$B \to D$ form factors beyond leading power and extraction of $|V_{cb}|$ and $R(D)$

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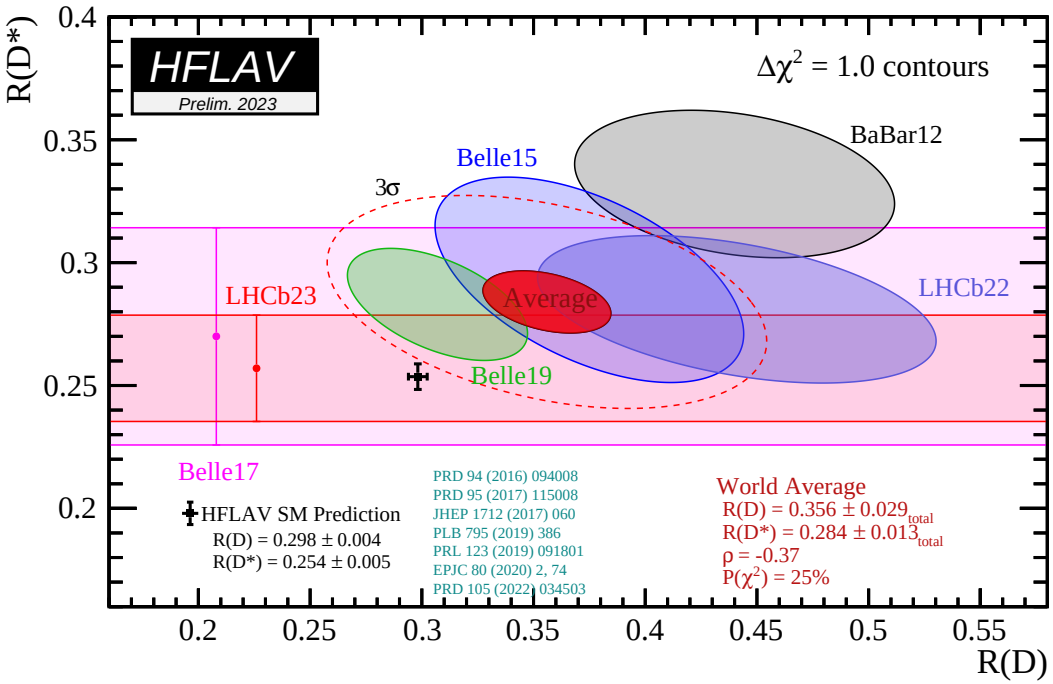
Outline

- Introduction to $B \to D\ell\nu_\ell$ decay
- Factorization formula of $B \to D$ form factors at leading power
- Subleading power corrections to $B \to D$ form factors
- Numeric applications

Introduction

New physics: $R(D^{(*)})$ anomalies $R(D) - R(D^*) \sim 3.2\sigma$

$$R(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)}, \qquad R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$



BaBar: [1205.5442]

Evidence for an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays

BaBar Collaboration • J.P. Lees (Annecy, LAPP) et al. (May, 2012)

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reference search 1,133 citations

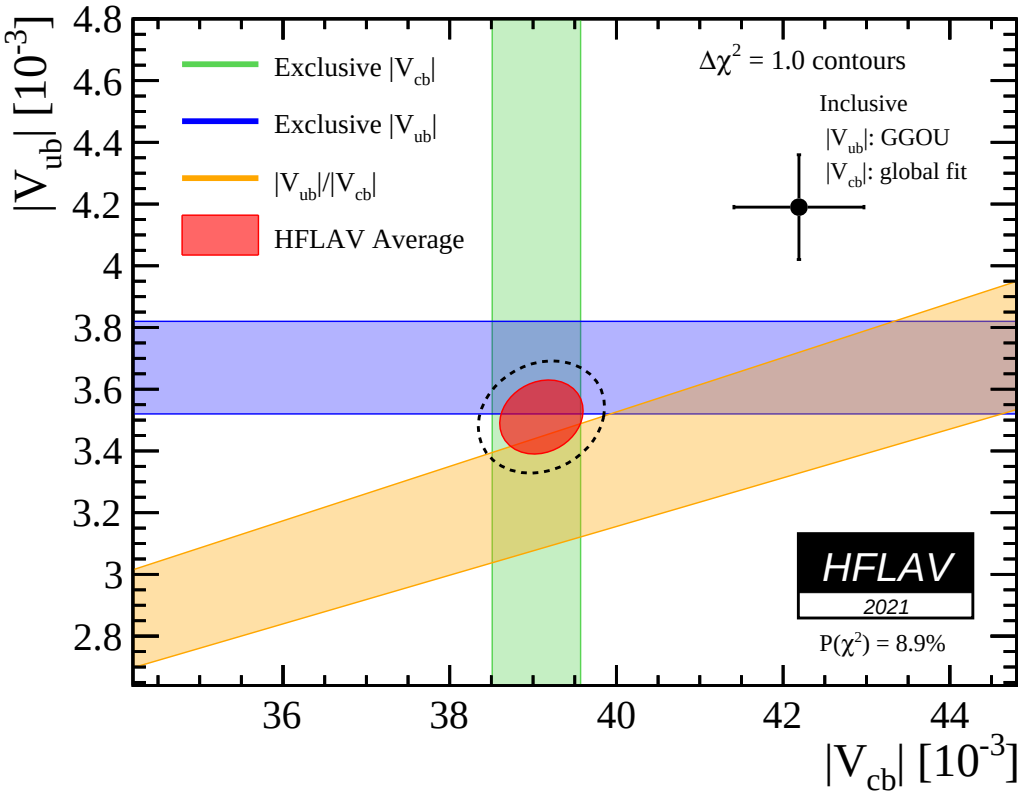
Belle: [1910.05864]

LHCb: [2302.02886]

Belle-II, HL-LHC

Introduction

$|V_{cb}|$: about 3σ tension between exclusive and inclusive results.



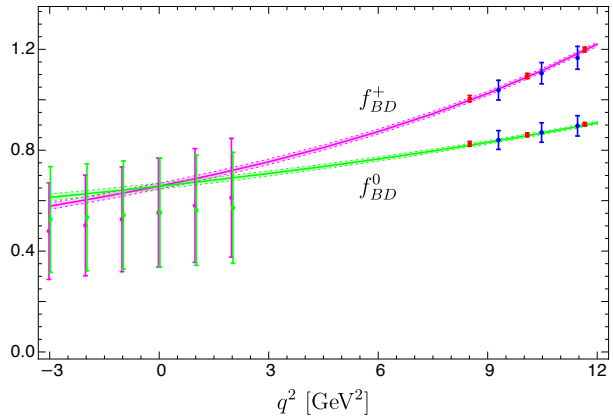
- Inclusive: $B \to X_c \ell \nu_\ell$
  CLEO: [hep-ex/0403052]
  BaBar: [0908.0415]
  Belle: [hep-ex/0610012]
- Exclusive: $B \to D \ell \nu_\ell$
  CLEO: [hep-ex/0203032]
  BaBar: [0712.3503]
  Belle: [1510.03657]
  Belle-II: [2008.07198]

$$\frac{d\Gamma(B \to D\ell\nu_\ell)}{dq^2} = |V_{cb}|^2 \left[C_{f+}(q^2) |f_{BD}^{+}(q^2)|^2 + C_{f0}(q^2) |f_{BD}^{0}(q^2)|^2 \right]$$

$B \to D$ form factors

$$\langle D(p)\,|\bar{c}\gamma_\mu\, b|\,\bar{B}(p_B)\rangle = f_{BD}^{+}(q^2)\left[2p_\mu + \left(1 - \frac{m_B^2 - m_D^2}{q^2}\right) q_\mu\right] + f_{BD}^{0}(q^2)\frac{m_B^2 - m_D^2}{q^2} q_\mu$$

- D-meson small recoil region
  - HQET: $1/m_b$, $1/m_c$ corrections [Bernlochner, Ligeti et al. 1703.05330], [Bigi, Gambino and Schacht, 1707.09509]
  - LQCD: 2+1 flavor [MILC 1503.07237], [HPQCD 1505.03925], [JLQCD 1912.11770]

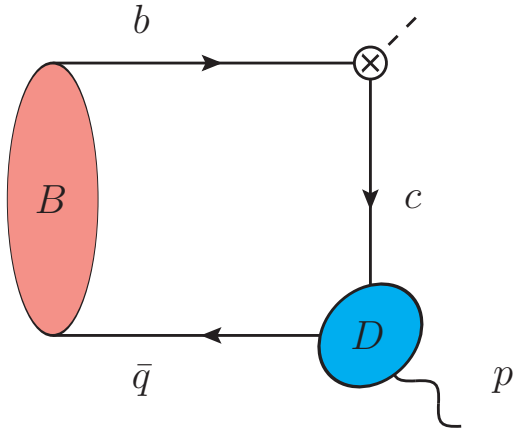


- D-meson large recoil region
  - SCET, QCD Factorization: endpoint singularity [Beneke and Feldmann, 0311335]
  - PQCD: NLO [Fan, Wang, Cheng and Xiao, 1301.6246], [Fan, Xiao, Wang and Li, 1505.07169], [Hu, Jin and Xiao, 1912.03918]
  - LCSR: LP [Wang, **YBW**, Shen and Lü, 1701.06810], [Zhang et al. 1709.02226]
    LP+LO, NLP (3P LCDA) [Gubernari, Kokulu and Dyk, 1811.00983]
    LP+NLO, NLP [Gao, Huber, Ji, Wang, Wang and **YBW**, 2112.12674]

$B \to D$ form factors in LCSR

Two-point correlation function [Colangelo and Khodjamirian, hep-ph/0010175]

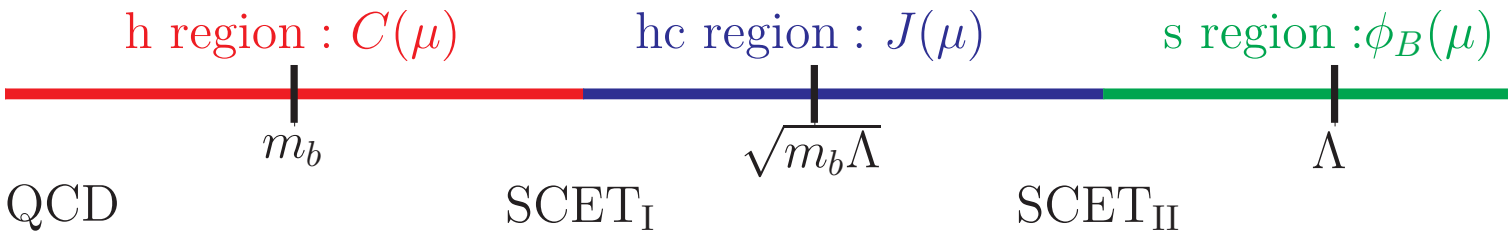
$$\Pi = i \int d^4x\, e^{ip\cdot x} \langle 0 \,|\, T\{\bar{q}(x) \not{n} \gamma_5\, c(x)\,,\, \bar{c}(0)\gamma_\mu\, b(0)\} |\, \bar{B}(p_B)\rangle$$



- Hadronic level: $\sum_n |n\rangle\langle n|$ $\Rightarrow$ $f_D \times f_{BD}^{+,0} + \text{cont. sta.}$
- Partonic level: factorization formula for Π_p
- Parton-hadron duality: $f_{BD}^{+,0} = (\Pi_p - \text{cont. sta.})/f_D$
- Borel transformation to avoid the endpoint divergence

Leading power

- hard (h) scale $\mathcal{O}(m_b)$, soft (s) scale $\mathcal{O}(\Lambda)$
- hard-collinear (hc) scale $\mathcal{O}(\sqrt{m_b\Lambda})$: $m_c \sim \sqrt{m_b\Lambda}$, $\sqrt{k_s \cdot k_c}$



Method of regions [Beneke and Smirnov, hep-ph/9711391]

SCET [Bauer, Fleming, Pirjol and Stewart, hep-ph/0011336], [Beneke, Chapovsky, Diehl and Feldmann, hep-ph/0206152]

$$\Pi_p = C(\mu) \otimes J(\mu) \otimes \phi_B(\mu)$$

Resummation of large logs: RG evolution

Subleading power corrections

Collider physics: refactorization of endpoint divergence

- $H \to \gamma\gamma$: [Liu and Neubert, 1912.08818], [Liu, Mecaj, Neubert and Wang, 2009.06779]
- DIS, DY: [Beneke et al., 2205.04479]

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

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

- Higher Fock states of the B meson: $|B\rangle \Rightarrow |b\,\bar{q}\,g\rangle$
- Charm-quark expansion: $p \sim hc$ and $k \sim s$

$$\frac{(\not{p}-\not{k})+m_c}{(p-k)^2-m_c^2} = \frac{1}{\bar{n}\cdot\hat{p}}\left\{\frac{\not{\bar{n}}}{2} + \underbrace{\frac{\bar{n}\cdot p}{n\cdot p}}_{\mathcal{O}(\lambda)}\left[\frac{\not{n}}{2}+\cdots\right]+\cdots\right\}$$

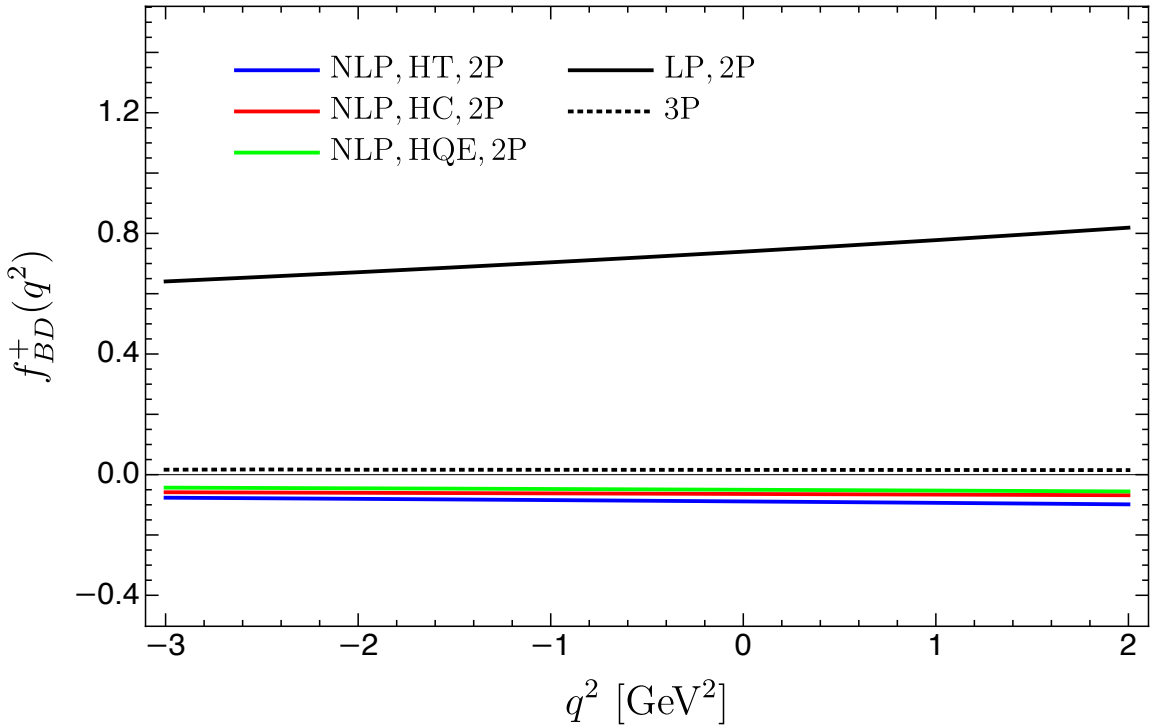
- Heavy-quark expansion: QCD $\to$ HQET

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

Numerical results

Large recoil region:

$\mu \in [1.0, 2.0]$ GeV
$C(\mu)$: NLL
$\phi_B(\mu)$: LL

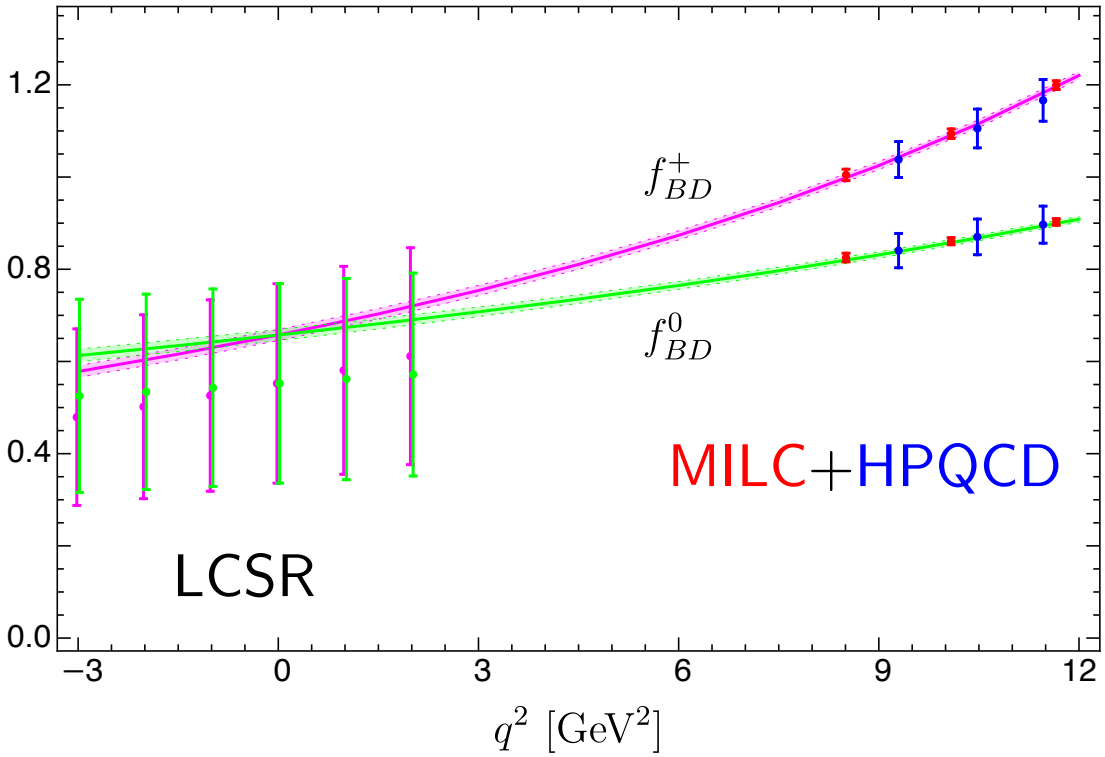


LP	NLP, HT	NLP, HC exp.	NLP, HQ exp.
0.74	−0.09	−0.06	−0.05

NLP: $\sim 20\%$

f_{BD}^+ decrease, $|V_{cb}|$ increase

Numerical results



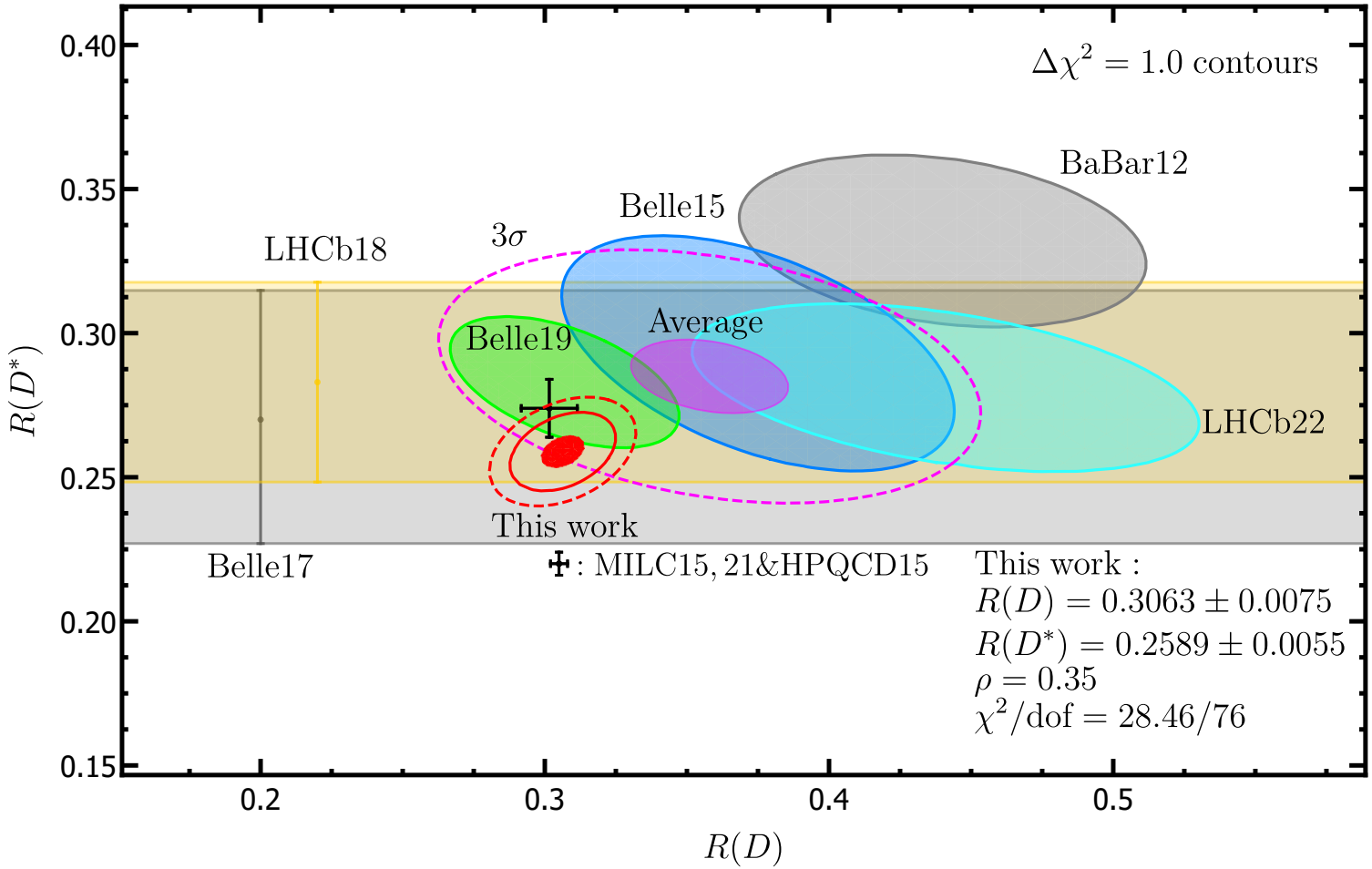
$R(D)$: $1.98\sigma \to 1.85\sigma$

$$|V_{cb}| = \begin{cases} (42.19 \pm 0.78)\,|_{\text{incl.}} \\ (39.10 \pm 0.50)\,|_{\text{excl.}} \end{cases}$$

	LCSR	Lattice	HQET	This work
$\lvert V_{cb}\rvert \times 10^3$	40.3(0.8)	39.36(68)	39.3(1.0)	$40.2^{+0.6}_{-0.5}\lvert_{\text{th}}\ ^{+1.4}_{-1.4}\lvert_{\text{BaBar}}$ $40.9^{+0.6}_{-0.5}\lvert_{\text{th}}\ ^{+1.0}_{-1.0}\lvert_{\text{Belle}}$
$R(D)$	0.297(3)	0.299(11)	0.299(3)	0.302(3)

Numerical results

$\bar{B}_{(s)} \to D^{(*)}_{(s)} \ell \bar{\nu}_\ell$ decays+LQCD results: $3.2\sigma \to 2.5\sigma$



[Cui, Huang, Wang and Zhao, 2301.12391]

Summary

- Introduction to the $B \to D\ell\nu_\ell$ decay
- $B \to D$ form factors with LCSR at large recoil
  - LP factorization formula: $C(\mu) \otimes J(\mu) \otimes \phi_B(\mu)$
  - NLP power corrections
    - B-meson higher Fock states
    - Charm-quark expansion
    - Heavy-quark expansion
- Extraction of $|V_{cb}|$ and $R(D)$: LCSR+LQCD

Thank you!