Precision Calculations of B-Meson Decay Form Factors

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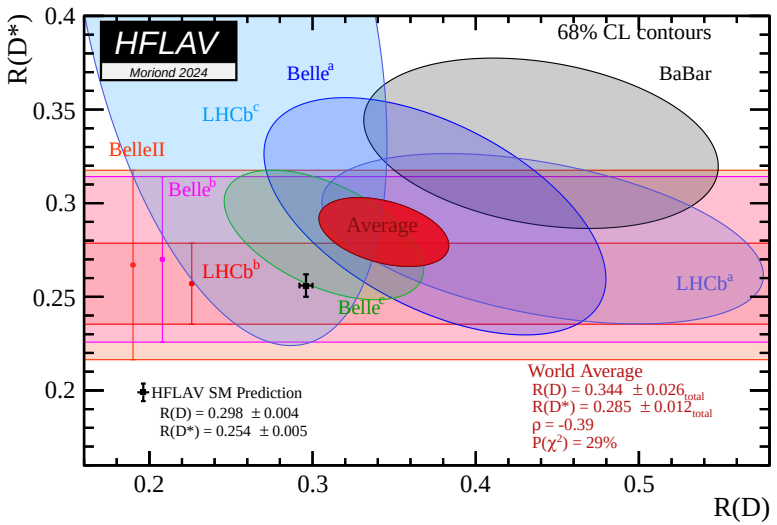
Outline

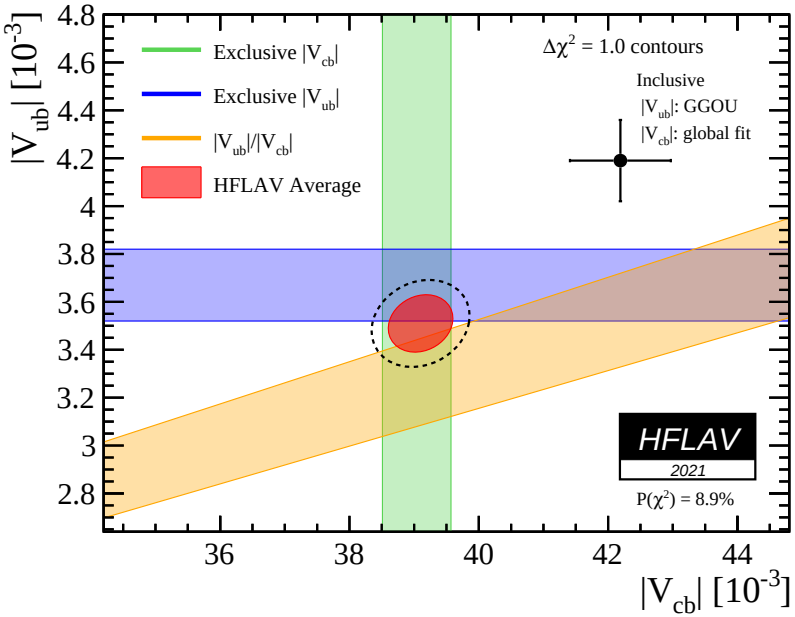
- B-meson decay form factors
- Power corrections to the form factors
- Numerical applications

B Physics

New physics beyond the SM

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





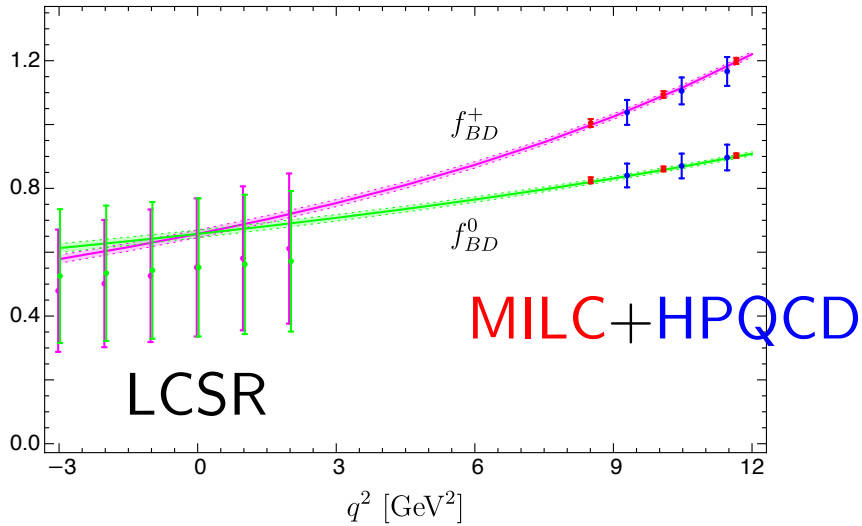
- BaBar, Belle
- LHC, Belle-II
- HL-LHC

B-meson decay form factors

Important in: $B \to M\ell\bar{\nu}_\ell$, $B \to \gamma\ell\bar{\nu}_\ell$, $B \to M_1 M_2$

$$\langle M(p)|\bar{q}\sigma_{\mu\nu}q^\nu b|\bar{B}(p+q)\rangle = i\frac{f_{B\to M}^T(q^2)}{m_B+m_M}\left[q^2(2p+q)_\mu - (m_B^2-m_M^2)q_\mu\right]$$

- At large q^2 region:
  - LQCD: 2+1 flavor [MILC 15'], [HPQCD 15'], [JLQCD 19']
  - HQET: $1/m_b$ corrections [Bernlochner, Ligeti et al. 17'], [Bigi et al. 17']

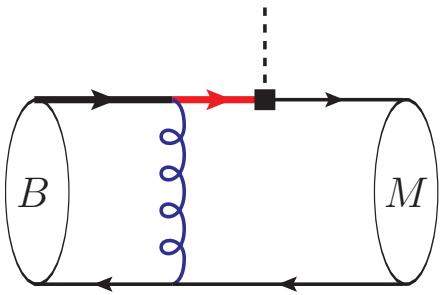


- At small q^2 region:
  - QCDF, SCET: NNLO [Beneke and Feldmann, 03'], [Bell et al. 10']
  - PQCD: NLO [Fan et al. 13'], [Fan et al. 15'], [Hu et al. 19']
  - **LCSR**: [Zhang et al. 17'], [Gubernari et al. 18'], [Gao, Huber, Ji, Wang, Wang and **YBW**, 21'], [Cui, Huang, Shen, Wang and Wang, 22'], [Cui, Huang, Wang and Zhao, 23'], [Gubernari et al. 23']

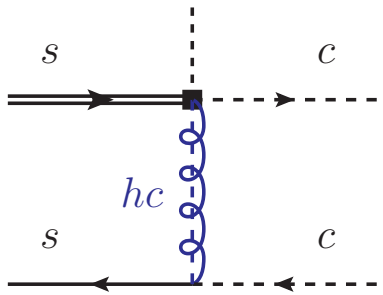
Form factors in SCET

Since there are two large scales, we need two-step matching

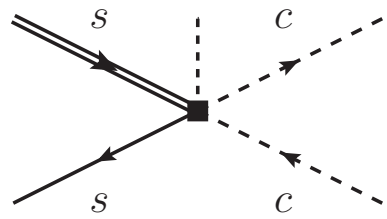
$$\text{QCD} \xrightarrow{\mathcal{O}(m_b)} \text{SCET}_\text{I} \xrightarrow{\mathcal{O}(\sqrt{\Lambda m_b})} \text{SCET}_\text{II}$$



QCD



SCET_I



SCET_II

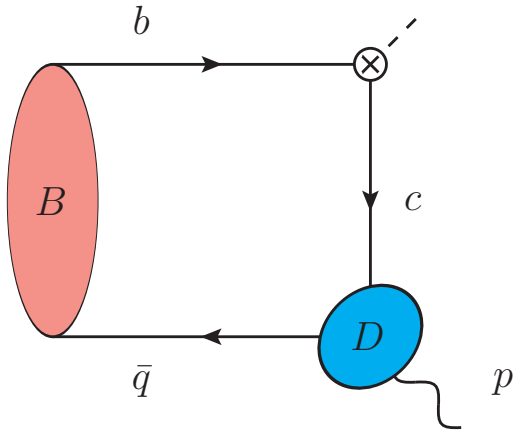
From QCD to SCET: factorization formula @ LP

$$f_{B\to M}(E) = C(E)\xi_a(E) + C^{(B1)}(\tau) \otimes J^{B1}(\tau,\omega) \otimes \phi_M(\tau) \otimes \phi_B(\omega)$$

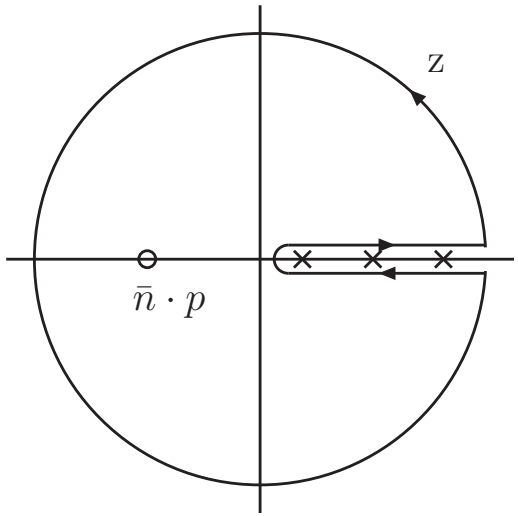
Form factors in LCSR

Two-point correlation function [Colangelo and Khodjamirian, 00'], [Shen and **YBW**, 21'], [Khodjamirian, Melić and Wang, 23']

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



- Dispersion relation
- Borel transformation to avoid the endpoint divergence
- Parton-hadron duality



Subleading power corrections

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

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

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

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

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

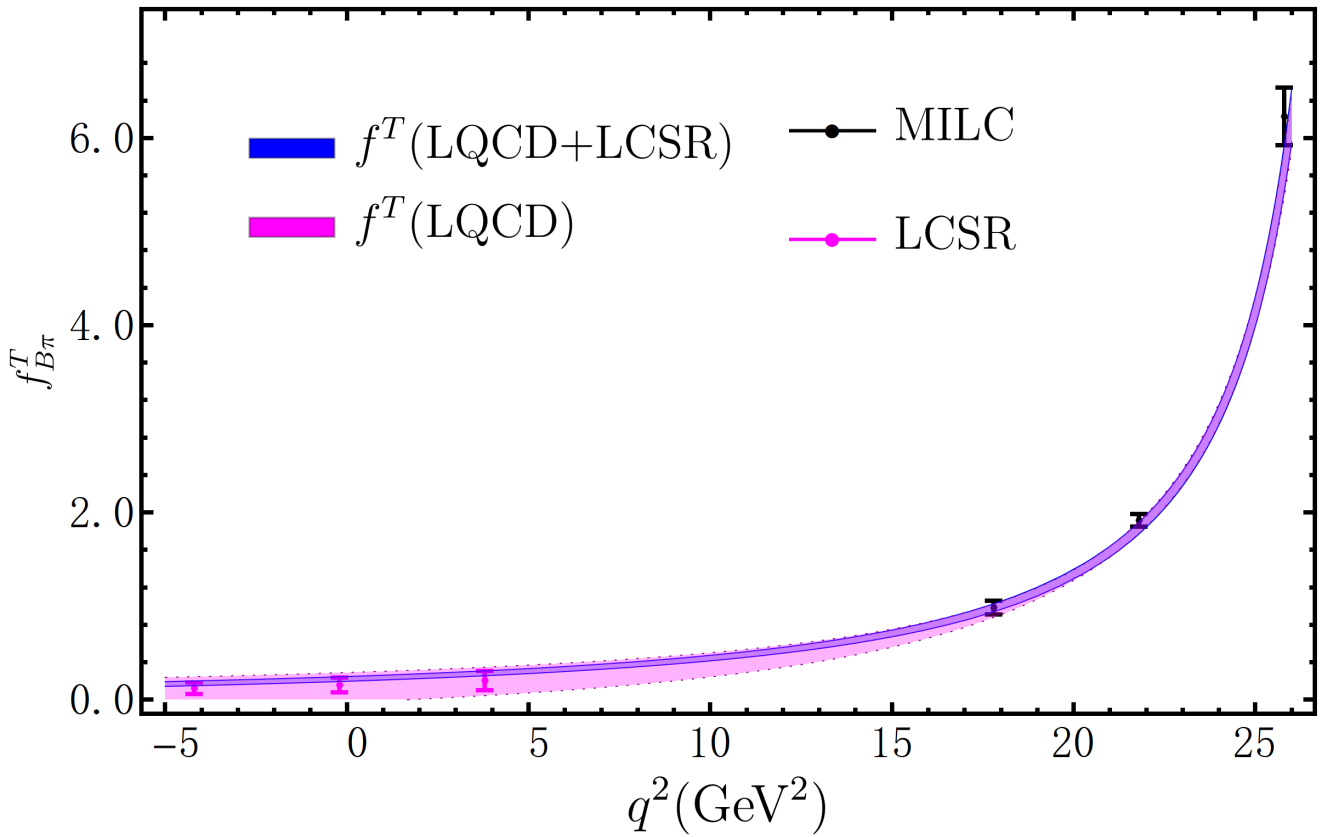
$$b = h_v + \frac{i\not{D}_\perp}{2m_b}h_v + \cdots, \qquad i\not{D}_\perp/m_b \sim \mathcal{O}(\lambda)$$

Collider physics: refactorization of endpoint divergence

- $H \to \gamma\gamma$: [Liu et al., 19'], [Liu et al., 20']
- DIS, DY: [Beneke et al., 22']

$B \to \pi$ form factors

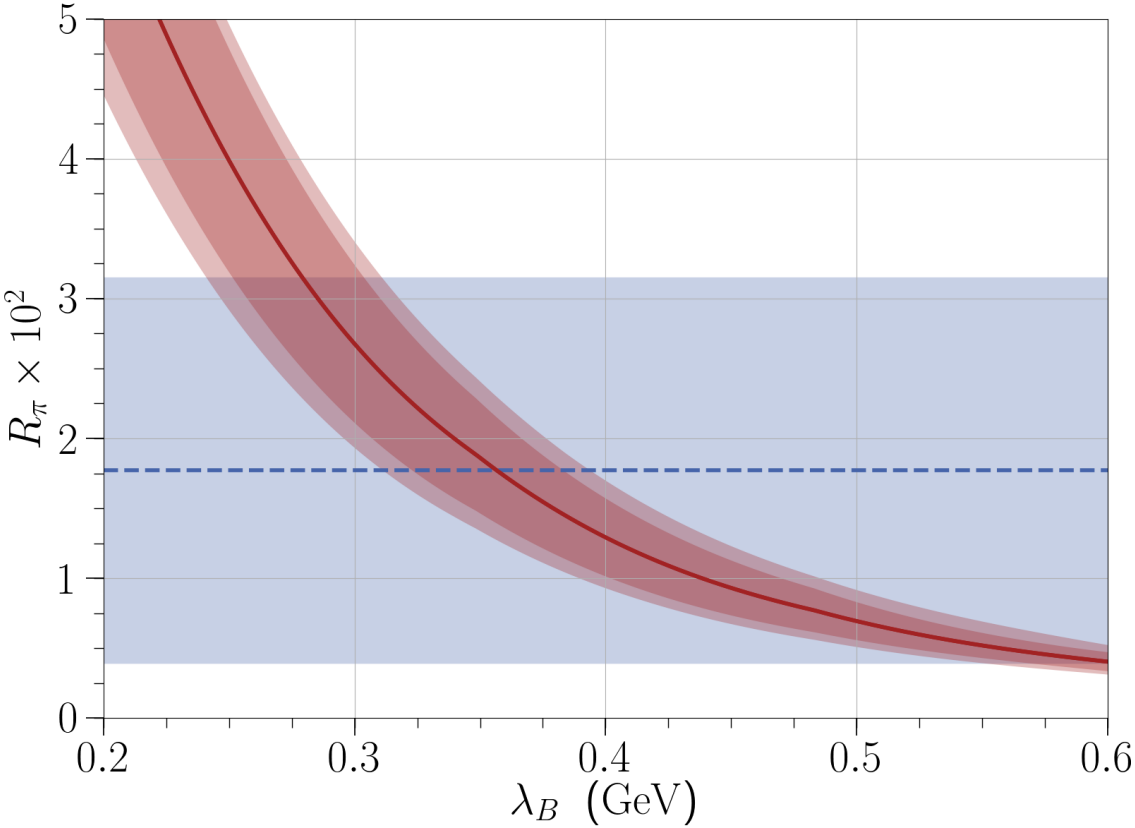
Precision + Accuracy



[Cui, Huang, Shen, Wang and Wang, 22']

$B \to \gamma \ell \nu$ decay: $B \to \gamma$ form factors

Determine the most important non-perturbative parameter in B-meson LCDA: λ_B

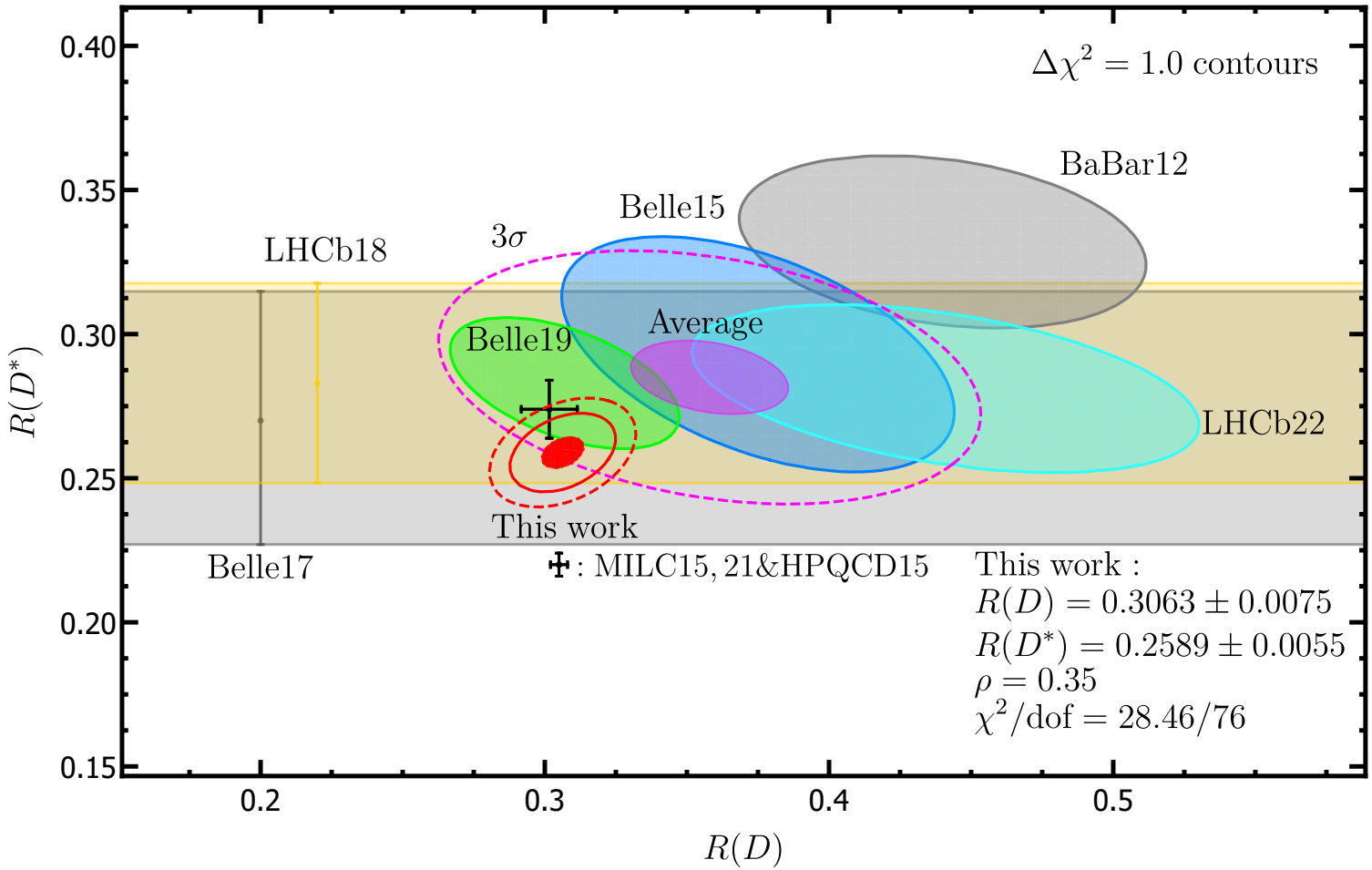


[Beneke, Braun, Ji, and **YBW**, 18']

[Belle, 18']

$R(D^{(*)})$: $B_{(s)} \to D_{(s)}^{(*)}$ form factors

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



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

Summary

- Introduction to the B-meson decay form factors
- $B \to M$ form factors with LCSR: NLP power corrections
  - B-meson higher Fock states
  - Quark-propagator expansion
  - Heavy-quark expansion
- Numerical applications
  - $B \to \gamma \ell \nu$ decay: extract λ_B
  - Determine $R(D^{(*)})$

Thank you!