

Probing the Color-Octet Mechanism via Dihadron Fragmentation in χ_b Decays

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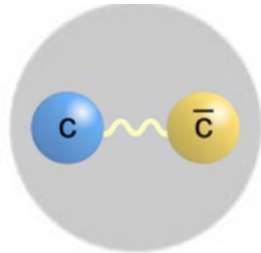
Based on Zhi-Guo He, Guanghui Li, Yu-Jie Tian, Xin-Kai Wen, **Bin Yan**, arXiv: 2603.18874

NRQCD and Heavy Quarkonium

- Heavy quarkonium: the non-relativistic bound state

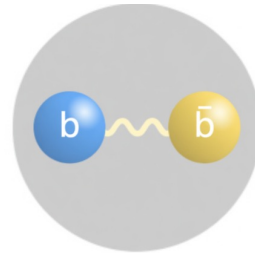
Charmonium

$$v_c^2 \simeq 0.23$$



Bottomonium

$$v_b^2 \simeq 0.08$$



- Color-Singlet Model

$Q\bar{Q}$ with the same quantum numbers as the final bound state $2S+1 L_J^{[c]}$

$$c\bar{c}({}^3S_1^{[1]}) \rightarrow J/\Psi$$

$$b\bar{b}({}^3S_1^{[1]}) \rightarrow \Upsilon$$

- **Theoretical issues:**

Infrared divergences in P-wave production and decay at higher orders in QCD

- **Exp issues:** Huge cross section discrepancy $\sigma_{pp \rightarrow J/\Psi} \gg \sigma_{CSM}$

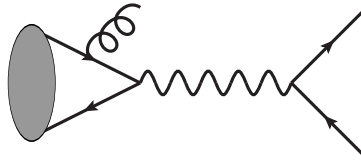
NRQCD and Heavy Quarkonium

➤ NRQCD factorization

G. T. Bodwin, E. Braaten, G. P. Lepage, PRD 51 (1995) 1125

❖ $Q\bar{Q}$ could be in all possible spin and color configurations

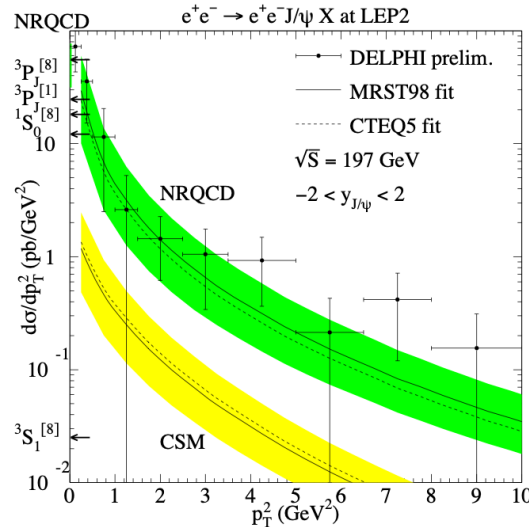
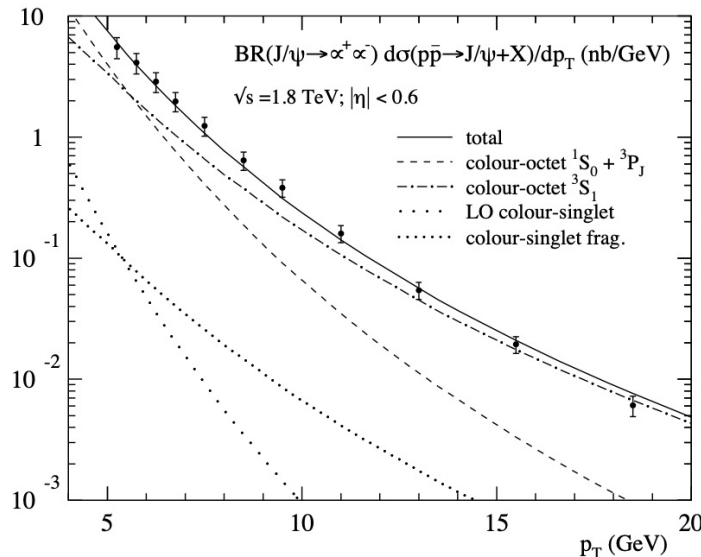
❖ Color-Octet Mechanism:



Physical quarkonium

$$|H\rangle = |Q\bar{Q}(1)\rangle + |Q\bar{Q}g(8)\rangle + \dots$$

❖ IR divergences in Color-Singlet are absorbed into Color-Octet matrix elements



CO contributions
can dominate in
some regimes

G. T. Bodwin,
hep-ph/0509203

NRQCD and Heavy Quarkonium

➤ NRQCD factorization

$$\Gamma(H \rightarrow LH) = \sum_n \frac{2 \operatorname{Im} f_n(\Lambda)}{m_Q^{d_n-4}} \langle H | \mathcal{O}_n(\Lambda) | H \rangle$$

Short distance coefficients α_s expansion	Long distance matrix elements v^2 expansion
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➤ Fock state expansion

$$\begin{aligned} |H^{(2S+1)L_J}\rangle &= O(1) |Q\bar{Q}^{(2S+1)L_J^{[1]}}\rangle \\ &+ O(v) |Q\bar{Q}^{(2S+1)(L \pm 1)_{J'}^{[8]}}g\rangle && \text{E1} \\ &+ O(v^2) |Q\bar{Q}^{(2S'+1)L_{J'}^{[8]}}g\rangle && \text{M1} \\ &+ O(v^2) |Q\bar{Q}^{(2S+1)L_J^{[1,8]}}gg\rangle && \text{E1} \cdot \text{E1} \\ &+ \dots \end{aligned}$$

Power counting



$$\langle H | \mathcal{O}_n(\Lambda) | H \rangle \sim v^{2i+j}$$

i for Fock state
 j for operator

Testing Color-Octet Mechanism

➤ P-wave quarkonium χ_{QJ} $|H^{(2S+1)L_J}\rangle = O(1) |Q\bar{Q}^{(2S+1)L_J^{[1]}}\rangle$
 $\langle H | \mathcal{O}_n(\Lambda) | H \rangle \sim v^{2i+j} + O(v) |Q\bar{Q}^{(2S+1)(L \pm 1)_{J'}^{[8]}}g\rangle$

$i = 0, j = 2$: Color-Singlet

Leading order in NRQCD!

$i = 1, j = 0$: Color-Octet

➤ Testing Color-Octet Mechanism

CS: $b\bar{b}({}^3P_J^{[1]}) \rightarrow gg$ **CO:** $b\bar{b}({}^3S_1^{[8]}) \rightarrow q\bar{q}$

How to distinguish the quark and gluon final state?

❖ Quark jet and gluon jet?

❖ Parton fragments into hadrons? PRD 78 (2008) 092007, CLEO

$$\chi_{bJ}(1P) \rightarrow D^0 X$$

CS and CO contributions are experimentally indistinguishable

Testing Color-Octet Mechanism

➤ Lattice VS Experiment

$$H_1^Q = \langle \chi_{QJ} | \mathcal{O}(^3P_J^{[1]}) | \chi_{QJ} \rangle$$

$$\rho_8(m_Q) = H_8^Q(m_Q) m_Q^2 / H_1^Q$$

$$H_8^Q(\mu_\Lambda) = \langle \chi_{QJ} | \mathcal{O}(^3S_1^{[8]}, \mu_\Lambda) | \chi_{QJ} \rangle$$

➤ Charmonium $\rho_8 = 0.128(2)(9)_{-47}^{+61}$ (Lattice)

$$\rho_8 = 0.095(43) \text{ (Exp)}$$

G. T. Bodwin, D. K. Sinclair, S. Kim, PRL 77 (1996) 2376

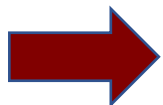
➤ Bottomonium $\rho_8 = 0.044 \pm 0.015$ (Lattice)

$$\rho_8 = 0.16_{-0.047}^{+0.071} \text{ (CLEO)}$$

Anomaly!

G. T. Bodwin, E. Braaten, D. Kang, J. Lee, PRD 76 (2007) 054001

CLEO: PRD 78 (2008) 092007



An independent cross-check of ρ_8 is very important!

How to separate CO from CS?

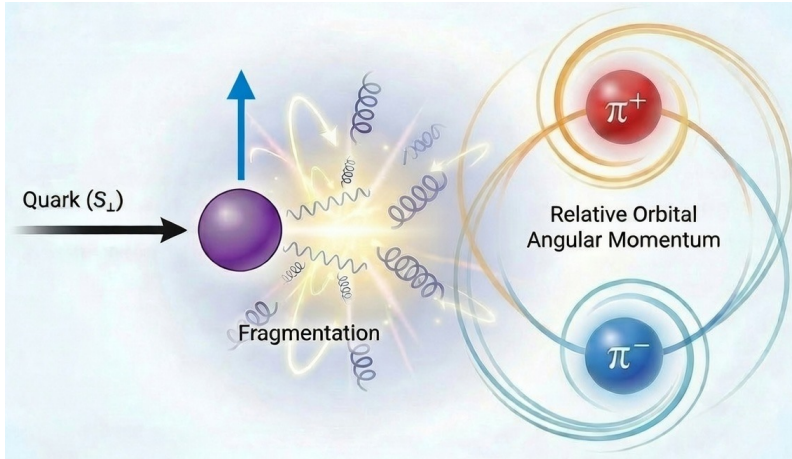
$$b\bar{b}(^3S_1^{[8]}) \rightarrow q\bar{q}$$

$$b\bar{b}(^3P_J^{[1]}) \rightarrow gg$$

 The spin of quark and gluon is different!

Spin effects in QCD

- Quark fragmentation carries transverse spin correlations



X. Artru, J. C. Collins, Z. Phys. C 69 (1996) 277

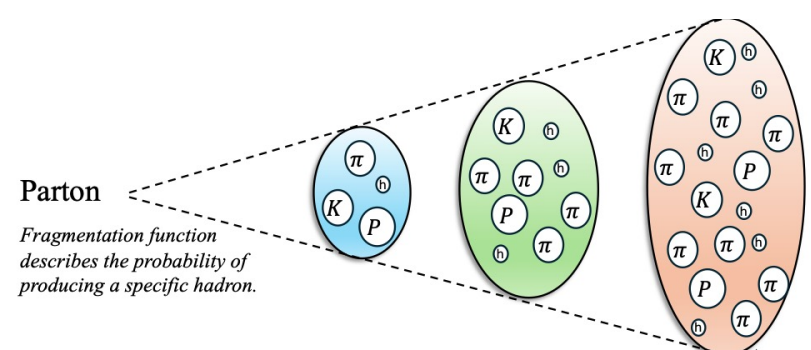
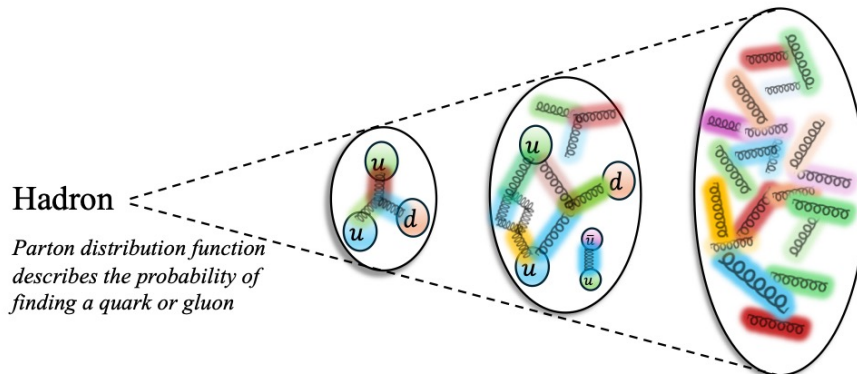
Artru-Collins asymmetry

$$b\bar{b}({}^3S_1^{[8]}) \rightarrow q\bar{q} \rightarrow (\pi^+\pi^-) + (\pi^+\pi^-) + X$$

$$b\bar{b}({}^3P_J^{[1]}) \rightarrow gg \rightarrow (\pi^+\pi^-) + (\pi^+\pi^-) + X$$

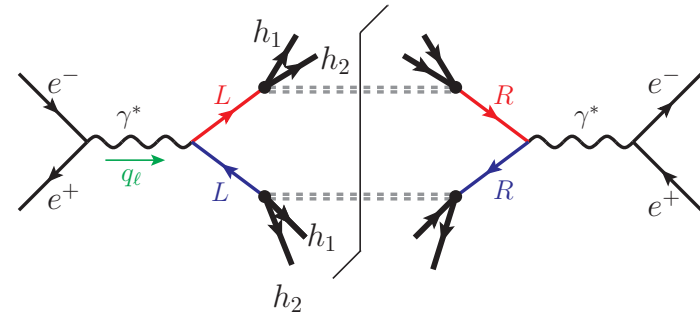
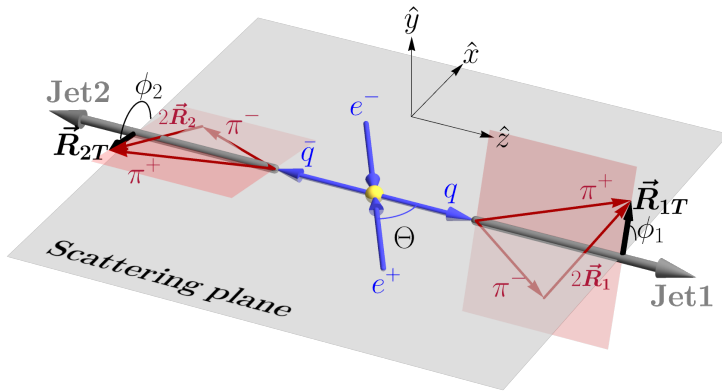
- PDFs and FFs

J. Datta et al, PRL 134 (2025) 111902

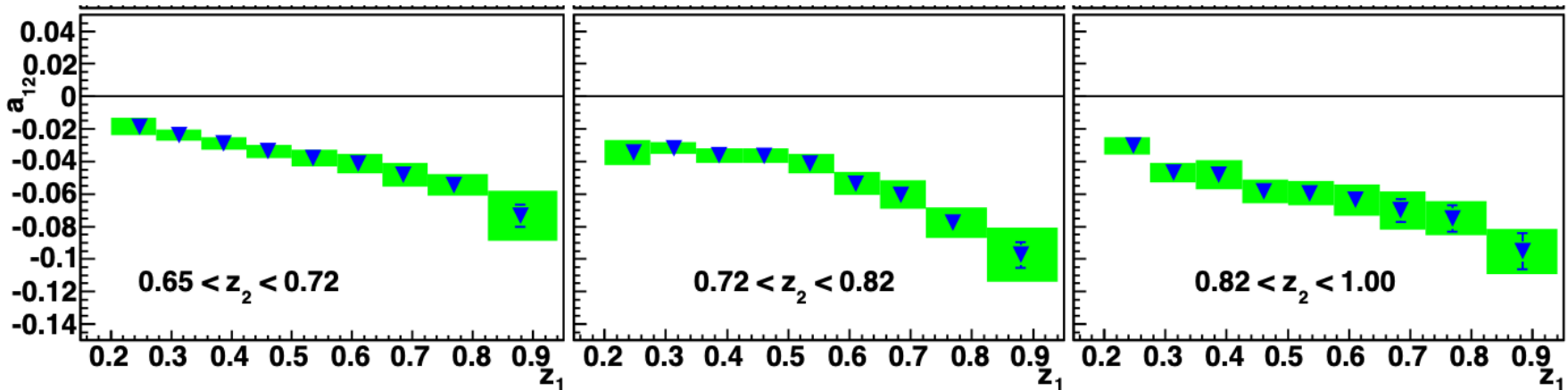


Interference dihadron FFs

Transverse spin of quark: The interference between the different helicity states



Belle, PRL 107 (2011) 072004



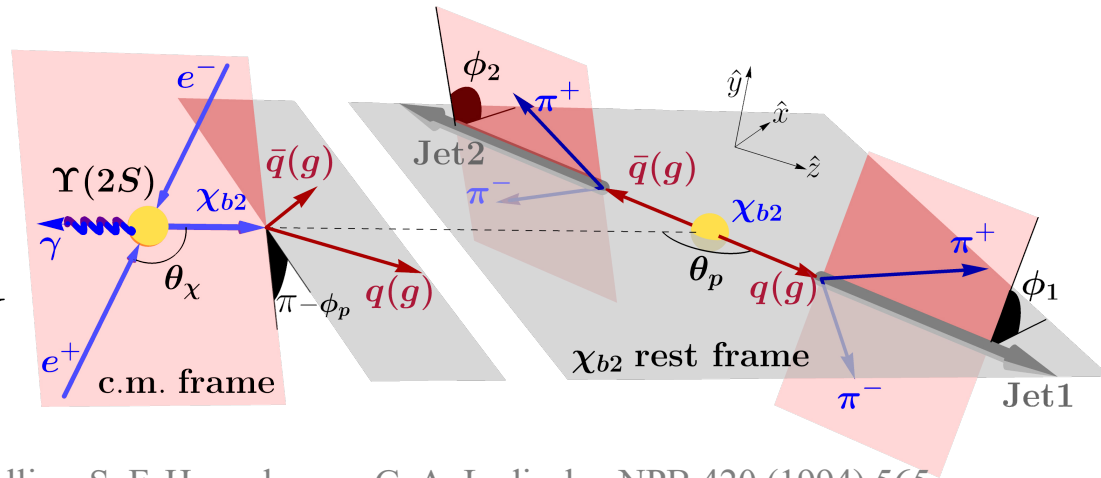
The transverse spin effects have been observed in dihadron pair production!

Artru-Collins asymmetry

➤ Kinematics

$$e^+e^- \rightarrow \Upsilon(2S) \rightarrow \gamma\chi_{bJ}$$

$$\chi_{bJ} \rightarrow q\bar{q}(gg) \rightarrow \pi^+\pi^-\pi^+\pi^- + X$$



➤ Collinear Factorization

J. C. Collins, S. F. Heppelmann, G. A. Ladinsky, NPB 420 (1994) 565

$$\frac{d\sigma}{\sigma_0 dz_1 dz_2 dM_1 dM_2 d\phi_1 d\phi_2 d\cos\theta_\chi d\cos\theta_p d\phi_p}$$

$$= H_8^b \sum_q C_q [D_1^q(z_1, M_1) D_1^{\bar{q}}(z_2, M_2)$$

$$+ \frac{1}{2} \mathcal{B} H_1^{\triangleleft, q}(z_1, M_1) H_1^{\triangleleft, \bar{q}}(z_2, M_2) \cos(\phi_1 + \phi_2)]$$

$$+ H_1^b C_g D_1^g(z_1, M_1) D_1^g(z_2, M_2),$$

Unpolarized quark diFF

Transverse polarized quark diFF

Unpolarized gluon diFF

- ❖ Gluon fragmentation does not generate the asymmetry
- ❖ Allows separation of CO ($q\bar{q}$) from CS (gg)

Artru-Collins asymmetry

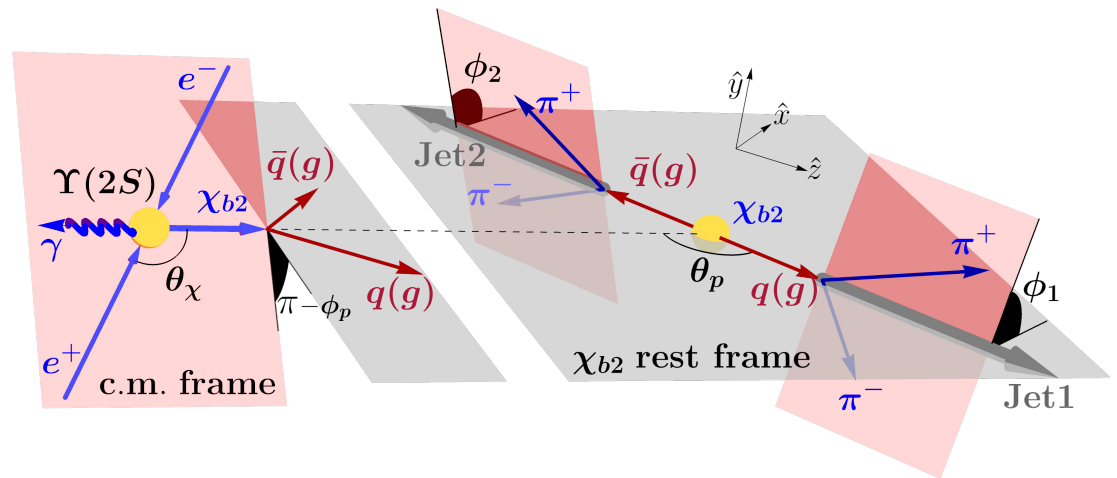
➤ Asymmetry

$$A_{12} \equiv 2 \langle \cos(\phi_1 + \phi_2) \rangle = \frac{1}{2} \frac{\rho_8(m_b) \mathcal{B} \sum_q C_q H_1^{\leftarrow, q}(z_1, M_1) H_1^{\leftarrow, \bar{q}}(z_2, M_2)}{\rho_8(m_b) \sum_q C_q D_1^q(z_1, M_1) D_1^{\bar{q}}(z_2, M_2) + m_b^2 C_g D_1^g(z_1, M_1) D_1^g(z_2, M_2)}$$

Asymmetry provides a clean probe of ρ_8

➤ Belle: boost effects

$$\mathcal{B} = \frac{42 \sin^2 \theta_p}{21 \cos^2 \theta_p + 73}$$

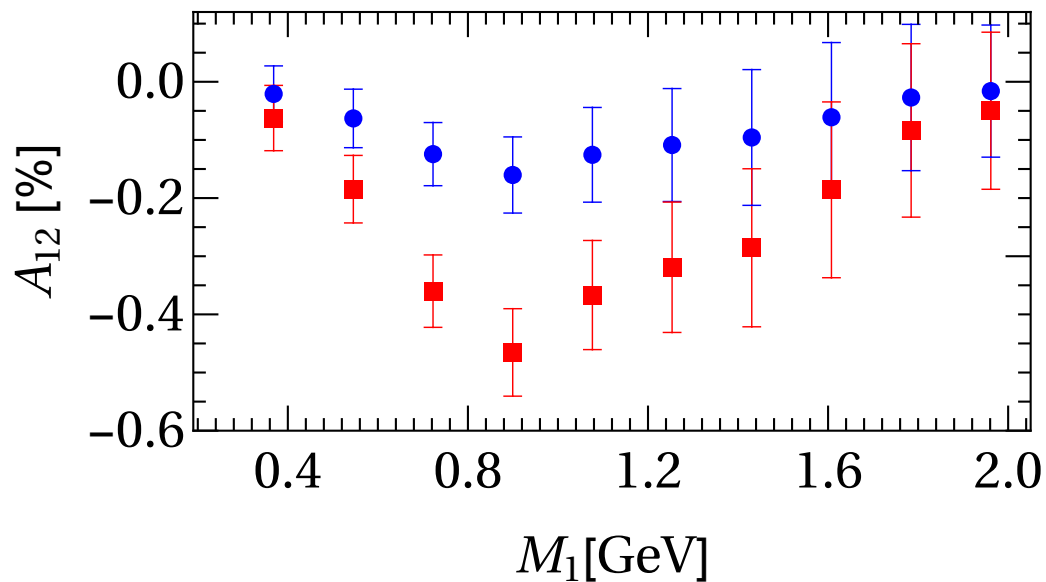
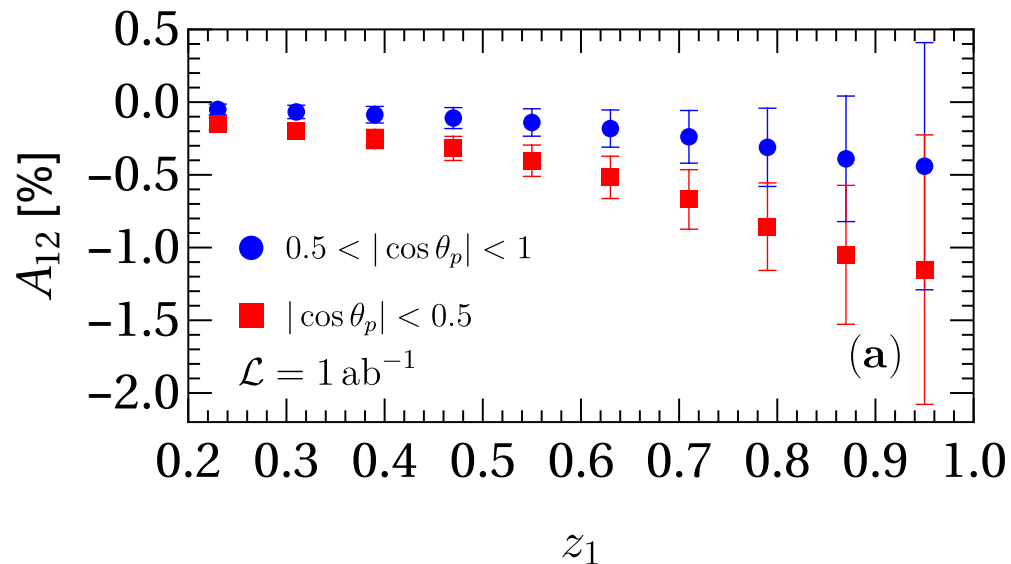


❖ χ_{b2} nearly collinearly with $\Upsilon(2S)$ in the Lab frame

❖ The coefficients does not depend on θ_χ, ϕ_p

❖ Enhanced in the central region

Artru-Collins asymmetry



$$\rho_8 = 0.044 \quad \chi_{b2}: \text{Lab frame}$$

- ❖ Asymmetry magnitude: $\sim 1\%$
- ❖ Enhanced in the central region

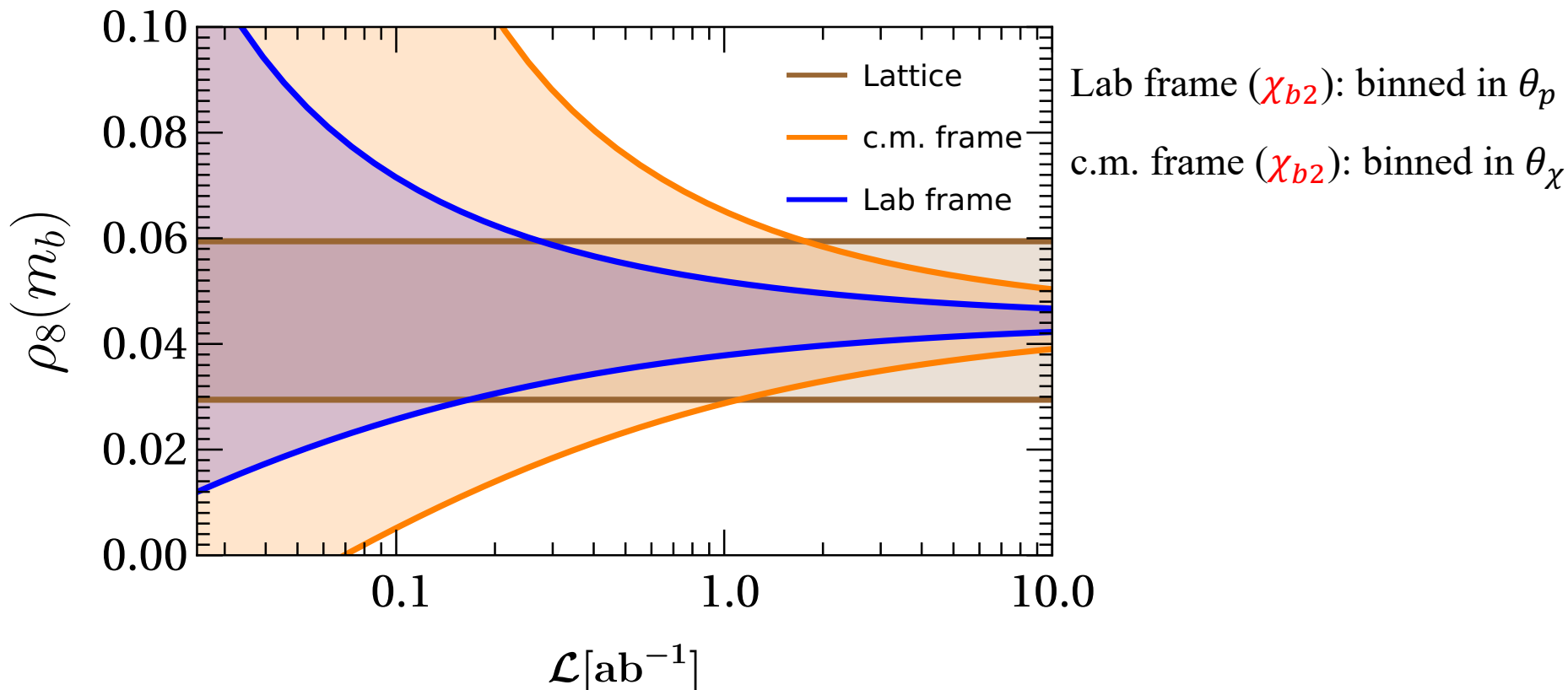
$$\mathcal{B} = \frac{42 \sin^2 \theta_p}{21 \cos^2 \theta_p + 73}$$

- ❖ Sign determined by DiFF properties

$$H_1^{\triangleleft, q} = -H_1^{\triangleleft, \bar{q}}$$

- ❖ Observable is measurable at Belle

Artru-Collins asymmetry



- ❖ Cancellation in phase space at c.m. frame
- ❖ Projected sensitivity surpasses current lattice uncertainty with $\mathcal{O}(0.1) \text{ ab}^{-1}$
- ❖ The potential to **resolve the long-standing discrepancy in ρ_8**

Summary

- We proposed a novel observable based on dihadron fragmentation to probe the color-octet mechanism
- Spin-dependent asymmetry provides a clean quark-gluon discriminator
- The observable is directly sensitive to the color-octet contribution
- It offers a new avenue to resolve ρ_8 discrepancy

A new way to test NRQCD via QCD spin effects!

Thank you