AZIMUTHAL ASYMMETRIES IN BACK-TO-BACK J/Ψ-JET AND J/Ψ-PHOTON PRODUCTION IN EP COLLISION

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LINEARLY POLARIZED GLUON DISTRIBUTIONS

Linearly polarized gluon distributions were first introduced in

Mulders and Rodrigues, PRD 63, 094021 (2001)

Can be Weizsacker-Williams (WW) or dipole type depending on gauge link or color flow. Can be probed in different processes: extensive literature

Operator structure of these two unintegrated gluon distributions are different : WW distribution contains both past or both future pointing gauge links and dipole distributions contain one past and one future pointing gauge link

Linearly polarized gluon TMD : Measures an interference between an amplitude when the active gluon is polarized along x (or y) direction and a complex conjugate amplitude with the gluon polarized in y (or x) direction in an unpolarized hadron

Affects unpolarized cross section as well as generates a $\cos 2\phi$ asymmetry

GLUON SIVERS FUNCTION (GSF)

Distribution of quarks and gluons in a transversely polarized proton is not left-right symmetric with respect to the plane formed by the momentum and spin directions – this generates an asymmetry called Sivers effect

D. Sivers, PRD 41, 83 (1990)

Highly sensitive to the color flow of the process and on initial/final state interactions (T-odd)

In some models, the Sivers function TMD is related to the orbital angular momentum of the quarks

Very little is known about GSF apart from a positivity bound

Depending on the gauge link in the operator structure there can be two different gluon Sivers function, f-type and d-type

Bomhof and Mulders, JHEP 02, 029 (2007),
Buffing, AM, Mulders, PRD 88, 054027 (2013)

Burkardt's sum rule, which states that the total transverse momentum of all quarks and gluon in a transversely polarized proton is zero, still leaves some room for GSF (30 %), moreover d type GSF is not constrained by it.

M. Burkardt, Phys. Rev. D 69, 091501 (2004)

J/ψ production and J/Ψ+ jet production at eP collision are effective ways to probe the GSF

GLUON TMDS IN J/Ψ AND PHOTON PRODUCTION

We consider the following process where the proton can be unpolarized or transversely polarized

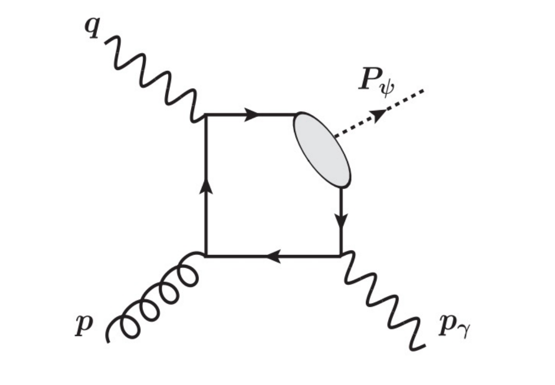
$$e(l) + p^{\uparrow}(P) \to e(l') + J/\psi(P_\psi) + \gamma(p_\gamma) + X,$$

$$P^\mu = n_-^\mu + \frac{M_p^2}{2} n_+^\mu \approx n_-^\mu,$$
$$q^\mu = -x_B n_-^\mu + \frac{Q^2}{2x_B} n_+^\mu \approx -x_B P^\mu + (P \cdot q) n_+^\mu,$$

$$l^\mu = \frac{1-y}{y} x_B n_-^\mu + \frac{1}{y}\frac{Q^2}{2x_B} n_+^\mu + \frac{\sqrt{1-y}}{y} Q \hat{l}_\perp^\mu,$$

$$Q^2 = x_b y S \qquad S = (P+l)^2$$

$$y = \frac{P \cdot q}{P \cdot l} \qquad x_B = \frac{Q^2}{2P \cdot q}$$



Partonic subprocess : virtual photon-gluon fusion

$$\mathrm{d}\sigma = \frac{1}{2S} \frac{\mathrm{d}^3 \boldsymbol{l}'}{(2\pi)^3 2E_{l'}} \frac{\mathrm{d}^3 \boldsymbol{P}_\psi}{(2\pi)^3 2E_\psi} \frac{\mathrm{d}^3 \boldsymbol{p}_\gamma}{(2\pi)^3 2E_\gamma} \times \int \mathrm{d}x \mathrm{d}^2 \boldsymbol{p}_T (2\pi)^4 \delta^4(q + p - P_\psi - p_\gamma) \times \frac{1}{Q^4} L^{\mu\nu}(l, q) \Phi_g^{\rho\sigma}(x, \boldsymbol{p}_T) H_{\mu\rho} H_{\nu\sigma}^*.$$

J/ψ production in color singlet channel in virtual photon-photon fusion is suppressed due to a larger gluon density

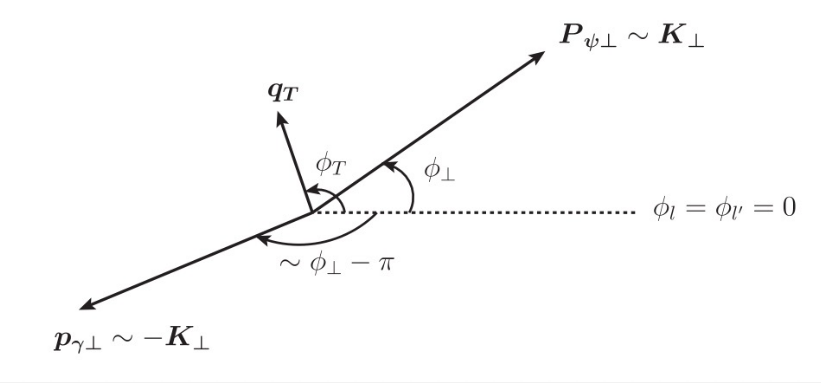
Use TMD factorization

GLUON TMDS IN J/Ψ AND PHOTON PRODUCTION

J/ψ and photon almost back to back

$$\boldsymbol{q}_T \equiv \boldsymbol{P}_{\psi\perp} + \boldsymbol{p}_{\gamma\perp}, \qquad \boldsymbol{K}_\perp \equiv \frac{\boldsymbol{P}_{\psi\perp} - \boldsymbol{p}_{\gamma\perp}}{2}.$$

$$q_T \ll K_\perp$$



We use NRQCD to calculate J/ψ production. At leading order only one CO state ${}^3S_1^{(8)}$ contributes

Cross section depends on only one LDME at LO , and the asymmetry becomes independent of the LDME

$$\Phi_U^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{1}{2x}\left\{-g_T^{\mu\nu} f_1^g(x,\boldsymbol{p}_T^2) + \left(\frac{p_T^\mu p_T^\nu}{M_p^2} + g_T^{\mu\nu}\frac{\boldsymbol{p}_T^2}{2M_p^2}\right) h_1^{\perp g}(x,\boldsymbol{p}_T^2)\right\}$$

$$\Phi_T^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{1}{2x}\left\{-g_T^{\mu\nu}\frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M_p} f_{1T}^{\perp g}(x,\boldsymbol{p}_T^2) + i\epsilon_T^{\mu\nu}\frac{\boldsymbol{p}_T\cdot\boldsymbol{S}_T}{M_p} g_{1T}^g(x,\boldsymbol{p}_T^2) + \frac{p_{T\rho}\epsilon_T^{\rho\{\mu} p_T^{\nu\}}}{2M_p^2}\frac{\boldsymbol{p}_T\cdot\boldsymbol{S}_T}{M_p} h_{1T}^{\perp g}(x,\boldsymbol{p}_T^2) - \frac{p_{T\rho}\epsilon_T^{\rho\{\mu} S_T^{\nu\}} + S_{T\rho}\epsilon_T^{\rho\{\mu} p_T^{\nu\}}}{4M_p} h_{1T}^g(x,\boldsymbol{p}_T^2)\right\}$$

In the back-to-back kinematics, we approximate

$$\boldsymbol{P}_{\psi\perp} \simeq -\boldsymbol{p}_{\gamma\perp} \simeq \boldsymbol{K}_\perp.$$

Mulders and Rodrigues, PRD 63, 094021 (2001)

CROSS SECTION AND ASYMMETRY

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z\mathrm{d}y\mathrm{d}x_B\mathrm{d}^2\boldsymbol{q}_T\mathrm{d}^2\boldsymbol{K}_\perp} \equiv \mathrm{d}\sigma(\phi_S,\phi_T,\phi_\perp) = \mathrm{d}\sigma^U(\phi_T,\phi_\perp) + \mathrm{d}\sigma^T(\phi_S,\phi_T,\phi_\perp).$$

$$\mathrm{d}\sigma^U = \mathcal{N}\Big[(\mathcal{A}_0 + \mathcal{A}_1\cos\phi_\perp + \mathcal{A}_2\cos 2\phi_\perp) f_1^g(x,\boldsymbol{q}_T^2) + (\mathcal{B}_0\cos 2\phi_T + \mathcal{B}_1\cos(2\phi_T-\phi_\perp) + \mathcal{B}_2\cos 2(\phi_T-\phi_\perp) + \mathcal{B}_3\cos(2\phi_T-3\phi_\perp) + \mathcal{B}_4\cos(2\phi_T-4\phi_\perp))\frac{\boldsymbol{q}_T^2}{M_p^2} h_1^{\perp g}(x,\boldsymbol{q}_T^2)\Big],$$

Unpolarized proton

$$\mathrm{d}\sigma^T = \mathcal{N}|\boldsymbol{S}_T|\Big[\sin(\phi_S-\phi_T)(\mathcal{A}_0 + \mathcal{A}_1\cos\phi_\perp + \mathcal{A}_2\cos 2\phi_\perp)\frac{|\boldsymbol{q}_T|}{M_p} f_{1T}^{\perp g}(x,\boldsymbol{q}_T^2) + \cos(\phi_S-\phi_T)(\mathcal{B}_0\sin 2\phi_T + \mathcal{B}_1\sin(2\phi_T-\phi_\perp) + \mathcal{B}_2\sin 2(\phi_T-\phi_\perp) + \mathcal{B}_3\sin(2\phi_T-3\phi_\perp) + \mathcal{B}_4\sin(2\phi_T-4\phi_\perp))\frac{|\boldsymbol{q}_T|^3}{M_p^3} h_{1T}^{\perp g}(x,\boldsymbol{q}_T^2) + (\mathcal{B}_0\sin(\phi_S+\phi_T) + \mathcal{B}_1\sin(\phi_S+\phi_T-\phi_\perp) + \mathcal{B}_2\sin(\phi_S+\phi_T-2\phi_\perp) + \mathcal{B}_3\sin(\phi_S+\phi_T-3\phi_\perp) + \mathcal{B}_4\sin(\phi_S+\phi_T-4\phi_\perp))\frac{|\boldsymbol{q}_T|}{M_p} h_{1T}^g(x,\boldsymbol{q}_T^2)\Big],$$

Transversely polarized proton

Weighted asymmetry :

$$A^{W(\phi_S,\phi_T)} \equiv 2\frac{\int \mathrm{d}\phi_S\mathrm{d}\phi_T\mathrm{d}\phi_\perp W(\phi_S,\phi_T)\mathrm{d}\sigma(\phi_S,\phi_T,\phi_\perp)}{\int \mathrm{d}\phi_S\mathrm{d}\phi_T\mathrm{d}\phi_\perp \mathrm{d}\sigma(\phi_S,\phi_T,\phi_\perp)},$$

Using the weight factors, specific azimuthal modulations are isolated.

C. Pisano, D. Boer, S. J. Brodsky, M. G. A. Buffing, and P. J. Mulders, J. High Energy Phys. 10 (2013) 024.

ASYMMETRY

$$A^{\cos 2\phi_T} = \frac{\boldsymbol{q}_T^2}{M_p^2}\frac{\mathcal{B}_0}{\mathcal{A}_0}\frac{h_1^{\perp g}(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)},$$

$$A^{\cos 2(\phi_T-\phi_\perp)} = \frac{\boldsymbol{q}_T^2}{M_p^2}\frac{\mathcal{B}_2}{\mathcal{A}_0}\frac{h_1^{\perp g}(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)}.$$

$$A^{\sin(\phi_S-\phi_T)} = \frac{|\boldsymbol{q}_T|}{M_p}\frac{f_{1T}^{\perp g}(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)},$$

$$A^{\sin(\phi_S+\phi_T)} = \frac{|\boldsymbol{q}_T|}{M_p}\frac{\mathcal{B}_0}{\mathcal{A}_0}\frac{h_1^g(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)}$$

$$A^{\sin(\phi_S-3\phi_T)} = -\frac{|\boldsymbol{q}_T|^3}{2M_p^3}\frac{\mathcal{B}_0}{\mathcal{A}_0}\frac{h_{1T}^{\perp g}(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)}.$$

$$h_1^g \equiv h_{1T}^g + \frac{\boldsymbol{p}_T^2}{2M_p^2}h_{1T}^{\perp g},$$

The coefficients A and B are calculated in NRQCD. Only one CO state contributes in the cross section namely

$$\langle 0|\mathcal{O}^{J/\psi}(^3S_1^{(8)})|0\rangle$$

Using cross section data one can fit the LDME

The LDME cancels in the asymmetries : clean probe of gluon TMDs

UNPOLARIZED DIFF CROSS SECTION

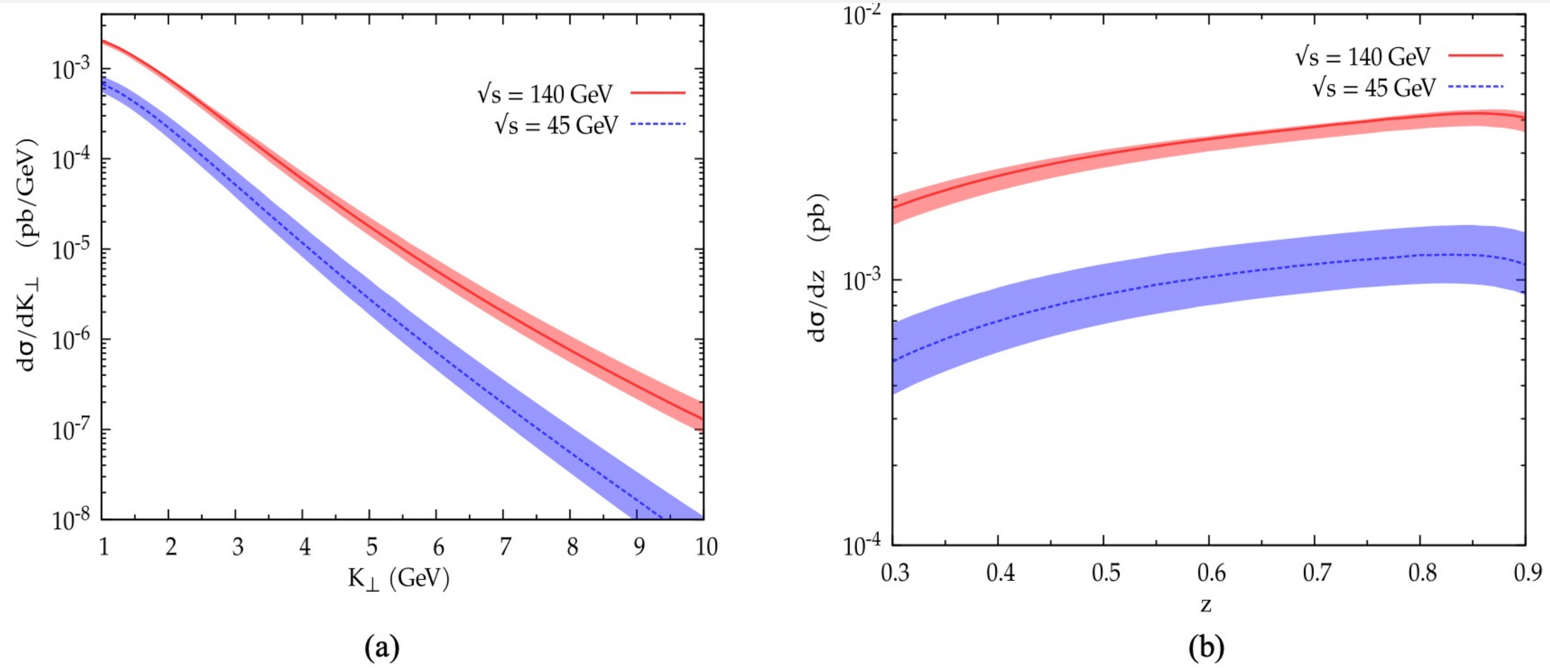


FIG. 3. Unpolarized differential cross section of $e + p \to e + J/\psi + \gamma + X$ process as a function of $K_\perp$ (a) and z (b) at $\sqrt{S} = 45$ and 140 GeV. The kinematical cuts are $1 < K_\perp < 10$ GeV, $0 < q_T < 1$ GeV, and $0.3 < z < 0.9$. For $\sqrt{s} = 140$ GeV we have taken $20 < W_{\gamma p} < 80$ GeV while for $\sqrt{s} = 45$ GeV, $10 < W_{\gamma p} < 40$ GeV. The bands are obtained by varying the factorization scale in the range $\frac{1}{2}\mu < \mu < 2\mu$.

D. Chakrabarti, R. Kishore, AM, S. Rajesh, Phys. Rev D *Phys.Rev.D* 107 (2023) 1, 014008

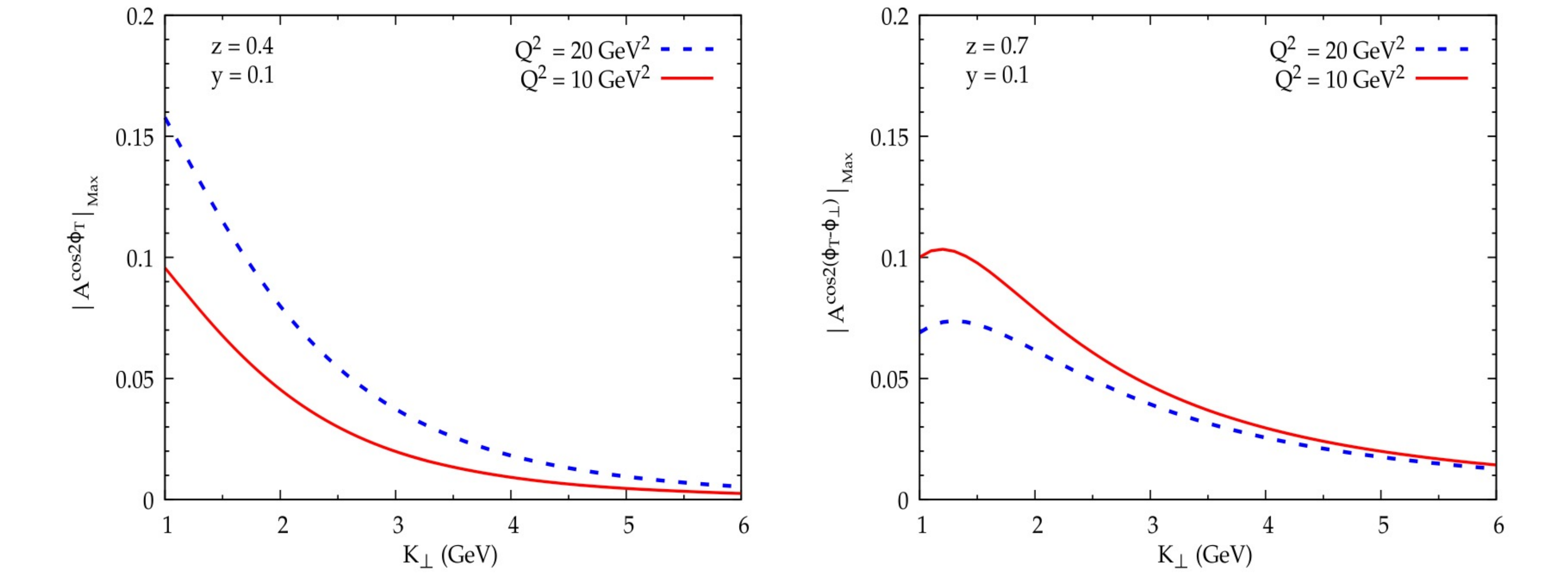
$$z = \frac{P.P_\psi}{P.q}$$

Higher cms energy probes smaller x region : high gluon density. Cross section larger

$$0.3 < z < 0.9.$$

Upper cutoff removes diffractive contribution and lower cutoff removes contribution from resolved photon

UPPER BOUND OF THE ASYMMETRIES



Upper bounds for two fixed values of Q^2

Model independent upper bound of the asymmetry is obtained by saturating the positivity bound of the TMDs

Upper bound is independent of CMS energy

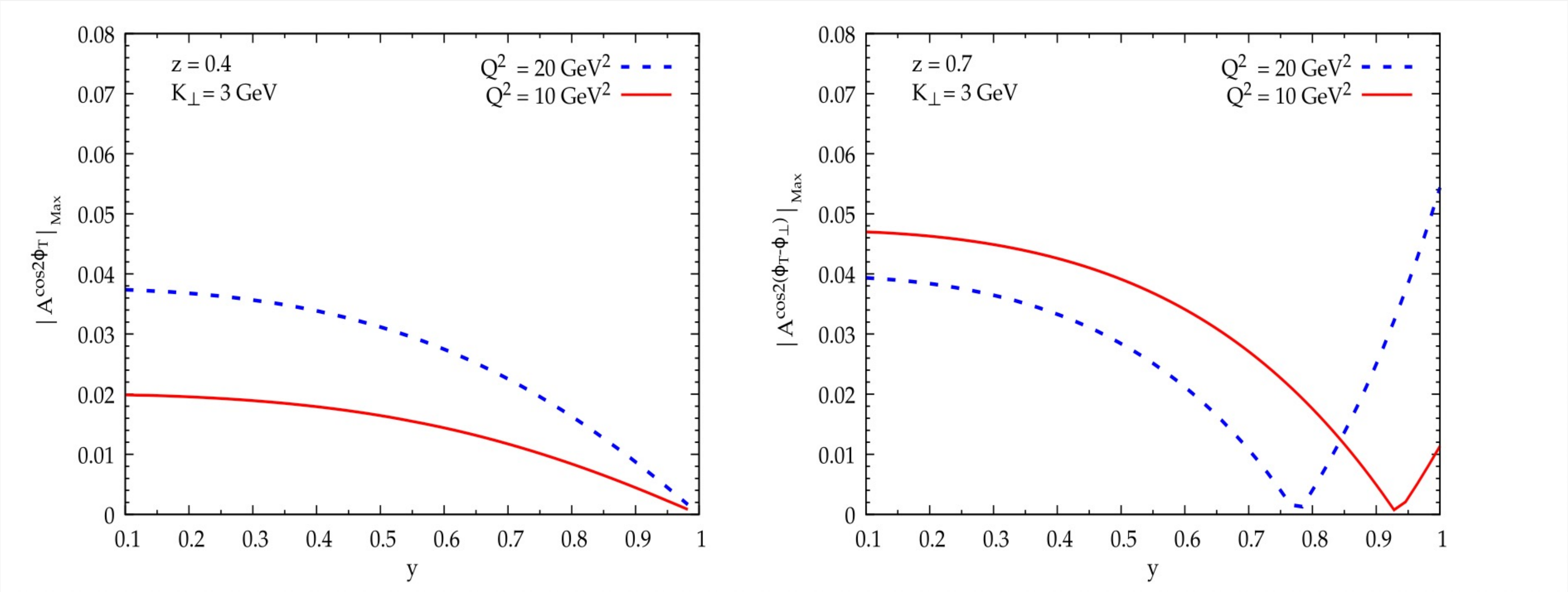
$$|A^{\cos 2\phi_T}| \leq 2\,\frac{|\mathcal{B}_0|}{\mathcal{A}_0}, \qquad |A^{\cos 2(\phi_T-\phi_\perp)}| \leq 2\,\frac{|\mathcal{B}_2|}{\mathcal{A}_0}$$

Also independent of the LDME as it cancels in the ratio

Upper bound of the other two asymmetries are related to the upper bound of $A^{\cos 2\phi_T}$

D. Chakrabarti, R. Kishore, AM, S. Rajesh, Phys. Rev D *Phys.Rev.D* 107 (2023) 1, 014008

UPPER BOUND OF THE ASYMMETRIES



Longitudinally polarized photon contributes to numerator

Both longitudinal and transverse photons contribute to the numerator

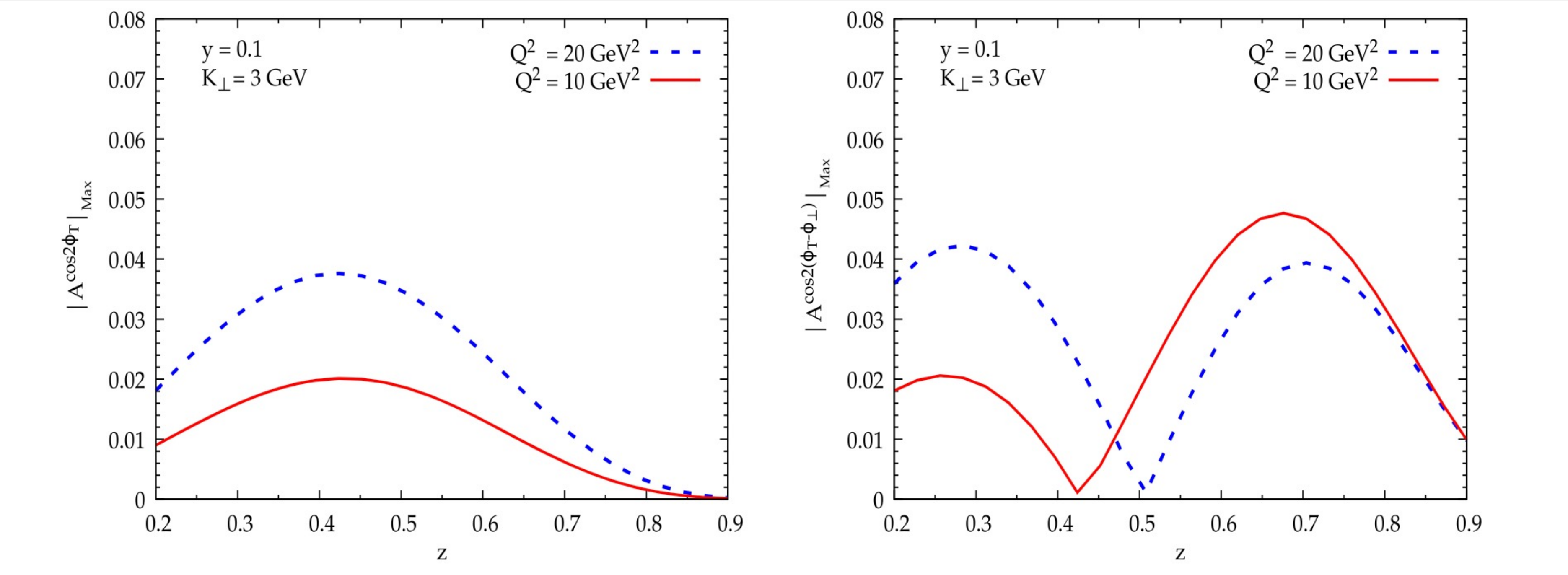
For lower y region the upper bound of the asymmetry saturates and we did not plot the low y region

$A^{\cos 2\phi_T}$ approaches zero as $y \to 1$

$A^{\cos 2(\phi_T - \phi_\perp)}$ Upper bound becomes zero for y<1: asymmetry changes sign

D. Chakrabarti, R. Kishore, AM, S. Rajesh, Phys. Rev D *Phys.Rev.D* 107 (2023) 1, 014008

UPPER BOUND AS FUNCTION OF Z



kinematical cuts

$z<0.9$ to avoid contribution from diffractive scattering (pomeron exchange), this cutoff also protects from IR divergence

D. Chakrabarti, R. Kishore, AM, S. Rajesh, Phys. Rev D
Phys.Rev.D 107 (2023) 1, 014008

$z>0.3$ to remove contribution from resolved photon

GAUSSIAN PARAMETRIZATION OF THE TMDS

Numerical estimate of the asymmetries are dependent on the TMD parametrization. We have used a Gaussian parametrization

$$f_1^g(x, \boldsymbol{q}_T^2) = f_1^g(x,\mu)\,\frac{e^{-\boldsymbol{q}_T^2/\langle q_T^2\rangle}}{\pi\langle q_T^2\rangle}$$

$f_1^g(x,\mu)$ Is the collinear unpolarized pdf at a scale $\langle q_T^2\rangle = 1\ \mathrm{GeV}^2$

$$\mu = \sqrt{M_\psi^2 + Q^2}$$

M. Anselmino, U. D'Alesio, and F. Murgia, Phys. Rev. D 67 (2003).

$$h_1^{\perp g}(x, \boldsymbol{q}_T^2) = \frac{M_p^2 f_1^g(x,\mu)}{\pi\langle q_T^2\rangle^2}\,\frac{2(1-r)}{r}\,e^{1-\frac{q_T^2}{r\langle q_T^2\rangle}}$$

M_p is the proton mass, r=1/3

D. Boer et al, PRL 108 (2012), Boer and Pisano, PRD 86 (2012)

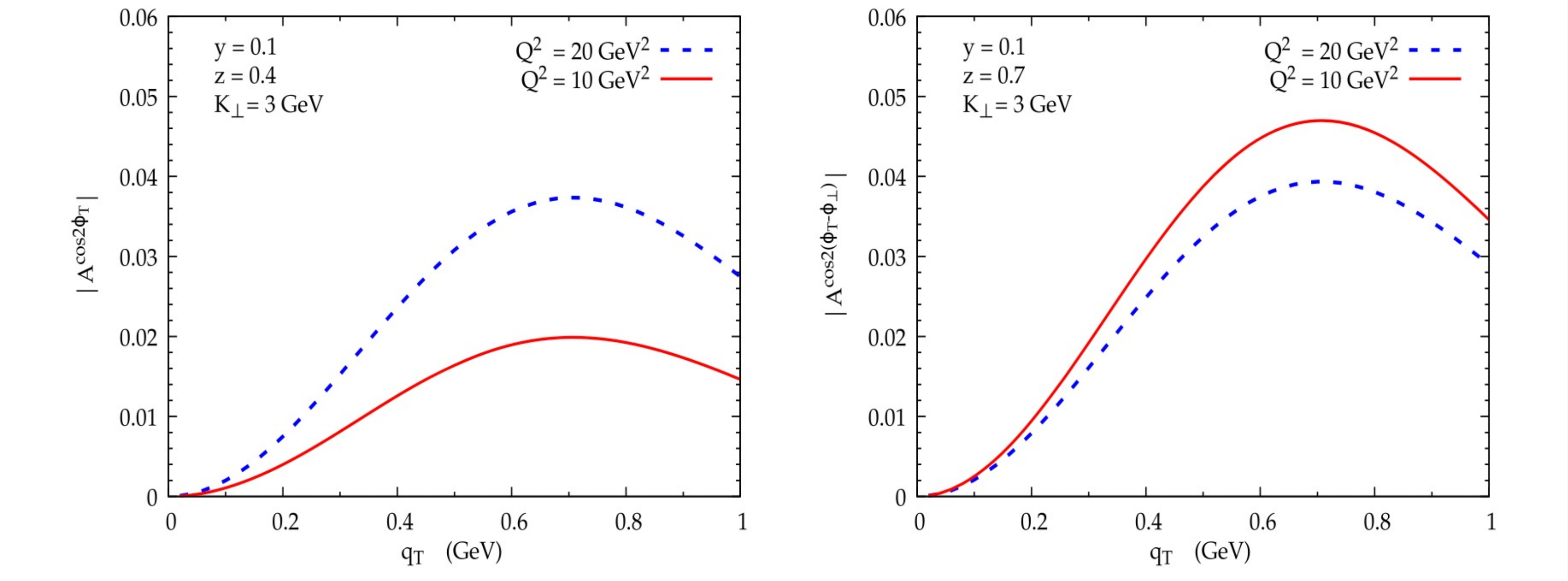
$$\Delta^N f_{g/p^\uparrow}(x, q_T) = \left(-\frac{2|\boldsymbol{q}_T|}{M_P}\right) f_{1T}^{\perp g}(x, q_T)$$
$$= 2\frac{\sqrt{2e}}{\pi}\mathcal{N}_g(x) f_{g/p}(x)\sqrt{\frac{1-\rho}{\rho}}\,q_T\,\frac{e^{-\boldsymbol{q}_T^2/\rho\langle q_T^2\rangle}}{\langle q_T^2\rangle^{3/2}}$$

$$\mathcal{N}_g(x) = N_g x^\alpha (1-x)^\beta\,\frac{(\alpha+\beta)^{(\alpha+\beta)}}{\alpha^\alpha \beta^\beta}$$

$$N_g = 0.25,\qquad \alpha = 0.6,\qquad \beta = 0.6,\qquad \rho = 0.1.$$

U. D'Alesio, C. Flore, F. Murgia, C. Pisano, and P. Taels, Phys. Rev. D 99 (2019)

ASYMMETRY WITH GAUSSIAN PARAMETRIZATION OF TMDS



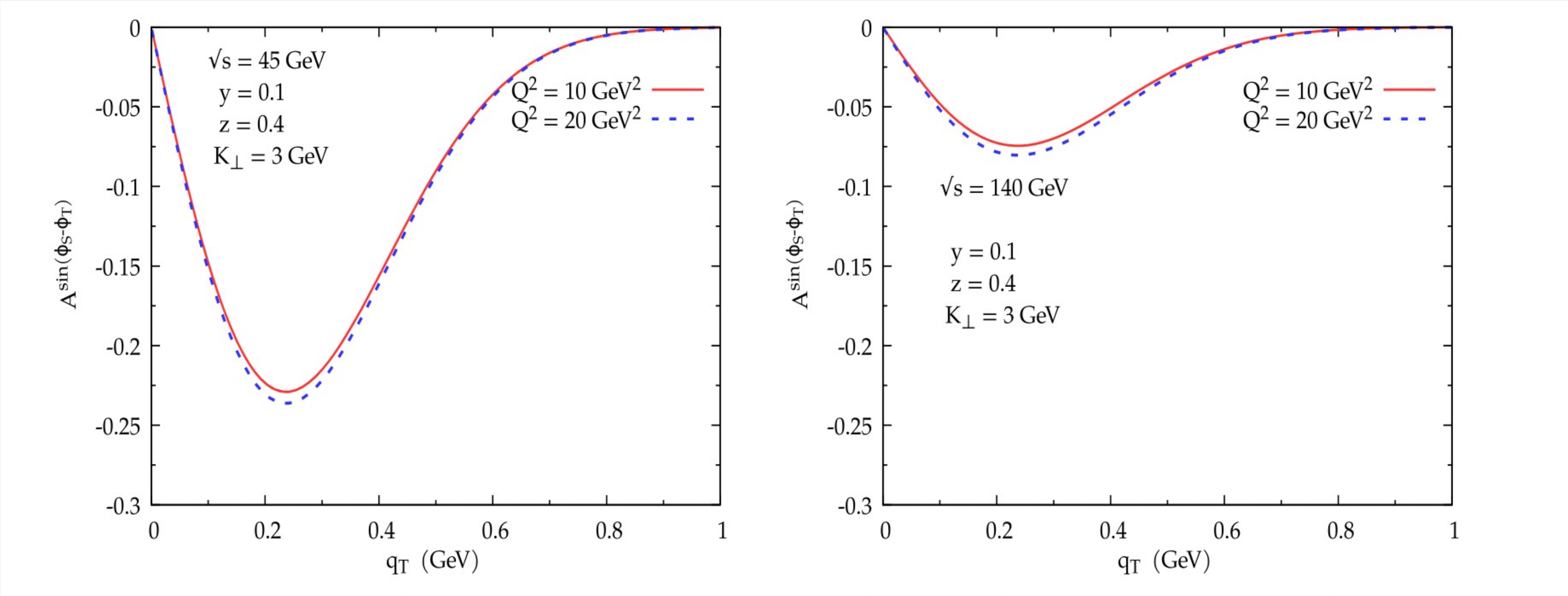
Asymmetry does not depend that much on CMS energy

Has peak value around q_T =0.7 GeV

kinematics chosen for back-to-back configuration

D. Chakrabarti, R. Kishore, AM, S. Rajesh, Phys. Rev D *Phys.Rev.D* 107 (2023) 1, 014008

SIVERS ASYMMETRY



Sivers asymmetry is negative, depends on the CMS energy

Does not depend much on the photon virtuality

Sivers asymmetry quite sizable at EIC kinematics and using Gaussian parametrization of the TMDs

D. Chakrabarti, R. Kishore, AM, S. Rajesh, Phys. Rev D *Phys.Rev.D* 107 (2023) 1, 014008

BACK-TO BACK PRODUCTION OF J/Ψ AND JET

$$e^-(l) + p(\mathrm{P}) \rightarrow e^-(l') + J/\psi(\mathrm{P}_\psi) + \mathrm{jet}(\mathrm{P}_j) + X,$$

$$Q^2 = -q^2, \qquad s = (P + l)^2, \qquad W^2 = (P + q)^2,$$

$$x_B = \frac{Q^2}{2P \cdot q}, \qquad y = \frac{P \cdot q}{P \cdot l}, \qquad z = \frac{P \cdot \mathrm{P}_\psi}{P \cdot q}.$$

Use TMD factorization in the kinematics where the outgoing J/ψ and (gluon) jet are almost back-to back

Use NRQCD to calculate the J/ψ production

Also compare with the color singlet (CS) model result

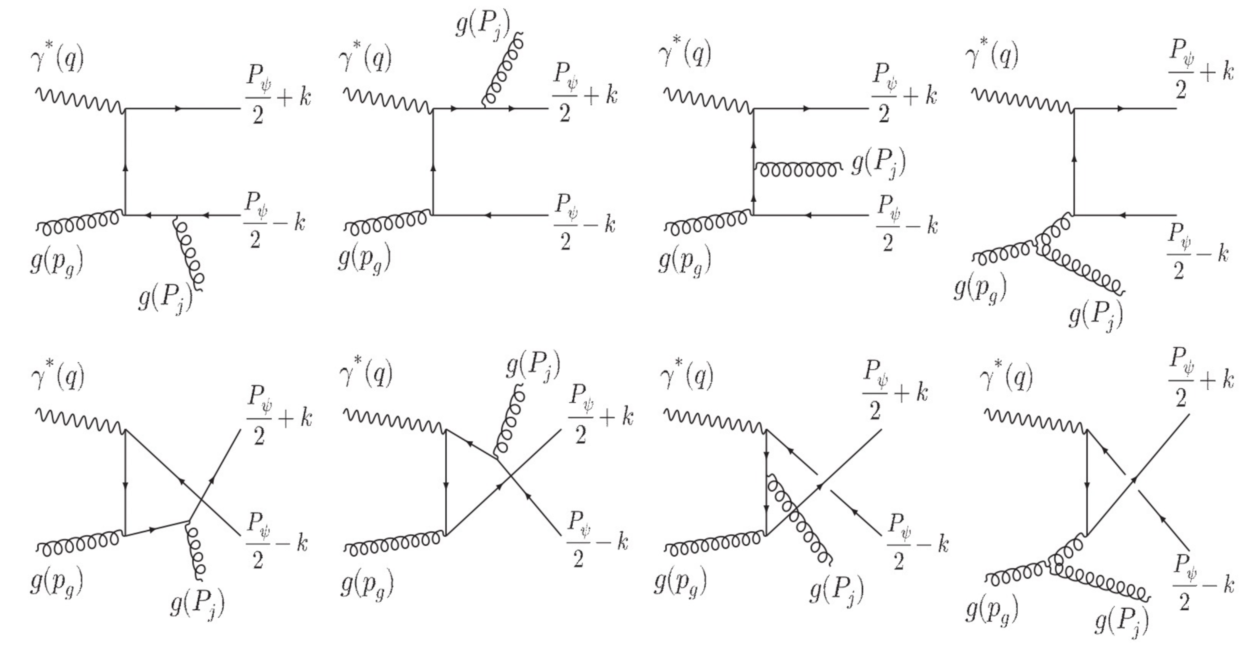


FIG. 1. Feynman diagrams for the partonic process $\gamma^*(q) + g(p_g) \rightarrow J/\psi(\mathrm{P}_\psi) + g(\mathrm{P}_j)$.

Raj Kishore, AM, Amol Pawar, M. Siddiqah, *Phys. Rev. D* 106 (2022) 3, 034009

BACK-TO-BACK PRODUCTION OF J/Ψ AND JET

$$d\sigma = \frac{1}{2s}\frac{d^3 l'}{(2\pi)^3 2E_{l'}}\frac{d^3 P_\psi}{2E_\psi(2\pi)^3}\frac{d^3 P_j}{2E_j(2\pi)^3} \times \int dx d^2\mathbf{p}_T (2\pi)^4 \delta^4(q+p_g-P_j-P_\psi) \times \frac{1}{Q^4} L^{\mu\mu'}(l,q)\Phi_g^{\nu\nu'}(x,\mathbf{p}_T^2)\mathcal{M}_{\mu\nu}^{g\gamma^*\to J/\psi g}\mathcal{M}_{\mu'\nu'}^{*g\gamma^*\to J/\psi g}.$$

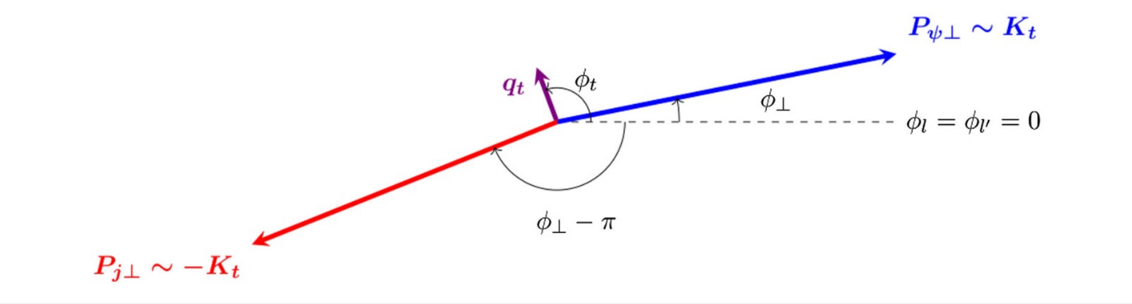
$$\mathcal{M}(\gamma^* g \to Q\bar{Q}[^{2S+1}L_J^{(1,8)}]g) = \sum_{L_z S_z}\int \frac{d^3\mathbf{k}}{(2\pi)^3}\Psi_{LL_z}(\mathbf{k})\langle LL_z; SS_z|JJ_z\rangle \times \mathrm{Tr}[O(q,p_g,P_\psi,k)\mathcal{P}_{SS_z}(P_\psi,k)],$$

$$O(q,p_g,P_\psi,k) = \sum_{i=1}^{8} C_i O_i(q,p_g,P_\psi,k),$$

Contribution comes from the color singlet state $(^3S_1^{(1)})$ And color octet states $(^3S_1^{(8)}, {}^1S_0^{(8)}, {}^3P_{J(0,1,2)}^{(8)})$

In NRQCD, k, the relative momentum of the charm quark is small.
We have Taylor expanded the amplitude about k=0. The first term gives the S wave contribution and second term the p wave contribution

Formation of the bound state J/ψ from the heavy quark pair is encoded in the non-perturbative long distance matrix elements (LDMEs). These are obtained by fitting data



Upper bound of the asymmetries : U. D'Alesio, F. Murgia, C. Pisano, and P. Taels *Phys.Rev.D* 100 (2019) 9, 094016

ASYMMETRY

$$\mathbf{q}_t \equiv \mathbf{P}_{\psi\perp} + \mathbf{P}_{j\perp}, \qquad \mathbf{K}_t \equiv \frac{\mathbf{P}_{\psi\perp} - \mathbf{P}_{j\perp}}{2}.$$

$$|\mathbf{q}_t| \ll |\mathbf{K}_t|.$$

$$\frac{d\sigma}{dz dy dx_B d^2\mathbf{q}_t d^2\mathbf{K}_t} = \frac{1}{(2\pi)^4}\frac{1}{16sz(1-z)Q^4}\Big\{(\mathbb{A}_0 + \mathbb{A}_1\cos\phi_\perp + \mathbb{A}_2\cos 2\phi_\perp) f_1^g(x,\mathbf{q}_t^2) + \frac{\mathbf{q}_t^2}{M_P^2} h_1^{\perp g}(x,\mathbf{q}_t^2)(\mathbb{B}_0\cos 2\phi_t + \mathbb{B}_1\cos(2\phi_t - \phi_\perp) + \mathbb{B}_2\cos 2(\phi_t - \phi_\perp) + \mathbb{B}_3\cos(2\phi_t - 3\phi_\perp) + \mathbb{B}_4\cos(2\phi_t - 4\phi_\perp))\Big\}.$$

$$\langle\cos 2\phi_t\rangle \equiv A^{\cos 2\phi_t} = \frac{\int q_t dq_t \frac{\mathbf{q}_t^2}{M_p^2}\mathbb{B}_0 h_1^{\perp g}(x,\mathbf{q}_t^2)}{\int q_t dq_t \mathbb{A}_0 f_1^g(x,\mathbf{q}_t^2)}.$$

Gaussian parametrization of TMDs :

$$f_1^g(x,\mathbf{q}_t^2) = f_1^g(x,\mu)\frac{1}{\pi\langle\mathbf{q}_t^2\rangle} e^{-\mathbf{q}_t^2/\langle\mathbf{q}_t^2\rangle},$$

$$h_1^{\perp g}(x,\mathbf{q}_t^2) = \frac{M_p^2 f_1^g(x,\mu)}{\pi\langle\mathbf{q}_t^2\rangle^2}\frac{2(1-r)}{r} e^{1-\frac{\mathbf{q}_t^2}{r\langle\mathbf{q}_t^2\rangle}},$$

Boer and Pisano, PRD, 2012

$$\langle\mathbf{q}_t^2\rangle = 0.25\ \mathrm{GeV}^2. \qquad r=1/3$$

Spectator model :

$$F^g(x,\mathbf{q}_t^2) = \int_M^\infty dM_X \rho_X(M_X)\hat{F}^g(x,\mathbf{q}_t^2;M_X).$$

M_X : mass of spectator : continuous

Spectral function

$$\rho_X(M_X) = \mu^{2a}\left[\frac{A}{B+\mu^{2b}} + \frac{C}{\pi\sigma} e^{-\frac{(M_X-D)^2}{\sigma^2}}\right],$$

$$L_X^2(\Lambda_X^2) = xM_X^2 + (1-x)\Lambda_X^2 - x(1-x)M^2.$$

$$\begin{aligned}\hat{f}_1^g(x,\mathbf{q}_t^2;M_X) &= -\frac{1}{2}g^{ij}[\Phi^{ij}(x,\mathbf{q}_t,S) + \Phi^{ij}(x,\mathbf{q}_t,-S)]\\ &= [(2Mxg_1 - x(M+M_X)g_2)^2[(M_X - M(1-x))^2 + \mathbf{q}_t^2]\\ &\quad + 2\mathbf{q}_t^2(\mathbf{q}_t^2 + xM_X^2)g_2^2 + 2\mathbf{q}_t^2 M^2(1-x)(4g_1^2 - xg_2^2)][(2\pi)^3 4xM^2(L_X^2(0) + \mathbf{q}_t^2)^2]^{-1},\end{aligned}$$

$$\begin{aligned}\hat{h}_1^{\perp g}(x,\mathbf{q}_t^2;M_X) &= \frac{M^2}{\varepsilon_t^{ij}\delta^{jm}(p_t^j p_t^m + g^{jm}\mathbf{q}_t^2)}\varepsilon_t^{ln}\delta^{nr}[\Phi^{nr}(x,\mathbf{q}_t,S) + \Phi^{nr}(x,\mathbf{q}_t,-S)]\\ &= [4M^2(1-x)g_1^2 + (L_X^2(0) + \mathbf{q}_t^2)g_2^2] \times [(2\pi)^3 x(L_X^2(0) + \mathbf{q}_t^2)^2]^{-1}.\end{aligned}$$

A. Bacchetta, F. G. Celiberto, M. Radici, and P. Taels, Eur. Phys. J. C 80, 733 (2020).

TMD EVOLUTION

Also incorportated TMD evolution in the asymmetry

TMD evolution is done in impact parameter space

$$\hat{f}(x, \mathbf{b}_t^2, Q_f^2) = \frac{1}{2\pi} \sum_{p=q,\bar{q},g} (C_{g/p} \otimes f_1^p)(x, Q_i^2) \times e^{-\frac{1}{2}S_A(\mathbf{b}_t^2, Q_f^2, Q_i^2)} e^{-S_{np}(\mathbf{b}_t^2, Q_f^2)},$$

Boer, D'Alesio, Murgia, Pisano, and Taels, JHEP (2020) 40.

Aybat and Rogers, PRD 83, 114042 (2011)

S_A and S_{np} are perturbative and non-perturbative Sudakov factors

$$S_A(\mathbf{b}_t^2, Q_f^2, Q_i^2) = \frac{C_A}{\pi} \int_{Q_i^2}^{Q_f^2} \frac{d\eta^2}{\eta^2} \alpha_s(\eta) \left(\log \frac{Q_f^2}{\eta^2} - \frac{11 - 2n_f/C_A}{6} \right)$$
$$= \frac{C_A}{\pi} \alpha_s \left(\frac{1}{2} \log^2 \frac{Q_f^2}{Q_i^2} - \frac{11 - 2n_f/C_A}{6} \log \frac{Q_f^2}{Q_i^2} \right).$$

$$S_{np} = \frac{A}{2} \log\left(\frac{Q_f}{Q_{np}}\right) \mathrm{b}_c^2, \qquad Q_{np} = 1 \text{ GeV}.$$

Scarpa, Boer, Echevarria, Lansberg, Pisano, Schlegel, EPJC(2020)

$$Q_f = \sqrt{M_\psi^2 + \mathrm{K}_t^2}.$$

$$A = 2.3 \text{ GeV}^2$$

$$Q_i = 2e^{-\gamma_E}/\mathrm{b}_t$$

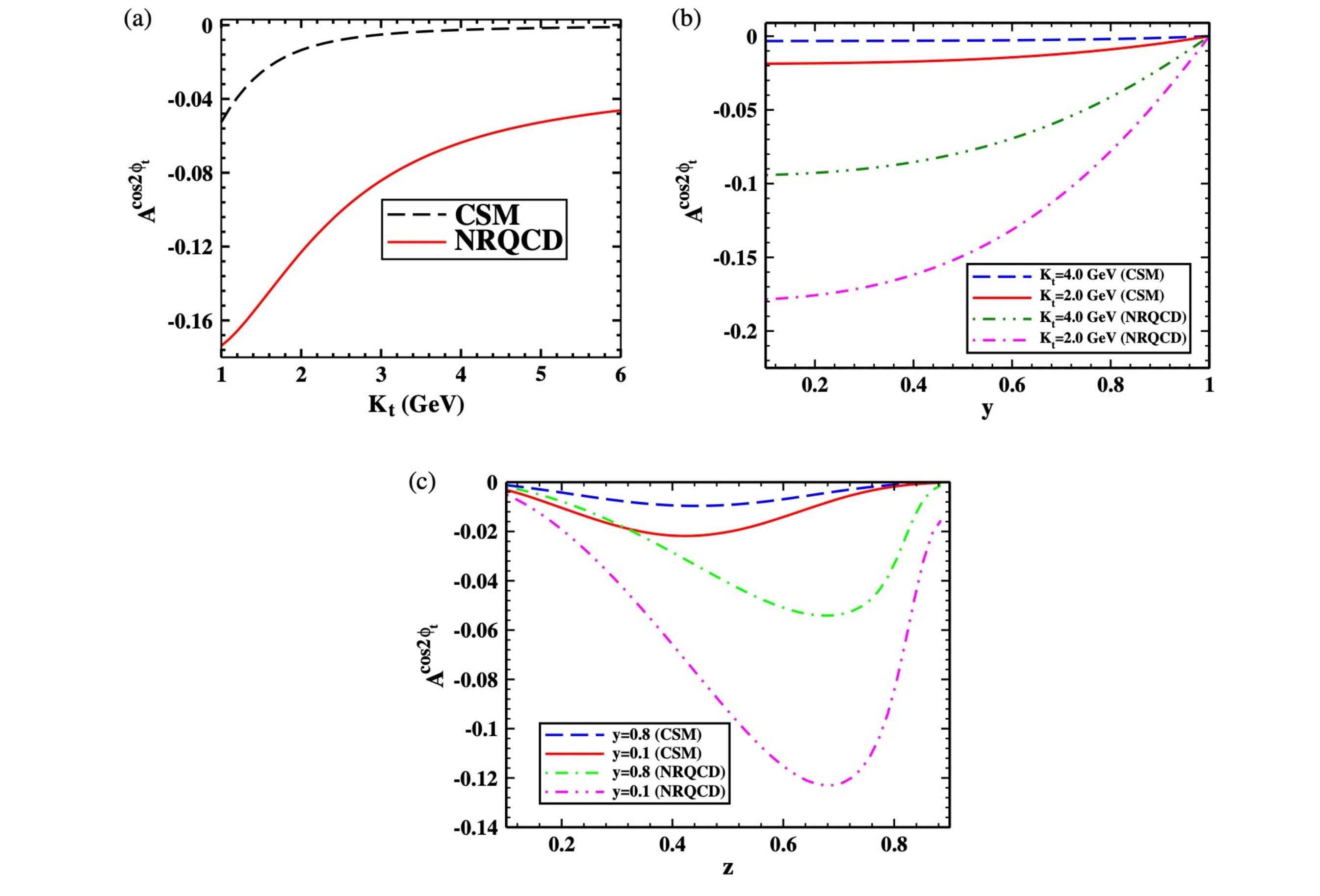
Used b_{t*} prescription to prevent Q_i larger than Q_f for low b_t

Final expressions are :

$$f_1^g(x, \mathbf{q}_t^2) = \frac{1}{2\pi} \int_0^\infty \mathrm{b}_t d\mathrm{b}_t J_0(\mathrm{b}_t \mathrm{q}_t) \Bigg\{ f_1^g(x, Q_f^2) - \frac{\alpha_s}{2\pi} \Bigg[\left(\frac{C_A}{2} \log^2 \frac{Q_f^2}{Q_i^2} - \frac{11C_A - 2n_f}{6} \log \frac{Q_f^2}{Q_i^2} \right) f_1^g(x, Q_f^2) + (P_{gg} \otimes f_1^g + P_{gi} \otimes f_1^i)(x, Q_f^2) \log \frac{Q_f^2}{Q_i^2} - 2 f_1^g(x, Q_f^2) \Bigg] \Bigg\} \times e^{-S_{np}(\mathbf{b}_t^2)}.$$

$$\frac{\mathbf{q}_t^2}{M_p^2} h_1^{\perp g(2)}(x, \mathbf{q}_t^2) = \frac{\alpha_s}{\pi^2} \int_0^\infty d\mathrm{b}_t \mathrm{b}_t J_2(\mathrm{q}_t \mathrm{b}_t) \left[C_A \int_x^1 \frac{d\hat{x}}{\hat{x}} \left(\frac{\hat{x}}{x} - 1 \right) f_1^g(\hat{x}, Q_f^2) + C_F \sum_{p=q,\bar{q}} \int_x^1 \frac{d\hat{x}}{\hat{x}} \left(\frac{\hat{x}}{x} - 1 \right) f_1^p(\hat{x}, Q_f^2) \right] \times e^{-S_{np}(\mathbf{b}_t{}^2)}.$$

ASYMMETRY WITH GAUSSIAN PARAMETRIZATION



$\sqrt{s} = 140\ GeV$

$z = 0.7$ in (a) and (b)

$0.1 < y < 1$ in (a)

$K_t = 0.3\ \ GeV$ in (c)

Magnitude of asymmetry does not change much if we take different value of cms energy

Showed both CSM and NRQCD results

LDMEs from Phys. Rev. Lett. 108, 242004 (2012).

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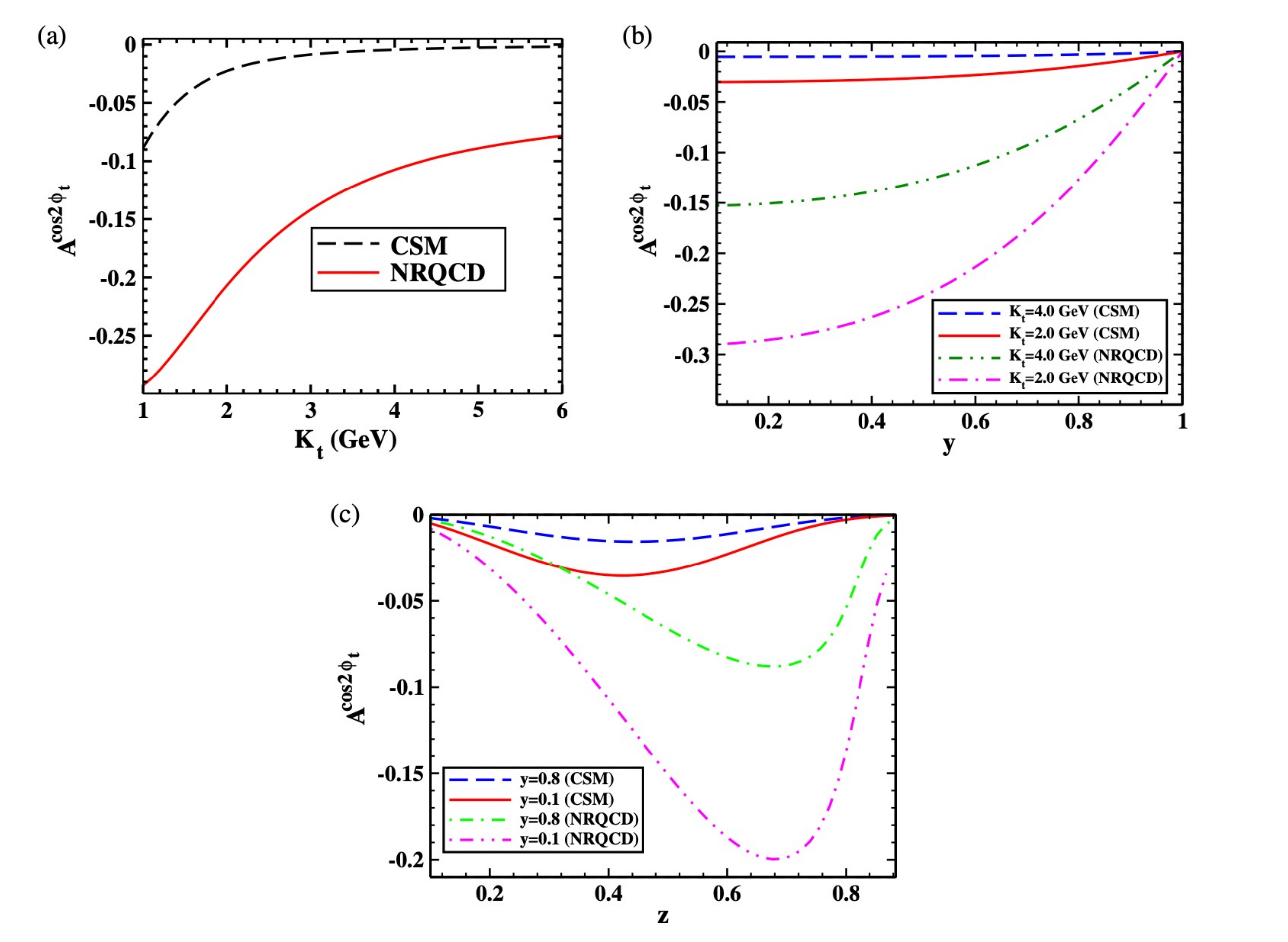
ASYMMETRY IN SPECTATOR MODEL



$$\sqrt{s} = 140\ GeV$$

Kinematics same as previous plot

LDMEs from Phys. Rev. Lett. 108, 242004 (2012).

Magnitude of asymmetry in spectator model larger than in Gaussian parametrization of gluon TMDs

Sizable negative asymmetry in NRQCD, in contrast to CSM

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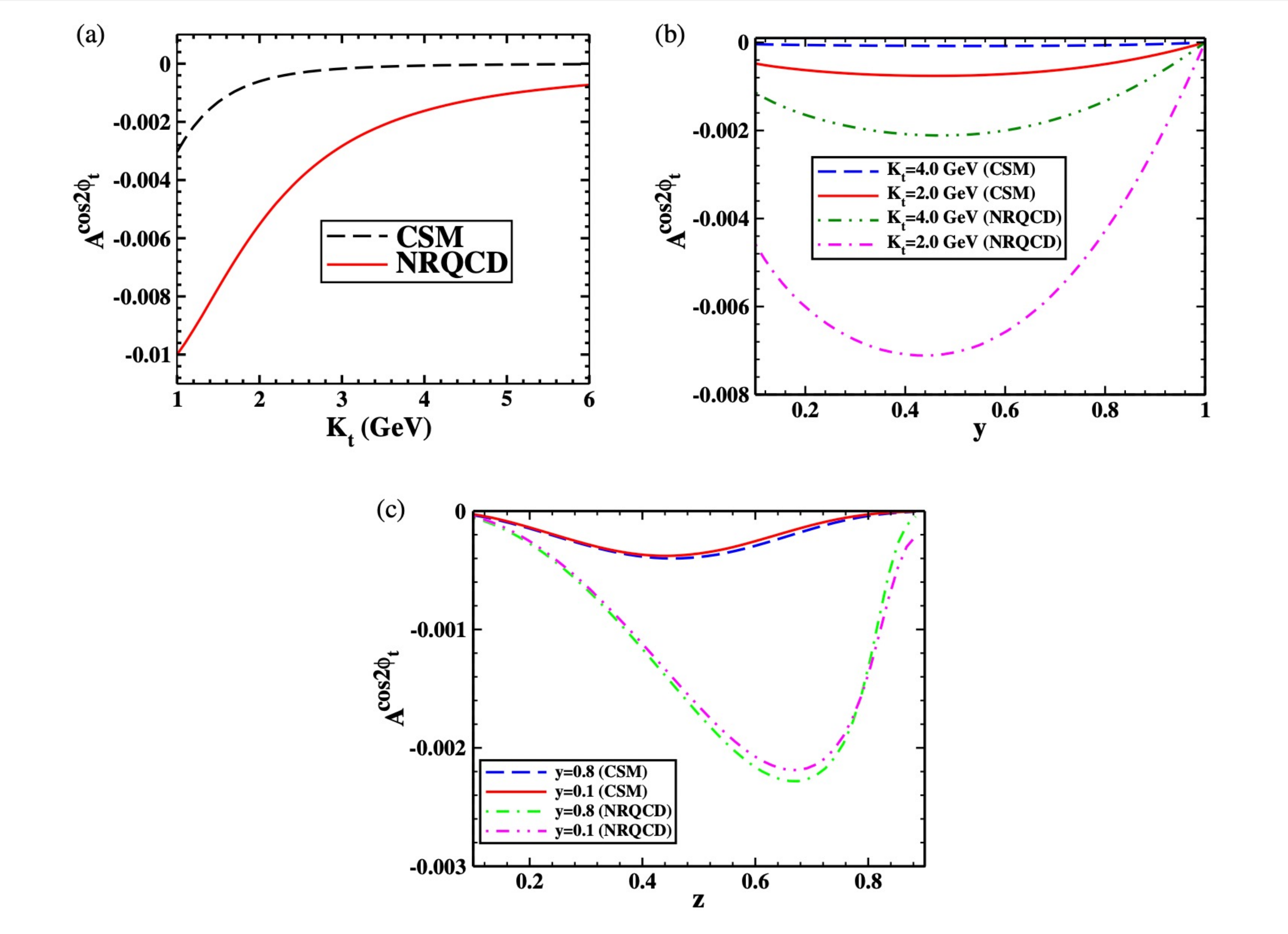
ASYMMETRY AFTER INCORPORATING TMD EVOLUTION



Kinematics same as other plots

TMD evolution gives smaller asymmetry

This is because unpolarized TMD in the denominator has a LO term whereas the linearly polarized gluon TMD in the numerator gets contribution at NLO

Magnitude of asymmetry does not change much with CMS energy

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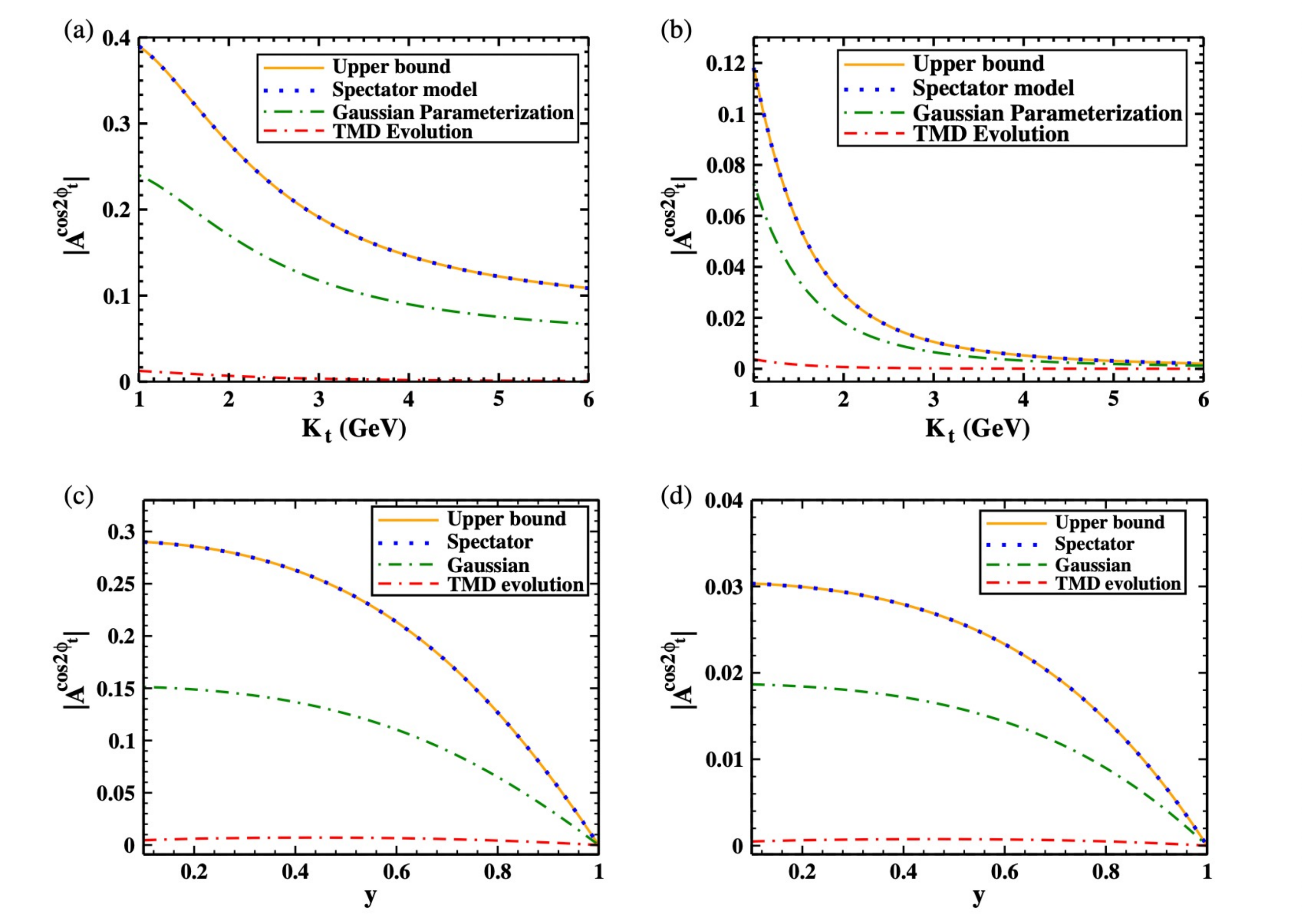
UPPER BOUND OF THE ASYMMETRY COMPARED WITH DIFFERENT RESULTS



NRQCD

CS

$y = 0.3$ In upper panels

$K_t = 0.2\ GeV$ In lower panels

Result in spectator model in the kinematics considered overlaps with the upper bound saturating the positivity bound

Result is Gaussian parametrization lower than in spectator model

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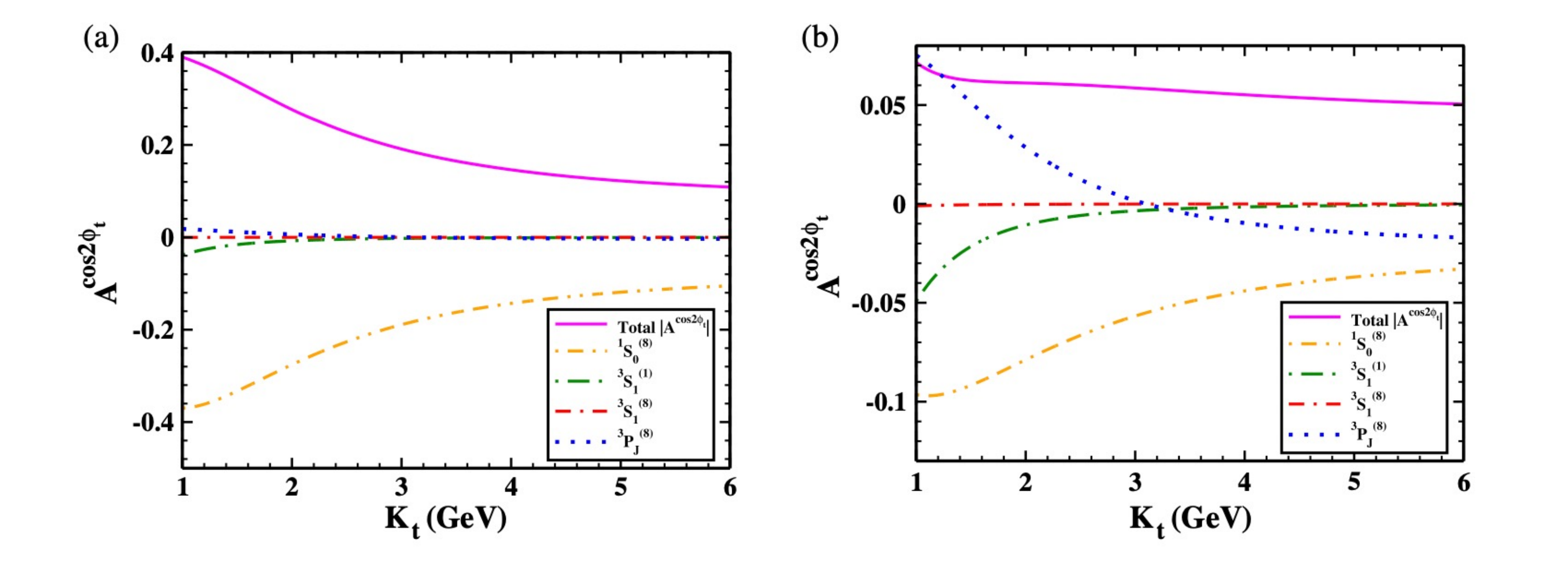
CONTRIBUTION TO ASYMMETRY FROM DIFFERENT STATES



$$\sqrt{s} = 140\ GeV$$

$$Q = \sqrt{M_\psi^2 + K_t^2},$$

y=0.3

(a) LDMEs from K.T. Chao et al, Phys. Rev. Lett. 108, 242004 (2012).

(b) LDMEs from Sharma and Vitev, Phys. Rev. C 87, 044905 (2013)

In (a) dominating contribution come from a single state whereas in (b) contributions come from several states

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SUMMARY AND CONCLUSION

Presented numerical estimates of azimuthal asymmetries in back-to-back production of J/ψ -photon and J/ψ-jet in eP collision in the kinematics of EIC

Used NRQCD and CS mechanisms to calculate the J/ψ production rate

In J/ψ-photon production only one LDME contributes : asymmetry is independent of LDME choice. Robust probe of gluon TMDs

Cos 2ϕ asymmetry small but sizable Sivers asymmetry (Gaussian parametrization of gluon TMDs)

In J/ψ-jet production, significant contribution to cos 2ϕ asymmetry in NRQCD, smaller in CSM. Also considered effect of TMD evolution

Asymmetry depends on LDME sets chosen, does not depend much on CMS energy

International School and Workshop on Probing Hadron Structure at the Electron-Ion Collider (QEIC-III)

Organizers : Asmita Mukherjee, Bedangadas Mohanty, Abhay Deshpande, Marco Radici

International Center for Theoretical Sciences (ICTS) Bangalore, India

School for PhD students and postdocs : 29.1.24 to 3.2.24
Workshop : 4.2.24 to 9.2.24

Topics of the workshop

(i) Spin and Nucleon tomography
(ii) Origin of mass
(iii) Small x physics and gluons:
(iv) EIC & BNL status and Indian participation.

Topics of the school

(i) Pedagogical lectures on QCD and physics of EIC
(ii) Elastic and deep inelastic scattering
(iii) Exclusive processes
(iv) Single spin asymmetries and TMDs
(v) Hadron structure in experiments
(vi) Heavy ion physics

All are welcome !

https://www.icts.res.in/program/QEICIII2024