兰州大學 | LANZHOU UNIVERSITY

Recent progress on heavy quark physics

——A personal perspective

报告人：徐吉　　兰州大学

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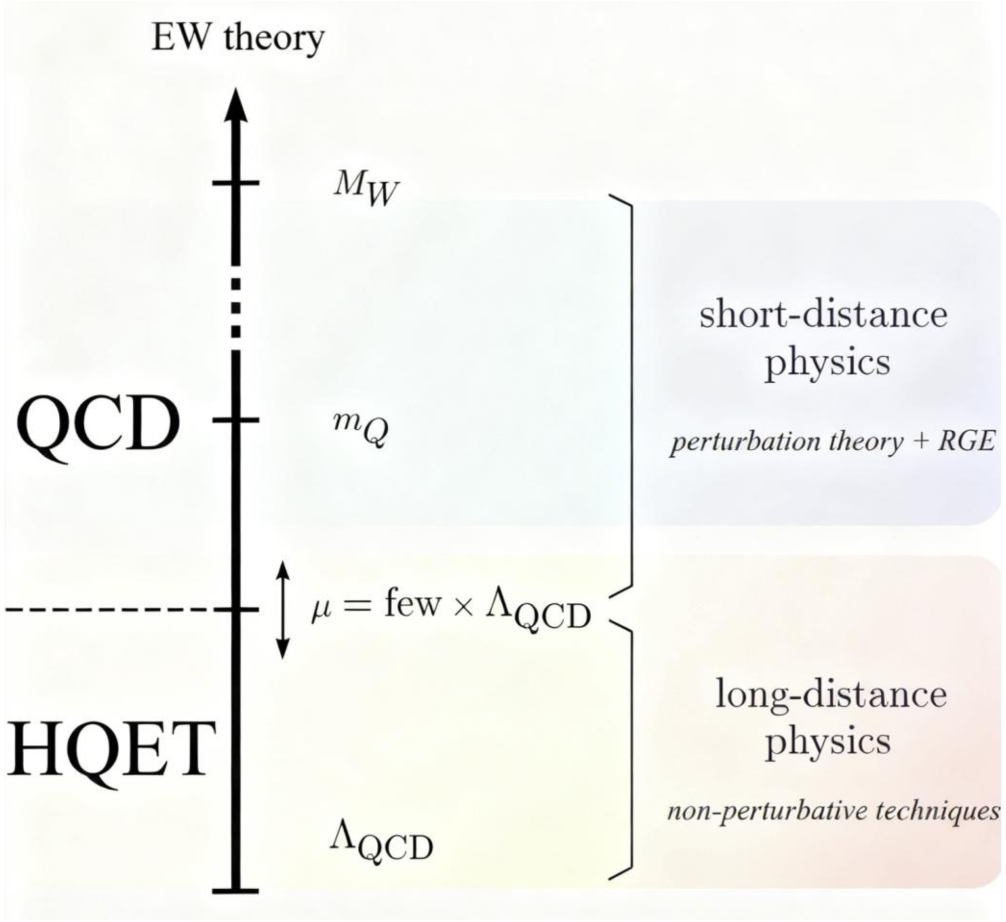
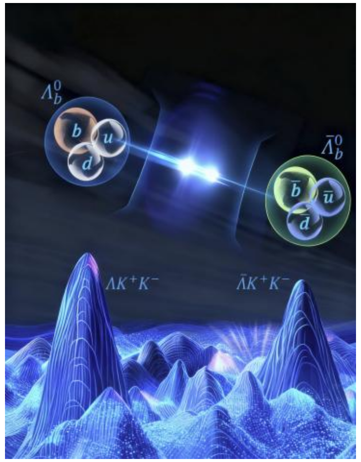
第二十二届全国重味物理与CP破坏研讨会

Importance of heavy quark physics

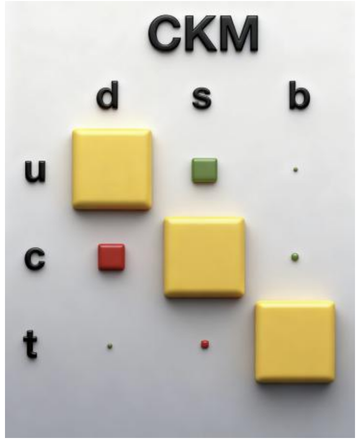
B-meson dynamics is an especially simple way in principle of learning about the properties of single, constituent quarks. —— **Bjorken**



- **Study on CP violation**



- **Precisely testing the SM**

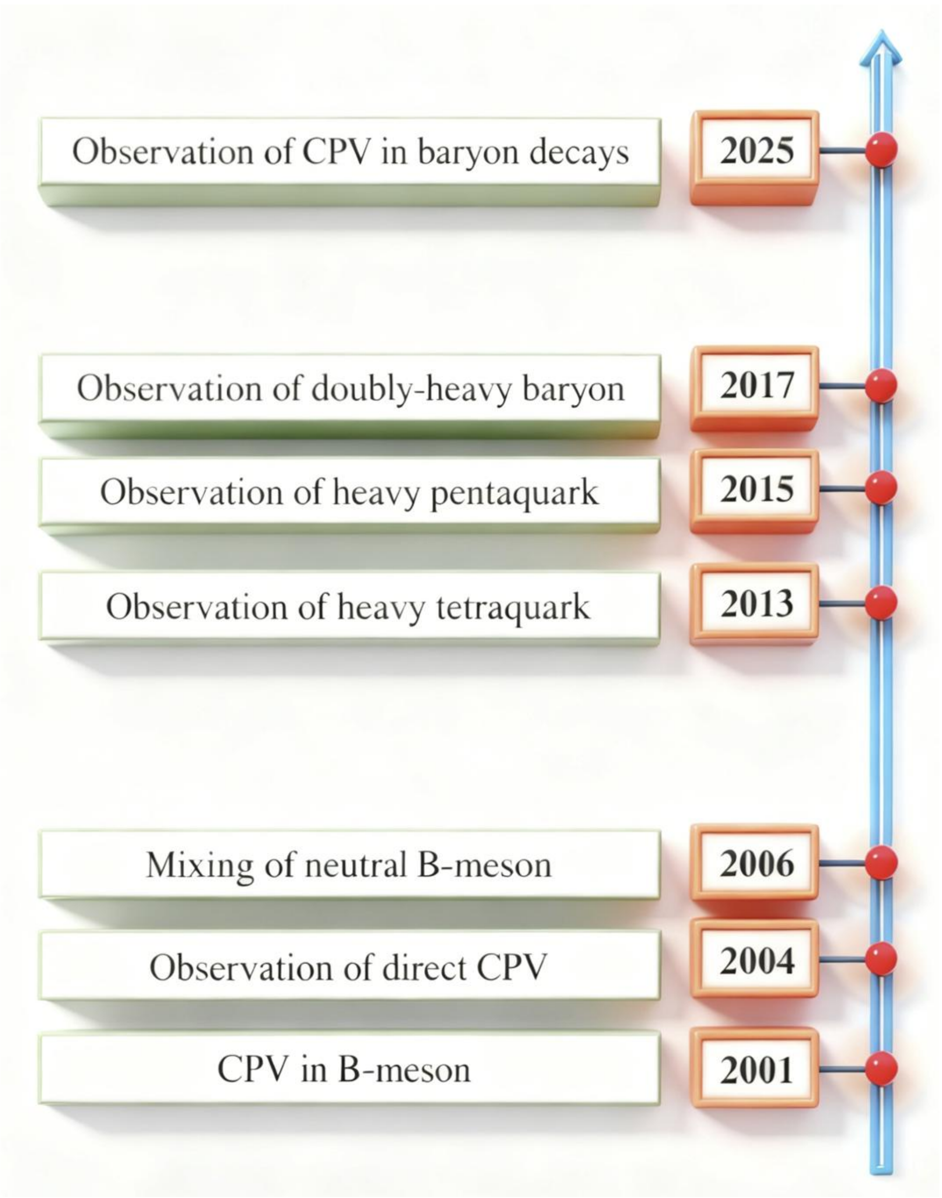


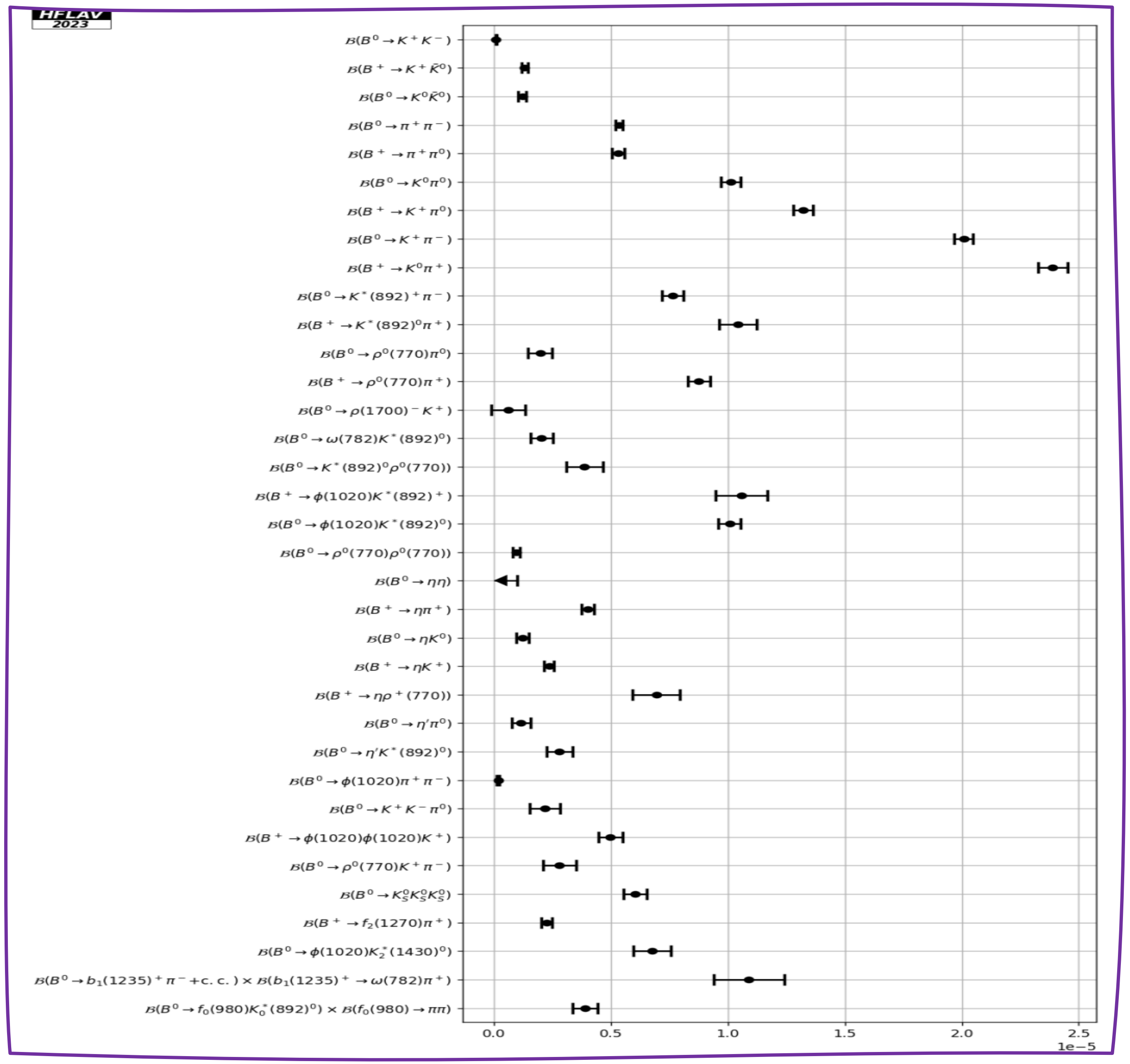
- **Searching for NP**

Era of high precision

B-meson dynamics is an especially simple way in principle **(alas, not so much in experimental practice)** of learning about the properties of single, constituent quarks. —— **Bjorken (1996)**

Era of high precision



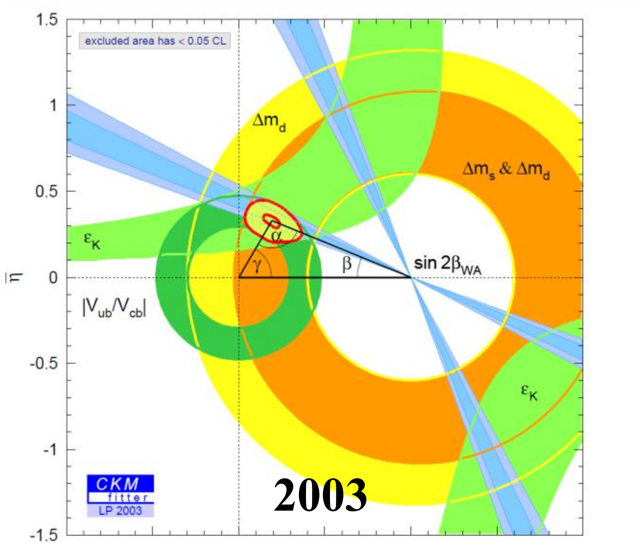


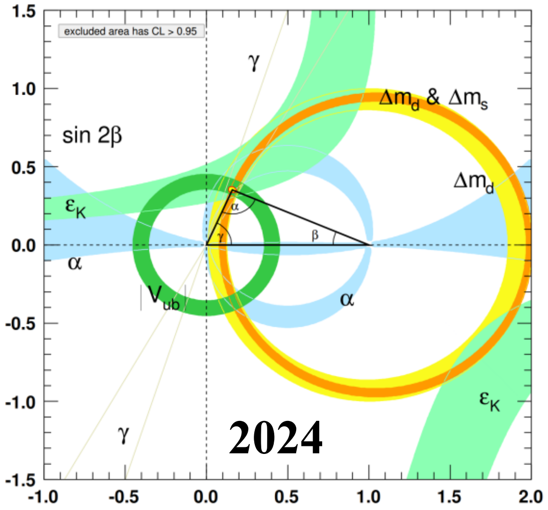
Era of high precision

Much progress achieved thanks to experiment and theory

- Test on Unitarity Triangle

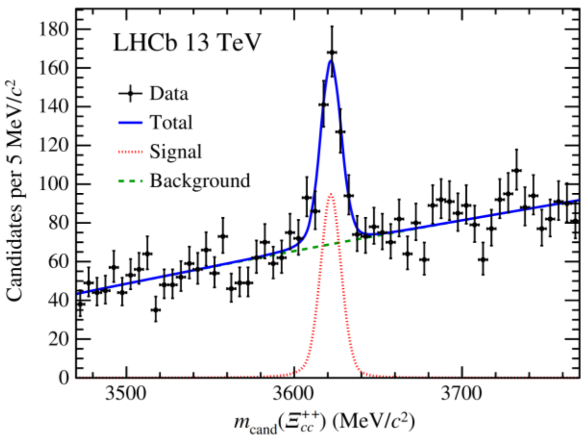
  $(2003 \rightarrow 2024)$

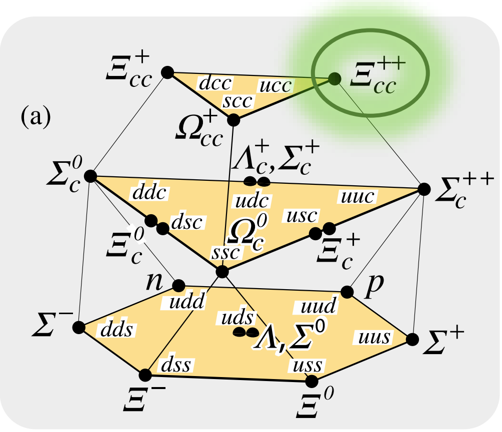




- Discovery on doubly-heavy baryon

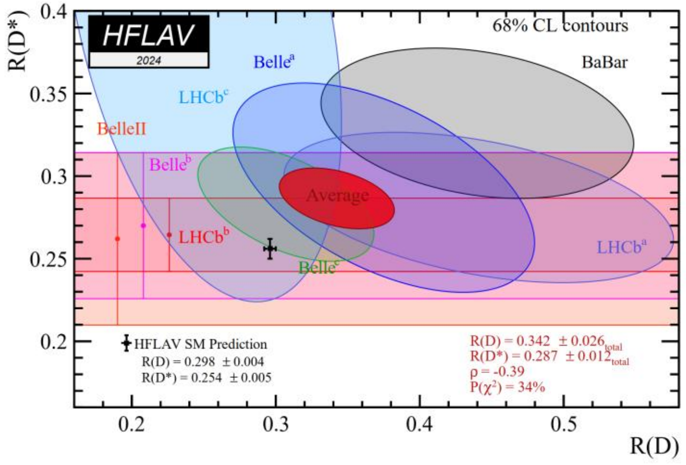
  (2017)



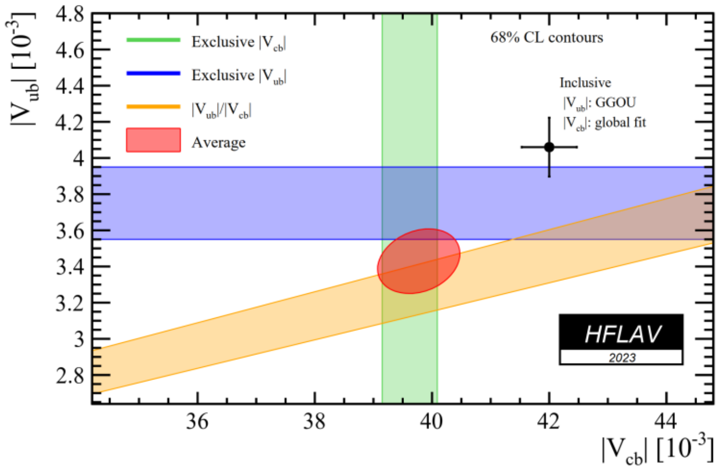


Flavor anomalies and puzzles

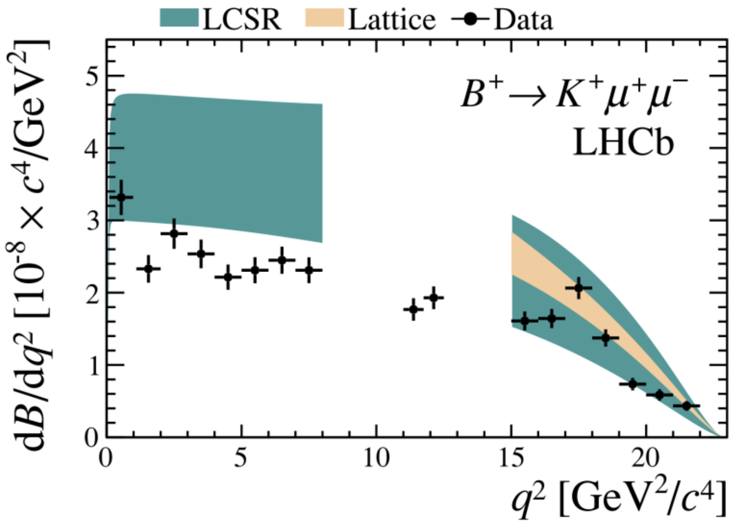
LFU violation in $R(D^{(*)})$



The $|V_{ub}|$ and $|V_{cb}|$ puzzle



$B \to K^{(*)}\ell\ell$ anomoly



$B \to \pi\,\pi$ puzzle

$$Br(B^0 \to \pi^0\pi^0) = (1.55 \pm 0.16) \times 10^{-6}$$

Much larger than theoretically calculated.

$B \to \pi\,K$ puzzle

$$\Delta A_{CP}(\pi K) = A_{CP}(\pi^0 K^-) - A_{CP}(\pi^+ K^-)$$
$$= (11.3 \pm 1.2)\%$$

9σ deviation from isospin limit.

$B \to K\,K$ puzzle

$B \to D_q^{(*)} L$ puzzle

… …

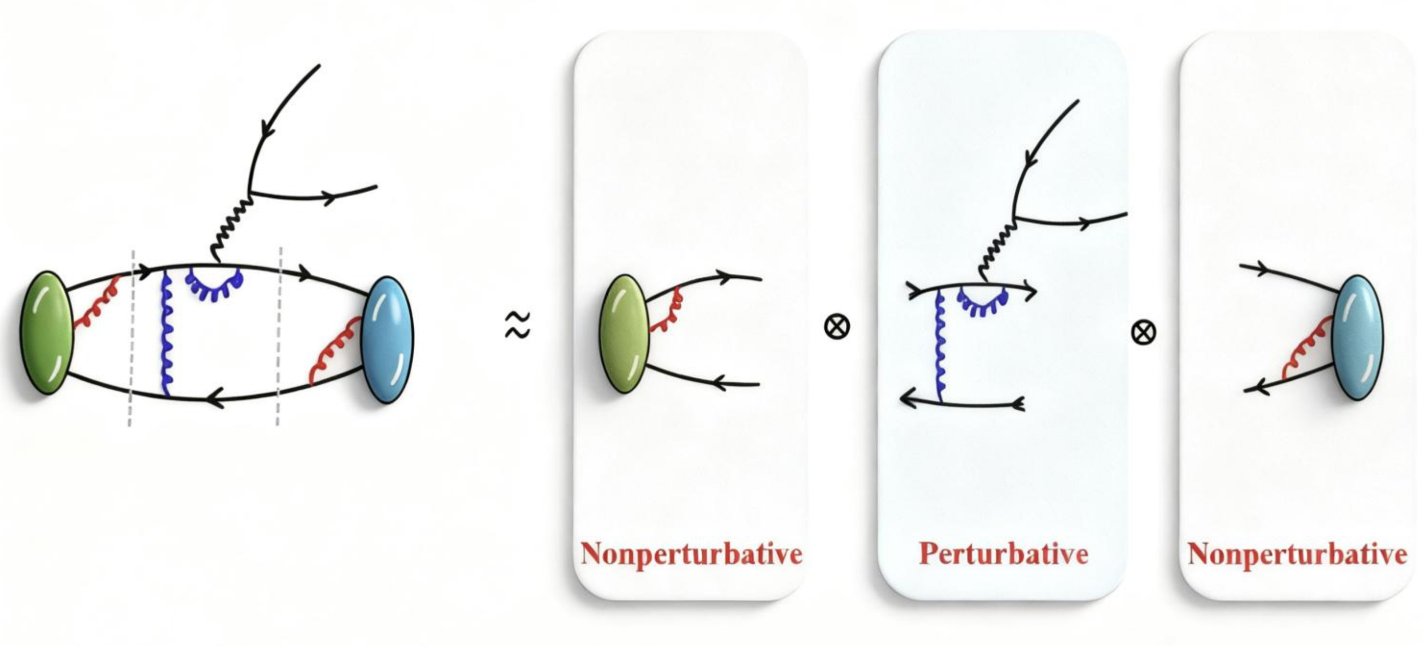
Weak Hamiltonian and hadronic matrix elements

Standard starting point for theoretical calculations.

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i C_i O_i + \sum_i C_i' O_i'$$

- **Wilson coefficients C_i: perturbatively calculable.**
- **Hadronic matrix elements $\langle f|O_i|B\rangle$: essentially nonperturbative quantities.**

Factorization



Factorization methods

- **Naïve factorization and Generalized factorization**

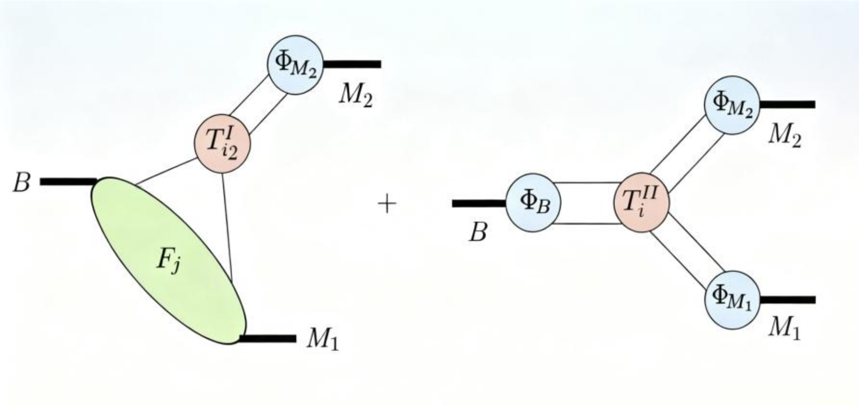
  [BSW (1985)] [Cheng etc., Ali, Kramer, Lü (1998)]

$$\langle M_1 M_2 | O_i | \bar{B} \rangle = C_1 F^{B\to M_1} f_{M_2} + C_2 F^{B\to M_2} f_{M_1}$$

- **QCD factorization and SCET**

  [Bauer et.al, (2001)] [Beneke, Buchalla, Neubert, Sachrajda (1999)]

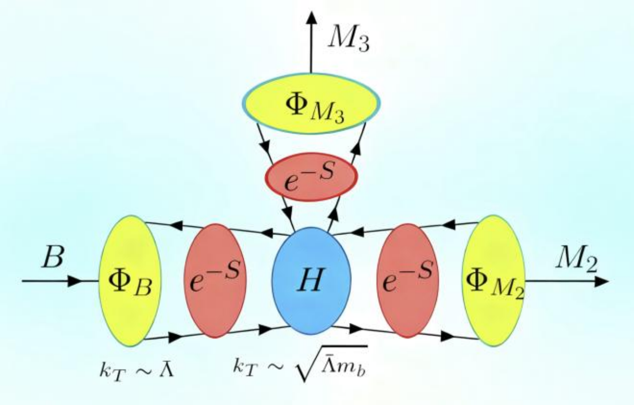
$$\langle M_1 M_2 | O_i | \bar{B} \rangle = F^{B\to M_1} T_i^{I} \otimes \phi_{M_2} + T_i^{II} \otimes \phi_B \otimes \phi_{M_1} \otimes \phi_{M_2}$$



- **Perturbative QCD (PQCD)**

  [Li, Lü, Xiao etc.]

$$\langle M_1 M_2 | O_i | \bar{B} \rangle = H \otimes \phi_B \otimes \phi_{M_1} \otimes \phi_{M_2} \otimes e^{-\Sigma S_i}$$



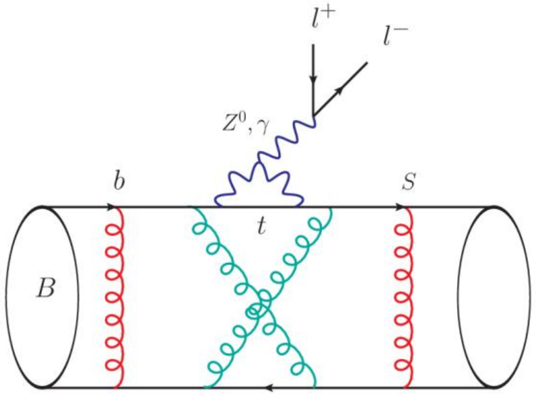
The LCDA of light meson

High precision predictions rely on reliable knowledge on nonperturbative inputs

- **The $B \to P$ and $B \to V$ form factors**

$$\Delta F_M(2E,\mu) = T(u,2E,\omega,\mu) \otimes \phi_B^+(\omega,\mu) \otimes \phi_M(u,\mu)\,.$$

- **The rare $B \to K\ell\ell$ decay**

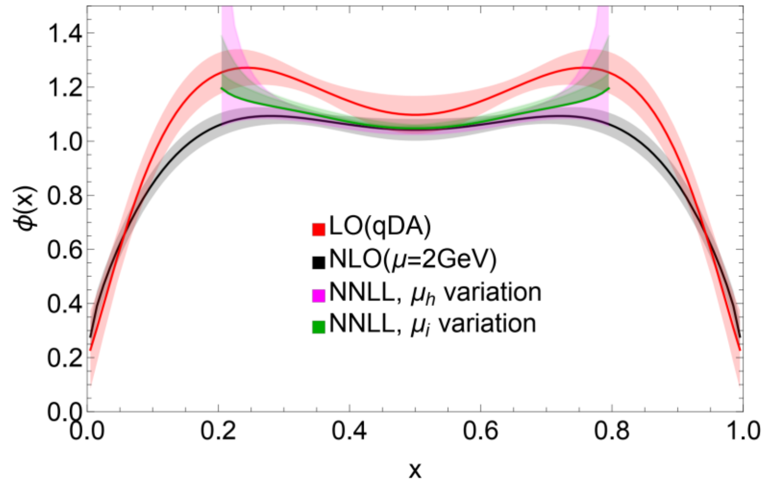


B-meson LCDA

$$\langle K_a^* \ell^+\ell^- | H_{eff} | B\rangle = T_a^I(q^2)\,\zeta_a(q^2) + \sum_{\pm}\int_0^\infty \frac{d\omega}{\omega}\phi_\pm^B(\omega)\int_0^1 du\,\phi_{K^*}^a(u) T_{a,\pm}^{II}(\omega,u,q^2)\,.$$

The LCDA of light hadron

- π and K distribution amplitude from lattice QCD: Hua, Wang, **JX**, Zhang et.al, PRL 129 (2022)
- Distribution amplitude of K^* and ϕ from Lattice QCD: Hua, Wang, **JX**, Zhang et.al, PRL 127 (2021)
- NNLO QCD corrections to pion electromagnetic form factors: Chen, Chen, Feng, Jia, PRL 132 (2024)
- NNLO QCD Prediction for the Pion Form Factor: Ji, Wang, Wang, Wang et.al, PRL 134 (2025)
- Lattice QCD calculation of the pion distribution amplitude: Baker, Zhao et.al, JHEP 07 (2024)

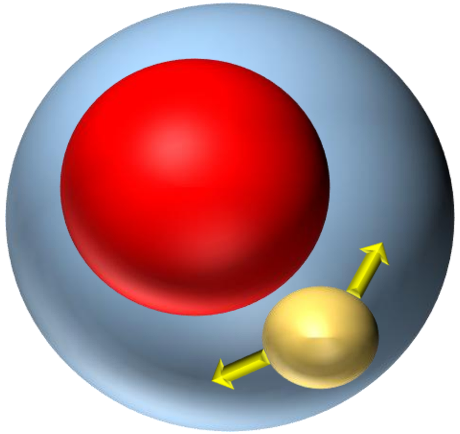


[Jun Hua's talk]

Structure of heavy meson

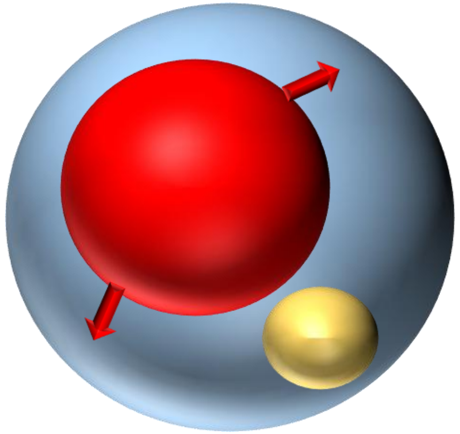
A heavy flavor meson consists of a pair of heavy and light quarks.

Light-cone distribution function



LCDA describes the momentum distribution amplitude of the light quark.

Shape function



SF characterizes the momentum distribution function of the heavy quark.

Together, they provide the most essential information about the profile of heavy mesons.

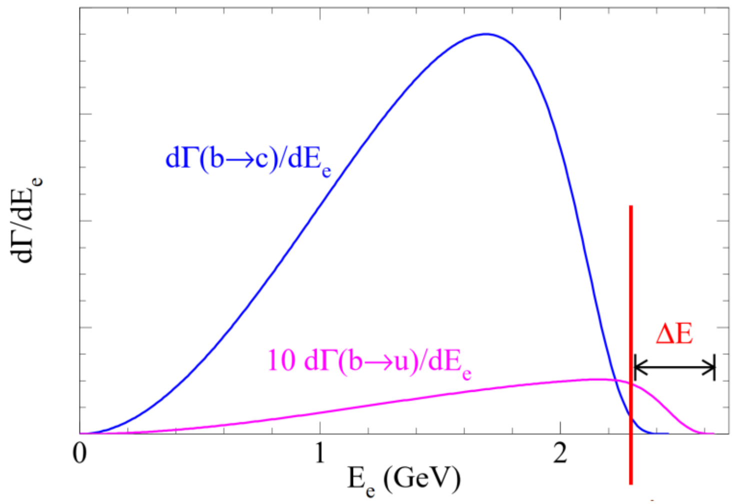
The $|V_{ub}|$ Puzzle

The $|V_{ub}|$ tension

$$|V_{ub}| = (4.13 \pm 0.12 \, {}^{+\,0.13}_{-\,0.14} \pm 0.18) \times 10^{-3} \quad \text{(inclusive)}, \qquad \text{via } B \to X_u \, \ell \, \nu \qquad \text{[PDG (2024)]}$$

$$|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3} \quad \text{(exclusive)}, \qquad \text{via } B \to \pi \, \ell \, \nu \qquad \text{[PDG (2024)]}$$

- The **inclusive** process: $B \to X_u \, \ell \, \nu$

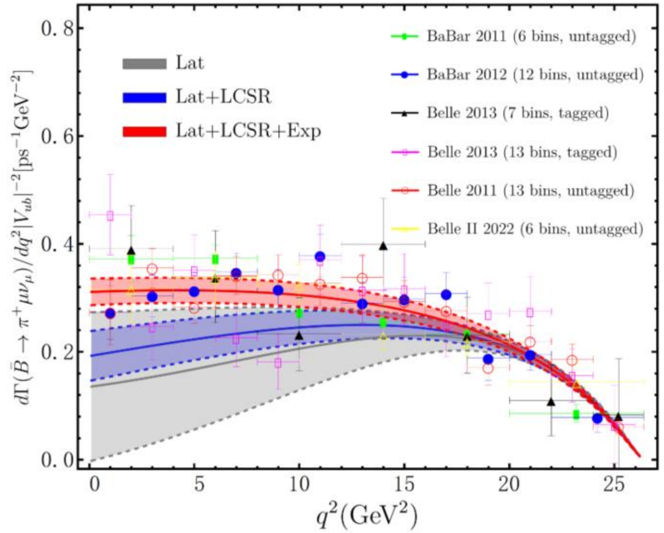


$$\frac{d\Gamma}{dq^2\, dE_e\, dE_\nu} = \frac{|V_{jb}|^2\, G_F^2}{2\pi^3} \left[W_1 q^2 + W_2 \left(2E_e E_\nu - \tfrac{1}{2} q^2 \right) + W_3 q^2 \left(E_e - E_\nu \right) \right],$$

$$W^{\mu\nu} = \sum_{i,j=1}^{3} H_{ij}(\bar{n} \cdot p) \, \mathrm{tr} \left(\bar{\Gamma}_j^{\mu} \frac{\not{p}_-}{2} \Gamma_i^{\nu} \frac{1 + \not{v}}{2} \right) \int d\omega \, J(p_\omega^2) \, S(\omega)$$

[Neubert et.al, NPB 699 (2004)]

- The **exclusive** process: $B \to \pi \, \ell \, \nu$



$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |p_\pi|^3 |f_+(q^2)|^2,$$

$$f_{B\pi}^+(0) + f_{B\pi}^-(0) = \frac{f_B}{f_\pi m_B} \int_0^{s_0^\pi} ds e^{-s/M^2} \left[\frac{m_B^2}{m_B^2 - s} \phi_+^B(s/m_B) - 2\frac{s}{m_B^2 - s} \phi_-^B(s/m_B) + 2\frac{m_B^3}{(m_B^2 - s)^2} \overline{\Phi}_\pm^B(s/m_B) \right],$$

[Khodjamirian et.al, PRD 75 (2007)]

Importance of heavy meson LCDA and SF

The form factors for $B \to K^*$ and $B \to \pi$

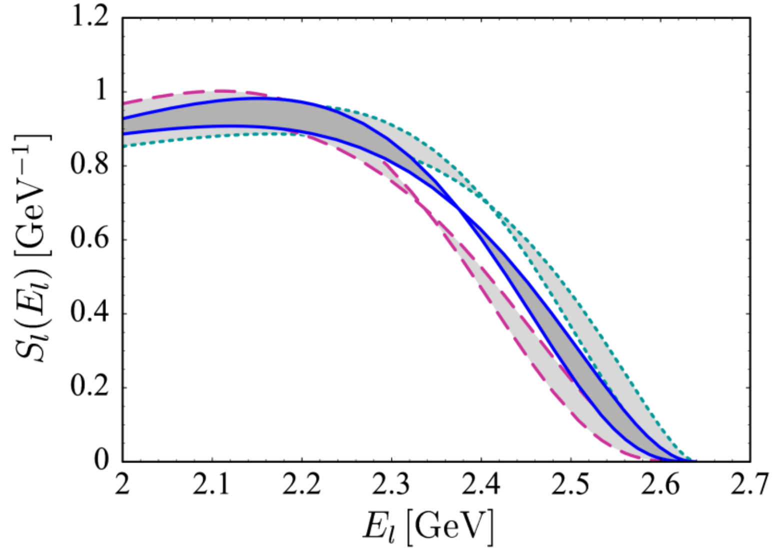
[Gao, Lü, Shen, Wang, Wei, PRD 101 (2020)]
[Cui, Huang, Shen, Wang, Wang, JHEP 03 (2023)]

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

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

The lepton energy spectrum for $B \to X_u \ell \nu$ and Br for $B \to X_s \gamma$

[Bosch, Lange, Neubert, Paz, NPB 699 (2004)]
[Czakon, Fiedler, Huber, et.al, JHEP 04 (2015)]



$$\mathcal{B}^{\rm SM}_{s\gamma} = (3.36 \pm 0.23) \times 10^{-4}$$

The nonperturbative contribution dominated by the shape function is the largest source of uncertainty, accounting for ~ 60-70%.

Our knowledge on LCDA

- **2001** — **Equation of motion** [Kawamura, Kodaira, Qiao, Tanaka, PLB 523 (2001)]
- **2003** — **Evolution equations** [Lange, Neubert, PRL 91 (2003)]
- **2005** — **Perturbative constraint for large ω** [Lee, Neubert, PRD 72 (2005)]
- **2008** — **Subleading Evolution equations** [Bell, Feldmann, JHEP 04 (2008)]
- **2013** — **Solution of evolution equations** [Bell, Feldmann, Wang and Yip, JHEP 11 (2013)]
- **2019** — **Two loop RG equations** [Braun, Ji, Manashov, PRD 100 (2019)]
- **2020** — **LCDA in QCD and HQET** [Ishaq, Jia, Xiong, Yang, PRL 125 (2020); Beneke, Finauri, Vos, Wei, JHEP 09 (2023)]

- **2004** — **Evolution equations** [Bauer, Manohar, PRD 70 (2004)]
- **2005** — **Perturbative constraint for large ω** [Bosch, Lange, Neubert, Paz, NPB 699 (2005)]
- **2008** — **Relation between LCDA and SF** [Yaouanc, Oliver, Raynal, PRD 77 (2008)]
- **2009** — **Two loop in SF region** [Beneke, Huber, Li, NPB 811 (2009)]
- **2019** — **TMD shape functions for quarkonia** [Echevarria, JHEP 10 (2019)]
- **2025** — **Renormalization of the subleading SF** [Bartocci, Böer, Hurth, JHEP 04 (2025)]

Our knowledge on SF

- **2001** — **Equation of motion** [Kawamura, Kodaira, Qiao, Tanaka, PLB 523 (2001)]
- **2003** — **Evolution equations** [Lange, Neubert, PRL 91 (2003)]
- **2005** — **Perturbative constraint for large ω** [Lee, Neubert, PRD 72 (2005)]
- **2008** — **Subleading Evolution equations** [Bell, Feldmann, JHEP 04 (2008)]
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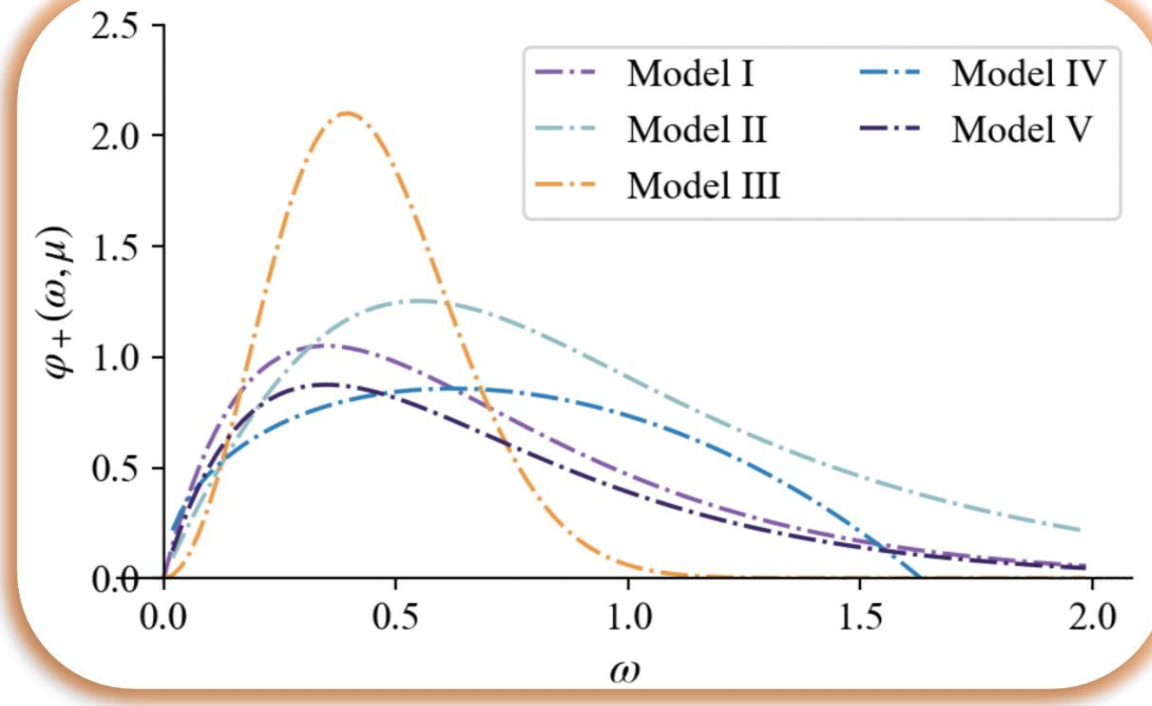
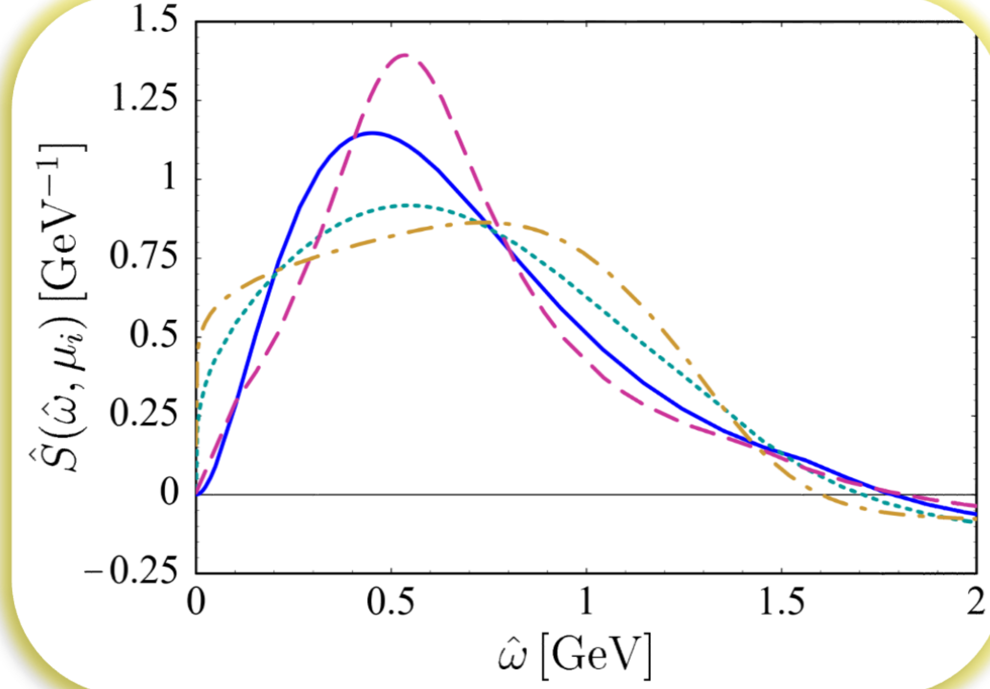
But we do not have the accurate LCDA and SF

Comparing several phenomenological models

Light-cone distribution amplitude



Shape function

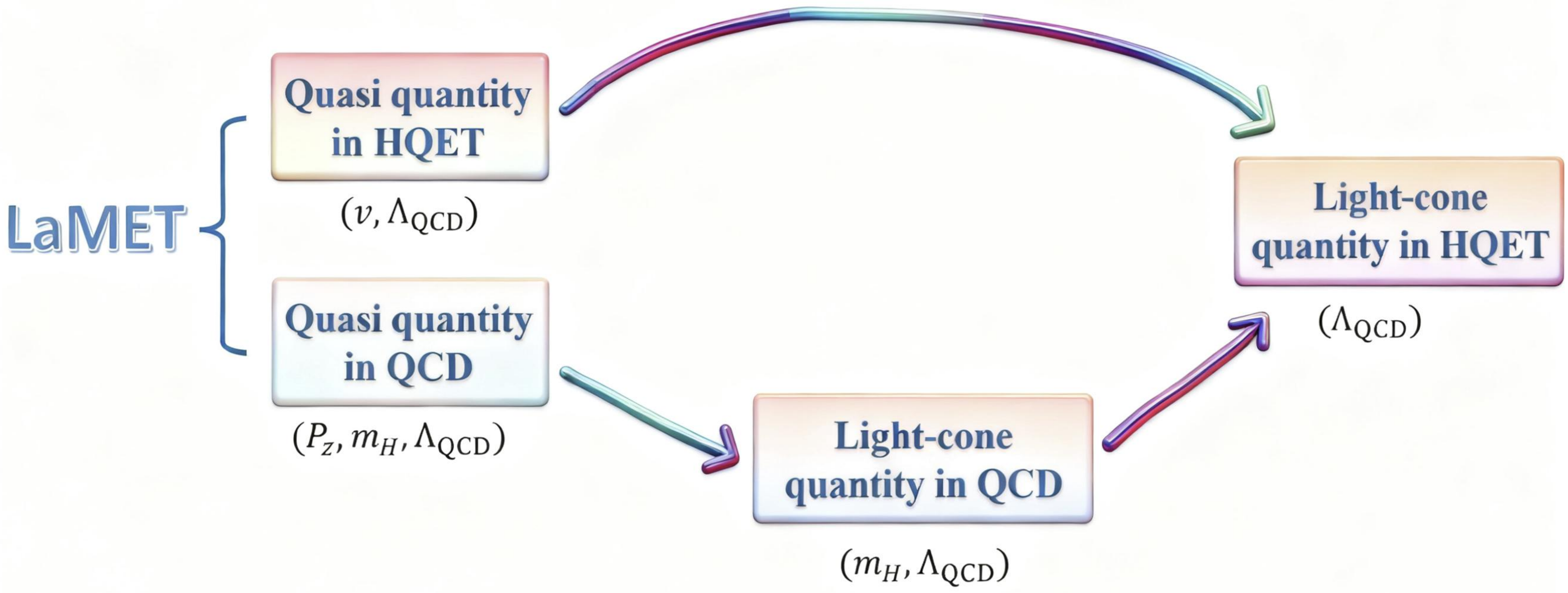


There are considerable differences between various models

Lattice QCD with LaMET

One-step factorization:

[Wang, Wang, **JX**, Zhao, PRD 102 (2020)]
[**JX**, Zhang, PRD 106 (2022)]
[**JX**, Zhang, Zhao, PRD 106L (2022)]
[Hu, Wang, **JX**, Zhao, PRD 109 (2024)]
[Hu, **JX**, Zhao, EPJC 84 (2024)]

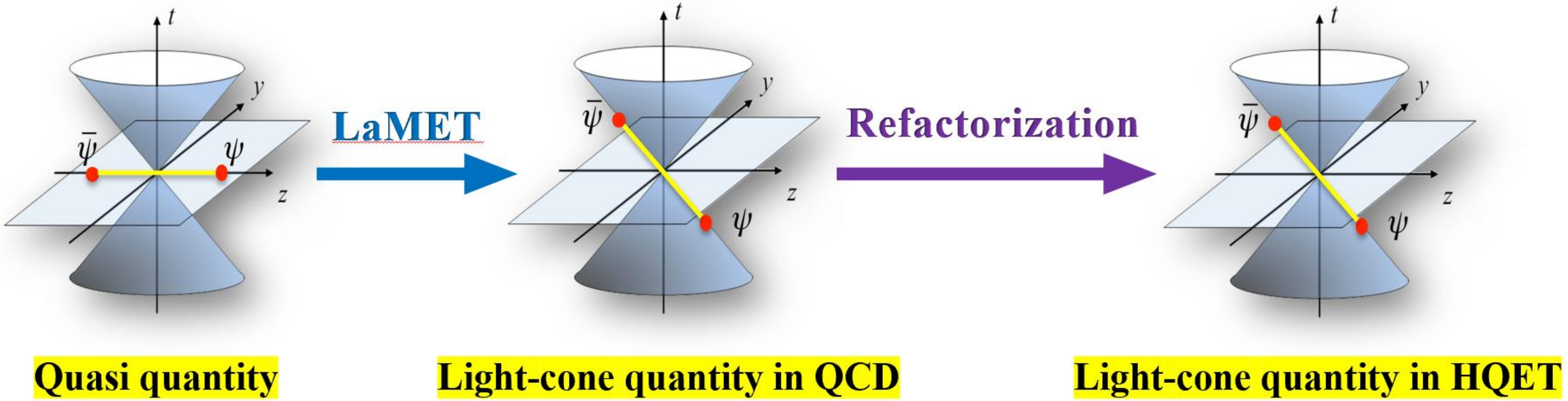


Two-step factorization:

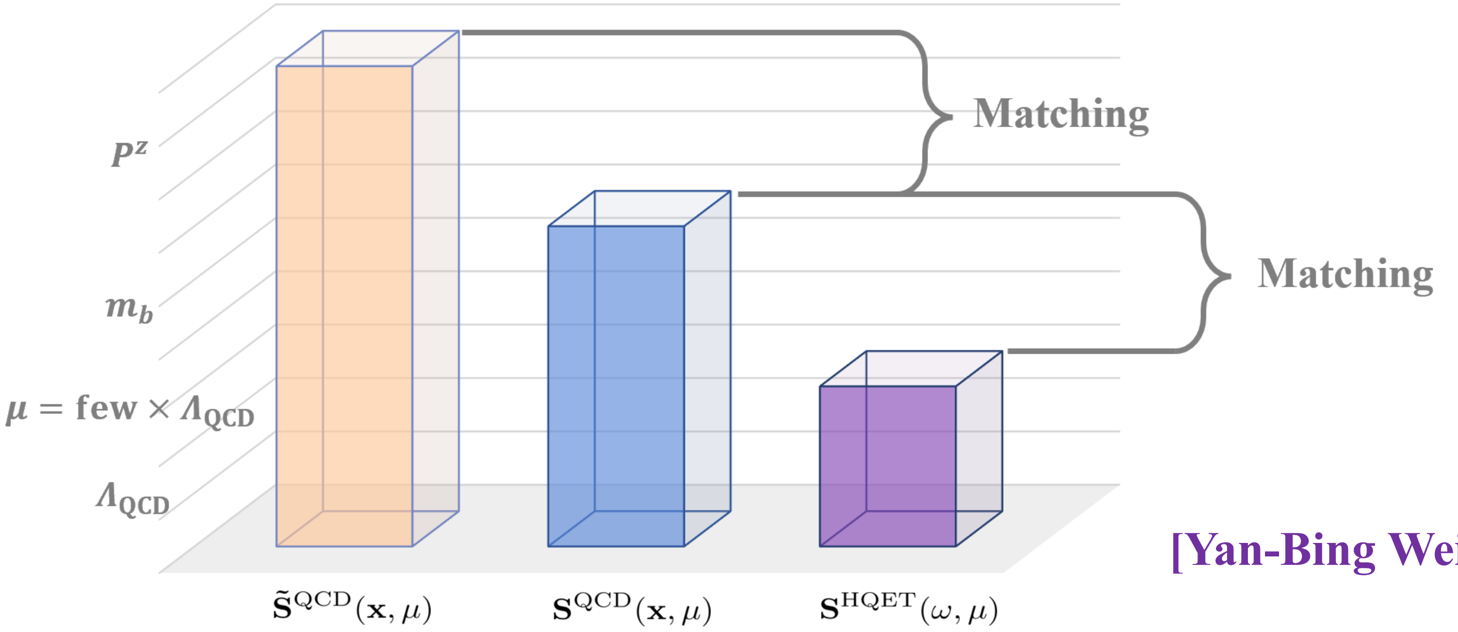
[Han, Wang, **JX**, Zhang, et.al, PRD 111, 3 (2025)]
[Han, Wang, **JX**, Zhang, et.al, PRD 111, 11 (2025)]
[Wang, **JX**, Zhang, Zhao, PRD 112 (2025)]

Lattice QCD with LaMET

Space-like to Light-like:



Integrating different scales:

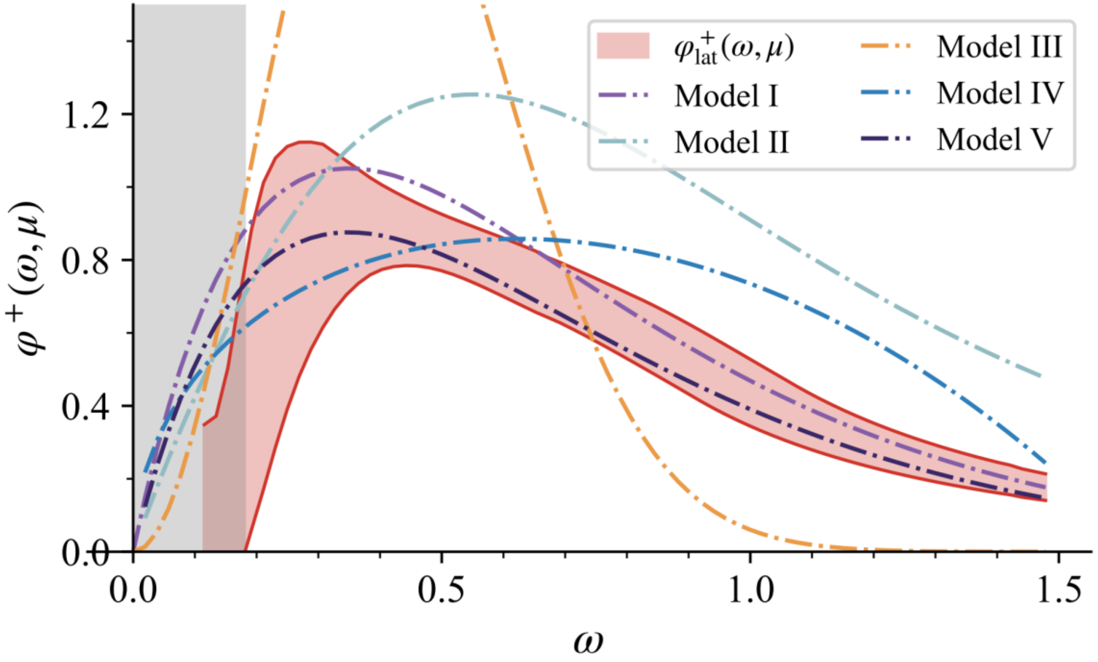


[Yan-Bing Wei's talk]

Lattice QCD with LaMET

Light-cone distribution amplitude

- Matching between quasi-DA to LCDA in QCD ✓
- Matching between LCDA in QCD to HQET ✓
- Lattice simulation ✓



[Han, Wang, **JX**, Zhang, et.al, PRD 111, 3 (2025)]
[Han, Wang, **JX**, Zhang, et.al, PRD 111, 11 (2025)]

Shape function

- Matching between quasi-SF to SF in QCD ✓
- Matching between SF in QCD to HQET ✓
- Lattice simulation

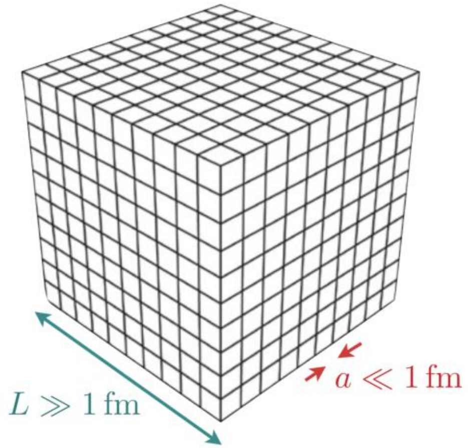
In progress

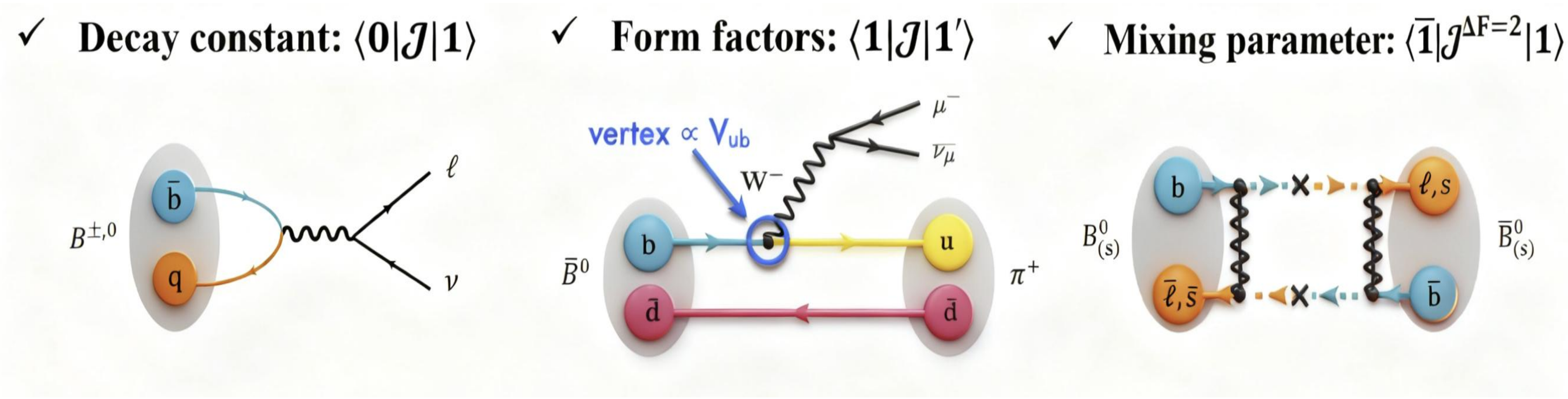
[Wang, **JX**, Zhang, Zhao, PRD 112 (2025)]

[Qi-An Zhang's talk]

Lattice QCD in heavy quark physics

Offering the first-principle results of nonperturbative quantities in heavy quark physics





LFU violation in $R(D^{(*)})$

- $B \to D\ell\nu$ form factors at nonzero recoil: MILC collaboration and HPQCD collaboration, PRD 92 (2015)
- Semileptonic form factors for $B \to D^*\ell\nu$ at nonzero recoil: MILC collaboration, EPJC 82 (2022)
- $B \to D^*$ and $B_s \to D_s^*$ form factors for the full q2 range: HPQCD collaboration, PRD 109 (2024)

The $|V_{ub}|$ and $|V_{cb}|$ puzzle

- $B_s \to D_s^*$ form factors for the full q^2 range from lattice QCD: HPQCD collaboration, PRD 105 (2022)
- $|V_{ub}|$ from $B \to \pi\ell\nu$ decays and (2+1)-flavor lattice QCD: Bailey et.al, PRD 92 (2015)
- $B_s \to D_s$ form factors form factors for the full q^2 range from lattice QCD: HPQCD collaboration, PRD 105 (2020)

$B \to K^{(*)}\ell\ell$ anomoly

- Rare decay $B \to K\ell\ell$ form factors from lattice QCD: HPQCD collaboration, PRD 88 (2013)
- SM predictions for $B \to K\ell\ell$ and $B \to K\nu\nu$ from Lattice QCD: Parrott, Bouchard, Davies, PRD 107 (2023)

[Lei-Yi Li's talk]
[Yu Meng's talk]

Precise theoretical prediction

Precise theoretical prediction: Loop corrections

NLO weak-annihilation correction to rare $B \to \{K, \pi\}\ell^+\ell^-$ decays

- $B \to \{K, \pi\}\ell^+\ell^-$ is an important probe for studying flavor-changing processes and new physics signals in the Standard Model.

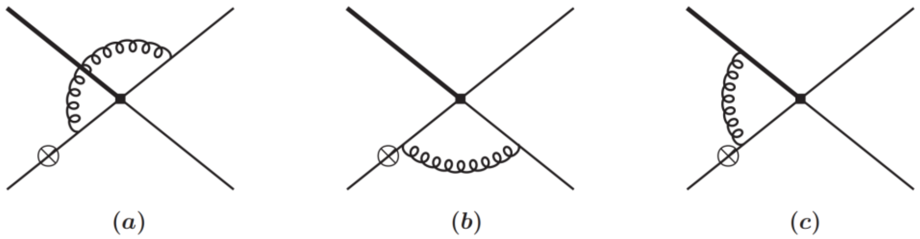
- Using SCET, the contributions of weak annihilation processes have been systematically calculated at NLO.

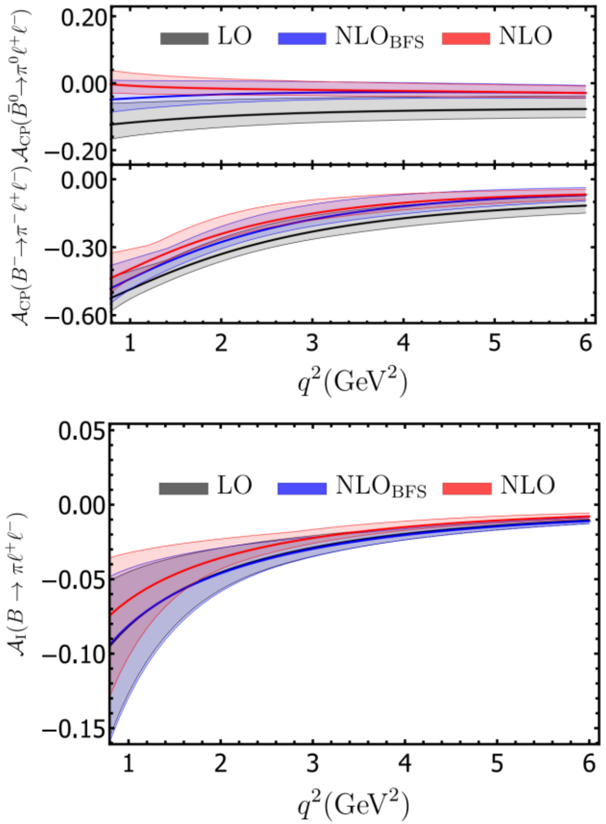
$$\mathcal{QCD} \to \mathcal{SCET}_{\mathrm{I}} \to \mathcal{SCET}_{\mathrm{II}}$$

$$\mathcal{T}_P^{(t,u)} = C_P^{(t,u)}(q^2)\, f_{BP}^{+}(q^2) - \frac{\pi^2}{N_c}\frac{\mathcal{F}_B\, f_P}{m_B}\sum_{m=\pm}\int_0^\infty \frac{d\omega}{\omega}\int_0^1 du\, T_{P,m}^{(t,u)}(\omega,u,\mu)\,\phi_{B,m}(\omega,\mu)\,\phi_P(u,\mu)$$

$$\Sigma C_i\, \mathbb{H}_i \otimes \mathbb{j}_{||}$$

[Huang, Shen, Wang, Wang, PRL 134 (2025)]





Precise theoretical prediction: Power corrections

Deciphering the long-distance penguin contribution to $\bar{B}_{d,s} \to \gamma\gamma$ decays

- These processes offer a remarkably clean environment to address the intricate strong interaction mechanism.

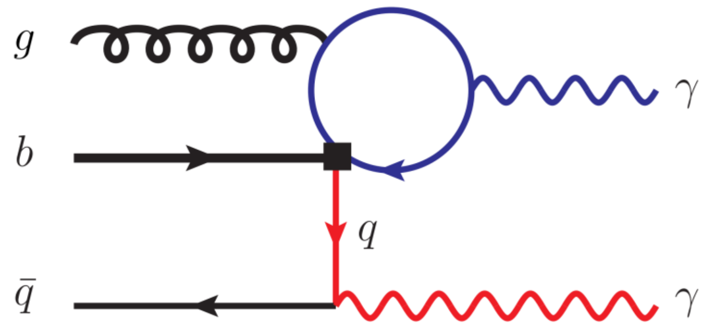
- The leading-power contribution has been investigated in QCD factorization approach. However, the long-distance penguin contribution has not been considered before.

- The power counting

$$m_b \gg m_c \sim \sqrt{m_b \Lambda_{QCD}} \gg \Lambda_{QCD}$$

- A new B-meson LCDA

$$\langle 0|(\bar{q}_s S_n)(\tau_1 n)\,(S_n^\dagger S_{\bar{n}})(0)\,(S_{\bar{n}}^\dagger g_s G_{\mu\nu} S_{\bar{n}})(\tau_2 \bar{n})\ \bar{n}^\nu\ \not{n}\gamma_\perp^\mu \gamma_5\,(S_{\bar{n}}^\dagger h_v)(0)|\bar{B}_v\rangle$$
$$= 2\,\tilde{f}_B(\mu)\,m_B \int_0^\infty d\omega_1 \int_0^\infty d\omega_2 \exp\left[-i(\omega_1\tau_1 + \omega_2\tau_2)\right] \Phi_G(\omega_1,\omega_2,\mu),$$



$$\mathcal{H} \cdot \mathcal{J} \star \bar{\mathcal{J}} \star \Phi_G$$

[Qin, Shen, Wang, Wang, PRL 131 (2023)]

Theoretical efforts and progress

LFU violation in $R(D^{(*)})$

- Shedding new light on $R(D^*)$: Cui, Huang, Wang, Zhao, PRD 108 (2023)
- On sum rules for semi-leptonic $b \to c$ and $b \to u$ decays: Li, Yang, et.al, JHEP 07 (2025)
- Probing semileptonic decay with new physics effects in the PQCD approach: Zhang, Sun, Xing, Zhu, PRD 111 (2025)
- Global fit to $b \to c\tau\nu$ anomalies as of Sping 2024: Iguro, Kitahara, Watanabe, PRD 110 (2024)
- Analysis of charmed B meson decays $B \to D$: Ou-Yang, Li, Zhou, PRD 112 (2025)
- Semileptonic and nonleptonic $\bar{B}_s \to D_{sJ}$ decays: Qi, Li, Zhao, EPJC 85 (2025)

……

$B \to K^{(*)}\ell\ell$ anomoly

- NLO weak-annihilation correction to rare $B \to \{K, \pi\}\ell^+\ell^-$ decays: Huang, Shen, Wang, Wang, PRL 134 (2025)
- Precision calculations of $B \to K^*$ form factors from SCET sum rules: Gao, Meißner, Shen, Li, PRD 112 (2025)
- Renormalization-group evolution for the bottom-meson soft function: Huang, Ji, Shen, Wang, Wang, Zhao, PRL 133 (2024)
- Deciphering the Long-Distance Penguin Contribution to $\bar{B}_{d,s} \to \gamma\gamma$ decays: Qin, Shen, Wang, Wang, PRL 131 (2023)
- The rare decay $B^+ \to K^+\ell^+\ell^-(\nu\bar{\nu})$ under the QCD sum rules approach: Tian, Fu, Zhong, Wang, Wu, PRD 111 (2025)

……

The $|V_{ub}|$ and $|V_{cb}|$ puzzle

- Investigating the ratio of CKM matrix elements $|V_{ub}/V_{cb}|$: Zhong, Fu, Wu, PRD 105 (2022)
- Extracting IM of LCDA and $|V_{ub}|$ from $B \to P$ form factors: Li, Lü, Meißner, Gao, In progress

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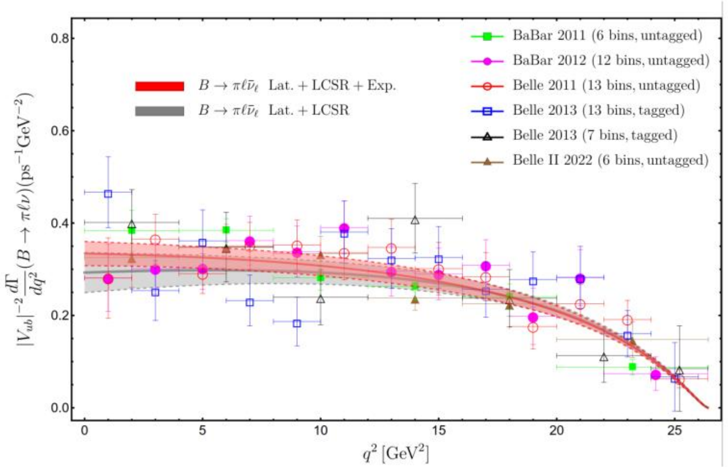

[Dong Hao Li's talk]

Era of high precision, challenges and opportunities

Theoretical efforts and progress

Leptonic B decays

- Factorization and Sudakov resummation in leptonic radiative B decay: Galda, Neubert, Wang, JHEP 07 (2022)
- QCD factorization for the $B \to \gamma \ell \nu$ decay beyond leading power: Cui, Shen, Wang, Wei, EPJC 85 (2025)
- QED corrections to $B_q \to \tau^+\tau^-$: Huang, Shen, Zhao, Zhou, JHEP 10 (2023)

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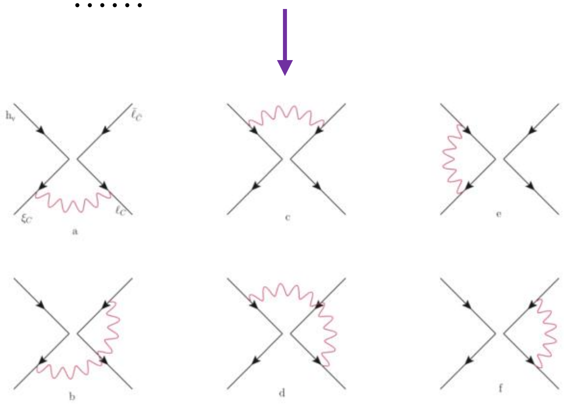

Figure 2. One-loop QED corrections to hard functions.

[Si-Hong Zhou's talk]

Nonleptonic B decays

- Study of the $B^+ \to \pi^+(\pi^+\pi^-)$ decay in PQCD approach: Chang, Yang, Zou, Li, EPJC 84 (2024)
- Systematic analysis of $B_s \to SP$ decays in perturbative QCD approach: Zou, He, Wang, Li, EPJC 85 (2025)
- NLO order QCD corrections to $B_c^* \to J/\psi$ form factors: Chang, Tao, Xiao, Zhu, PRD 111 (2025)
- Study of $B \to PP$ decays in the modified PQCD approach: Lü, Wang, Yang, PRD 110 (2024)
- On the equivalence of Flavor SU(3) analyses of $B \to PP$ decays: Shi, Wang, **JX**, ePrint: 2505.21283
- Form factors of light pseudoscalar mesons from the PQCD approach: Chai, Cheng, JHEP 06 (2025)

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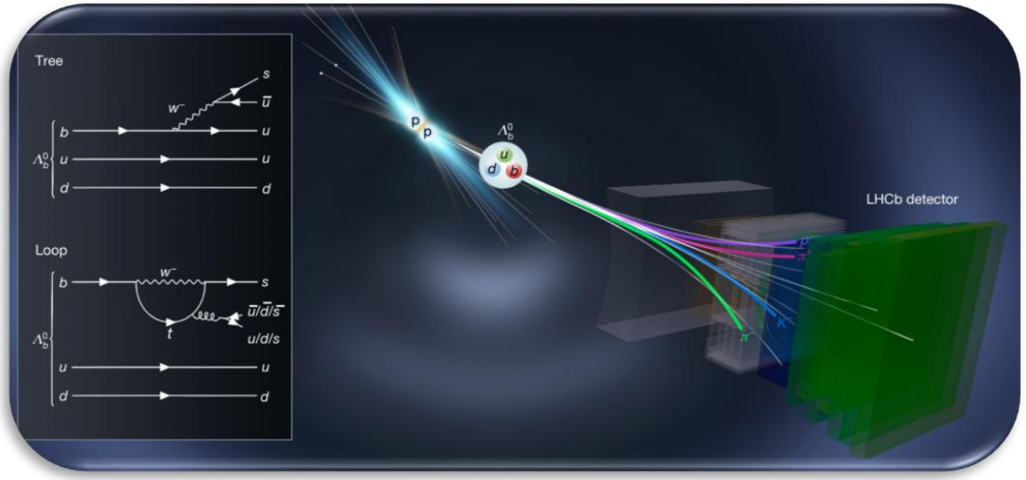
Era of high precision, challenges and opportunities

Heavy baryon CP violation

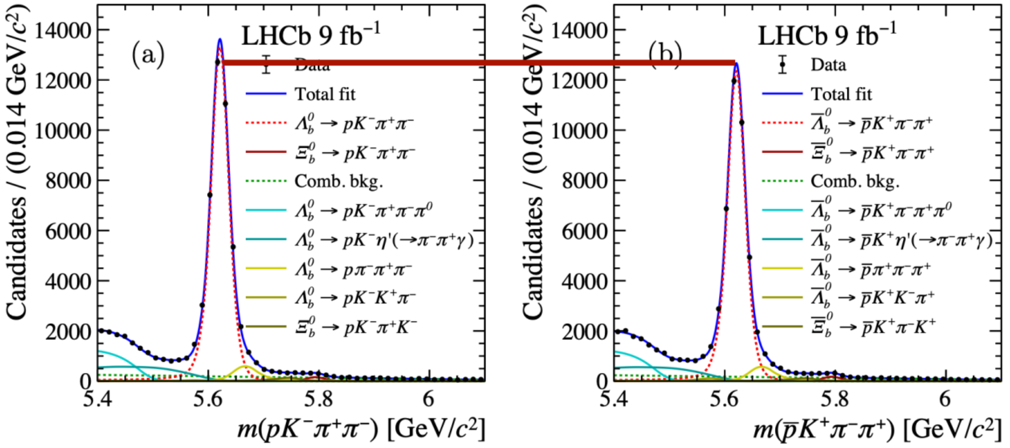
A milestone in particle physics: First observation of baryon CP violation



$$\Lambda_b^0 \to pK^-\pi^+\pi^-$$

$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$$

$$5.2\sigma$$



[LHCb, Nature 643, 8074 (2025)]

Heavy baryon CP violation

Experiment

$\Lambda_b^0 \to pK_S^0h^-$, LHCb, JHEP 04 (2014)
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$, LHCb, Nature Phys. 13 (2017)
$\Lambda_b^0 \to p\pi^-K^+K^-$, LHCb, Nature Phys. 13 (2017)
$\Lambda_b^0 \to ph^-$, LHCb, PRD 11 (2025)
$\Lambda_b^0 \to \Lambda h^+h^-$, LHCb, PRL 134 (2025)
$\Lambda_c^+ \to ph^+h^-$, LHCb, JHEP 03 (2018)
$\Xi_c^+ \to pK^-\pi^+$, LHCb, EPJC 80 (2020)
$\Sigma_0 \to \Lambda\,\pi^0$, BESIII, PRD 108 (2023)
$\Sigma_0 \to \Lambda\,\gamma$, BESIII, PRL 133 (2024)
$\Lambda_c^+ \to ph^+h^-, \Xi_c^+ \to \Sigma^+h^+h^-$, Belle II collaboration
$\Lambda_c^+ \to \Lambda h^+, \Lambda_c^+ \to \Sigma^0h^+$, Belle, Sci.Bull. 68 (2023)
……

Theory

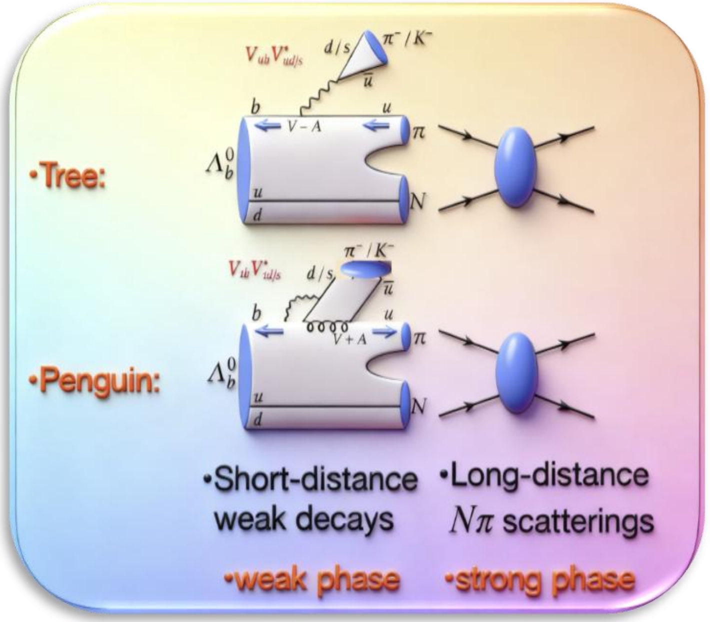
A novel strategy for searching for CPV in the baryon sector: Zhang, Guo, JHEP 07 (2021)
New extraction of CPV in b-baryon decays: Geng et.al, PLB 834 (2022)
Searching for CP violation in four-body decays of bottom and charmed baryons: Zhang, PRD 107 (2023)
Estimates of CPV observables in Λ_b decay: Zhou et.al, PRD 107 (2023)
Possible large CP violation in charmed Λ_b decays: Yu, Wang, Qin, PRD 108 (2023)
Complementary CPV induced by T-odd and T-even correlations: Wang, Qin, Yu, PRD 111 (2025)
Establishing CP Violation in b-Baryon Decays: Han, Li, Xiao, Yu et.al, PRL 134 (2025)
……

[Zhi-Peng Xing's talk]

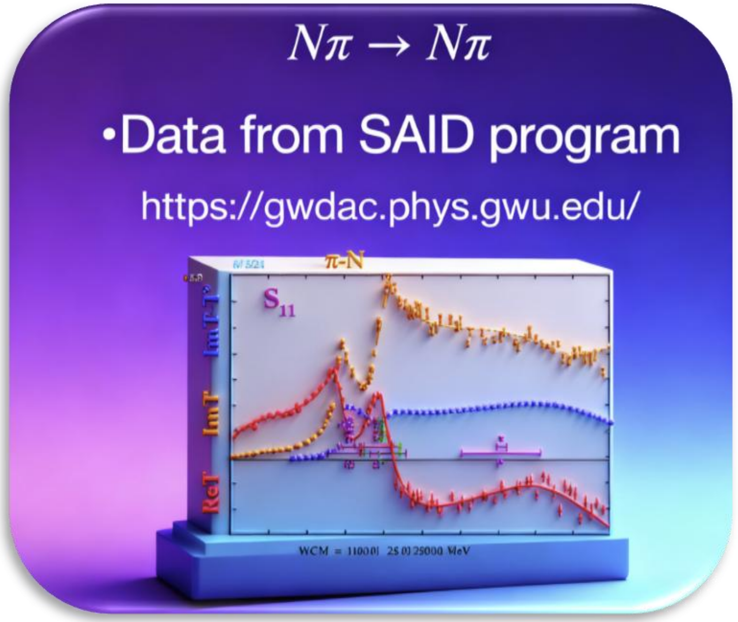
[Tian-Liang Feng's talk]

Heavy baryon CP violation

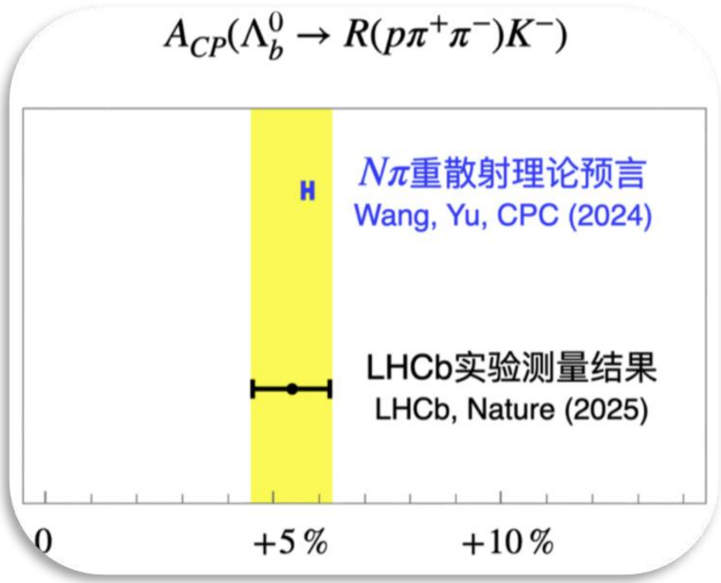
- Studying the processes of $\Lambda_b^0 \to (p\pi^+\pi^-)h^-$ and $(p\pi^0)h^-$ with $h^- = p$ or K.
- The global CPV of the above processes in the invariant mass regions of $N\pi$ scatterings are at the order of several percent.



Mixing between Tree and Penguin



Using data from SAID program



Good agreement

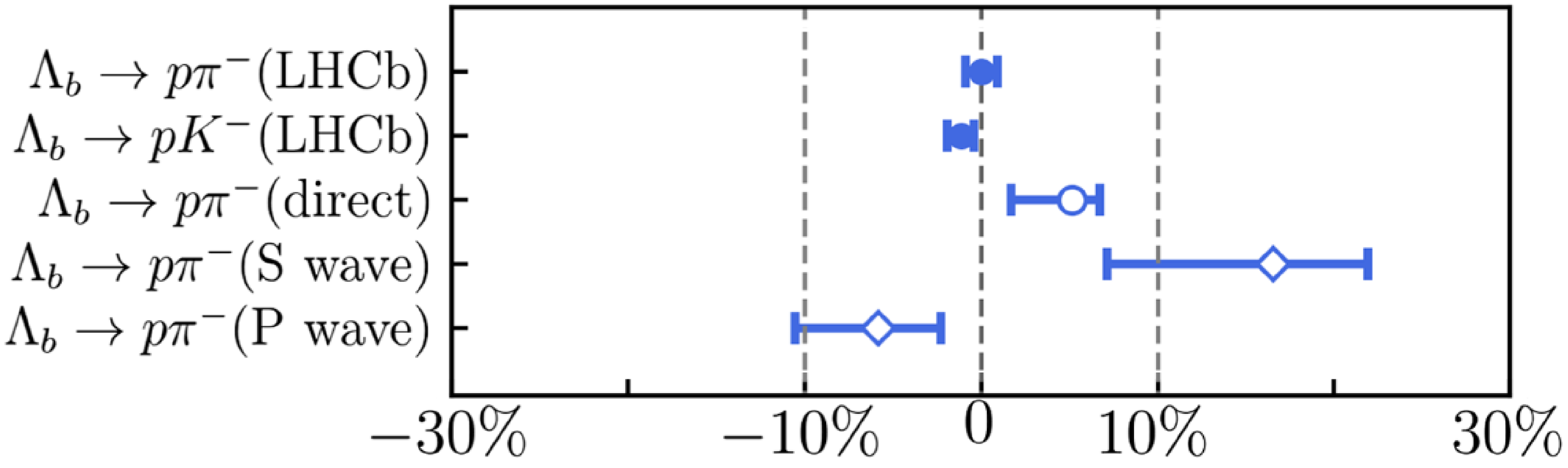
[Wang, Yu, CPC 48 (2024)]

Good agreement between theory and experiment

Heavy baryon CP violation

Cancellation between different partial wave CPVs.

	A_{CP}^{dir}	$A_{CP}^{S\text{-wave}}(\kappa_S)$	$A_{CP}^{P\text{-wave}}(\kappa_P)$
$\Lambda_b \to p\pi^-$	$0.05^{+0.02}_{-0.03}$	$0.17^{+0.05}_{-0.09}(49\%)$	$-0.06^{+0.04}_{-0.05}(51\%)$
$\Lambda_b \to pK^-$	$-0.06^{+0.03}_{-0.02}$	$-0.05^{+0.05}_{-0.04}(94\%)$	$-0.21^{+0.39}_{-0.46}(6\%)$



[Han, Yu, Li, Li, Wang, Xiao, Yu PRL 134 (2025)]

[Jia-Jie Han's talk]

Topics not included

- Multi-body B decays [Shan Cheng's talk]
- Inclusive decays of heavy quarks [Qin Qin's talk]
- Hadronic B decays in PQCD [Rui Zhou's talk] [Ya Li's talk]
- The charm physics [Xiao-Hui Hu's talk]
- Heavy quarkonium [Xiang-Peng Wang's talk] [Zi-Qiang Chen's talk]
- Heavy quark exotics [Rui-Lin Zhu's talk]
- NP in heavy flavor physics [Xing-Bo Yuan's talk]

……

Summary

- Heavy quark physics is now entering a precision era, thanks to advances in both experiment and theory.
- Several anomalies and puzzles between experiment data and theoretical calculations in SM are observed.
- Through efforts in nonperturbative inputs, loop corrections and power corrections, theoretical predictions will match the precision of experimental data. Providing crucial support for understanding QCD and hadron structure, as well as searching for new physics.

Thanks！

Back up

Page 6

$B \to \pi\,\pi$ puzzle

$Br(B^0 \to \pi^0\pi^0) = (1.55 \pm 0.16) \times 10^{-6}$

Much larger than expected. NNLO hard function does not work.

$B \to \pi\,K$ puzzle

$\Delta A_{CP} = A_{CP}(B^- \to K^-\pi^0) - A_{CP}(B^0 \to K^-\pi^+) = (11.3 \pm 1.2)\%$

9 σ deviation from isospin limit.

$B \to K\,K$ puzzle

$$R_{KK}^{sd} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{\Gamma(B_s \to K^0\bar{K}^0)}{\Gamma(B_d \to K^0\bar{K}^0)} = 0.62 \pm 0.14$$

Over 3σ deviation from SM prediction.

$B \to D_q^{(*)} L$ puzzle

$$R_{s(L)}^{(*)} = \frac{\Gamma\left(\bar{B}_{(s)}^0 \to D_{(s)}^{(*)+} L^-\right)}{d\Gamma\left(\bar{B}_{(s)}^0 \to D_{(s)}^{(*)+} \ell^- \nu_\ell\right) / dq^2|_{q^2=m_L^2}}$$

$R_\pi^{(*)}, R_K, R_{s\pi}$: Over 4σ deviation from SM prediction.

- **The definition on LCD defined in HQET** [Grozin, Neubert, PRD 55 (1997)]

$$i\tilde{f}_B(\mu)m_B\phi^+(\omega,\mu) = \int_{-\infty}^{+\infty}\frac{d\eta}{2\pi}e^{i\bar{n}\cdot v\omega\eta}\langle 0|\bar{q}(\eta\bar{n})\,W(\eta\bar{n},0)\,\bar{\not{n}}\gamma_5\,h_v(0)|B(v)\rangle\,.$$

Here h_v is the heavy quark field defined in HQET. The variable has support $0 < \omega < \infty$.

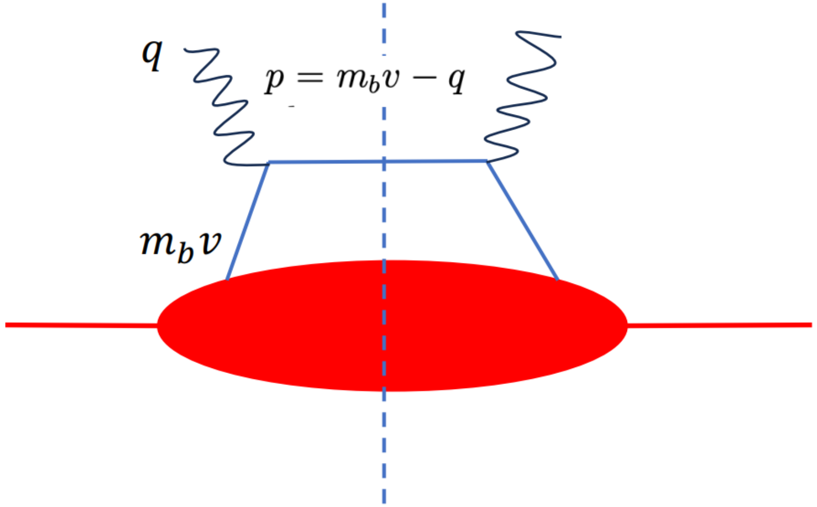
- **The definition on SF defined in HQET** [Neubert, PRD 49 (1994)]

$$S(\omega,\mu) = \int_{-\infty}^{+\infty}\frac{dt}{2\pi}e^{i\omega v^+ t}\frac{\langle B(v)|\bar{h}_v(0)\,W(0,tn_+)\,h_v(tn_+)|B(v)\rangle}{\langle B(v)|\bar{h}_v(0)\,h_v(0)|B(v)\rangle}\,.$$

The variable has support $-\infty < \omega < \bar{\Lambda}$, with $\bar{\Lambda} = m_B - m_b$. “Fermi motion” of the heavy quark.

QCD analysis for inclusive B decays

- Inclusive decay rate is related to the hadronic tensor



$$W^{\mu\nu} = \frac{1}{\pi}\,\mathrm{Im}\,\frac{\langle \bar{B}(v)|\,T^{\mu\nu}\,|\bar{B}(v)\rangle}{2M_B}$$

$$T^{\mu\nu} = i\int d^4x\, e^{iq\cdot x}\,\mathrm{T}\left\{J^{\dagger\mu}(0),\, J^{\nu}(x)\right\}$$

$$J^{\mu} = \bar{u}\gamma^{\mu}(1-\gamma_5)b$$

$p = m_b v - q$: momentum of light partons

- When $p^{\mu} \sim m_b \gg \Lambda_{QCD}$: heavy quark expansion (local OPE)
- When $p^{\mu} = (p^+, p^-, p_\perp) \sim E(\lambda, 1, \sqrt{\lambda})$: twist expansion (light-cone OPE) $\lambda = \frac{\Lambda_{QCD}}{E}$

Infinite set of power corrections are resummed into the shape function

B meson inclusive decays and shape function

- The differential decay rates are expressed in terms of shape function

$B \to X_u \ell \nu$ $$\frac{d\Gamma}{dE_\ell} = \frac{G_F^2 |V_{ub}|^2 m_b^4}{96\pi^3} \int d\omega \theta(m_b - 2E_\ell - \omega) S(\omega)$$

$B \to X_s \gamma$ $$\frac{d\Gamma}{dE_\gamma} = \frac{G_F^2 |V_{tb} V_{ts}^*|^2 \alpha |C_7^{\text{eff}}|^2 m_b^5}{32\pi^4} S(E_\gamma)$$

Bauer, Manohar, 2003; Bosch, Lange, Neubert, Paz, 2004,…

- Shape function reflects the fermi motion of b-quark inside B-meson
- Shape function is universal
- Shape function is defined with matrix elements of nonlocal HQET operators

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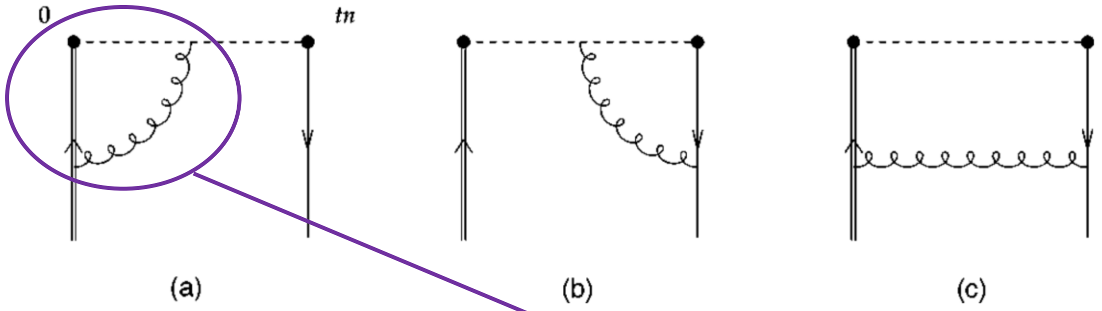
- The LCDAs are defined on the light-cone. [Grozin, Neubert, PRD 55, 272-290 (1997)]
- Non-negative moments $\int dk\, k^n \varphi_B^+(k)$ for $n = 0, 1, 2 \ldots$ are not related to matrix elements of local operators.



[Braun, Ivanov, Korchemsky, PRD 69, 034014 (2004)]

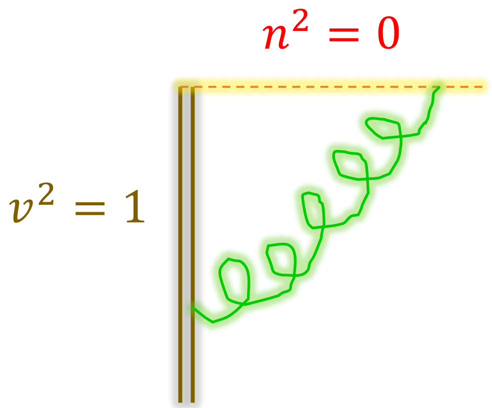
$$O_+^{\rm ren}(t,\mu) = O_+^{\rm bare}(t) + \frac{\alpha_s C_F}{4\pi}\left\{\left(\frac{4}{\hat{\epsilon}^2} + \frac{4}{\hat{\epsilon}}\ln(it\mu)\right) O_+^{\rm bare}(t) - \frac{4}{\hat{\epsilon}}\int_0^1 du\, \frac{u}{1-u}\left[O_+^{\rm bare}(ut) - O_+^{\rm bare}(t)\right] - \frac{1}{\hat{\epsilon}} O_+^{\rm bare}(t)\right\},$$

$$[\bar{q}(tn)\not{n}[tn,0]\Gamma h_v(0)]_R \neq \sum_{p=0}^{\infty} \frac{t^p}{p!}\left[\bar{q}(0)(\overleftarrow{D}\cdot n)^p h_v(0)\right]_R .$$

Cannot get φ_B^+ by their moments

$$\langle H(p_H)|\bar{h}_v(0)\not{n}_+\gamma_5[0,tn_+]q_s(tn_+)|0\rangle = -i\tilde{f}_H m_H n_+\cdot v\int_0^\infty d\omega e^{i\omega t n_+\cdot v}\varphi_+(\omega;\mu)\,.$$

Cusp divergence:



$$\cosh\theta = \frac{n\cdot v}{\sqrt{n^2}\sqrt{v^2}}$$

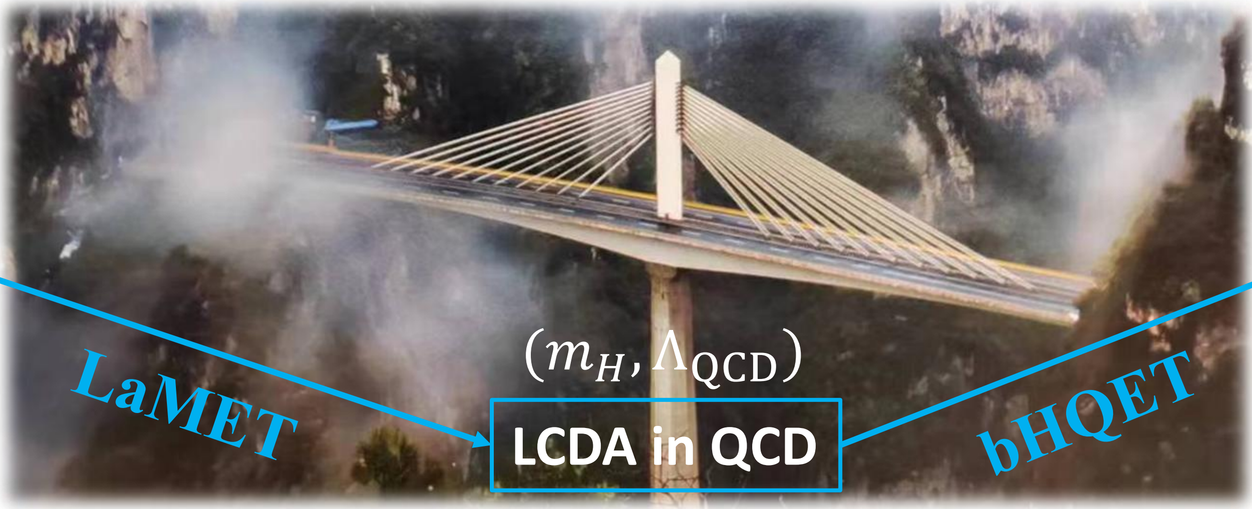
✓ $n^2 \neq 0$, still heavy quark field h_v

✓ $n^2 \neq 0$, and No h_v: QCD heavy quark

- **Two-step factorization to access heavy meson LCDA.**

$(P_z, m_H, \Lambda_{\mathrm{QCD}})$

Quasi-DA in QCD



(Λ_{QCD})

LCDA in HQET

$\Rightarrow$ **Hierarchy** $\boldsymbol{\Lambda_{\mathrm{QCD}} \ll m_H \ll P_z}$**:**

$\boldsymbol{\Lambda_{QCD}}$**~ hundreds MeV** $\ll$ $\boldsymbol{m_H}$ $\ll$ $\boldsymbol{P^z}$ **can achieve 4 GeV currently**

1 GeV m_D $\cdots$ $1.6m_D$ 5 GeV

A big challenge for lattice simulation but still calculable on the lattice

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- The factorization formula between S^{QCD} and S^{HQET}.

$$S^{\text{QCD}}(x,\mu) = \begin{cases} Z_{\text{peak}}(x,\omega,\mu) \otimes S^{\text{HQET}}(\omega,\mu)\,, & 1-x \sim \mathcal{O}(\lambda)\,, \quad \text{(peak region)} \\ Z_{\text{tail}}(x,\mu)\,, & 1-x \sim \mathcal{O}(1)\,, \quad \text{(tail region)} \end{cases}$$

- Expand the shape functions and matching coefficient,

$$S^{\text{QCD}}(x,\mu) = S^{\text{QCD}(0)}(x,\mu) + \frac{\alpha_s C_F}{2\pi} S^{\text{QCD}(1)}(x,\mu) + \mathcal{O}(\alpha_s^2)\,,$$

$$S^{\text{HQET}}(\omega,\mu) = S^{\text{HQET}(0)}(\omega,\mu) + \frac{\alpha_s C_F}{2\pi} S^{\text{HQET}(1)}(\omega,\mu) + \mathcal{O}(\alpha_s^2)\,.$$

$$Z_{\text{peak}}(x,\omega,\mu) = Z^{(0)}_{\text{peak}}(x,\omega,\mu) + \frac{\alpha_s C_F}{2\pi} Z^{(1)}_{\text{peak}}(x,\omega,\mu) + \mathcal{O}(\alpha_s^2)\,,$$

$$Z_{\text{tail}}(x,\mu) = Z^{(0)}_{\text{tail}}(x,\omega,\mu) + \frac{\alpha_s C_F}{2\pi} Z^{(1)}_{\text{tail}}(x,\mu) + \mathcal{O}(\alpha_s^2)\,.$$

➢ The matching function at one-loop

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

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

1. This result implies the validity of the factorization formula.

2. The plus distributions cancel out in the matching, yielding remarkably simple form of factorization formula.

3. The “refactorization framework” developed in this work is in a similar spirit to LCDAs defined in QCD and HQET.

[Yu Jia, De-Shan Yang et.al, PRL, 125 (2020)] [Beneke, Yan-Bing Wei et.al, JHEP, 09 (2023)]

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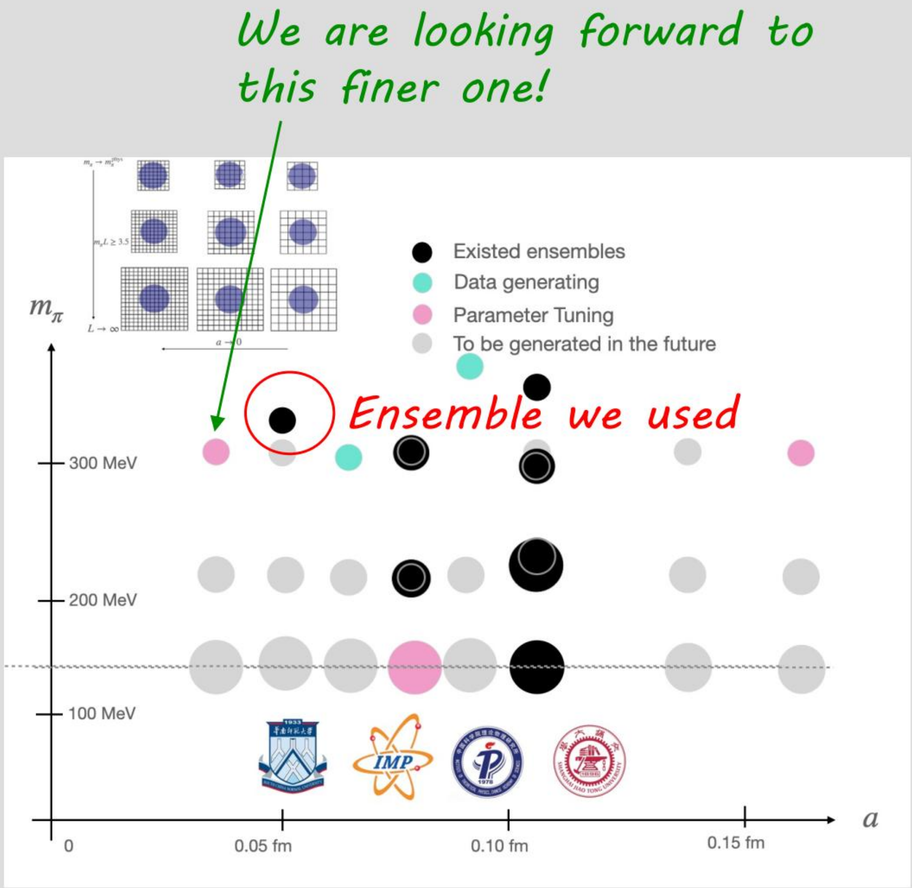
- Simulating on the finest CLQCD ensemble:

  $n_s^3 \times n_t = 48^3 \times 144$, $a \simeq 0.052\text{fm}$;

- $m_\pi \simeq 317\text{MeV}$, $m_D \simeq 1.92\text{GeV}$;
- $P^z = \{2.99, 3.49, 3.98\}\text{GeV}$ up to about 4GeV;
- Dispersion relation consistent with the relativistic one up to possible discretization error;
- The state-of-the-art techniques in renormalization and extrapolation on the lattice are adopted.



[Hu, et·al·, 2004]

➢ First inverse moment (IM)

$$\lambda_B^{-1}(\mu) \equiv \int_{-\infty}^{\infty} d\omega \frac{\phi_B^+(\omega,\mu)}{\omega}.$$

✓ We determine the IM by employing a model-independent parametrization formula.

μ		λ_B (GeV)	$\sigma_B^{(1)}$	
1GeV	$N=1$	0.389(35)	1.63(8)	[e-Print: 2403.17492]
1GeV	Ref. [31]	>0.24		[PRD 98, 112016 (2018)]
	Ref. [18]	0.383(153)		[JHEP 10, 043 (2020)]
	Ref. [7]	0.48(11)	1.6(2)	[PRD 72, 094082 (2005)]
	Ref. [15]	0.46(11)	1.4(4)	[PRD 69, 034014 (2004)]
	Ref. [1]	0.35(15)		[PRD 55, 272 (1997)]
	Ref. [21]	$0.343^{+0.064}_{-0.079}$		[PRD 101, 7, 074035 (2020)]
	Ref. [73]	0.338(68)		[PLB 848, 138345 (2024)]

Page 21

$$\mathcal{C}_{9,P}^{(i)}(q^2) = C_9\,\delta^{it} + \frac{2m_b}{m_B}\,\frac{\mathcal{T}_P^{(i)}(q^2)}{f_{BP}^{+}(q^2)}\,. \qquad (6)$$

$$\mathcal{J}_P^{(\mathrm{A0})} = \frac{\mathcal{F}_B m_B}{2}\int_0^\infty d\omega\,\frac{\mathbb{J}_{\parallel,-}(n\cdot q,\bar{n}\cdot q,\omega)}{\bar{n}\cdot q-\omega+i\,0}\,\phi_{B,-}(\omega,\mu),$$

$$\mathcal{J}_P^{(\mathrm{B1})} = \frac{\mathcal{F}_B m_B}{2}\int_0^\infty d\omega\,\mathbb{J}_{\parallel,+}(n\cdot q,\bar{n}\cdot q,\omega,\tau)\phi_{B,+}(\omega,\mu).$$

$$\mathcal{A}_{\mathrm{CP}} = \frac{\Gamma(\bar{B}\to\bar{P}\ell^+\ell^-)-\Gamma(B\to P\ell^+\ell^-)}{\Gamma(\bar{B}\to\bar{P}\ell^+\ell^-)+\Gamma(B\to P\ell^+\ell^-)}\,,$$

$$\mathcal{A}_{\mathrm{I}} = \frac{\kappa\,\Gamma(\bar{B}^0\to\bar{P}^0\ell^+\ell^-)-\Gamma(B^-\to P^-\ell^+\ell^-)}{\kappa\,\Gamma(\bar{B}^0\to\bar{P}^0\ell^+\ell^-)+\Gamma(B^-\to P^-\ell^+\ell^-)}\,, \qquad (20)$$

with the factor $\kappa = 2, 1$ for $P = \pi^0, K^0$. Un-

[3] for their explicit definitions). It turns out that such subleading power corrections can enhance the theory predictions for the mixing induced CP asymmetries $\mathcal{A}_{\rm CP}^{\rm mix,\,\parallel}$ and $\mathcal{A}_{\rm CP}^{\rm mix,\,\perp}$ by approximately an amount of $\mathcal{O}(30\,\%)$ with the default inputs, while yielding insignificant effects in the remaining observables numerically. Moreover, our

Multi-body decays of Λ_b

- Advantage: more resonances, more chances for large CPV
- Disadvantage: Too many resonances, and with large uncertainties

$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	****
$N(1720)$	$3/2^+$	****

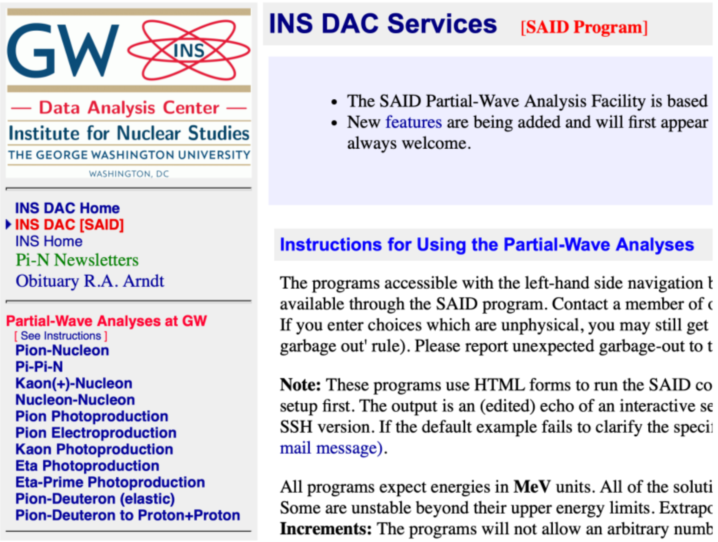
$N(1700)$ BREIT-WIGNER MASS	1650 to 1800 (≈ 1720) MeV
$N(1700)$ BREIT-WIGNER WIDTH	100 to 300 (≈ 200) MeV
$N(1710)$ BREIT-WIGNER MASS	1680 to 1740 (≈ 1710) MeV
$N(1710)$ BREIT-WIGNER WIDTH	80 to 200 (≈ 140) MeV
$N(1720)$ BREIT-WIGNER MASS	1680 to 1750 (≈ 1720) MeV
$N(1720)$ BREIT-WIGNER WIDTH	150 to 400 (≈ 250) MeV

- Close to each other, with large decay widths. No clear dominant one.

$N\pi$ scatterings

- N^* usually from $N\pi$ scatterings
- Data from SAID program

https://gwdac.phys.gwu.edu/


GW INS
— Data Analysis Center —
Institute for Nuclear Studies
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

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Pi-N Newsletters
Obituary R.A. Arndt

Partial-Wave Analyses at GW
[See Instructions]
Pion-Nucleon
Pi-Pi-N
Kaon(+)-Nucleon
Nucleon-Nucleon
Pion Photoproduction
Pion Electroproduction
Kaon Photoproduction
Eta Photoproduction
Eta-Prime Photoproduction
Pion-Deuteron (elastic)
Pion-Deuteron to Proton+Proton

INS DAC Services [SAID Program]

- The SAID Partial-Wave Analysis Facility is based
- New features are being added and will first appear always welcome.

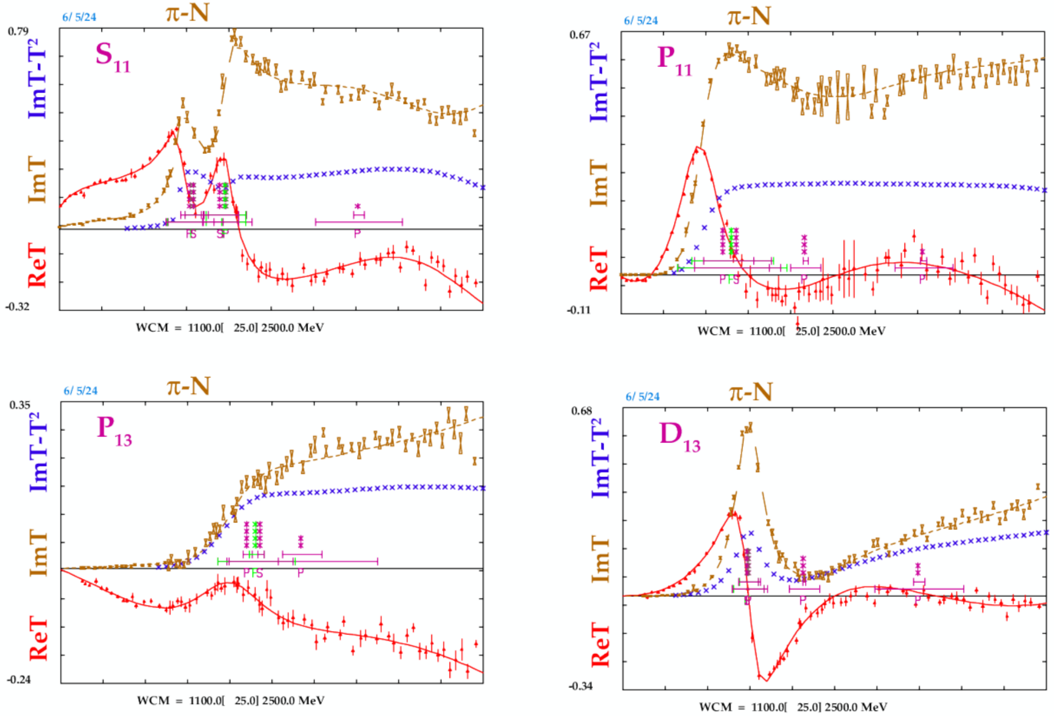
Instructions for Using the Partial-Wave Analyses

The programs accessible with the left-hand side navigation t available through the SAID program. Contact a member of c If you enter choices which are unphysical, you may still get garbage out' rule). Please report unexpected garbage-out to t

Note: These programs use HTML forms to run the SAID co setup first. The output is an (edited) echo of an interactive se SSH version. If the default example fails to clarify the speci mail message).

All programs expect energies in **MeV** units. All of the soluti Some are unstable beyond their upper energy limits. Extrapo **Increments:** The programs will not allow an arbitrary numb

$N\pi \to N\pi$



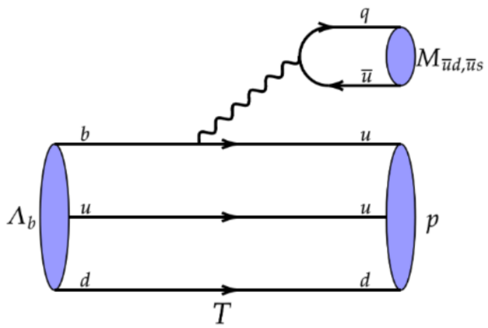
- Partial-wave amplitudes with strong phases!

- Data driven, **model independent**. Circumvent N*, more precise strong phases.

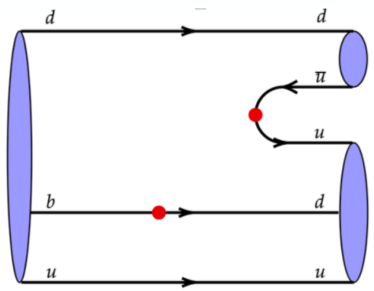
CPV cancelled between S- and P-waves

$$\mathscr{M} = \bar{u}_p\,(\,S\,+\,P\,\gamma_5\,)\,u_{\Lambda_b}$$

tree:



penguin:



$$q^\mu\;\bar{u}_p\gamma_\mu(1-\gamma_5)u_{\Lambda_b} \to m_{\Lambda_b}\bar{u}_p(1+\gamma_5)u_{\Lambda_b}$$

$$\bar{u}_p(1+\gamma_5)(\gamma_5 \not{p}_\pi)(\not{p}_{\Lambda_b}\gamma_5)\not{p}_p(1-\gamma_5)u_{\Lambda_b} \to \bar{u}_p(1-\gamma_5)u_{\Lambda_b}$$

$$S_T \approx P_T \qquad S_{PC_2} \approx -P_{PC_2}$$

- CPVs of S- and P-waves might be as large as B mesons, but cancelled with each other.
- Baryons have spinors and Dirac structures, and thus partial waves.