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

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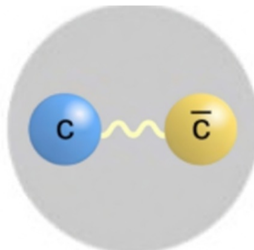
Based on Zhi-Guo He, Guanghui Li, Yu-Jie Tian, Xin-Kai Wen, Bin Yan, arXiv: 2603.18874

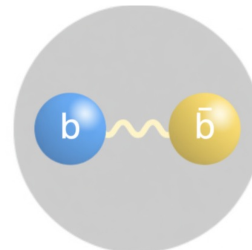
NRQCD and Heavy Quarkonium

- 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 $\quad {}^{2S+1}L_J^{[c]}$

$c\bar{c}({}^3S_1^{[1]}) \to J/\Psi \qquad b\bar{b}({}^3S_1^{[1]}) \to \Upsilon$

- Theoretical issues:

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

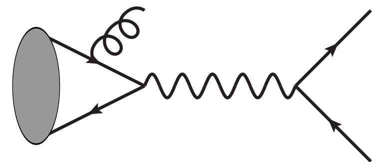
- Exp issues: Huge cross section discrepancy $\quad \sigma_{pp\to J/\Psi} \gg \sigma_{CSM}$

NRQCD and Heavy Quarkonium

- ➢ NRQCD factorization   G. T. Bodwin, E. Braaten, G. P. Lepage, PRD 51 (1995) 1125

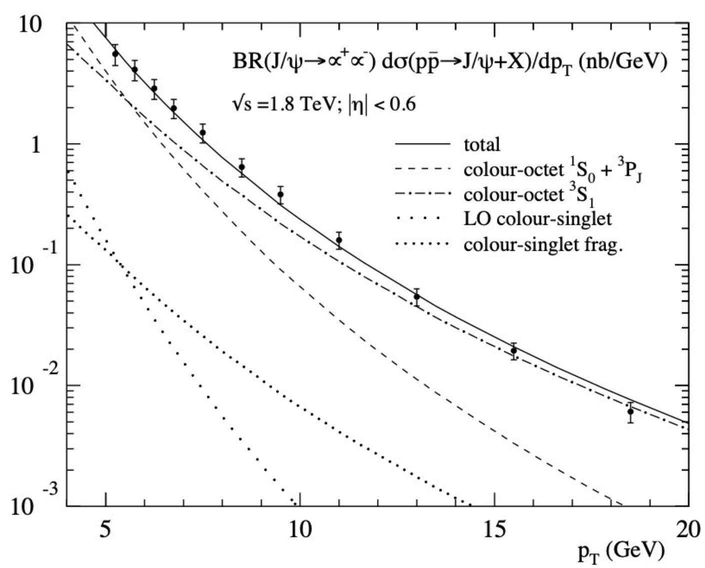
- ❖ $Q\bar{Q}$ could be in all possible spin and color configurations

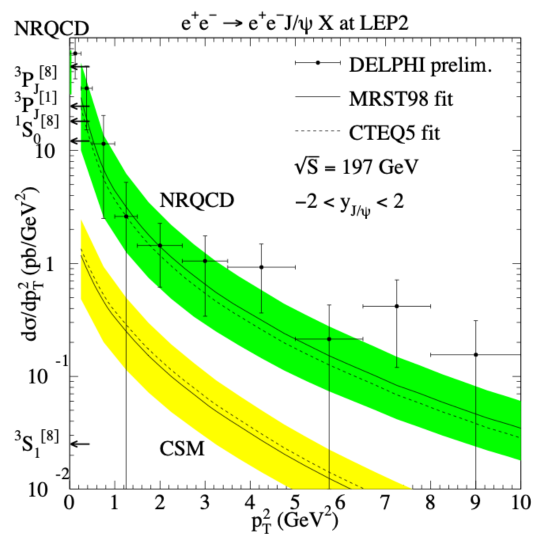
- ❖ Color-Octet Mechanism:



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

- ❖ 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

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

Short distance coefficients
α_s expansion

Long distance matrix elements
v^2 expansion

- Fock state expansion

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

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}

$$|H(^{2S+1}L_J)\rangle = O(1)\,|Q\overline{Q}(^{2S+1}L_J^{[1]})\rangle + O(v)\,|Q\overline{Q}(^{2S+1}(L\pm 1)_{J'}^{[8]})g\rangle$$

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

$i = 0, j = 2$: Color-Singlet
$i = 1, j = 0$: Color-Octet

Leading order in NRQCD!

- Testing Color-Octet Mechanism

CS: $b\bar{b}(^3P_J^{[1]}) \to gg$

CO: $b\bar{b}(^3S_1^{[8]}) \to q\bar{q}$

How to distinguish the quark and gluon final state?

- Quark jet and gluon jet?
- Parton fragments into hadrons? PRD 78 (2008) 092007, CLEO

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

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

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

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!

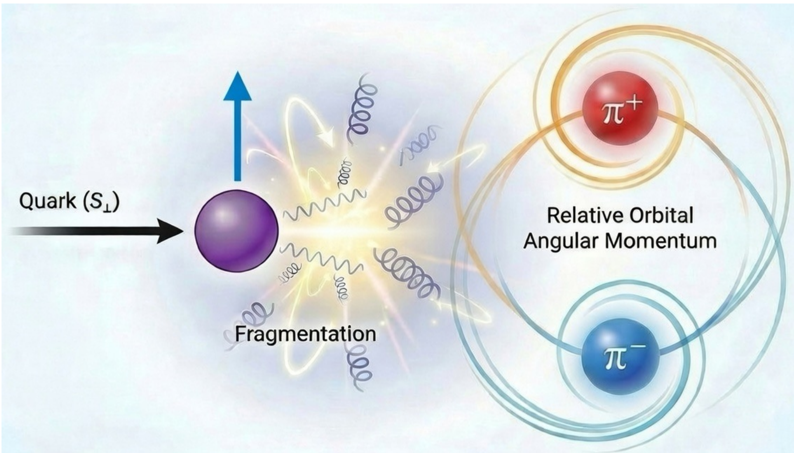
How to separate CO from CS?

$$b\bar{b}(^3S_1^{[8]}) \to q\bar{q} \qquad\qquad b\bar{b}(^3P_J^{[1]}) \to gg$$

→ 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

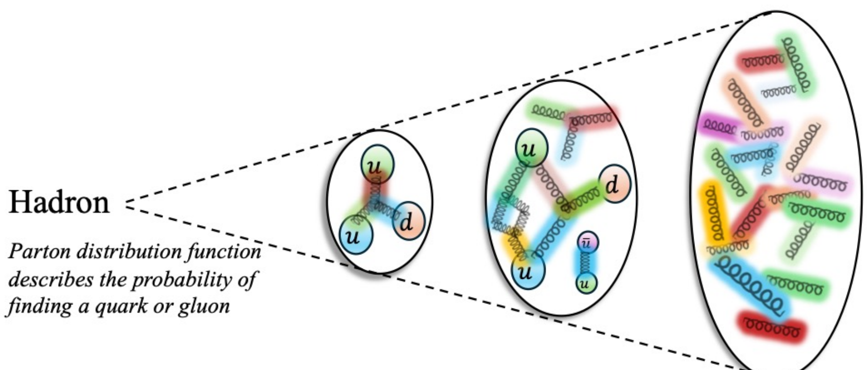
Artru-Collins asymmetry

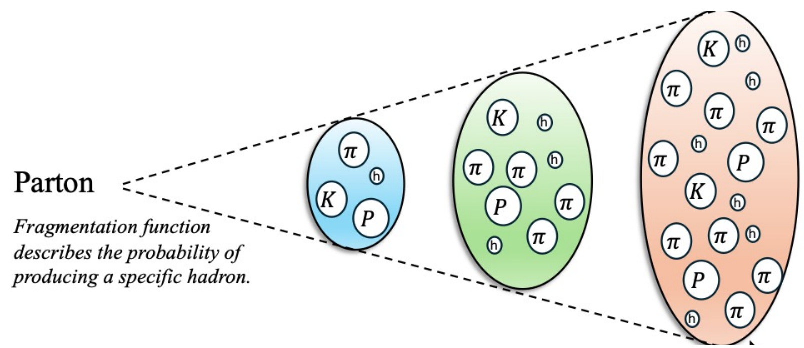
$$b\bar{b}(^3S_1^{[8]}) \rightarrow q\bar{q} \rightarrow (\pi^+\pi^-) + (\pi^+\pi^-) + X$$

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

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

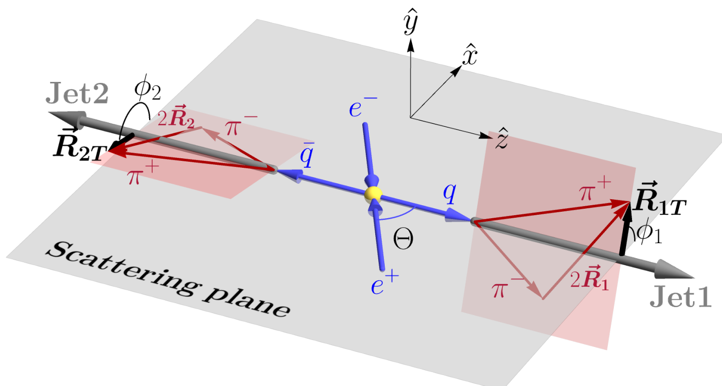
- PDFs and FFs

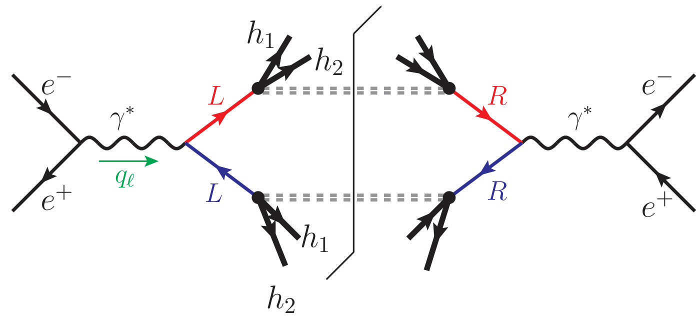




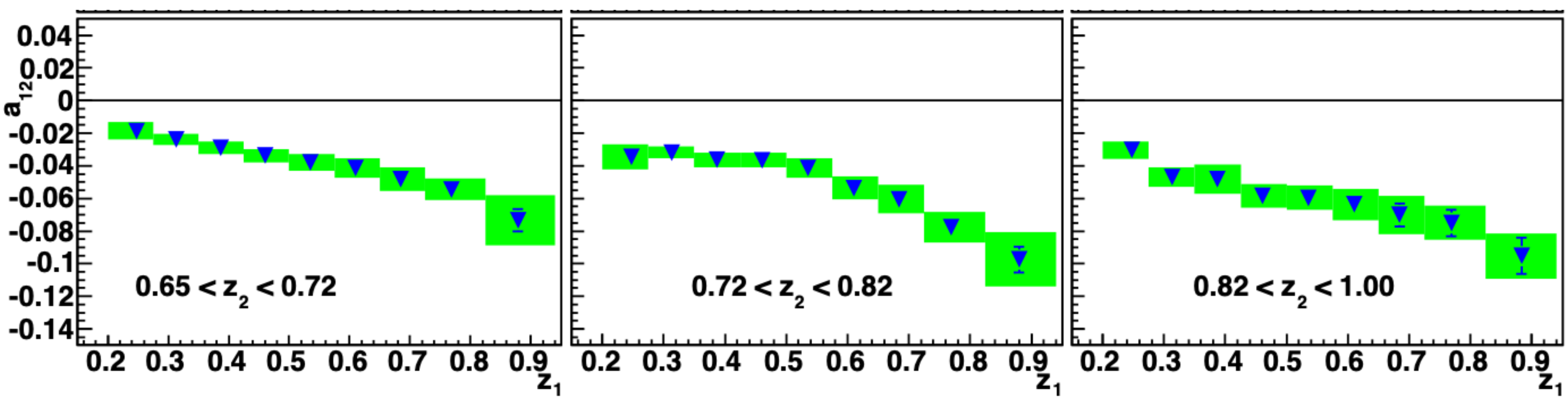
Interference dihadron FFs

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





Belle, PRL 107 (2011) 072004



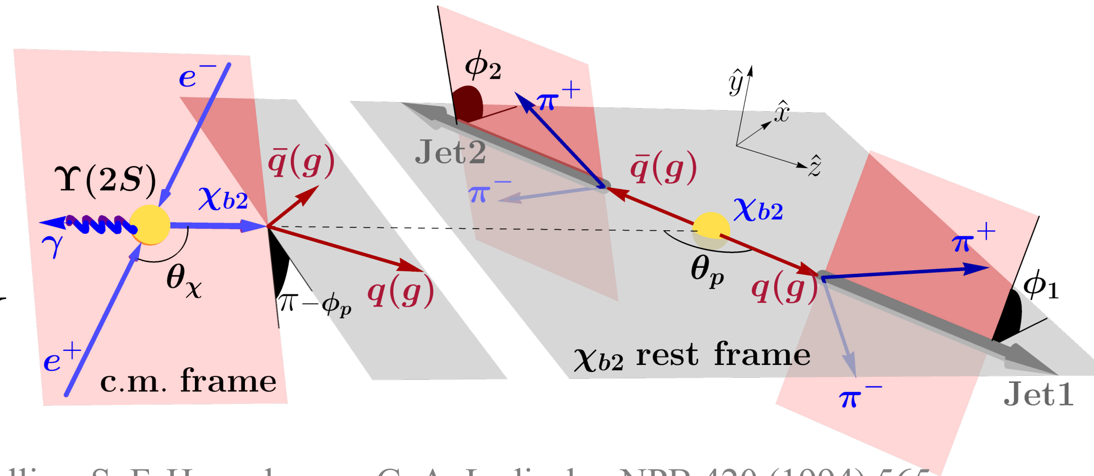
The transverse spin effects have been observed in dihadron pair production!

Artru-Collins asymmetry

➢ Kinematics

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

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



➢ Collinear Factorization

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

$$\frac{d\sigma}{\sigma_0 dz_1 dz_2 dM_1 dM_2 d\phi_1 d\phi_2 d\cos\theta_\chi d\cos\theta_p d\phi_p}$$
$$= H_8^b \sum_q \mathcal{C}_q \Big[D_1^q(z_1, M_1) D_1^{\bar{q}}(z_2, M_2)$$
$$+ \frac{1}{2}\mathcal{B}\, H_1^{\sphericalangle,q}(z_1, M_1) H_1^{\sphericalangle,\bar{q}}(z_2, M_2) \cos(\phi_1 + \phi_2) \Big]$$
$$+ H_1^b \mathcal{C}_g\, D_1^g(z_1, M_1) D_1^g(z_2, M_2),$$

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

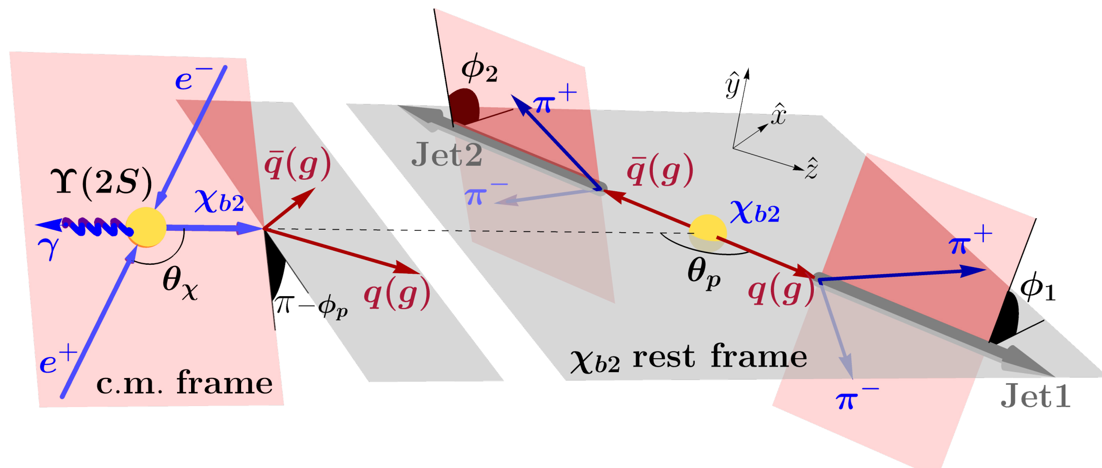
- Asymmetry

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

Asymmetry provides a clean probe of ρ_8

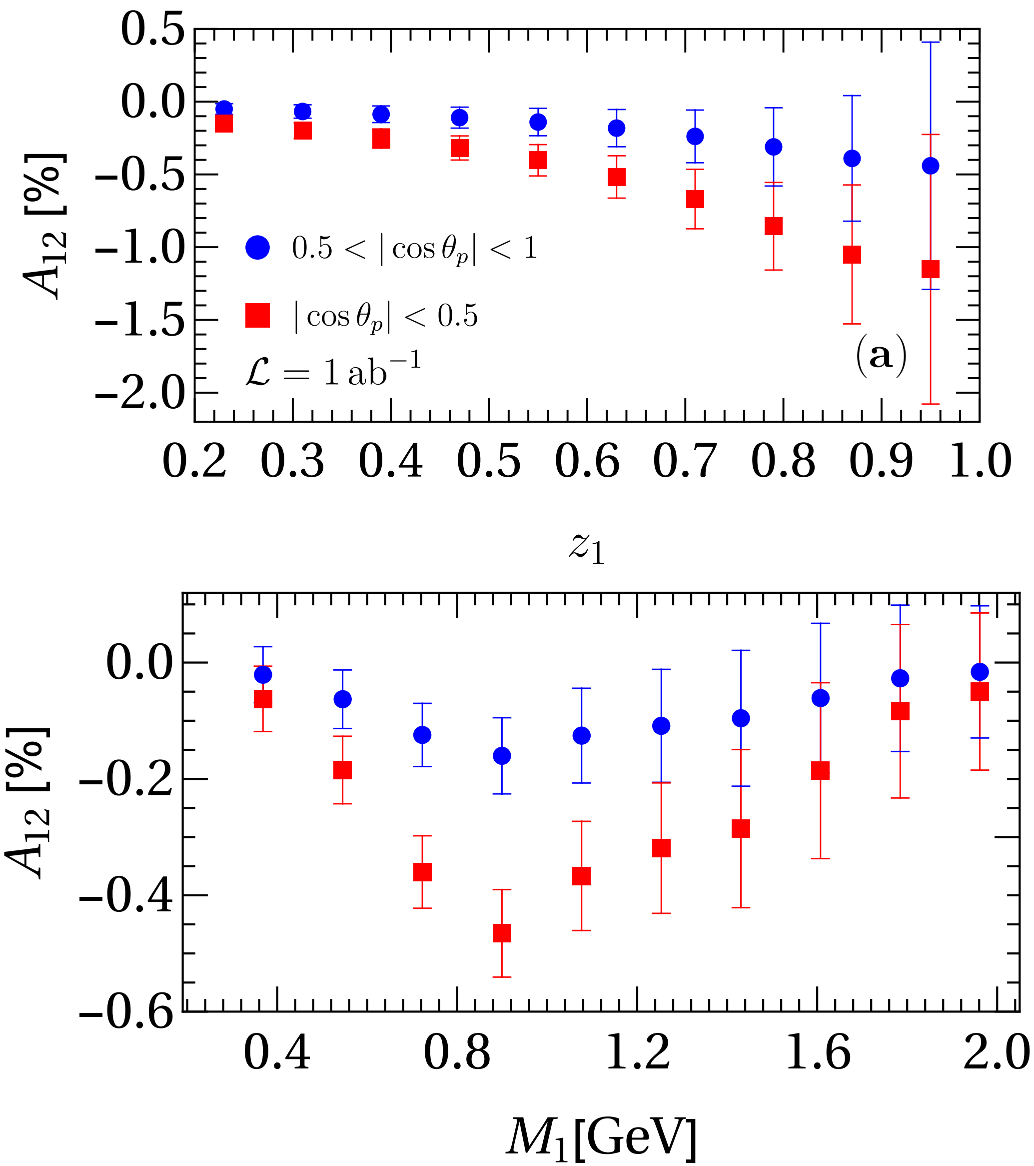
- Belle: boost effects

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



- ❖ χ_{b2} nearly collinearly with $\Upsilon(2S)$ in the Lab frame
- ❖ The coefficients does not depend on θ_χ, ϕ_p

Artru-Collins asymmetry



$\rho_8 = 0.044$ χ_{b2}: Lab frame

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

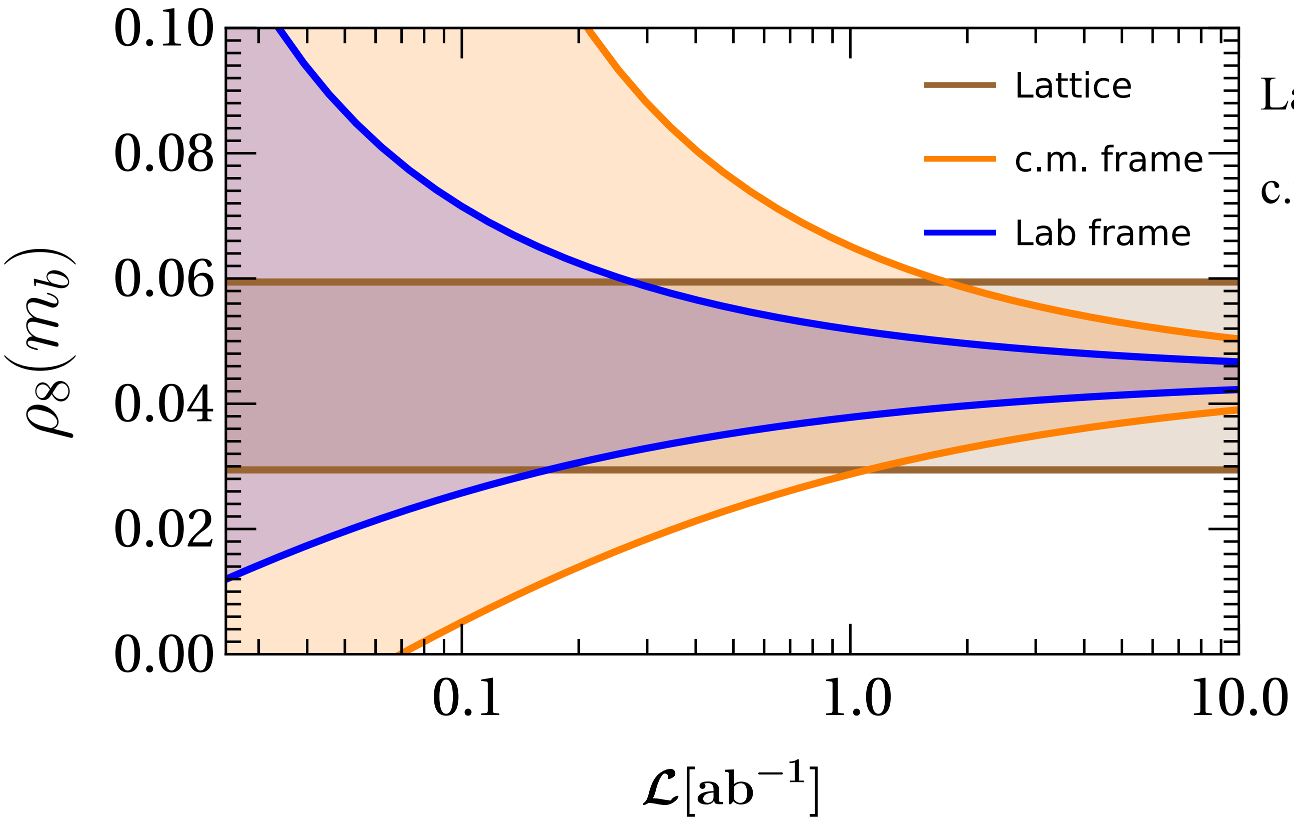
$$\mathcal{B} = \frac{42\sin^2\theta_p}{21\cos^2\theta_p + 73}$$

- ❖ Sign determined by DiFF properties

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

- ❖ Observable is measurable at Belle

Artru-Collins asymmetry



Lab frame (χ_{b2}): binned in θ_p

c.m. frame (χ_{b2}): binned in θ_χ

- Cancellation in phase space at c.m. frame
- Projected sensitivity surpasses current lattice uncertainty with $\mathcal{O}(0.1)\ \mathrm{ab}^{-1}$
- 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