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

Heavy Quarkonium and CSM

- Heavy quarkonium: the non-relativistic bound state

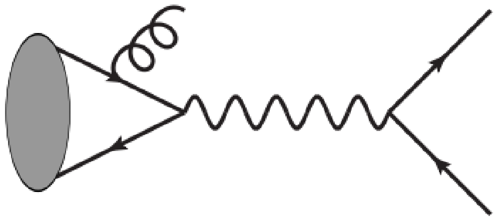
  Charmonium $v_c^2 \simeq 0.23$ Bottomonium $v_b^2 \simeq 0.08$

- Color-Singlet Mechanism

  Only the color singlet bound state of valence quarks in decay or production process

  - Theoretical issues

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



  - Experiment issues

    Significant discrepancy between σ_{Exp} and σ_{CSM} in $p\bar{p} \to J/\Psi$

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

COM and NRQCD Factorization

- Color-Octet Mechanism

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

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 χ_{QJ}

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

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

- 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!

ρ_8 Lattice VS Experiment

- Definition

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

- Lattice VS Experiment

Charmonium: in good agreement

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

G. T. Bodwin, D. K. Sinclair, and S. Kim, Phys.Rev.Lett. 77, 2376 (1996).

Bottomonium: significantly different

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

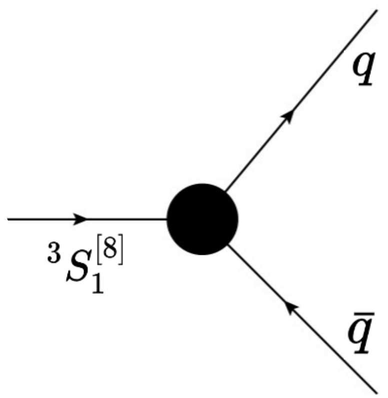
G. T. Bodwin, E. Braaten, D. Kang, and J. Lee, Phys. Rev. D 76, 054001 (2007).

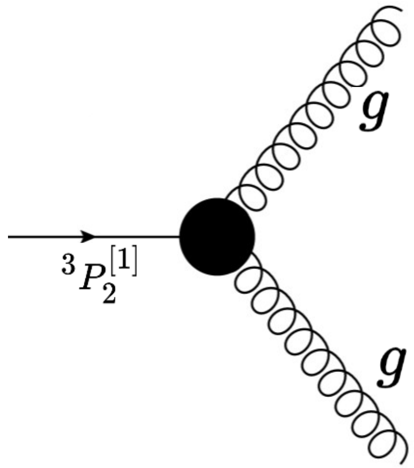
R. A. Briere et al. (CLEO), Phys. Rev. D 78, 092007 (2008).

Mismatch!

χ_{b2} Decay via $q\bar{q}$ and gg

- J/C/P Conservation



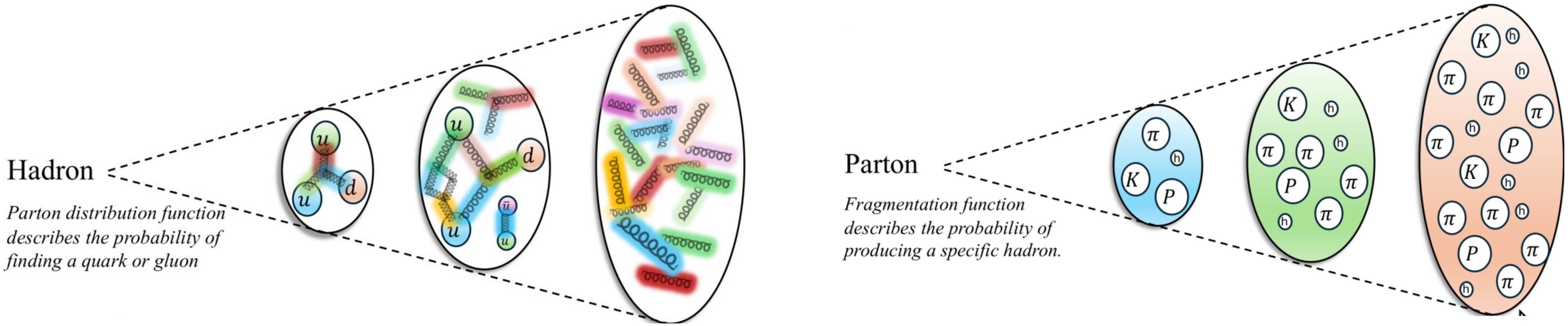


- How to separate CO from CS?

The spin of quark and gluon is different!

Parton Fragmentation Functions

- PDFs and FFs



J. Datta et al, Phys. Rev. Lett. 134 (2025) 111902

- Dihadron FFs

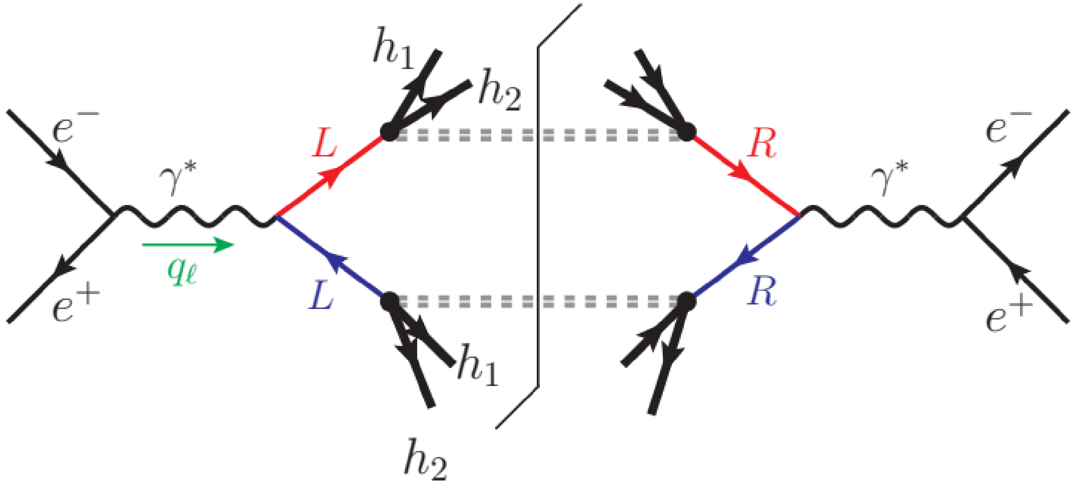
The probability for a parton to hadronize into a hadron pair

Interference Dihadron FFs

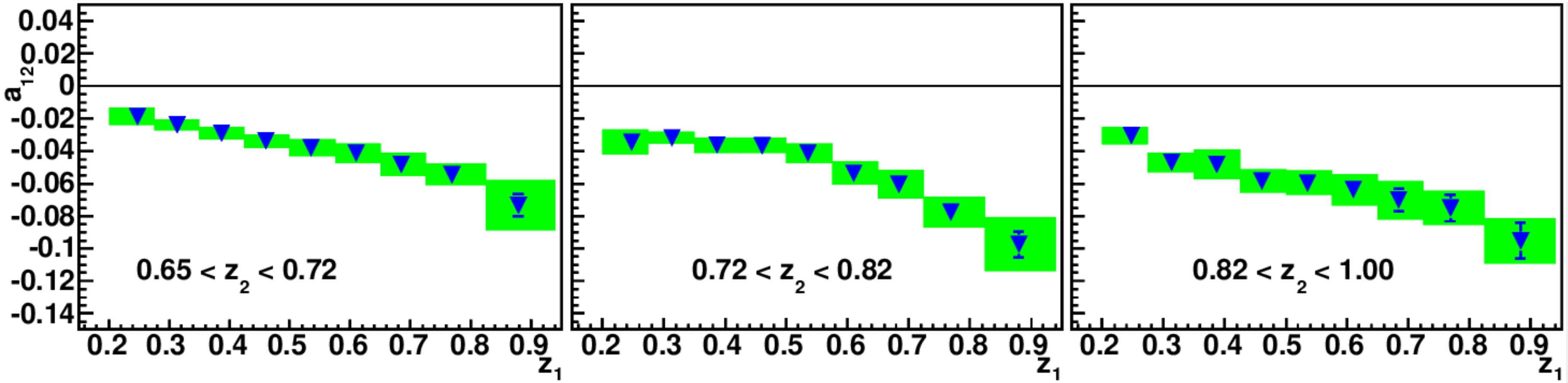
- Interference DiFFs

  Quark transverse spin / gluon linear polarization

  The interference between the different helicity states



- Artru-Collins asymmetry



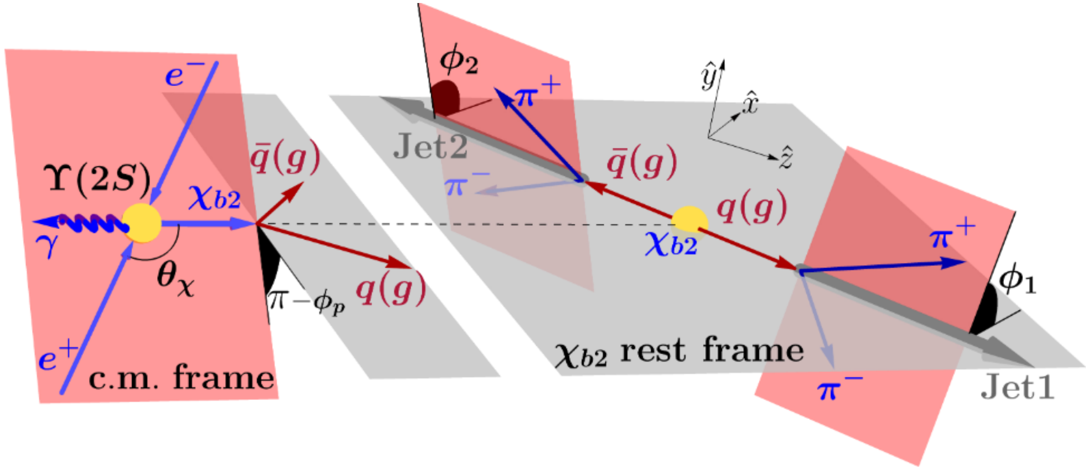
A. Vossen et al. (Belle), Phys. Rev. Lett. 107, 072004 (2011).

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

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

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

Unpolarized quark diFF — Transverse polarized quark diFF — Unpolarized gluon diFF

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

Artru-Collins asymmetry

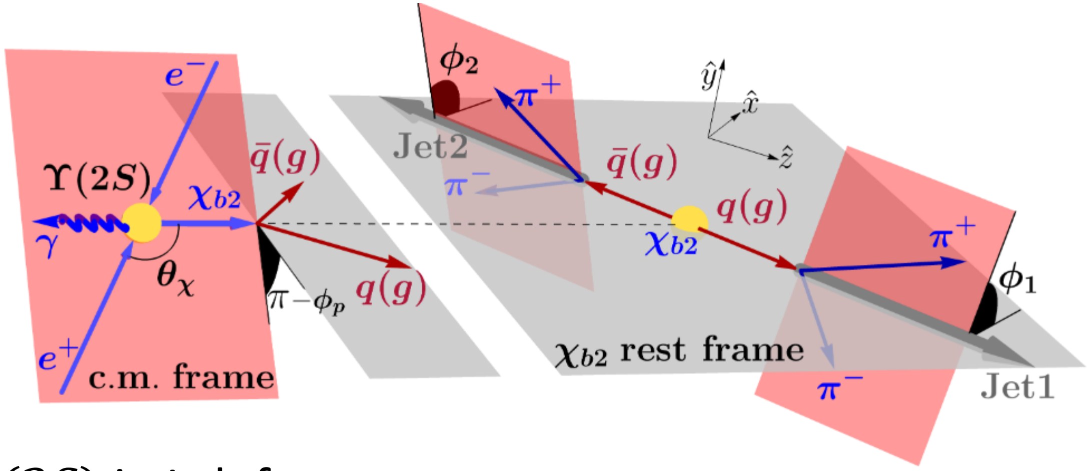
- Observable

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

Asymmetry provides a clean probe of ρ_8

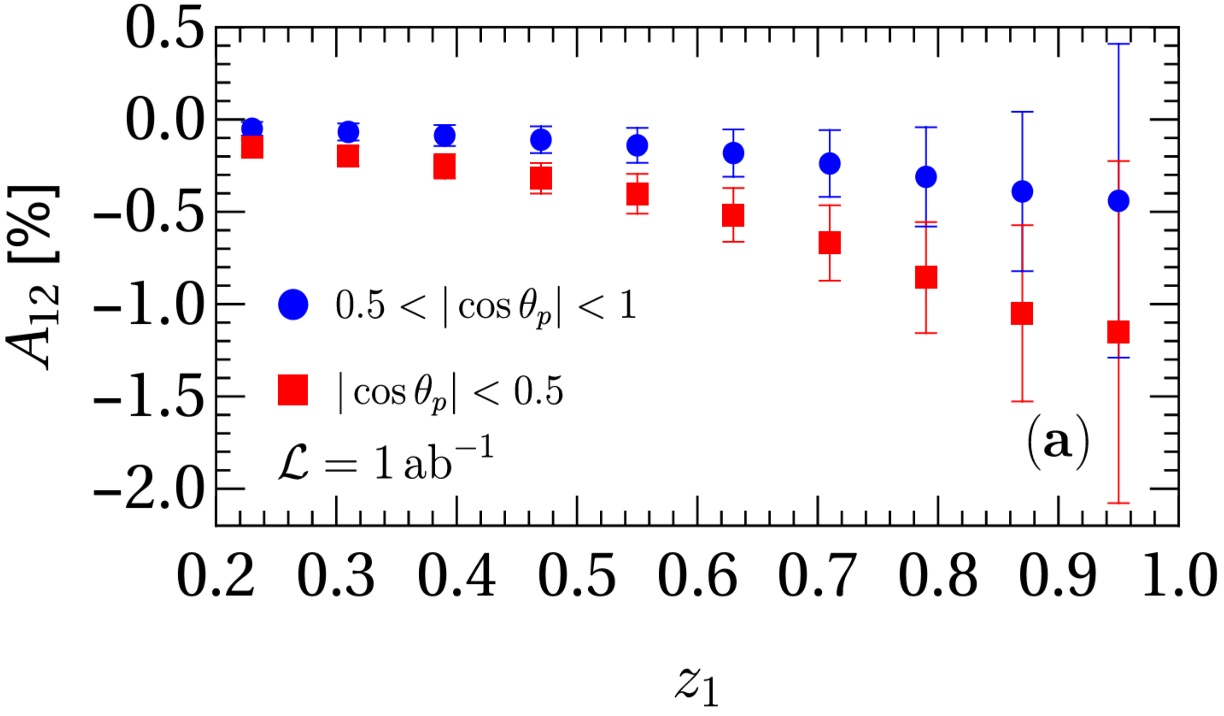
- Belle: boost effects

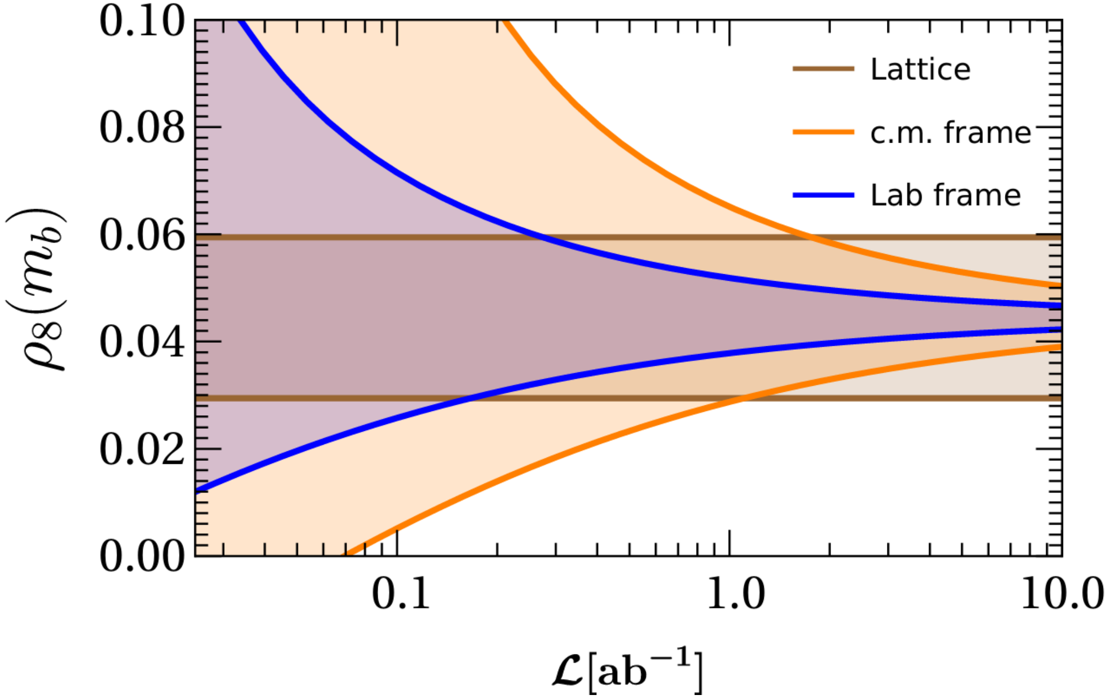
$$\mathcal{B} = \frac{42\sin^2\theta_p}{21\cos^2\theta_p+73}$$



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

Results





- Asymmetry magnitude:~ 1%
- Observable is measurable at Belle

- Projected sensitivity surpasses current lattice uncertainty with $O(0.1)\ ab^{-1}$

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

Thank you!