西安交通大學
XI'AN JIAOTONG UNIVERSITY

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Experimental review of weak decays of heavy hadrons

(recent updated results)

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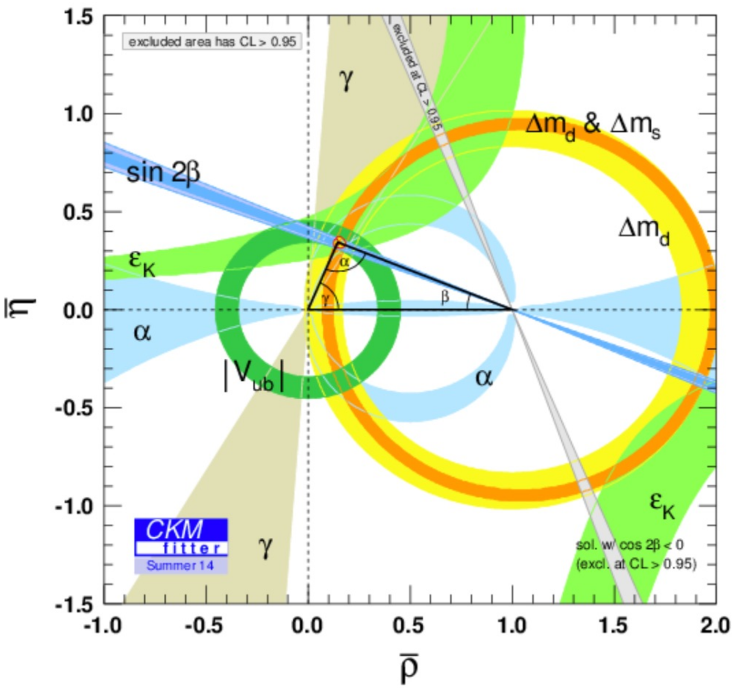
第六届重味物理与量子色动力学研讨会

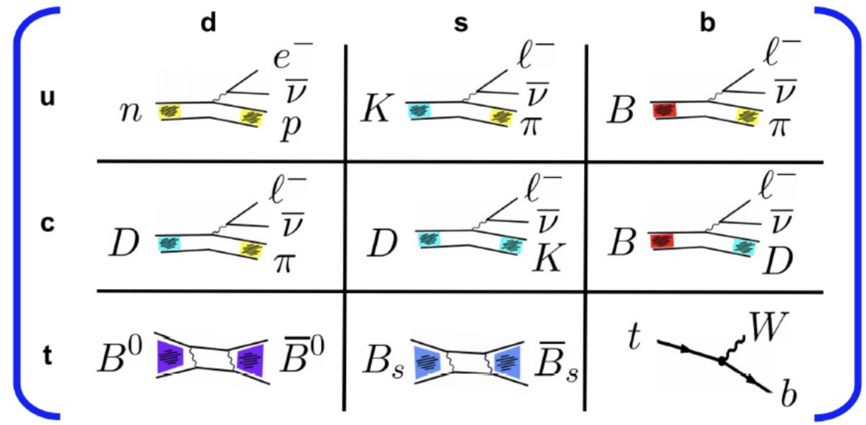
2023年8月

Why weak decay?

How do quarks participate in weak decays? -> CKM matrix



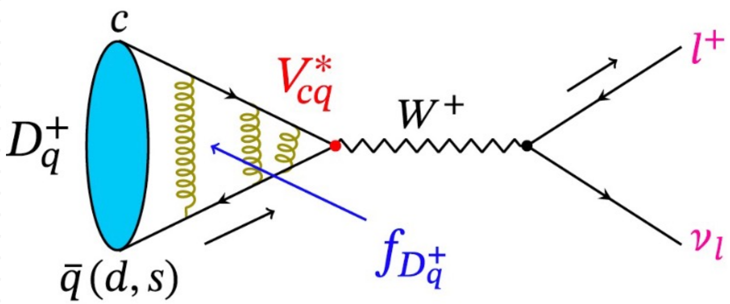
$V =$



$$\alpha = \phi_2 \qquad \beta = \phi_1 \qquad \gamma = \phi_3$$

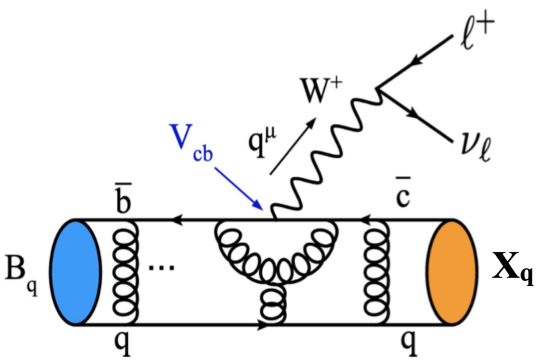
- ❖ d → u: Nuclear physics (superallowed β decays)
- ❖ s → u: Kaon physics (KLOE, KTeV, NA62)
- ❖ **c → d, s: Charm physics (CLEO-c, Babar, Belle, BESIII)**
- ❖ **b → u, c and t → d, s: B physics (Babar, Belle, CDF, DØ, LHCb)**
- ❖ t → b: Top physics (CDF/DØ, ATLAS, CMS)

Why weak decay?



Leptonic decay

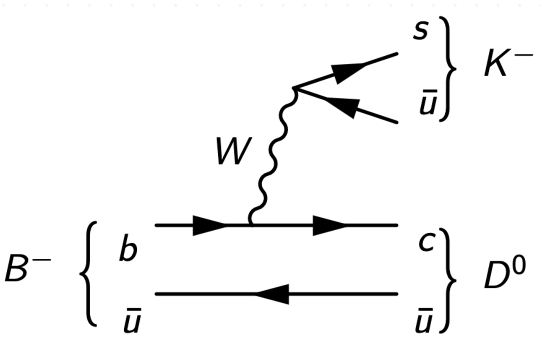
$$B[M \to l\nu_l]_{SM} = \frac{G_F^2 m_M m_l^2}{8\pi}\left(1-\frac{m_l^2}{m_M^2}\right)^2 \left|V_{q_i q_j}\right|^2 f_M^2 \tau_M\left(1+\delta_{em}^{Ml2}\right)$$



Semi-leptonic decay

$$\frac{d\Gamma(M\to P l\nu)}{dq^2} = \frac{G_F^2\left|V_{q_u q_d}\right|^2}{24\pi^3}\frac{(q^2-m_l^2)^2\sqrt{E_P^2-m_P^2}}{q^4 m_H^2}$$
$$\times\left[\left(1+\frac{m_l^2}{2q^2}\right)m_M^2(E_P^2-m_P^2)\left|f_+(q^2)\right|^2+\frac{3m_l^2}{8q^2}(m_M^2-m_P^2)^2\left|f_0(q^2)\right|^2 \ldots\right]$$

	0^+	0^-	1^-	1^+	2^+
$B_{(l)} \to X\ell\bar{\nu}$	f_0	–	f_+	–	f_T
$B_{(l)} \to X^*\ell\bar{\nu}$	–	A_0	V_0	A_1, A_2	T_1, T_2, T_3

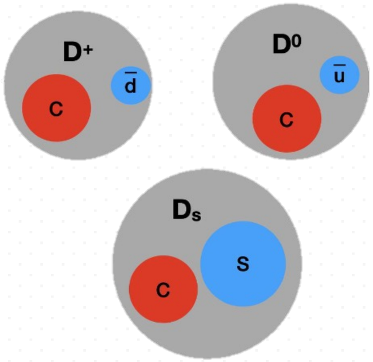


hadronic decay

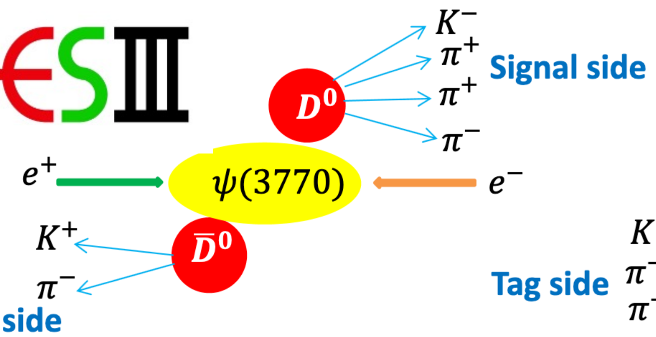
- ❖ **Extract CKM Matrix parameters: $|V_{qq}|$, ϕ_i (test unitarity)**
- ❖ **CPV** ❖ **FCNC** ❖ **LFU (new physics)**
- ❖ **Decay constants and hadronic Form factor (LQCD)**
- ❖ **Decay parameters, Branching fraction, PWA (QCD, other hadrons)**
- ❖ **……**

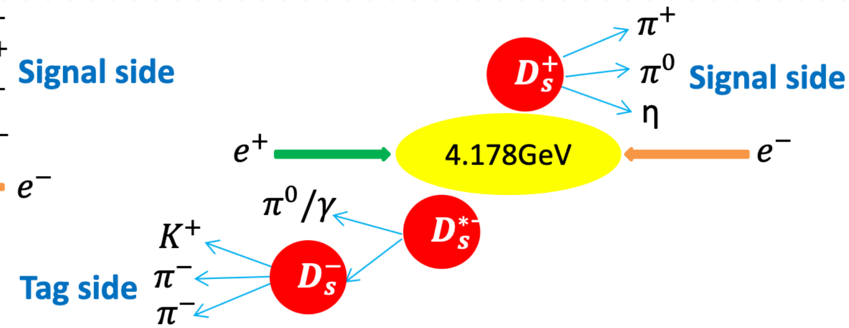
Charm Decays

leptonic decay of $D_{(s)}$

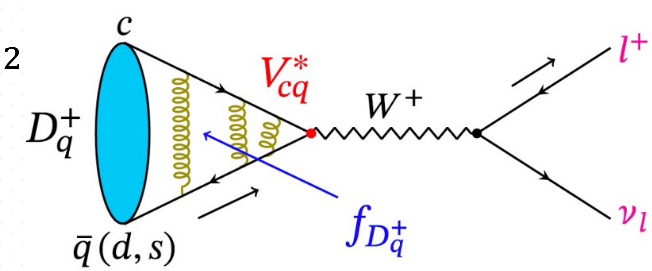


BESIII





$$\Gamma\left(D^+_{(s)} \to l^+ \nu_l\right) = \frac{G_F^2 f_{D_{(s)}}^2}{8\pi} \left|V_{cd(s)}\right|^2 m_l^2 m_{D_{(s)}} \left(1 - \frac{m_l^2}{m_{D_{(s)}}^2}\right)^2$$



$f_{D_{(s)}}$: extracted with $V_{cd(s)}$ taken from the CKM global fit -> Calibration of LQCD

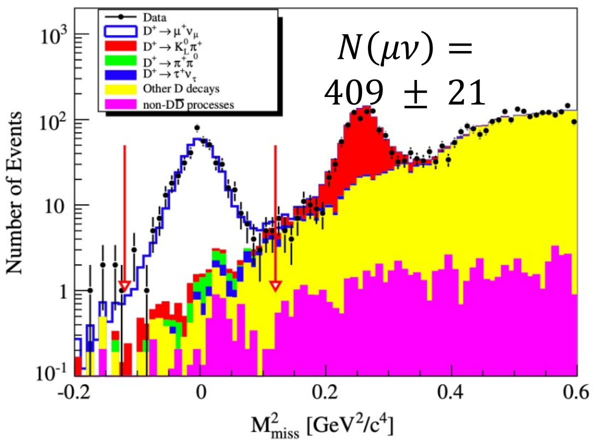
$V_{cd(s)}$: determined with $f_{D_{(s)}}$ taken from the LQCD -> test CKM unitary

Charm Decays

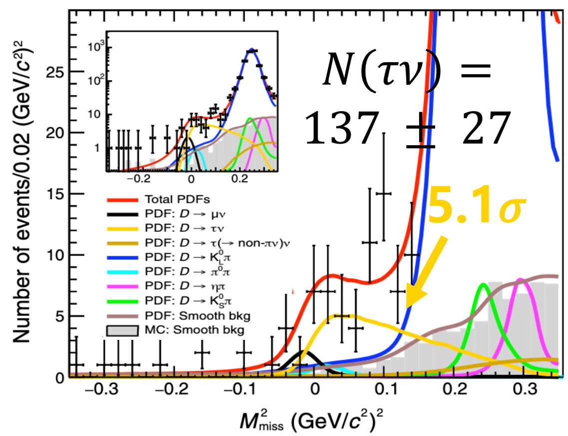
leptonic decay of $D^+ \to l^+ \nu_l$

2.93 fb^{-1} data @ 3.773 GeV

PRD 89, 051104 (2014)



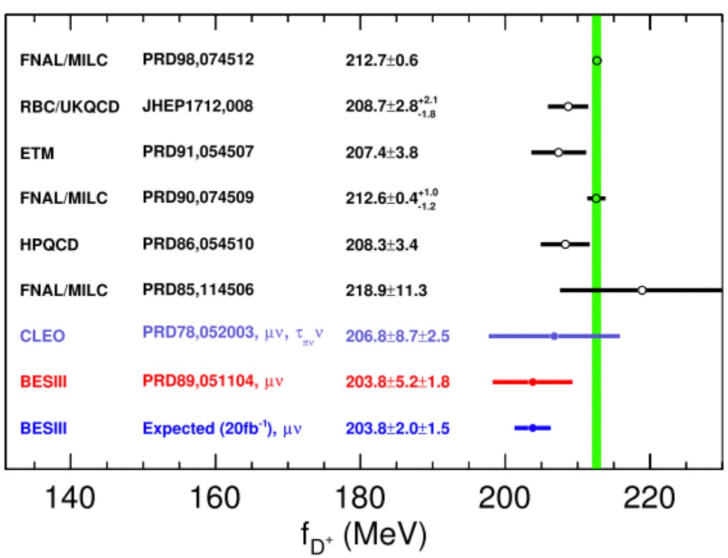
PRL.123.211802 (2019)

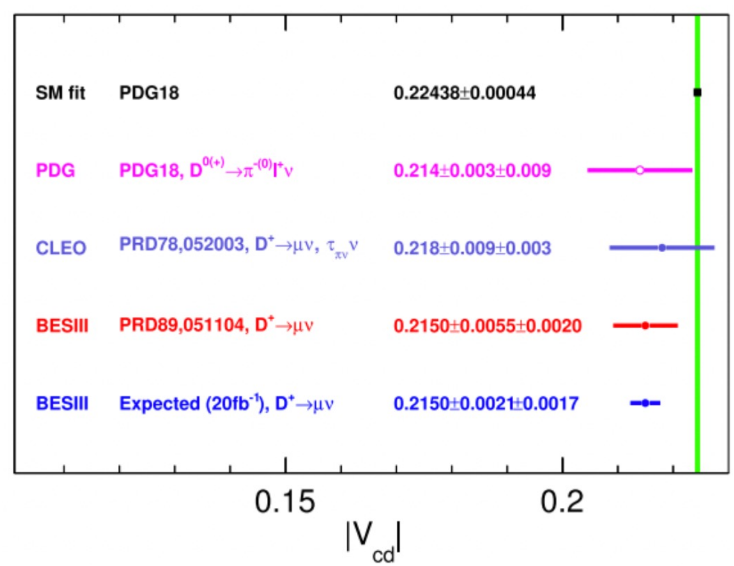


$$R_{D^+} = \frac{\Gamma(D^+\to\tau^+\nu_\tau)}{\Gamma(D^+\to\mu^+\nu_\mu)} = 3.21 \pm 0.64 \pm 0.43$$

SM : 2.67

Consistent





2.7%

1%

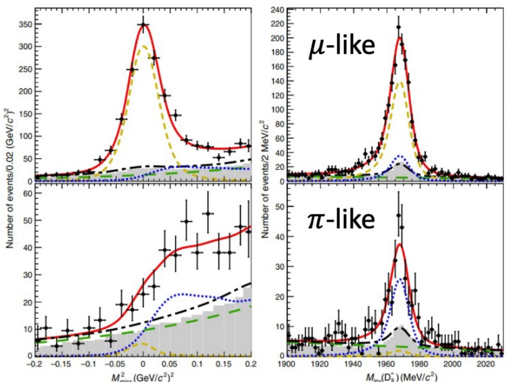
Charm Decays

leptonic decay of $D_s^+ \to \ell\nu$

SM: $R_{D_s^+} = \frac{\Gamma(D_s^+ \to \tau^+\nu_\tau)}{\Gamma(D_s^+ \to \mu^+\nu_\mu)} = 9.75$

❖ **6.32 fb^{-1} @ 4.18-4.23 GeV:**

$\tau^+ \to \pi^+\pi^0\nu_e\,\bar{\nu}_\tau$ [PRD 104, 052009 (2021)]



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

$D_s^+ \to \tau^+(\pi^+\bar{\nu}_\tau)\nu_\tau$

- $N_{sig} = 2198 \pm 55$
- $N_{sig} = 946 \pm 46$

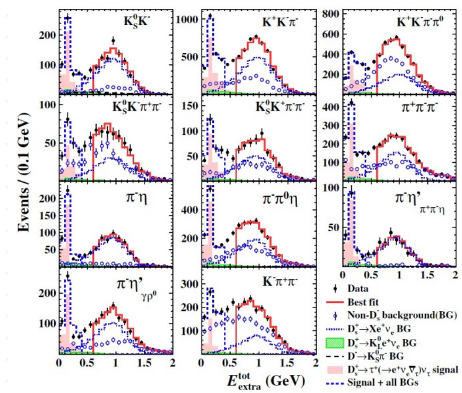
$R_{D_s^+} = 9.72 \pm 0.7$

$\mathcal{B}(\tau^+ \to \pi^+\bar{\nu}_\tau) = 10.82\%$

$D_s^+ \to \mu\nu$ Updated in 2307.14585

$\tau^+ \to e^+\nu_e\,\bar{\nu}_\tau$ [PRL 127, 171801 (2019)]

$\mathcal{B}(\tau^+ \to e^+\nu_e\bar{\nu}_\tau) = 17.82\%$



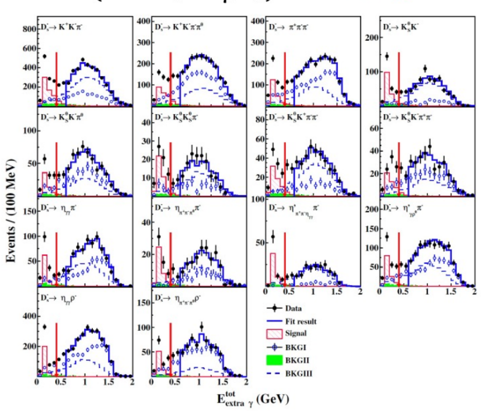
$N_{sig} = 4940 \pm 97$

$R_{D_s^+} = 9.72 \pm 0.37$

❖ **7.33 fb^{-1} @ 4.13-4.23 GeV :**

$\tau^+ \to \mu^+\nu_\mu\,\bar{\nu}_\tau$ [arXiv:2303.12468]

$\mathcal{B}(\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau) = 17.39\%$

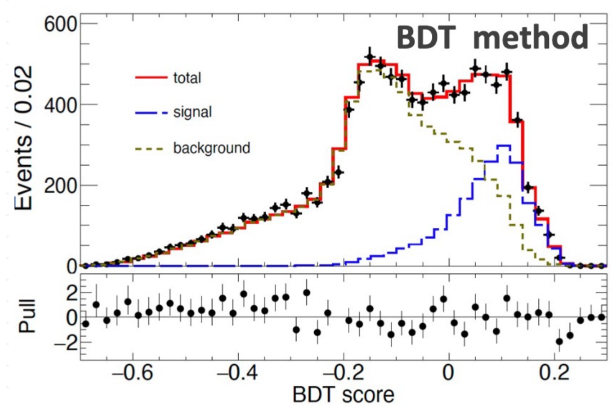


$N_{sig} = 2714 \pm 64$

$R_{D_s^+} = 9.83 \pm 0.43$

$\tau^+ \to \pi^+\,\bar{\nu}_\tau$ [arXiv:2303.12600]

$\mathcal{B}(\tau^+ \to \pi^+\bar{\nu}_\tau) = 10.82\%$

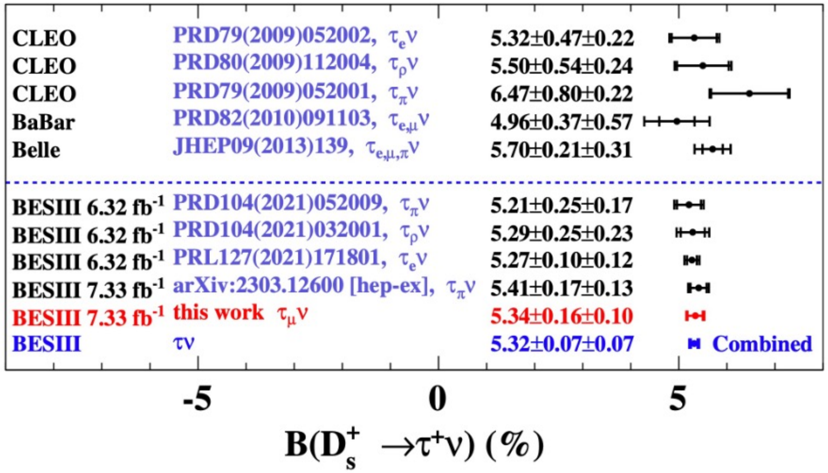


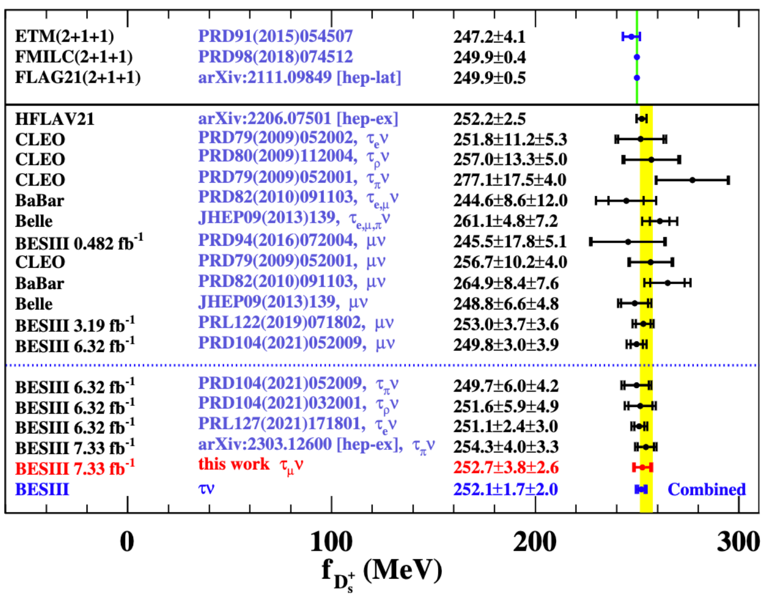
$N_{sig} = 2731 \pm 74$

$R_{D_s^+} = 9.79 \pm 0.33$

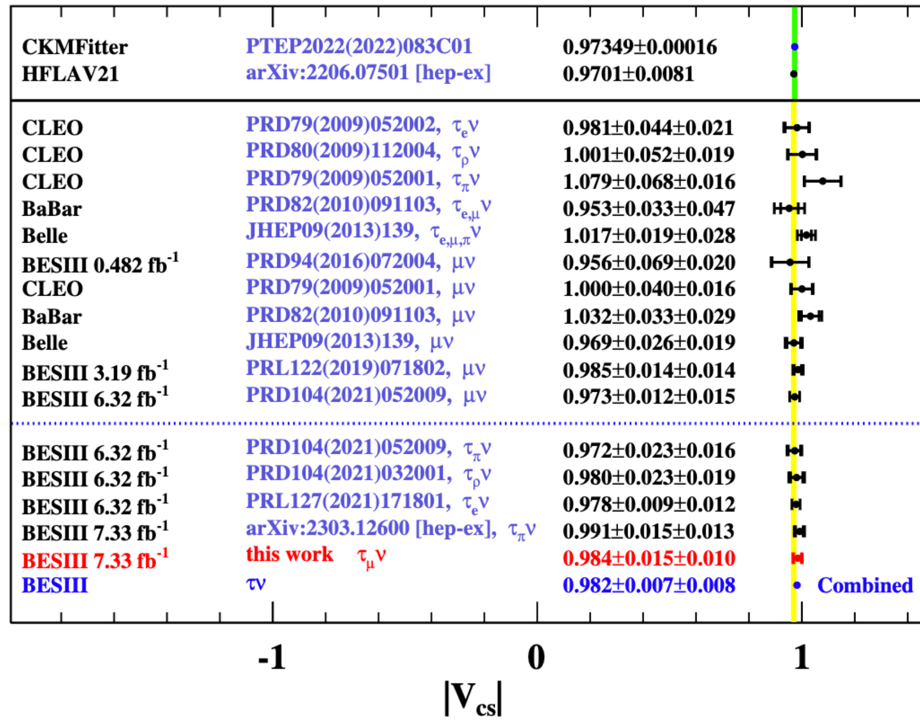
Charm Decays

leptonic decay of $D_s^+ \to \ell\nu$





0.8σ



0.14σ

Charm Decays

leptonic decay of $D_s^{*+} \to \ell\nu$ ❖ 7.33 fb^{-1} @ 4.13-4.23 GeV :

$B(D_s^{*+} \to e^+\nu) = (2.1^{+1.2}_{-0.9}{}_{stat} \pm 0.2_{syst})\times10^{-5}$ (2.9σ) Total width $\Gamma^{tot}_{D_s^{*+}} = (121.9^{+69.6}_{-52.2} \pm 11.8)$eV

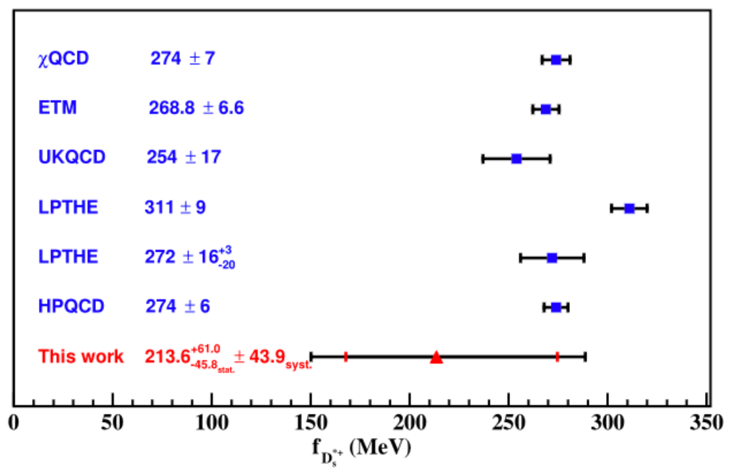
$f_{D_s^{*+}} = (213.6^{+61.0}_{-45.8}{}_{stat} \pm 43.9_{syst})$ MeV

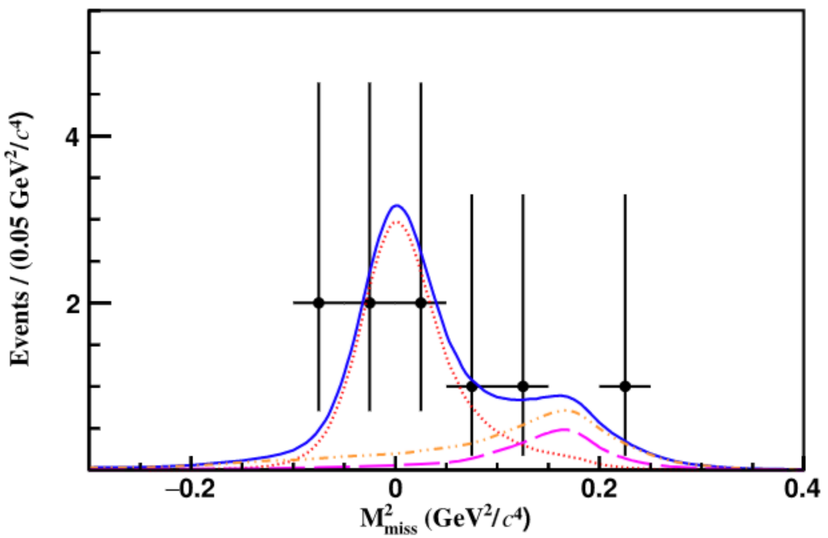
- $\Gamma^{tot} = 2.4\times10^{-3}\times\left(\frac{f_{D_s^{*+}}}{f_{D_s^+}}\right)^2 / \mathcal{B}(D_s^{*+}\to e^+\nu_e)$eV

Theoretical prediction:

EPJC 82, 1037 (2022); PRL 112, 212002 (2022)

- Constrain the U.L. from MeV to KeV level





Arxiv:2307.14585

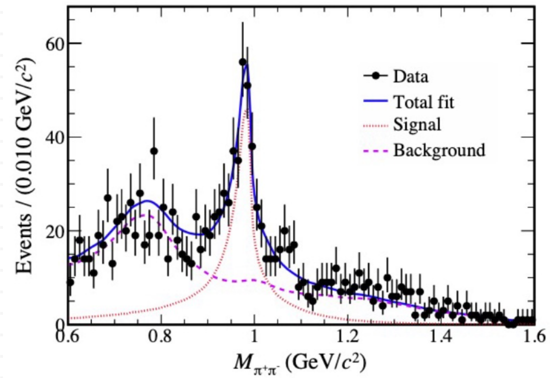
The first hint of leptonic decays of the excited D_s^{*+}

Semi-leptonic decay of $D_s^+ \to f_0(980)e^+\nu_e$

❖ **7.33 fb^{-1} @ 4.13-4.23 GeV :**

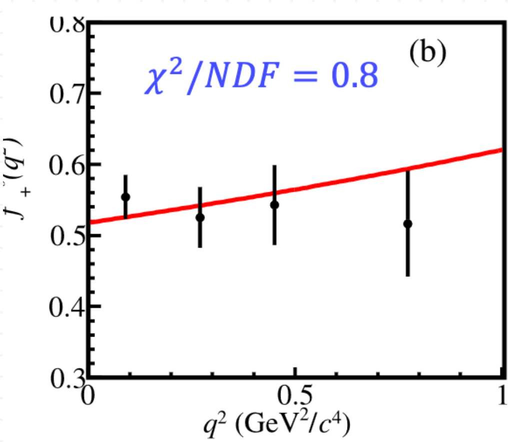
$$\frac{d^2\Gamma(D_{(s)}\to S\ell^+\nu_\ell)}{dsdq^2} = \frac{G_F^2|V_{cd(s)}|^2}{192\pi^4 m_{D_{(s)}}^3}\lambda^{3/2}(m_{D_s}^2, s, q^2)|f_+(q^2)|^2 P(s)$$

$$P(s) = \begin{cases} \frac{g_1\rho_{\pi\pi}}{|m_0^2 - s - i(g_1\rho_{\pi\pi} + g_1\rho_{KK})|^2}, & \text{Flatte for } a_0(980)/f_0(980) \\ \frac{m_{f_0}\Gamma(s)}{(s-m_{f_0}^2)^2 + m_{f_0}^2\Gamma^2(s)}, & \text{RBW for } f_0(500) \end{cases}$$



$f_0(980) \to \pi^+\pi^-$ arXiv:2303.12927

$$\mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e) = (1.72 \pm 0.13_{stat} \pm 0.10_{syst}) \times 10^{-3}$$



	$f_+^{f_0(0)}$
This work	$0.518 \pm 0.018_{\rm stat} \pm 0.036_{\rm syst}$
CLFD [6]	0.45
DR [6]	0.46
QCDSR [7]	0.50 ± 0.13
QCDSR [8]	0.48 ± 0.23
LCSR. [9]	0.30 ± 0.03
LFQM [11]	0.24 ± 0.05
CCQM [12]	0.39 ± 0.02

$f_0 \to \pi^0\pi^0/K_S^0K_S^0$

PRD. 105, L031101 (2022)

- First BFs Measurement:

$$\mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e, f_0(980) \to \pi^0\pi^0) = (7.9 \pm 1.4 \pm 0.4)\times 10^{-4}$$

- No significant signal and upper limit on BF @90% C.L. :

$$\mathcal{B}(D_s^+ \to f_0(500)e^+\nu_e, f_0(500) \to \pi^0\pi^0) < 7.3 \times 10^{-4}$$

$$\mathcal{B}(D_s^+ \to K_S^0K_S^0e^+\nu_e) < 3.8 \times 10^{-4}$$

[6] Phys. Rev. D79, 076004 (2009). [7] Phys. Lett. B579, 59-66 (2004).
[8] EPL90, 61001 (2010). [9] Phys. Rev. D81, 074001 (2010).
[11] Phys. Rev. D80, 074030 (2009). [12] Phys. Rev. D102, 016013 (2020).

Charm Decays

Semi-leptonic decay of $D^+_{(s)} \to \eta^{(\prime)} e^+ \nu_e$ arXiv: 2306.05194

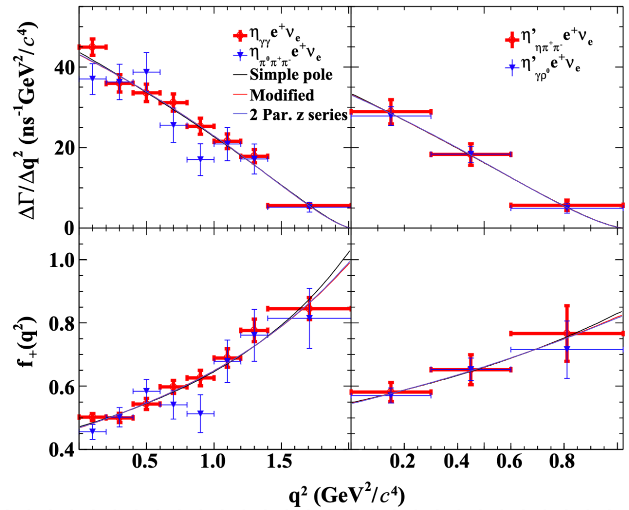
❖ **$7.33\ fb^{-1}$ @ 4.13-4.23 GeV :**

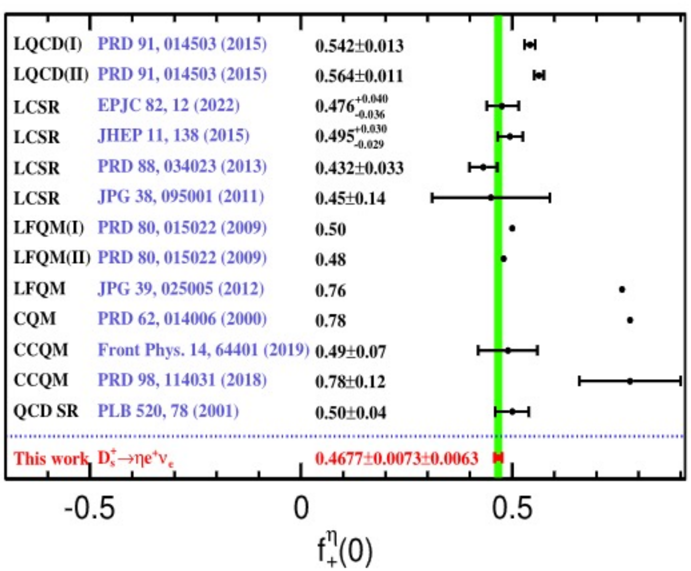
$\mathcal{B}_{\eta e^+\nu_e}$: $(2.251 \pm 0.039_{stat.} \pm 0.051_{syst.})\%$

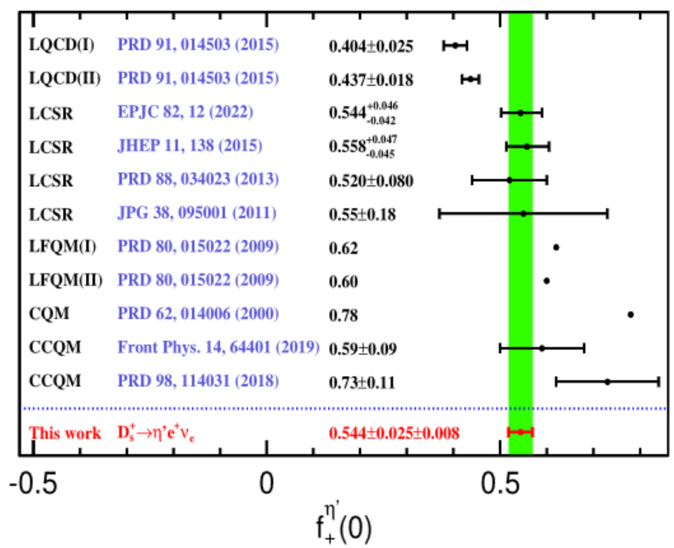
$\mathcal{B}_{\eta' e^+\nu_e}$: $(0.810 \pm 0.038_{stat.} \pm 0.024_{syst.})\%$

- $\eta - \eta'$ mixing angle: $\phi_P = (40.0 \pm 2.0_{stat.} \pm 0.6_{syst.})^\circ$

$$\cot^4 \phi_P = \frac{\Gamma_{D_s^+ \to \eta' e^+ \nu_e} / \Gamma_{D_s^+ \to \eta e^+ \nu_e}}{\Gamma_{D^+ \to \eta' e^+ \nu_e} / \Gamma_{D^+ \to \eta e^+ \nu_e}}.$$





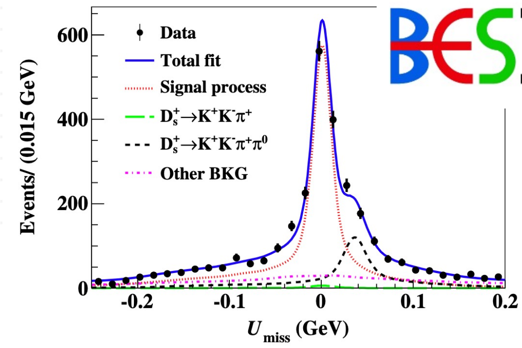


Charm Decays

PWA of Semi-leptonic decay

- ❖ **7.33 fb^{-1} @ 4.13-4.23 GeV :**

$D_s^+ \to K^+K^-\mu^+\nu$ arXiv:2307.03024



$$\mathcal{B}(D_s^+ \to \phi\mu^+\nu_\mu) = (2.25 \pm 0.09 \pm 0.07)\times 10^{-2}$$

$$\mathcal{B}(D_s^+ \to \phi\mu^+\nu_\mu)/\mathcal{B}(D_s^+ \to \phi e^+\nu_e) = 0.94 \pm 0.08$$ ➔ No LFU violation

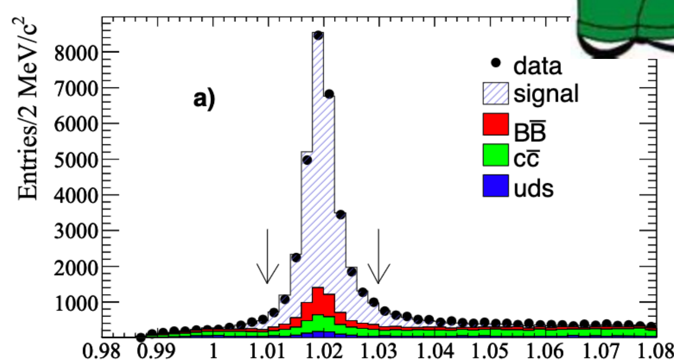
$$\mathcal{B}(D_s^+ \to f_0(980)\mu^+\nu_\mu)\cdot\mathcal{B}(f_0(980) \to K^+K^-) < 5.45\times 10^{-4} @90\% \text{ C.L.}$$ $\sim 2.2\sigma$

Table 5. Measured FF ratios and comparison with previous measurements.

Experiments	r_V	r_2
PDG [42]	1.80±0.08	0.84±0.11
This analysis	1.58±0.17±0.02	0.71±0.14±0.02
BABAR [25]	1.807±0.046±0.065	0.816±0.036±0.030
FOCUS [58]	1.549±0.250±0.148	0.713±0.202±0.284
Theory	r_V	r_2
CCQM [5]	1.34±0.27	0.99±0.20
CQM [6]	1.72	0.73
LFQM [7]	1.42	0.86
LQCD [3]	1.72±0.21	0.74±0.12
HMχT [8]	1.80	0.52

BaBar 214 fb^{-1}:

PRD 78 (2008) 051101



Decay Mode	Exp/Year/Yield	BF/FF/Polarization	BESIII Status
$D_s^+ \to \phi(K^+K^-)e^+\nu_e$	BESIII/2018/26 CLEO/2015/207 BABAR/2008/25k CLEO-II/1994/308	Y/N/N Y/N/N Y/Y/N N/Y/Y	Internal Review@4.13 ~ 4.23GeV
$D_s^+ \to \phi(K^+K^-)\mu^+\nu_\mu$	BESIII/2018/22 FOCUS/2004/793 E687/1994/90	Y/N/N N/Y/N N/Y/Y	Internal Review@4.13 ~ 4.23GeV
$D^+ \to \bar{K}^{*0}(K^-\pi^+)e^+\nu_e$	BESIII/2016/18k BABAR/2011/70k CLEO/2010/5k	Y/Y/N Y/Y/N Y/Y/N	✓
$D^+ \to \bar{K}^{*0}(K^-\pi^+)\mu^+\nu_\mu$	CLEO/2010/5k FOCUS/2002/15k	Y/Y/N N/Y/N	In process
$D^+ \to \bar{K}^{*0}(\bar{K}^0\pi^0)e^+\nu_e$	N	N/N/N	In process
$D^+ \to \bar{K}^{*0}(\bar{K}^0\pi^0)\mu^+\nu_\mu$	N	N/N/N	In process
$D^0 \to K^{*-}(K^-\pi^0)e^+\nu_e$	CLEO/2005/94	Y/N/N	In process
$D^0 \to K^{*-}(K^-\pi^0)\mu^+\nu_\mu$	N	N/N/N	In process
$D^0 \to K^{*-}(\bar{K}^0\pi^-)e^+\nu_e$	BESIII/2019/3k CLEO/2005/125	Y/Y/N Y/N/N	✓
$D^0 \to K^{*-}(\bar{K}^0\pi^-)\mu^+\nu_\mu$	FOCUS/2005/175	Y/Y/N	In process
$D_s^+ \to K^{*0}(K^+\pi^-)e^+\nu_e$	CLEO/2015/32 BESIII/2019/155	Y/N/N Y/Y/N	In process@4.13 ~ 4.23GeV
$D_s^+ \to K^{*0}(K^+\pi^-)\mu^+\nu_\mu$	**N**	**N**	In process@4.13 ~ 4.23GeV
$D^+ \to \rho^0(\pi^-\pi^+)e^+\nu_e$	CLEO/2013/447 BESIII/2019/1.7k	Y/Y/N Y/Y/N	✓
$D^+ \to \rho^0(\pi^-\pi^+)\mu^+\nu_\mu$	FOCUS/2006/320	Y/N/N	In process
$D^+ \to \omega(\pi^-\pi^+\pi^0)e^+\nu_e$	BESIII/2016/491	Y/Y/N	✓
$D^+ \to \omega(\pi^-\pi^+\pi^0)\mu^+\nu_\mu$	BESIII/2020/194	Y/N/N	✓
$D^0 \to \rho^-(\pi^-\pi^0)e^+\nu_e$	CLEO/2013/305 BESIII/2019/1.1k	Y/Y/N Y/Y/N	✓
$D^0 \to \rho^-(\pi^-\pi^0)\mu^+\nu_\mu$	BESIII/2021/570	Y/N/N	✓
$D^+ \to \phi(K^+K^-)e^+\nu_e$	BESIII/2016/-	Y/N/N	In process
$D^+ \to \phi(K^+K^-)\mu^+\nu_\mu$	N	N	In process

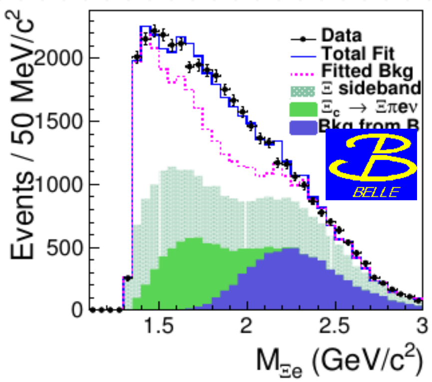
From Shulei Zhang
More can be seen in:
Charm 2023

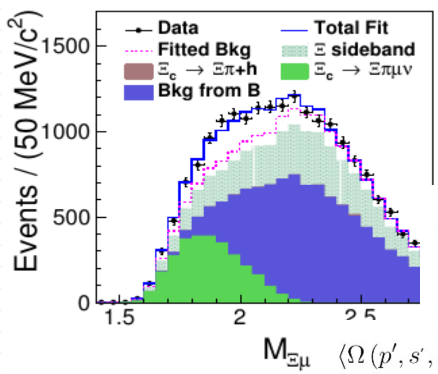
Charm Decays

Semi-leptonic decay of charmed baryons

Λ_c Semi-leptonic decay will be reported by 张圣奇 in the next talk.

$\boldsymbol{\Xi_c^0 \to \Xi^- \ell^+ \nu}$:





Belle: PRL 127 (2021) 12, 121803

$$\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = (1.31 \pm 0.39)\%$$

$$\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu) = (1.27 \pm 0.39)\%$$

ALICE

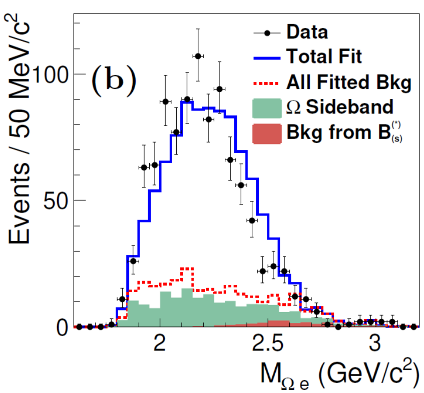
PRL 127 (2021) 27, 272001

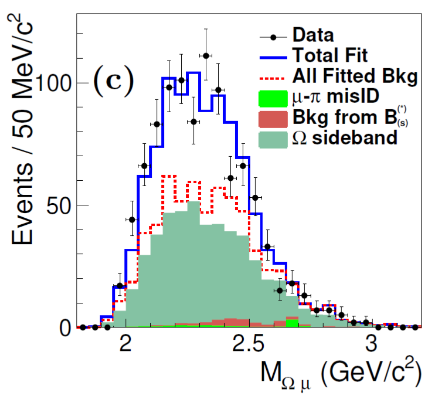
$$\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = (2.5 \pm 0.7)\%$$

$$\langle \Omega(p', s', s_z') | V_\mu | \Omega_c(p, s, s_z') \rangle = \bar{u}(p', s_z') \left[\frac{p^\alpha}{m_{\Omega_c}} \left(F_1^V \gamma_\mu + F_2^V \frac{p_\mu}{m_{\Omega_c}} + F_3^V \frac{p'_\mu}{m_\Omega} \right) + g^{\alpha\mu} F_4^V \right] \gamma_5 u(p, s_z)$$

$$\langle \Omega(p', s', s_z') | A_\mu | \Omega_c(p, s, s_z') \rangle = \bar{u}(p', s_z') \left[\frac{p^\alpha}{m_{\Omega_c}} \left(F_1^A \gamma_\mu + F_2^A \frac{p_\mu}{m_{\Omega_c}} + F_3^A \frac{p'_\mu}{m_\Omega} \right) + g^{\alpha\mu} F_4^A \right] u(p, s_z)$$

$\boldsymbol{\Omega_c^0 \to \Omega^- \ell^+ \nu}$:





$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- e^+ \nu)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 1.98 \pm 0.15$$

$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- \mu^+ \nu)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 1.94 \pm 0.21$$

Previous: 2.4 ± 1.2

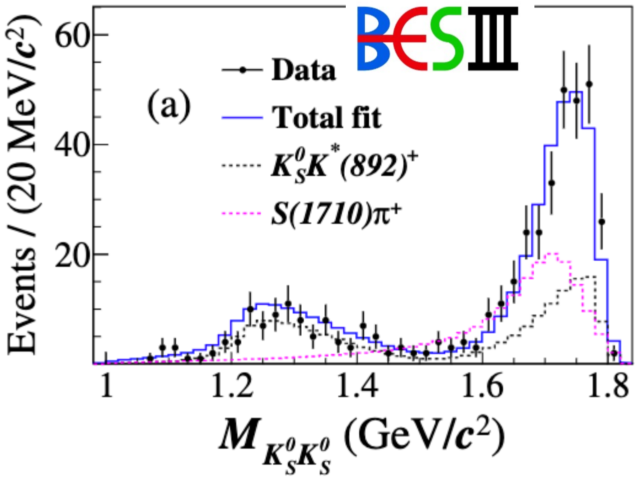
PRD 105 (2022) 9, L091101

It is unlike for us to extract BF vs q2 for Ξ_c^0 and Ω_c^0.

$\boldsymbol{\Xi_c^+ \to \Xi^0 \ell^+ \nu}$: bkg/signal mixed due to contamination of gamma

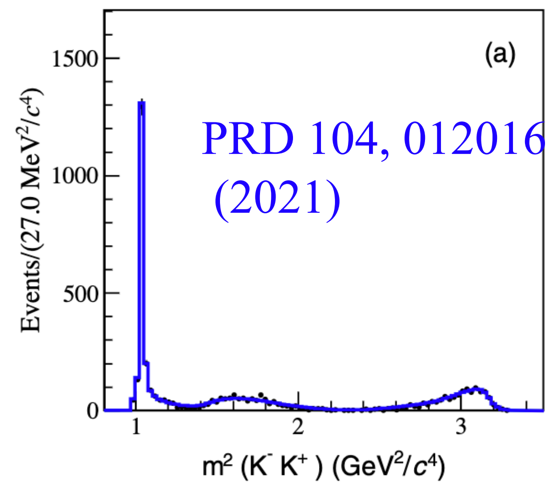
Charm Decays

Hadronic decay of $D_s^+ \to K_S^0 K_S^0 \pi^+$ PRD 105,L051103 (2022)



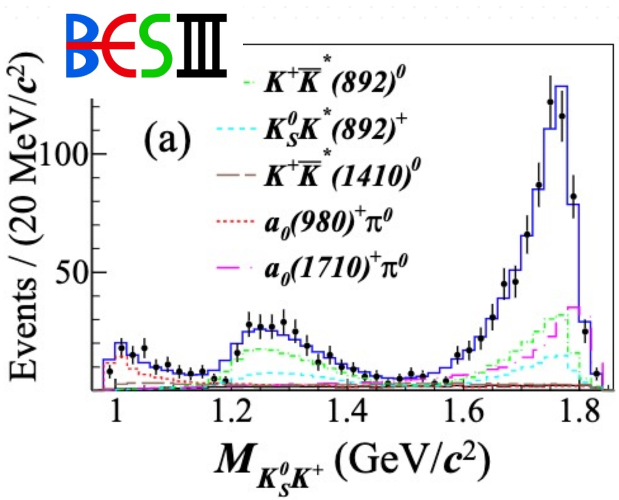
Amplitude	Phase	FF (%)
$D_s^+ \to K_S^0 K^*(892)^+$	0.0 (fixed)	$43.5 \pm 3.9 \pm 0.5$
$D_s^+ \to S(1710)\pi^+$	$2.3 \pm 0.1 \pm 0.1$	$46.3 \pm 4.0 \pm 1.2$

$f_0(1710)$ not seen in
$D_s^+ \to K^+K^-\pi^+$ decay
-> $K^*\bar{K}^*$ molecule
-> isospin one partner $a_0(1710)^0$



PRD 104, 012016 (2021)

$D_s^+ \to K_S^0 K^+ \pi^0$ PRL 129 18 (2022)



Observation of $a_0^+(1710)$

Amplitude	Phase (rad)	FF (%)	BF (10^{-3})	σ
$D_s^+ \to \bar{K}^*(892)^0 K^+$	0.0(fixed)	$32.7 \pm 2.2 \pm 1.9$	$4.77 \pm 0.38 \pm 0.32$	> 10
$D_s^+ \to K^*(892)^+ K_S^0$	$-0.16 \pm 0.12 \pm 0.11$	$13.9 \pm 1.7 \pm 1.3$	$2.03 \pm 0.26 \pm 0.20$	> 10
$D_s^+ \to a_0(980)^+ \pi^0$	$-0.97 \pm 0.27 \pm 0.25$	$7.7 \pm 1.7 \pm 1.8$	$1.12 \pm 0.25 \pm 0.27$	6.7
$D_s^+ \to \bar{K}^*(1410)^0 K^+$	$0.17 \pm 0.15 \pm 0.08$	$6.0 \pm 1.4 \pm 1.3$	$0.88 \pm 0.21 \pm 0.19$	7.6
$D_s^+ \to a_0(1710)^+ \pi^0$	$-2.55 \pm 0.21 \pm 0.07$	$23.6 \pm 3.4 \pm 2.0$	$3.44 \pm 0.52 \pm 0.32$	> 10

Charm Decays

Decay mode	Paper	comment
$D_s^+ \to K^+K^-\pi^+\pi^0$	PRD104,032011(2021)	
$D_s^+ \to K_S^0K^-\pi^+\pi^+$	PRD103,092006 (2021)	Mainly $K^*(892)^+K^*(892)^0$
$D_s^+ \to \pi^+\pi^-\pi^+\eta$	PRD104,L071101(2021)	W-annihilation $\to a_0$ (980)ρ
$D_s^+ \to K_S^0\pi^+\pi^0$	JHEP 06,181(2021)	
$D_s^+ \to K_S^0K^+\pi^0$	PRL129,182001(2022)	$a_0^+(1710)$
$D_s^+ \to K_S^0K_S^0\pi^+$	PRD105,L051103(2022)	
$D_s^+ \to \pi^+\pi^0\eta'$	JHEP04,058(2022)	$\rho^+\eta'$ dominant
$D_s^+ \to \pi^+\pi^-\pi^+$	BESIII: PRD 106,112006(2022) LHCb: JHEP 06 (2023) 044	$\pi^+\pi^-$ S-wave dominant
$D_s^+ \to \pi^+\pi^0\pi^0$	JHEP 01,052 (2022)	
$D_s^+ \to K^+\pi^+\pi^-$	JHEP 08,196 (2022)	
$D_s^+ \to K^+K^-\pi^+\pi^+\pi^-$	JHEP 07,051(2022)	$a1(1260)^+\phi$ dominant
$D_s^+ \to K^+\pi^+\pi^-\pi^0$	JHEP 09 242 (2022)	
$D_s^+ \to \omega\pi^+\eta$	arXiv: 2302.04670	First observation

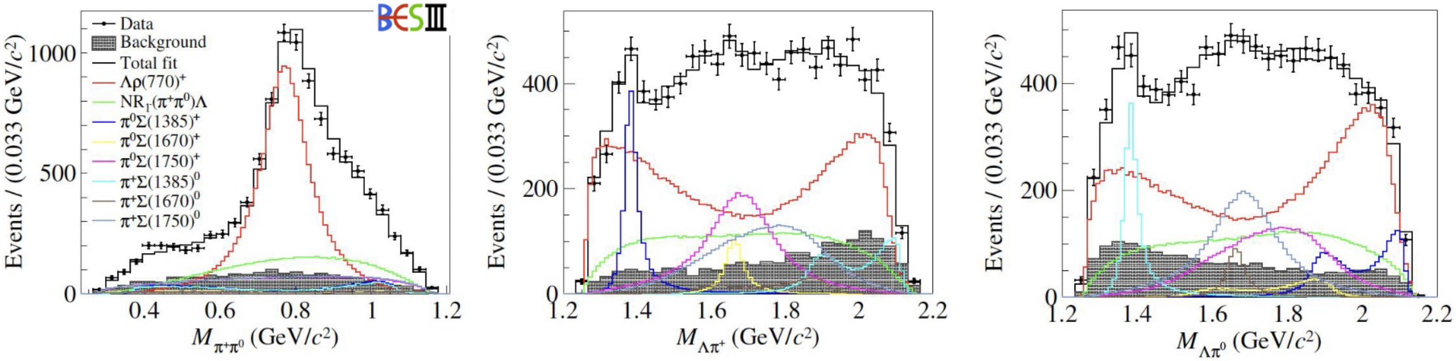
Charm Decays

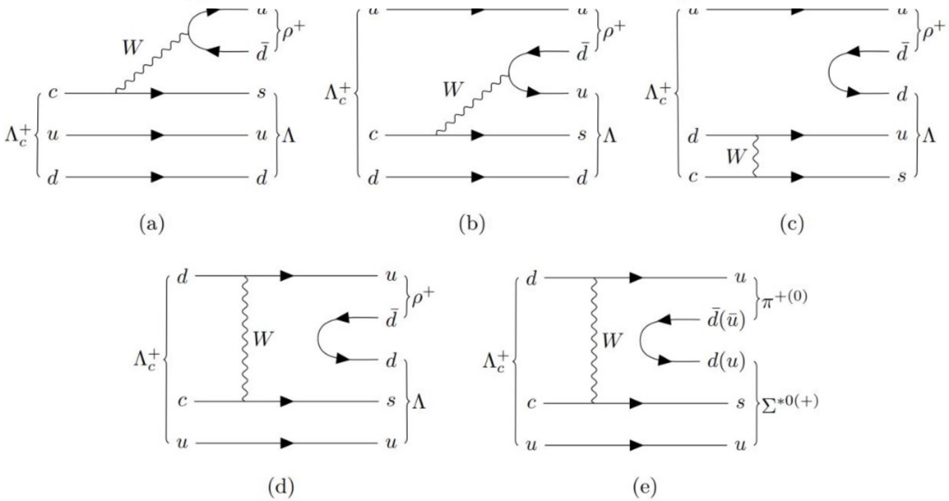
Decay mode	Paper	comment
$D^0 \to \omega\phi$	BESIII: PRL 128 011803 (2022)	$\omega\phi$ transversely polarized
$D^0 \to K_L\pi\pi$	BESIII: arXiv:2212.09048	
$D^0 \to K_sK^+K^-$	BESIII: arXiv:2006.02800	
$D^0 \to K^+\pi^-\pi^0$, $\to K^+\pi^-\pi^0\pi^0$	BESIII: PRD 105,112001 (2022)	No signal for$K^+\pi^-\pi^0\pi^0$
$D^+ \to \pi^+\pi^-\pi^+X$	BESIII: PRD 167, 032802 (2023)	Important for $R_{D^{(*)}}$
$D_s^+ \to \pi^+\pi^-\pi^+X$	BESIII: PRD 108, 032001 (2023)	
$D^+ \to K^+K^-\pi^+\pi^0$ $D_{(s)}^+ \to K^+\pi^-\pi^+\pi^0$,	Belle: PRD 107,033003 (2023)	

Charm Decays

$\Lambda_c \to \Lambda\pi^+\pi^0$

JHEP12 (2022) 033





$\Lambda_c^+ \to \Lambda\rho^+$ consists of both factorizable(a) and non-factorizable(b-d) contributions.

$\Lambda_c^+ \to \Sigma(1385)\pi$ consists of pure non-factorizable(e) contribution.

- Decay asymmetry parameters: relevant to the interference of the internal partial wave amplitudes.
- Provide important inputs to the theoretical calculations for non-factorizable.

Decay mode	Paper	comment
$\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$	Belle: PRL 130, 151903 (2023)	Peaks at 1434 MeV $M_{\Lambda\pi^\pm}$
$\Lambda_c^+ \to \Lambda\eta^{(\prime)}$	Belle: PRD 107, 032003 (2023) BESIII: PRD 106,072002(2022)	
$\Lambda_c^+ \to \Lambda h, \Sigma^0 h$	Belle: 科学通报 68 583 (2023) BESIII: PRD 106,L111101(2022) PRD106,052003(2022)	CPV measurement for Belle
$\Lambda_c^+ \to pK_sK_s, pK_s\eta$	Belle: PRD 107, 032004 (2023)	
$\Lambda_c^+ \to \Sigma^+\gamma, \Xi_c^0 \to \Xi^0\gamma$	Belle: PRD 107, 032001 (2023) BESIII: arXiv 2212.07214	no evident signal
$\Lambda_c^+ \to pK^+\pi^-$	Belle: PRD 108 3 (2023) LHCb: PRD 108 012023 (2023)	Amplitude analysis from LHCb, observe $\Lambda(2000)$
$\Lambda_c^+ \to \Sigma^+K^+K^-, \Sigma^+\phi$ $\to \Sigma^+K^+\pi^-(\pi^0)$	BESIII: arXiv 2304.09405	no evidence $\Sigma^+K^+\pi^-\pi^0$
$\Lambda_c^+ \to n + X$	BESIII: PRD 108 L031101(2023)	
$\Lambda_c^+ \to n\pi^+$	BESIII: PRL 128,142001(2022)	Less Non-factorization contributions
$\Lambda_c^+ \to n\pi^+\pi^0$, $n\pi^+\pi^-\pi^+, nK^+\pi^-\pi^+$	BESIII: CPC 47 023001 (2023)	
$\Lambda_c^+ \to p\eta, p\omega$ $\Lambda_c^+ \to p\pi^0$	BESIII: arXiv 2307.09266 Belle: PRD 104, 072008 (2021) Belle: PRD 103, 072004 (2021)	
$\Lambda_c^+ \to p\eta'$	Belle: JHEP 03 2022, 090 (2022)	
$\Xi_c^+ \to \Lambda K_S, \Sigma^0 K_S, \Sigma^+K^-$	Belle: PRD 105, L011102 (2022)	
$\Omega_c^0 \to \Xi^-\pi^+, \Xi K^+, \Omega^-K^+$	Belle: JHEP 01 055 (2023) LHCb: arXiv 2308.08512	No evidence of CS decay from Belle CS decay observed by LHCb

Charm Decays

CP violation effects are small at charm sector $\leq O(10^{-3})$

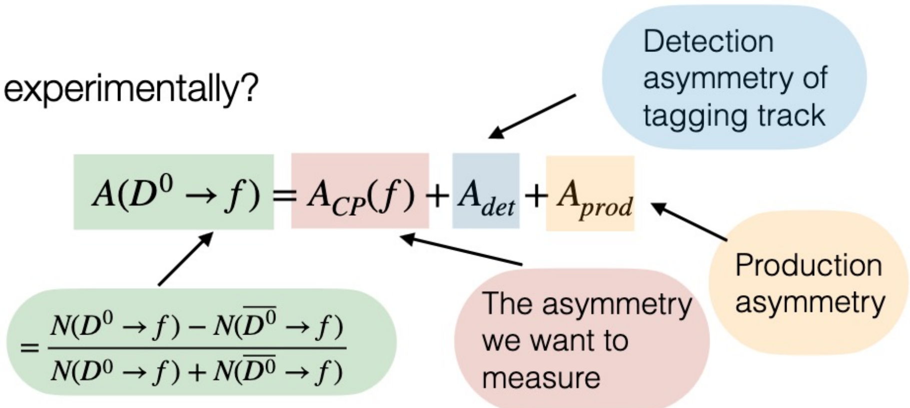
-- Only bound HF system made of up–type quarks, high sensitivity to NP effect wrt K and B_s

—— difficult for the observation

The only observationof CPV of D is $D \to \mathrm{KK}, \pi\pi$ PRL 122 211803 (2019)

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

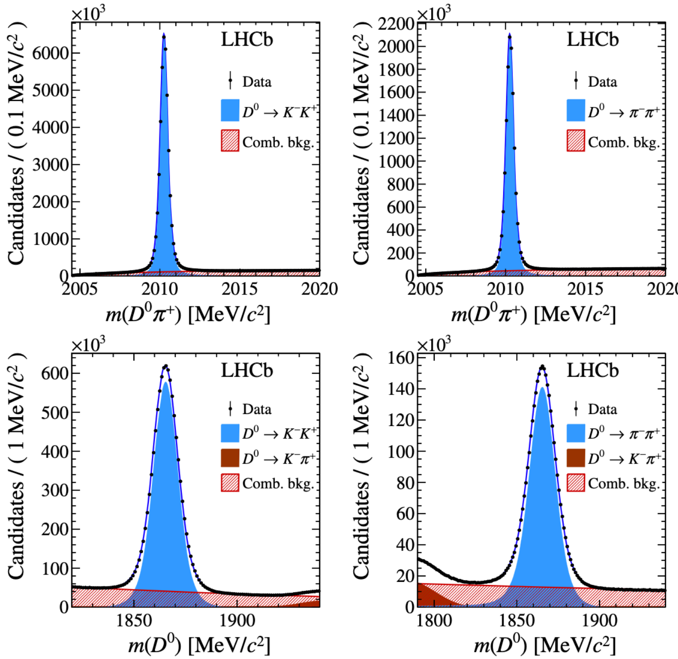
How experimentally?



to cancel Detection and production asymmetry

$$\Delta A_{CP} = A(D \to K^+K^-) - A(D \to \pi^+\pi^-)$$
$$= (-15.4 \pm 2.9)\times 10^{-4}$$

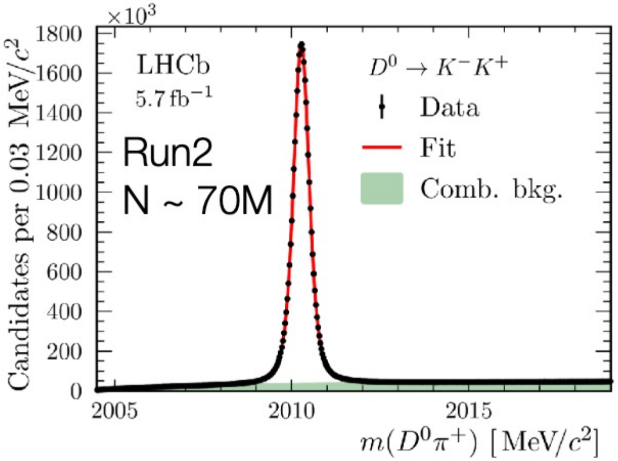
Run 2 (5.6fb^{-1}) data



See M. Piscopo`s talk @ BEAUTY 2023 for theory review.

Charm Decays

observationof CPV of $D \to \mathrm{hh}$： arXiv:2209.03179

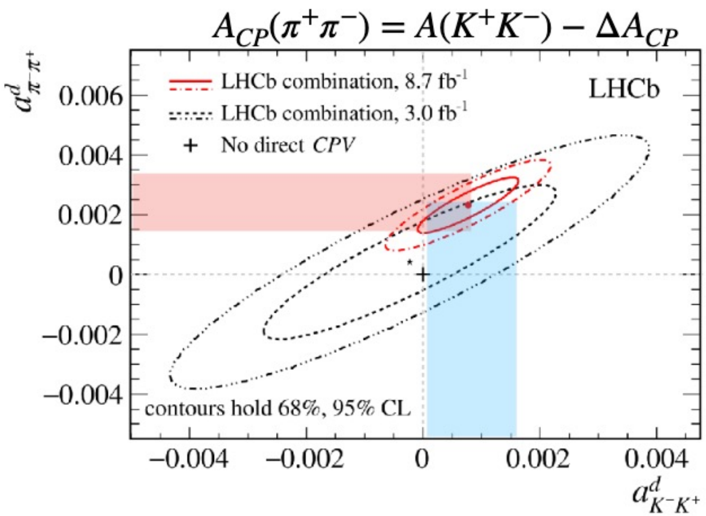


Run 2 (5.6fb[-1]) only：

$$A_{CP}(K^+K^-) = [6.8 \pm 5.4(\text{stat}) \pm 1.6(\text{sys})] \times 10^{-4}$$

$$a_f^d = A_{CP}(f) - \frac{\langle \tau_f \rangle}{\tau_D} \Delta Y_f$$

Indirect term, asymmetries in effective width, lifetimes



Run1+Run2：

$$a_{CP}^d(K^+K^-) = [7.7 \pm 5.7] \times 10^{-4}$$
$$a_{CP}^d(\pi^+\pi^-) = [23.2 \pm 6.1] \times 10^{-4}$$

First evidence (3.8 σ) of CPV in $D \to \pi^+\pi^-$

Charm Decays

Other recent search for CPV in Charm sector: **not see CPV in all cases**

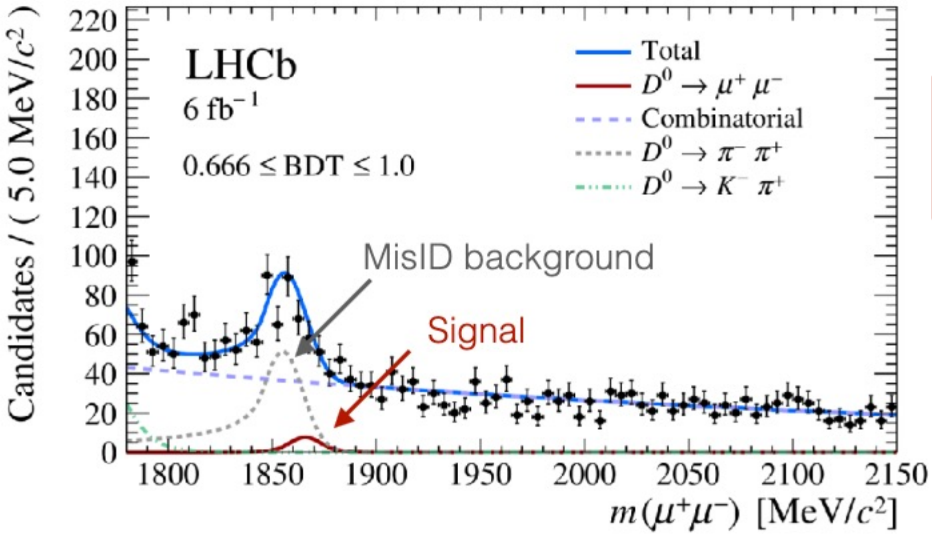
Decay mode	Paper
$D^+_{(s)} \to K^+K^-K^+$	LHCb: JHEP 07 067 (2023)
$D^0 \to \pi^+\pi^-\pi^+$	LHCb: arXiv:2306.12746
$D^+_{(s)} \to \eta^{(\prime)}\pi^+$	LHCb: JHEP 04 081 (2023)
$D^+_{(s)} \to K^+K^-\pi^+\pi^0$, $\to K^+\pi^-\pi^+\pi^0$ $D^+ \to K^-\pi^+\pi^+\pi^0$	Belle: arXiv 2305.12806
$D^0 \to K^0_S K^0_S \pi^+\pi^-$	Belle: PRD 107, 052001 (2023)
$D^+_{(s)} \to K^+K^0_S h^+h^-$ $D^+_s \to K^+K^-K^0_S\pi^+$	Belle: arXiv 2305.11405
$D^0 \to h^+h^-\mu^+\mu^-$	LHCb: PRL 128, 221801 (2022)

Angular analysis

Charm Decays

Rare decays:

•PRL 131 041804 (2023)



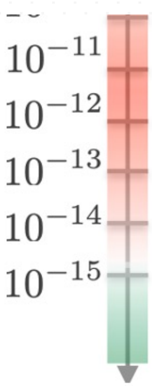
$B(D^0 \to \mu^+\mu^-) < 2.94 \times 10^{-9}$ @ 90 % CL

(LHCb 9/fb Run1+2)

Most stringent
limit on charm FCNC!

$B(D^{0*}(2007) \to \mu^+\mu^-) < 2.6 \times 10^{-8}$ @ 90 % CL

Eur.Phys.J.C 83 (2023) 7, 666



Flavour Changing Neutral Current

$D^0 \to \mu^-\mu^+$

$D^0 \to e^-e^+$

$D \to h\ell^+\ell^-$

$D \to hh'\ell^-\ell^+$

$D \to V\ell^+\ell^-$

Lepton/Baryon Number Violating

Lepton Flavor Violating

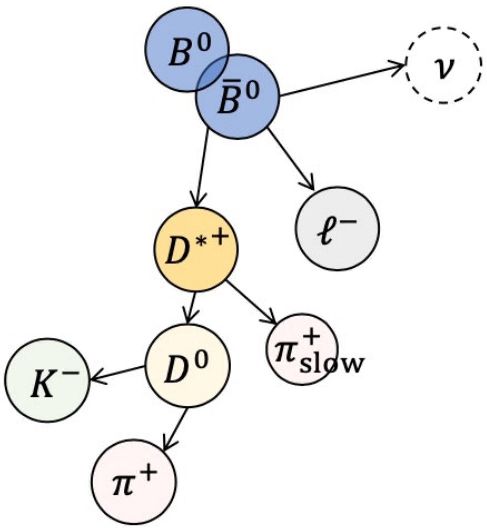
$D \to (h)e^-\mu^+$

$D \to (h)\ell^+\ell^+$

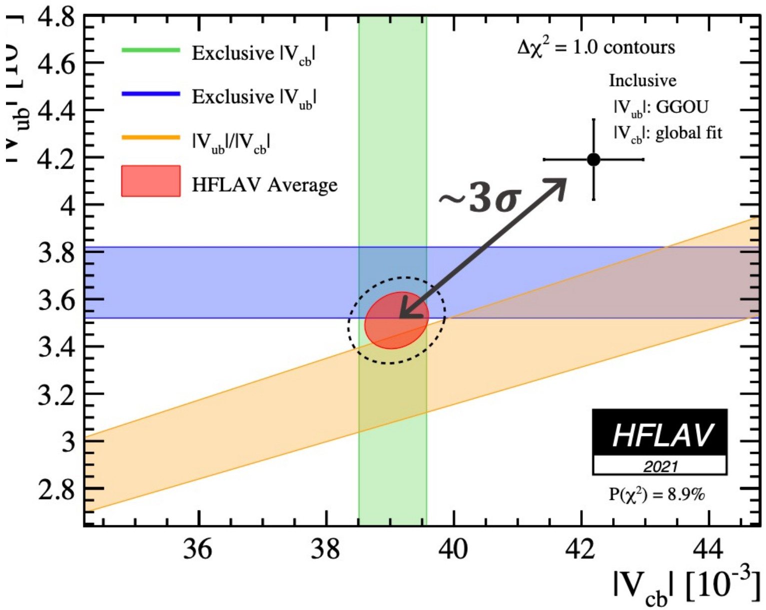
Semileptonic B Decays

- determine the CKM elements $|V_{cb}|$ and $|V_{ub}|$
- Tests of lepton universality, $R(D^{(*)}), R(K^{(*)})$

Exclusive

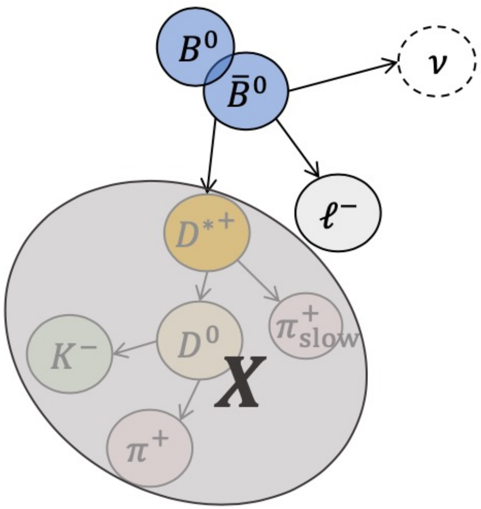


Reconstruct all daughters through specific channels exclusively.



The current experimental focus is on understanding the origin of this discrepancy.

Inclusive

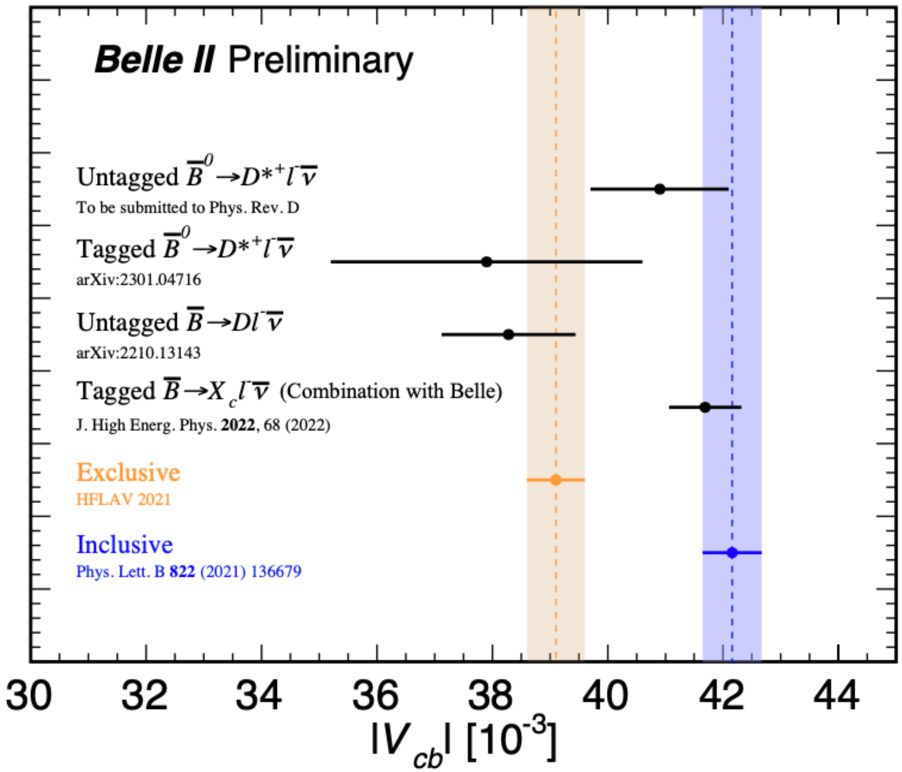


Reconstruct a lepton and assign other tracks and clusters as an inclusive daughter X.

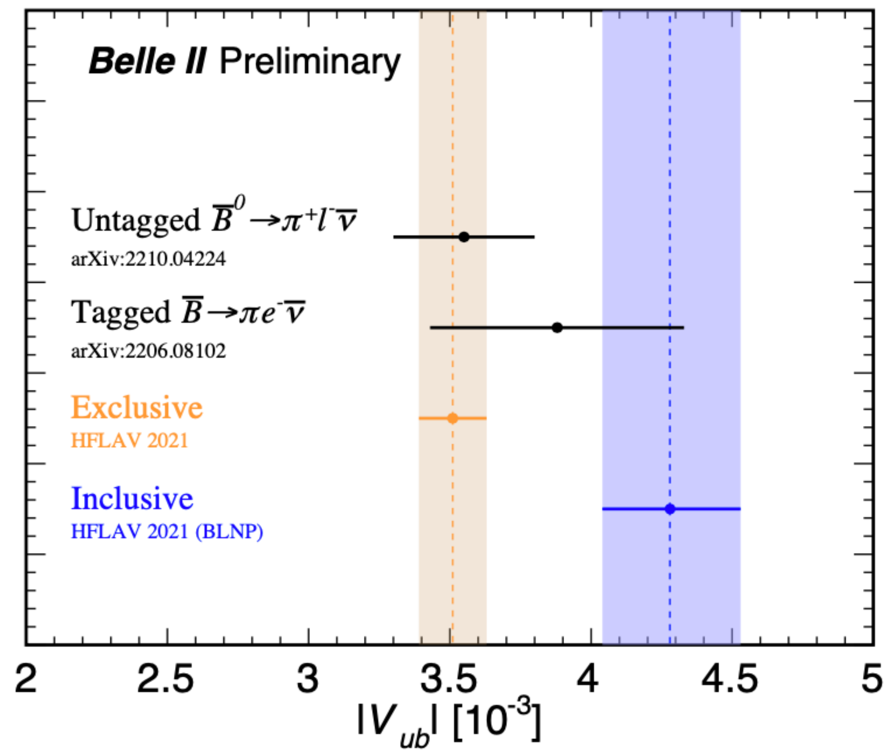
Beauty Decays

Semileptonic B Decays

$|V_{cb}|$ from $\mathrm{B} \to D^{*} l\nu(l = e, \mu)$:



$|V_{ub}|$ from $\mathrm{B} \to \pi l\nu(l = e, \mu)$:

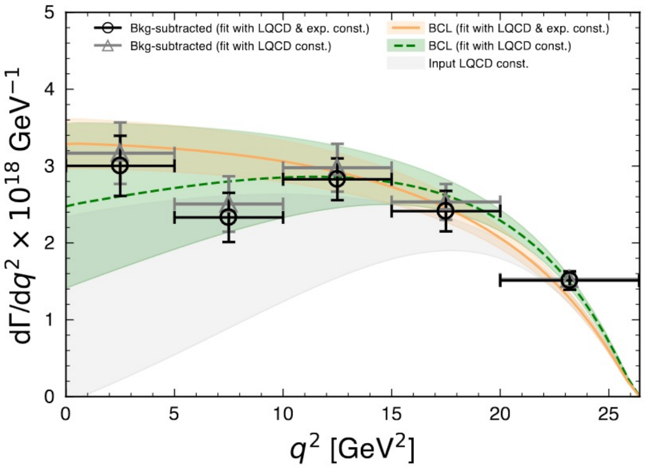


Beauty Decays

First Simultaneous Determination of Inclusive and Exclusive $|V_{ub}|$

BELLE

arXiv:2303.17309

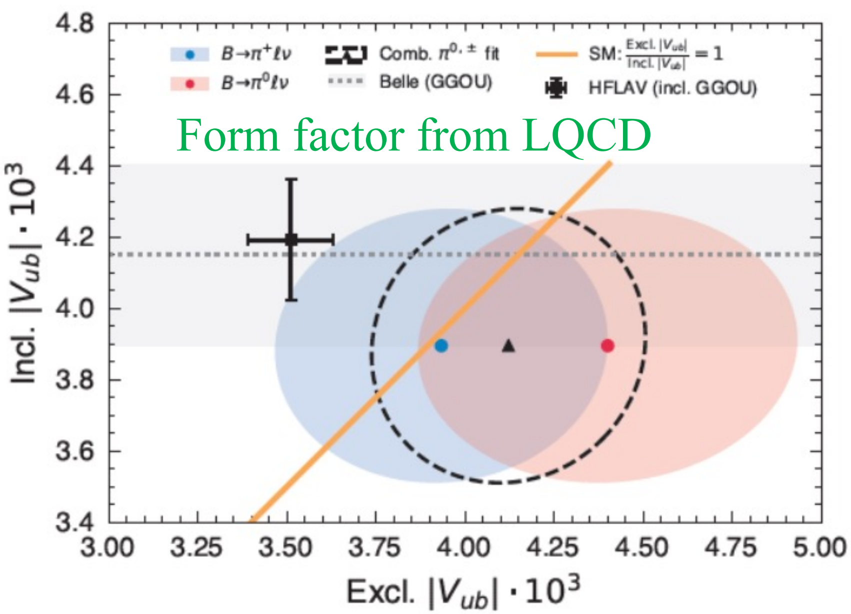


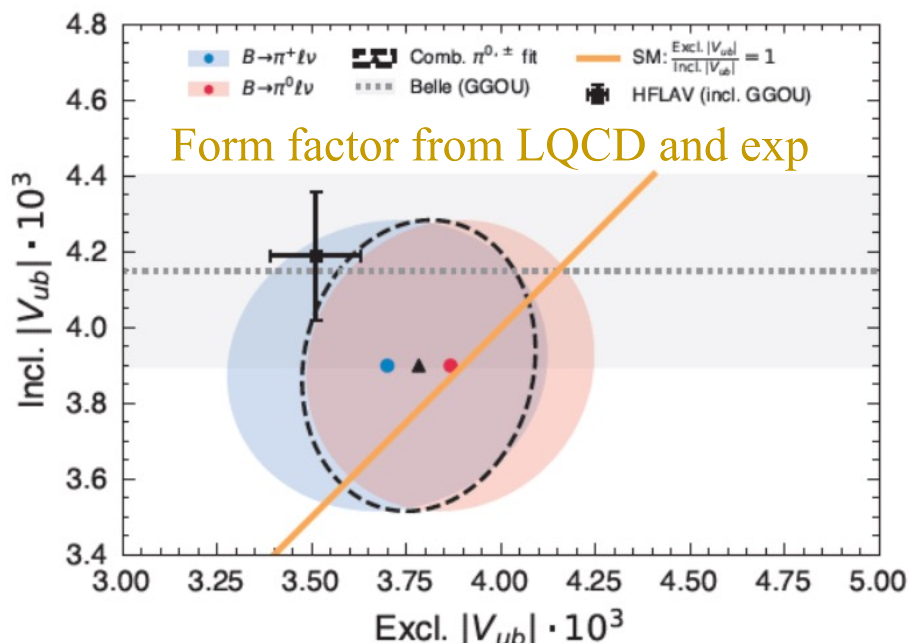
$$|V_{ub}^{\text{excl.}}| = (3.78 \pm 0.23^{\text{stat}} \pm 0.16^{\text{syst}} \pm 0.14^{\text{theo}})\times 10^{-3}$$

$$|V_{ub}^{\text{incl.}}| = (3.90 \pm 0.20^{\text{stat}} \pm 0.32^{\text{syst}} \pm 0.09^{\text{theo}})\times 10^{-3}$$

Correlation = 0.10

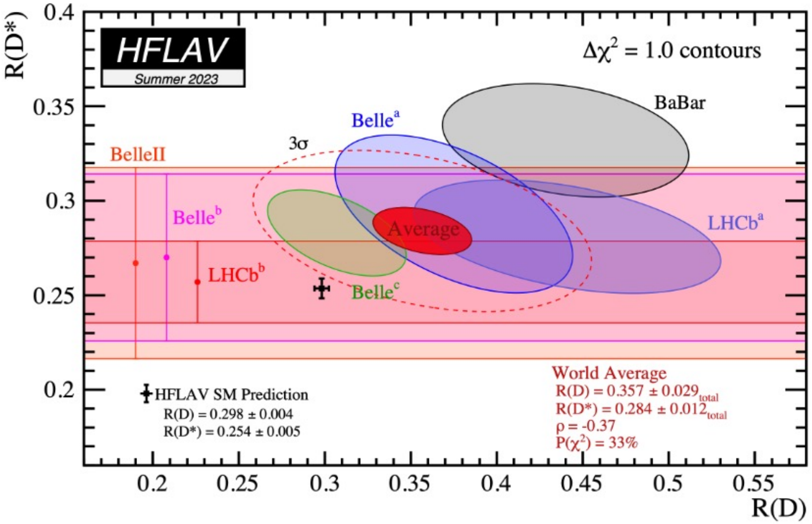
$$|V_{ub}^{\text{excl.}}| \,/\, |V_{ub}^{\text{incl.}}| = 0.97 \pm 0.12^{\text{exp}}$$



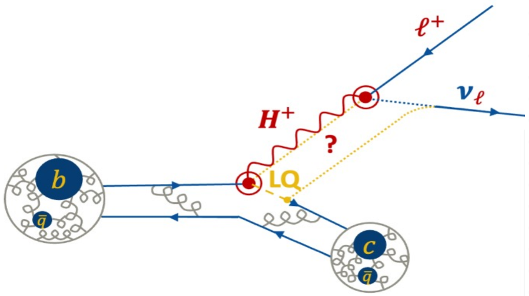


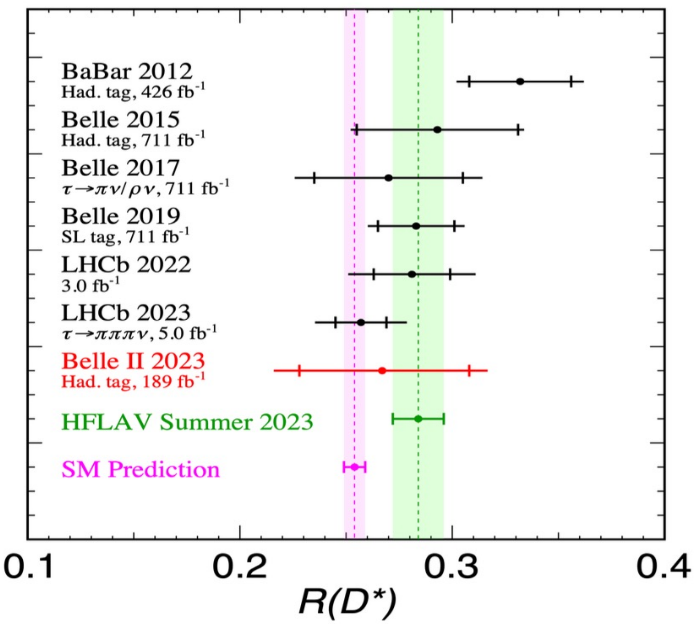
Beauty Decays

❖ Tests of lepton universality, $R(D^{(*)}), R(K^{(*)})$



$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}, (\ell = e \text{ or } \mu)$$





- LHCb: PRD 108 012018 (2023)
  - =>reduce tension $2.49\sigma \to 2.15\sigma$
- Belle II: PRD 108 012018 (2023)
  - => 40% improvement in statistical precision over Belle at the same sample size

LHCb: arXiv 2302.02886

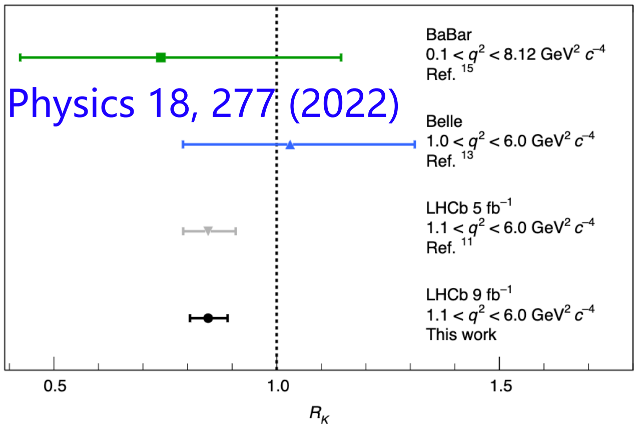
=> simultaneous measurement of $R(D)$ and $R(D^*)$, 1.9σ tension

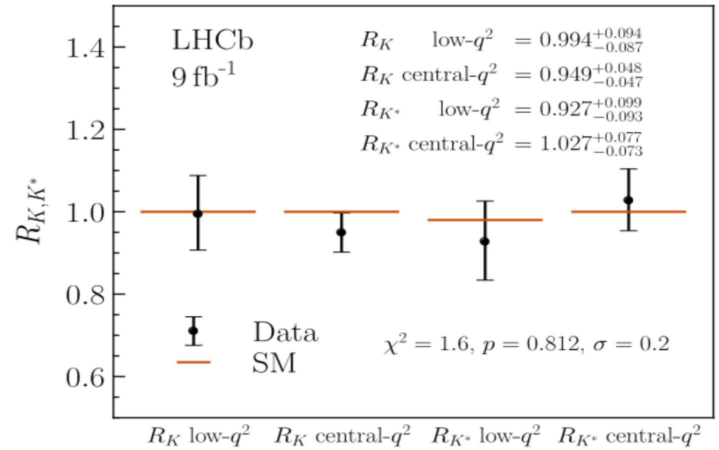
Beauty Decays

❖ Other recent checks:

LHCb: PRL 131 051803 (2023), Phys. Rev. D 108, 032002 (2023)

Nature Physics 18, 277 (2022)





$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}\ (B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}\ (B\to He^+e^-)}{dq^2} dq^2}$$

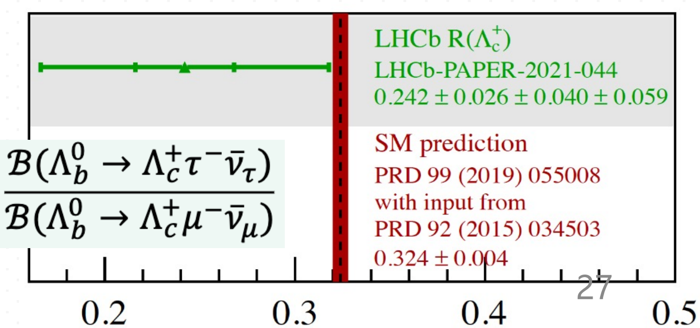
$$R_{K,K^*}(q_a^2, q_b^2) = \frac{\int_{q_a^2}^{q_b^2} \frac{d\Gamma(B^{(+,0)}\to K^{(+,*0)}\mu^+\mu^-)}{dq^2} dq^2}{\int_{q_a^2}^{q_b^2} \frac{d\Gamma(B^{(+,0)}\to K^{(+,*0)}e^+e^-)}{dq^2} dq^2}.$$

BelleII: Phys. Rev. Lett. 131, 051804 (2023)

$$R(X_{e/\mu}) = \mathcal{B}(B \to Xe\nu)/\mathcal{B}(B \to X\mu\nu)$$
$$= 1.007 \pm 0.009 \pm 0.019$$

LHCb: Phys. Rev. Lett. 128, 191803 (2022)

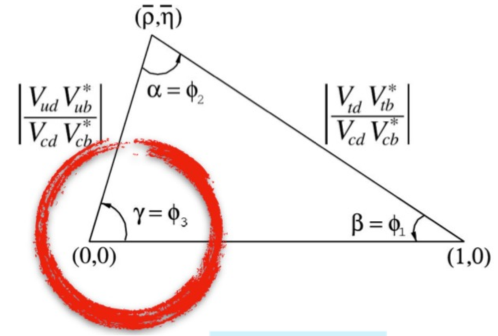
$$R_{\Lambda_c^+} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)}$$

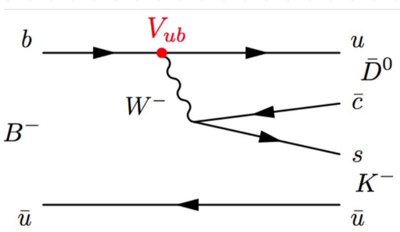


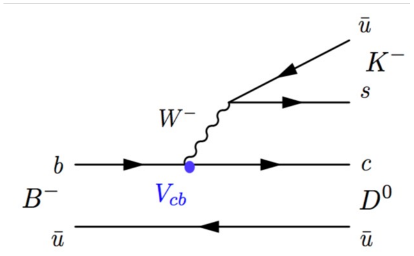
Beauty Decays

Hadronic decay(**Measurement of CKM angle** $\phi_3 = \arg[\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}]$)

- **Theoretical uncertainty on measurement is** $\frac{\delta\phi_3}{\phi_3} \sim 10^{-7}$
- **Test physics beyond SM**
- **CPV in the interference** $b \to c\bar{u}s$ **and** $b \to u\bar{c}s$ **:**







-- $B^0 \to D(\to K_S h^+ h^-)K^{*0}$

LHCb-PAPER-2023-009

- Limited statistics,
- CPV still observed in some bins

$\phi_3 = (49^{+23}_{-18})^\circ$

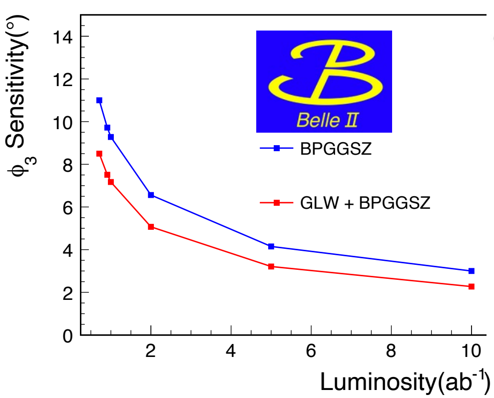
JHEP02(2022)063 $\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ$

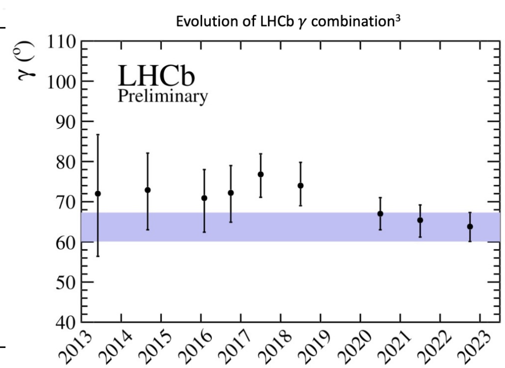
-- $B^- \to D^*(\to D(\to K_S h^+ h^-)\pi^0/\gamma)h^-$

LHCb-PAPER-2023-012 $\phi_3 = (69 \pm 14)^\circ$

-- $B^- \to D(\to K^+K^-\pi^+\pi^-))h^-$

Eur. Phys. J. **C83** (2023) 547 $\phi_3 = (116^{+12}_{-14})^\circ$





Precision in 2013	LHCb 2018	Upgrade I ($50\ fb^{-1}$)	Upgrade II ($300\ fb^{-1}$)
~10−12°	4°	1°	0.35°

~ 1.5° (50 ab^{-1} @Belle II)

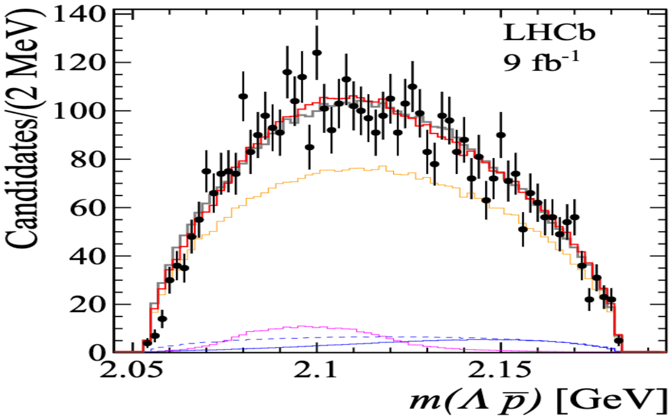
Data limited!

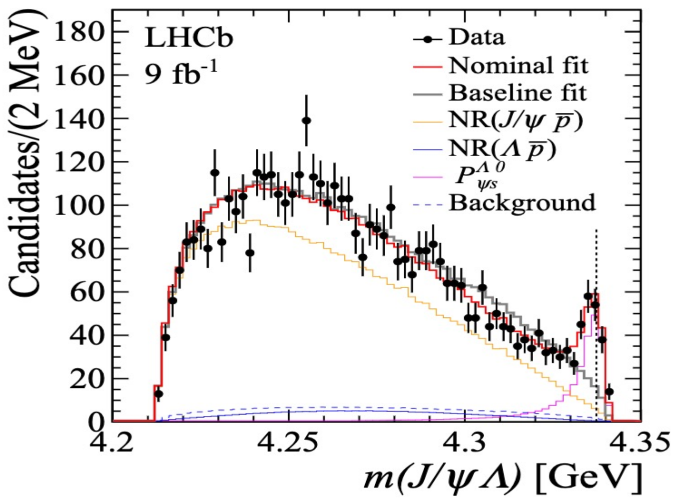
Beauty Decays

Hadronic decay (exotic, light hadron states)

$B^- \to J/\psi \Lambda \bar{p}$

PRL 131 031901 (2023)

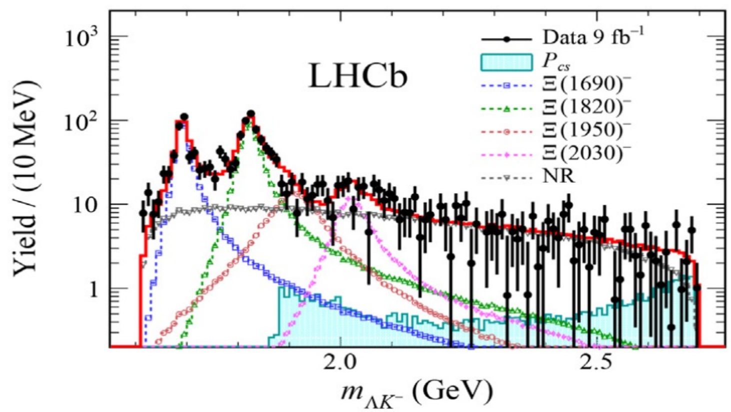


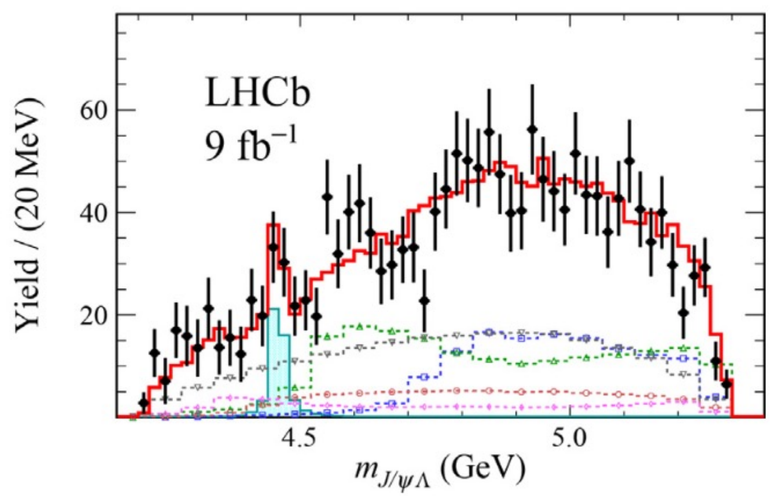


$P_{cs}(4338)$: $\Xi_c^+ \, D^-$ threshold

$\Xi_b^- \to J/\psi \Lambda K^-$

Science Bulletin 66 (2021) 1278



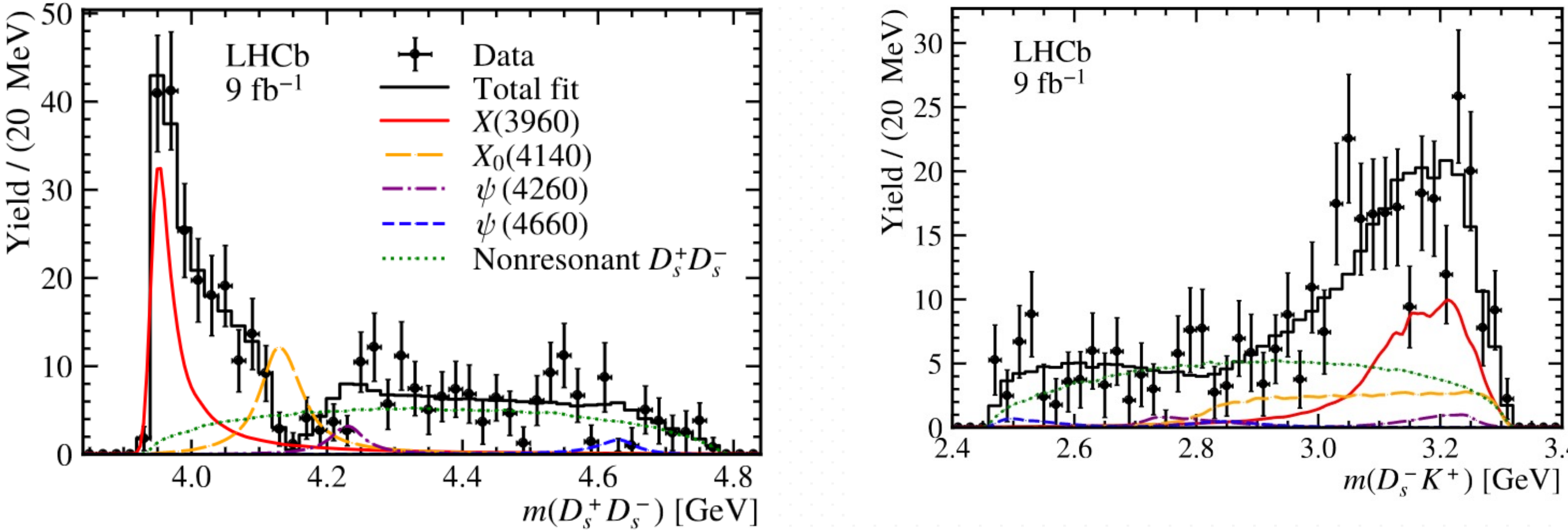


$P_{cs}(4459)$: ~ < $\Xi_c^0 \bar{D}^{*0}$ threshold

Beauty Decays

Hadronic decay (exotic, light hadron states)

$B^+ \to D_s^+ D_s^- K^+$ PRL 131, 071901 (2023)

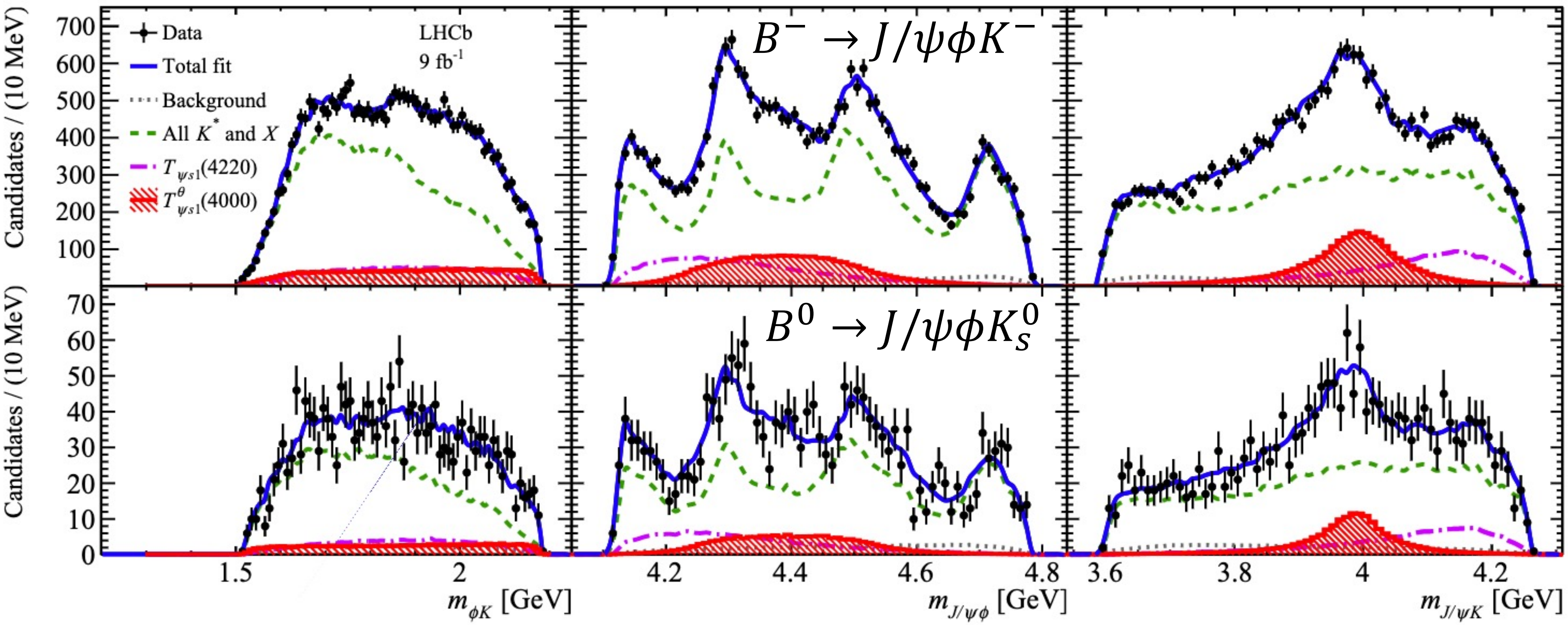


Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	$\mathcal{F}$ (%)	$\mathcal{S}$ (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 11$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 8.0$	12.6 (14.3)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 11$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 7.5$	3.7 (3.9)
$\psi(4260)$	1^{--}	4230	55	$3.6 \pm 0.4 \pm 3.0$	3.1 (3.3)
$\psi(4660)$	1^{--}	4633	64	$2.2 \pm 0.2 \pm 0.5$	2.9 (3.2)
NR	S-wave	-	-	$46.1 \pm 13.2 \pm 11.1$	3.1 (3.4)

Hrongrong Qi, https://indico.itp.ac.cn/event/161/attachments/293/660/2023HAPOF_X3960.pdf

Beauty Decays

Hadronic decay (exotic, light hadron states) arXiv 2301.04899



State	Mass (MeV)	Width (MeV)	Fit fraction (%)	ΔM (MeV)
$T^{\theta}_{\psi s1}(4000)^0$	$3991\,^{+12}_{-10}\,^{+9}_{-17}$	$105\,^{+29}_{-25}\,^{+17}_{-23}$	$7.9 \pm 2.5\,^{+3.0}_{-2.8}$	$-12\,^{+11}_{-10}\,^{+6}_{-4}$

$T^{\theta}_{\psi s1}(4000)^0$: **$4.0\ \sigma$**

Change to $5.4\ \sigma$ when isospin symmetry imposed on $T^{\theta}_{\psi s1}(4000)^{0,\pm}$

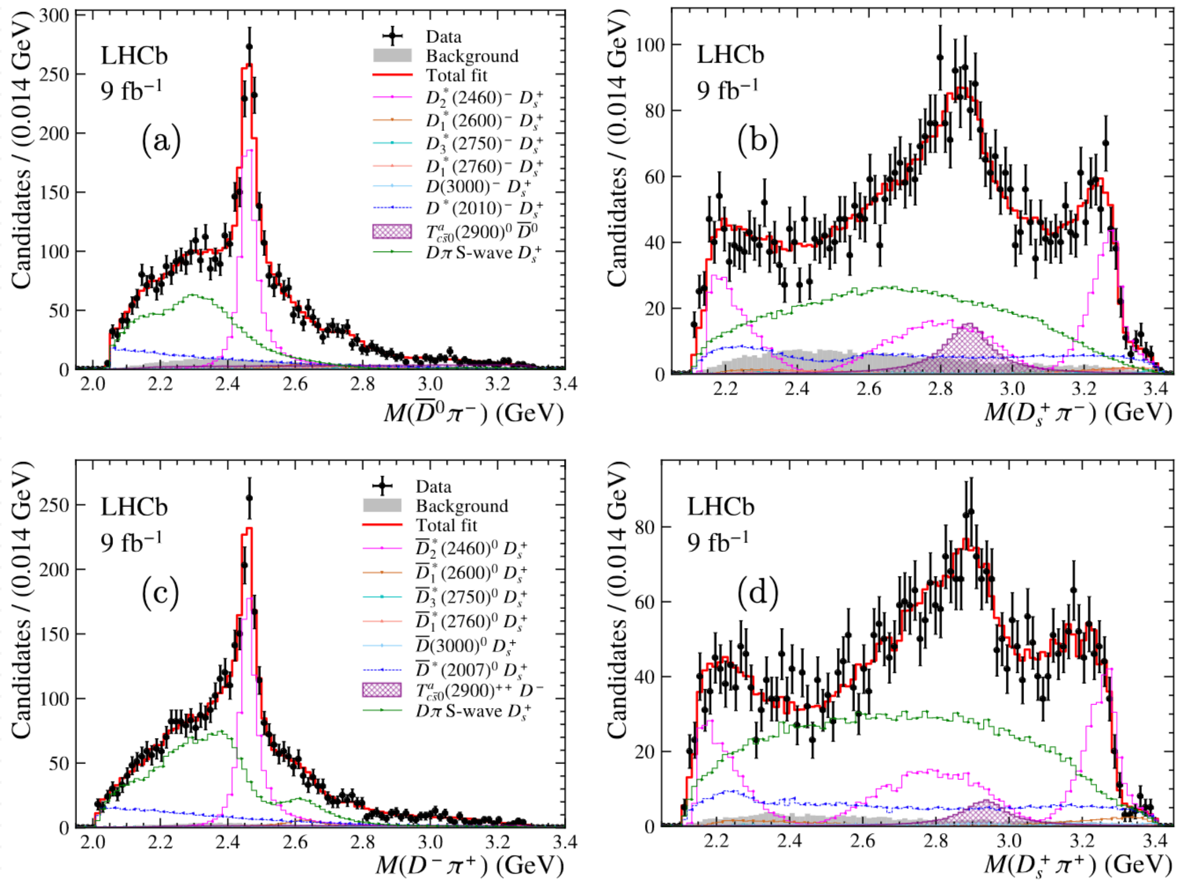
Beauty Decays

Hadronic decay (exotic, light hadron states)

PRD PRD 108 (2023) 012017

$B^0 \to \overline{D}^0 D_s^+ \pi^-$

$B^+ \to D^- D_s^+ \pi^+$

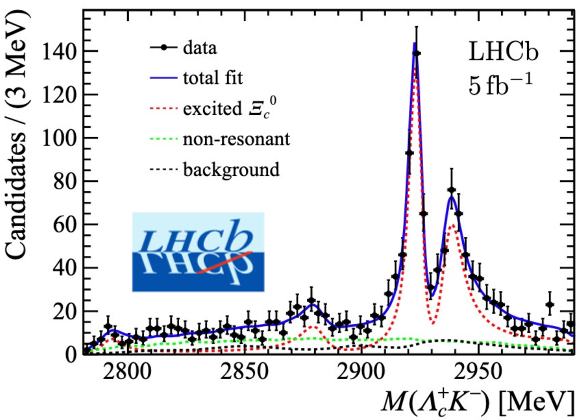


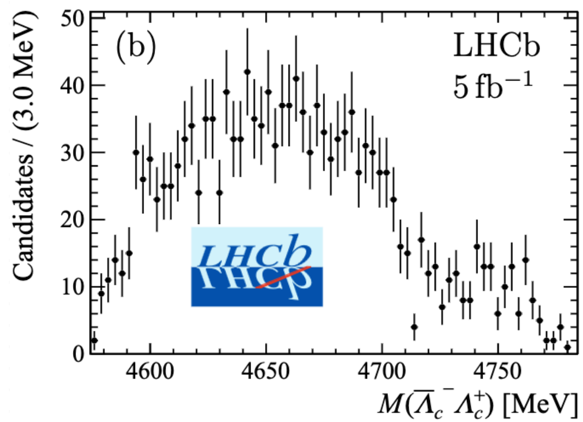
	Particle	Mass (GeV)	Width (GeV)
6.6 σ	$T^a_{c\bar{s}0}(2900)^0$	$2.879 \pm 0.017 \pm 0.018$	$0.153 \pm 0.028 \pm 0.020$
4.8σ	$T^a_{c\bar{s}0}(2900)^{++}$	$2.935 \pm 0.021 \pm 0.013$	$0.143 \pm 0.038 \pm 0.025$

Hadronic decay (heavy hadrons)

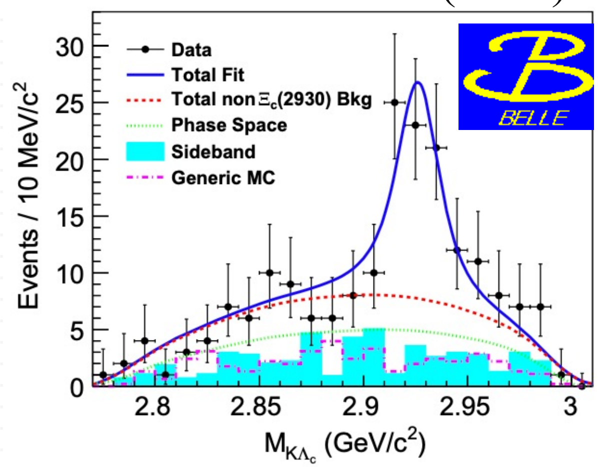
$B^+ \to \Lambda_c^+ \overline{\Lambda}_c^- K^+$

LHCb： PRD 108, 012020 (2023)

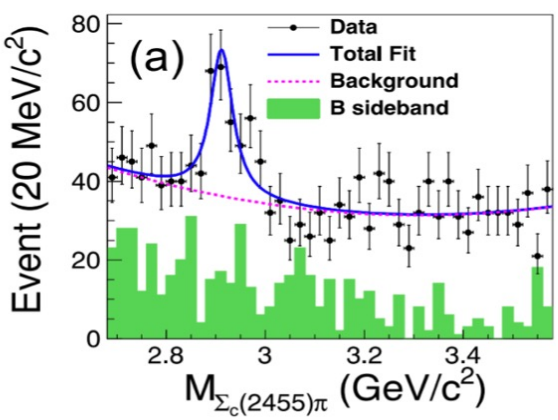




Belle: EPJC 78 252 (2018)



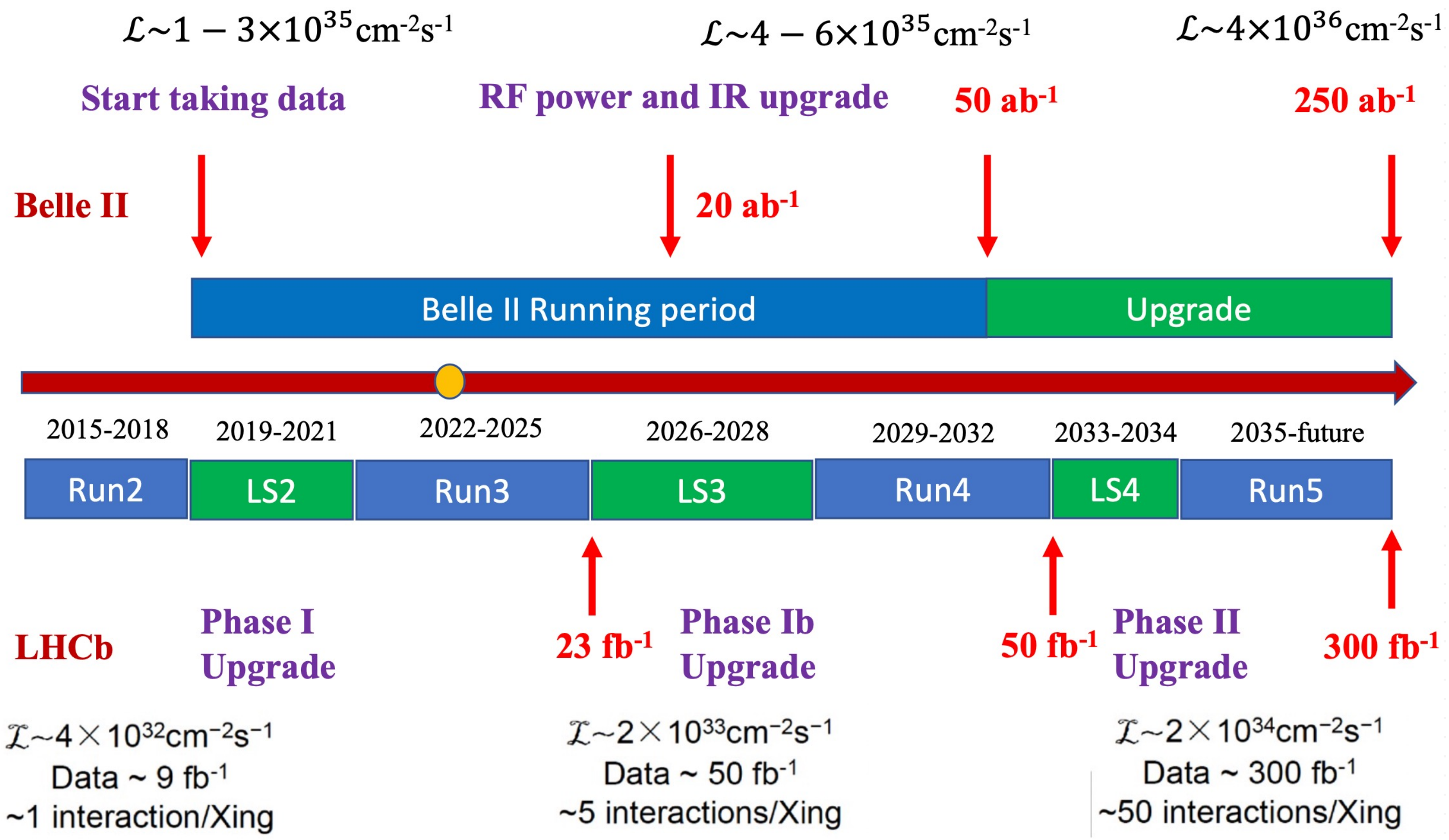
$\overline{\mathrm{B}}^0 \to \Sigma_c(2455)\pi\bar{p}$ Belle： PRL 130, 031901 (2023)



Possible $J^p = \frac{1}{2}^-$, agrees with $\Lambda_c\left(\frac{1}{2}^-, 2P\right)$,

named: $\Lambda_c(2910)$

Future



The more we know, the more we do not know!
路漫漫其修远兮，吾将上下而求索

谢谢大家

CKM	Process	Observables			Theoretical inputs		
$\|V_{ud}\|$	$0^+ \to 0^+\ \beta$	$\|V_{ud}\|_{\text{nucl}}$	$=$	$0.97420 \pm 0 \pm 0.00021$	Nuclear matrix elements		
$\|V_{us}\|$	$K \to \pi\ell\nu$	$\|V_{us}\|_{\text{SL}} f_+^{K\to\pi}(0)$	$=$	0.2165 ± 0.0004	$f_+^{K\to\pi}(0)$	$=$	$0.9681 \pm 0.0014 \pm 0.0022$
	$K \to e\nu$	$\mathcal{B}(K \to e\nu)$	$=$	$(1.582 \pm 0.007) \cdot 10^{-5}$	f_K	$=$	$155.6 \pm 0.2 \pm 0.6$ MeV
	$K \to \mu\nu$	$\mathcal{B}(K \to \mu\nu)$	$=$	0.6356 ± 0.0011			
	$\tau \to K\nu$	$\mathcal{B}(\tau \to K\nu)$	$=$	$(0.6960 \pm 0.0096) \cdot 10^{-2}$			
$\frac{\|V_{us}\|}{\|V_{ud}\|}$	$K \to \mu\nu / \pi \to \mu\nu$	$\frac{\mathcal{B}(K \to \mu\nu)}{\mathcal{B}(\pi \to \mu\nu)}$	$=$	1.3367 ± 0.0029	f_K/f_π	$=$	$1.1959 \pm 0.0007 \pm 0.0029$
	$\tau \to K\nu / \tau \to \pi\nu$	$\frac{\mathcal{B}(\tau \to K\nu)}{\mathcal{B}(\tau \to \pi\nu)}$	$=$	$(6.438 \pm 0.094) \cdot 10^{-2}$			
$\|V_{cd}\|$	νN	$\|V_{cd}\|_{\text{not lattice}}$	$=$	0.230 ± 0.011			
	$D \to \mu\nu$	$\mathcal{B}(D \to \mu\nu)$	$=$	$(3.74 \pm 0.17) \cdot 10^{-4}$	f_{D_s}/f_D	$=$	$1.175 \pm 0.001 \pm 0.004$
	$D \to \pi\ell\nu$	$\|V_{cd}\| f_+^{D\to\pi}(0)$	$=$	0.1426 ± 0.0019	$f_+^{D\to\pi}(0)$	$=$	$0.621 \pm 0.016 \pm 0.012$
$\|V_{cs}\|$	$W \to c\bar{s}$	$\|V_{cs}\|_{\text{not lattice}}$	$=$	$0.94^{+0.32}_{-0.26} \pm 0.13$			
	$D_s \to \tau\nu$	$\mathcal{B}(D_s \to \tau\nu)$	$=$	$(5.55 \pm 0.24) \cdot 10^{-2}$	f_{D_s}	$=$	$247.8 \pm 0.3 \pm 2.0$ MeV
	$D_s \to \mu\nu$	$\mathcal{B}(D_s \to \mu\nu)$	$=$	$(5.39 \pm 0.16) \cdot 10^{-3}$			
	$D \to K\ell\nu$	$\|V_{cs}\| f_+^{D\to K}(0)$	$=$	0.7226 ± 0.0034	$f_+^{D\to K}(0)$	$=$	$0.741 \pm 0.010 \pm 0.012$
$\|V_{ub}\|$	semileptonic B	$\|V_{ub}\|_{\text{SL}}$	$=$	$(3.98 \pm 0.08 \pm 0.22) \cdot 10^{-3}$	form factors, shape functions		
	$B \to \tau\nu$	$\mathcal{B}(B \to \tau\nu)$	$=$	$(1.08 \pm 0.21) \cdot 10^{-4}$	f_{B_s}/f_B	$=$	$1.205 \pm 0.004 \pm 0.006$
$\|V_{cb}\|$	semileptonic B	$\|V_{cb}\|_{\text{SL}}$	$=$	$(41.8 \pm 0.4 \pm 0.6) \cdot 10^{-3}$	form factors, OPE matrix elements		
$\|V_{ub}/V_{cb}\|$	semileptonic Λ_b	$\frac{\mathcal{B}(\Lambda_p \to p\mu^-\bar{\nu})_{q^2>15}}{\mathcal{B}(\Lambda_p \to \Lambda_c\mu^-\bar{\nu})_{q^2>7}}$	$=$	$(0.947 \pm 0.081) \cdot 10^{-2}$	$\frac{\zeta(\Lambda_p \to p\mu^-\bar{\nu})_{q^2>15}}{\zeta(\Lambda_p \to \Lambda_c\mu^-\bar{\nu})_{q^2>7}}$	$=$	$1.471 \pm 0.096 \pm 0.290$
α	$B \to \pi\pi,\ \rho\pi,\ \rho\rho$	branching ratios, CP asymmetries			isospin symmetry		
β	$B \to (c\bar{c})K$	$\sin(2\beta)_{[c\bar{c}]}$	$=$	0.699 ± 0.017	subleading penguins neglected		
$\cos(2\beta)$	$B^0 \to D^{(*)}h^0$	$\cos(2\beta)$	$=$	0.91 ± 0.25			
γ	$B \to D^{(*)}K^{(*)}$	inputs for the 3 methods			GGSZ, GLW, ADS methods		
ϕ_s	$B_s \to J/\psi(KK, \pi\pi)$	$(\phi_s)_{b\to c\bar{c}s}$	$=$	-0.021 ± 0.031			
$V_{tq}^* V_{tq'}$	Δm_d	Δm_d	$=$	$0.5065 \pm 0.0019\ \text{ps}^{-1}$	$\hat{B}_{B_s}/\hat{B}_{B_d}$	$=$	$1.007 \pm 0.013 \pm 0.014$
	Δm_s	Δm_s	$=$	$17.757 \pm 0.021\ \text{ps}^{-1}$	$\hat{B}_{B_s}$	$=$	$1.327 \pm 0.016 \pm 0.030$
	$B_s \to \mu\mu$	$\mathcal{B}(B_s \to \mu\mu)$	$=$	$(2.8^{+0.7}_{-0.6}) \cdot 10^{-9} [\times(1-0.063)]$	f_{B_s}	$=$	$226.0 \pm 1.3 \pm 2.0$ MeV
$V_{td}^* V_{ts}$ and $V_{cd}^* V_{cs}$	ε_K	$\|\varepsilon_K\|$	$=$	$(2.228 \pm 0.011) \cdot 10^{-3}$	$\hat{B}_K$	$=$	$0.7567 \pm 0.0021 \pm 0.0123$
					κ_ε	$=$	$0.940 \pm 0.013 \pm 0.023$

https://indico.cern.ch/event/684284/contributions/2952455/attachments/1719296/2774804/Vale_Silva_3.pdf

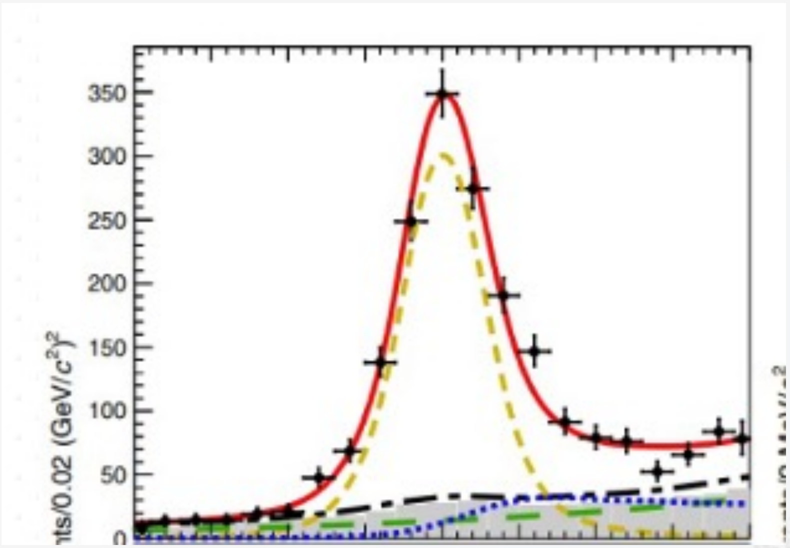
Experiment	Machine	Operation	C.M.	Lumin.	N(D^0)	efficiency	☺advantage/☹disadvantage
CLEO	CESR (e^+e^-)	2003-2008	3.77	0.8 fb^{-1}	2.9 M D^+: 2.3 M	~10-30%	☺ extremely clean environment ☺ pure D-beam, almost no bkg ☺ quantum coherence ☹ no CM boost, no T-dep analyses
			4.18 GeV	0.6 fb^{-1}	0.6 M		
BESIII	BEPC-II (e^+e^-)	2010-2011(2021-)	3.77 GeV	2.92($\rightarrow$ 20) fb^{-1}	10.5($\rightarrow$ 72) M D^+: 8.4 M		
		2016-2019	4.18-4.23 GeV	7.3 fb^{-1}	4.6 M		
		2014+2020	4.6-4.7 GeV	4.5 fb^{-1}	Λ_c^+ : ? M		
					★	★★★	
Belle II	SuperKEKB (e^+e^-)	2019-	10.58 GeV	428+ fb^{-1}	0.6+ G D^+: 0.3 G	~5-10%	☺ clear event environment ☺ high trigger efficiency ☺ high-efficiency detection of neutrals ☺ many high-statistics control samples ☺ time-dependent analysis ☹ smaller cross-section than pp colliders
Belle	KEKB (e^+e^-)	1999-2010	10.58 GeV	1000 fb^{-1}	1.4 G D^+: 0.8 G		
BaBar	PEP-II (e^+e^-)	1999-2008	10.58 GeV	500 fb^{-1}	0.65 G		
					★★	★★	
CDF	Tevatron ($p\bar{p}$)	2002-2011	1960	9.6 fb^{-1}	0.13 T	<0.5%	☺ very large production cross-section ☺ large boost ☺ excellent time resolution ☹ dedicated trigger required
LHCb	LHC (pp)	2011 2012	7 TeV 8 TeV	1.0 fb^{-1} 2.0 fb^{-1}	5.0 T		
		2015-2018	13 TeV	6 fb^{-1}	?		
					★★★	★	

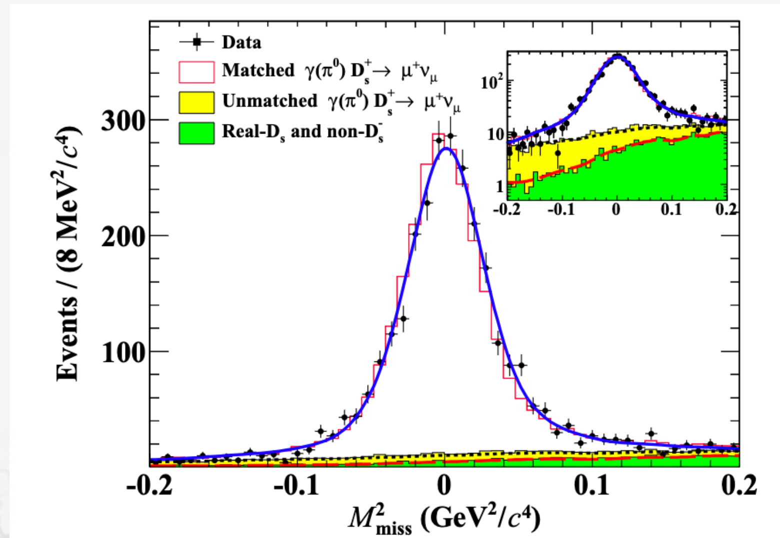
here using $\sigma(D^0\bar{D}^0 @ 3.77\,\text{GeV})$=3.61 nb, $\sigma(D^+D^- @ 3.77\,\text{GeV})$=2.88 nb, $\sigma(D_s^*D_s @ 4.17\,\text{GeV})$=0.967 nb, $\sigma(c\bar{c} @ 10.58\,\text{GeV})$=1.3 nb, $\sigma(D^0 @ CDF)$=13.3 μb, and $\sigma(D^0 @ LHCb)$=1661 μb, mainly referring to *Int. J. Mod. Phys.* *A* **29** *(2014) 24, 14300518.*

Charm Decays

leptonic decay of D_s

$$\mathrm{SM}: R_{D^+} = m_\tau^2\left(1-\frac{m_{\tau^+}^2}{m_{D_q^+}^2}\right)^2 \Big/ m_\mu^2\left(1-\frac{m_\mu^2}{m_{D_q^+}^2}\right)^2 = 2.67$$





Experiment	$E_{\rm cm}$ (GeV)	Reaction chain	$\mathcal{B}$ (%)	$f_{D_s^+}\lvert V_{cs}\rvert$ (MeV)
CLEO [2]	4.170	$e^+e^- \to D_s^\pm D_s^{*\mp}$	$0.565 \pm 0.045 \pm 0.017$	$249.8 \pm 10.0 \pm 3.8 \pm 1.0$
BaBar [5]	10.56	$e^+e^- \to DKX\gamma D_s^-$	$0.602 \pm 0.038 \pm 0.034$	$257.8 \pm 8.2 \pm 7.3 \pm 1.0$
Belle [6]	10.56	$e^+e^- \to DKX\gamma D_s^-$	$0.531 \pm 0.028 \pm 0.020$	$242.2 \pm 6.4 \pm 4.7 \pm 1.0$
BESIII[b] [7]	4.009	$e^+e^- \to D_s^+ D_s^-$	$0.517 \pm 0.075 \pm 0.021$	$238.9 \pm 17.5 \pm 4.9 \pm 0.9$
BESIII[a] [8]	4.178	$e^+e^- \to D_s^\pm D_s^{*\mp}$	$0.549 \pm 0.016 \pm 0.015$	$246.2 \pm 3.6 \pm 3.4 \pm 1.0$
BESIII[b] [9]	4.178-4.226	$e^+e^- \to D_s^\pm D_s^{*\mp}$	$0.535 \pm 0.013 \pm 0.016$	$243.1 \pm 3.0 \pm 3.6 \pm 1.0$
This work[a]	**4.128-4.226**	$\boldsymbol{e^+e^- \to D_s^\pm D_s^{*\mp}}$	$\mathbf{0.5294 \pm 0.0108 \pm 0.0085}$	$\mathbf{241.8 \pm 2.5 \pm 2.2 \pm 1.0}$

Charm Decays

Semi-leptonic decay of $D_{(s)}$

$$\frac{d\Gamma(D_{(s)}\to P\ell^+\nu_\ell)}{dq^2} = \frac{G_F^2|V_{cd(s)}|^2}{24\pi^3} p_{f_0}^3 |f_+(q^2)|^2$$

$$\frac{d^2\Gamma(D_{(s)}\to S\ell^+\nu_\ell)}{ds\,dq^2} = \frac{G_F^2|V_{cd(s)}|^2}{192\pi^4 m_{D_{(s)}}^3} \lambda^{3/2}(m_{D_s}^2, s, q^2)|f_+(q^2)|^2 P(s)$$

$$P(s) = \begin{cases} \frac{g_1\rho_{\pi\pi}}{|m_0^2 - s - i(g_1\rho_{\pi\pi} + g_1\rho_{KK})|^2}, & \text{Flatte for } a_0(980)/f_0(980) \\ \frac{m_{f_0}\Gamma(s)}{(s-m_{f_0}^2)^2 + m_{f_0}^2\Gamma^2(s)}, & \text{RBW for } f_0(500) \end{cases}$$

– **Single pole form**

$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/M_{pole}^2}$$

– **Modified pole model**

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{M_{pole}^2}\right)\left(1 - \alpha\frac{q^2}{M_{pole}^2}\right)}$$

– **ISGW2 model**

$$f_+(q^2) = f_+(q_{max}^2)\left(1 + \frac{r^2}{12}(q_{max}^2 - q^2)\right)^{-2}$$

– **Series expansion model**

$$f_+(t) = \frac{1}{P(t)\Phi(t,\ t_0)} a_0(t_0)(1 + \sum_{k=1}^{\infty} r_k(t_0)\left[z(t, t_0)\right]^k)$$

Charm Decays

Phys. Rev. D. 105, L031101 (2022)

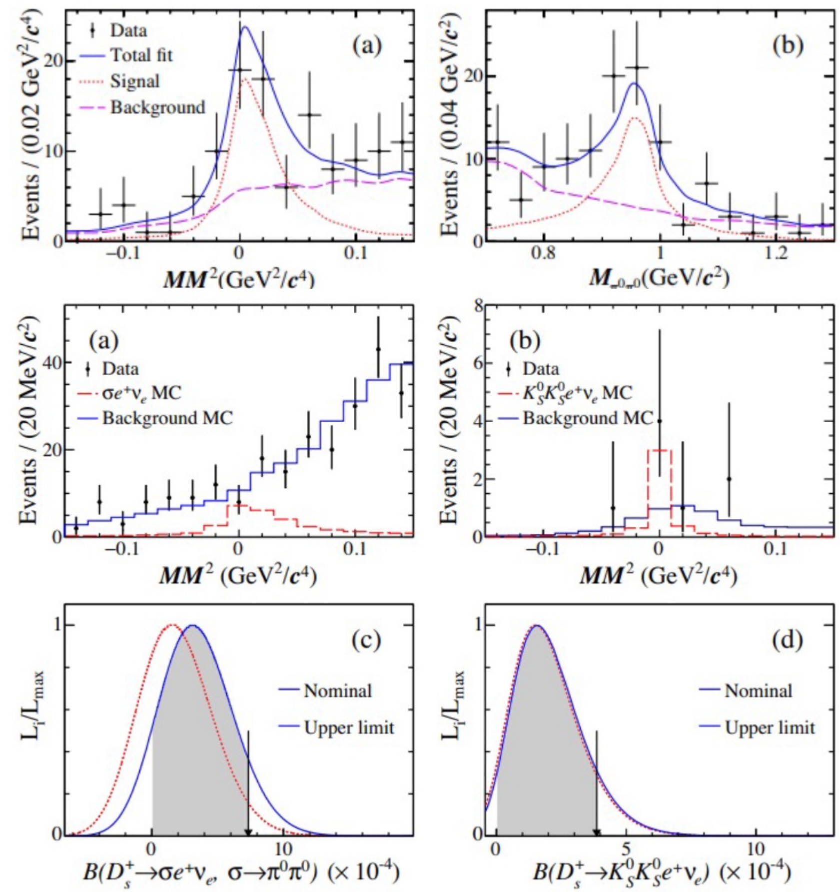
- 6.32 fb^{-1} data @ 4.178 - 4.226 GeV
- $N_{sig}^{f_0(980)} = 54.8 \pm 10.1$ (7.8 σ significance)
- First BFs Measurement:

$$\mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e, f_0(980) \to \pi^0\pi^0)$$
$$= (7.9 \pm 1.4 \pm 0.4)\times10^{-4}$$

- No significant signal and upper limit on BF @90% C.L. :

$\mathcal{B}(D_s^+ \to f_0(500)e^+\nu_e, f_0(500) \to \pi^0\pi^0) < 7.3\times10^{-4}$
$\mathcal{B}(D_s^+ \to K_S^0 K_S^0 e^+\nu_e) < 3.8\times10^{-4}$

- BFs help to understand the nature of the $f_0(500)$ and $f_0(980)$, and test different theoretical calculations.



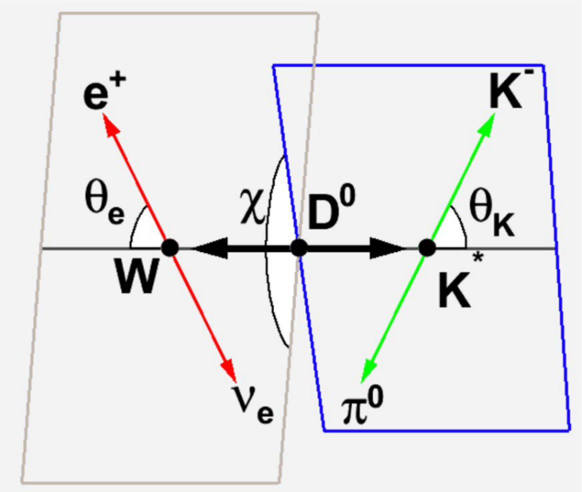
Charm Decays

$$\Gamma(D_{(s)} \to V(S)\ell^+ \nu_\ell) \propto \left|V_{cd(s)}\right|^2 \mathfrak{T}(A_1(q^2), A_2(q^2), V(q^2), \ldots) dm^2 dq^2 d\cos(\theta_h) d\cos(\theta_\ell) d\chi$$

V: ρ, ω, K^*, ϕ
S: $f_0(500), f_0(980)$

Formula: Phys. Rev. **137**, B438 (1965)
Phys. Rev. D **46**,5040 (1992)

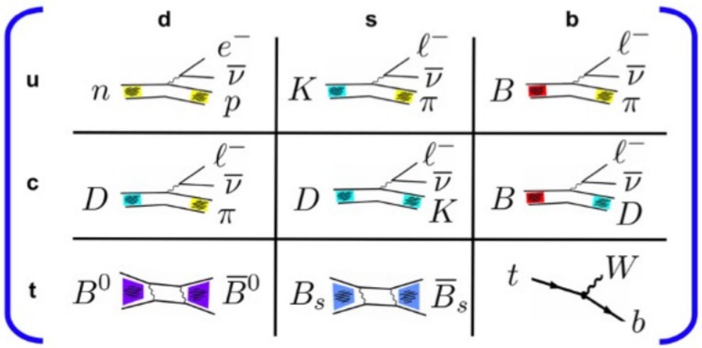
- Decay intensity $\mathfrak{T}$ include *S, P, D* wave components
- Un-binned Maximum likelihood (Based on RooFit)
- FF parameterization (single pole)



$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_A^2} \qquad V(q^2) = \frac{V(0)}{1 - q^2/M_V^2}$$

$$r_V = \frac{V(0)}{A_1(0)} \qquad r_2 = \frac{A_2(0)}{A_1(0)}$$

Charm Decays

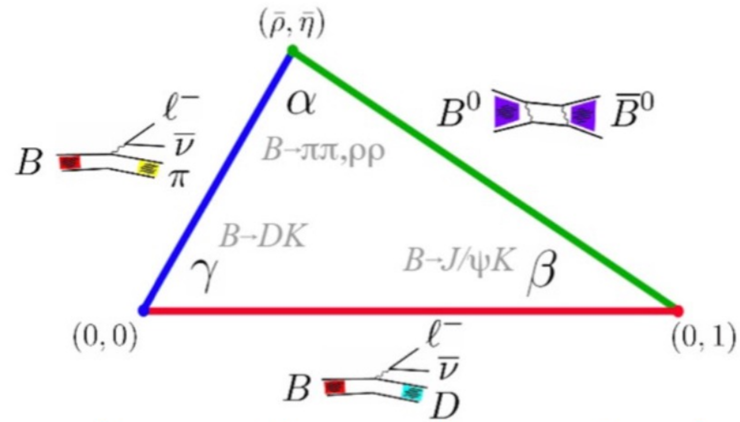


From S. Descotes-Genon

$|V_{cs}|, |V_{cd}|$: (semi-)leptonic charm decays (can be done and should be done, but none has done anything yet)

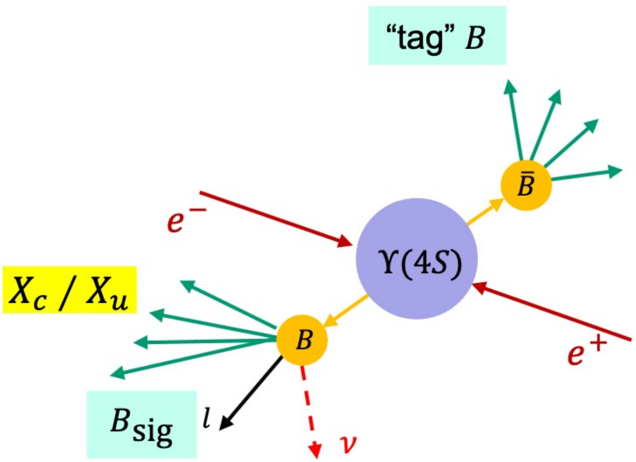
$|V_{ub}|, |V_{cb}|$: (semi-)leptonic B decays

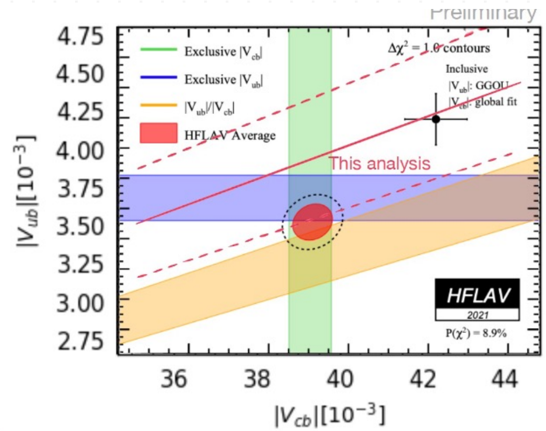
$|V_{td}|, |V_{ts}|$: Δm_d, Δm_s



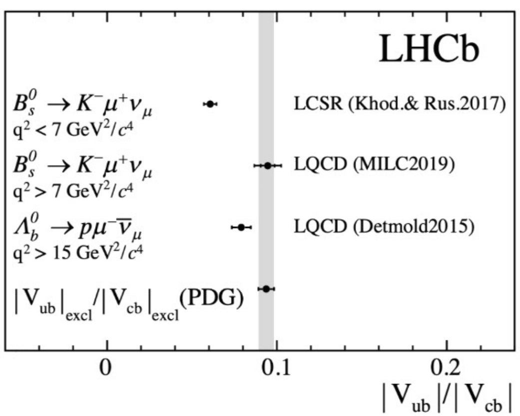
- α: $B\to\pi\pi, B\to\rho\pi, B\to\rho\rho$, isospin analyses
- β: $B\to(\bar c c)K, B\to Dh^0$, time-dependent CP violation
- γ: $B\to DK$, ADS/GLW/GGSZ
- ϕ_s: $B_s^0\to(c\bar c)(KK,\pi\pi)$, time-dependent CP violation
- $-2\beta_s+\gamma$: $B_s\to D_sK$

$$\phi_s^{s\bar s s} = -0.042 \pm 0.075 \pm 0.009 \text{ rad},$$





Belle Preliminary
711 fb^{-1}



$$|V_{ub}|/|V_{cb}|(\text{low}) = 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008\,(D_s) \pm 0.0030\,(\text{FF}),$$

$$|V_{ub}|/|V_{cb}|(\text{high}) = 0.0946 \pm 0.0030(\text{stat})^{+0.0024}_{-0.0025}(\text{syst}) \pm 0.0013\,(D_s) \pm 0.0068\,(\text{FF}),$$

- Belle: inclusive $|V_{ub}|$ measurement complicated
  - ✓ Large "bg" contribution from $B \to X_c l\nu$
- Treat $B \to X_c l\nu$ as part of signal
  - ✓ Simultaneously measure $|V_{ub}|$ & $|V_{ub}|$
  - ✓ $B \to X_u l\nu$ dominate (>86%) in high p_l^B bins

- LHCb: 2 fb^{-1}data at 8 pp collisions
- Observation of $B_s^0 \to K^-\mu^+\nu_\mu l$
  - ✓ Branching fraction measurement

$$R_{\text{BF}} = \frac{\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^-\mu^+\nu_\mu}$$

  - ✓ Determination of $|V_{ub}|$ / $|V_{ub}|$ in low/high q^2 bins

LHCb, PRL126.081804(2021), [arXiv: 2303.17309]

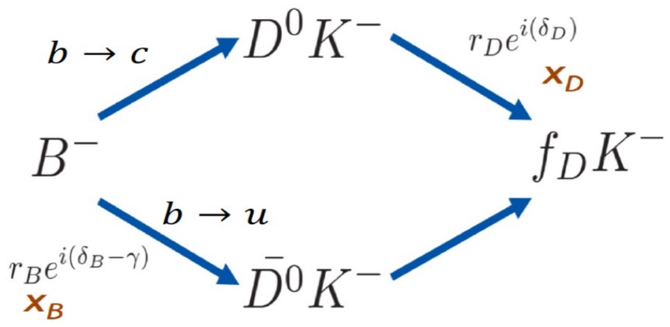
- A few selected recent measurements from Belle(II) and LHCb experiments
  - ✓ Measurements of $|V_{cb}|$ & $|V_{ub}|$
  - ✓ Tests of lepton universality

- Discrepancies ($> 3\sigma$) of measured $|V_{cb}|$ and $|V_{ub}|$ between inclusive and exclusive final states remains
  - ✓ Measurements not limited by statistical precision
  - ✓ Better design analysis choice to reduce systematic uncertainties
  - ✓ Many systematic uncertainties can be reduced with more data
  - ✓ Important to improve precision of theoretical calculations

- Deviation of measured $R_{D^{(*)}}$ from the SM prediction remains ($> 3\sigma$)
  - ✓ More precise measurement expected with more coming data
  - ✓ Measurements as a function of q^2 and angular distributions

- Test muon and electron universality: inclusive and angular distributions
  - ✓ Systematic uncertainties that will further be reduced with more data

- **Semileptonic b-hadron offer reach opportunities to look for NP, expect new results soon**



D^0 and $\bar{D}^0$ decay to same final states to interference

GLW: D = CP eigenstates, e.g. KK, ππ — PLB 253 (1991) 483, PLB 265 (1991) 172

ADS: D = quasi-flavour-specific states e.g. Kπ — PRL 78 (1997) 3257

GGSZ: D = self-conjugate multi(3)-body states e.g. $K_s\pi\pi$ — PRD 68 (2003) 054018

GLS: ADS variant with singly Cabbibo-suppressed decay $D \to K_s K\pi$ — PRD 67 (2003) 071301

time-dependent $B_s \to D_s K$, $B^0 \to D\pi$ etc — Nucl. phys. B 672 (2003) 459

Dalitz (GW) method: $B^0 \to DK\pi$ — PRD 79 (2009) 051301

Sensitivities of γ from many channels, important to measure as many as possible

GLS result (Belle+BelleII!)

- $B^\pm \to DK^\pm$ with $D \to K^0_S K^+ \pi^-$ (SS) or $D \to K^0_S K^- \pi^+$ (OS)
- Measure 4 Acp and 3 BR ratios.
- Get results in full D phase space and in the K*K region (large δ_D).

$$A_{SS}^{DK} = \frac{2r_B^{DK} r_D \kappa_D \sin(\delta_B^{DK} - \delta_D) \sin\phi_3}{1 + (r_B^{DK})^2 r_D^2 + 2r_B^{DK} r_D \kappa_D \cos(\delta_B^{DK} - \delta_D)\cos\phi_3},$$

$$A_{OS}^{DK} = \frac{2r_B^{DK} r_D \kappa_D \sin(\delta_B^{DK} + \delta_D) \sin\phi_3}{(r_B^{DK})^2 + r_D^2 + 2r_B^{DK} r_D \kappa_D \cos(\delta_B^{DK} + \delta_D)\cos\phi_3},$$

$$A_{SS}^{D\pi} = \frac{2r_B^{D\pi} r_D \kappa_D \sin(\delta_B^{D\pi} - \delta_D) \sin\phi_3}{1 + (r_B^{D\pi})^2 r_D^2 + 2r_B^{D\pi} r_D \kappa_D \cos(\delta_B^{D\pi} - \delta_D)\cos\phi_3},$$

$$A_{OS}^{D\pi} = \frac{2r_B^{D\pi} r_D \kappa_D \sin(\delta_B^{D\pi} + \delta_D) \sin\phi_3}{(r_B^{D\pi})^2 + r_D^2 + 2r_B^{D\pi} r_D \kappa_D \cos(\delta_B^{D\pi} + \delta_D)\cos\phi_3}.$$

$$R_{SS}^{DK/D\pi} = R\frac{1 + (r_B^{DK})^2 r_D^2 + 2r_B^{DK} r_D \kappa_D \cos(\delta_B^{DK} - \delta_D)\cos\phi_3}{1 + (r_B^{D\pi})^2 r_D^2 + 2r_B^{D\pi} r_D \kappa_D \cos(\delta_B^{D\pi} - \delta_D)\cos\phi_3},$$

$$R_{OS}^{DK/D\pi} = R\frac{(r_B^{DK})^2 + r_D^2 + 2r_B^{DK} r_D \kappa_D \cos(\delta_B^{DK} + \delta_D)\cos\phi_3}{(r_B^{D\pi})^2 + r_D^2 + 2r_B^{D\pi} r_D \kappa_D \cos(\delta_B^{D\pi} + \delta_D)\cos\phi_3},$$

$$R_{SS/OS}^{D\pi} = \frac{1 + (r_B^{D\pi})^2 r_D^2 + 2r_B^{D\pi} r_D \kappa_D \cos(\delta_B^{D\pi} - \delta_D)\cos\phi_3}{(r_B^{D\pi})^2 + r_D^2 + 2r_B^{D\pi} r_D \kappa_D \cos(\delta_B^{D\pi} + \delta_D)\cos\phi_3}.$$

- 2D Fit ($\Delta E, C'$) of 8 categories ($DK, D\pi$)x(SS, OS)x(+,-)

GLS result (Belle+BelleII!)

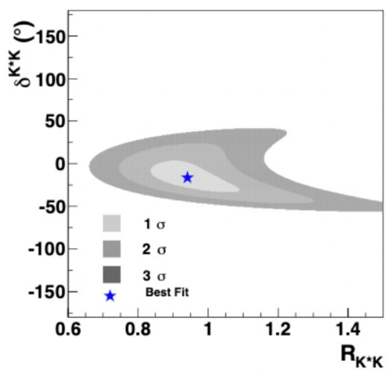
- $B^{\pm} \to DK^{\pm}$ with $D \to K_S^0 K^+ \pi^-$ (SS) or $D \to K_S^0 K^- \pi^+$ (OS)
- Measure 4 Acp and 3 BR ratios.
- Get results in full D phase space and in the K*K region (large δ_D).

In K*K region:

$$A_{SS}^{DK} = 0.055 \pm 0.119 \pm 0.020,$$
$$A_{OS}^{DK} = 0.231 \pm 0.184 \pm 0.014,$$
$$A_{SS}^{D\pi} = 0.046 \pm 0.029 \pm 0.016,$$
$$A_{OS}^{D\pi} = 0.009 \pm 0.046 \pm 0.009,$$
$$R_{SS}^{DK/D\pi} = 0.093 \pm 0.012 \pm 0.005,$$
$$R_{OS}^{DK/D\pi} = 0.103 \pm 0.020 \pm 0.006,$$
$$R_{SS/OS}^{D\pi} = 2.412 \pm 0.132 \pm 0.019,$$

arXiv:2306.02940

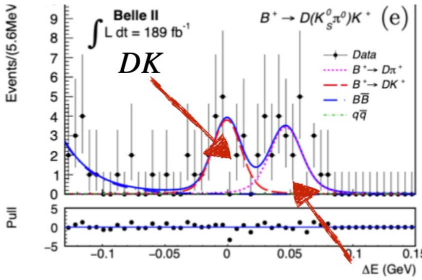
- First Belle/Belle II result from this channel.
- The precision is worse than LCHb's🙁[arXiv:2002.08858]
- With the D information from CLEO-c, will contributed in a combined ϕ_3 from Belle/BelleII. (May get out this summer)



- Model-independent result from CLEO-c.[arXiv:1203.3804]

GLW result (Belle+BelleII!)

- $B^{\pm} \to DK^{\pm}$ with $D \to K_S^0\pi^0$ (CP-odd) or $D \to K^+K^-$ (CP-even)

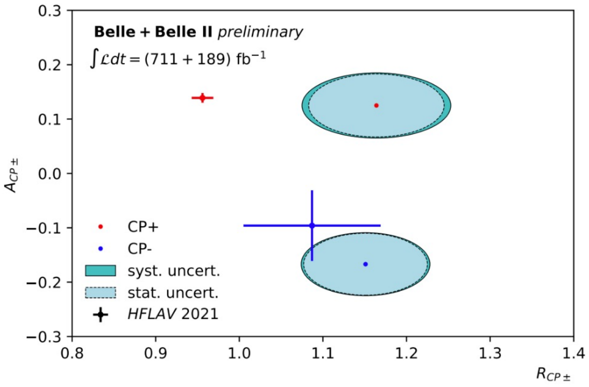


$$R_{CP\pm} = \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D^0K^-) + \mathcal{B}(B^+ \to \bar{D}^0K^+)}, = 1 + r_B^2 + 2\eta_{CP} r_B \cos(\delta_B)\cos(\phi_3),$$

$$A_{CP\pm} = \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) - \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}, = 2\eta_{CP} r_B \sin(\delta_B)\sin(\phi_3)/R_{CP\pm}.$$

- 2D Fit $(\Delta E, C')$ of 6 categories $(DK, D\pi)$x$(K_S^0\pi^0, K^+K^-, K^-\pi^+)$

Large Rcp+ than W.A.
Competitive Rcp- and Acp- with W.A.



	68.3% CL	95.4% CL
	[8.5, 16.5]	[5.0, 22.0]
ϕ_3 (°)	[84.5, 95.5]	[80.0, 100.0]
	[163.3, 171.5]	[157.5, 175.0]
r_B	[0.321, 0.465]	[0.241, 0.522]

$$\mathcal{R}_{CP+} = 1.164 \pm 0.081 \pm 0.036,$$
$$\mathcal{R}_{CP-} = 1.151 \pm 0.074 \pm 0.019,$$
$$\mathcal{A}_{CP+} = (+12.5 \pm 5.8 \pm 1.4)\%,$$
$$\mathcal{A}_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%.$$

3.5σ

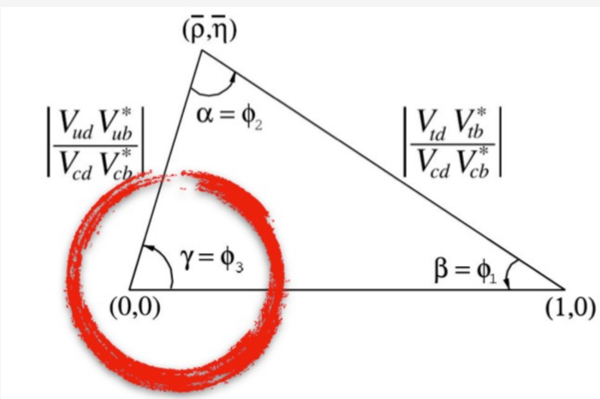
world average: $\phi_3(\circ) = 66.2^{+3.4}_{-3.6}$ $r_B = 0.0996 \pm 0.0026$

Measurement of CKM angle ϕ_3

- Theoretical uncertainty on measurement is $\frac{\delta\phi_3}{\phi_3} \sim 10^{-7}$

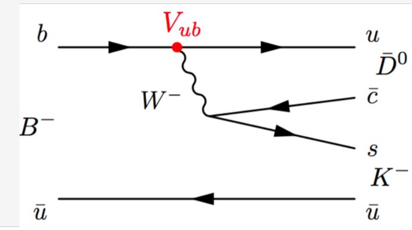
arxiv:1308.5663

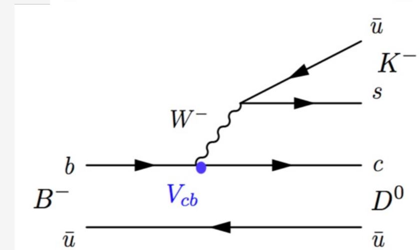
- Test physics beyond SM
- CPV in the interference $b \to c\bar{u}s$ and $b \to u\bar{c}s$:



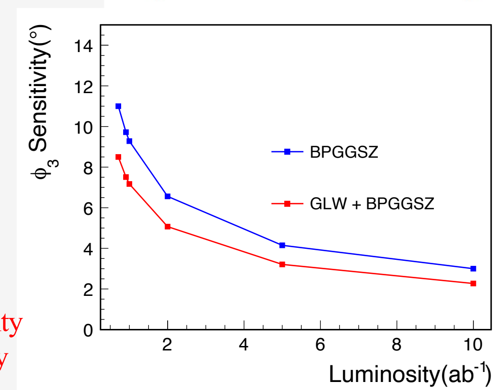
$$\frac{A^{suppr.}[B^- \to \overline{D^0}K^-]}{A^{favor.}[B^- \to D^0K^-]} = r_B e^{i(\delta_B - \phi_3)}$$

$$\phi_3 = \arg\left[\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$





- Foreseen precision of ϕ_3 is expected (current world-average $\delta\phi\sim4°$) with the future Belle II dataset



The expected uncertainty of ϕ_3 versus luminosity

Belle II Measurements of CKM angle ϕ_3

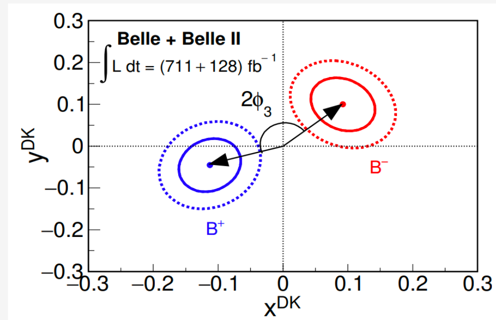
- **(ΔE, C′) 2D simultaneous fit for all methods**
- **GGSZ method with $B^- \to D(\to K_S h^+ h^-)h^-$ decays**

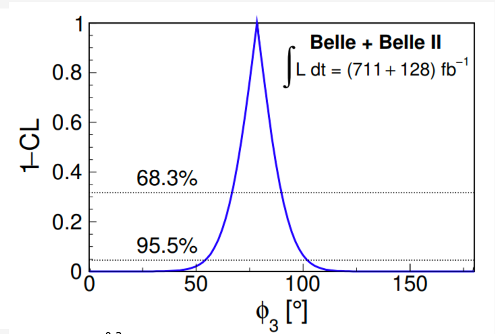
JHEP02(2022)063

-- The CP observables of interests

$x_- = +(9.24 \pm 3.27 \pm 0.17 \pm 0.23)\times 10^{-2}$
$x_+ = -(11.28 \pm 3.15 \pm 0.18 \pm 0.22)\times 10^{-2}$
$y_- = +(10.00 \pm 4.20 \pm 0.23 \pm 0.67)\times 10^{-2}$
$y_+ = -(4.55 \pm 4.20 \pm 0.11 \pm 0.55)\times 10^{-2}$

$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ$

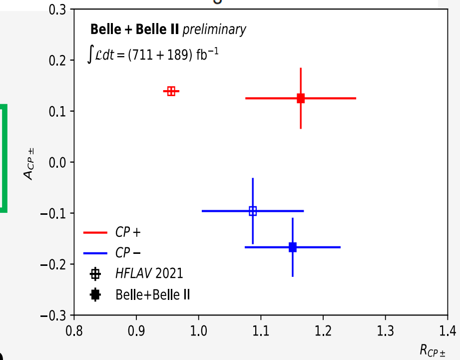




- **GLW method** $A_{CP\pm} = \pm 2 r_B \sin\delta_B \sin\phi_3 / R_{CP\pm}$ $\quad R_{CP\pm} = 1 + r_B^2 \pm 2 r_B \cos\delta_B \cos\phi_3$

arXiv:2308.05048

$A_{CP+} = (+12.5 \pm 5.8(stat.) \pm 1.4(syst.))\%$ $\quad R_{CP+} = 1.164 \pm 0.081(stat.) \pm 0.036\,(syst.)$
$A_{CP-} = (-16.7 \pm 5.7(stat.) \pm 0.6(syst.))\%$ $\quad R_{CP-} = 1.151 \pm 0.074(stat.) \pm 0.019\,(syst.)$



- **GLS method with $B^- \to D(\to K_S K^\pm \pi^\mp)h^-$ decays** arXiv:2306.02940
  - 7 CP observables: 4 asymmetries, 3 BRs ratios
  - Measurement performed in full D phase space and in the enhanced-interference $D \to K^* K$ region
  - These results can provide constraint on ϕ_3

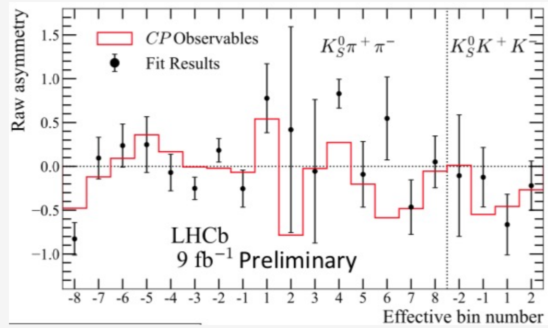
LHCb Measurements of CKM angle ϕ_3

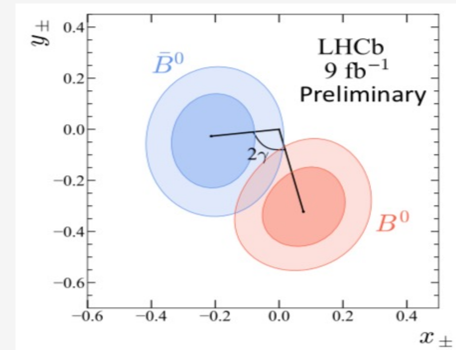
- GGSZ method

  -- $B^0 \to D(\to K_S h^+ h^-)K^{*0}$

  - Limited statistics,
  - CPV still observed in some bins

  $\phi_3 = (49^{+23}_{-18})^\circ$

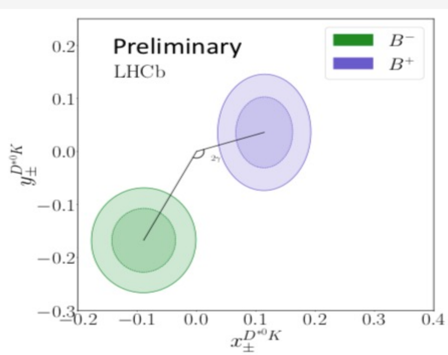




LHCb-PAPER-2023-009

-- $B^- \to D^*(\to D(\to K_S h^+ h^-)\pi^0/\gamma)h^-$

LHCb-PAPER-2023-012



- Opposite CPV between $D^{*0} \to D\pi$ and $D^{*0} \to D\gamma$
- Irreducible bkg
- 2D invariant mass fit

$\phi_3 = (69 \pm 14)^\circ$

-- $B^- \to D(\to K^+K^-\pi^+\pi^-))h^-$

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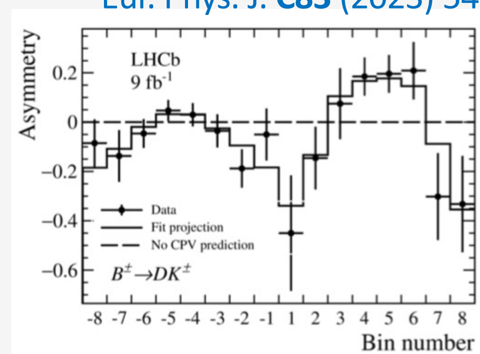

- Measured firstly
- Complicated binning scheme

$\phi_3 = (116^{+12}_{-14})^\circ$