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

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

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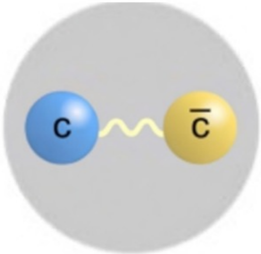
第一届强相互作用自旋物理会议, 26~31 July, 2026

Heavy Quarkonium and NRQCD

- Heavy quarkonium: the non-relativistic bound state

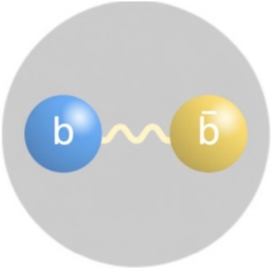
Charmonium

$v_c^2 \simeq 0.23$



Bottomonium

$v_b^2 \simeq 0.08$



- Color-Singlet Mechanism

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

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

- Theoretical issues

P-wave (decays into light hadrons):infrared divergence(α_s^3)

- Experiment issues

Significant discrepancy between σ_{exp} and σ_{CSM} in $pp \to J/\Psi$

F. Abe et al. (CDF Collaboration), Phys. Rev. Lett. 79, 578 (1997).

Heavy Quarkonium and NRQCD

- Color-Octet Mechanism

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

G. T. Bodwin, E. Braaten, and G. P. Lepage,Phys. Rev. D 51, 1125 (1995)

- NRQCD factorization

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

Double expansion: $\frac{2\ \mathrm{Im}\, f_n(\Lambda)}{M^{d_n-4}}$ short distance coefficients α_s

$\langle H|\mathcal{O}_n(\Lambda)|H\rangle$ long distance matrix elements v^2

LDMEs power counting and χ_{QJ} Decay

- LDMEs power counting

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

i for Fock state
j for operator

For P-wave quarkonium

$^3P_J^{[1]}$ i=0,j=2 $\langle \chi_{QJ}|O_1(^3P_J)|\chi_{QJ}\rangle \sim v^2$

$^3S_1^{[8]}$ i=0,j=1 $\langle \chi_{QJ}|O_8(^3S_1)|\chi_{QJ}\rangle \sim v^2$

- Decay rate

$$\Gamma(\chi_{QJ} \to \mathrm{LH}) = \frac{2\,\mathrm{Im}\, f_1(^3P_J)}{M^4}\langle \chi_{QJ}|O_1(^3P_J)|\chi_{QJ}\rangle + \frac{2\,\mathrm{Im}\, f_8(^3S_1)}{M^2}\langle \chi_{QJ}|O_8(^3S_1)|\chi_{QJ}\rangle + O(v^2\Gamma), \quad J = 0, 1, 2$$

Color octet also contributes to the leading order!

Testing Color-Octet Mechanism

- Lattice VS Experiment

$$\rho_8(m_Q) = H_8^Q(m_Q)m_Q^2/H_1^Q \qquad H_1^Q = \langle \chi_{QJ}|\mathcal{O}(^3P_J^{[1]})|\chi_{QJ}\rangle \qquad H_8^Q(\mu_\Lambda) = \langle \chi_{QJ}|\mathcal{O}(^3S_1^{[8]},\mu_\Lambda)|\chi_{QJ}\rangle$$

Charmonium: in good agreement

$$\rho_8 = 0.128(2)(9)^{+61}_{-47}\ \text{(Lattice)}$$
$$\rho_8 = 0.095(43)\ \text{(Exp)}$$

Bottomonium: significantly different

$$\boxed{\begin{aligned}\rho_8 &= 0.044 \pm 0.015\ \text{(Lattice)}\\ \rho_8 &= 0.16^{+0.071}_{-0.047}\ \text{(Exp)}\end{aligned}}$$

Mismatch!

G. T. Bodwin, E. Braaten, D. Kang, and J. Lee, Phys. Rev. D 76, 054001 (2007), 0704.2599.
R. A. Briere et al. (CLEO), Phys. Rev. D 78, 092007 (2008), 0807.3757.

→ **An independent cross-check of ρ_8 is important!**

How to separate CO from CS?

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

$\Rightarrow$ The spin of quark and gluon is different!

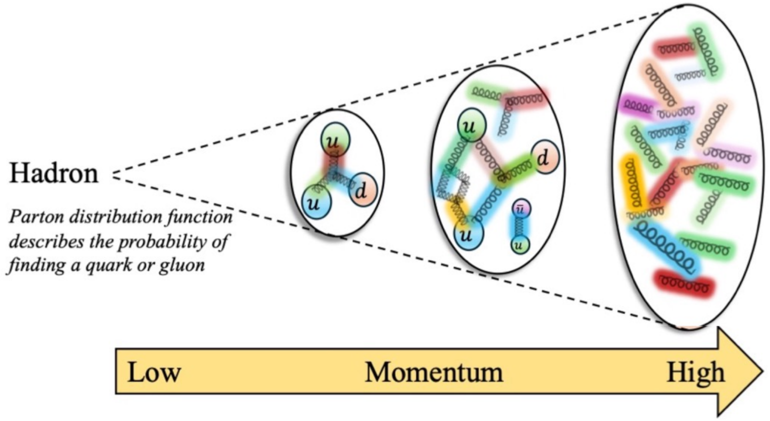
Fragmentation Functions and Spin Effect in QCD

- PDF and FFs

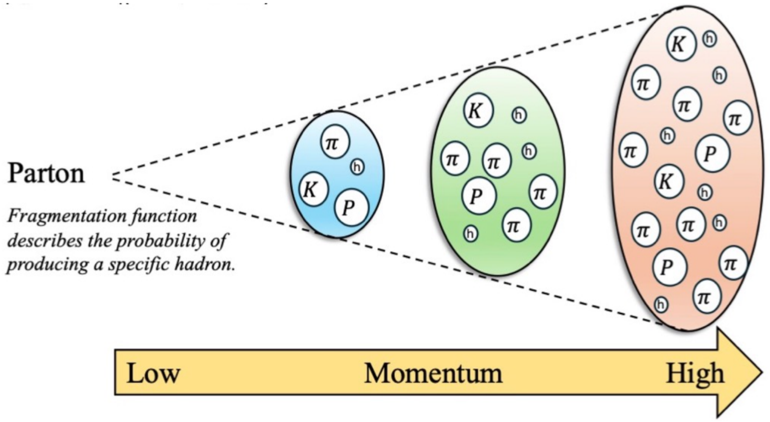
J. Datta et al, PRL 134 (2025) 111902

$$\sigma = f \otimes \hat{\sigma} \otimes D$$

f : parton distribution functions

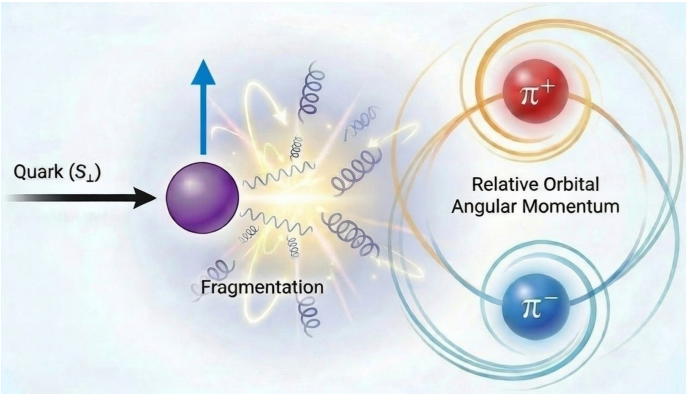


D : fragmentation functions



The process from partons to hadrons can be described with un-perturbative **fragmentation functions**.👍

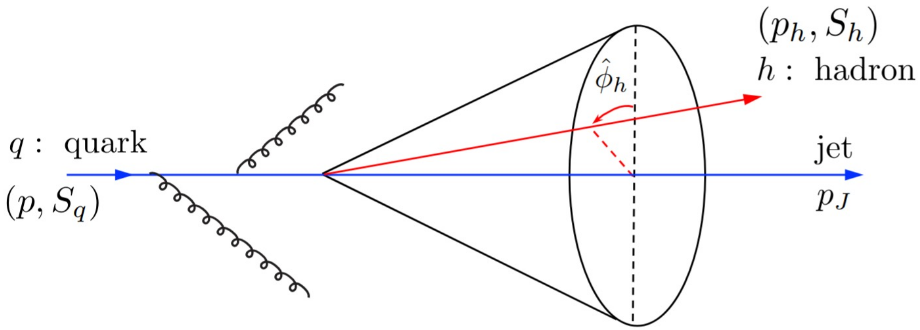
- Parton fragmentation carries transverse spin correlations

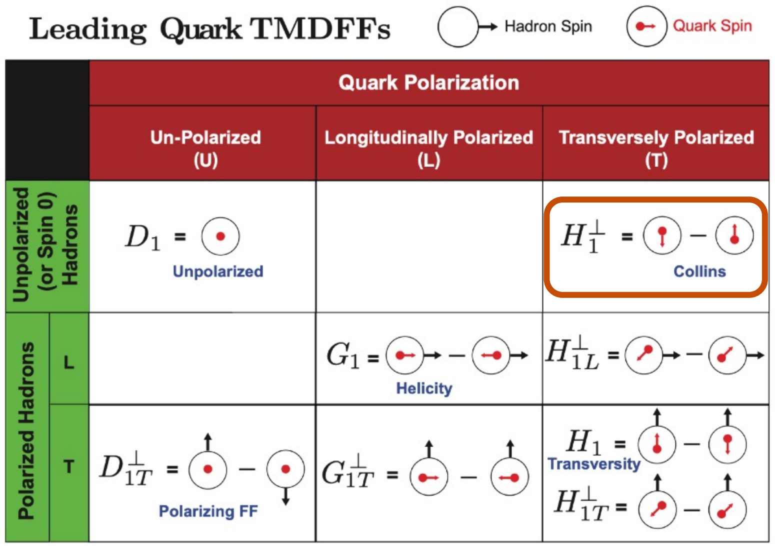


$$b\bar{b}(^3S_1^{[8]}) \to q\bar{q} \to h + X$$
$$b\bar{b}(^3P_J^{[8]}) \to gg \to h + X$$

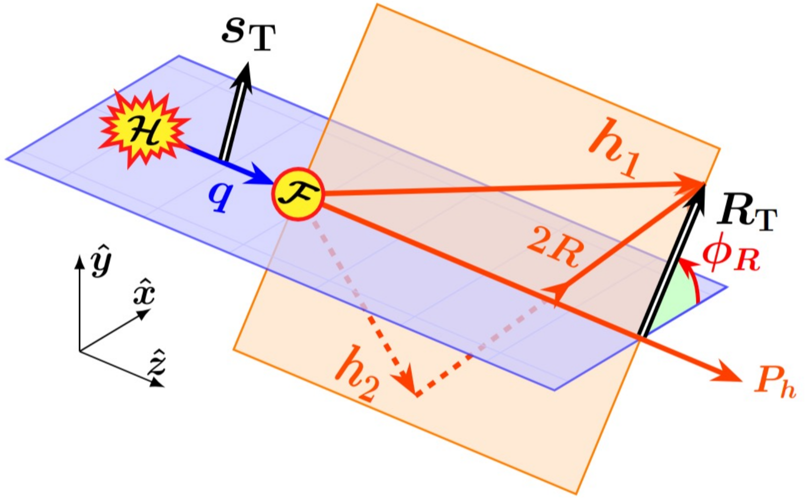
Fragmentation Functions and Spin Effect in QCD

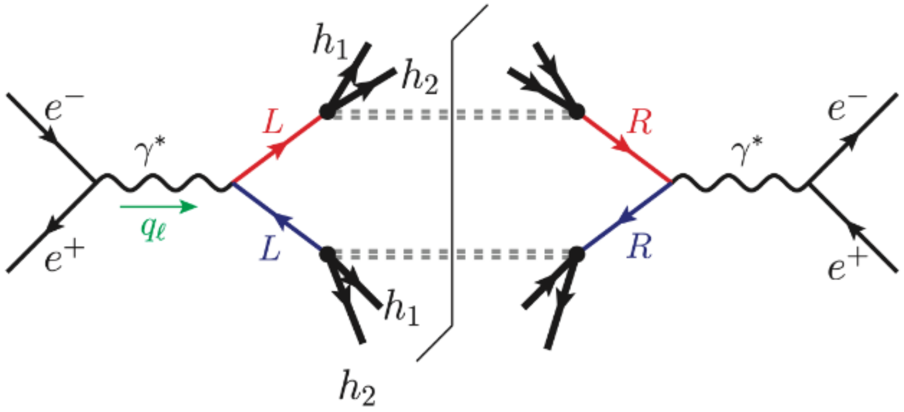
TMD fragmentation:





Di-hadron fragmentation:





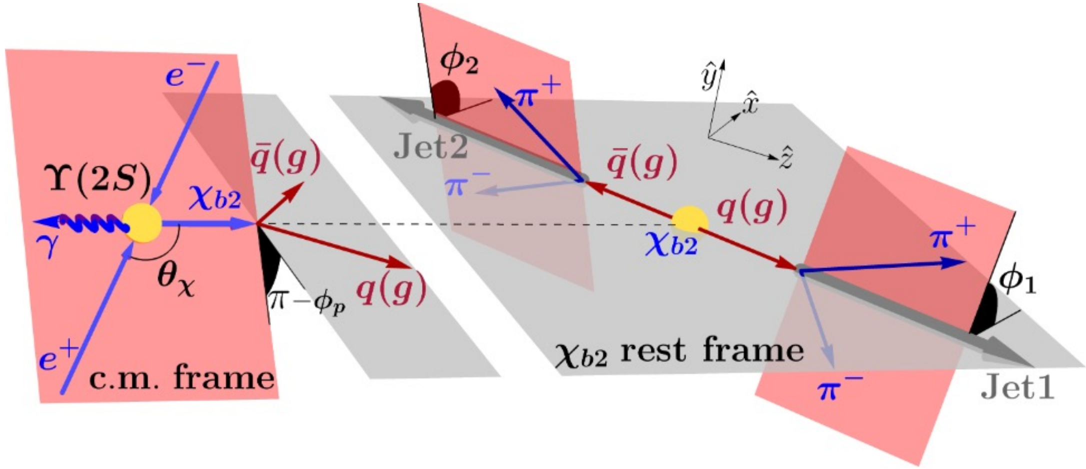
Kang, Prokudin, Sun, Yuan, *Phys.Rev.D* **93** (2016) 014009;
Zeng, Dong, Liu, Sun, Zhao, *Phys.Rev.D* **109** (2024) 056002;
TMD Handbook, *arXiv:* 2304.03302; ......

Artru-Collins Asymmetry

- Kinematics

$$e^+e^- \to \Upsilon(2S) \to \gamma\chi_{b2}$$

$$\chi_{b2} \to q\bar{q}(gg) \to \pi^+\pi^-\pi^+\pi^- + X$$



- Collinear Factorization

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

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

$$= H_8^b \sum_q \mathcal{C}_q \left[\boxed{D_1^q(z_1, M_1) D_1^{\bar{q}}(z_2, M_2)} + \frac{1}{2}\mathcal{B} \boxed{H_1^{\sphericalangle,q}(z_1, M_1) H_1^{\sphericalangle,\bar{q}}(z_2, M_2)} \cos(\phi_1+\phi_2) \right] + H_1^b \mathcal{C}_g \boxed{D_1^g(z_1, M_1) D_1^g(z_2, M_2)}$$

Unpolarized quark diFF | Transverse polarized quark diFF | Unpolarized gluon diFF

Only quark fragmentation generate the asymmetry ⇨ Separation CO from CS!

Artru-Collins Asymmetry

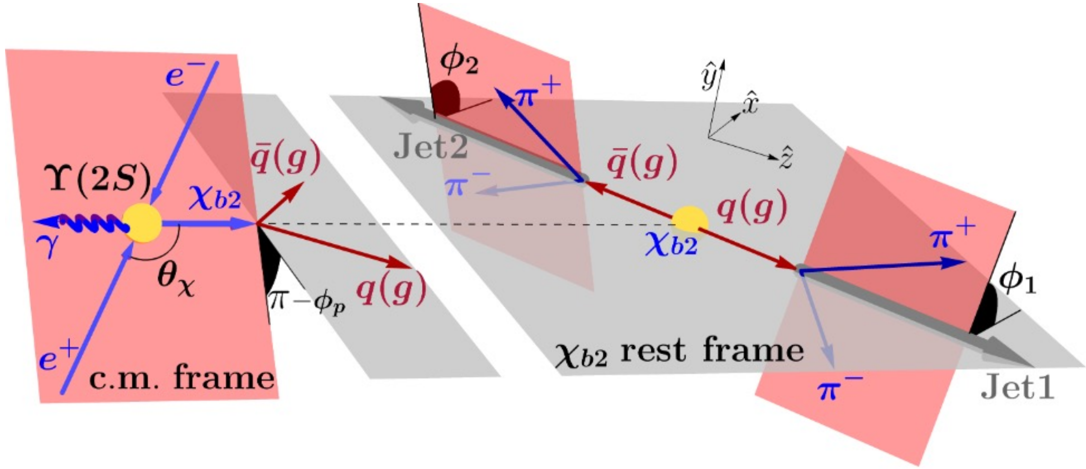
- Observable

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

Asymmetry provides a clean probe of ρ_8

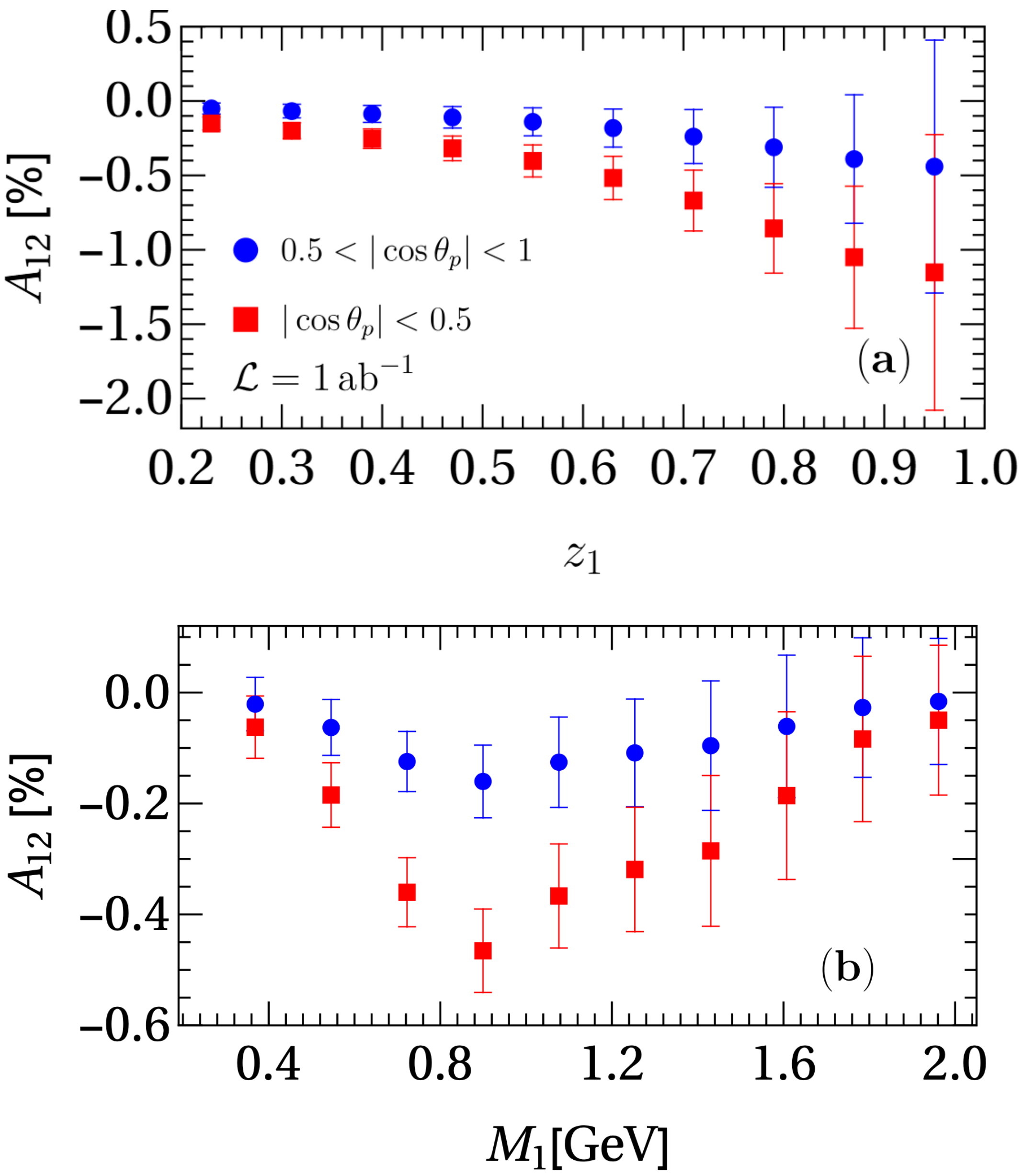
- Belle: boost effects

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



- The coefficients does not depend on θ_χ, ϕ_p
- Enhanced in the central region

Results and Sensitivity



$\rho_8 = 0.044$

- Asymmetry magnitude:~ 1%
- Enhanced in the central region

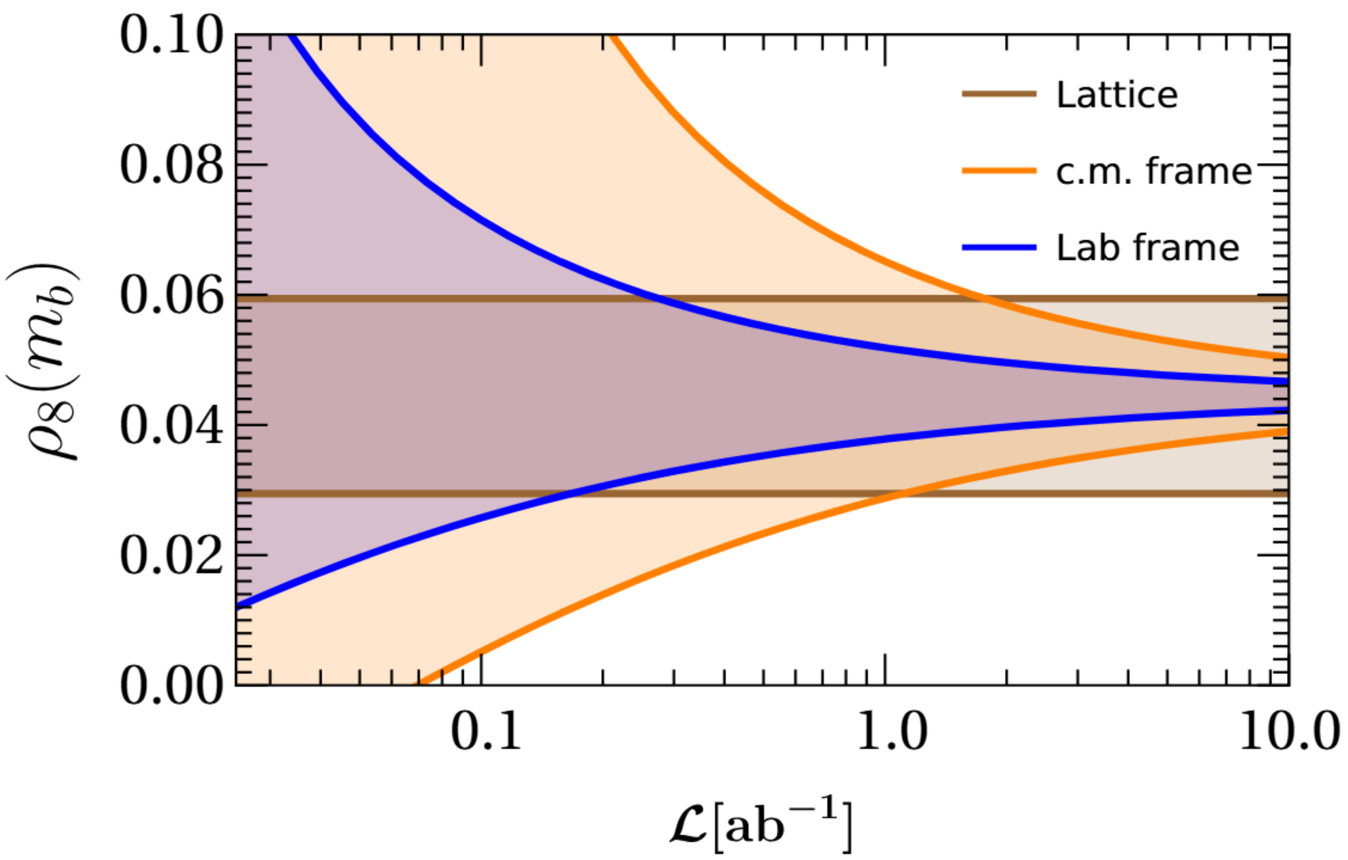
$$\mathcal{B} = \frac{42\sin^2\theta_p}{21\cos^2\theta_p + 73}$$

- Sign determined by DiFF properties

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

- Observable is measurable at Belle

Results and Sensitivity



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 $O(0.1)\ ab^{-1}$
- 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