

Personal perspectives on b quark weak decays

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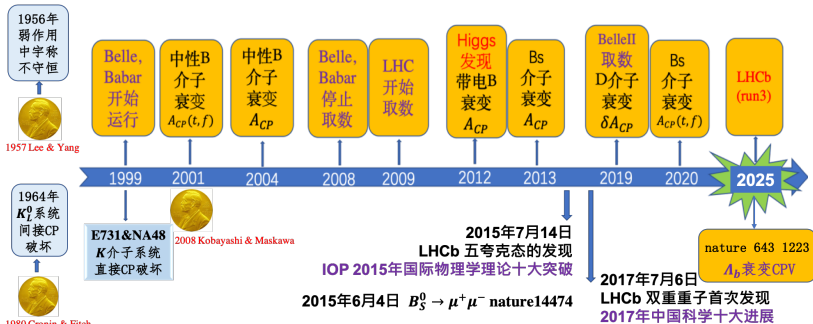
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LHCb has become a general purpose detector

- CKM, CPV and rare decays in b and c hadrons
 - Indirect search of BSM via precise measurements
- precise QCD + EW
- hadron spectroscopy
- heavy-ion and fixed-target physics
- direct search of new physics dark sector, ...
- this talk focus on precision calculations of b quark weak decays

B physics and CP Violation

- "Matter \neq Antimatter" indicates the interaction with CPV
- Heavy flavour physics (HFP) provides many processes with CPV although it is inadequate and new mechanism of CPV is imminent
- Great running of (super) B factories(1999-) and LHC(2009-)



How about the branching fractions ?

Processes	Exp. Precision (10^{-6})	The. Precision (10^{-6})	Physics Goals
$B_{(s)} \rightarrow \gamma\gamma$	$< 0.33, < 3.1$	$0.05 \pm 0.04, 2.1 \pm 1.6$ [Bosch 02, Qin 23]	$C_{7\gamma}, \gamma$ angle, B DAs
$B \rightarrow X_d\gamma, X_s\gamma$	$9.2 \pm 3.0, 349 \pm 19$	$17.36^{+1.2}_{-2.2} \quad 336 \pm 23$ [Czakon 15, Misiak 15]	$C_{7\gamma}, NP$
$B \rightarrow X_S II$ {[1,6], $>14.4 \text{ GeV}^2$ }	$1.58 \pm 0.37, 0.48 \pm 0.1$	$1.62 \pm 0.09, 0.25 \pm 0.07$ [Huber 15]	C_9, C_{10}, LD, NP perturbative regions
$B \rightarrow K II, K^* II$	$0.33 \pm 0.03, 0.99 \pm 0.12$	perturbative + $J/\Psi, \Psi'$	$A_{CP}, A_{FB}, P'_5 \uparrow$
$B^+ \rightarrow X_u l^+ \nu$ $B^+ \rightarrow X_c e^+ \nu$ $B \rightarrow \pi^- l^+ \nu$ $B \rightarrow D^- l^+ \bar{\nu}$	$(0.165 \pm 0.021) \times 10^4$ $(10.8 \pm 0.4) \times 10^4$ 150 ± 5 $(2.10 \pm 0.07) \times 10^4$	$(0.19 \pm 0.02) \times 10^4$ $(10.63 \pm 0.15) \times 10^4$ [Finauri 24] $\mathcal{O}(10\%)$ uncertainty of FFs	$ V_{ub} , V_{cb} $ $V_{ub}, V_{cb} , R_{D^{(*)}}$
$B \rightarrow \pi^+ \pi^- l^+ \nu$	23.9 ± 6.2	19.1 ± 4.5 [SC 25] (0.6, 0.9)&[0, 4]	$ V_{ub} , \pi\pi$ spectrum
$B^- \rightarrow \bar{D} K^-$	$360 \pm 24, 364 \pm 15$	204^{+239}_{-104} [Piscopo 23]	γ angle
$B \rightarrow \pi^0 \pi^0$ $B \rightarrow \pi^0 \rho^0$ $B \rightarrow \rho^0 \rho^0$ $B \rightarrow K_S \pi^0$ $B \rightarrow K_S \rho^0$ $B \rightarrow K^{*0} \rho^0$	1.55 ± 0.17 2.0 ± 0.5 0.96 ± 0.15 10.1 ± 0.4 3.4 ± 1.1 3.9 ± 1.3	0.23 ± 0.05 0.32 ± 0.12 0.54 ± 0.18 [Chai 22] 7.38 ± 2.15 3.64 ± 0.68 3.37 ± 0.58 [Chai 22]	α angle isospin relation \uparrow time-dependent CPV penguin-dominated
$B \rightarrow p\bar{p}$ $B \rightarrow p\bar{p}p\bar{p}$	$(1.27 \pm 0.14) \times 10^{-2}$ $(2.2 \pm 0.4) \times 10^{-2}$	$(1.47^{+2.19}_{-0.56}) \times 10^{-2}$ [Chua 14,17] $(2.2 \pm 0.56) \times 10^{-2}$ [Hsiao 23]	baryon CPV tree-dominated
$\Lambda_b \rightarrow p\pi, pK$	$4.6 \pm 0.8, 5.5 \pm 1.0$	$3.34^{+2.90}_{-1.71}, 2.83^{+3.30}_{-1.59}$ [Han 25]	nonzero spin
$\Lambda_b \rightarrow pK\pi\pi$	51 ± 5	?	baryon CPV

Overview

I Low energy effective hamiltonian and Factorization approaches

II Towards to high precision

i CP Violations

ii $|V_{ub}|$ and $\pi\pi$ spectrum

III Conclusion

Low energy effective hamiltonian and Factorization approaches

Low energy effective hamiltonian

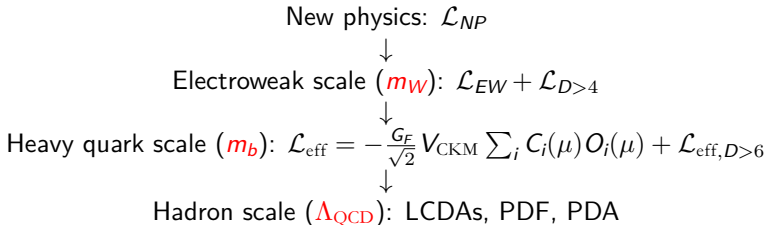
- No direct evidence of BSM due to the **mass gap**
 - NP is either very heavy or light and weakly coupled to the SM
- Use **Effective Field Theories** and **Data** to bridge the gap

- describe heavy NP via high dimension operators
- use data (electroweak, flavor) to constrain the Wilson coefficients

$$C_g(q^2) = \underbrace{C_g^{SM}}_{\text{known}} + \underbrace{Y(q^2)}_{\text{parametrized}} + \underbrace{Y(q^2)}_{\text{possibly unaccounted for}} + \underbrace{C_g^{NP}}_{\text{what we would like to know}}$$

Disentangling long-distance and NP in $b \rightarrow s\mu\mu$

- Roadmap of the low energy EFT of heavy flavor decays



Low energy effective hamiltonian

- derive the low energy effective Hamiltonian by integrating over m_W

$$\begin{aligned} \mathcal{A} &= -\frac{G_F}{\sqrt{2}} V_{ud}^* V_{ub} (\bar{u}b)_{V-A} \frac{M_W^2}{k^2 - M_W^2} (\bar{d}u)_{V-A} \\ &= \frac{G_F}{\sqrt{2}} V_{ud}^* V_{ub} (\bar{u}b)_{V-A} (\bar{d}u)_{V-A} \left(1 + \mathcal{O}\left(\frac{k^2}{M_W^2}\right) \right). \end{aligned}$$

$$\mathcal{H}_{eff}^0 = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{ub} (\bar{u}b)_{V-A} (\bar{d}u)_{V-A} + \text{High D Operatoes,}$$



[Buchalla 1996]

$b \rightarrow \bar{u}ud$

- product of two charged currents \sim a series of local operators O_i with the weighted coefficients C_i

$$\mathcal{H} \rightarrow \mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \left\{ \xi_u \sum_{i=1,2} C_i(\mu) O_i^u(\mu) - \xi_t \sum_{i=3}^{10} C_i(\mu) O_i(\mu) \right\},$$

$$\mathcal{A}(B \rightarrow M_1 M_2) = \frac{G_F}{\sqrt{2}} \sum_i C_i V_i \langle M_1 M_2 | O_i | B \rangle,$$

• 弱作用标度 $\mathcal{O}(m_Z)$ 的动力学由 $C_i(\mu)$ 描述

• $\mathcal{O}(m_b)$ 标度的动力学
由四费米有效算符 $O_i(\mu)$ 描述

• 强子能标 $\mathcal{O}(\Lambda_{\text{QCD}})$ 的动力学由强子波函数描述

- dynamics at the scale $\mathcal{O}(m_W)$ is absorbed into Wilson coefficients $C_i(\mu)$

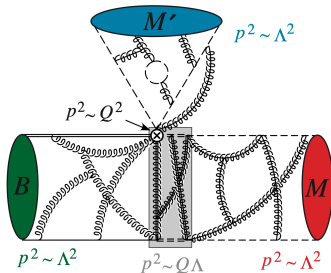
- $C_i \sim$ match the \mathcal{L}_{eff} with the full theory of weak decays [Ma '80, Inami&Lim '81, Clements '83]
- the NLO QCD/QED corrections to C_i has been finished [Buchalla, 1996, Rev. Mod. Phys]
- the NNLL program [Gorbahn, Haisch '04; Misiak, Steinhauser '04]

Factorization approaches $\langle MM'|O_i|B\rangle$

- the rest goes into the four fermion effective operators $O_i(\mu)$
- the key is to calculate the hadron matrix element $\langle MM'|O_i|B\rangle$

see the talks given by Y.L. Shen tomorrow, by Y. Li and X.Q. Li in the past workshops

- a multi-scale QCD & QED problem



- **QCD symmetry:** isospin, U spin, V spin, $SU(3)_F$ [Zeppenfeld, '81] [London, Gronau, Rosner, He, Chiang, Cheng et al.]
- **Factorization-assisted topological-amplitude approach (FAT)** universal decay amplitudes to be determined by data [Li, Lü, Yu '12, Qin, Li, Lü, Yu '14]
- **Naive factorization:** $\sim F_{B \rightarrow M} \otimes f_{M'}$ [Bauer, Stech, Wirbel '85, '87]
- **Generalized factorization:** QCD corrections from $O_{i=1, \dots, 10}$ [Ali, Kramer, Lü '98, '99]
- **QCD factorization (QCDF):** VC to $\mathcal{M}_{t,p}$ + corrections to spectator scattering [Beneke, Buchalla, Neubert, Sachrajda '01]
- **Soft-collinear effective theory (SCET):** introduces different fields in different energy regions, simple kinematics but complicated dynamics with several typical scales [Bauer, Fleming, Pirjol, Stewart '01, Beneke, Chapovsky, Diehl, Feldmann, '02]
- **Light-cone sum rules (LCSRs):** redundant formalism, hard for phenomena [Khodjamirian '01, '03, '05]
- **Perturbative QCD (PQCD):** pick up the transversal momentum to regularize end-point singularity, resummations, prediction of CPV [Keum, Li '01, Sanda, Lü, Yang '01]

Towards to high precision

- i. CPV: $K\pi$ puzzle and VV channels, $\Lambda_b \rightarrow p\pi, pK$
- ii. $|V_{ub}|$, B_{I4} decays and $\pi\pi$ spectrum

$K\pi$ puzzle

$$\begin{aligned}\sqrt{2}\mathcal{A}(\pi^0 K^-) &= \lambda_p A_{\pi K} [\delta_{pu}\alpha_1 + \hat{\alpha}_4^p + \alpha_{4,EW}^p] + \lambda_p A_{K\pi} \left[\delta_{pu}\alpha_2 + \frac{3}{2}\alpha_{3,EW}^p \right] + \dots, \\ \sqrt{2}\mathcal{A}(\pi^+ K^-) &= \lambda_p A_{\pi K} [\delta_{pu}\alpha_1 + \hat{\alpha}_4^p + \alpha_{4,EW}^p] + \dots\end{aligned}$$

- $\lambda_p = V_{pb}V_{ps}^*$ with $p = u, c$, $A_{M_1 M_2} = f_{M_2} F_{B \rightarrow M_1}$
- \dots denotes the power-suppressed annihilation topologies
- the $\Delta S = 1$ amplitudes are dominated by the **charm penguin topology** $\hat{\alpha}_4^c$
- non-zero CPV is generated via its interference with $\propto \lambda_u$
- consider the color-allowed tree topology $\propto \alpha_1$ **by neglecting the other topologies**
 $\Delta A_{K\pi} = A_{CP}^{\pi^0 K^-} - A_{CP}^{\pi^+ K^-} = 0$ [M. Beneke and M. Neubert, NPB 675 (2003) 333]
- the observed value is $\Delta A_{K\pi} = (11.0 \pm 1.2)\%$, the so-called **$K\pi$ puzzle**
- a possible NP hint to the electroweak penguin amplitude $\alpha_{3,EW}^c$?
- remaining topologies such as color-suppressed tree and annihilation topologies (hadronic effects)

$K\pi$ puzzle

- $\mathcal{O}(\alpha_s^2)$ correction in the **QCDF/SCET**, NLO since the A_{CP} first arise at $\mathcal{O}(\alpha_s)$
- two hard scattering kernels for tree and penguin topologies: vertex (T_i^V) and spectator-scattering (T_i^S) corrections [Beneke, Huber, Li 09, Huber, Krankl, Li 16, Bell, Beneke, Huber, Li 20], [Pillip 07, Jain, Rothstion, Stewart 07]

Observers	NLO	NNLO	NNLO-LD [Bell, et.al., 15]	PDG (%)
$A_{CP}^{\pi^0 K^-}$	9.42 ± 2.58	$10.18^{+2.79}_{-3.24}$	$-1.17^{+20.0}_{-6.62}$	2.7 ± 1.2
$A_{CP}^{\pi^+ K^-}$	$7.25^{+2.53}_{-2.92}$	$8.08^{+2.94}_{-3.05}$	$-3.23^{+19.2}_{-3.41}$	-8.3 ± 0.3
ΔA_{CP}	$2.17^{+1.45}_{-0.84}$	$2.10^{+1.46}_{-2.89}$	$2.07^{+2.79}_{-4.57}$	11.0 ± 1.2

LD: estimate of non-factorizable annihilation contributions

- pure annihilation channels ($\bar{B}_s \rightarrow \pi\pi, \bar{B} \rightarrow \phi\phi$) are calculable, finite strong phase the missing hard-collinear contribution eliminates rapidity divergences in factorization formulae, a perturbative enhancement mechanism [Lu, Shen, Wang², NPB 990 (2023) 116175]
- global fit from $SU(3)_F$ symmetry/breaking: 26 Br + 16 A_{CP} + 6 C, S to fit 17/16 amplitudes [Fang, Huber, Malami, Li, Tetlalmatzi-Xolocotzi 2604.19612]

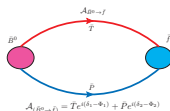
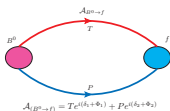
$$\left(2.74^{+2.85}_{-2.71}\right) \%, \quad \left(-8.35^{+0.76}_{-0.77}\right) \%, \quad \Delta A_{CP} = (11.1 \pm 2.9)\%$$

$K\pi$ puzzle

- **PQCD**: pick up k_T in $H(x_i, Q, k_T, \mu_f)$ to regulate the end-point singularity [Huang, Shen, Kroll 91, Huang, Shen, Ma 94], [Botts, Sterman 89, Li, Sterman 92]
- $F_{B \rightarrow M}$ and annihilation amplitudes are both calculable
- Sources of strong phase difference to generate \mathcal{CP}

- emission and annihilation ($\delta_2 \neq 0$)

$$\frac{1}{k_T^2 - x m_B^2 - i\epsilon} = \mathcal{P} \left(\frac{1}{k_T^2 - x m_B^2} \right) + i\delta(k_T^2 - x m_B^2)$$



- Sudakov exponent (NLO)
- NLO corrections to spectator emission amplitude from Glauber gluon
- on shell charm quark loop correction (NLO), leading source in QCDF
- predicted a large CPV in $\pi^- K^+$ (2000), confirmed by the B factories (2004)
- improved with relativistic potential model of B -meson WF and soft form factor [Wang and Yang, PRD 108 (2023) 013003]
- **NLO** ($\mathcal{O}(\alpha_s^2)$) corrections and the state-of-the-art PQCD calculation

$K\pi$ puzzle

- **NLO** ($\mathcal{O}(\alpha_s^2)$) corrections and the state-of-the-art PQCD calculations

[Chai, SC, Ju, Yan, Lü and Xiao, CPC 46 (2022) 123103]]

Observers	LO	+VC	+QL	+MP	+ $F_{B \rightarrow M}^{\text{NLO}}$	PDG (%)	LHCb, [PRL 136 (2026) 161801]
$A_{CP}^{\pi^0 K^-}$	-10.9	-5.20	2.26	2.48	$2.28^{+1.61}_{-1.74}$	2.7 ± 1.2	
$A_{CP}^{\pi^+ K^-}$	-15.2	-14.2	-4.16	-5.42	$-5.43^{+2.24}_{-2.34}$	-8.3 ± 0.3	
ΔA_{CP}	4.30	9.00	6.42	7.90	$7.81^{+2.76}_{-2.92}$	11.0 ± 1.2	
$A_{CP}^{K_S \pi^-}$	-1.19	-0.95	-0.06	-0.08	$-0.08^{+0.08}_{-0.09}$	-0.3 ± 1.5	-2.8 ± 1.27
$A_{CP}^{K_S^+ K^-}$	20.7	19.04	1.41	1.76	$1.83^{+1.95}_{-1.89}$	-21 ± 14	11.8 ± 6.93
$\frac{B^{K_S^+ K^-}}{B^{K_S^+ \pi^-}}$	11.72	11.89	12.12	11.98	$7.68^{+3.18}_{-2.41}$	5.5 ± 0.7	5.5 ± 0.4

- $K_S \pi^+$ is crucial to test the isospin sum rules $I_{K\pi}$ [Gronau PLB 627 (2005) 82], its CPV is expected to be zero no tree-level contribution and a highly CKM-suppressed annihilation
- $K_S K^+$ channel could have sizable CPV comparable amplitudes from CKM-favored annihilation and CKM-suppressed penguin diagrams
- the LHCb measurements ($2.1\sigma, 1.4\sigma$ derivations) indicates **sizable corrections from spectator diagrams** for these tree and penguin-suppressed channels ?

- some VV predictions are confirmed by the first/new measurements

Observers	PQCD-NLO [Chai 2022]	the first/new measurements
$C_{KS\pi^0}^{K_S\pi^0}, S_{KS\pi^0}^{K_S\pi^0}$	$-0.08^{+0.01}_{-0.01}, 0.72^{+0.01}_{-0.01}$	$-0.04^{+0.14}_{-0.15}, 0.75^{+0.20}_{-0.23}$ [Belle II, PRL 131 (2023) 111803]
$B^{\omega\omega}(10^{-6}), f_L^{\omega\omega}$	$1.21^{+0.39}_{-0.31}, 0.66^{+0.10}_{-0.11}$	$1.53 \pm 0.34, 0.87 \pm 0.18$ [Belle, PRL 133 (2024) 081801]
$B^{\rho^+\rho^-}(10^{-6}), f_L^{\rho^+\rho^-}$	$22.7^{+6.3}_{-5.0}, 95.0 \pm 1.0$	$28.9^{+3.7}_{-3.5}, 92.1 \pm 2.9$
$C^{\rho^+\rho^-}, S^{\rho^+\rho^-}$	$-1.85^{+0.20}_{-0.11}, -12.7^{+0.4}_{-0.3}$	$-2.0 \pm 13, -26 \pm 21$ [Belle II, PRD 111 (2025) 092001]
$A_{CP}^{\rho^0 K^{*+}}, f_L^{\rho^0 K^{*+}}$	$30.6^{+0.5}_{-0.7}, 75^{+4}_{-5}$	$50.7 \pm 6.6, 72 \pm 29$ [LHCb, PRL 136 (2026) 021803]

- sizable corrections from spectator diagrams ?
- the signal channels are $B \rightarrow 4\pi, \pi\pi KK, \pi\pi K\pi$ and et.al., a QCD-based framework is required to calculate them ?
- a big question is how to describe $\pi\pi, K\pi, KK$ spectra in a general way (crosslink to B_{14} decays and $|V_{ub}|, |V_{cb}|$ tensions, as well as $B \rightarrow K^{(*)}$ anomalies)

$\Lambda_b \rightarrow p\pi, pK$ modes

- $A_{CP}(\Lambda_b^0 \rightarrow p\pi^+\pi^-K^-) = (2.45 \pm 0.47) \times 10^{-2}$ [LHCb, Nature 634 (2025) 8074]
- multibody decay with the resonant enhancement of the strong phase difference
- Why not in $\Lambda_b \rightarrow p\pi, pK$ decays? $\mathcal{O}(10\%)$ due to large weak phase difference

$$\mathcal{A}(\Lambda_b \rightarrow ph) = \bar{u}_p (S + P\gamma_5) u_{\Lambda_b}, \quad A_{CP}^{\text{dir}} \approx \frac{|S|^2 A_{CP}^S + |P|^2 A_{CP}^P}{|S|^2 + |P|^2}$$

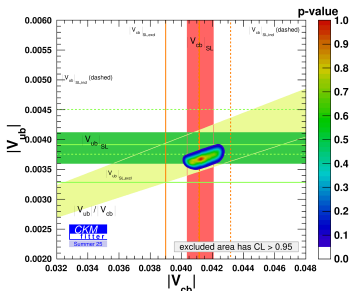
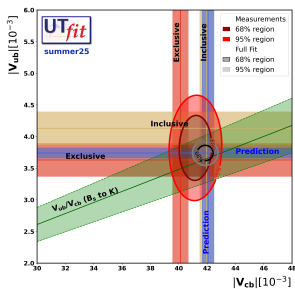
	A_{CP}^{dir}	$A_{CP}^{\text{S-wave}}(\kappa_S)$	$A_{CP}^{\text{P-wave}}(\kappa_P)$	[PRL 134 (2025) 221801], see J.J. Han's talk
$\Lambda_b \rightarrow p\pi^-$	$0.05_{-0.03}^{+0.02}$	$0.17_{-0.09}^{+0.05}$ (49%)	$-0.06_{-0.05}^{+0.04}$ (51%)	destruction between the partial waves the suppression by the small partial-wave weight
$\Lambda_b \rightarrow pK^-$	$-0.06_{-0.02}^{+0.03}$	$-0.05_{-0.04}^{+0.05}$ (94%)	$-0.21_{-0.46}^{+0.39}$ (6%)	

- How about the hyperon decays like $\Lambda \rightarrow p\pi^-$? see H.B Li's talk

$$\alpha_Y = \frac{2\text{Re}(S^*P)}{|S|^2 + |P|^2}, \quad \beta_Y = \frac{2\text{Im}(S^*P)}{|S|^2 + |P|^2}, \quad \gamma_Y = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}; \quad A_{CP} \propto \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} + \Delta$$

- similar S, P -waves contributions, SM prediction $\mathcal{O}(10^{-5} - 10^{-4})$
[Donoghue, He and Pakvasa, PRD 34 (1986) 833, Lee and Yang, Physical Review 108 (1957) 1645-1647]
- $A_{CP}(\Lambda \rightarrow p\pi^-) = (-0.25 \pm 0.47) \times 10^{-2}$ [BESIII, Nature Phys. 15 (2019) 631-634]
- destruction or construction? underlying mechanism?

$|V_{ub}|, |V_{cb}|$ tensions



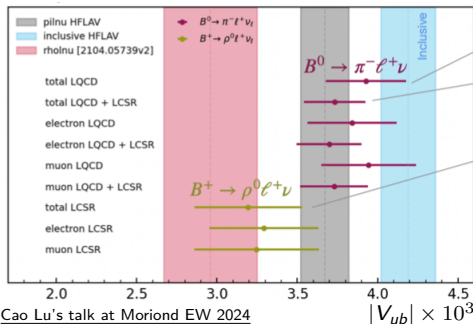
- $|V_{ub}|$ tension $|V_{ub}| = (3.82 \pm 0.20) \times 10^{-3}$ [PDG 2024, 25 update]
 - * 2.5σ tension between $(4.13 \pm 0.25) \times 10^{-3}$ and $(3.67 \pm 0.15) \times 10^{-3}$ determined via the $B \rightarrow X_u l^- \bar{\nu}$ and $B \rightarrow \pi l^- \bar{\nu}$ processes, respectively
- $|V_{cb}|$ tension $|V_{cb}| = (41.1 \pm 1.2) \times 10^{-3}$ [PDG 2024, 25 update]
 - * 2.5σ tension between $(42.2 \pm 0.5) \times 10^{-3}$ and $(39.8 \pm 0.6) \times 10^{-3}$ determined via the $B \rightarrow X_c l^- \bar{\nu}$ and $B \rightarrow D^{(*)} l^- \bar{\nu}$ processes, respectively

$|V_{ub}|$ from $B \rightarrow \pi\pi l^+\nu$

- 含有激发态粒子的过程也可以提供独立的测量 $b \rightarrow u$ transition
- $B \rightarrow V$ transitions updated via B -meson LCSRs [Gao, et.al., PRD 101.074035(2020)]

$$|V_{ub}| \times 10^3 \xrightarrow{B \rightarrow \rho l \nu} 3.05_{-1.30}^{+1.34} |_{\text{th}}^{+0.19}_{-0.20} |_{\text{da}}, \quad \xrightarrow{B \rightarrow \omega l \nu} 2.54_{-1.05}^{+1.09} |_{\text{th}}^{+0.18}_{-0.19} |_{\text{da}}$$

- simultaneous measurements of $d\mathcal{B}/dq^2$ for $B \rightarrow \pi^- l^+ \nu_l$ and $B \rightarrow \rho^0 l^+ \nu_l$



$|V_{ub}|_{B \rightarrow \pi l \nu_l} = (3.93 \pm 0.09 \pm 0.13 \pm 0.19) \times 10^{-3}$
 LQCD[HFLAV 2023] _{stat} _{syst} _{theo}

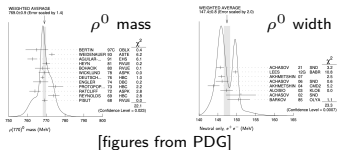
$|V_{ub}|_{B \rightarrow \pi l \nu_l} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$
 LQCD+LCSR [P. Bharucha, et.al., JHEP 08(2016)098]

$|V_{ub}|_{B \rightarrow \rho l \nu_l} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$
 LCSR

- Leading systematic unc. are the modelling of continuum and non-resonant $B \rightarrow X_u \ell \nu$ decays
- Overall **theoretical** uncertainty dominating ↓

- different partial waves (P, D, S)
- different resonants in P -wave
- non-resonant QCD background

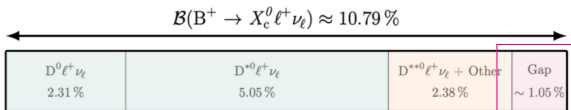
Cao Lu's talk at Moriond EW 2024
 [Belle-II PRD 111 (2025) 112009]



- the $\pi\pi$ spectra in $[0.554, 0.996]$ GeV serves as the candidate region for ρ
- ρ is usually treated as a stable single particle in the QCD studies of $B \rightarrow \rho$ transitions (LQCD, LCSRs)

- the signal channel in a $B \rightarrow \rho l \nu$ -type decay is $B \rightarrow \pi\pi l \nu$ (B_{ll})
- How to accurately describe the **width effects** of unstable intermediate particles, the contributions and **interference effects** of different partial waves, and the **QCD backgrounds** from non-resonant states
- Dipion LCDAs (2π DAs) provide a most general description of $\pi\pi$ spectral
- Successfully explained the energy-dependent partonic structure of $f_0(980)/[\pi\pi]_S$
Failure of the cascade decay framework for f_0 [SC, Dai, Shen and Zhang, PRD 113 (2026) L031901]

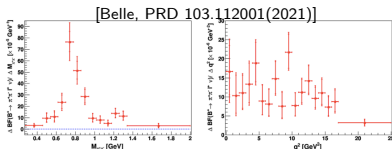
- opportunities for $|V_{cb}|$ from $B \rightarrow D^* l \nu$, $X_c l \bar{l} \nu$ and $B \rightarrow K^* l^+ l^-$ anomalies



- careful study of $D\pi$, $D\pi\pi$ and $D\pi\pi\pi$ spectral
...or is it even bigger?

- 2D partial differential decay width and the measurement (10^{-5})

$$\frac{d^2\Gamma}{dq^2 dk^2} = G_F^2 |V_{ub}|^2 \frac{\beta_\pi \sqrt{\lambda} q^2}{3 (4\pi)^5 m_B^3} \left[(|F_0^{(S)}|^2 + |F_0^{(P)}|^2) + \beta_\pi^2 (|F_{\parallel}^{(P)}|^2 + |F_{\perp}^{(P)}|^2) + \dots \right]$$

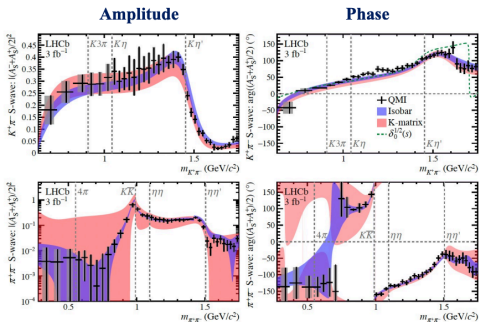


take the PDG value: $|V_{ub}| \times 10^3 = 3.82 \pm 0.20 \Rightarrow$

Bins	\sqrt{s}	q^2	ΔB^i	ΔB^i [20]
1	$[4m_\pi^2, 0.6]$	$[0, 8]$	$0.27 \pm 0.03 \pm 0.06$	$0.84^{+0.39}_{-0.32} \pm 0.18$
2	$(0.6, 0.9]$	$[0, 4]$	$1.91 \pm 0.21 \pm 0.38$	$2.39^{+0.53}_{-0.47} \pm 0.32$
3	$(0.6, 0.9]$	$(4, 8]$	$1.54 \pm 0.17 \pm 0.27$	$2.16^{+0.47}_{-0.42} \pm 0.23$
4	$(0.9, 1.2]$	$[0, 4]$	$0.65 \pm 0.07 \pm 0.12$	$0.70^{+0.32}_{-0.25} \pm 0.20$
5	$(0.9, 1.2]$	$(4, 8]$	$0.41 \pm 0.04 \pm 0.08$	$0.64^{+0.28}_{-0.22} \pm 0.11$
6	$(1.2, 1.5]$	$[0, 4]$	$0.57 \pm 0.05 \pm 0.10$	$0.91^{+0.35}_{-0.28} \pm 0.12$
7	$(1.2, 1.5]$	$(4, 8]$	$0.16 \pm 0.02 \pm 0.02$	$0.64^{+0.32}_{-0.26} \pm 0.08$

- $|V_{ub}| \times 10^3 = 4.27 \pm 0.49|_{\text{Data}} \pm 0.55|_{\text{LCSR}_S}$ and $3.96 \pm 0.47|_{\text{Data}} \pm 0.52|_{\text{LCSR}_S}$ in ρ and f_0 region of $B_{\mathcal{M}}$ decays, respectively [SC PRD 112 (2025) L111301]
- close to that obtained via $B \rightarrow \pi l \nu$, with sizable uncertainties
- Lattice QCD in the ρ resonance region with a simple BW model, **HChPT** in the large q^2 and full phase-space by a novel parameterization [Leskovec, et.al, PRL 134 (2025) 161901], [Herren, et.al., PRD 112 (2025) 014037]
- LHCb will extract $|V_{ub}|$ and $B \rightarrow \pi\pi$ FFs in 10 q^2 bins with ~ 3 times better precision, Michel De Cian's talk at "Challenges in semileptonic B decays 2026", Bad Honnef

$\pi\pi, K\pi$ phase shifts from LHCb



• LHCb preliminary result
 screenshot from W.B Qian's talk
 at "2026 轻强子专题研讨会", 商丘

- CPV studies in $B^+ \rightarrow K^+ \pi^- \pi^-$ decays
 - 3 ways to model S-wave
 - include $\pi\pi\text{-}\pi\pi, KK\text{-}\pi\pi$ rescattering contributions

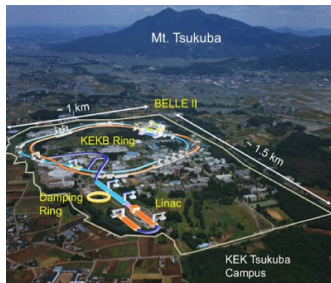
- significant difference of the $K\pi$ phase shifts in contrast to the Watson theorem
- how about the case in charm decays like $D \rightarrow K\pi\pi$?
- scale sensitivity of $K\pi$ phase shift in the large $m_{K\pi}$ regions, QCD background, $K\pi$ DAs

A_{CP}	PQCD-NLO [Chai 22']	QCDF [Cheng 09']	SCET [Wang 08']	LHCb-preliminary-QMI
$B^+ \rightarrow \rho K^+$	$58.7^{+5.4}_{-4.9}$	$45.4^{+36.1}_{-30.2}$	$16.0^{20.5}_{-22.5}$	35.9 ± 6.1
$B^+ \rightarrow \omega K^+$	$31.5^{+0.6}_{-1.3}$	$12.3^{+16.6}_{-17.3}$	$22.1^{19.6}_{-18.2}$	-0.4 ± 13.9

- theoretical calculations are done under the single particle approximation of ρ
- a general description of $\pi\pi$ spectrum to predict CPVs in their mass regions

Conclusion

重味物理研究即将全面进入精确测量的时代，这为深入理解基本相互作用和探索新物理机制提供了极佳的机遇。



Belle II has collected 783.22 fb^{-1} data so far with record peak luminosity $4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$



HL-LHC(2030-2033) $\mathcal{L} = 23(300) \text{ fb}^{-1}$ in phase 1(2)
2 order larger than LHC, $2 \times 10^{33(34)} \text{ cm}^{-2} \text{ s}^{-1}$

Thank you for your patience.