Theory Overview: Heavy Flavor Physics

A personal perspective

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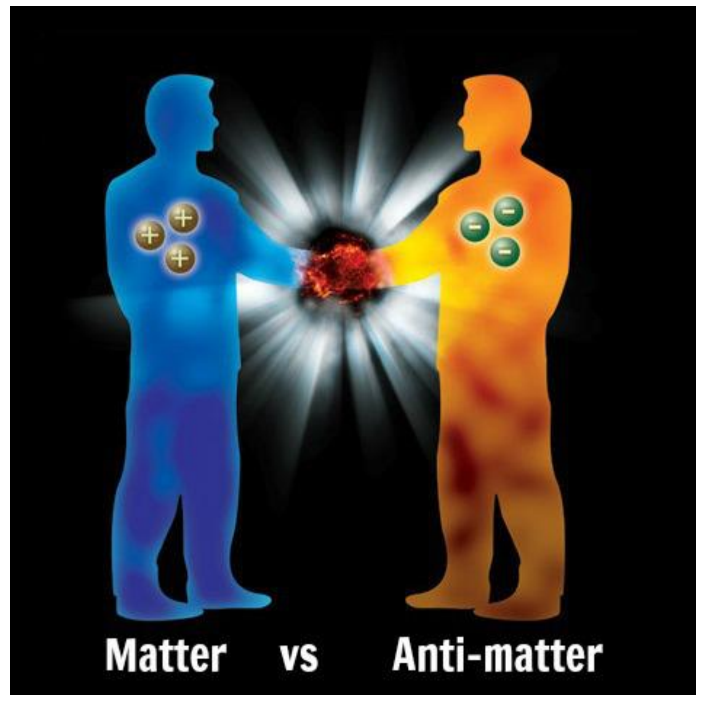
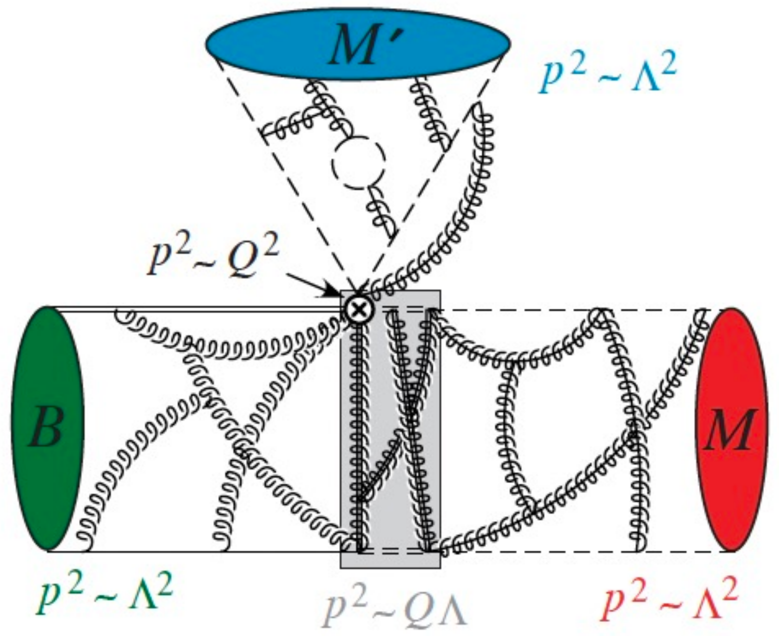


- Recent progress of **CP violation**

  Novel observables, complementary to direct CPV



- Recent progress of **QCD factorization**

  Singularity & nonperturbative inputs by Lattice

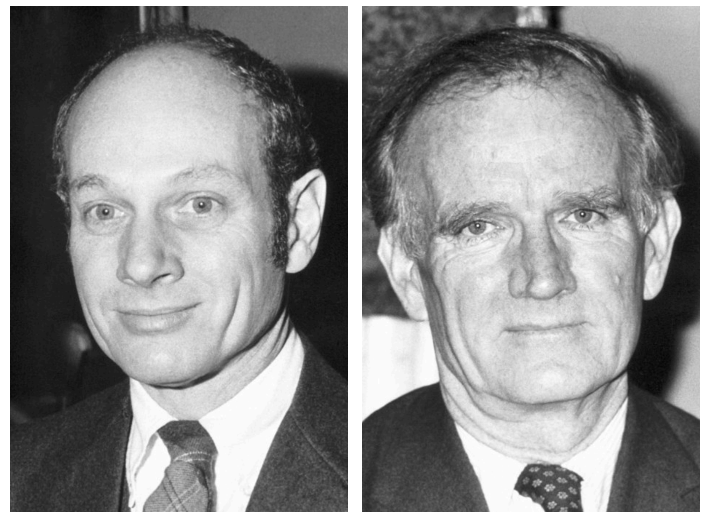
- Other highlights

Recent Progress of CP violation

Milestones of CP violation

- Mixing-induced CPV observed in Kaon decays

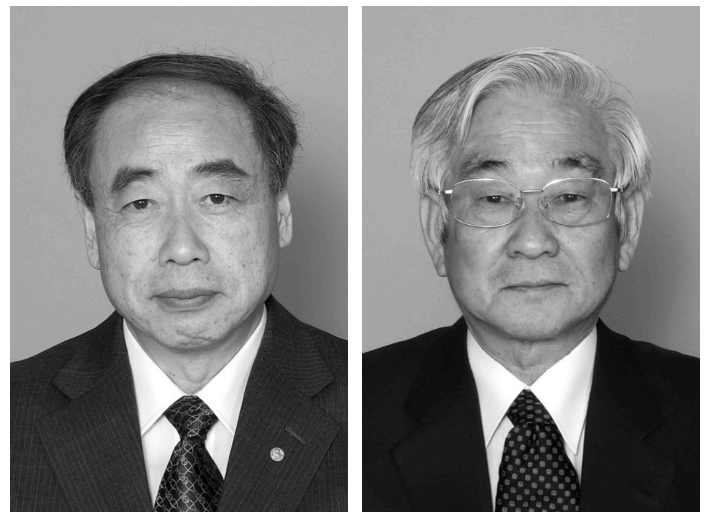
  [Christenson, Cronin, Fitch, Turlay, ’64]



Cronnin Fitch
[Nobel Prize for Physics in 1980]

- The Kobayashi-Maskawa mechanism

  [Kobayashi, Maskawa, ’73]



Kobayashi Maskawa
[Nobel Prize for Physics in 2008]

- Direct CPV discovered in B meson decays

  [BaBar & Belle, ’01]

- Direct CPV confirmed in D meson decays

  [LHCb, ’19]

physicsworld TOP 10 BREAKTHROUGH 2019

- What’s next? CPV in the baryon sector.

Experimental opportunities for baryonic CPV

- LHCb is a **baryon factory**!

$$f_{\Lambda_b}/f_{u,d} \sim 0.5$$

Machine	CEPC (10^{12} Z)	Belle II (50 ab^{-1} + 5 ab^{-1} at $\Upsilon(5S)$)	LHCb (50 fb^{-1})
Data taking	2030-2040	$\to$ 2025	$\to$ 2030
B^+	6×10^{10}	3×10^{10}	3×10^{13}
B^0	6×10^{10}	3×10^{10}	3×10^{13}
B_s	2×10^{10}	3×10^{8}	8×10^{12}
B_c	6×10^{7}	–	6×10^{10}
b baryons	10^{10}	–	10^{13}

- BESIII and Belle II have fruitful results for charmed baryons and hyperons

- First baryonic CPV evidence: 3.3σ in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ [LHCb, Nature Physics 2017]

- Experimental precision reached **1%** [LHCb, PLB 2018]

$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (-3.5 \pm 1.7 \pm 2.0)\,\%\,, \quad A_{CP}(\Lambda_b^0 \to pK^-) = (-2.0 \pm 1.3 \pm 1.0)\,\%$$

Discovery soon?

- Direct CPV in some B meson decays can reach 10%.

$$A_{CP}(\overline{B}^0 \to \pi^+\pi^-) = -0.32 \pm 0.04, \quad A_{CP}(\overline{B}_s^0 \to K^+\pi^-) = +0.213 \pm 0.017$$

Theoretical consideration for baryonic CPV

- For baryonic CPV, what observables to be measured?

- Is direct CP asymmetry the correct observable?

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2},$$

$$A = A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2} = A_1 e^{i\phi_1} e^{i\delta_1}(1 + r e^{i\phi} e^{i\delta})$$

$$\bar{A} = A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2} = A_1 e^{-i\phi_1} e^{i\delta_1}(1 + r e^{-i\phi} e^{i\delta})$$

$$\Rightarrow \quad \boxed{A_{CP} \propto 2r \sin\phi \sin\delta}$$

Requirements:

1. r is large
2. weak phase ϕ is large
3. strong phase δ is large

Far beyond control!

- Alternative observables to relax the requirements?

Partial wave CP asymmetry

- In multi-body ($n \geq 3$) decays $H \to R\ldots \to h_1 h_2 \ldots$, decay width can be expanded with the Legendre's polynomials, and the partial wave CP asymmetry is hereby defined

$$\overline{|\mathcal{M}|^2} \propto \sum_{j=0}^{\infty} w^{(j)} P_j(c_{\theta_1^*}), \quad \Rightarrow \quad A_{CP}^{(j)} \equiv \frac{w^{(j)} - \bar{w}^{(j)}}{w^{(j)} + \bar{w}^{(j)}}$$

θ_1^* : angle between h_1 and H in the $h_1 h_2$ rest frame

- It has at least the following advantages:

1. Combine information in each bins in Dalitz plots

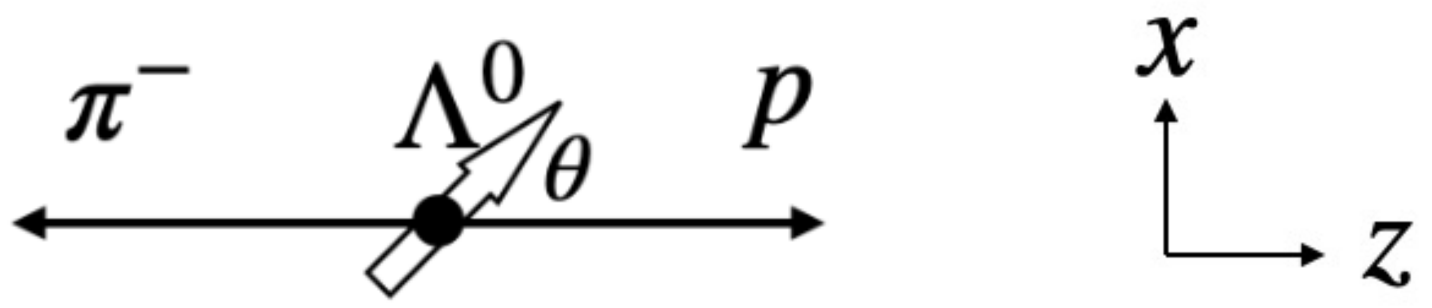
2. Different resonances R may induce interferences with large relative strong phases

[Zhang, Guo, et al, 2103.11335, 2208.13411, 2209.13196]

Polarization induced observables

- **Polarizations/helicities** of baryons provide fruitful observables.

- Lee-Yang parameters: α, β, γ



$$A(\Lambda^0 \to p\pi) = \bar{u}_p(S + P\gamma_5)u_\Lambda$$

General Partial Wave Analysis of the Decay of a Hyperon of Spin $\frac{1}{2}$

T. D. Lee* and C. N. Yang

Institute for Advanced Study, Princeton, New Jersey

(Received October 22, 1957)

Theoretically, they are expressed by partial wave amplitudes (helicity amplitudes $h_\pm = S \pm P$) as:

$$\alpha = \frac{2Re(S^*P)}{|S|^2 + |P|^2}, \quad \beta = \frac{2Im(S^*P)}{|S|^2 + |P|^2}, \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha\cos\theta$$

Experimentally, they are measured by proton polarizations:

$$P_p = \frac{(\alpha + \cos\theta)\hat{p} + \beta\hat{p}\times\hat{s} + \gamma(\hat{p}\times\hat{s})\times\hat{p}}{1 + \alpha\cos\theta}$$

Spin measurements are difficult!

Polarization induced observables

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha\cos\theta$$

- **Key point: particle spins are encoded in their decay products.**

- With entangled $\Xi^-\bar{\Xi}^+$ and $\Xi^- \to \Lambda\pi^- \to p2\pi^-$, BESIII measure the Lee-Yang parameters and their induced CPV

[BESIII, Nature 2022]

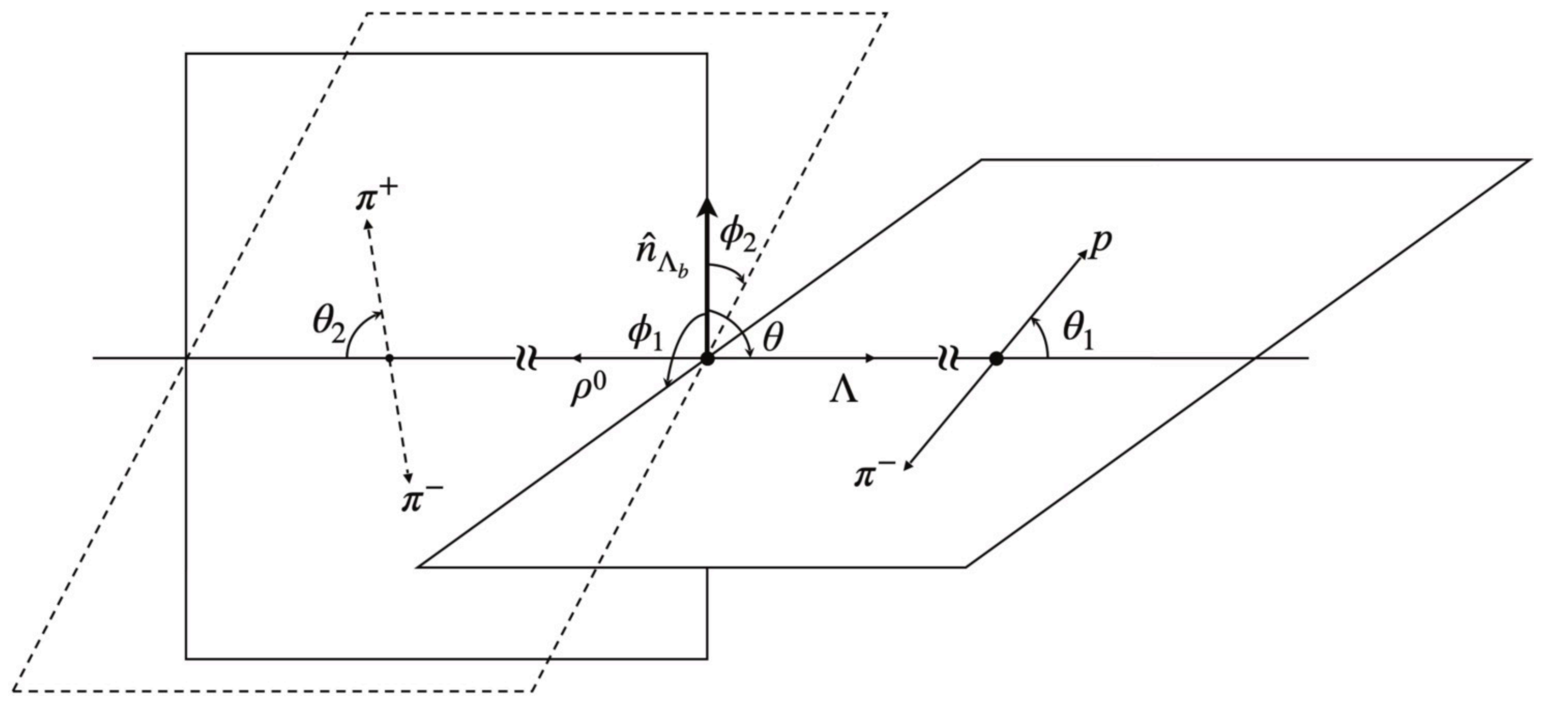
Strong phase independent! ←

$$\Delta\phi_{\rm CP} \approx \frac{\langle\alpha\rangle}{\sqrt{1-\langle\alpha\rangle^2}}\left(\frac{\beta+\bar\beta}{\alpha-\bar\alpha}\right)_\Xi = (-5\pm15)\times10^{-3}$$

- Application to more channels with Cascade decays (e.g. $\Lambda_b \to \Lambda V$)

1. Angular distribution reflects the **helicity amplitudes**
2. They induce CPVs with **different strong phase dependences**

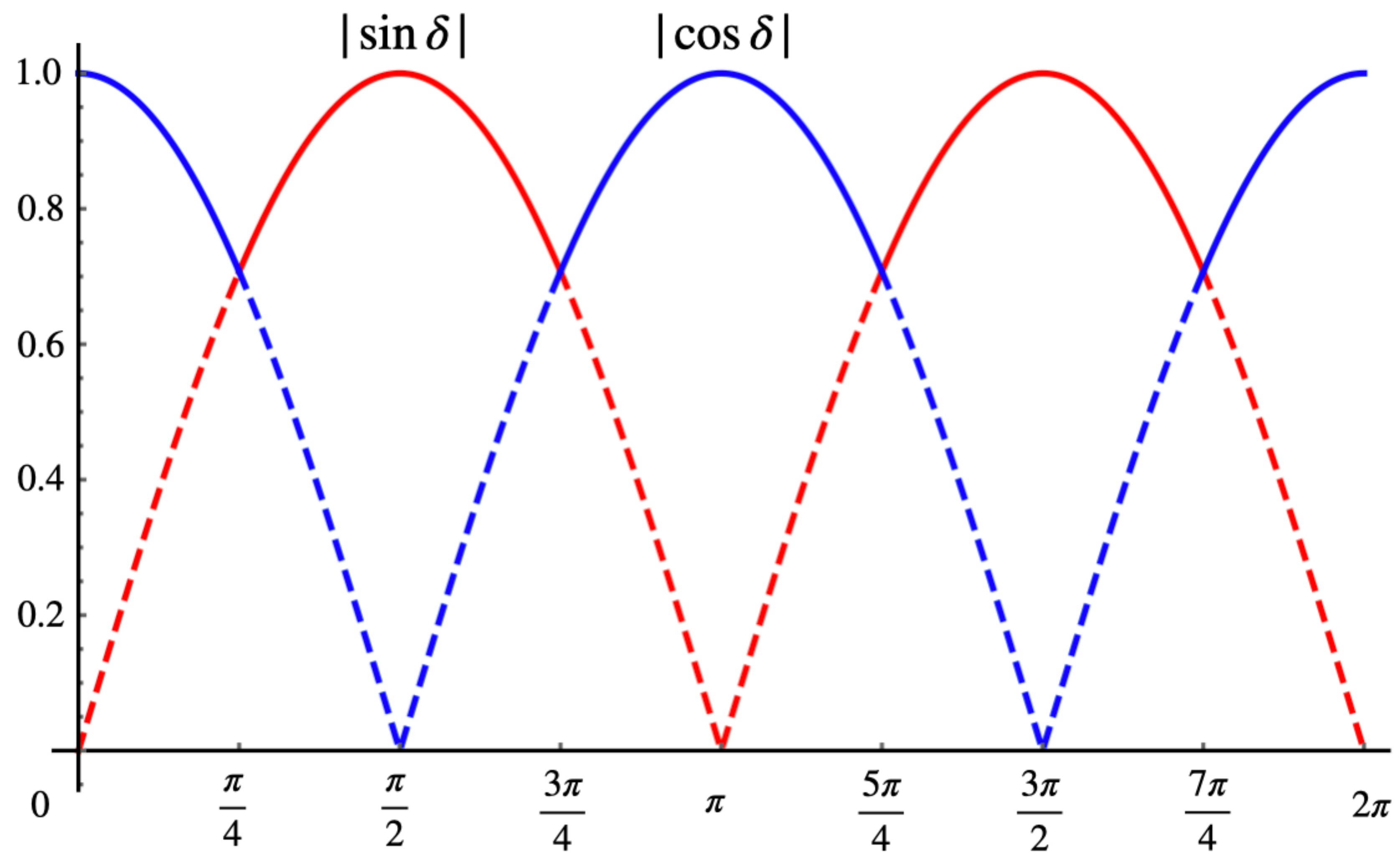
$\sin\delta_s$ **vs** $\cos\delta_s$



[Geng, Liu, et al, 2106.10628,2109.09524,2206.00348]
[Zhou, et al, 2210.15357]

Polarization induced observables

- **Strong phase dependence:** $\sin \delta_s$ **vs** $\cos \delta_s$



Whatever the strong phase is, either $|\sin \delta|$ or $|\cos \delta|$ would be larger than 0.7.

- **Question:** does this complementarity generally exist?
- **Question:** if yes, how to find them systematically?

T-odd correlation induced CP asymmetry

- T-odd correlation Q_- induced CPV have cosine dependence on strong phases

$$TQ_- = -Q_- T, \qquad A_{CP}^{Q_-} \equiv \frac{\langle Q_-\rangle - \langle \bar{Q}_-\rangle}{\langle Q_-\rangle + \langle \bar{Q}_-\rangle} \propto \cos\delta_s$$

if it satisfies two conditions: (i) for the final-state basis $\{|\psi_n\rangle$, n =1,2,…}, there is a unitary transformation U, s.t. $UT|\psi_n\rangle = e^{-i\alpha}|\psi_n\rangle$; (2) $UQ_-U^\dagger = Q_-$.

Proof:

$$\begin{aligned}\langle f|Q_-|f\rangle &= \langle i|S^\dagger Q_- S|i\rangle \\ &= \sum_{m,n}\langle\psi_i|S^\dagger|\psi_m\rangle\langle\psi_m|Q_-|\psi_n\rangle\langle\psi_n|S|\psi_i\rangle \\ &= \sum_{m,n} A_m^* A_n \langle\psi_m|Q_-|\psi_n\rangle\ .\end{aligned}$$

$$\begin{aligned}\langle\psi_m|Q_-|\psi_n\rangle &= \langle\psi_m|\mathcal{T}^\dagger\mathcal{T}\,Q_-|\psi_n\rangle^* \\ &= -\langle\psi_m|\mathcal{T}^\dagger Q_-\mathcal{T}|\psi_n\rangle^* \\ &= -\langle\psi_m|\mathcal{T}^\dagger\,\mathcal{U}^\dagger\mathcal{U}\,Q_-\,\mathcal{U}^\dagger\mathcal{U}\,\mathcal{T}|\psi_n\rangle^* \\ &= -\langle\psi_m|\mathcal{T}^\dagger\mathcal{U}^\dagger\,Q_-\,\mathcal{U}\mathcal{T}|\psi_n\rangle^* \\ &= -\langle\psi_m|Q_-|\psi_n\rangle^*\ ,\end{aligned}$$

$\longrightarrow$ $\langle f|Q_-|f\rangle \ni \mathrm{Im}(A_m^* A_n)$ $\longrightarrow$ $A_{CP}^{Q_-} \propto \sin\delta_w \cos\delta_s$

[Wang, **QQ**, Yu, 2211.07332]

T-odd correlation induced CP asymmetry

- Example 1. Triple product $Q_1 \equiv (\vec{s}_1 \times \vec{s}_2) \cdot \hat{p}$ in $P \to P_1 P_2$

$T: \vec{p} \to -\vec{p}, h \to h;$ $\quad U = R(\pi): -\vec{p} \to \vec{p}, h \to h$ $\longrightarrow$ condition (i)

$T: Q_1 \to -Q_1;$ $\quad U = R(\pi): Q_1 \to Q_1$ $\longrightarrow$ condition (ii)

- Example 2. Triple product $Q_p \equiv (\hat{p}_1 \times \hat{p}_2) \cdot \hat{p}_3$ in $P \to P_1 P_2 P_3 P_4$

$T: \vec{p} \to -\vec{p};$ $\quad U = P: -\vec{p} \to \vec{p}$ $\longrightarrow$ condition (i)

$T: Q_p \to -Q_p;$ $\quad U = P: Q_p \to -Q_p$ $\not\longrightarrow$ condition (ii)

[Wang, **QQ**, Yu, 2211.07332]

T-odd correlation induced CP asymmetry

- For the decay $\Lambda_b \to N^*(1520)K^*$, three such T-odd correlations

$$Q_1 \equiv (\vec{s}_1 \times \vec{s}_2) \cdot \hat{p} = \frac{i}{2}(s_1^+ s_2^- - s_1^- s_2^+)$$

$$Q_2 \equiv (\vec{s}_1 \cdot \hat{p})(\vec{s}_2 \cdot \hat{p})Q_1 + Q_1(\vec{s}_1 \cdot \hat{p})(\vec{s}_2 \cdot \hat{p}) = \frac{i}{2}s_1^z s_2^z (s_1^+ s_2^- - s_1^- s_2^+) + \frac{i}{2}(s_1^+ s_2^- - s_1^- s_2^+) s_1^z s_2^z$$

$$Q_3 \equiv (\vec{s}_1 \cdot \vec{s}_2)Q_1 + Q_1(\vec{s}_1 \cdot \vec{s}_2) - Q_2 = \frac{i}{2}(s_1^+ s_1^+ s_2^- s_2^- - s_1^- s_1^- s_2^+ s_2^+)$$

- Their expectations are imaginary helicity amplitude interferences

$$\langle Q_3 \rangle = 2\sqrt{3}\ \mathrm{Im}\ (H_{+1,+\frac{3}{2}} H^*_{-1,-\frac{1}{2}} + H^*_{-1,-\frac{3}{2}} H_{+1,+\frac{1}{2}})$$

$\cos\delta_s$ **vs** $\sin\delta_s$

Complementary!

- Moreover, complementary T-even correlations are found

$$P_1 \equiv \vec{s}_1 \cdot \vec{s}_2 - (\vec{s}_1 \cdot \hat{p})(\vec{s}_2 \cdot \hat{p}),\ P_2 \equiv (\vec{s}_1 \cdot \hat{p})(\vec{s}_2 \cdot \hat{p})P_1 + P_1(\vec{s}_1 \cdot \hat{p})(\vec{s}_2 \cdot \hat{p}),$$

$$P_3 \equiv P_1^2 - [\vec{s}_1^{\,2} - (\vec{s}_1 \cdot \hat{p})^2][\vec{s}_2^{\,2} - (\vec{s}_2 \cdot \hat{p})^2] - [(\vec{s}_1 \times \vec{s}_1) \cdot \hat{p}][(\vec{s}_2 \times \vec{s}_2) \cdot \hat{p}]$$

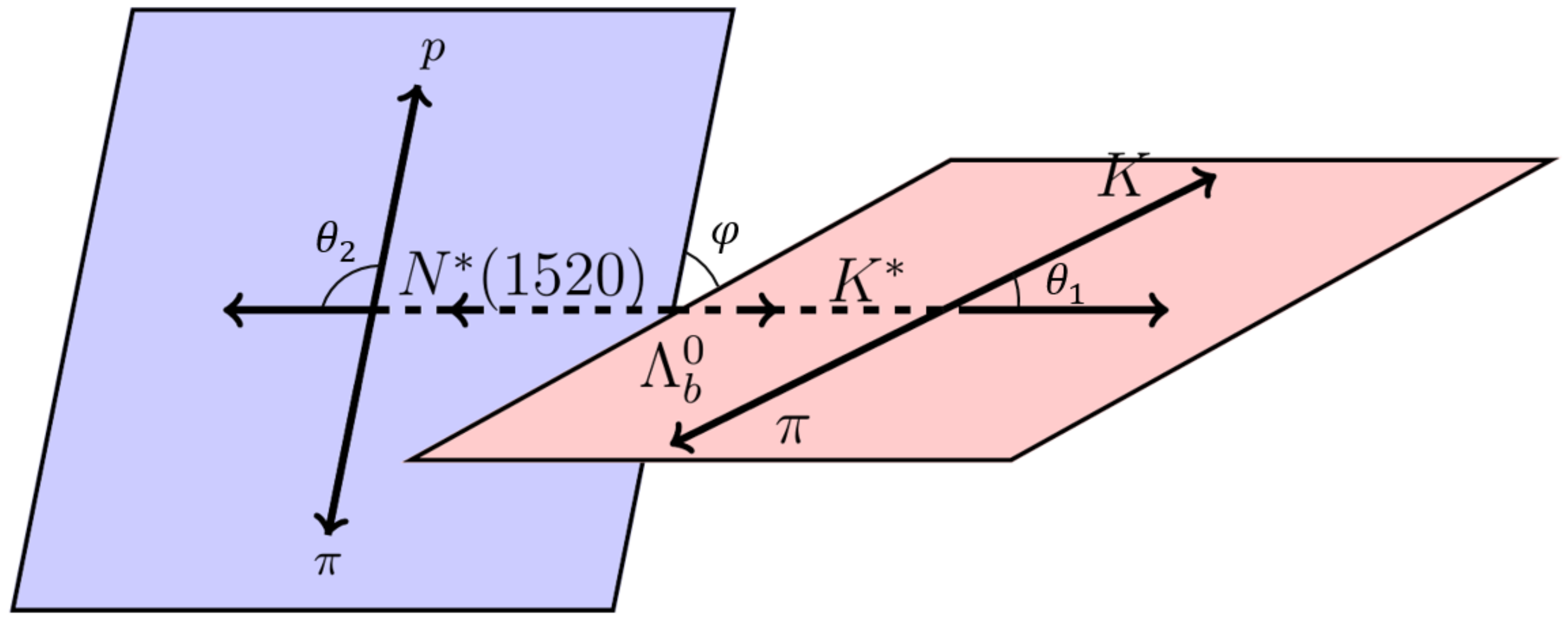
Real part

$$\langle P_3 \rangle \propto \mathrm{Re}\ (H_{+1,+\frac{3}{2}} H^*_{-1,-\frac{1}{2}} + H^*_{-1,-\frac{3}{2}} H_{+1,+\frac{1}{2}})$$

[Wang, **QQ**, Yu, 2211.07332]

T-odd correlation induced CP asymmetry

- The expectations of the complementary T-odd and T-even correlations are both encoded in angular distribution of secondary decays of $N^*(1520)K^*$



$$
\begin{aligned}
\frac{d\Gamma}{dc_1\,dc_2\,d\varphi} \propto\ & s_1^2 s_2^2 \left(\left|\mathcal{H}_{+1,+\frac{3}{2}}\right|^2 + \left|\mathcal{H}_{-1,-\frac{3}{2}}\right|^2\right) \\
& + s_1^2\left(\frac{1}{3} + c_2^2\right)\left(\left|\mathcal{H}_{+1,+\frac{1}{2}}\right|^2 + \left|\mathcal{H}_{-1,-\frac{1}{2}}\right|^2\right) \\
& + 2c_1^2\left(\frac{1}{3} + c_2^2\right)\left(\left|\mathcal{H}_{0,-\frac{1}{2}}\right|^2 + \left|\mathcal{H}_{0,+\frac{1}{2}}\right|^2\right) \\
& - \frac{s_1^2 s_2^2}{\sqrt{3}} \mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin 2\varphi \qquad \langle Q_3 \rangle \\
& + \frac{s_1^2 s_2^2}{\sqrt{3}} \mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos 2\varphi \qquad \langle P_3 \rangle \\
& - \frac{4 s_1 c_1 s_2 c_2}{\sqrt{6}} \mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin\varphi \qquad \langle Q_1 + 2Q_2 \rangle \\
& + \frac{4 s_1 c_1 s_2 c_2}{\sqrt{6}} \mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos\varphi \qquad \langle P_1 + 2P_2 \rangle
\end{aligned}
$$

- Complementary CP asymmetries can thereby be measured, which depend on $\cos\delta_s$ & $\sin\delta_s$.

[Wang, **QQ**, Yu, 2211.07332]

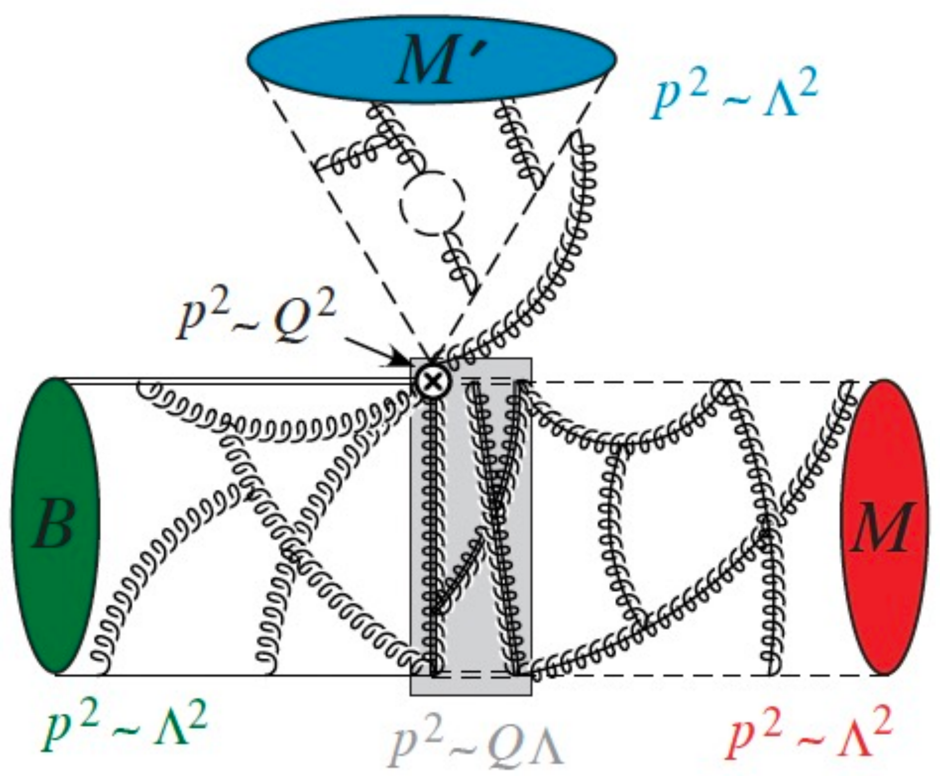
Recent progress of QCD Factorization

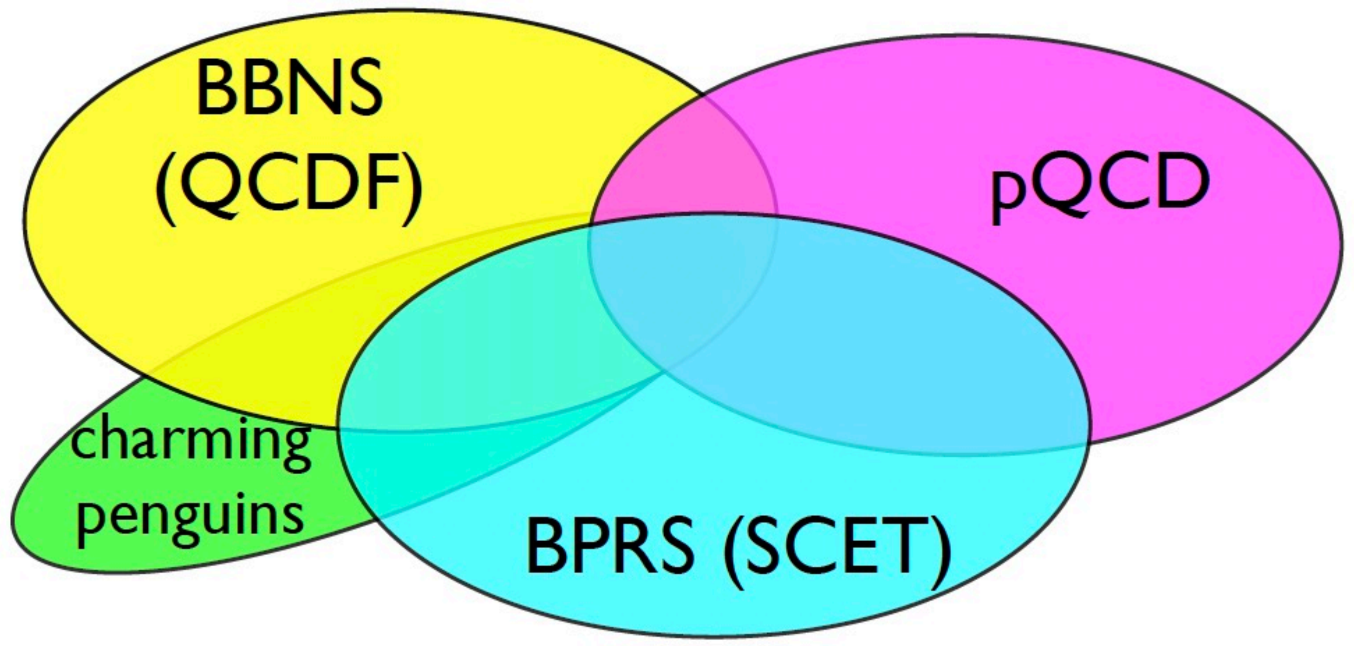
QCD Factorization

- Factorization makes **hadron** involved physical processes **calculable**

  ➡ **Short-distance** dynamics: perturbatively calculable

  ➡ **Long-distance** dynamics: universal inputs, e.g., form factors, LCDAs





[Beneke,Buchalla,Neubert,Sachradja, BBNS]

[Keum,Li,Lu,Sanda,Xiao, PQCD]

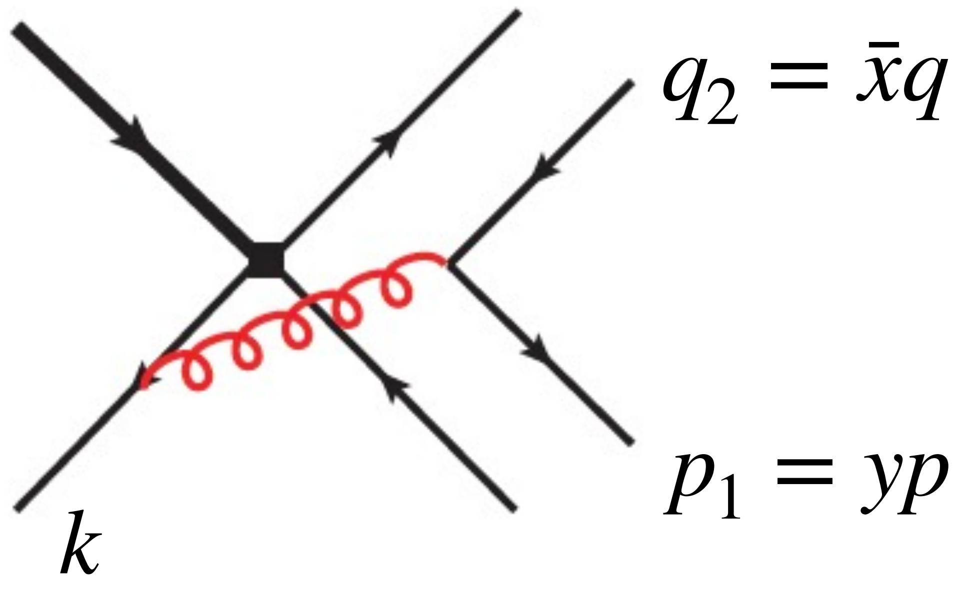
[Bauer, Pirjol, Rothstein, Stewart, SCET]

- Crucial to SM predictions for two-body B decays, especially CP violation

- Data + short-distance dynamics ⇨ nonperturbative QCD

Annihilation amplitude

- BBNS suffers from endpoint singularities in annihilation diagrams



$$\frac{1}{[(p_1+q_2+k)^2+i\epsilon][(p_1+q_2)^2+i\epsilon]}$$

Quark propagator   Gluon propagator

$(p_1+q_2)^2 \sim m_b^2$

Soft $k \sim \Lambda_{\rm QCD} \to 0$

$$\int_0^\infty d\omega\,\phi_B^+(\omega)\int_0^1 dx\,\phi_{M_2}(x)\int_0^1 dy\,\phi_{M_1}(y)\frac{1}{\bar{x}^2 y}$$

$\phi_P(x) = 6x(1-x)$

Divergence!

- Parametrization of the logarithmic divergence by BBNS

$$\int_0^1 dx\frac{\phi_M(x,\mu)}{\bar{x}^2} = \left(\lim_{u\to 1}\frac{\phi_M(u,\mu)}{\bar{u}}\right)\underbrace{\int_0^1\frac{dx}{\bar{x}}}_{} + \underbrace{\int_0^1\frac{dx}{\bar{x}}\left[\frac{\phi_M(x,\mu)}{\bar{x}} - \left(\lim_{u\to 1}\frac{\phi_M(u,\mu)}{\bar{u}}\right)\right]}_{\text{finite}}$$

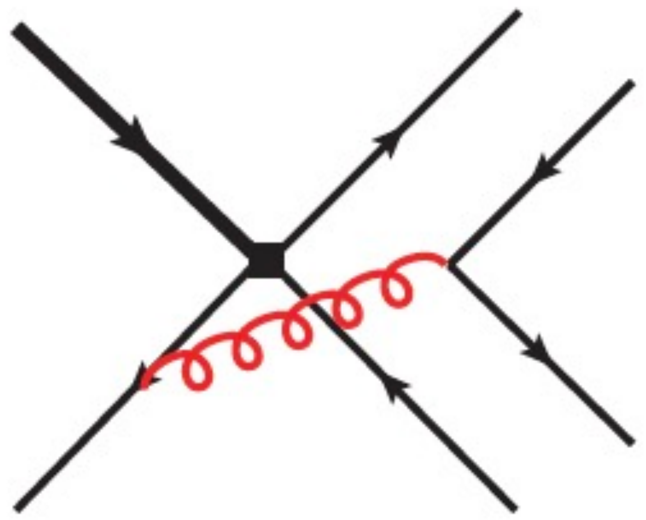
$$X_A^M = (1+\rho_A e^{i\varphi_A})\ln\frac{m_B}{\Lambda_h}\,.$$

[BBNS, '01]

- Make BBNS **much less predictive**
  - ➡ for pure annihilation channels
  - ➡ for CP violation, which is sensitive to strong phase

Annihilation amplitude

- The fact: **no divergence here!** The power counting **Soft** $k \sim \Lambda_{\rm QCD} \to 0$ **is wrong.**
- They key: pick up **the missing piece!**



Hard gluon contribution

$(p_1 + q_2)^2 \sim m_b^2$

$\sim$

The missing piece

Hard-collinear gluon contribution

$(p_1 + q_2)^2 \sim m_b \Lambda_{\rm QCD}$

Both leading power!

- **The complete formulation (keep $p_1 \cdot k$):**

$$\int_0^\infty d\omega \phi_B^+(\omega) \int_0^1 dx \phi_{M_2}(x) \int_0^1 dy \phi_{M_1}(y) \frac{1}{\bar{x} y (\bar{x} - \omega/m_B + i\epsilon)} \approx 18 \left[\left(\ln(m_B/\lambda_B) + \gamma_E + 2 \right) - i\pi \right]$$

From hard-collinear gluon exchange

- The annihilation diagram is **calculable, finite,** and contains **strong phase!**

[Lu, Shen, Wang, Wang, 2202.08073]

Annihilation amplitude

- It **corrects the BBNS factorization** of the annihilation diagram!
- It makes the BBNS formalism **more predictive!**
- It is important to phenomenology, especially to CPV!

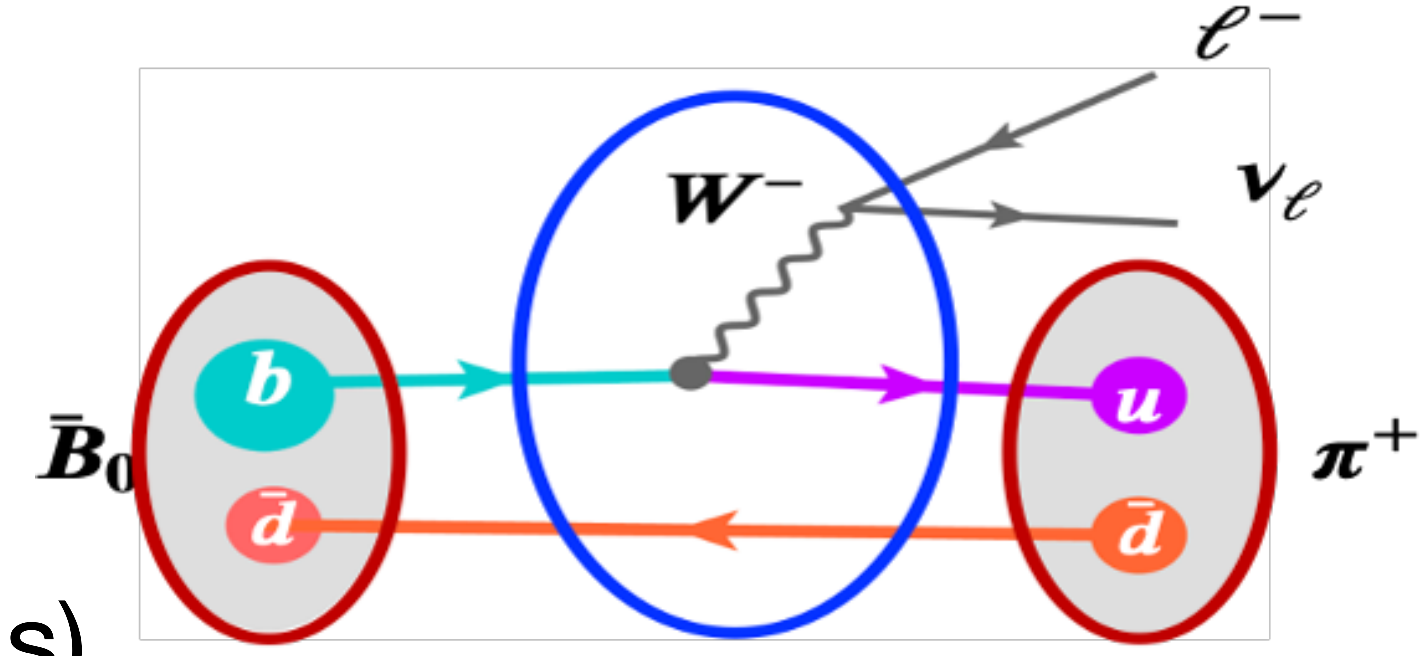
	$\mathcal{A}_{\rm CP}^{\rm dir}$	$\mathcal{A}_{\rm CP}^{\rm mix}$
$\bar{B}_s \to \pi^+\pi^-,\ \pi^0\pi^0$	$-36.3^{+8.2}_{-1.3}$ (0.0 ± 0.0)	$-4.2^{+21.4}_{-9.0}$ $(35.9^{+15.6}_{-11.2})$
$\bar{B}_s \to \rho_L^+\rho_L^-,\ \rho_L^0\rho_L^0$	$-36.3^{+8.3}_{-1.8}$ (0.0 ± 0.0)	$-4.3^{+21.5}_{-9.0}$ $(35.9^{+15.6}_{-11.2})$
$\bar{B}_s \to \omega_L\,\omega_L$	$-36.3^{+8.3}_{-3.1}$ (0.0 ± 0.0)	$-3.8^{+21.8}_{-9.7}$ $(35.9^{+15.6}_{-11.2})$
$\bar{B}_s \to \rho_L\,\omega_L$	0.0 ± 0.0 (0.0 ± 0.0)	$-71.0^{+6.3}_{-5.4}$ $(-71.0^{+6.3}_{-5.4})$
$\bar{B}_d \to K^+K^-$	$39.0^{+3.2}_{-5.6}$ (0.0 ± 0.0)	$-2.2^{+19.1}_{-26.4}$ $(-47.0^{+15.7}_{-18.8})$
$\bar{B}_d \to K_L^{*+}K_L^{*-}$	$39.6^{+4.9}_{-6.7}$ (0.0 ± 0.0)	$-1.4^{+19.7}_{-26.9}$ $(-47.0^{+15.7}_{-18.8})$
$\bar{B}_d \to \phi_L\,\phi_L$	$38.3^{+11.4}_{-15.8}$ (0.0 ± 0.0)	$27.8^{+5.7}_{-25.9}$ (0.0 ± 0.0)

[Lu, Shen, Wang, Wang, 2202.08073]

Light-cone Distribution Amplitudes

- LCDA: parton momentum fraction distribution in the light-cone direction

$$\int \frac{d\xi^-}{2\pi} e^{ixp^+\xi^-} \langle 0|\bar{\psi}_1(0) n\cdot\gamma\gamma_5 U(0,\xi^-)\psi_2(\xi^-)|\pi(p)\rangle = i f_\pi \Phi_\pi(x)$$



- Critical nonperturbative inputs to factorization calculation

  ➡ Extracted from data (suffer pollution from power corrections)

  ➡ Calculated by nonperturbative methods, e.g., Sum Rules, Dyson-Schwinger equation, inverse problem, …

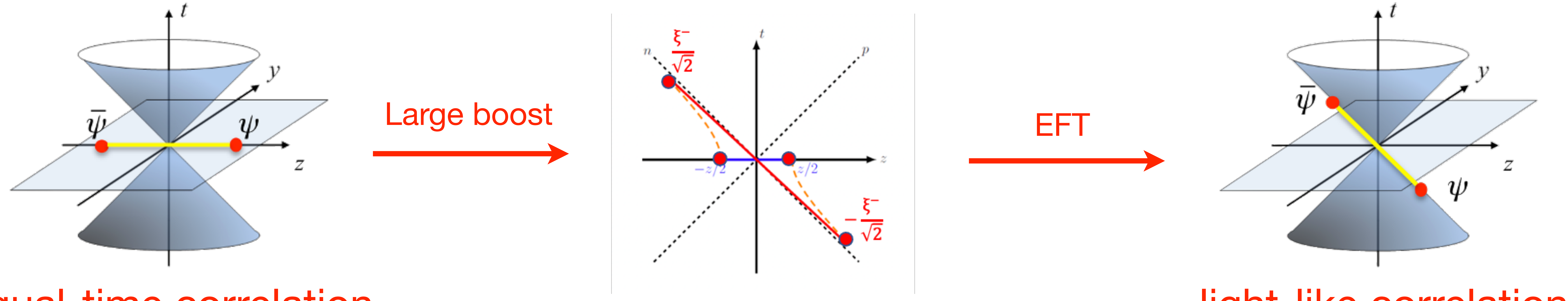
[Ball,'07; Cheng,'20; Chang,Roberts,…,'13; H.n.Li, 2205.06746]

- A **first-principle lattice QCD calculation** is available.

[Lattice Parton Collaboration, J.Hua et al,
*Phys.Rev.Lett.*129 (2022) 132001;
*Phys.Rev.Lett.*127 (2021) 062002]

Light-cone Distribution Amplitudes

- LCDA is a light-like correlation. Cannot be directly calculated by lattice.
- Instead, a **quasi-DA** can be calculated



equal-time correlation

light-like correlation

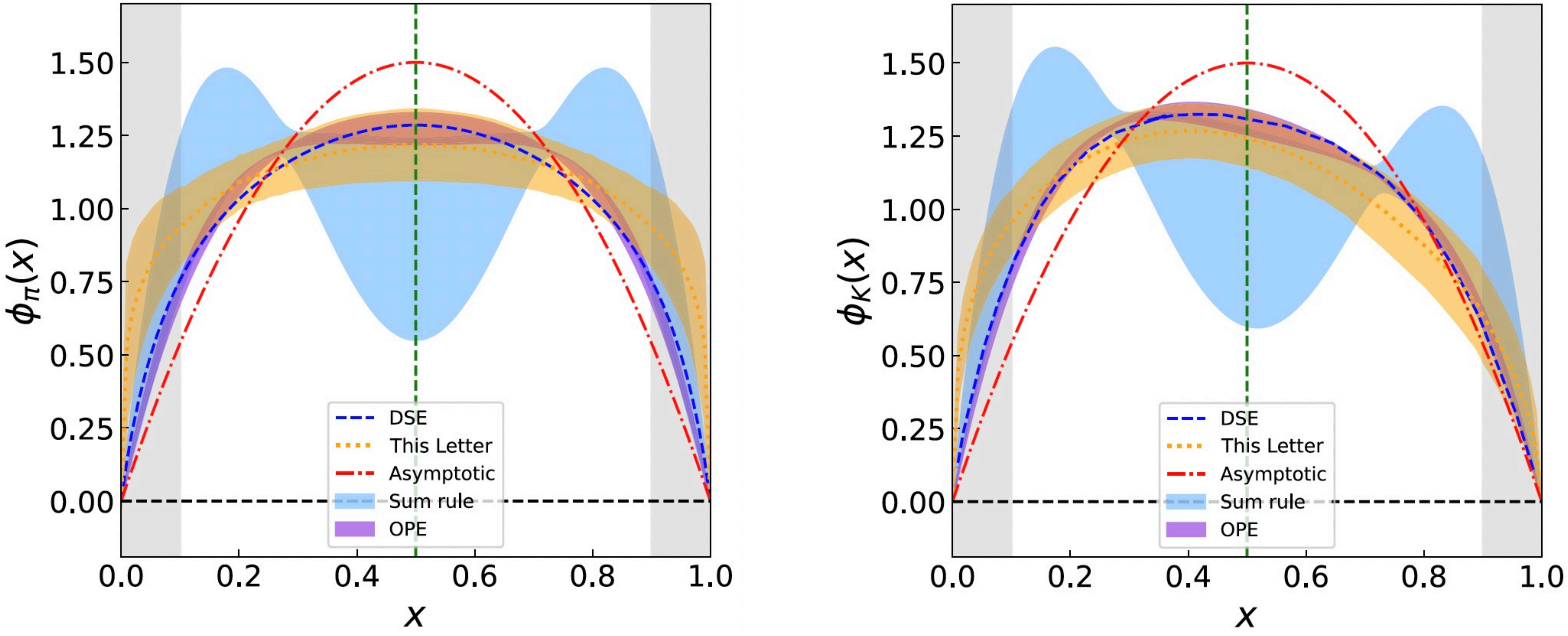
- Large momentum effective theory (LaMET): extract LCDA from quasi-DA [Xi,…,'13,'21]

$$\underbrace{\tilde{q}(x,P^z,\mu)}_{\text{Quasi-DA}} = \int \frac{dy}{|y|} \underbrace{C(x,y,P^z,\mu)}_{\text{Matching kernel}} \underbrace{q(y,\mu)}_{\text{LCDA}} + \underbrace{\mathcal{O}\left(\frac{\Lambda^2, M^2}{(P^z)^2}\right)}_{\text{Power suppressed}}$$

[LPC, J.Hua et al, *Phys.Rev.Lett.*129 (2022) 132001]

Light-cone Distribution Amplitudes

- Lattice results for leading-twist pion and kaon LCDAs



 [LPC, J.Hua et al, *Phys.Rev.Lett.*129 (2022) 132001]

Other Highlights

Other highlights

New mechanism

- The long-distance penguin contribution to $\bar{B} \to \gamma\gamma$, a novel B meson DA [QQ, Y.L.Shen, C.Wang, Y.M.Wang, 2207.02691]
- Modified PQCD and its application in in B→ππ decays [S.Lü, M.Z.Yang, 2211.10917]

New Calculation

- PQCD calculation of baryon decays [J.J.Han, Y.Li, H.n.Li, Y.L.Shen, Z.J.Xiao, F.S.Yu, 2202.04804; C.Q.Zhang, J.M.Li, M.K.Jia, Zhou Rui, 2202.09181, 2206.04501, 2210.15357]
- Sum Rule calculation of baryon decays [Yan Miao, Hui Deng, Ke-Sheng Huang, Jing Gao, Yue-Long Shen, 2206.12189; K.S.Huang, W.Liu, Y.L.Shen, F.S.Yu, 2205.06095]

New correction

- NLO QCD corrections to inclusive $b \to c\ell\bar{\nu}$ decay spectra up to $1/m_Q^3$ [T.Mannel, D.Moreno, A.A.Pivovarov, 2111.06418]
- A Reappraisal of $B \to \gamma\ell\bar{\nu}$: Factorization and Sudakov Resummation [A.M.Galda, M.Neubert, X.Wang, 2203.08202]
- Strange quark mass effect in $B_s \to \gamma\gamma, \gamma\ell\bar{\ell}$ decays [D.H.Li, L.Y.Li, C.D.Lü, Y.L.Shen, 2205.05528]

Other highlights

New channels

- Weak decays of excited-state mesons, e.g. $D^*_{(s)}, B^*_c$

See S. Cheng's talk
[S.Cheng, Y.H.Ju, QQ, F.S.Yu, 2203.06797; J.H.Sheng, Q.Y.Hu,R.M.Wang, EPJC'22; Y.L.Yang, L.T. Wang, K.Li, L.T.Li, J.S.Huang, Q.Chang, J.F.Sun, 2207.10277,2208.02396]

- Inclusive weak-annihilation decays and lifetimes of Ξ_{bc} [G.H.Yang, E.P.Liang, QQ, K.K.Shao, 2208.06834]

- PQCD calculation of four-body non-leptonic B decays [Y.Li, D.C.Yan, R.Zhou, Z.J.Xiao, 2204.01092,2208.06834 C.Q.Zhang, J.M.Li, M.K.Jia, Y.Li, R.Zhou, 2112.10939]

New observables

- Probing hyperon CP violation from charmed baryon decays [J.P.Wang, F.S.Yu, 2208.01589]

- Angular distributions for $\Lambda_b \to \Lambda^*_J(pK^-)J/\psi$ Decays

See F. Huang's talk
[Zhi-Peng Xing, Fei Huang, Wei Wang, 2203.13524]

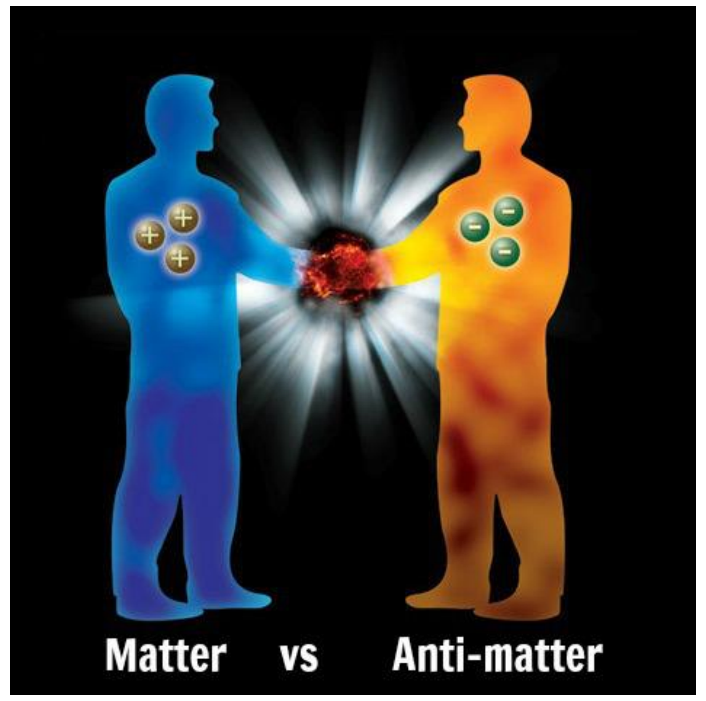
New Physics

- Scrutinizing new physics in semi-leptonic $B_c \to J/\psi\tau\nu$ decay [R.Y.Tang, Z.R.Huang, C.D.Lü, R.L.Zhu, 2204.04357]

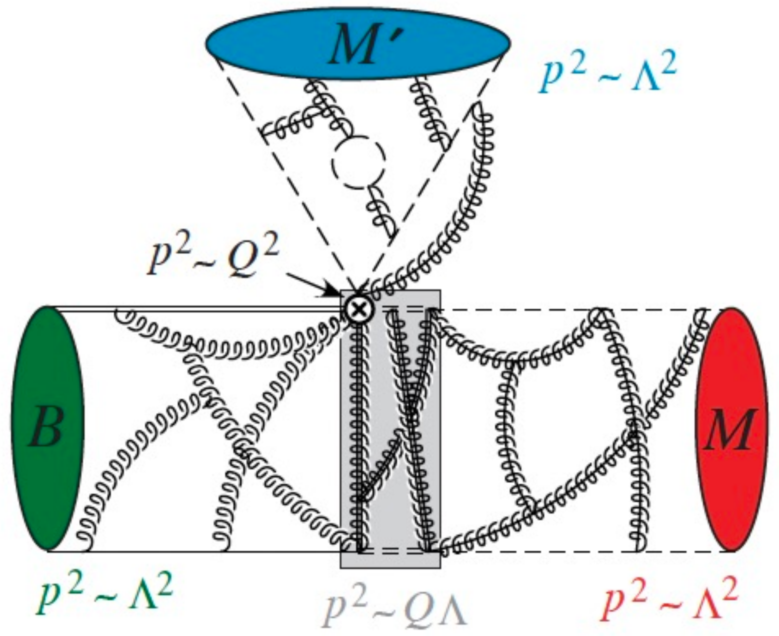
- Linking $R_{K^{(*)}}$ anomalies to H_0 tension via Dirac neutrino [W.F.Duan, S.P.Li, X.Q.Li, Y.D.Yang, 2111.05178]

Summary

Summary



- **Novel CPV observables** are proposed, including those **complementary** to each other, which would help discover **baryonic CPV**.



- QCD factorization has been reanalyzed with **endpoint singularities** "disappearing" in annihilation amplitudes, and it become more predictive with **lattice calculation of LCDAs**.

- There are many other beautiful works in flavor physics in the past year, including progresses of **new mechanisms, new calculations, new corrections, new channels, new observables** and **new physics**.

Thank you!