Charm at BESIII

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on behalf of the BESIII collaboration

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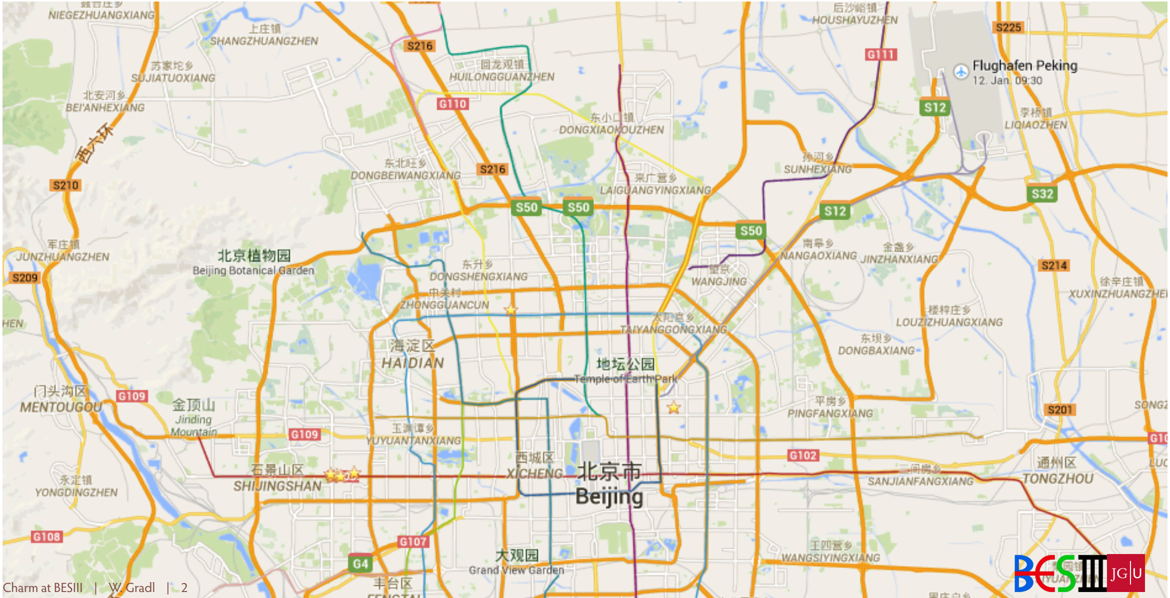
SFB 1044

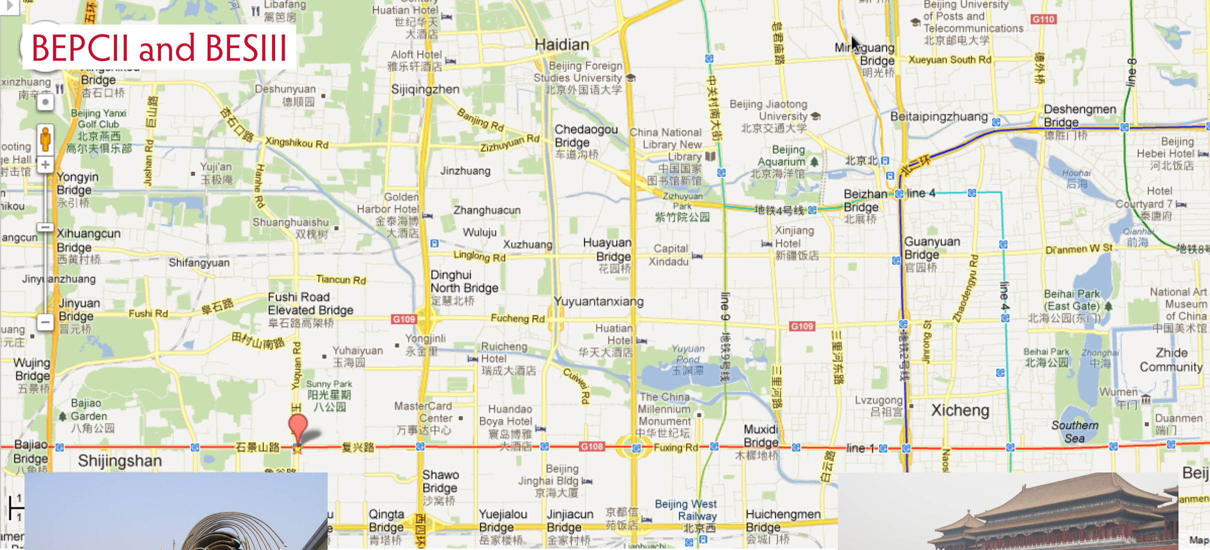
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRISMA

BEPCII and BESIII

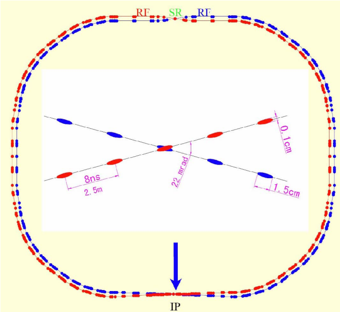


BEPCII and BESIII



BEPCII and BESIII

BEPCII storage rings: a τ-charm factory



Upgrade of BEPC (started 2004, first collisions July 2008)	
Beam energy	**$1 \cdots 2.45$ GeV**
Optimum energy	**1.89 GeV**
Single beam current	**0.91 A**
Crossing angle	**± 11 mrad**

Design luminosity	**10^{33} cm^{-2}s^{-1}**
Achieved	**1×10^{33} cm^{-2}s^{-1}**

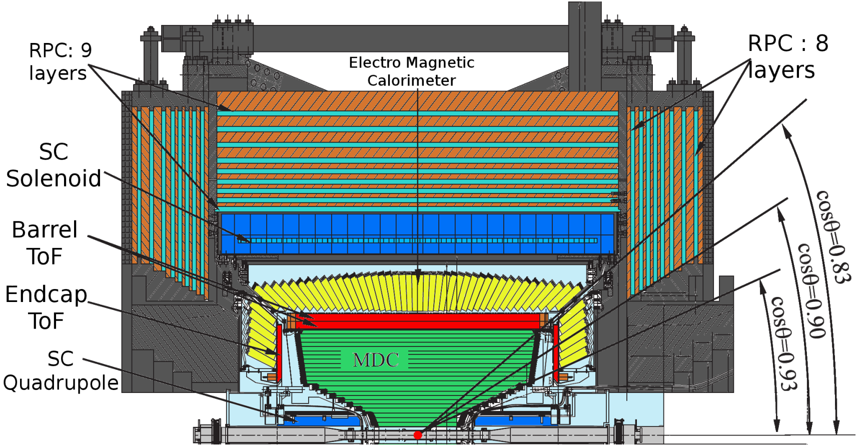
Beam energy measurement:

Laser Compton backscattering

$\Delta E/E \approx 5 \times 10^{-5}$

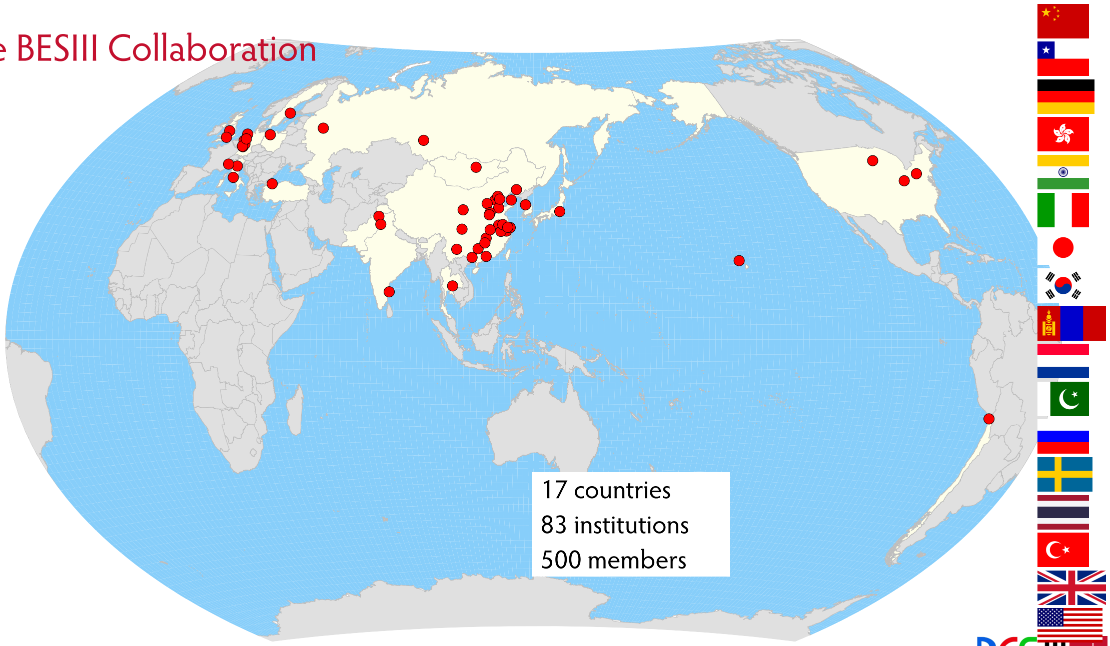
($\approx$ 50 keV at τ threshhold)

BESIII



At BEPCII in Beijing: e^+e^- collisions at $\sqrt{s}$ between 2 and 5 GeV

The BESIII Collaboration

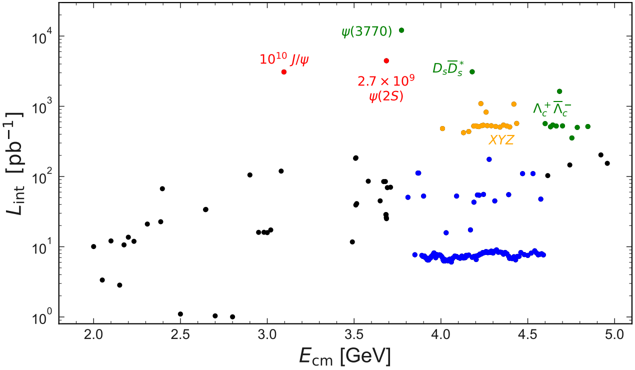


17 countries
83 institutions
500 members

12 years data taking at BESIII

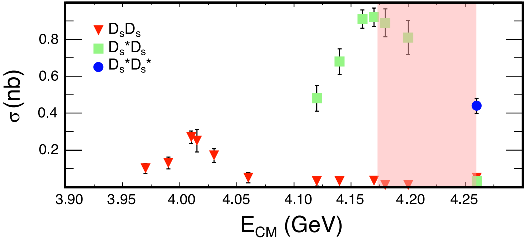
Data sets collected so far include

- 10×10^9 J/ψ events
- 2.7×10^9 ψ' events
- $12\,\text{fb}^{-1}$ on $\psi(3770)$
- scan data between 2.0 and 3.08 GeV, and above 3.735 GeV
- large datasets for *XYZ* studies: scan with $> 500\,\text{pb}^{-1}$ per energy point spaced 10 – 20 MeV apart
  $14.8\,\text{fb}^{-1}$ in large datasets above 3.8 GeV



Charm production at BESIII

$\sqrt{s}$[GeV]	$\mathcal{L}_{\text{int}}$ [pb^{-1}]	decay chain
3.773	2930 9000	$e^+e^- \to \psi(3770) \to D\bar{D}$ (2021–2023)
4.178 4.189 4.199 4.209 4.219 4.226	3189 526.7 526.0 517.1 514.6 1047	$e^+e^- \to D_s^* D_s$ 6 fb^{-1} in total
4.6 $>$ 4.6	567 5700	$e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$

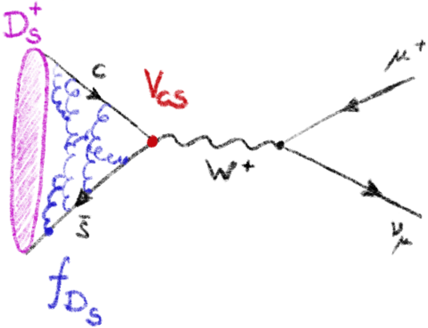


CLEO, PRD 80 (2009) 072001

- $D\bar{D}$ pairs from $\psi(3770)$
  +9 fb^{-1} taken in 2021–23. Goal is 20 fb^{-1} by 2024.
- $D_s^+ D_s^-$ pairs near threshold, but
- $D_s^+ D_s^{*-}$ ($\to D_s^- \gamma$ or $D_s^- \pi^0$) has much higher cross section
- $\Lambda_c^+ \bar{\Lambda}_c^-$ cross section flat near threshold

Leptonic *D* decays

Leptonic decays of charmed mesons

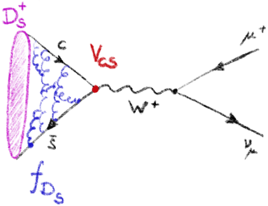


$$\Gamma(D_q^+ \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi} f_{D_q}^2 \left|V_{cq}\right|^2 m_\ell^2 m_{D_q} \left(1 - \frac{m_\ell^2}{m_{D_q}^2}\right)^2$$

to leading order, neglecting radiative corrections

D_q: charged, charmed meson, *i.e.* D^+ $(c\bar{d})$ or D_s^+ $(c\bar{s})$

Leptonic decays of charmed mesons



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

Precise measurement of $f_{D_q}^2 \left|V_{cq}\right|^2$ allows determination of

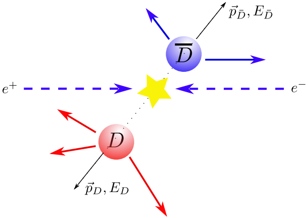
- $f_{D_q}^2$, using global value for $|V_{cq}|^2$
- $\left|V_{cq}\right|^2$, using lattice QCD result for f_{D_q}

charged lepton must have 'wrong' helicity for its chirality: decay rate suppressed with m_ℓ^2
e.g. for $D^+ \to \ell\nu$, SM predicts ratio of rates

$$e : \mu : \tau = 2.35 \times 10^{-5} : 1 : 2.67$$

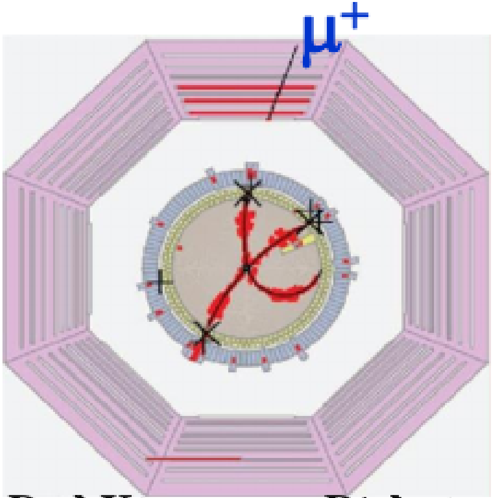
Analysis principle: Double tag analysis

- Final state of signal decay: lepton (+ hadrons) + missing energy / momentum
- Difficulty: identify signal decay and separate it from background
- e^+e^- at D^+D^- threshold: clean environment, no extra particles, closed kinematics
- Reconstruct one $D^\mp$ in the event (D_{tag}): know kinematics of the other $D^\pm$
- Infer four-momentum of undetected neutrino:



$$p^\mu_{\text{miss}} = p^\mu_{e^+e^-} - p^\mu_{D_{\text{tag}}} - p^\mu_\ell$$

Double-tag candidate in BESIII



$D^- \rightarrow K^+\pi^-\pi^-$ vs. $D^+ \rightarrow \mu^+\nu$

Single tag selection

- Single hadronic decay modes of D mesons have appreciable branching fraction can use $\sim 25\%$ of the total D width for tagging
- Kinematic variables for **tag-side** selection:

$$\Delta E = E_D^* - E_{\text{beam}}^*$$

$$m_{BC} = \sqrt{E_{\text{beam}}^2 - \vec{p}_{\text{tag}}^{\,2}}$$

- Typically, select candidates in ΔE, use m_{BC} spectrum to count ST events and to perform final ST selection

Single-tag data samples:

E_{cm} [GeV]	$\mathcal{L}$ [fb^{-1}]	D^0 yield	D^+ yield	D_s^+ yield
3.773	2.93	2.7×10^6	1.7×10^6	
4.009	0.48			13×10^3
4.13 – 4.23	7.33			0.8×10^6

Double tag selection

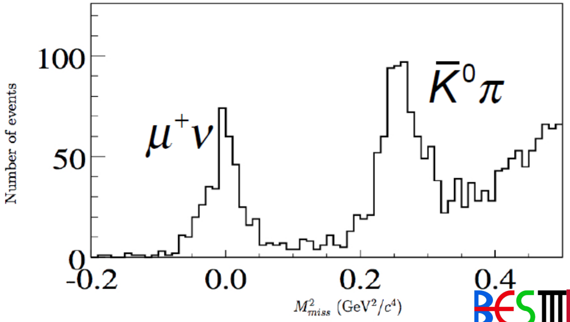
Signal side selection ('double tag'):
look in events with ST candidates for signature of signal decay

- Reject combinations with extra tracks
- Veto combinations with too much extra activity in calorimeter (E_{extra})
- Apply criteria to further reject background based on detailed MC studies

- Identify signal using one of

$$U_{\text{miss}} = E_{\text{miss}} - |\vec{p}_{\text{miss}}|$$
$$M^2_{\text{miss}} = E^2_{\text{miss}} - |\vec{p}_{\text{miss}}|^2$$

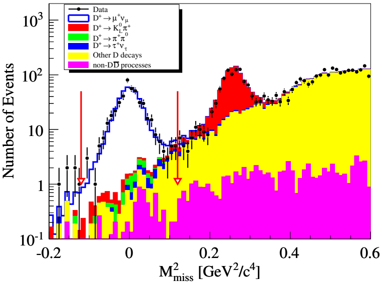
both peak at 0 for signal events



$D^+ \to \ell^+ \nu$

$D^+ \to \mu^+ \nu_\mu$

BESIII, Phys. Rev. D **89** (2014) 051104



409 ± 21 signal events

$$\mathcal{B}(D^+ \to \mu^+ \nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$$

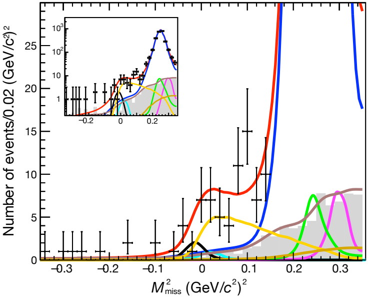
$$f_{D^+} |V_{cd}| = 45.7 \pm 1.2 \pm 0.4 \text{ MeV}$$

Precision ≈ 2.7%

*

$D^+ \to \tau^+ \nu_\tau$

BESIII, Phys. Rev. Lett. **123** (2019) 211802



137 ± 27 signal events

$$\mathcal{B}(D^+ \to \tau^+ \nu_\tau) = \left(1.20 \pm 0.24_{\text{stat}} \pm 0.12_{\text{syst}}\right) \times 10^{-3}$$

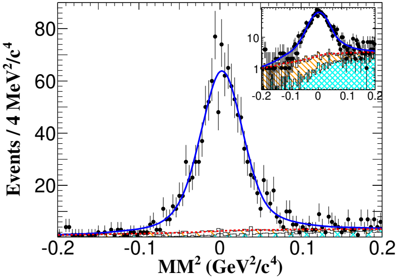
$$f_{D^+} |V_{cd}| = 50.4 \pm 5.1 \pm 2.5 \text{ MeV}$$

Precision ≈ 11%

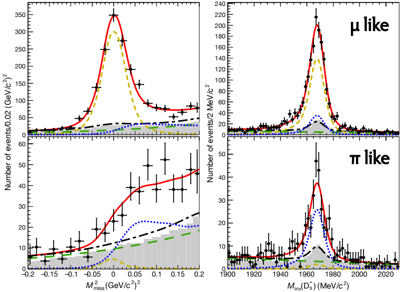
First observation

$D_s^+ \to \mu^+ \nu_\mu$

$3.19\,\mathrm{fb}^{-1}$ at 4.18 GeV, Phys. Rev. Lett. **122** (2019) 071802



$6.3\,\mathrm{fb}^{-1}$ at 4.18–4.23 GeV, Phys. Rev. D **104** (2021) 052009



$$\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu) = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$
$$f_{D_s^+} |V_{cs}| = 246.2 \pm 3.6 \pm 3.5 \text{ MeV}$$

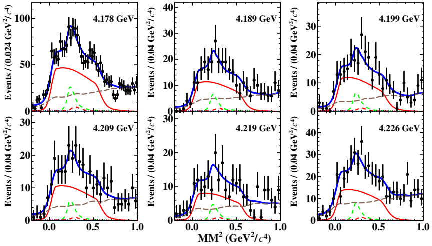
using μ ID in the MUC
superseded by result shown on right

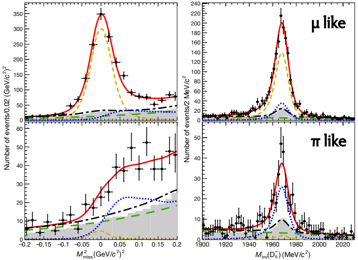
$$\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu) = (5.35 \pm 0.13 \pm 0.16) \times 10^{-3}$$
$$f_{D_s^+} |V_{cs}| = 243.1 \pm 3.0 \pm 3.7 \text{ MeV}$$

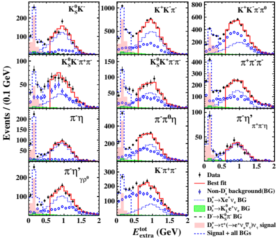
no MUC requirements; $\approx$ 50% overlap in event sample, but different analysis, different systematic uncertainties

$D_s^+ \to \tau^+ \nu_\tau$

Phys. Rev. D **104**(2021)032001	Phys. Rev. D **104**(2021)052009	Phys. Rev. Lett. **127**(2021)171801
$D_s^+ \to \tau^+[\rho^+\nu]\nu$	$D_s^+ \to \tau^+[\pi^+\nu]\nu$	$D_s^+ \to \tau^+[e^+\nu\nu]\nu$
$6.3\ \text{fb}^{-1}$ $\quad 1745 \pm 48$	$6.3\ \text{fb}^{-1}$ $\quad 946 \pm 46$	$6.3\ \text{fb}^{-1}$ $\quad 4940 \pm 97$







$\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.29 \pm 0.25 \pm 0.20) \times 10^{-2}$ $\quad (5.21 \pm 0.25 \pm 0.17) \times 10^{-2}$ $\quad (5.27 \pm 0.10 \pm 0.12) \times 10^{-2}$

$f_{D_s^+}|V_{cs}| = 244.8 \pm 5.8 \pm 4.8$ MeV $\quad 243.0 \pm 5.8 \pm 4.0$ MeV $\quad 244.4 \pm 2.3 \pm 2.9$ MeV

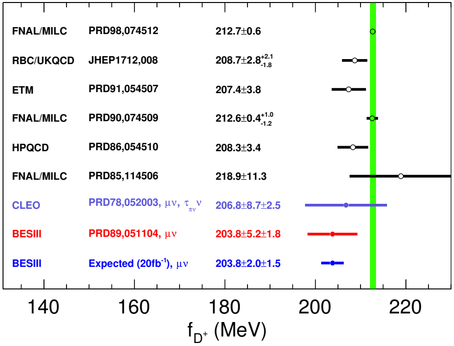
Same dataset, but different τ^+ decay modes: independent results, excellent compatibility.

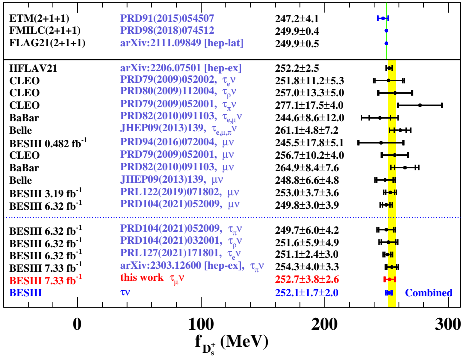
Precision $\approx 1.5\%$

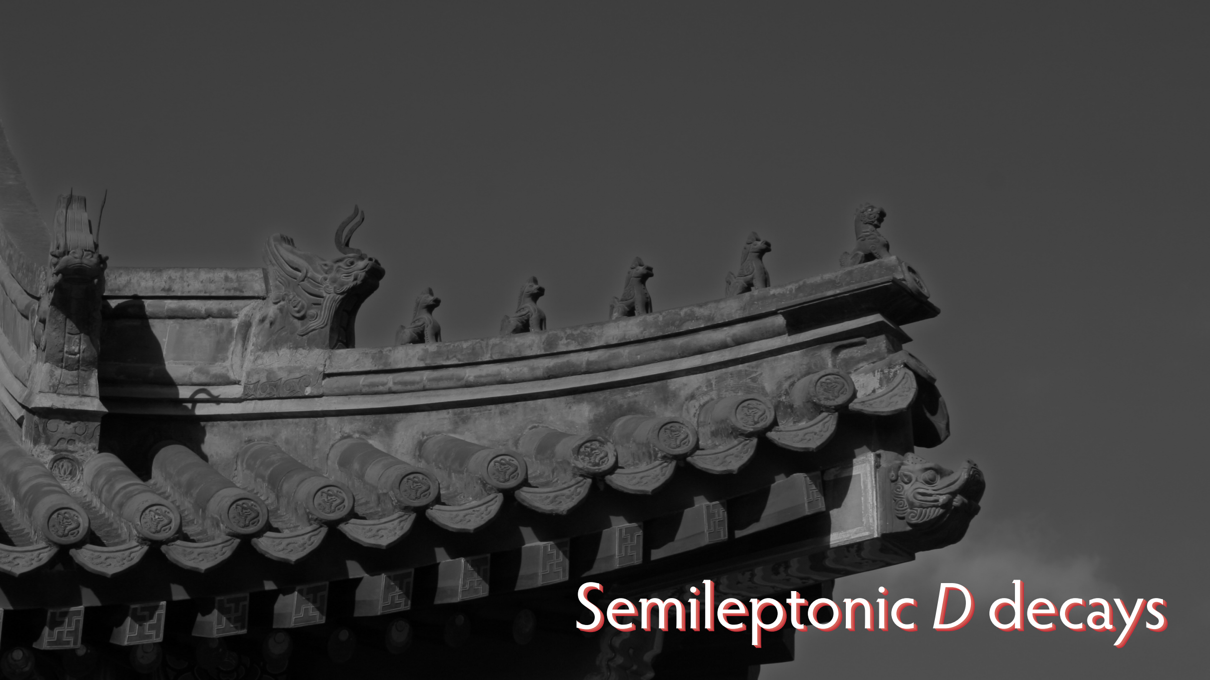
D and D_s Decay constants

BESIII, Chin. Phys. C 44 (2020) 040001

Take $|V_{cd(s)}|$ from global fits to CKM matrix, determine $f_{D^+_{(s)}}$

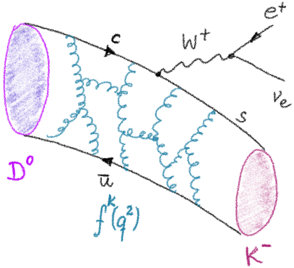






Semileptonic *D* decays

Semileptonic decays: form factors

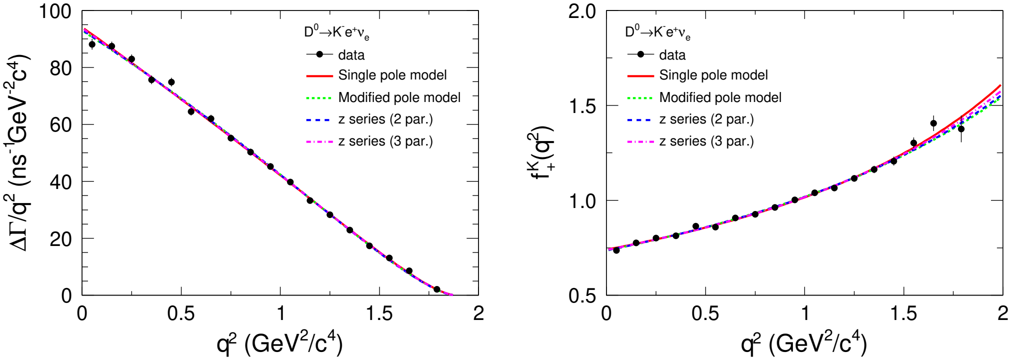


For decay into one pseudoscalar P, one extra degree of freedom:
form factor $f_+^P(q^2)$, function of four-momentum transfer $q \equiv p_D - p_P$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = \frac{G_F^2}{24\pi^3} \, |\vec{p}_P|^3 \, |V_{cq}|^2 |f_+^P(q^2)|^2$$

Decay dynamics for $D^0 \to K^- e^+ \nu_e$

BESIII, Phys.Rev.D 92 (2015) 072012



$$f_+^K(0)|V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$$

$$f_+^K(0) = 0.7368 \pm 0.0026 \pm 0.0036$$ using SM constraint fit for V_{cs}

$$|V_{cs}| = 0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239$$ using LQCD and LCSR for $f_+^K(0)$

Branching fractions for $D \to \bar{K} e \nu$

BESIII, Phys. Rev. D 104 (2021) 052008

New approach: $D \to \bar{K} e^+ \nu_e$ and $\bar{D} \to K e^- \bar{\nu}_e$ in the same event
largest semi-leptonic branching fraction, clear experimental signature

Advantage: statistically independent from hadronic tags, no dependence on hadronic BFs, absolute measurement of $\mathcal{B}$ possible
Disadvantage: no access to form factor

$$\mathcal{B}(D \to \bar{K} e^+ \nu_e) = \sqrt{\frac{N_{\mathrm{DT}}}{N_{D\bar{D}} \cdot \varepsilon_{\mathrm{DT}}}}$$

Produced $D\bar{D}$ pairs in 2.93 fb^{-1} data at $\psi(3770)$:

$$N_{D^0\bar{D}^0} = (10\,597 \pm 28 \pm 98) \times 10^3$$
$$N_{D^+D^-} = (8296 \pm 31 \pm 65) \times 10^3$$

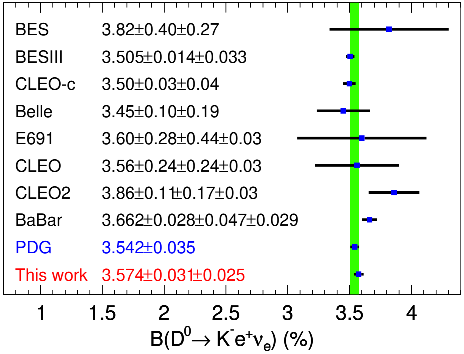
$D \to K e \nu$ results

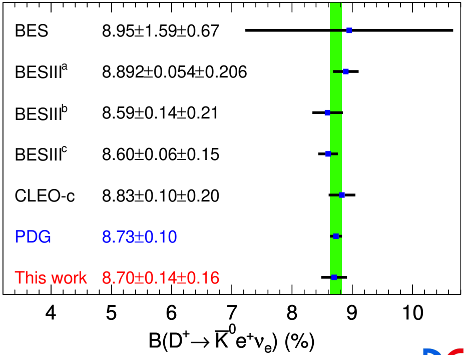
BESIII, Phys. Rev. D 104 (2021) 052008

$$\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.567 \pm 0.031 \pm 0.021) \times 10^{-2}$$

$$\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.68 \pm 0.14 \pm 0.16) \times 10^{-2}$$

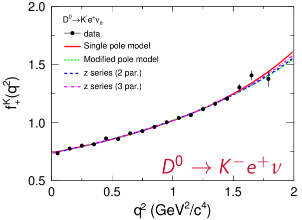
$$\frac{\Gamma(D^0 \to K^- e^+ \nu_e)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e)} = 1.039 \pm 0.021$$ supports isospin symmetry within 1.9σ





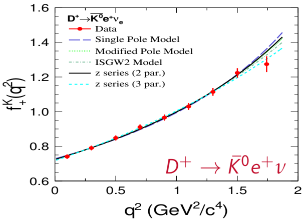
Other $c \to s\ell^+\nu$ SL decays with pseudoscalars

Phys. Rev. D **92**(2015)072012



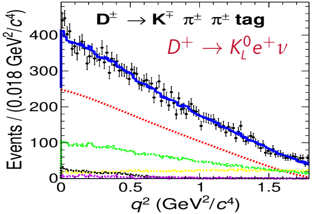
$f_+^{D\to K}(0)|V_{cs}| = 0.717(03)(04)$

Phys. Rev. D **96**(2017)012002



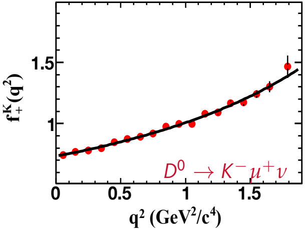
$f_+^{D\to K}(0)|V_{cs}| = 0.705(04)(11)$

Phys. Rev. D **92**(2017)112008



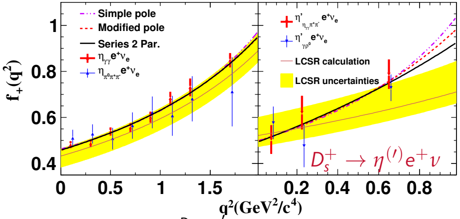
$f_+^{D\to K}(0)|V_{cs}| = 0.728(06)(11)$

Phys. Rev. Lett. **122**(2019)011804



$f_+^{D\to K}(0)|V_{cs}| = 0.7148(38)(29)$

Phys. Rev. Lett. **122**(2019)121801



$f_+^{D_s\to\eta}(0)|V_{cs}| = 0.446(05)(04)$ $f_+^{D_s\to\eta'}(0)|V_{cs}| = 0.477(49)(11)$

$D_s^+ \to X e^+ \nu_e$

BESIII, Phys. Rev. D 104 (2021) 012003

Mode	Averaged $\mathcal{B}$
$D_s^+ \to \phi e^+ \nu_e$	$(2.37 \pm 0.11)\%$
$D_s^+ \to \eta e^+ \nu_e$	$(2.32 \pm 0.08)\%$
$D_s^+ \to \eta' e^+ \nu_e$	$(0.80 \pm 0.07)\%$
$D_s^+ \to K^0 e^+ \nu_e$	$(0.34 \pm 0.04)\%$
$D_s^+ \to K^*(892)^0 e^+ \nu_e$	$(0.21 \pm 0.03)\%$
$D_s^+ \to f_0(980) e^+ \nu_e,\ f_0(980) \to \pi\pi$	$(0.30 \pm 0.05)\%$
Sum of Semielectronic Modes	$(6.34 \pm 0.17)\%$
$\mathcal{B}(D_s^+ \to X e^+ \nu_e)$ [CLEO]	$(6.5 \pm 0.4)\%$
$D_s^+ \to \tau^+ \nu_\tau \to e^+ \overline{\nu}_\tau \nu_e \nu_\tau$	$(0.96 \pm 0.04)\%$

Are there unobserved semi-electronic D_s^+ decays?

Single tags using $D_s^- \to K^+ K^- \pi^-$ only: sufficient statistics, well-known backgrounds

Signal-side: require electron candidate with $p_e > 200\,\text{MeV}$

Analysis requires very careful modelling of PID efficiencies and mis-ID rates

$D_s^+ \to X e^+ \nu_e$

BESIII, Phys. Rev. D 104 (2021) 012003

Mode	Averaged $\mathcal{B}$
$D_s^+ \to \phi e^+ \nu_e$	$(2.37 \pm 0.11)\%$
$D_s^+ \to \eta e^+ \nu_e$	$(2.32 \pm 0.08)\%$
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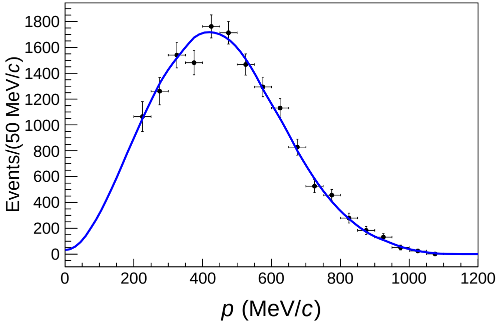
$D_s^+ \to \tau^+ \nu_\tau \to e^+ \bar{\nu}_\tau \nu_e \nu_\tau$	$(0.96 \pm 0.04)\%$

Are there unobserved semi-electronic D_s^+ decays?

Momentum spectrum of decay electrons



extrapolating to $p_e < 200$ MeV introduces model dependence, 0.7% relative syst. uncertainty

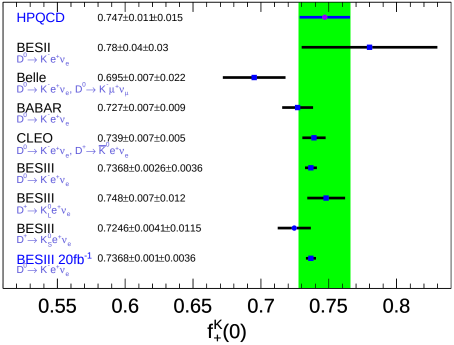
$$\mathcal{B}(D_s^+ \to X e^+ \nu_e) = (6.30 \pm 0.13\ (\text{stat.}) \pm 0.10\ (\text{syst.}))\ \%$$

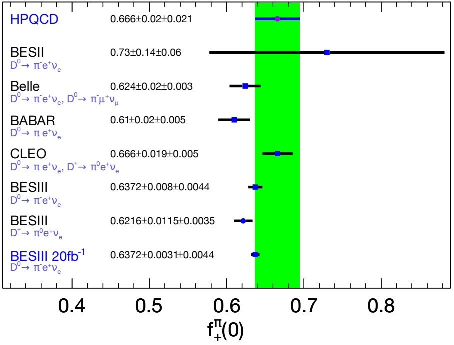
saturated by sum of exclusive channels

Form factors for SL decays, $f_+^{K/\pi}(0)$

BESIII, Chin. Phys. C 44 (2020) 040001

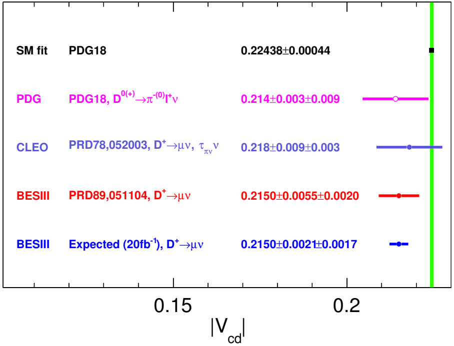
Take $|V_{cd(s)}|$ from global fits to CKM matrix, determine $f_+(0)$

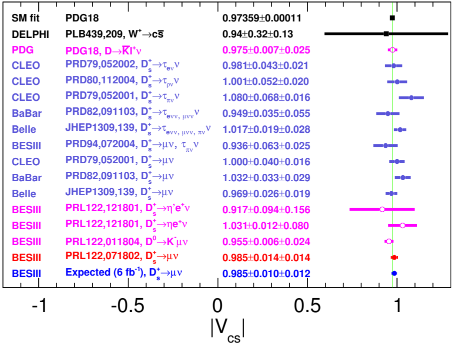




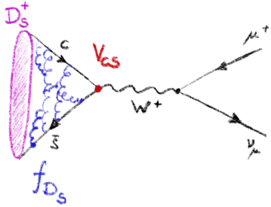
CKM matrix elements V_{cd} and V_{cs}

BESIII, Chin. Phys. C 44 (2020) 040001





Tests of lepton flavour universality (LFU)



Ratio of decay widths to different lepton flavours:

$$R_{\ell/\ell'} \equiv \frac{\Gamma(D^+ \to \ell^+\nu)}{\Gamma(D^+ \to \ell'^+\nu)} = \frac{m_\ell^2\, m_{D^+} \left(1 - \frac{m_\ell^2}{m_{D^+}^2}\right)^2}{m_{\ell'}^2\, m_{D^+} \left(1 - \frac{m_{\ell'}^2}{m_{D^+}^2}\right)^2}$$

in the SM, coupling of $W^\pm$ to leptons universal
R depends only on masses of leptons and charmed meson

very precise prediction

similar relations for semi-leptonic decays

Tests of lepton flavour universality (LFU)

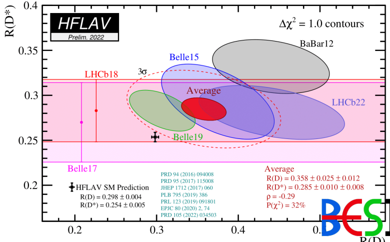
Deviations from SM prediction: charged intermediate boson coupling differently to leptons of different flavour, *e.g.* leptoquarks

In some SUSY models (*e.g.* two-Higgs-doublet) couplings are standard-model like: $\Gamma(D^+ \to \ell^+ \nu)$ modified by lepton-flavour independent factor, leaving R unchanged.

Some intriguing hints for violation of LFU from B decays (LHCb, Belle, BABAR):
~~R_K $(b \to s\ell^+\ell^-)$~~, $R_{D^{(*)}}$ $(b \to c\ell\nu)$

so, worthwhile to look in more detail,
and in the charm sector

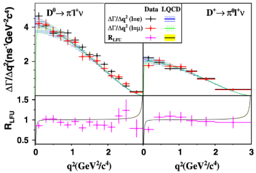
First observations of $D^+ \to \tau^+\nu$
and six semi-muonic D decays:



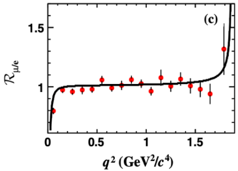
Summary of LFU measurements in charm decays

		References	Measured B(l)/B(l')	SM prediction
μ/e	$D^0\to K^-$	PRL**122**(2019)011804	0.974±0.014	~0.975
	$D^0\to \pi^-$	PRL**121**(2018)171803	0.922±0.038	~0.985
	$D^0\to \rho^-$	PRD**104**(2021)L091103	0.90±0.11	0.93-0.96
	$D^+\to \bar{K}^0$	EPJ C (2016) **76**:369	0.988±0.033	~0.970
	$D^+\to \pi^0$	PRL**121**(2018)171803	0.964±0.045	~0.985
	$D^+\to \omega$	PRD**101**(2020)072005	1.05±0.14	0.93–0.99
	$D^+\to \eta$	PRL**124**(2020)231801	0.91±0.13	0.97-1.00
	$D_s^+\to \eta$		1.05±0.24	
	$D_s^+\to \eta'$	PRD**97**(2018)012006	1.14±0.68	~1.0
	$D_s^+\to \phi$		0.86±0.29	
	$\Lambda_c^+\to \Lambda$	PLB**676**(2017)42,47	0.96±0.16	~1.0
τ/μ	$D^+\to \tau^+\nu$	PRL**123**(2019)211802	3.21±0.77	2.66
	$D_s^+\to \tau^+\nu$	PRL**127**(2021)171801	9.72±0.37	9.75

PRL**121**(2018)171803



PRL**122**(2019)011804



Deviation from one due to the different PS available

No deviation from SM within statistics

Hadronic *D* decays

Strong phase in $D^0 \to K_S^0 \pi^+ \pi^-$

BESIII Phys. Rev. Lett. 124 (2020) 241802

Phys. Rev. D 101 (2020) 112002

Measurement of γ with GGSZ needs strong phase
between D^0 and $\bar{D}^0$ across Dalitz plot, will limit uncertainty on γ

Direct measurement of strong phase requires quantum-correlated $D^0\bar{D}^0$ pairs. So far, only CLEO.

Use model-independent approach to measure phase
developed by Bondar & Poluektov, Eur. Phys. J. C 47 (2006) 347:

Determine amplitude-weighted averages

$$c_i = \frac{1}{\sqrt{F_i F_{-i}}} \int_i |f_D(m_+^2, m_-^2)||f_D(m_-^2, m_+^2)| \times \cos[\Delta\delta_D(m_+^2, m_-^2)] dm_+^2 dm_-^2$$

in symmetric bins i on the Dalitz plot

Strong phase in $D^0 \to K_S^0\pi^+\pi^-$

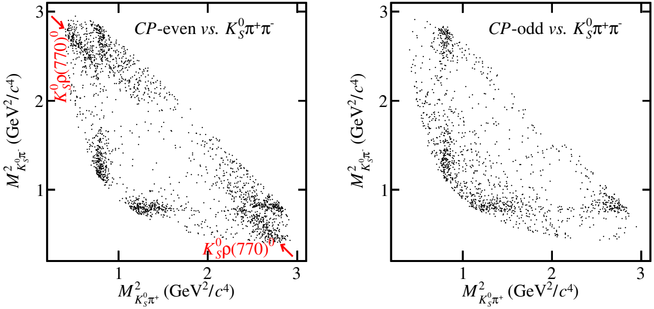
BESIII Phys. Rev. Lett. 124 (2020) 241802

Phys. Rev. D 101 (2020) 112002

Exploit quantum-correlated $D^0\bar{D}^0$ pairs at $\psi(3770)$:

Reconstruct signal decay vs. flavour specific, CP-even, CP-odd, and CP-mixed tags:
17 tag modes in total.

Effect of quantum correlation clearly visible: $D^0 \to K_S^0\pi^+\pi^-$ vs. CP tags

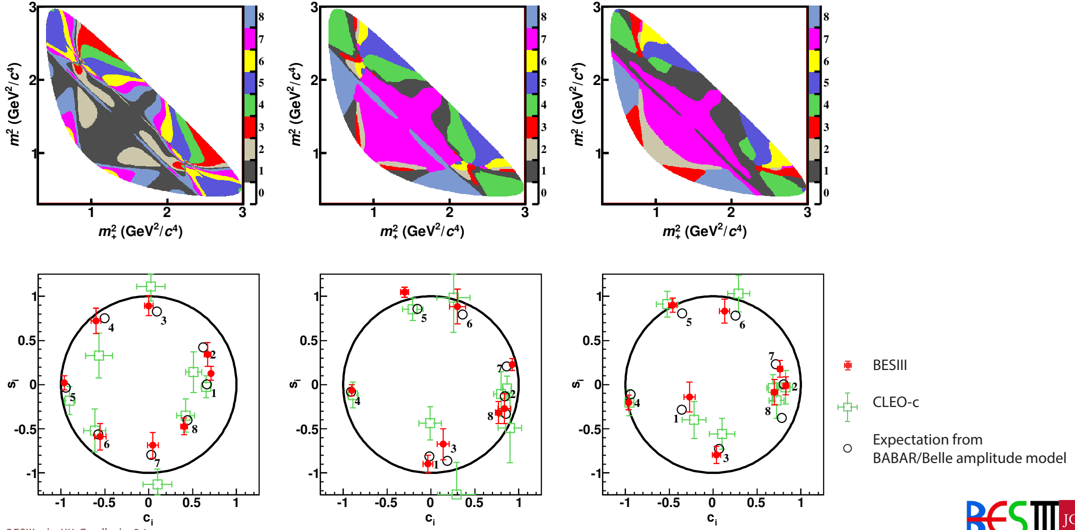


Strong phase in $D^0 \to K_S^0 \pi^+ \pi^-$

BESIII Phys. Rev. Lett. 124 (2020) 241802

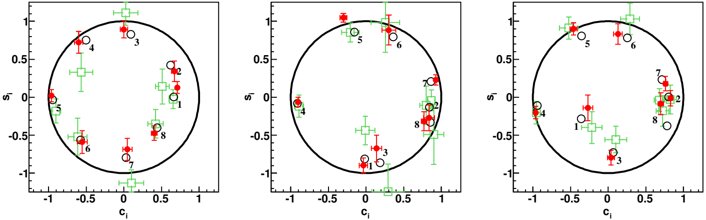
Phys. Rev. D 101 (2020) 112002

Use three binning schemes (regions with ≈ constant strong phase):

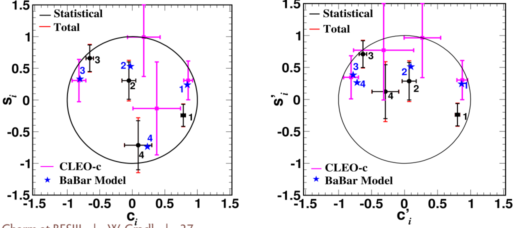


Strong phase difference between D^0 and $\bar{D}^0$

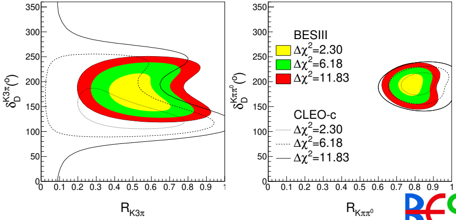
$D^0 \to K^0_{S,L}\pi^+\pi^-$ Phys. Rev. Lett. **124**(2020)241802



$D^0 \to K^0_{S,L}K^+K^-$ Phys. Rev. D **102**(2020)052008



$D^0 \to K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^0$ JHEP05(2021)164

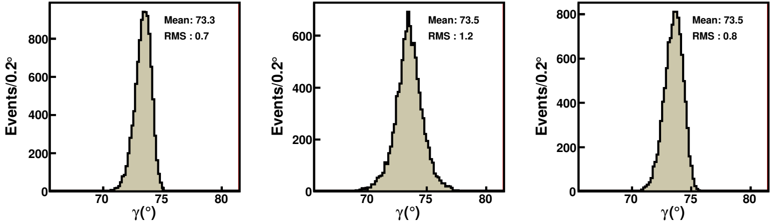


Impact on γ in $B^+ \to DK^+$

BESIII, Phys. Rev. D 101 (2020) 112002

Toy study: use world average values for γ, r_B, δ_B, generate large samples of $B^+ \to DK^+ \to [K_S^0\pi^+\pi^-]K^+$ decays.

Sample s_i, c_i from BESIII measurement, determine γ:



Using modified optimal binning, contribution to $\Delta\gamma$ due to strong phases in D decays is 0.8°

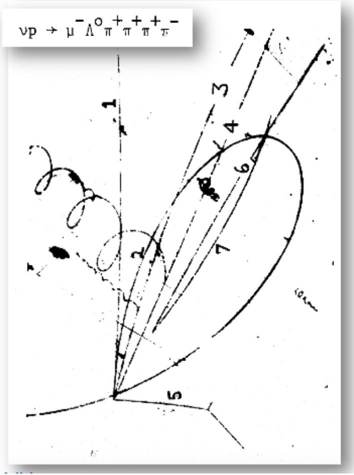
Sufficiently small for expected statistical uncertainties at LHCb prior to HL-LHC, and for Belle II

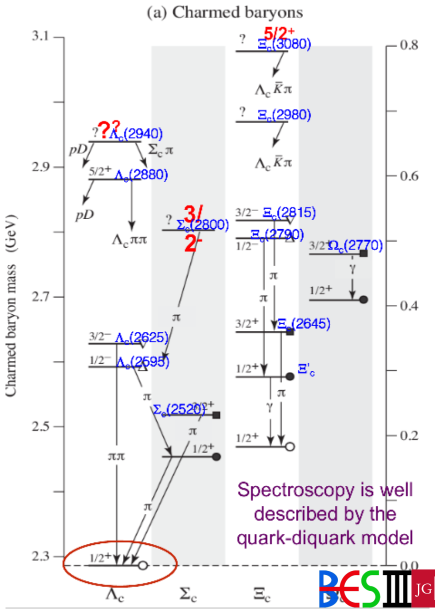
Charmed baryons

Charmed baryons

First hint for a charmed baryon at BNL PRL34(1975)1125

candidate for $\Sigma_c^{++} \to \Lambda_c^+ \pi^+$





Λ_c^+

Situation before 2014:
fixed-target experiments (FOCUS, SELEX), e^+e^- B-factories (ARGUS, CLEO, BABAR, Belle)

- Known decays only $\approx$ 60% of total width
- Many unknown decay channels
- Large uncertainties
- Most BF measured relative to $\Lambda_c^+ \to pK^-\pi^+$

Large experimental uncertainties
➡ slow development in theory

Winter 2014: BESIII collects 567 pb^{-1} at 4.6 GeV, close to $\Lambda_c^+\overline{\Lambda}_c^-$ threshold
(35 days beam time)

Λ_c^+ data in PDG2015

Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)	
Hadronic modes with a p: $S = -1$ final states					
$p\overline{K}^0$		(3.21 ± 0.30) %			
$pK^-\pi^+$		$(6.84^{+0.32}_{-0.40})$ %			
$p\overline{K}^*(892)^0$	[q]	(2.13 ± 0.30) %			
$\Delta(1232)^{++}K^-$		(1.18 ± 0.27) %			22.9%
$\Lambda(1520)\pi^+$	[q]	(2.4 ± 0.6) %			25.0%
$pK^-\pi^+$ nonresonant		(3.8 ± 0.4) %			10.5%
$p\overline{K}^0\pi^0$		(4.5 ± 0.6) %			13.3%
$p\overline{K}^0\eta$		(1.7 ± 0.4) %			23.5%
$p\overline{K}^0\pi^+\pi^-$		(3.5 ± 0.4) %			11.4%
$pK^-\pi^+\pi^0$		(4.6 ± 0.8) %			13.0%
$pK^*(892)^-\pi^+$	[q]	(1.5 ± 0.5) %			33.3%
$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(5.0 ± 0.9) %			18.0%
$\Delta(1232)\overline{K}^*(892)$		seen			
$pK^-\pi^+\pi^+\pi^-$		$(1.5 \pm 1.0) \times 10^{-3}$			66.7%
$pK^-\pi^+\pi^0\pi^0$		(1.1 ± 0.5) %			45.4%
Hadronic modes with a p: $S = 0$ final states					
$p\pi^+\pi^-$		$(4.7 \pm 2.5) \times 10^{-3}$			45.4%
$pf_0(980)$	[q]	$(3.8 \pm 2.5) \times 10^{-3}$			53.2%
$p\pi^+\pi^+\pi^-\pi^-$		$(2.5 \pm 1.6) \times 10^{-3}$			64.0%
pK^+K^-		$(1.1 \pm 0.4) \times 10^{-3}$			36.4%
$p\phi$	[q]	$(1.12 \pm 0.23) \times 10^{-3}$			
pK^+K^- non-ϕ		$(4.8 \pm 1.9) \times 10^{-4}$			
Hadronic modes with a hyperon: $S = -1$ final states					
$\Lambda\pi^+$		(1.46 ± 0.13) %			8.9%
$\Lambda\pi^+\pi^0$		(5.0 ± 1.3) %			26.0%
$\Lambda\rho^+$		< 6 %	CL=95%		
$\Lambda\pi^+\pi^+\pi^-$		(3.59 ± 0.28) %			7.8%
$\Sigma(1385)^+\pi^+\pi^-$, $\Sigma^{*+} \to \Lambda\pi^+$		(1.0 ± 0.5) %			20.0%
$\Sigma(1385)^-\pi^+\pi^+$, $\Sigma^{*-} \to \Lambda\pi^-$		$(7.5 \pm 1.4) \times 10^{-3}$			18.7%

Λ_c^+

Situation before 2014:
fixed-target experiment
(ARGUS, CLEO, BABAR,

- Known decays only
- Many unknown de
- Large uncertainties
- Most BF measured

Large experimental unce
➡ slow development in

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(35 days beam time)

n PDG2015

Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)	
th a p: $S = -1$ final states				
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	$(6.84^{+0.32}_{-0.40})$ %			
[q]	(2.13 ± 0.30) %			
	(1.18 ± 0.27) %			22.9%
[q]	(2.4 ± 0.6) %			25.0%
	(3.8 ± 0.4) %			10.5%
	(4.5 ± 0.6) %			13.3%
	(1.7 ± 0.4) %			23.5%
	(3.5 ± 0.4) %			11.4%
	(4.6 ± 0.8) %			13.0%
[q]	(1.5 ± 0.5) %			33.3%
	(5.0 ± 0.9) %			18.0%
	seen			
	$(1.5 \pm 1.0) \times 10^{-3}$			66.7%
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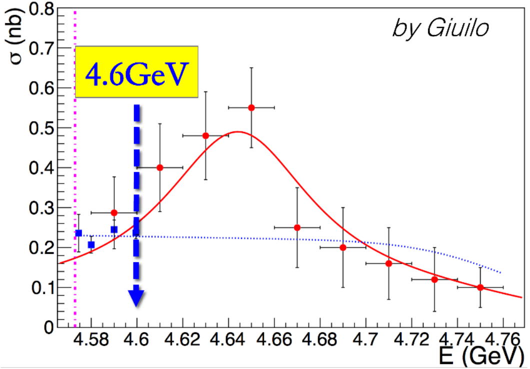
	$(1.1 \pm 0.4) \times 10^{-3}$			36.4%
[q]	$(1.12 \pm 0.23) \times 10^{-3}$			
	$(4.8 \pm 1.9) \times 10^{-4}$			
hyperon: $S = -1$ final states				
	(1.46 ± 0.13) %			8.9%
	(5.0 ± 1.3) %			26.0%
	< 6 %	CL=9[illegible]%		
$\Lambda\pi^+\pi^+\pi$	(3.59 ± 0.28) %			7.8%
$\Sigma(1385)^+\pi^+\pi^-$, $\Sigma^{*+} \to \Lambda\pi^+$	(1.0 ± 0.5) %			20.0%
$\Sigma(1385)^-\pi^+\pi^+$, $\Sigma^{*-} \to \Lambda\pi^-$	$(7.5 \pm 1.4) \times 10^{-3}$			18.7%

Λ_c^+ production close to threshold



Cross section measurement at threshold:

BESIII, Phys. Rev. Lett. **120** (2018) 132001

BESIII dataset contains $\approx 0.1M\ \Lambda_c^+$ pairs

BESIII compared to Belle via ISR Phys. Rev. Lett. **101** (2008) 172001

Cross section jumps abruptly at threshold!

BESIII Λ_c^+ results from first round of data

17 publications from first 34 days of data taking at 4.6 GeV:

- Precise, absolute BF measurements for hadronic, semi-leptonic and inclusive decays
- Observation of CS decay $p\pi^+\pi^-$
- Evidence for CS decay $p\eta$
- First measurements for many decay asymmetries
- Λ_c^+ spin
- EM formfactor near threshold

Very successful programme: increase energy, take more data!

2014 : 0.567 fb^{-1} at 4.6 GeV

Hadronic decay	
$\Lambda_c^+ \to pK^-\pi^+$ + 11 CF 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)
$\Lambda_c^+ \to \Xi^{0(*)}K^+$	PLB 783, 200 (2018)
$\Lambda_c^+ \to \Lambda\eta\pi^+$	PRD 99, 032010 (2019)
$\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta'$	CPC 43, 083002 (2019)
$\Lambda_c^+ \to$ BP decay asymmetries	PRD 100, 072004 (2019)
$\Lambda_c^+ \to pK_s\eta$	PLB 817, 136327 (2021)
Λ_c^+ spin determination	PRD 103, L091101(2021)
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)
$\Lambda_c^+ \to K_S^0X$	EPJC 80, 935 (2020)
Production	
$\Lambda_c^+\Lambda_c^-$ cross section	PRL 120,132001(2018)

Λ_c^+ after 2015

Λ_c^+ data in PDG2015

Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)	
Hadronic modes with a p: $S=-1$ final states					
$p\overline{K}^0$		(3.21 ± 0.30) %			
$pK^-\pi^+$		$(6.84^{+0.32}_{-0.40})$ %			
$p\overline{K}^*(892)^0$	[q]	(2.13 ± 0.30) %			22.9%
$\Delta(1232)^{++}K^-$		(1.18 ± 0.27) %			25.0%
$\Lambda(1520)\pi^+$	[q]	(2.4 ± 0.6) %			10.5%
$pK^-\pi^+$ nonresonant		(3.8 ± 0.4) %			13.3%
$p\overline{K}^0\pi^0$		(4.5 ± 0.6) %			23.5%
$p\overline{K}^0\eta$		(1.7 ± 0.4) %			11.4%
$p\overline{K}^0\pi^+\pi^-$		(3.5 ± 0.4) %			13.0%
$pK^-\pi^+\pi^0$		(4.6 ± 0.8) %			33.3%
$pK^*(892)^-\pi^+$	[q]	(1.5 ± 0.5) %			18.0%
$p(K^-\pi^+)_{nonresonant}\pi^0$		(5.0 ± 0.9) %			
$\Delta(1232)\overline{K}^*(892)$		seen			
$pK^-\pi^+\pi^+\pi^-$		$(1.5 \pm 1.0) \times 10^{-3}$			66.7%
$pK^-\pi^+\pi^0\pi^0$		(1.1 ± 0.5) %			45.4%
Hadronic modes with a p: $S=0$ final states					
$p\pi^+\pi^-$		$(4.7 \pm 2.5) \times 10^{-3}$			45.4%
$pf_0(980)$	[q]	$(3.8 \pm 2.5) \times 10^{-3}$			53.2%
$p\pi^+\pi^+\pi^-\pi^-$		$(2.5 \pm 1.6) \times 10^{-3}$			64.0%
pK^+K^-		$(1.1 \pm 0.4) \times 10^{-3}$			36.4%
$p\phi$	[q]	$(1.12 \pm 0.23) \times 10^{-3}$			
pK^+K^- non-ϕ		$(4.8 \pm 1.9) \times 10^{-4}$			
Hadronic modes with a hyperon: $S=-1$ final states					
$\Lambda\pi^+$		(1.46 ± 0.13) %			8.9%
$\Lambda\pi^+\pi^0$		(5.0 ± 1.3) %			26.0%
$\Lambda\rho^+$		< 6 %	CL=95%		
$\Lambda\pi^+\pi^+\pi^-$		(3.59 ± 0.28) %			7.8%
$\Sigma(1385)^+\pi^+\pi^-$, $\Sigma^{*+} \to \Lambda\pi^+$		(1.0 ± 0.5) %			20.0%
$\Sigma(1385)^-\pi^+\pi^+$, $\Sigma^{*-} \to \Lambda\pi^-$		$(7.5 \pm 1.4) \times 10^{-3}$			18.7%

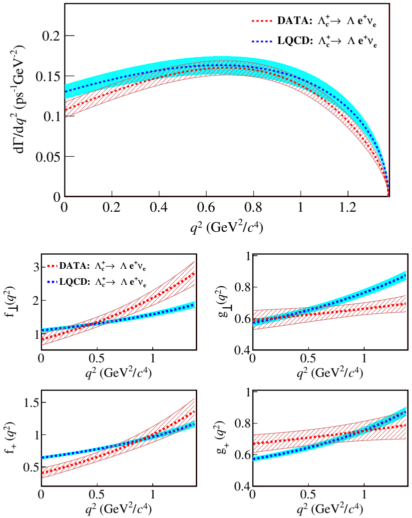
PDG 2020

	Mode		Fraction		
	Hadronic modes with a p or n: $S=-1$ final states				
Γ_1	pK_S^0		(1.59 ± 0.08) %	↓44%	S=1.1
Γ_2	$pK^-\pi^+$		(6.28 ± 0.32) %		S=1.4
Γ_3	$p\overline{K}^*(892)^0$	[a]	(1.96 ± 0.27) %		
Γ_4	$\Delta(1232)^{++}K^-$		(1.08 ± 0.25) %		
Γ_5	$\Lambda(1520)\pi^+$	[a]	(2.2 ± 0.5) %		
Γ_6	$pK^-\pi^+$ nonresonant		(3.5 ± 0.4) %		
Γ_7	$pK_S^0\pi^0$		(1.97 ± 0.13) %	↓50%	S=1.1
Γ_8	$nK_S^0\pi^+$		(1.82 ± 0.25) %	First	
Γ_9	$p\overline{K}^0\eta$		(1.6 ± 0.4) %		
Γ_{10}	$pK_S^0\pi^+\pi^-$		(1.60 ± 0.12) %	↓28%	S=1.1
Γ_{11}	$pK^-\pi^+\pi^0$		(4.46 ± 0.30) %	↓61%	S=1.5
Γ_{12}	$pK^*(892)^-\pi^+$	[a]	(1.4 ± 0.5) %		
Γ_{13}	$p(K^-\pi^+)_{nonresonant}\pi^0$		(4.6 ± 0.8) %		
Γ_{14}	$\Delta(1232)\overline{K}^*(892)$		seen		
Γ_{15}	$pK^-2\pi^+\pi^-$		$(1.4 \pm 0.9) \times 10^{-3}$		
Γ_{16}	$pK^-\pi^+2\pi^0$		(1.0 ± 0.5) %		
	Hadronic modes with a p: $S=0$ final states				
Γ_{17}	$p\pi^0$		$< 2.7 \times 10^{-4}$		CL=90%
Γ_{18}	$p\eta$		$(1.24 \pm 0.30) \times 10^{-3}$	First	
Γ_{19}	$p\omega(782)^0$		$(9 \pm 4) \times 10^{-4}$		
Γ_{20}	$p\pi^+\pi^-$		$(4.61 \pm 0.28) \times 10^{-3}$	First	
Γ_{21}	$pf_0(980)$	[a]	$(3.5 \pm 2.3) \times 10^{-3}$		
Γ_{22}	$p2\pi^+2\pi^-$		$(2.3 \pm 1.4) \times 10^{-3}$		
Γ_{23}	pK^+K^-		$(1.06 \pm 0.06) \times 10^{-3}$		
Γ_{24}	$p\phi$	[a]	$(1.06 \pm 0.14) \times 10^{-3}$	↓36%	
Γ_{25}	pK^+K^- non-ϕ		$(5.3 \pm 1.2) \times 10^{-4}$		
Γ_{26}	$p\phi\pi^0$		$(10 \pm 4) \times 10^{-5}$		
Γ_{27}	$pK^+K^-\pi^0$ nonresonant		$< 6.3 \times 10^{-5}$		CL=90%
	Hadronic modes with a hyperon: $S=-1$ final states				
Γ_{28}	$\Lambda\pi^+$		(1.30 ± 0.07) %		S=1.1
Γ_{29}	$\Lambda\pi^+\pi^0$		(7.1 ± 0.4) %	↓78%	S=1.1
Γ_{30}	$\Lambda\rho^+$		< 6 %		CL=95%
Γ_{31}	$\Lambda\pi^-2\pi^+$		(3.64 ± 0.29) %		S=1.4
Γ_{44}	$\Sigma^0\pi^+$		(1.29 ± 0.07) %	↓45%	S=1.1
Γ_{45}	$\Sigma^+\pi^0$		(1.25 ± 0.10) %	↓33%	
Γ_{46}	$\Sigma^+\eta$		$(4.4 \pm 2.0) \times 10^{-3}$		
Γ_{47}	$\Sigma^+\eta'$		(1.5 ± 0.6) %		
Γ_{48}	$\Sigma^+\pi^+\pi^-$		(4.50 ± 0.25) %	↓46%	S=1.3

Λ_c^+ semileptonic decays: LQCD vs data

BESIII, Phys. Rev. Lett. **129** (2022) 231803

LQCD: S. Meinel, Phys. Rev. Lett. **118** (2017) 082001

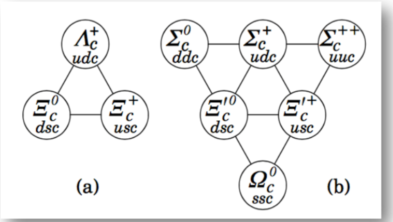


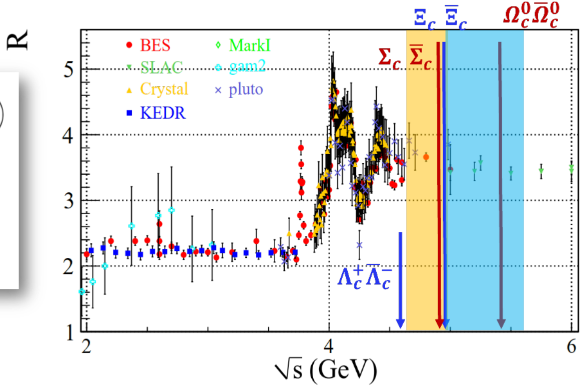
LQCD calculation used measured branching fraction as input: differential decay rate in rather good agreement

Form factors in data quite different from LQCD calculations

Availability of high-quality, precise data essential!

Heavier charmed baryons





Energy thresholds

$\Lambda_c^+\bar{\Sigma}_c^-$	4.74 GeV
$\Lambda_c^+\bar{\Sigma}_c\pi$	4.88 GeV
$\Sigma_c\bar{\Sigma}_c$	4.91 GeV
$\Xi_c\bar{\Xi}_c$	4.94 GeV
$\Xi_c'\bar{\Xi}_c'$	5.16 GeV
$\Omega_c\bar{\Omega}_c$	5.40 GeV

With energy upgrade to 5.6 GeV, can cover all ground-state charmed baryons in detail

Study production and decays of excited charmed baryons

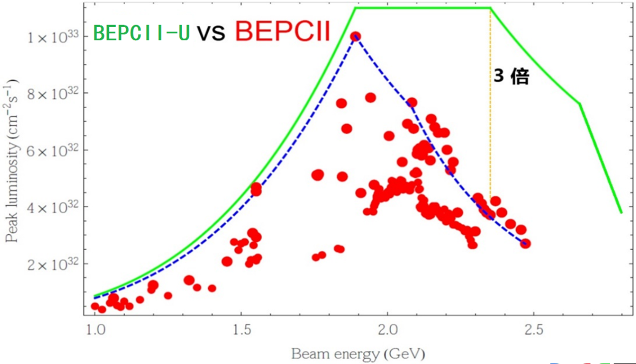
BESIII Quo Vadis?

- Flavour physics at BESIII: charm
- Large data samples compared to predecessors (CLEO, ...), but small compared to LHCb
- Big advantage: production near threshold, closed kinematics, clean events, neutrals and missing energy!
- (Semi-)Leptonic decays of charmed hadrons
- Unique data sample: quantum-correlated $D^0\bar{D}^0$ pairs to measure strong phases

just submitted our 500th paper: mini-workshop to celebrate on 31st May
`https://indico.ihep.ac.cn/event/19694/timetable/`

Upgrade to accelerator: BEPCII-U project

- **Goal**: improve luminosity at large $\sqrt{s}$
- **Easiest upgrade**: install more RF power, optimize machine lattice
- **Bonus**: running above $\sqrt{s} \sim 5$ GeV becomes feasible
  charmed baryons besides Λ_c^+: $\Sigma_c, \Xi_c, \Omega_c$



Outlook for BESIII

- Currently running on $\psi(3770)$, with the goal to collect 20 fb^{-1} in total
- Challenge: improve systematic uncertainties!
- Upgrade of inner tracking system (ageing):
  installation of 3-layer CGEM detector (2024)
- Upgrades to accelerator already performed
  - better feedback systems
  - automated switching from e^- to e^+, for top-up injection ($\mathcal{L}_{\text{int}} + 30\%$)
  - power supplies and cooling for magnets, to allow running at higher $\sqrt{s}$
  - RF power upgrade to reach up to 5.6 GeV

Operate BESIII for several years after upgrade (2030?)

More exciting and precise results to come from the new larger datasets

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謝謝!

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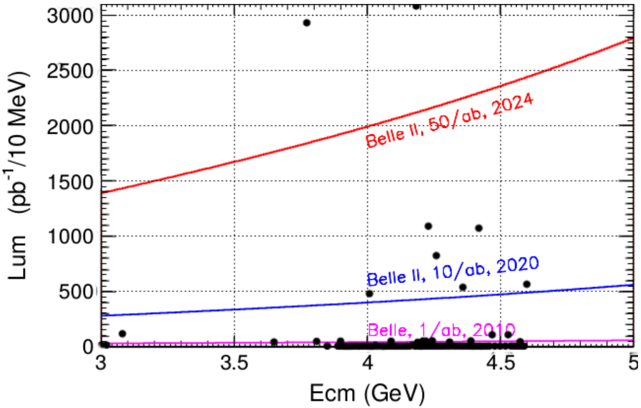
謝謝！

Luminosity expectation Belle II (ISR) vs BESIII (direct)

B2TiP WG7



Note: old luminosity projection for Belle II; current $\mathcal{L}_{\text{int}} = 428\,\text{fb}^{-1}$, target is $4\,\text{ab}^{-1}$ by 4/2026