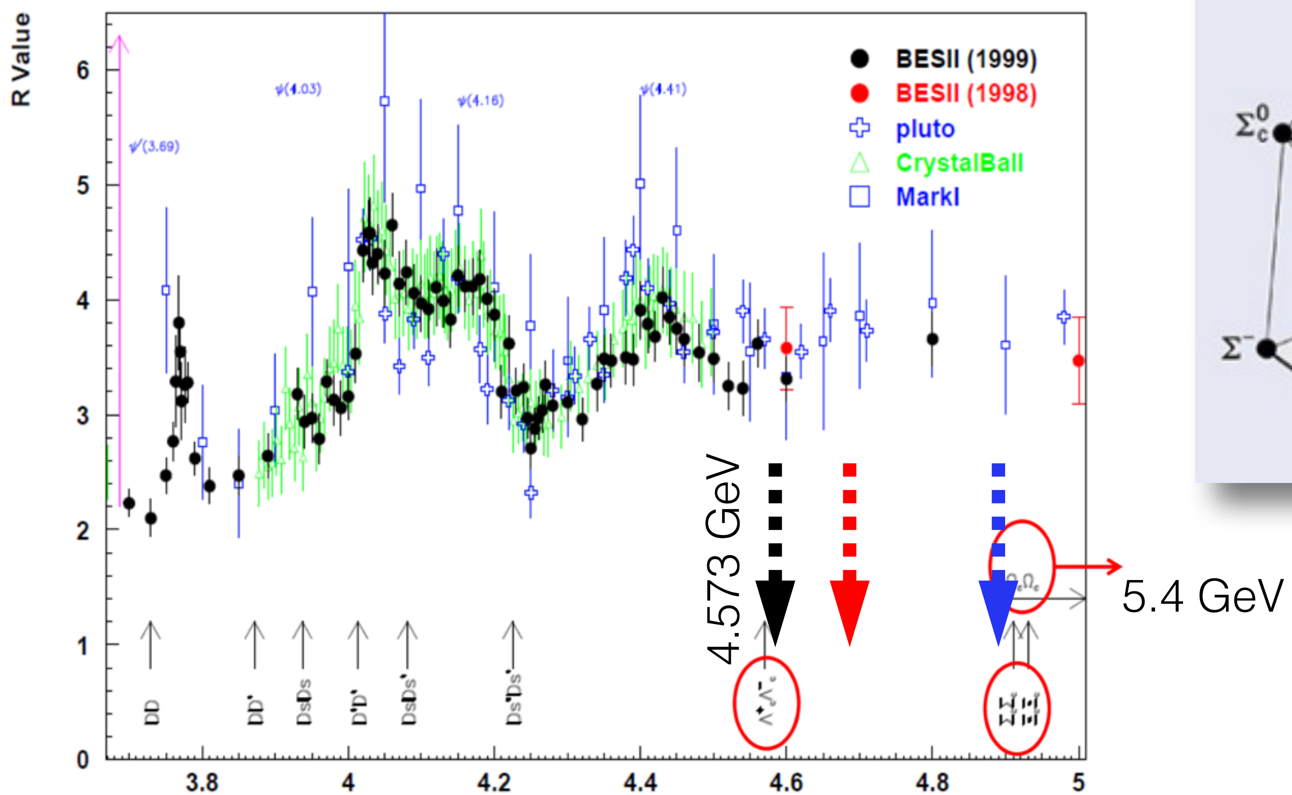
Belle: 2.5%

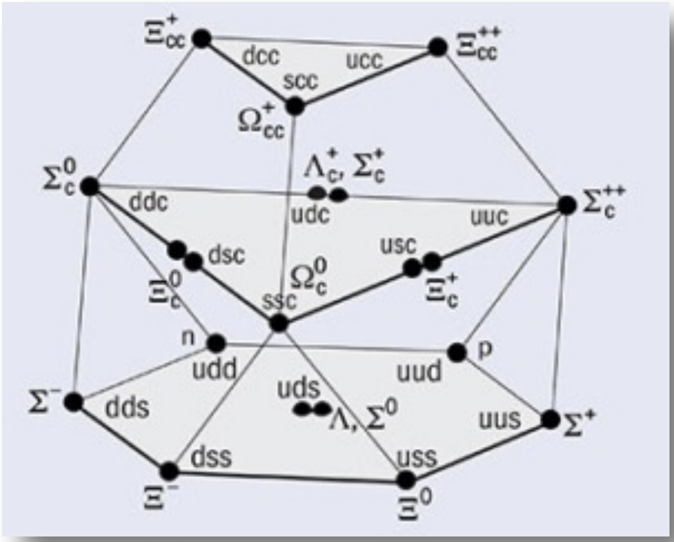
BESIII: 20fb^{-1} @ 3770 MeV, 6fb^{-1} @ 4180 MeV (BESIII physics book)

Belle-II: 50 ab^{-1} @ Υ(4S) arXiv: 1808.10567 (Belle-II physics book)

LHCb: : arXiv:1808.08865 for upgrade-II

Charmed baryon thresholds





BESIII Energy upgrade plan:

4.6 GeV → 4.7 GeV(Done!) → 4.9 GeV (by 2020)

Approved data taking between 4.6~4.7 GeV in 2020

- We hope to accumulate ~10x more Λ_c pairs (~1M)
- Irreplaceable sample to systematically refresh the whole Λ_c knowledge and impact relevant theoretical and experimental studies

- Collected data at energy points:
  4.61 GeV (~100/pb), 4.626 GeV (~500/pb),
  4.64 GeV (~500/pb), 4.66 GeV (~500/pb),
  4.68 GeV (~500/pb), 4.70 GeV (~500/pb)
- These data can also be used to study XYZ physics, such as Y(4630/4660)

Impacts on Λ_c decay data

D_s^+ BRANCHING RATIOS

A number of older, now obsolete results have been omitted. They may be found in earlier editions.

Inclusive modes

$\Gamma(e^+ \text{semileptonic})/\Gamma_{total}$ — Γ_1/Γ

This is the purely e^+ semileptonic branching fraction: the e^+ fraction from τ^+ decays has been subtracted off. The sum of our (non-τ) ... fractions — ... $e^+\nu_e$ with an η, η', ϕ, K^0, or K^{*0} — is 5.99 ± 0.3 %.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
6.52±0.39±0.15	536 ± 29	[1] ASNER	10	CLEO	e^+e^- at 3774 MeV

[1] Using the D_s^+ and D^0 lifetimes, ASNER 10 finds that the ratio of the D_s^+ and D^0 semileptonic widths is 0.828 ± 0.051 ± 0.025.

$\Gamma(\pi^+ \text{anything})/\Gamma_{total}$ — Γ_2/Γ

Events with two π^+'s count twice, etc. But π^+'s from $K_S^0 \to \pi^+\pi^-$ are not included.

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
119.3±1.2±0.7	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\pi^- \text{anything})/\Gamma_{total}$ — Γ_3/Γ

Events with two π^-'s count twice, etc. But π^-'s from $K_S^0 \to \pi^+\pi^-$ are not included.

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
43.2±0.9±0.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\pi^0 \text{anything})/\Gamma_{total}$ — Γ_4/Γ

Events with two π^0's count twice, etc. But π^0's from $K_S^0 \to$ ... are not included.

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
123.4±3.8±5.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(K^- \text{anything})/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
18.7±0.5±0.2	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(K^+ \text{anything})/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
28.9±0.6±0.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(K_S^0 \text{anything})/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
19.0±1.0±0.4	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\eta \text{anything})/\Gamma_{total}$ — Γ_8/Γ

This ratio includes η particles from η' decays.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
29.9±2.2±1.7		DOBBS	09	CLEO	e^+e^- at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
23.5±3.1±2.0	674 ± 91	HUANG	06B	CLEO	See DOBBS 09

$\Gamma(\omega \text{anything})/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
6.1±1.4±0.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\eta' \text{anything})/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
10.3±1.4 OUR AVERAGE	Error includes scale factor of 1.1.				
8.8±1.8±0.5	68	ABLIKIM	15Z	BES3	482 pb^{-1}, 4009 MeV
11.7±1.7±0.7		DOBBS	09	CLEO	e^+e^- at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.7±1.9±0.8	68	HUANG	06B	CLEO	See DOBBS 09

$\Gamma(f_0(980) \text{anything}, f_0 \to \pi^+\pi^-)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
<1.3	90	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\phi \text{anything})/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
15.7±0.8±0.6		DOBBS	09	CLEO	e^+e^- at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
16.1±1.2±1.1	398 ± 27	HUANG	06B	CLEO	See DOBBS 09

$\Gamma(K^+K^- \text{anything})/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
15.8±0.6±0.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

CLEOc dominants the D_s Branching Fraction measurements. (Sys. Err. Dominates CF modes. Many SCS&DCS modes observed.)

Baryon Particle Listings

Λ_c^+

$\Gamma(\Lambda\pi^+)/\Gamma(pK^-\pi^+)$ — Γ_{28}/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.208±0.009 OUR FIT	Error includes scale factor of 1.2.					
0.204±0.019 OUR AVERAGE						
0.217±0.013±0.020		750	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV
0.18 ±0.03 ±0.04			ALBRECHT	92	ARG	$e^+e^- \approx$ 10.4 GeV
0.18 ±0.03 ±0.03		87	AVERY	91	CLEO	e^+e^- 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.33	90		ANJOS	90	E691	γBe 70–260 GeV
<0.16	90		ALBRECHT	88C	ARG	e^+e^- 10 GeV

$\Gamma(\Lambda\pi^+\pi^0)/\Gamma_{total}$ — Γ_{29}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
7.0 ±0.4 OUR FIT	Error includes scale factor of 1.1.				
7.01±0.37±0.19	1497	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

$\Gamma(\Lambda\pi^+\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{29}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.13±0.06 OUR FIT	Error includes scale factor of 1.1.				
0.73±0.09±0.16	464	AVERY	94	CLE2	$e^+e^- \approx \Upsilon(3S), \Upsilon(4S)$

$\Gamma(\Lambda\rho^+)/\Gamma(pK^-\pi^+)$ — Γ_{30}/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.95	95	AVERY	94	CLE2	$e^+e^- \approx \Upsilon(3S), \Upsilon(4S)$

$\Gamma(\Lambda\pi^-2\pi^+)/\Gamma_{total}$ — Γ_{31}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
3.61±0.29 OUR FIT	Error includes scale factor of 1.1.				
3.81±0.24±0.18	609	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

$\Gamma(\Lambda\pi^-2\pi^+)/\Gamma(pK^-\pi^+)$ — Γ_{31}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.58 ±0.05 OUR FIT	Error includes scale factor of 2.0.				
0.522±0.032 OUR AVERAGE					
0.508±0.024±0.024	1356	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV
0.65 ±0.11 ±0.12	289	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.82 ±0.29 ±0.27	44	ANJOS	90	E691	γBe 70–260 GeV
0.94 ±0.41 ±0.13	10	BARLAG	90D	NA32	π^- 230 GeV
0.61 ±0.16 ±0.04	105	ALBRECHT	88C	ARG	e^+e^- 10 GeV

$\Gamma(\Sigma(1385)^+\pi^+\pi^-, \Sigma^{*+} \to \Lambda\pi^+)/\Gamma(\Lambda\pi^-2\pi^+)$ — Γ_{32}/Γ_{31}

VALUE	DOCUMENT ID		TECN	COMMENT
0.28±0.10±0.08	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV

$\Gamma(\Sigma(1385)^-2\pi^+, \Sigma^{*-} \to \Lambda\pi^-)/\Gamma(\Lambda\pi^-2\pi^+)$ — Γ_{33}/Γ_{31}

VALUE	DOCUMENT ID		TECN	COMMENT
0.21±0.03±0.02	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV

$\Gamma(\Lambda\pi^+\rho^0)/\Gamma(\Lambda\pi^-2\pi^+)$ — Γ_{34}/Γ_{31}

VALUE	DOCUMENT ID		TECN	COMMENT
0.40±0.12±0.12	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV

$\Gamma(\Sigma(1385)^+\rho^0, \Sigma^{*+} \to \Lambda\pi^+)/\Gamma(\Lambda\pi^-2\pi^+)$ — Γ_{35}/Γ_{31}

VALUE	DOCUMENT ID		TECN	COMMENT
0.14±0.09±0.07	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV

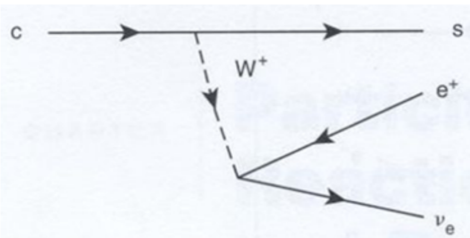
$\Gamma(\Lambda\pi^-2\pi^+ \text{nonresonant})/\Gamma(\Lambda\pi^-2\pi^+)$ — Γ_{36}/Γ_{31}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.3	90	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV

Can BESIII dominate Λ_c? Most Brs are Stat. Error dominated. Many SCS &DCS modes NOT observed.

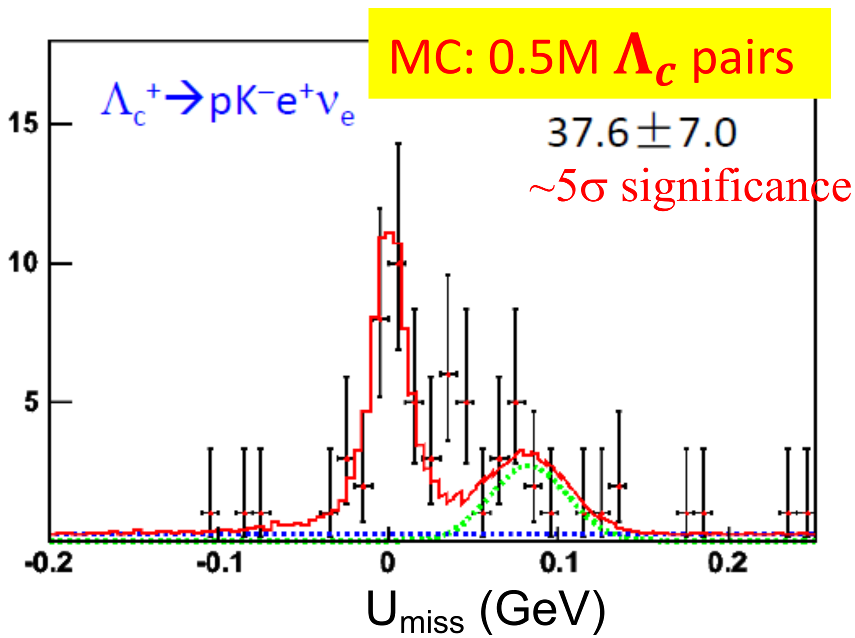
Prospects on semi-leptonic decays

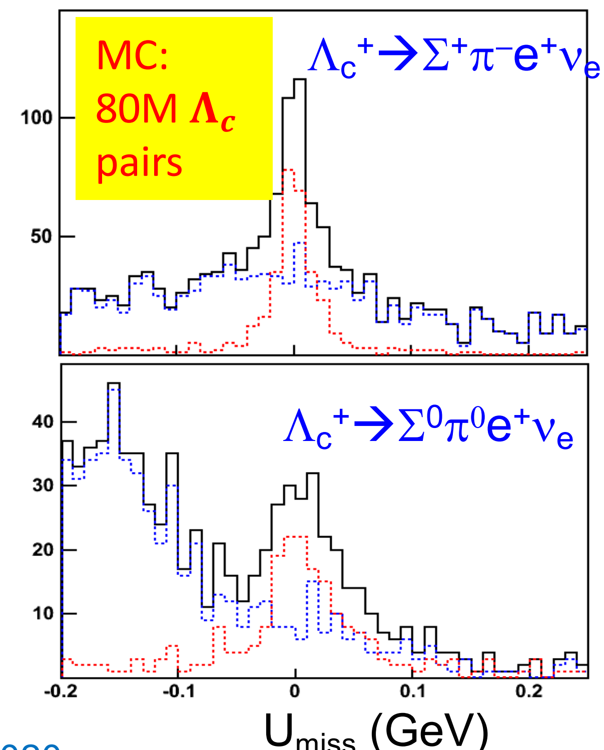
- Cleanest way to access the dynamics inside charmed baryon



Mode	Expected rate (%)	Relative uncertainty (%)
$\Lambda_c^+ \to \Lambda l^+ \nu$	3.6 [94, 95]	3.3
$\Lambda_c^+ \to \Lambda^* l^+ \nu$	0.7 [96, 97]	10
$\Lambda_c^+ \to NKe^+\nu_e$	0.7 [96]	10
$\Lambda_c^+ \to \Sigma\pi l^+ \nu$	0.7 [96]	10
$\Lambda_c^+ \to ne^+\nu_e$	0.2 [94, 98, 99]	17

first measurement

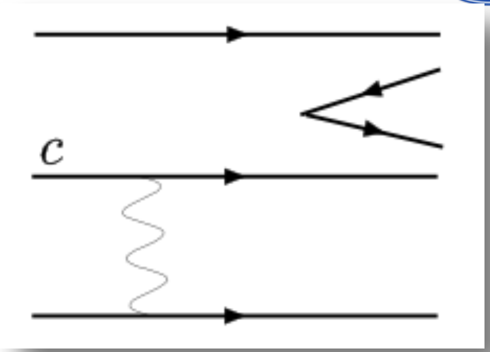




Λ_c^+ hadronic decay

- **Systematically study channels via W-exchange**

  Important ingredient contribution to explain the life times of Λ_c, D^0 and D^+ [PDG2017]:



$\tau_{\Lambda C}$ =(200±6)×10^{-15} s τ_{D0} =(410.1±1.5)×10^{-15} s τ_{D+} =(1040±7)×10^{-15} s

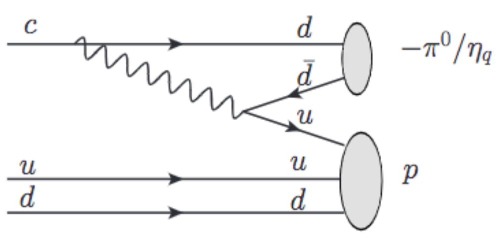
✓ It is expected that the W-exchange (no helicity suppression) mechanism plays an important role in Λ_c^+ decays.

✓ Important to study the only W-exchanges Λ_c^+ decays: clean and straightforward

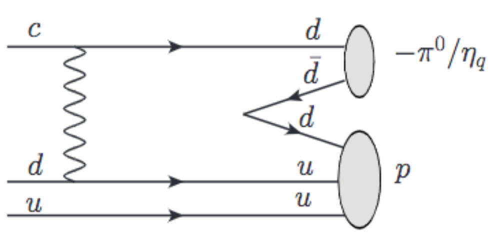
	BFs in PDG 2017	
$\Lambda_C^+ \to \Xi^0 K^+$	$(5.0\pm1.2)\times10^{-3}$	BESIII will systematically study and precisely measure their branching fractions.
$\Lambda_C^+ \to \Delta^{++} K^-$	$(1.09\pm0.25)\times10^{-2}$	
$\Lambda_C^+ \to \Sigma^+ K^+ K^-$	$(3.6\pm0.4)\times10^{-3}$	
$\Lambda_C^+ \to \Sigma^+ \phi$	$(4.0\pm0.6)\times10^{-3}$	

Cabibbo-Suppressed Λ_c^+ decays

- Many measurements are absent.
- Cabibbo-suppressed (CS) processes are **essential for flavor SU(3) symmetry and its breaking**



C_1 ***non-factorizable***



E_1 ***W-exchange***

Modes	Representation	$\mathcal{B}_{\rm exp}$
$p\pi^0$	$\lambda_{dd}\left[-\frac{1}{2\sqrt{2}}(C'-C+E_{2A}-B)-\frac{1}{2\sqrt{6}}(E_{2S}+2E_{1S})\right]$	$<2.7\times10^{-4}$
$n\pi^+$	$\lambda_{dd}\left[\frac{1}{2}(T+C'+E_{2A}-B)-\frac{1}{2\sqrt{3}}E_{2S}\right]$	
$p\eta$	$\lambda_{dd}\left[\frac{1}{2\sqrt{2}}(C'-C-E_{2A}+B)+\frac{1}{2\sqrt{6}}(2E_{1S}-E_{2S})\right]\cos\phi$ $+\frac{1}{2}\lambda_{ss}C\sin\phi$	$(1.24\pm0.30)\times10^{-3}$
$p\eta'$	$\lambda_{dd}\left[\frac{1}{2\sqrt{2}}(C'-C-E_{2A}+B)+\frac{1}{2\sqrt{6}}(2E_{1S}-E_{2S})\right]\sin\phi$ $-\frac{1}{2}\lambda_{ss}C\cos\phi$	
ΛK^+	$\frac{1}{2\sqrt{6}}\lambda_{ss}(2T+C'+2B-2E_{2A})$	$(0.61\pm0.12)\times10^{-3}$
Σ^0K^+	$\lambda_{ss}\left[\frac{1}{2\sqrt{2}}C'+\frac{1}{\sqrt{6}}E_{2S}\right]$	$(0.52\pm0.08)\times10^{-3}$
Σ^+K^0	$\lambda_{ss}\frac{1}{2}C'+\lambda_{dd}\frac{1}{\sqrt{3}}E_{1S}$	
$p\rho^0$	$\lambda_{dd}\left[-\frac{1}{2\sqrt{2}}(C'-C+E_{2A}-B)-\frac{1}{2\sqrt{6}}(E_{2S}+2E_{1S})\right]$	
$p\omega$	$\lambda_{dd}\left[-\frac{1}{2\sqrt{2}}(-C'+C+E_{2A}-B)-\frac{1}{2\sqrt{6}}(-E_{2S}+2E_{1S})\right]$	$(9.4\pm3.9)\times10^{-4}$
$p\phi$	$\lambda_{ss}C$	$(1.04\pm0.21)\times10^{-3}$
$n\rho^+$	$\lambda_{dd}\left[\frac{1}{2}(T+C'+E_{2A}-B)-\frac{1}{2\sqrt{3}}E_{2S}\right]$	
Λ^0K^{*+}	$\frac{1}{2\sqrt{6}}\lambda_{ss}(2T+C'+2B-2E_{2A})$	
Σ^0K^{*+}	$\lambda_{ss}\left[\frac{1}{2\sqrt{2}}C'+\frac{1}{\sqrt{6}}E_{2S}\right]$	
Σ^+K^{*0}	$\lambda_{ss}\frac{1}{2}C'+\lambda_{dd}\frac{1}{\sqrt{3}}E_{1S}$	$(3.6\pm1.0)\times10^{-3}$
$\Delta^{++}\pi^-$	$-\lambda_{dd}E_{1S}$	
$\Delta^+\pi^0$	$\lambda_{dd}(E_{1S}-E_{2S})/\sqrt{6}$	
$\Delta^0\pi^+$	$\lambda_{dd}E_{2S}/\sqrt{3}$	
$\Delta^+\eta$	$\lambda_{dd}(E_{1S}+E_{2S})\cos\phi/\sqrt{6}$	
$\Delta^+\eta'$	$\lambda_{dd}(E_{1S}+E_{2S})\sin\phi/\sqrt{6}$	
$\Sigma^{*0}K^+$	$\lambda_{dd}E_{2S}/\sqrt{6}$	
$\Sigma^{*+}K^0$	$\lambda_{dd}E_{1S}/\sqrt{3}$	

CS BF: Order of 10^{-3} or below

BESIII Predictions and Measurements

Hai-Yang Cheng etc, arXiv: 1801.08625

	Sharma *et al.* [24]	Uppal *et al.* [41]	Chen *et al.* [42]	Lu *et al.* [25]	Geng *et al.* [26]	This work [in units of 10^{-3}]	Expt [7, 19]
$\Lambda_c^+ \to p\pi^0$	0.2	0.1-0.2	0.11-0.36	0.48	0.56 ± 0.15	0.08	< 0.27 **?**
$\Lambda_c^+ \to p\eta$	$0.2^a(1.7)^b$	0.3			1.24 ± 0.41	1.28	1.24 ± 0.29
$\Lambda_c^+ \to p\eta'$	0.4-0.6	0.04-0.2			$1.22^{+1.43}_{-0.87}$		**?**
$\Lambda_c^+ \to n\pi^+$	0.4	0.8-0.9	0.10-0.21	0.97		0.27	**?**
$\Lambda_c^+ \to \Lambda K^+$	1.4	1.2	0.18-0.39		0.46 ± 0.09	1.06	0.61 ± 0.12
$\Lambda_c^+ \to \Sigma^0 K^+$	0.4-0.6	0.2-0.8			0.40 ± 0.08	0.72	0.52 ± 0.08
$\Lambda_c^+ \to \Sigma^+ K^0$	0.9-1.2	0.4-0.8			0.80 ± 0.16	1.44	**?**

- Measuring the decay BFs of these decay channels can provide important data for understanding the W-exchange and non-factorizable mechanism.

SU(3) symmetry test in Λ_c CS decays

- Based on (broken) SU(3) symmetry, there are predicted branching fractions of SCS channels

	SU(3)	Broken SU(3)	Exp./PDG
$10^4\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K^0)$	8.0 ± 1.6	10.4 ± 1.5	---
$10^4\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)$	$(4.0 \pm 0.8)^\dagger$	$(5.2 \pm 0.7)^\dagger$	5.2 ± 0.8
$10^4\mathcal{B}(\Lambda_c^+ \to p\pi^0)$	5.7 ± 1.5	5.4 ± 1.0	<2.7
$10^4\mathcal{B}(\Lambda_c^+ \to n\pi^+)$	11.3 ± 2.9	10.7 ± 1.9	---
$10^4\mathcal{B}(\Lambda_c^+ \to \Lambda^0 K^+)$	$(4.6 \pm 0.9)^\dagger$	$(6.1 \pm 0.9)^\dagger$	6.1 ± 1.2

PRD97, 073006 (2018); EPJC78, 593 (2018)

2M Λ_c pairs needed to statistically guarantee the test on the SU(3) effect.

- Crucial test using larger Λ_c data set will be important to find large SU(3) breaking effect in SCS decays
  ➔ Useful input to search CPV in charmed baryon sector
  [PRD86, 014023(2012); JHEP 1210, 161 (2012)]
- No observations of $\Lambda_c \to \Lambda K^+, p\pi^0$ and $n\pi^+$: important channels to test SU(3) symmetry by examining $\frac{B(\Lambda_c \to N\pi)}{B(\Lambda_c \to \Lambda K^+)}$

Other relevant topics

- **Λ_c^+ hadronic weak decays**
  - ✓ *Decay asymmetry parameters in Λ_c^+ two-body decays, $\Lambda_c^+ \to BP/BV$*

    which can be used to study the relative phase between S-wave and P-wave decays
- **Exclusive decays containing neutron or K_L^0**
  - ✓ *First observation of $\Lambda_c^+ \to n\pi^+$, nK^+, $n\pi^+\pi^0$, $nK^+\pi^0$, etc*

    It can provides a good test on isospin/SU(3) symmetry by combing the measurements of the Λ_c^+ decays proton channels.
  - ✓ *$\Lambda_c^+ \to pK_S^0/K_L^0$, $pK_S^0\pi^0/K_L^0\pi^0$, etc*

$$R \equiv \frac{\Gamma(\Lambda_c^+ \to pK_S^0) - \Gamma(\Lambda_c^+ \to pK_L^0)}{\Gamma(\Lambda_c^+ \to pK_S^0) + \Gamma(\Lambda_c^+ \to pK_L^0)}$$

[Fu-Sheng Yu, arXiv: 1709.09873]

Helps to explore K_S^0-K_L^0 asymmetry in Λ_c^+ decays.
- **Weak radiative decays**

  First evidence or observation of $\Lambda_c^+ \to \gamma\Sigma^+$ and γp

  The BF for $\Lambda_c^+ \to \gamma\Sigma^+$ is predicted to be 2.8×10^{-4} [PRD47,2858(1993)]

Prospects on weak decay asymmetry

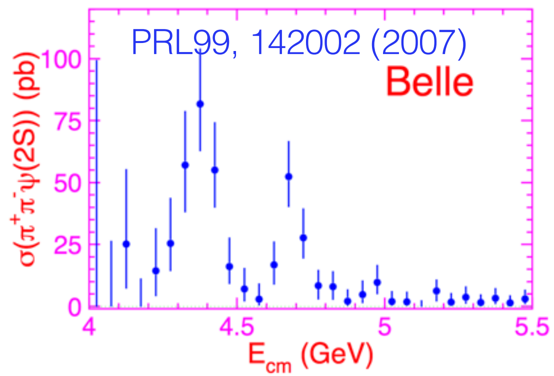
first or improved measurements of decay asymmetry parameters the following modes $\Lambda_c^+ \to B(\frac{1}{2}^+)+P$

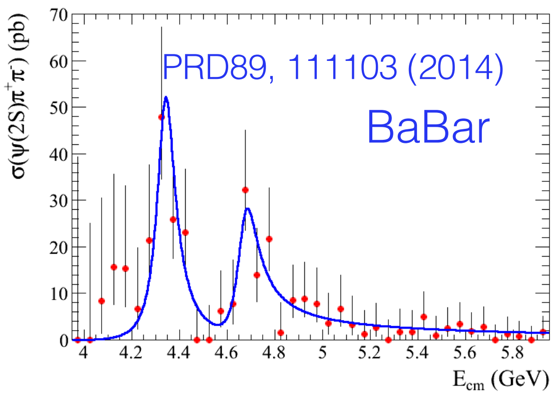
$$\frac{dW}{d\cos\theta} = \frac{1}{2}(1+\alpha_{\Lambda_c}\alpha_B\cos\theta) \qquad \alpha = \frac{2\,\mathrm{Re}(S^* P)}{|S|^2+|P|^2}$$

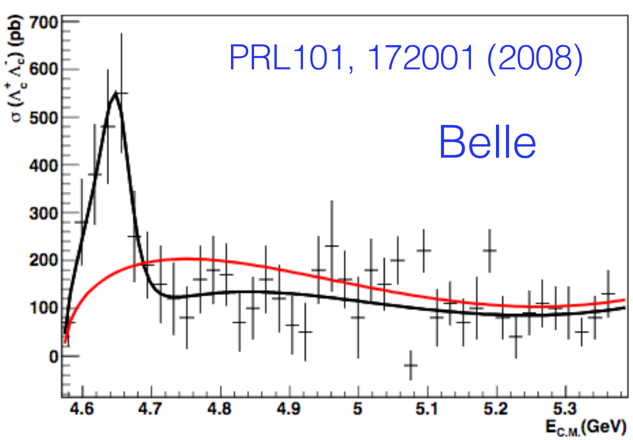
Decay	Körner	Xu	Cheng		Ivanov	Żenczykowski	Sharma	Geng	Expt.	Future BESIII precision
$\Lambda_c^+ \to \Lambda\pi^+$	−0.70	−0.67	−0.99	−0.95	−0.95	−0.99	−0.99	-0.87 ± 0.10	-0.91 ± 0.15	
									-0.80 ± 0.11[1]	0.03
$\Lambda_c^+ \to p\bar{K}^0$	−1.0	0.51	−0.90	−0.49	−0.97	−0.66	−0.99	$-0.90^{+0.22}_{-0.10}$	0.18 ± 0.45[1]	0.10
$\Lambda_c^+ \to \Sigma^0\pi^+$	0.70	0.92	−0.49	0.78	0.43	0.39	−0.31	-0.35 ± 0.27	-0.73 ± 0.18[1]	0.05
$\Lambda_c^+ \to \Sigma^+\pi^0$	0.70	0.92	−0.49	0.78	0.43	0.39	−0.31	-0.35 ± 0.27	-0.45 ± 0.32	
									-0.57 ± 0.12[1]	0.03
$\Lambda_c^+ \to \Sigma^+\eta$	0.33				0.55	0	−0.91	-0.40 ± 0.47		first meas.
$\Lambda_c^+ \to \Sigma^+\eta'$	−0.45				−0.05	−0.91	0.78	$1.00^{+0.00}_{-0.17}$		first meas.
$\Lambda_c^+ \to \Xi^0 K^+$	0	0			0	0	0	$0.94^{+0.06}_{-0.11}$		first meas.

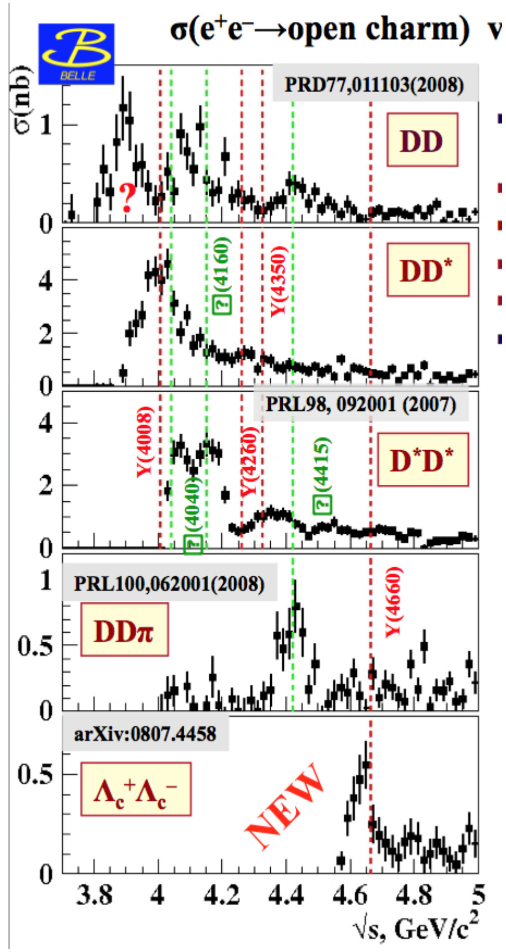
- Advantages for threshold measurement
  - Spin correlations of Λ_c^+ pairs near threshold production
  - Most of the modes involve photon final states
- We will provide rigid tests on the theoretical calculations

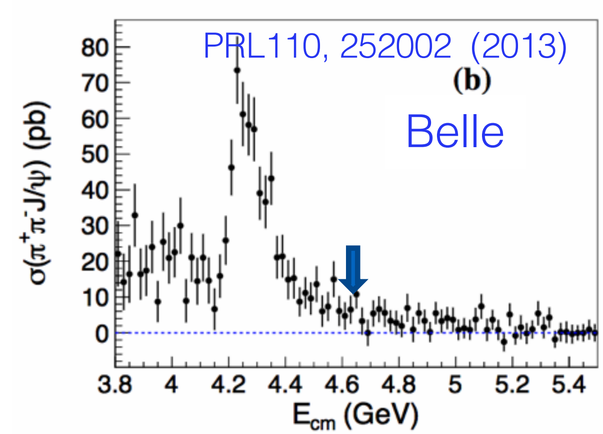
The Y(4630)/Y(4660) with 4.6-4.7GeV data in 2020











$$\frac{\mathcal{B}(Y_B \to \Lambda_c\bar{\Lambda}_c)}{\mathcal{B}(Y_B \to \psi(2S)\pi^+\pi^-)} = 25 \pm 7,$$

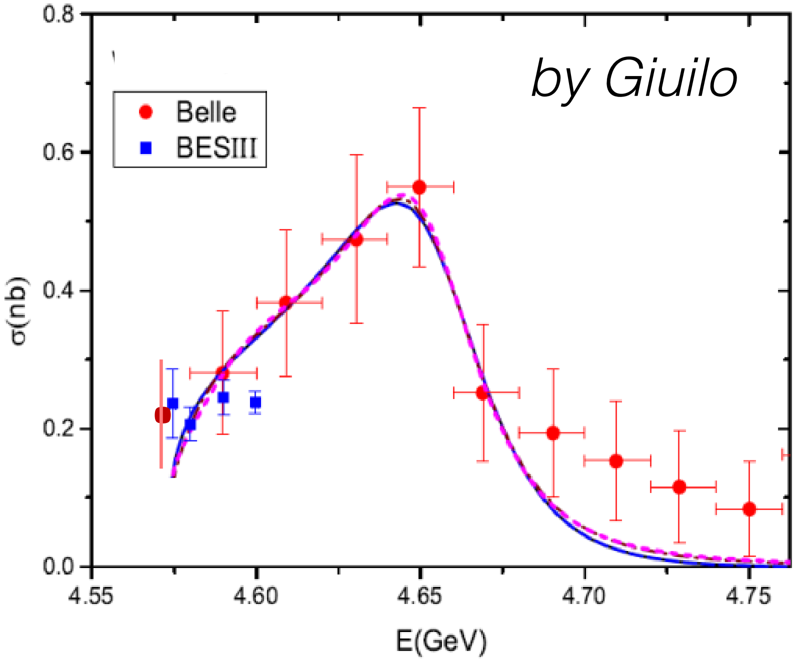
Phys.Rev.Lett. 104 (2010) 132005

$$\frac{B(Y_B \to D^0 D^{*-}\pi^+)}{B(Y_B \to \psi(2S)\pi^+\pi^-)} < 10$$

PDG

- Y(4660) baryonic coupling ≥ 10 mesonic coupling (unexpected!)
- Another missing large mesonic decay? Or Y(4660) is a charmed baryonium?

Lineshape of $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$

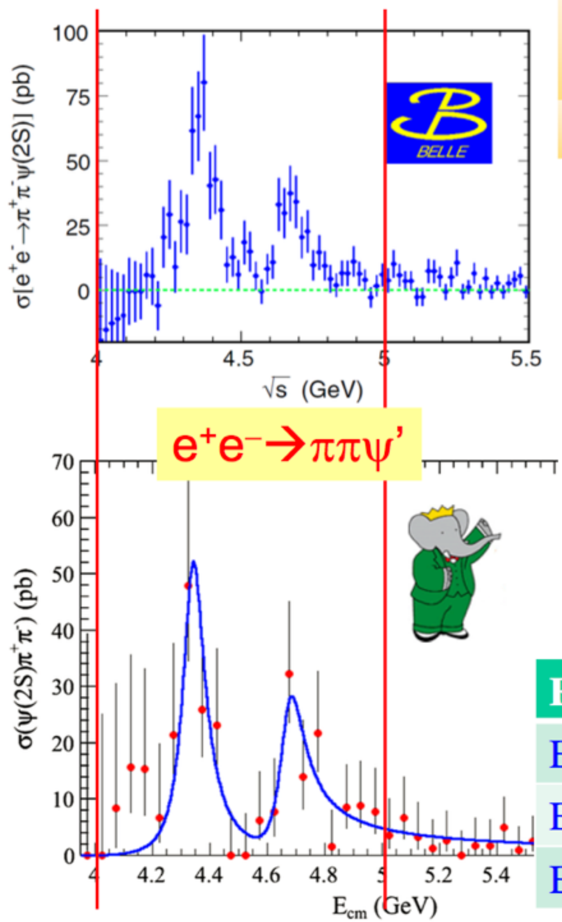


Belle: PRL101, 172001 (2008)
BESIII: PRL120,132001(2018)

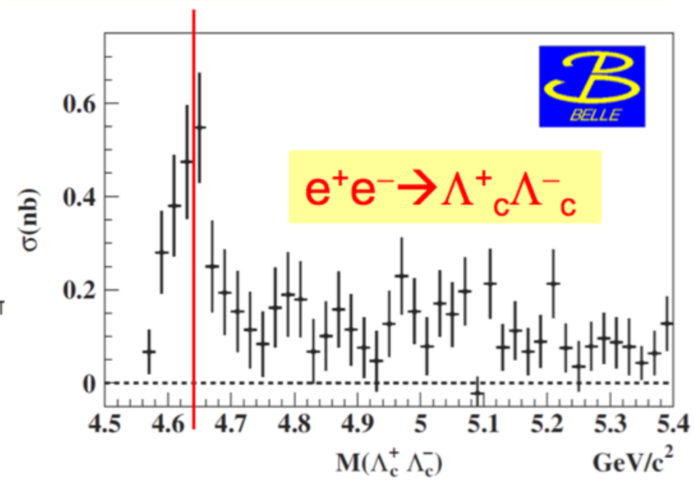
- Some tension between BELLE and BESIII data on $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$
- BESIII future data above 4.6 GeV will follow a sharp rise of the Y(4660) or a flat cross section near threshold?

4.6~4.9 GeV

Y(4630)=Y(4660)? $Z_c(4430)$ in $e^+e^- \to \pi^+\pi^-\psi'$? Z_{cs} exists?

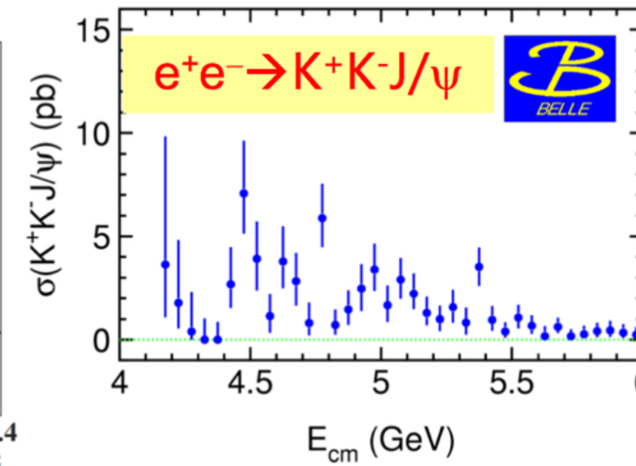


Belle: PRD91, 112007 (2015), 980/fb
BaBar: PRD89, 111103 (2014), 520/fb
Belle: PRL101, 172001 (2008), 695/fb



Experiment	Mass (MeV)	Width (MeV)
Belle, Y(4630)	$4634^{+8}_{-7}{}^{+5}_{-8}$	$92^{+40}_{-24}{}^{+10}_{-21}$
Belle, Y(4660)	4652±10±8	68±11±1
Babar, Y(4660)	4669±21±3	104±48±10

Z_{cs} related to $D_sD^*/D_s^*D/D_s^*D^*$ thresholds?



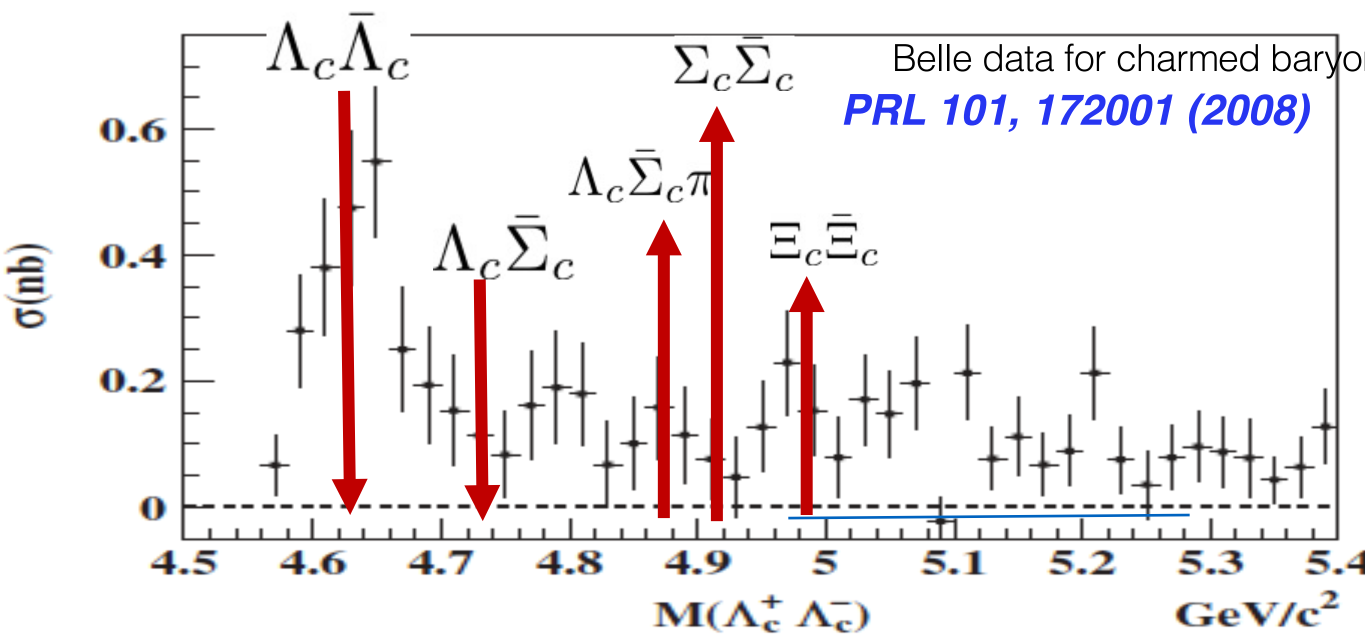
Search for Z_{cs} ($c\bar{c}u\bar{s}$) in K^+K^-J/ψ, $K^+D_s^-D^*$, $K^+D_s^{*-}D$, and $K^+D_s^{*-}D^*$ final states.

5

Future data taking proposals

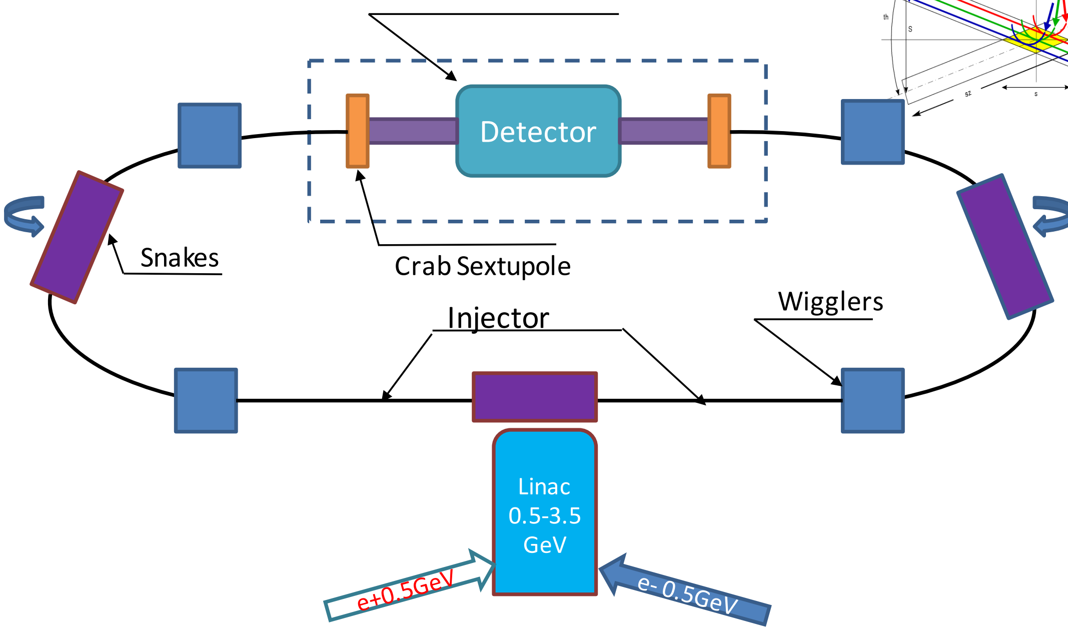
A simple reference table (can be modified according to future machine status)

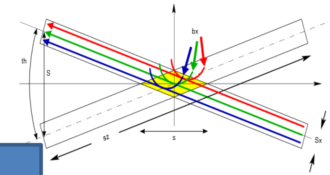
Energy	Physics motivations	Current data	Expected final data	T_C / T_U
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days



Belle data for charmed baryon
PRL 101, 172001 (2008)

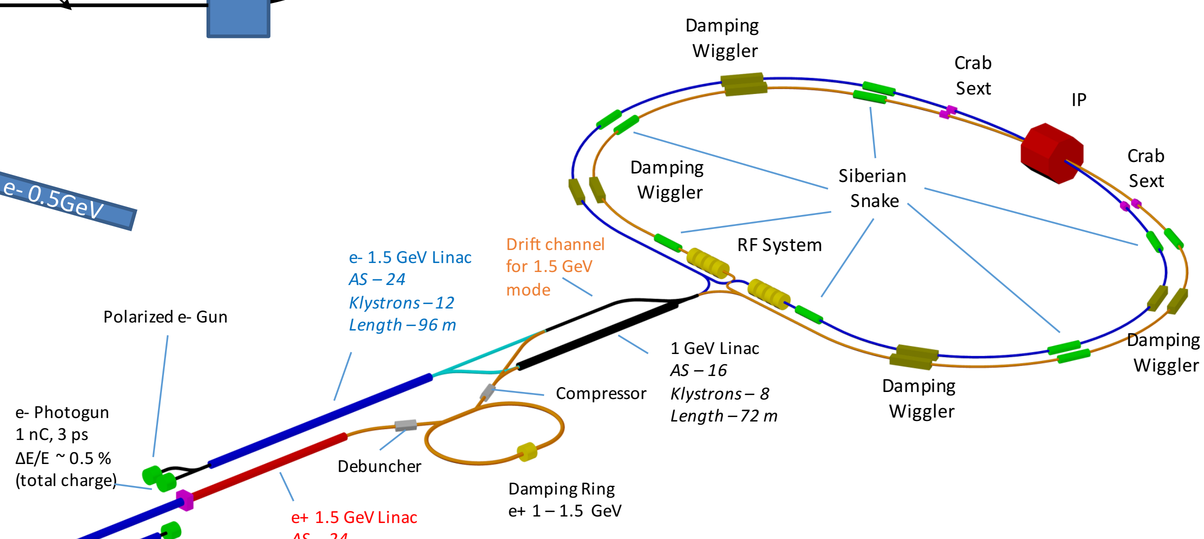
Proposals of the Super Tau-Charm Factory (STCF)





HIEPA in China

Super-CT Project in Russia



Total number of accelerating structures: 104
Klystron number: 52
Total length of the linacs: ~440 m

energy of 1.5 – 2.5 (3) GeV

Prospects at the STCF

Data samples with 1 ab^{-1} integral luminosity

	STCF					Belle II		
Data Set	process	σ/nb	N	ST eff./%	ST N	σ/nb	N	Tag N
J/ψ	–	–	1.0×10^{12}	–	–	–	–	–
$\psi(2S)$	–	–	3.0×10^{11}	–	–	–	–	–
D^0	$D^0\bar{D}^0(3.77)$	~ 3.6	3.6×10^9	10.8	0.78×10^9	–	1.4×10^9	–
D^+	$D^+D^-(3.77)$	~ 2.8	2.8×10^9	9.4	0.53×10^9	–	7.7×10^8	–
D_s	$D_sD_s^*(4.18)$	~ 0.9	0.9×10^9	6.0	0.11×10^9	–	2.5×10^8	–
τ^+	$\tau^+\tau^-(3.68)$	~ 2.4	2.4×10^9	–	–	0.9	0.9×10^9	–
	$\tau^+\tau^-(4.25)$	~ 3.6	3.5×10^9	–	–	–	–	–
Λ_c	$\Lambda_c\Lambda_c(4.64)$	~ 0.6	5.5×10^8	5.0	0.55×10^8	–	1.6×10^8	$3.6 \times 10^{4*}$

The luminosity is 1.0 ab^{-1}. * process $e^+e^- \to D^{(*)-}\bar{p}\pi^+\Lambda_c^+$.

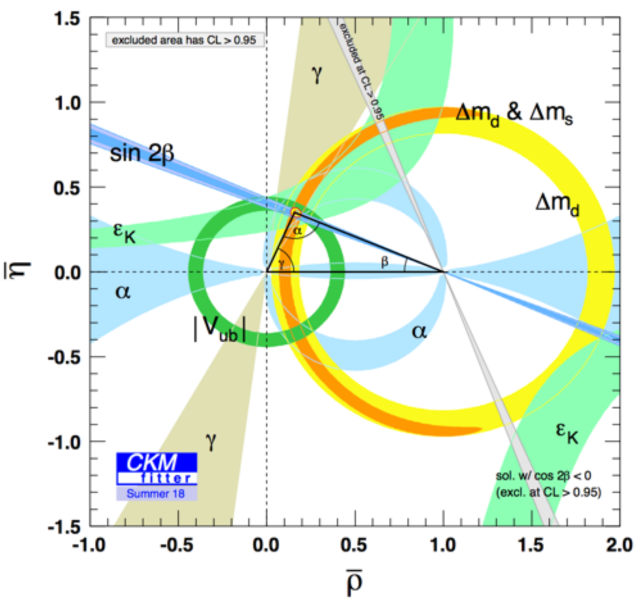
- Belle-II (50/ab) has 50~100 times more statistics
- STCF is expected to have higher detection efficiency
- STCF has low backgrounds for productions at threshold

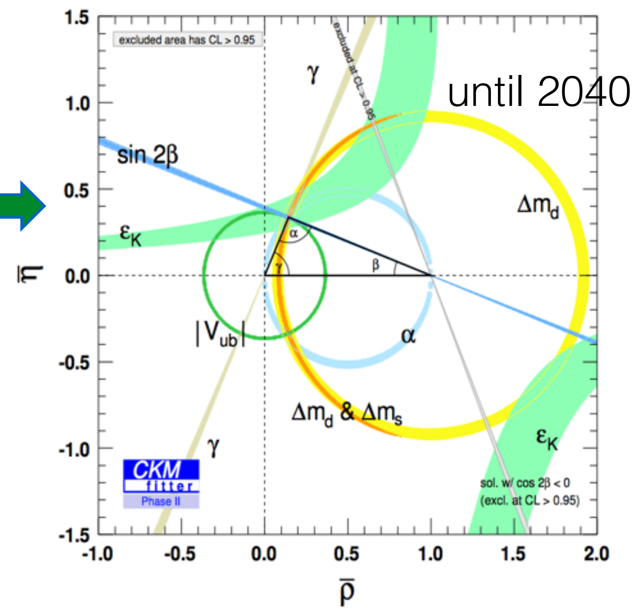
Sensitivities of the charmed meson decays

	BESIII	STCF	Belle II
Luminosity	2.92 fb^{-1} at 3.773 GeV	1 ab^{-1} at 3.773 GeV	50 ab^{-1} at $\Upsilon(nS)$
$\mathcal{B}(D^+\to\mu^+\nu_\mu)$	$5.1\%_{\rm stat.}$ $1.6\%_{\rm syst.}$ [6]	$0.28\%_{\rm stat.}$	–
f_{D^+} (MeV)	$2.6\%_{\rm stat.}$ $0.9\%_{\rm syst.}$ [6]	$0.15\%_{\rm stat.}$	–
$\lvert V_{cd}\rvert$	$2.6\%_{\rm stat.}$ $1.0\%^{*}_{\rm syst.}$ [6]	$0.15\%_{\rm stat.}$	–
$\mathcal{B}(D^+\to\tau^+\nu_\tau)$	$20\%_{\rm stat.}$ $10\%^{\dagger}_{\rm syst.}$ [7]	$0.41\%_{\rm stat.}$	–
$\frac{\mathcal{B}(D^+\to\tau^+\nu_\tau)}{\mathcal{B}(D^+\to\mu^+\nu_\mu)}$	$21\%_{\rm stat.}$ $10\%^{\dagger}_{\rm syst.}$ [7]	$0.50\%_{\rm stat.}$	–
Luminosity	3.2 fb^{-1} at 4.178 GeV	1 ab^{-1} at 4.009 GeV	50 ab^{-1} at $\Upsilon(nS)$
$\mathcal{B}(D_s^+\to\mu^+\nu_\mu)$	$2.8\%_{\rm stat.}$ $2.7\%_{\rm syst.}$ [8]	$0.30\%_{\rm stat.}$	$0.8\%_{\rm stat.}$ $1.8\%_{\rm syst.}$
$f_{D_s^+}$ (MeV)	$1.5\%_{\rm stat.}$ $1.6\%_{\rm syst.}$ [8]	$0.15\%_{\rm stat.}$	–
$\lvert V_{cs}\rvert$	$1.5\%_{\rm stat.}$ $1.6\%_{\rm syst.}$ [8]	$0.15\%_{\rm stat.}$	–
$f_{D_s^+}/f_{D^+}$	$3.0\%_{\rm stat.}$ $1.5\%_{\rm syst.}$ [8]	$0.21\%_{\rm stat.}$	–
$\mathcal{B}(D_s^+\to\tau^+\nu_\tau)$	$2.2\%_{\rm stat.}$ $2.6\%^{\dagger}_{\rm syst.}$	$0.24\%_{\rm stat.}$	$0.6\%_{\rm stat.}$ $2.7\%_{\rm syst.}$
$f_{D_s^+}$ (MeV)	$1.1\%_{\rm stat.}$ $1.5\%^{\dagger}_{\rm syst.}$	$0.11\%_{\rm stat.}$	–
$\lvert V_{cs}\rvert$	$1.1\%_{\rm stat.}$ $1.5\%^{\dagger}_{\rm syst.}$	$0.11\%_{\rm stat.}$	–
$\overline{f}^{\mu\&\tau}_{D_s^+}$ (MeV)	$0.9\%_{\rm stat.}$ $1.0\%^{\dagger}_{\rm syst.}$	$0.09\%_{\rm stat.}$	$0.3\%_{\rm stat.}$ $1.0\%_{\rm syst.}$
$\lvert\overline{V}^{\mu\&\tau}_{cs}\rvert$	$0.9\%_{\rm stat.}$ $1.0\%^{\dagger}_{\rm syst.}$	$0.09\%_{\rm stat.}$	–
$\frac{\mathcal{B}(D_s^+\to\tau^+\nu_\tau)}{\mathcal{B}(D_s^+\to\mu^+\nu_\mu)}$	$3.6\%_{\rm stat.}$ $3.0\%^{\dagger}_{\rm syst.}$	$0.38\%_{\rm stat.}$	$0.9\%_{\rm stat.}$ $3.2\%_{\rm syst.}$

Determination of γ/ϕ_3 angle in CKM

STCF will provide complementary information on the strong phase and allow detailed comparisons in different models

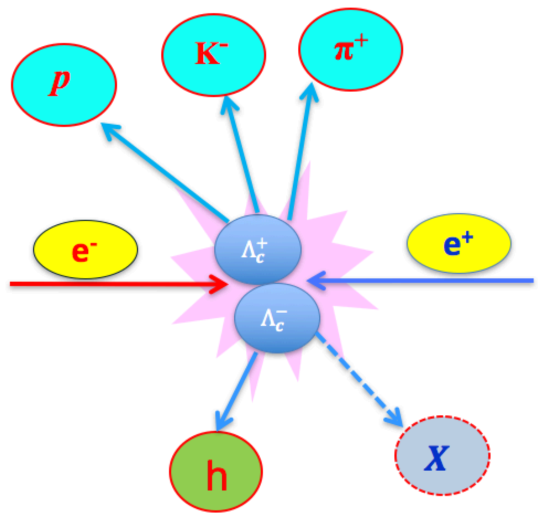




Decay mode	Quantity of interest
$D\to K^0_S\pi^+\pi^-$	c_i and s_i
$D\to K^0_S K^+K^-$	c_i and s_i
$D\to K^\pm\pi^\mp\pi^+\pi^-$	R,δ
$D\to K^+K^-\pi^+\pi^-$	c_i and s_i
$D\to \pi^+\pi^-\pi^+\pi^-$	F_+ or c_i and s_i
$D\to K^\pm\pi^\mp\pi^0$	R,δ
$D\to K^0_S K^\pm\pi^\mp$	R,δ
$D\to \pi^+\pi^-\pi^0$	F_+
$D\to K^0_S\pi^+\pi^-\pi^0$	F_+, c_i and s_i
$D\to K^+K^-\pi^0$	F_+
$D\to K^\pm\pi^\mp$	δ

Charmed Baryons at STCF

Charmed baryons are produced via $e^+e^- \to B_{1c}B_{2c}$ with $B_{ic} = n_1n_2c$



	Structure	J^P	Mass, MeV	Width,MeV	Decay
Λ_c^+	udc	$(1/2)^+$	2286.46 ± 0.14	(200 ± 6) fs	weak
Ξ_c^+	usc	$(1/2)^+$	$2467.8^{+0.4}_{-0.6}$	(442 ± 26) fs	weak
Ξ_c^0	dsc	$(1/2)^+$	$2470.88^{+0.34}_{-0.8}$	112^{+13}_{-10} fs	weak
Σ_c^{++}	uuc	$(1/2)^+$	2454.02 ± 0.18	2.23 ± 0.30	$\Lambda_c^+\pi^+$
Σ_c^+	udc	$(1/2)^+$	2452.9 ± 0.4	< 4.6	$\Lambda_c^+\pi^0$
Σ_c^0	ddc	$(1/2)^+$	2453.76 ± 0.18	2.2 ± 0.4	$\Lambda_c^+\pi^-$
$\Xi_c^{\prime +}$	usc	$(1/2)^+$	2575.6 ± 3.1	—	$\Xi_c^+\gamma$
$\Xi_c^{\prime 0}$	dsc	$(1/2)^+$	2577.9 ± 2.9	—	$\Xi_c^0\gamma$
Ω_c^0	ssc	$(1/2)^+$	2695.2 ± 1.7	(69 ± 12) fs	weak
Σ_c^{*++}	uuc	$(3/2)^+$	2518.4 ± 0.6	14.9 ± 1.9	$\Lambda_c^+\pi^+$
Σ_c^{*+}	udc	$(3/2)^+$	2517.5 ± 2.3	< 17	$\Lambda_c^+\pi^0$
Σ_c^{*0}	ddc	$(3/2)^+$	2518.0 ± 0.5	16.1 ± 2.1	$\Lambda_c^+\pi^-$
Ξ_c^{*+}	usc	$(3/2)^+$	$2645.9^{+0.5}_{-0.6}$	< 3.1	$\Xi_c\pi$
Ξ_c^{*0}	dsc	$(3/2)^+$	2645.9 ± 0.5	< 5.5	$\Xi_c\pi$
Ω_c^{*0}	ssc	$(3/2)^+$	2765.9 ± 2.0	—	$\Omega_c^0\gamma$

- Systematic measurement of absolute decay BFs with well controlled systematics and low backgrounds

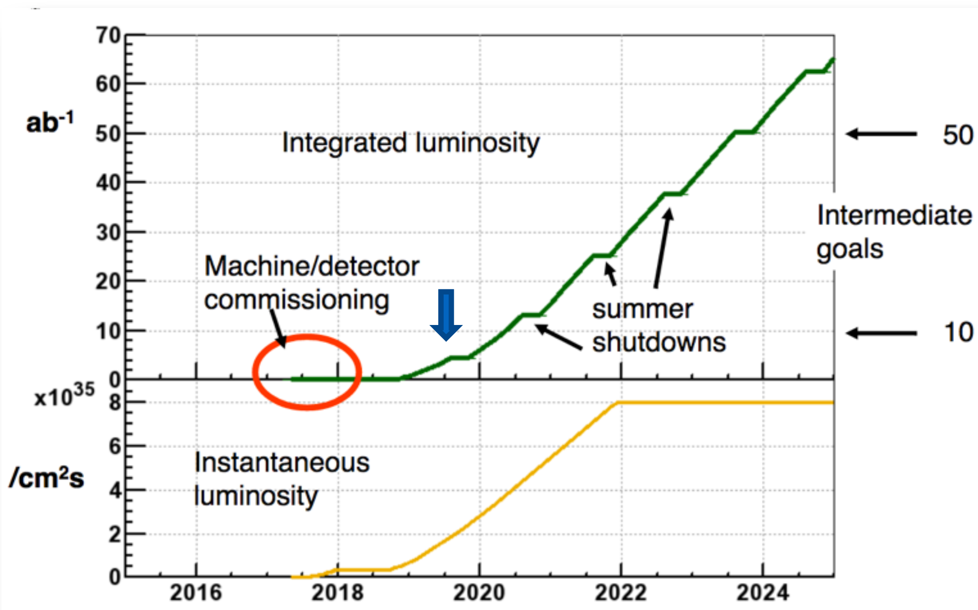
Summary and Outlook

- The charm program at BESIII is well proceeding.
- Near threshold production is unique to directly measure the decay properties of the charmed hadrons, such as D, Ds, Λ_c
  - Most precise measurements of decay constant and form factors
  - Firstly mapping out the full picture of **Λ_c decay patterns**.
- More data will be accumulated in the future 5-10 years
  - To improve our knowledge on NPQCD in charmed region
- Opportunities to study Ξ_c @4.95 GeV
- More comprehensive precision studies will be promising at STCF

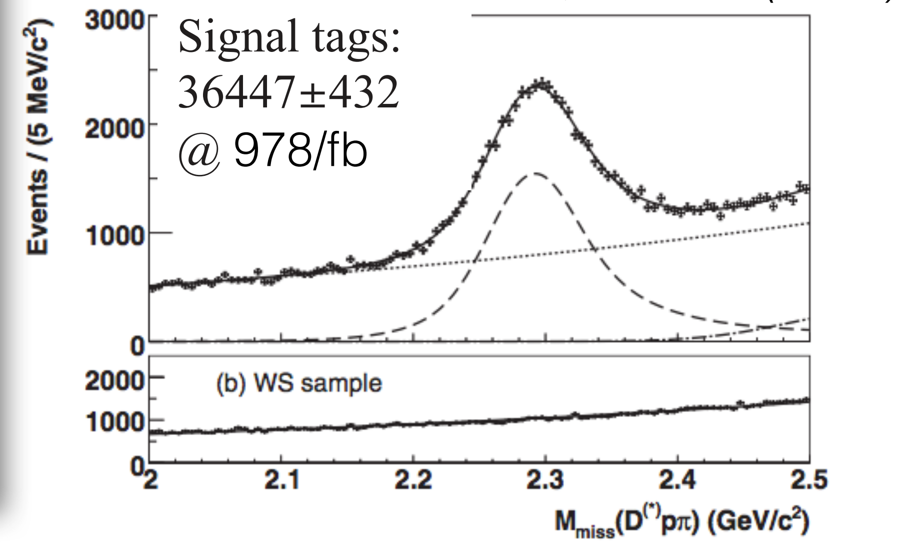
Thank you!

谢谢！

Competition from Belle & BelleII



Belle, PRL113, 042002 (2014)



- Belle tags ~36K Λ_c^+, while BESIII now tags 15K Λ_c^+ (567/pb@4.6GeV)
- By middle of 2019, BELLEII will have 5/ab data, 5x of BELLE data;
  ➔ 180K tagged Λ_c^+;
- We will have 150K tagged Λ_c^+, however, BESIII is very clean
- Many precise measurements at BESIII will reach to the level of systematic dominated
  ➔ BESIII has advantages on backgrounds and systematics

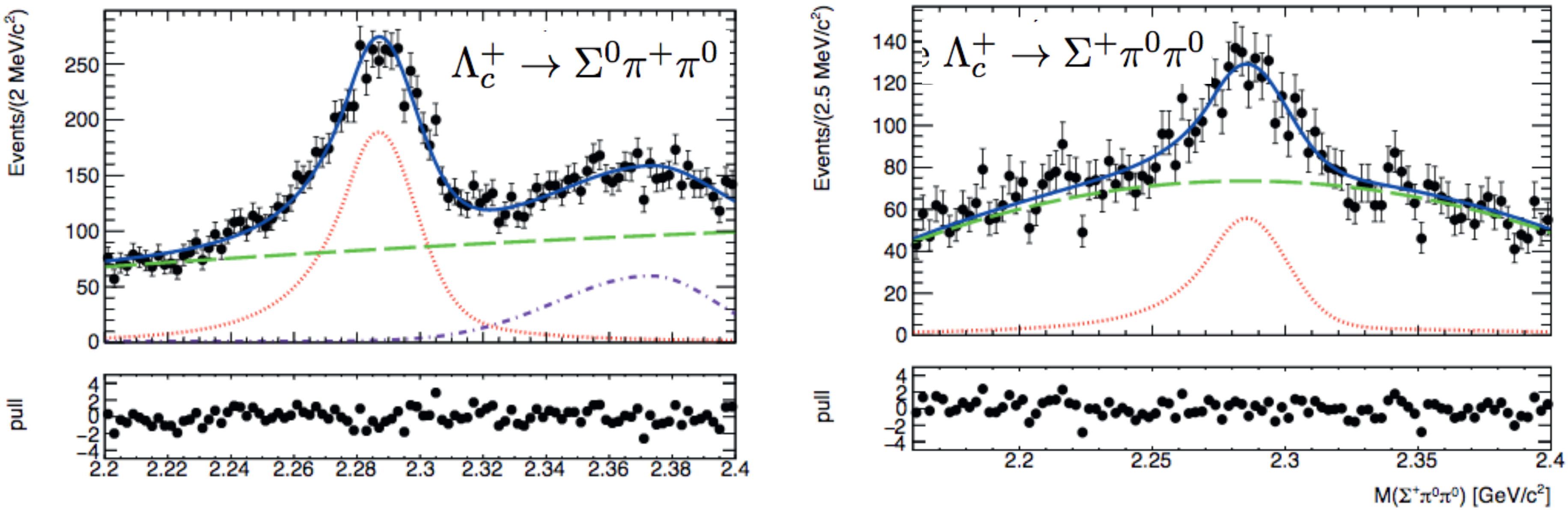
World campaign on the Λ_c^+

	BESIII	Belle(-II)	LHCb
Λ_c^+ total yields	★★★	★★★★	★★★★★
S/B ratio	★★★★★	★★	★★
Systematic error	★★★★★	★★★	★★
Systematic research	★★★★★	★★★	★
Semi-leptonic mode	★★★★★	★★★	★
n/K_L-involved mode	★★★★★	★★	☆
Photon final state	★★★★★	★★★★	☆
Absolute measurement	★★★★★	★★★	☆

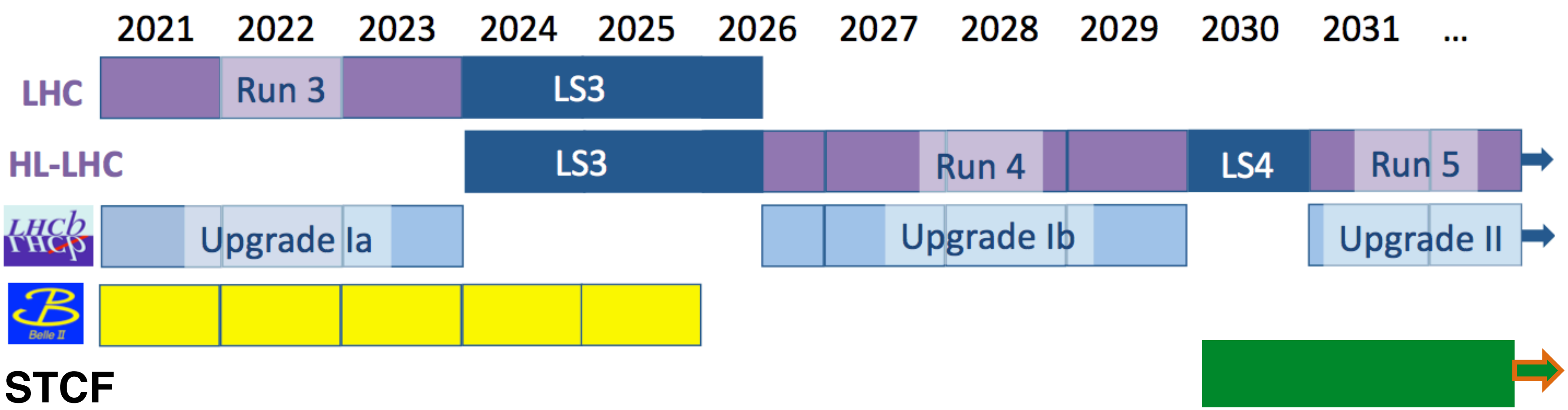
- The threshold data at BESIII have systematic advantage over Belle(-II) and LHCb in the Λ_c^+ studies.
- This proposal holds an optimal time window to maximize the visibility of BESIII physics.

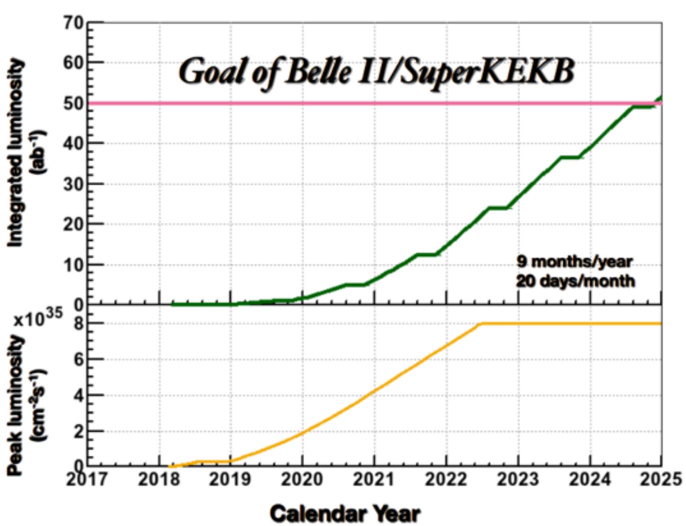
arXiv: 1802.03421

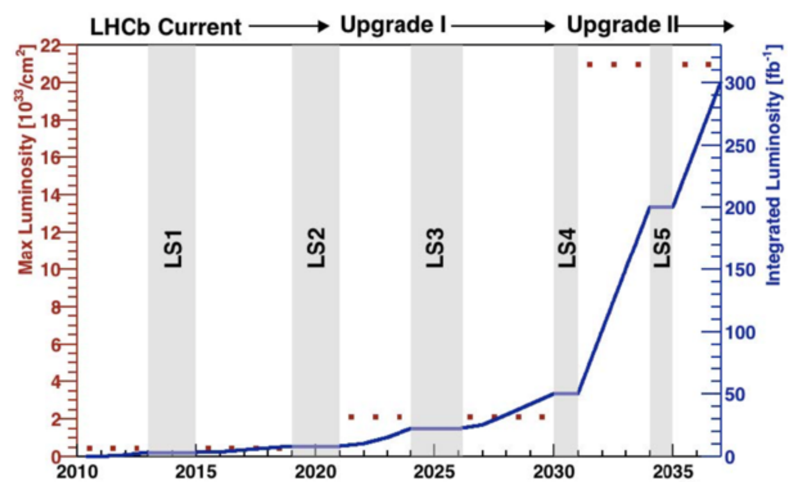
Measurement of the Decays $\Lambda_c \to \Sigma\pi\pi$ at Belle



Future Facilities for Charm study







Charmed baryons productions

from Marek Karliner

In the charmed baryon system, the light quarks are more like di-quarks

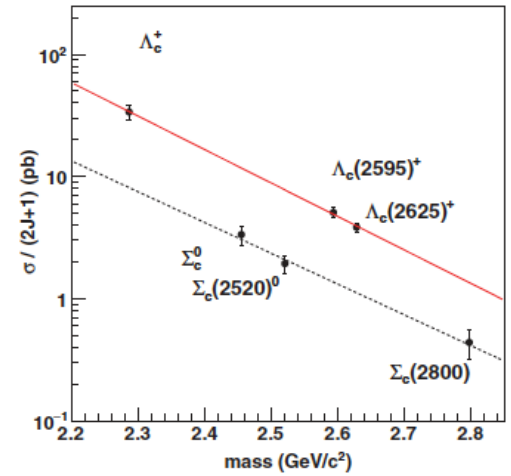
$$\Lambda_c^+(c[ud]_{spin=0}),\ \Sigma_c(c[ud]_{spin=1})$$

The spin-0 diquarks: "good" diquarks

The spin-1 one : "bad" diquarks.

The bad diquarks are heavier. So if the hadronization from the initial (ccbar) proceeds in one step, by attaching diquarks, it will provide a simple and natural explanation for the fact that the Λ_c cross section is much bigger than that of Σ_c.

Belle, arXiv:1706.06791



Then how about the behaves at the threshold, and to test it at BESIII will be very interesting!