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Heavy Meson Profiles from First-Principle: Challenges, Advances, and Implementations

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LHCb

Outline

- Motivation
- Challenges in profiling the heavy mesons
- Sequential Effective Theory
- Heavy Meson Light-Cone Distribution Amplitudes & Shape Functions
- Power Corrections
- Heavy Quark Mass RGE
- Summary and Outlook

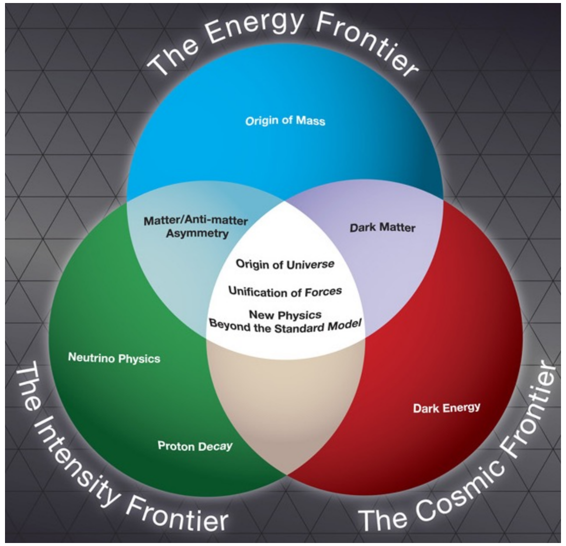
New Physics Hunting

Energy frontier

Search for new particles directly

Intensity frontier

Indirect search of new particles and forces through precision measurements



Cosmic frontier

- **Precision** is key for indirect search of new physics
- Need predictions **as precise as** or **better than** measurements

New Physics Hunting

Physics of interest

Where lattice can help

$$\Gamma = (\text{Weak})\,(\text{EM})\,(\text{QCD})$$

Experimental measurements

Precisely calculated by QED

- Theoretical inputs as important as experimental measurements

$$\frac{\Gamma_1}{\Gamma_2} = \frac{(\text{Weak})_1}{(\text{Weak})_2}\,\frac{(\text{EM})_1}{(\text{EM})_2}\,\frac{(\text{QCD})_1}{(\text{QCD})_2}$$

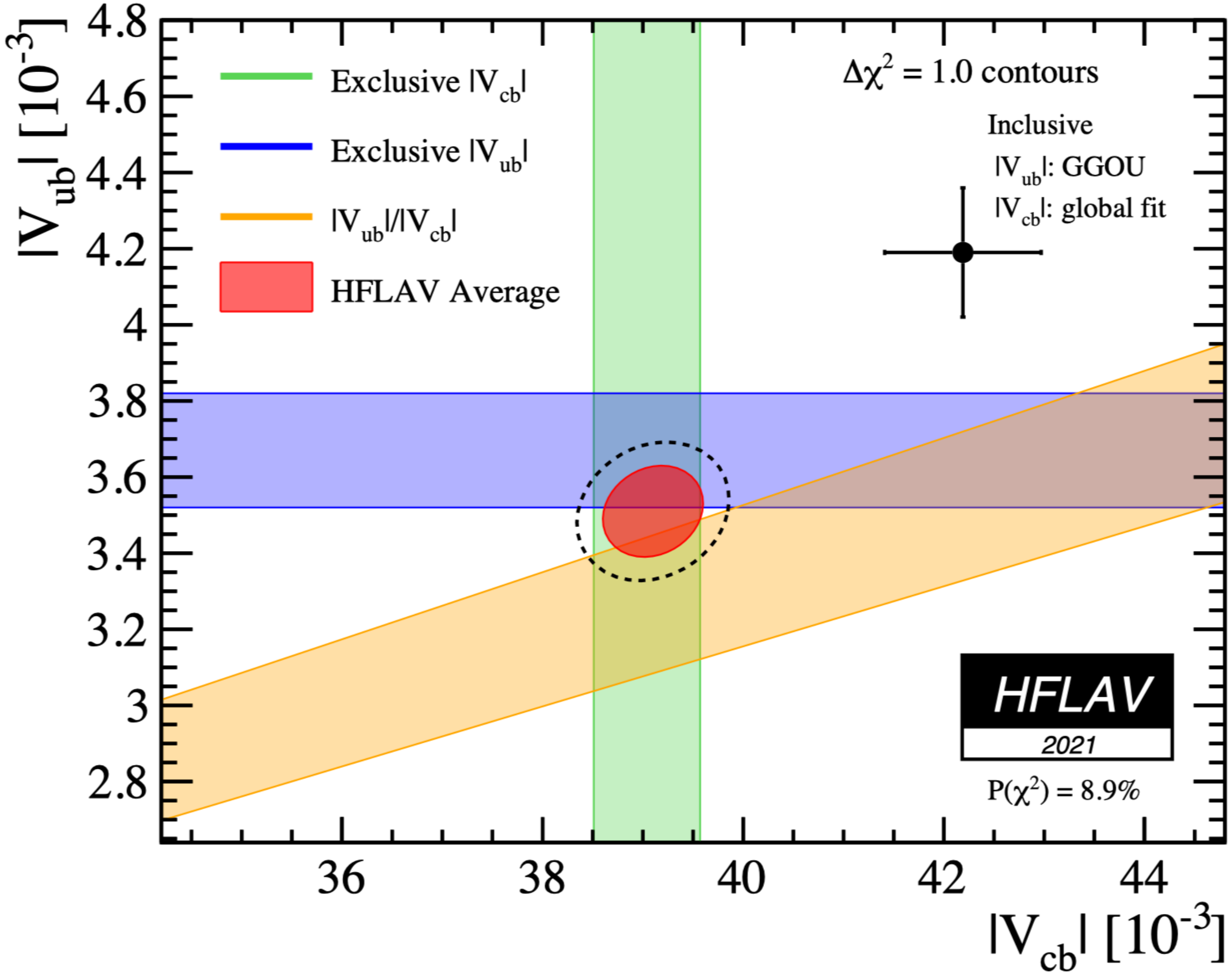
Ratios generally preferred both experimentally and theoretically

$|V_{xb}|$ Puzzle

	$\|V_{ub}\|$ $(\cdot\ 10^{-3})$	$\|V_{cb}\|$ $(\cdot\ 10^{-3})$
Exclusive	3.51 ± 0.12	39.10 ± 0.50
Inclusive	4.19 ± 0.17	42.19 ± 0.78

- Inclusive / exclusive discrepancies for $|V_{ub}|$ and $|V_{cb}|$
- Current tensions stand at $\approx 3.3\sigma$

HFLAV, PRD 107, 052008 (2023)



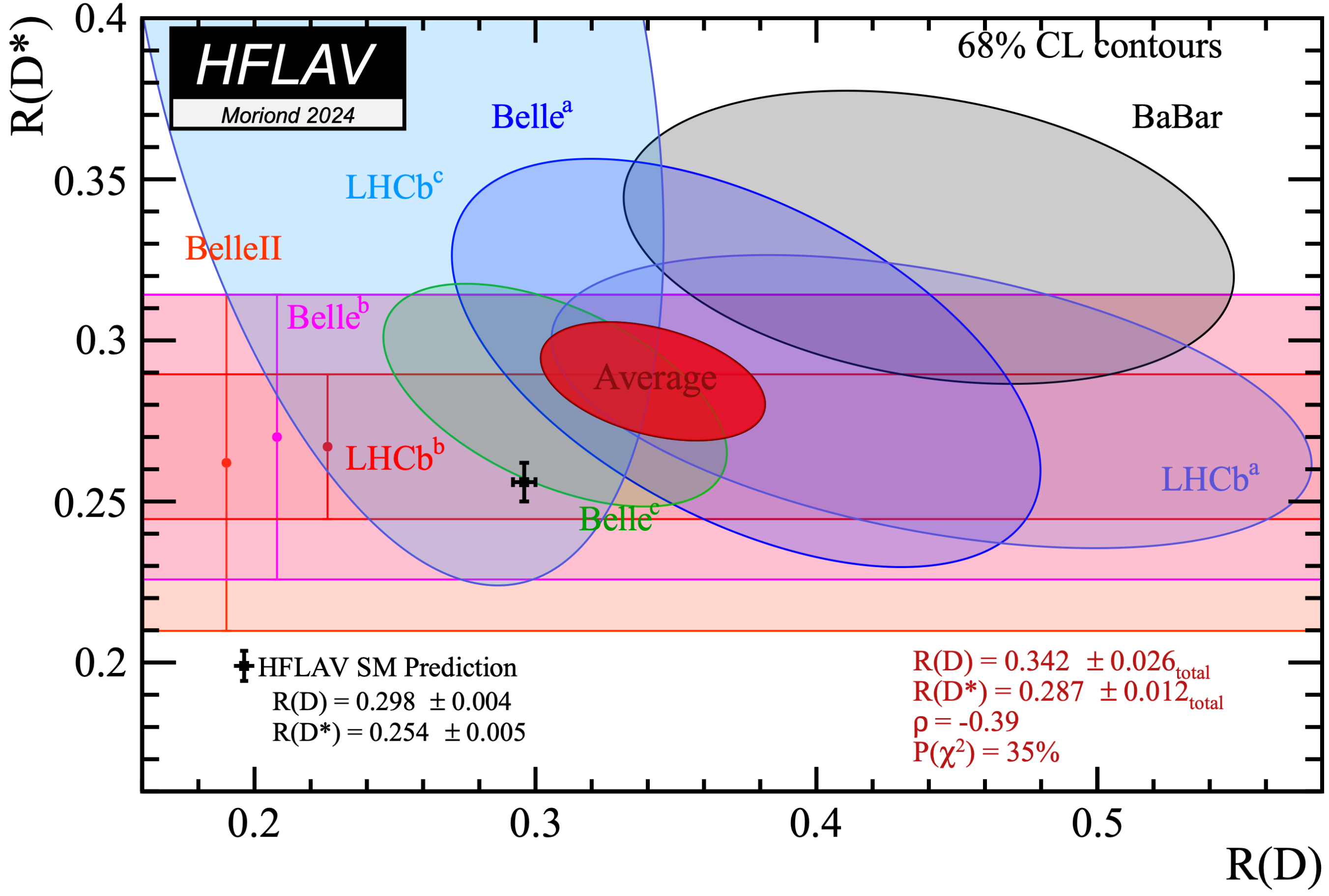
$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

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

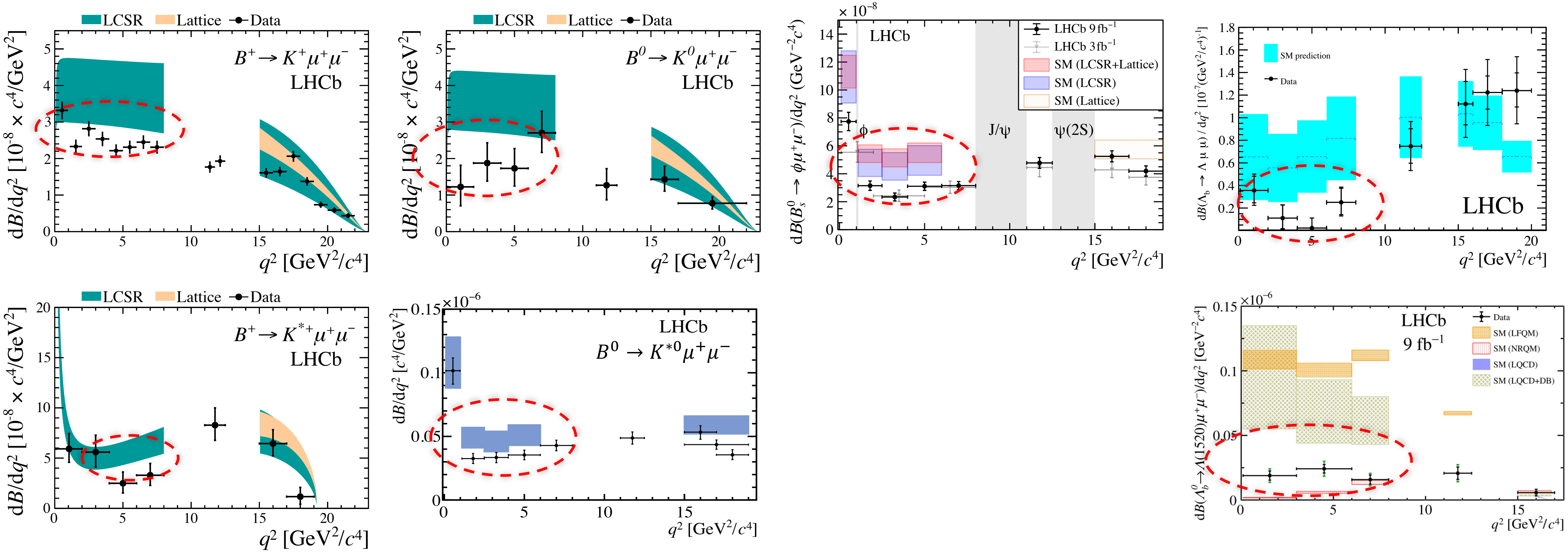
	R(D)	R(D*)
Exp	0.342 ± 0.026	0.287 ± 0.012
SM	0.298 ± 0.004	0.254 ± 0.005

- **Current combined tensions at $\approx 3.31\sigma$**

HFLAV, preliminary average for Moriond 2024

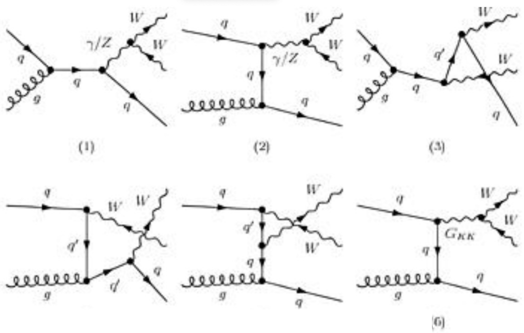
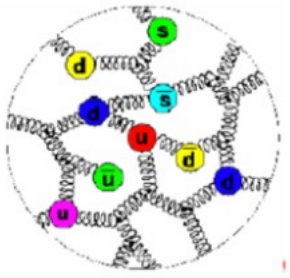


$b \to s\ell\ell$ rare decays



- **Significant deviations** between experiment data and theoretical predictions
- Ubiquitous: $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$, $\Lambda_b \to \Lambda\mu\mu$

QCD Factorization Theorem

Perturbative	Nonperturbative
High energy Small distance Asymptotic freedom	Low energy Large distance Confinement
 << 0.1 fm	 > 1 fm

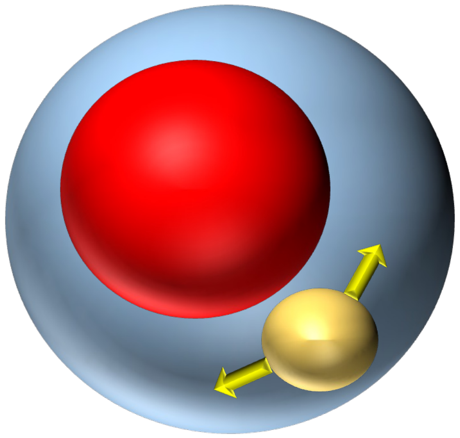
- Semileptonic decays $B \to M\ell\bar{\nu}$:
- FCNC processes $B^0 \to K^*\ell\ell$:
- Nonleptonic decays $B \to \pi\pi, \pi K$:

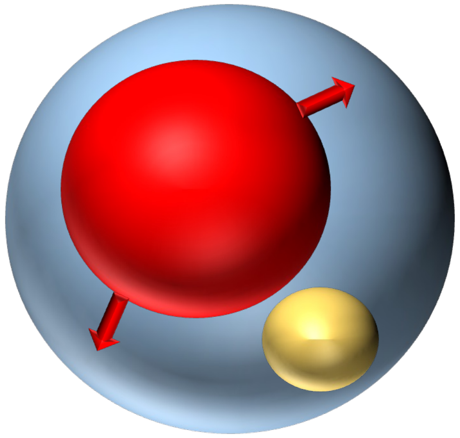
Hard kernel $\otimes$ **Form factor** $\otimes$ Light-cone distribution amplitudes (LCDAs)

- Inclusive decays $\bar{B} \to X_s\gamma, X_u\ell\bar{\nu}$: Hard function $\otimes$ Jet function $\otimes$ Shape function

Heavy Meson Profiles

- A heavy flavor meson consists of a pair of heavy and light quarks.





LCDAs describe the momentum distribution amplitude of the light quark.

Shape function characterizes the momentum distribution function of the heavy quark.

$$\varphi^+(\omega,\mu) = \frac{1}{i\,\tilde{f}_{H_Q} m_{H_Q} n_+\cdot v}\int \frac{dt}{2\pi}\, e^{-i\omega t n_+\cdot v} \times \langle 0\,|\,\bar{q}(tn_+)\not{n}_+\gamma_5\, W_c(tn_+,0)h_v(0)\,|\,H_Q(v)\rangle$$

$$S(\omega,\mu) = \frac{1}{2m_{H_Q}}\int \frac{dt}{2\pi}\, e^{-i\omega t n_+\cdot v} \times \langle H_Q(v)\,|\,\bar{h}_v(tn_+,0)W_c(tn_+,0)h_v(0)\,|\,H_Q(v)\rangle$$

- **They provide the most essential information about the profile of heavy mesons.**

What we know?

- **Limited understanding** of the nonperturbative heavy meson LCDAs and SFs:
  - Only models for heavy meson LCDAs:

    Grozin, Neubert, 1997; Braun, Ivanov, Korchemsky, 2004; Beneke, Braun, Ji, Wei, 2018; ……
  - Only models for heavy meson SFs:

    Korchemsky, Sterman, 1994; Bauer, Luke, Mannel, 2001; Neubert, 2005; Lee, Ligeti, Stewart, Tackmann, 2006; ……
  - Relations between LCDAs and SFs?

    Yaouanc, Oliver, Raynal, 2008

- Uncertainties from heavy meson LCDAs **dominate** the errors in theoretical calculation.
  - *e.g.*: $B \to \pi,\ K^*$ form factors from LCSRs:

$$\mathcal{V}_{B\to K^*}(0) = 0.359^{+0.141}_{-0.085}\Big|_{\lambda_B}{}^{+0.019}_{-0.019}\Big|_{\sigma_1}{}^{+0.001}_{-0.062}\Big|_{\mu}{}^{+0.010}_{-0.004}\Big|_{M^2}{}^{+0.016}_{-0.017}\Big|_{s_0}{}^{+0.153}_{-0.079}\Big|_{\varphi_\pm(\omega)},$$

$$f^+_{B\to\pi}(0) = 0.122 \times \Big[1 \pm 0.07\Big|_{S_0^\pi} \pm 0.11\Big|_{\Lambda_q} \pm 0.02\Big|_{\lambda_E^2/\lambda_H^2}{}^{+0.05}_{-0.06}\Big|_{M^2} \pm 0.05\Big|_{2\lambda_E^2+\lambda_H^2}{}^{+0.06}_{-0.10}\Big|_{\mu_h} \pm 0.04\Big|_{\mu}{}^{+1.36}_{-0.56}\Big|_{\lambda_B}{}^{+0.25}_{-0.43}\Big|_{\sigma_1,\sigma_2}\Big].$$

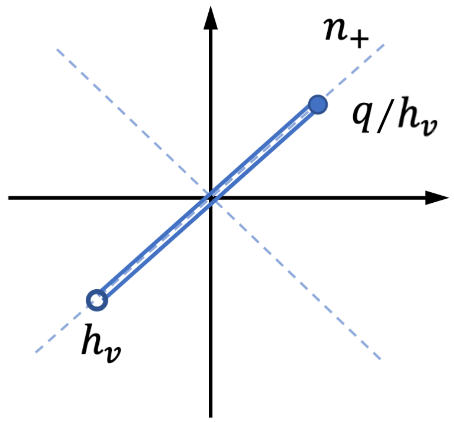
Gao, Lu, Shen, Wang, Wei, PRD 101 (2020) 074035

Cui, Huang, Shen, Wang, JHEP 03 (2023) 140

Challenges in profiling the heavy mesons from first-principles

- Light-like correlators containing HQET fields:

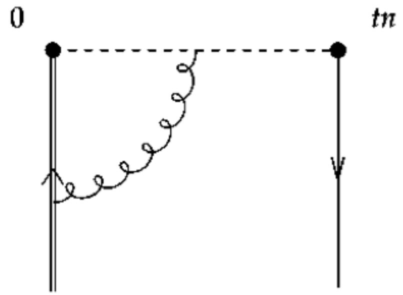
$$\langle 0|\bar{q}\, W_c\, h_v|H_Q\rangle, \qquad \langle H_Q|\bar{h}_v\, W_c\, h_v|H_Q\rangle$$



Challenge 1: light-like correlators

- **OPE**: Expansion into **local** operators matrix elements ⇒ QCD sum rule, Lattice QCD
- **LaMET**: From equal-time correlation functions to light-cone variables ⇒ Lattice QCD

Challenge 2: Cusp divergence



$$O_v^{\rm ren}(t,\mu) = \frac{4}{\hat{\epsilon}} \ln(it\mu)\, O_v^{\rm bare}(t) + \ldots \xrightarrow{t\to 0} \log 0! \Rightarrow$$ NO LOCAL LIMIT!

OPE Breakdown……

…… the remaining issues can only be addressed by LaMET

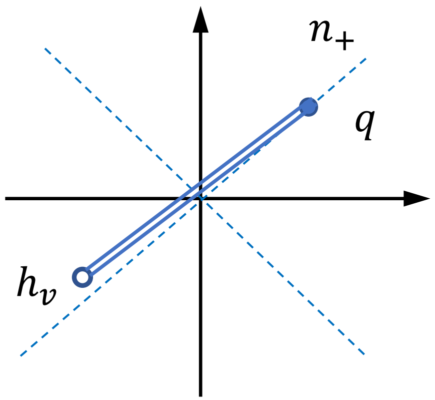
LaMET: matching from **equal-time correlators** of highly boosted hadrons to **light-cone observables**.

🤔 **Equal-time correlator?**

An intuitive approach: adopt **off light-cone Wilson line** to avoid cusp divergence

$$\langle H_Q(P_{H_Q})\,|\,\bar{q}(z)\not{n}_z\gamma_5\,W_c(z,0)h_v(0)\,|\,0\rangle \qquad \langle H_Q(v)\,|\,\bar{h}_v(z,0)W_c(z,0)h_v(0)\,|\,H_Q(v)\rangle$$

Wang, Wang, Xu, Zhao, PRD 102, 011502 (2020);
Xu, Zhang, PRD 106, 114019 (2022);
Hu, Xu, Zhao, EPJC 84, 502 (2024); ……



Need to realize the **boosted HQET fields on lattice**.

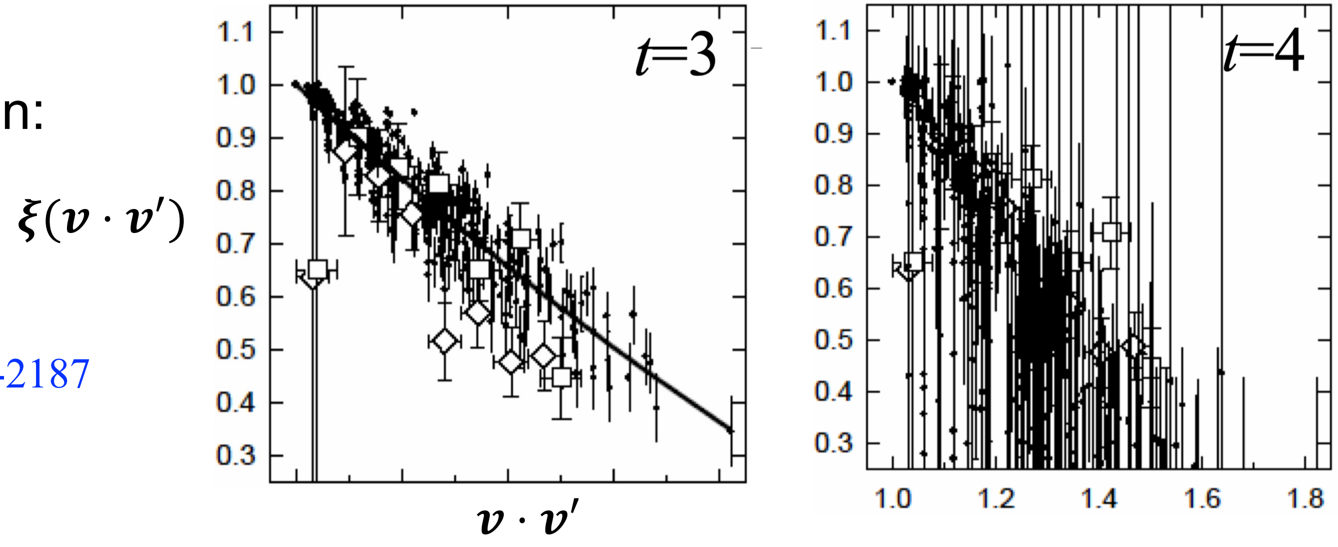
Boosted HQET on Lattice

- HQET: $\mathcal{L}_{\mathbf{HQET}} = \bar{h}_v(x)\, i v\cdot D h_v(x)$ $\xrightarrow{\text{Discretization}}$ $\bar{h}_v(x)\,(-v_0 D_0 + i\vec{v}\cdot\vec{D})\, h_v(x)$
- The QCD field is recovered by: $\psi(x) = e^{-imv\cdot x}\dfrac{1+\not{v}}{2} h_v(x)$
- Evolution equation of HQET propagator:

$$G(x+\hat{t}) = U_4^{\dagger}(x)\,(1 + i\vec{v}\cdot\vec{D})G(x)$$

Significant signal-to-noise (StN) problem

e.g. Isgur-Wise function:



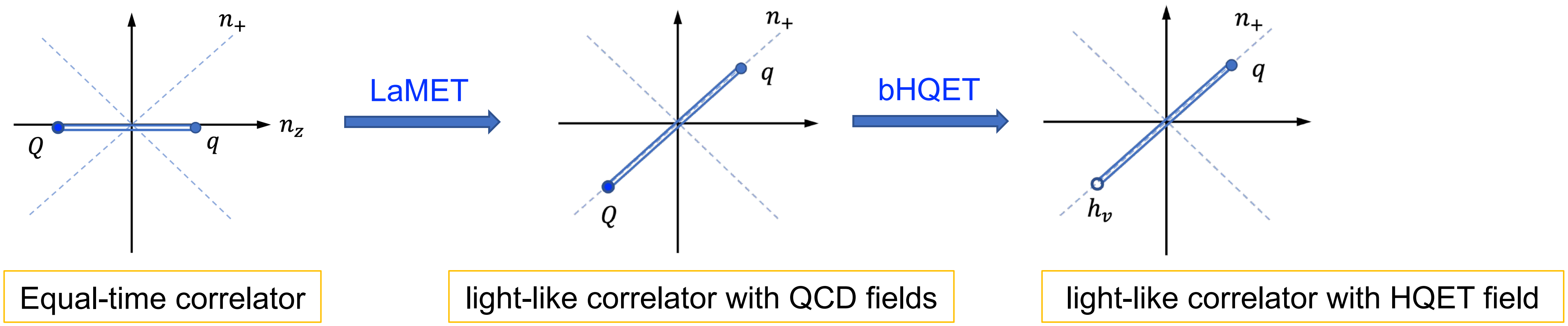
Mandula, Ogilvie, PRD 45, 2183-2187 (1992); NPB 34, 480-482 (1994)

Sequential Effective Theory (SET)

🤔 **Equal-time correlator + QCD fields?**

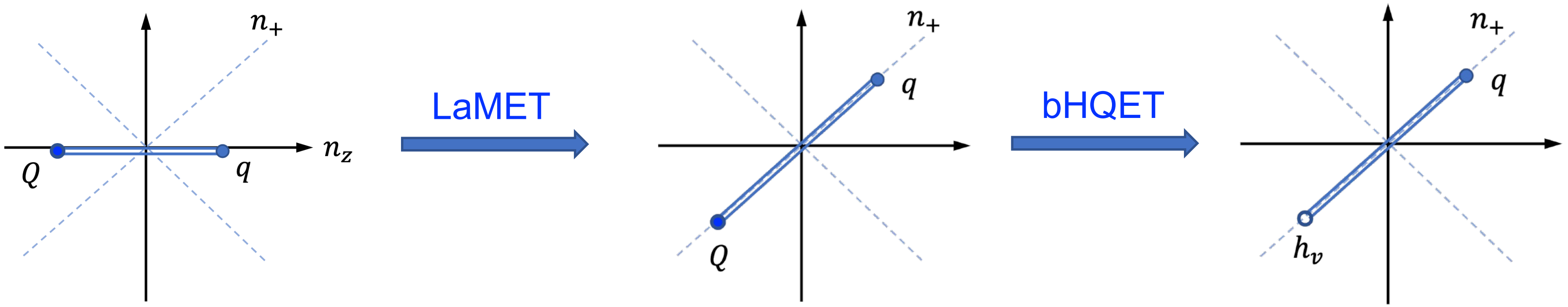
- Equal-time correlator ⇒ light-like correlator: **LaMET**
- QCD field ⇒ moving HQET field: **boosted HQET**

⇒ **A two-step factorization to combine LaMET and bHQET.**



arXiv:2403.17492 [hep-ph]; PRD111, 034503, (2025)

SET on lattice



Equal-time correlator | light-like correlator with QCD fields | light-like correlator with HQET field

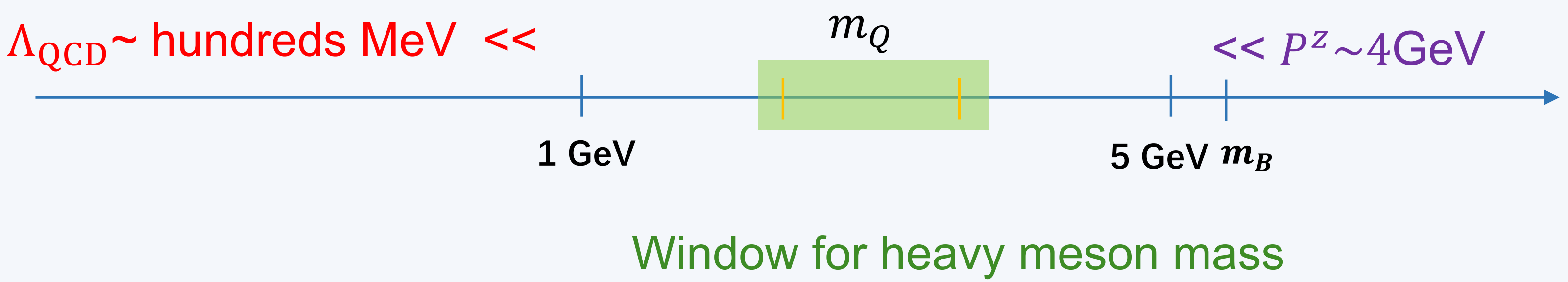
- **3 scales** in the equal-time correlator: $\boldsymbol{\Lambda_{\rm QCD}, m_Q, P^z}$

- Effective theories:
  - LaMET: $\Lambda_{\rm QCD}, m_{\rm Q} \ll P^z$ and integrate out P^z
  - bHQET: $\Lambda_{\rm QCD} \ll m_{\rm Q}$ and integrate out $m_{\rm Q}$

$\Rightarrow$ Introduce a hierarchy $\boldsymbol{\Lambda_{\rm QCD} \ll m_Q \ll P^z}$

SET on lattice

- **Lattice feasibility** at this stage:



Only valid for *D* mesons, rather than *B* mesons?

✓ Heavy quark flavor symmetry ensures that the HQET measurement is independent of heavy quark mass;

✓ m_Q (m_c or m_b) only contributes to the power corrections.

Implementing SET: Heavy Meson LCDAs

Quasi DA → (**LaMET**) → **QCD LCDA** → (**bHQET**) → **HQET LCDA**

- Step I: matching in LaMET

$$\tilde{\phi}(x,P^z) = \int_0^1 dy C\left(x,y,\frac{\mu}{P^z}\right)\phi(y,\mu) + \mathcal{O}\left(\frac{m_H^2}{(P^z)^2}, \frac{\Lambda_{\rm QCD}^2}{(xP^z,\bar{x}P^z)^2}\right)$$

matching kernel @ NLO:

$$C\left(x,y,\frac{\mu}{P^z}\right) = \delta(x-y) + C_B^{(1)}\left(x,y,\frac{\mu}{P^z}\right) - C_{CT}^{(1)}(x,y) + \mathcal{O}(\alpha_s^2),$$

$$C_B^{(1)}\left(x,y,\frac{\mu}{P^z}\right) = \frac{\alpha_s C_F}{2\pi}\begin{cases} [H_1(x,y)]_+ & x<0<y \\ [H_2(x,y,P^z/\mu)]_+ & 0<x<y \\ \left[H_2\left(1-x,1-y,\frac{P^z}{\mu}\right)\right]_+ & y<x<1 \\ [H_1(1-x,1-y)]_+ & y<1<x \end{cases},$$

$$C_{CT}^{(1)} = -\frac{3\alpha_s C_F}{4\pi}\left[\frac{2\mathrm{Si}[(x-y)z_s P^z]}{\pi(x-y)}\right]_+,$$

- Step II: matching in bHQET

$$\varphi^+(\omega,\mu) = \begin{cases} \varphi^+_{\rm peak}(\omega,\mu), & \omega\sim\Lambda_{\rm QCD} \\ \varphi^+_{\rm tail}(\omega,\mu). & \omega\sim m_H \end{cases}$$

with:

$$\varphi^+_{\rm peak}(\omega,\mu) = \frac{1}{m_H}\frac{f_H}{\tilde{f}_H}\frac{1}{\mathcal{J}_{\rm peak}}\phi(y,\mu;m_H)$$

$$\varphi^+_{\rm tail}(\omega,\mu) = \frac{\alpha_s C_F}{\pi\omega}\left[\left(\frac{1}{2}-\ln\frac{\omega}{\mu}\right) + \frac{4\bar{\Lambda}}{3\omega}\left(2-\ln\frac{\omega}{\mu}\right)\right],$$

Liu, Wang, Xu, **QAZ**, Zhao, PRD 99, 094036 (2019)

Han, **QAZ**, *et.al.*, PRD111, 034503, (2025)

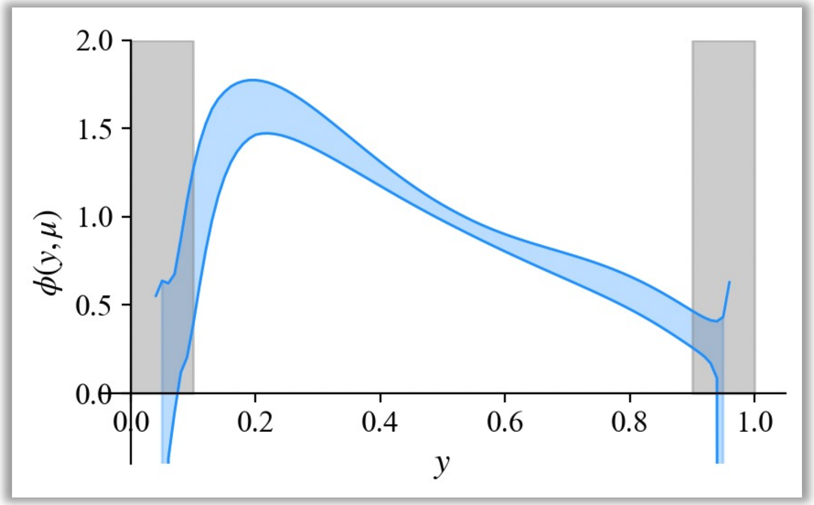
Ishaq, Jia, Xiong, Yang, PRL125, 132001 (2020)

Beneke, Finauri, Vos, Wei, JHEP 09, 066 (2023)

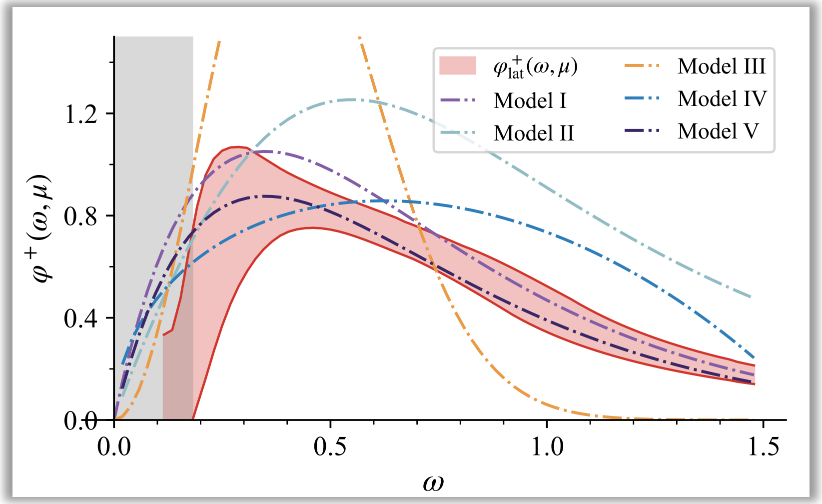
Lee, Neubert, PRD 72, 094028 (2005)

Implementing SET: Heavy Meson LCDAs

D meson QCD LCDA



HQET LCDA φ^+



⇐ Numerical results for heavy meson LCDAs

⇓ Inverse and inverse-logarithmic moments

	λ_B (GeV)	$\sigma_B^{(1)}$	
This work	0.376(63)	1.66(13)	PRD111, 034503, (2025)
Ref.[16]	> 0.24		PRD98, 112016, (2018)
Ref.[54]	0.383(153)		JHEP 10, 043 (2020)
Ref.[7]	0.48(11)	1.6(2)	PRD72, 094028 (2005)
Ref.[12]	0.46(11)	1.4(4)	PRD69, 034014 (2004)
Ref.[5]	0.35(15)		PRD55, 272290 (1997)
Ref. [14]	$0.343^{+0.064}_{-0.079}$		PRD101, 074035 (2020)
Ref.[56]	0.338(68)		PLB848, 138345 (2024)

Implementing SET: Heavy Meson LCDAs

	Existing	On-going
Action	Tadpole improved Wilson clover fermion action	
Improvement	—	HYP smear for Wilson line; Multi-source enhancement
Lattice spacing	a=0.05187fm	a=0.0775fm, 0.06826fm, 0.05187fm
NPR	Simplified hybrid scheme	Hybrid scheme based on self-renormalization
Pz extrapolation	—	Infinite momentum extrapolation
Statistics	~5k	60k~100k

Han, **QAZ**, *et.al.*, arXiv:2403.17492 [hep-ph]; PRD111, 034503, (2025)

QAZ, *et.al.*, arXiv:25xx.xxxxx

Implementing SET: Heavy Meson Shape Functions

- Connections between SFs with HQET and QCD fields:

$$S^{\rm QCD}(x,\mu) = \begin{cases} Z_{\rm peak}(x,\omega,\mu) \otimes S^{\rm HQET}(\omega,\mu)\,, & x\sim 1 \\ Z_{\rm tail}(x,\mu)\,, & x \sim 0 \end{cases}$$

with NLO matching kernel in peak region:

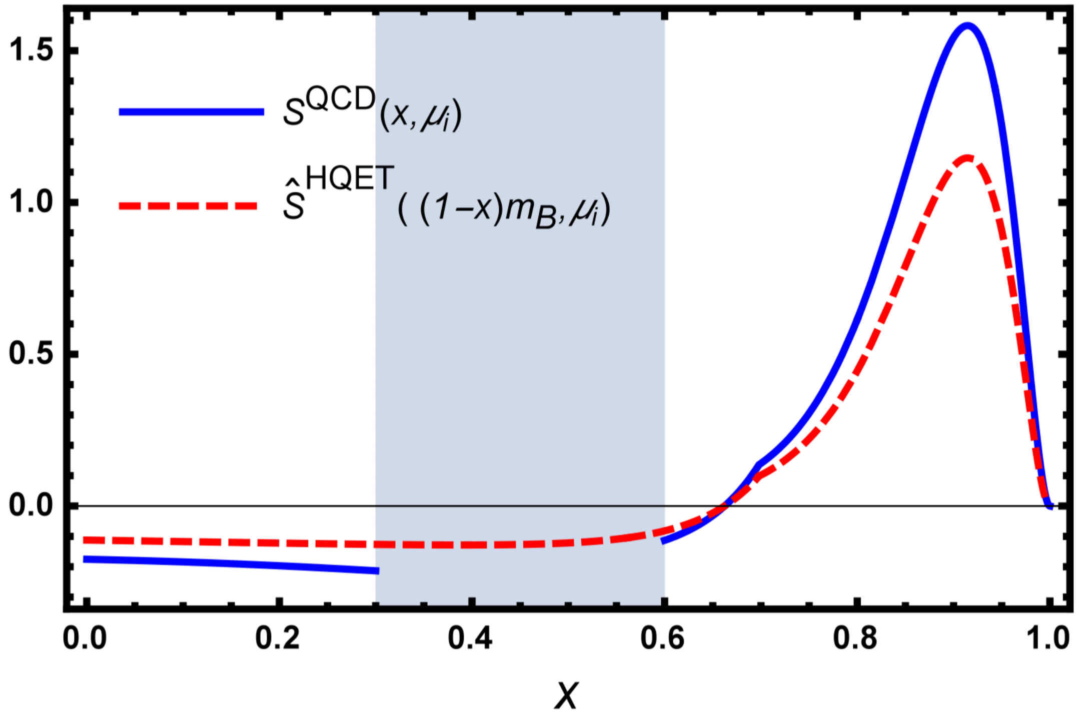
$$Z^{(1)}_{\rm peak}(x,\omega,\mu) = \left(\frac{1}{2}\ln^2\frac{\mu^2}{m_b^2} - \frac{3}{2}\ln\frac{\mu^2}{m_b^2} + \frac{\pi^2}{12} - 2\right) \times\delta(x m_B v^+ - m_b v^+ - \omega v^+)\,.$$

and tail region

$$Z^{(1)}_{\rm tail}(x,\mu) = \frac{1}{m_b v^+}\frac{1+x^2}{1-x}\left[-1+\ln\frac{\mu^2}{(1-x)^2 m_b^2}\right].$$

- QCD SFs are refer to the PDF of B meson.

Illustration of the matching based on modelized QCD SF

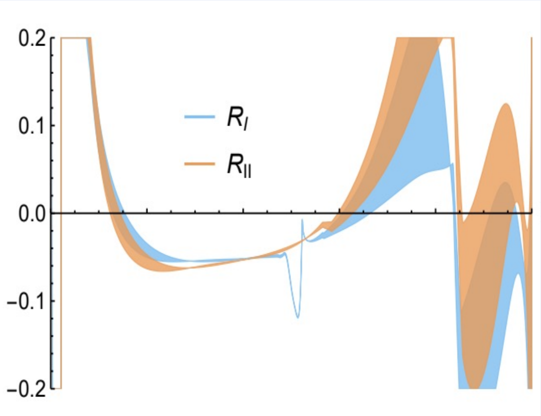


Wang, Xu, **QAZ**, Zhao, arXiv:25xx.xxxx

Improving SET: Power Corrections

3 scales in SET introducing the following powers:

- Heavy hadron mass correction in LaMET: $M^2/(P^z)^2$:



- Smaller than 20% in most region;
- Smaller than 10% in the region we perform bHQET matching.

Han, Wang, Zhang, Zhang, *PRD* 110, 094038 (2024)

- Power correction in LaMET: $\Lambda^2_{\rm QCD}/(xP^z)^2$:
  - Significant at end-point region ($x \to 0, 1$) of the QCD LCDA;
  - Can be improved by considering the renormalon resummation, …

Su, Holligan, Ji, Yao, Zhang, Zhang, NPB 991, 116201 (2023)

- Heavy quark mass correction in bHQET: $\Lambda_{\rm QCD}/m_Q$:
  - A possible solution proposed in [Deng, Wang, Wei, Zeng, PRD110, 114006, (2024)]
  - HQET LCDA shows degeneracy in the Dirac structures due to heavy quark spin symmetry;
  - This power correction can be estimated from pseudoscalar and vector meson HQET LCDA.

Extending SET: Heavy Quark Mass RGE

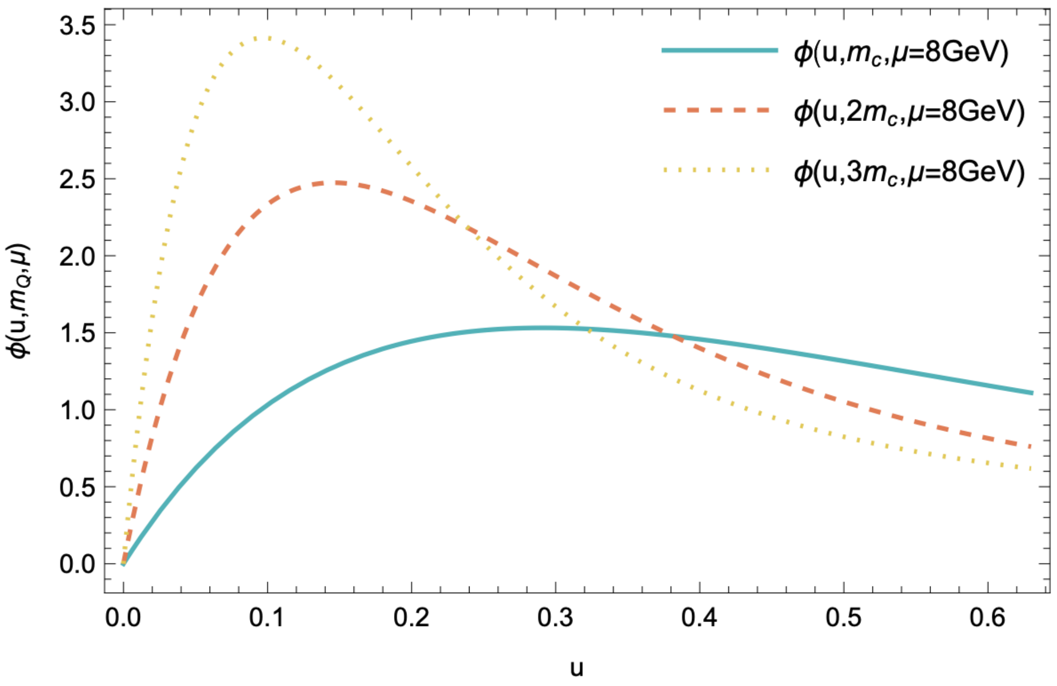
- As a key scale in HQET, m_Q reflects the intrinsic dynamics in heavy hadrons.
- Theoretically, m_Q is either $\boldsymbol{m_c}$ **or** $\boldsymbol{m_b}$. While lattice QCD enables simulations at arbitrary m_Q, this motivates systematic studies of $\boldsymbol{m_Q}$ **evolutions** in heavy hadronic systems.
- The $\boldsymbol{m_Q}$**-RGE** of heavy meson LCDAs:

Wang, Xu, **QAZ**, Zhao, arXiv:2411.07101 [hep-ph]

$$m_Q \frac{\partial}{\partial m_Q}\phi(u, m_Q; \mu) - u\frac{\partial}{\partial u}\phi(u, m_Q; \mu) - (1 + \gamma(m_Q, \mu))\phi(u, m_Q; \mu) = 0,$$

and its solution

$$\phi(u, m_Q; \mu) \approx \exp\left[\frac{2C_F}{\beta_0}\ln\frac{\alpha_s(m_Q)}{\alpha_s(m_{Q_0})} - \frac{4\pi C_F}{\beta_0^2}\left(\frac{1}{\alpha_s(m_{Q_0})}\ln\frac{\alpha_s(\mu)}{\alpha_s(m_{Q_0})e} - \frac{1}{\alpha_s(m_Q)}\ln\frac{\alpha_s(\mu)}{\alpha_s(m_Q)e}\right)\right]\frac{m_Q}{m_{Q_0}}\phi_0\left(u\frac{m_Q}{m_{Q_0}}\right).$$



Summary and Outlook

- Sequential effective theory (SET) bridges lattice calculable Euclidean correlators to the parton distribution profiles of heavy mesons.

  - **Heavy meson LCDAs:**
    - ✓ Factorization has been established;
    - ✓ Preliminary lattice QCD results are now available;
    - ☐ Awaiting for more systematic lattice QCD investigations.

  - **Heavy meson shape function:**
    - ✓ Factorization has been proposed;
    - ☐ Expecting further validation in lattice QCD calculations.

- Significant progress has been made in the perturbative sector. Opportunity now lies with lattice QCD!

Thanks for your attention!