

Theoretical Progress in Heavy-Flavor Physics

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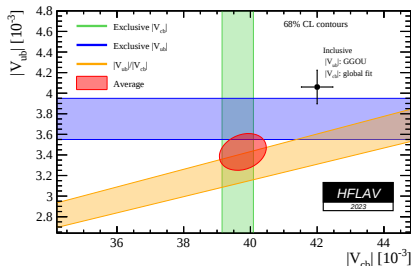
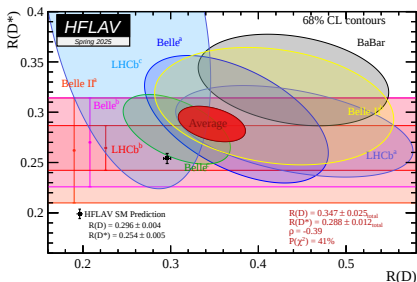
CLHCP2025 · Xinxiang

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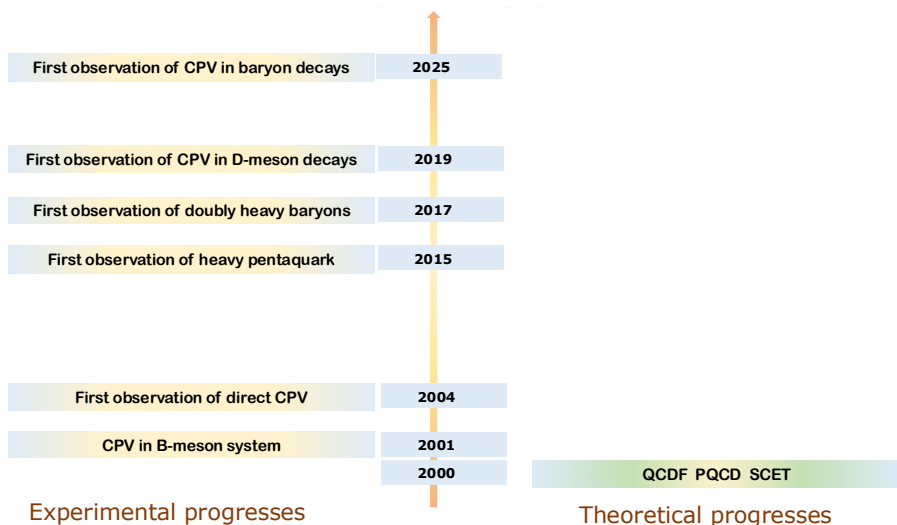
New physics beyond the SM

- Direct search: new particles
- Indirect search: flavour physics
CPV, $R(D^{(*)})$, $|V_{ub}|$, $|V_{cb}|$, $\dots$



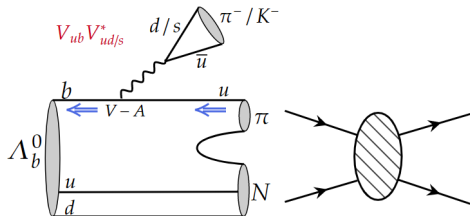
- LHC, Belle-II
- HL-LHC

Milestones since 2000



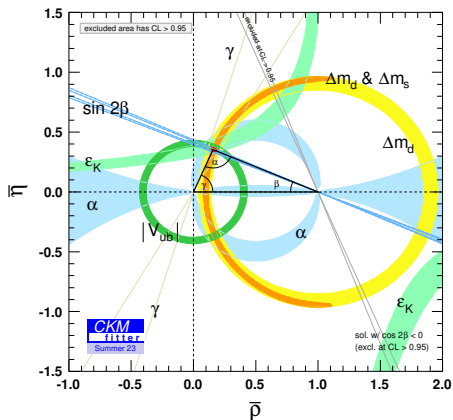
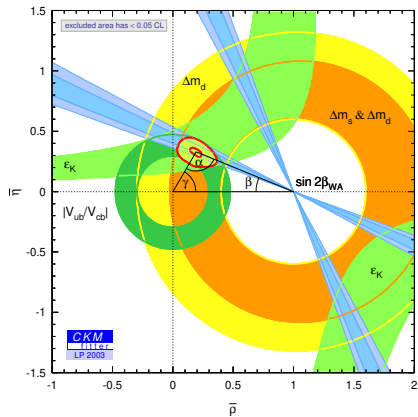
CP violation in baryon decays

- CPV in $\Lambda_b^0 \rightarrow (p\pi^+\pi^-)h^-$:
 $N\pi$ rescatterings
[Wang and Yu, 24'], [Yu, Lü, 25']
- CPV in $\Lambda_b^0 \rightarrow p\pi^+\pi^-K^-$: 5.2σ
[LHCb, 25']
- Small CP violation in $\Lambda_b \rightarrow p\pi, pK$
Cancellation between S-wave and P-wave: in PQCD
[Han, et al., 22'], [Han, et al., 24']

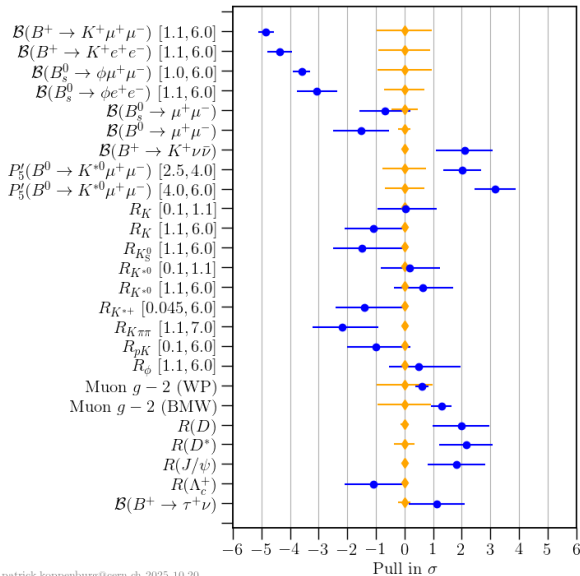


CKM matrix element

2003 $\Rightarrow$ 2023



Flavor anomaly



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Outline

- ✧ Subleading power corrections
- ✧ Nonperturbative functions
- ✧ QED corrections and LFUV
- ✧ QCD corrections

Subleading power corrections

Power corrections are numerically **important in B decays**, $\lambda = \Lambda/m_b$

$$\lambda \sim \alpha_s(\mu) \sim 20\% \Rightarrow \text{NLP@LO} \sim \text{LP@NLO}$$

- * Higher Fock states of the B meson: $|B\rangle \Rightarrow |b \bar{q} g\rangle$
- * Quark-propagator expansion
- * Heavy-quark expansion: QCD $\rightarrow$ HQET

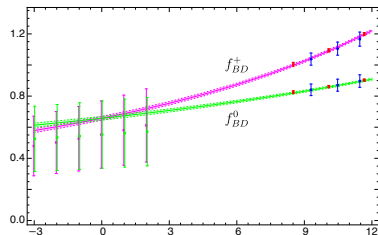
$$b = h_v + \frac{i\not{D}_\perp}{2m_b} h_v + \cdots, \quad i\not{D}_\perp/m_b \sim \mathcal{O}(\lambda)$$

$R(D^{(*)}): B_{(s)} \rightarrow D^{(*)}_{(s)}$ form factors

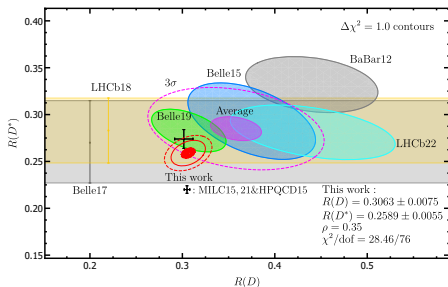
Large recoil region:

NLO: [Wang, **YBW**, Shen and Lü, 17']

NLO+**NLP**: [Gao, Huber, Ji, Wang, Wang and **YBW**, 21'], [Cui, Huang, Wang and Zhao, 23']



[Gao, Huber, Ji, Wang, Wang and **YBW**, 21']



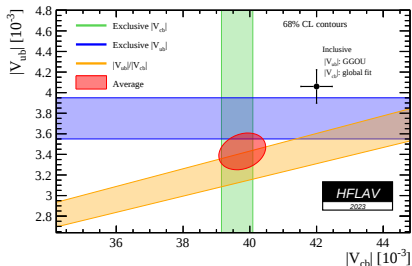
[Cui, Huang, Wang and Zhao, 23']

$\bar{B}_{(s)} \rightarrow D^{(*)}_{(s)}$
 LCSR+LQCD
3.3σ → **2.6σ** (2023)
3.8σ (HFLAV 2025)

$|V_{ub,cb}|$ and heavy-to-light form factors

LCSR: [Khodjamirian, Melić, and Wang, 23']

- Light-meson LCDA: [Khodjamirian, Mannel, Offen and Wang, 11'], [Bharucha, 12']
- B -meson LCDA: [Lü, Shen, Wang and YBW, 18'], [Gao, Lü, Shen, Wang and YBW, 19'], [Shen and YBW, 21']



[Cui, Huang, Wang and Zhao, 23']

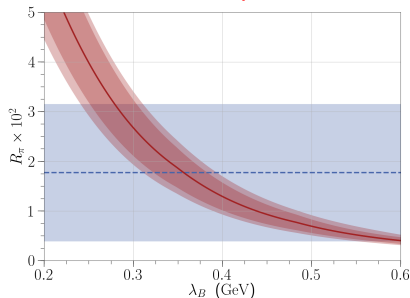
$$|V_{ub}| = (3.71 \pm 0.13) \times 10^{-3}$$

$$|V_{cb}| = (39.64 \pm 0.63) \times 10^{-3}$$

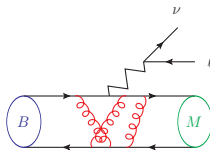
Tension with inclusive decay
 $\{1.5\sigma, 2.5\sigma\}$

HQET LCDA of heavy meson

HQET LCDA: Most important function in exclusive B decays



[Belle, 18'], [Beneke, Braun, Ji, and YBW, 18']



- Non-leptonic decays: $B \rightarrow \pi K \dots$
- Semi-leptonic decays: $B \rightarrow D^{(*)} \ell \nu \dots$
- Radiative decay: $B \rightarrow \gamma \ell \nu \dots$

Direct study of HQET LCDA

HQET LCDA: non-perturbative physics

- RG evolution properties: [Braun, Ji and Manashov, 19'], [Galda and Neubert, 20'], [Cui, Shen, Wang and **YBW**, 23']
- EOM [Kawamura, Kodaira, Qiao and Tanaka, 02'], [Lü, Shen, Wang and **YBW**, 18']
- generalized LCDA [Beneke, Böer, Toelstede, and Vos, 22'], [Qin, Shen, Wang and Wang, 22'], [Huang, Ji, Shen, Wang and Wang, 23']

Direct determination:

- Calculate with LQCD [LPC collaboration, 22']
- Extract from the experiments: simple clean process $B \rightarrow \gamma \ell \nu$
Inverse moments λ_B : [Wang and Shen, 18'], [Beneke, Braun, Ji, and **YBW**, 18'], [Belle, 18'], [Galda, Neubert and Wang, 22']

Indirect study of HQET LCDA

Indirect determination:

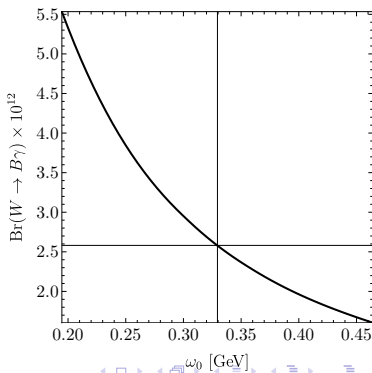
Production of B meson [Ishaq, Jia, Xiong and Yang, 19'], [Zhao, 19'], [Beneke, Finauri, Vos and YBW, 23'], [Deng, Wang, YBW and Zeng, 24']

$$\phi(u) = \mathcal{J}(u, \omega) \otimes \varphi_+(\omega)$$

Simple clean process $W \rightarrow B\gamma$:
with $\ln \Lambda_{\text{QCD}}/m_Q$ resummation

$$\text{Br} = (2.58 \pm 0.21_{\text{in } -0.08}^{+0.05} \mu_h \text{ }_{-0.98}^{+2.95} \lambda_B) \cdot 10^{-12}$$

30% increase [Beneke, Finauri, Vos and YBW, 23']



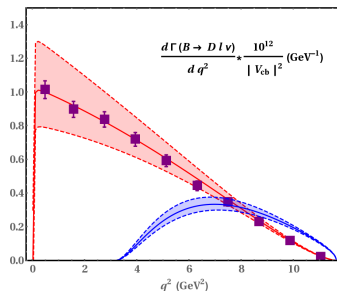
QED corrections in B decays

Testing LFU: m_τ and m_μ

- Phase space
- QED correction: $\ln m_\tau/m_\mu$

QCD: color neutral external states

QED: electrically charged exte. stat.



[Wang, YBW, Shen and Lü, 17']

Extraction of α_s at
 $N^3\text{LO}_{\text{QCD}} \otimes \text{NLO}_{\text{QED}}$
[Ball et al. 25']

$$\alpha_{\text{em}} \sim \alpha_s^3 \sim 0.01$$

- $B \rightarrow \mu^+ \mu^-$: power enhancement [Beneke, Bobeth and Szafron, 19', 20']
- $B \rightarrow M_1 M_2$: [Beneke et al., 21']
- $B \rightarrow \mu^- \nu$: [Cornella, König, and Neubert, 22']

$$B_u \rightarrow \tau \nu_\tau \text{ and } |V_{ub}|$$

QED correction in $B_u \rightarrow \tau \nu_\tau$: [Shen, Wang, **YBW** and Zhou, in progress]

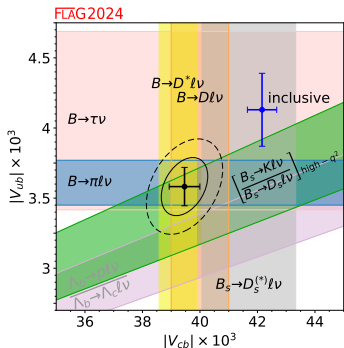
- **Helicity suppression** offers sensitive probe of new interactions

$$B_\tau \sim 10^{-5}, \quad B_\mu \sim 10^{-7}, \quad B_e \sim 10^{-12}, \quad [\text{Belle II Physics Book}]$$

- **Determination of $|V_{ub}|$**

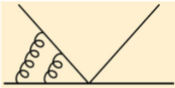
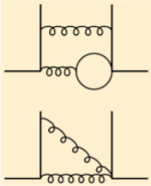
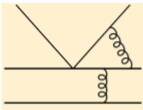
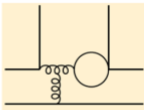
Belle II [Belle II, 2502.04885]

$$|V_{ub}| = (4.41^{+0.74}_{-0.89}) \times 10^{-3}$$



QCDF: two loop

$$\langle M_1 M_2 | O_i | \bar{B} \rangle = F^{B \rightarrow M_1} T_i^I \otimes \phi_{M_2} + T_i^{II} \otimes \phi_B \otimes \phi_{M_1} \otimes \phi_{M_2} + \mathcal{O}(\Lambda_{\text{QCD}}/m_b)$$

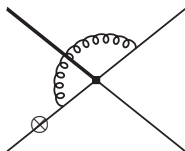
$\mathcal{O}(\alpha_s^2)$	 Bell '07, '09 Beneke, Huber, Li '09 Huber, Krankl, Li '16	 Kim, Yoon '11 Bell, Beneke, Huber, Li '15, '20	 Beneke, Jager '05 Kivel '06, Pilipp '07	 Beneke, Jager '06 Jain, Rothstein, Stewart '07
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[From Xin-Qiang Li's talk]

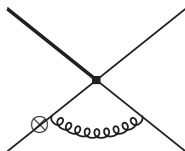
- NNLO jet function in $B \rightarrow \gamma \ell \nu$ [Liu and Neubert, 20']
- $B \rightarrow \pi^0 \pi^0$: strong cancellation between T_i^I and T_i^{II}
- $B \rightarrow \pi K$: strong cancellation between tree and penguin operators

QCD correction: $B^- \rightarrow \{\pi^-, K^-\} \ell^+ \ell^-$

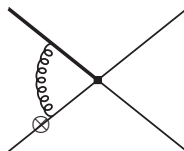
Complete NLO calculation: [Huang, Shen, Wang and Zhao, 24']



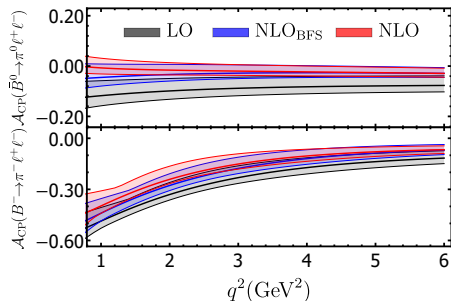
(a)



(b)



(c)



Annihilation contribution

- No endpoint singularity
- Factorization scale independent
- 15% corrections in $\mathcal{A}_{\text{CP}}$

Topics not included

- Heavy hadron spectroscopy
- Inclusive decays of heavy hadrons
- Charm physics
- Testing new physics models in heavy flavor physics
- ...

Summary

- ✧ **Power corrections** to $B \rightarrow M$ form factors
 - $R(D^{(*)})$
 - $|V_{ub}|, |V_{cb}|$
- ✧ **Nonperturbative functions**: B -meson HQET LCDA
 - From B decays: $B \rightarrow \gamma \ell \nu$
 - From B productions: $W \rightarrow B \gamma$
- ✧ **QED corrections**: LFUV and $|V_{ub}|$ from $B \rightarrow \tau \nu$
- ✧ **QCD corrections**: annihilation contribution to $B \rightarrow P \ell^+ \ell^-$

Thank you!