AZIMUTHAL ASYMMETRIES IN J/Ψ PRODUCTION PROCESSES AT THE ELECTRON-ION COLLIDER (EIC)

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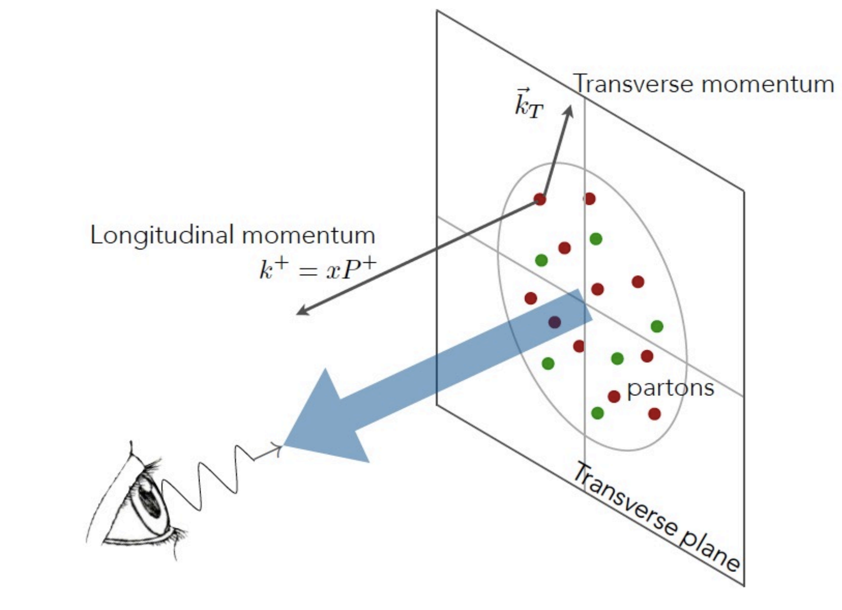
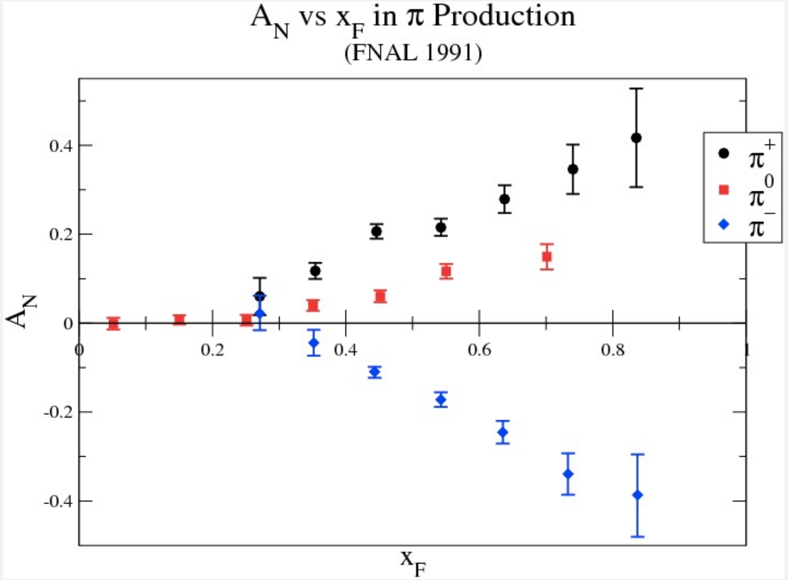
TRANSVERSE MOMENTUM DEPENDENT PARTON DISTRIBUTIONS (TMDS)



Large (30-40%) Single transverse spin asymmetries were seen at FermiLab and RHIC experiments

Such large asymmetries cannot be explained in terms of collinear leading twist pdfs : need TMDs, or twist three pdfs

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

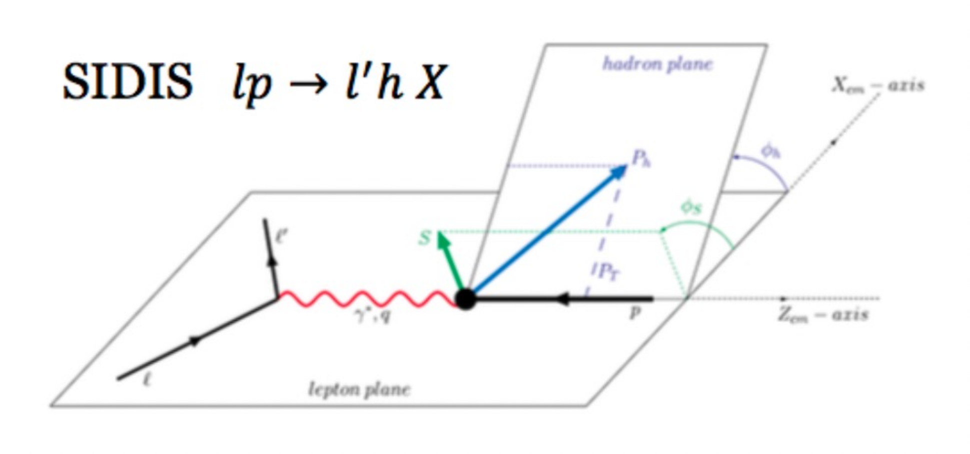


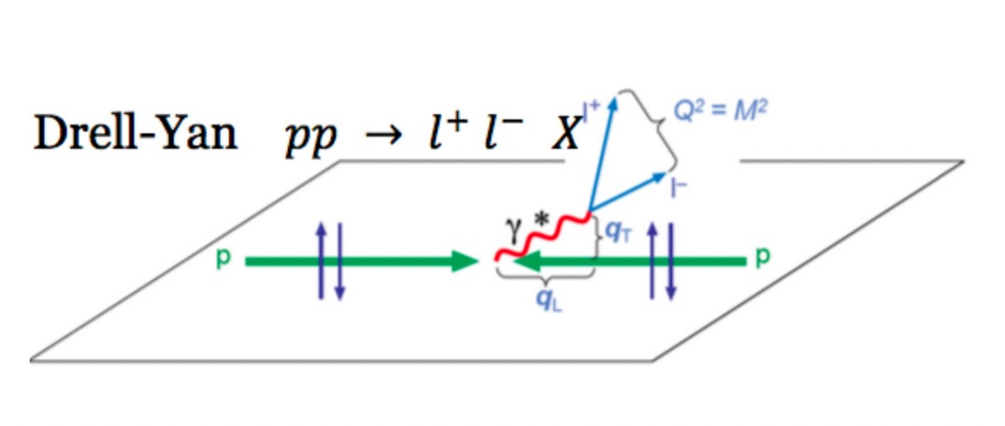
TMDs : functions of x and intrinsic transverse momentum : Gives a 3 D picture of the nucleon in momentum space

Correlations of spin, OAM and k_T : in terms of TMDs

TRANSVERSE MOMENTUM DEPENDENT PDFS (TMDS)

TMDs play a role in processes where two scales are present $Q^2 >> q_T^2$





For SIDIS and DY, TMD factorization is proven to all orders in α_s and leading twist

Collins, Cambridge University Press (2011)
Boussarie et al, TMD handbook 2304.03302

For some processes, attempts have been made to prove TMD factorization at one loop and beyond leading twist

GLUON TMDS

GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g,\ h_{1T}^{\perp g}$

$h_1^{\perp g}$: Linearly polarized gluon distribution in unpolarized hadron; T even

$f_{1T}^{\perp g}$ Gluon Sivers function in Transversely polarized proton

Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)
Mulders, Rodrigues, PRD 63 (2001)
Meissner, Metz, Goeke, PRD 76 (2007)

$$h_1^g \equiv h_{1T}^g + \frac{p_T^2}{2M_p^2} h_{1T}^{\perp g}$$ Vanish under p_T integration

In contrast to quark TMDs, very little is known about gluon TMDs

$$\Gamma^{[\mathcal{U},\mathcal{U}']\mu\nu} \propto \langle P,S|\,\mathrm{Tr}_c\left[F^{+\nu}(0)\,\mathcal{U}^{\mathcal{C}}_{[0,\xi]}\,F^{+\mu}(\xi)\,\mathcal{U}^{\mathcal{C}'}_{[\xi,0]}\right]|P,S\rangle$$

Gluon TMDs need two gauge links for gauge invariance

Mulders, Rodrigues, PRD 63 (2001)
Buffing, Mukherjee, Mulders, PRD 88 (2013)
Boer, Cotogno, Van Daal, Mulders, Signori, Zhou, JHEP 1610 (2016)

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. 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 2ϕ 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)

Back-to-back J/ψ-photon/jet/pion production processes in eP collision are effective ways to probe the gluon TMDs : expect TMD factorization

GLUON TMDS IN J/Ψ AND PHOTON PRODUCTION

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

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

$$P^\mu = n_-^\mu + \frac{M_p^2}{2} n_+^\mu \approx n_-^\mu,$$

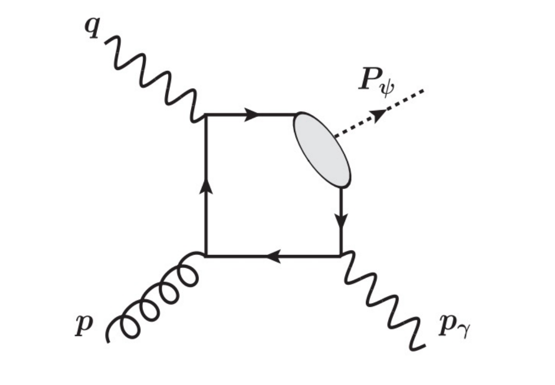
$$q^\mu = -x_B n_-^\mu + \frac{Q^2}{2x_B} n_+^\mu \approx -x_B P^\mu + (P \cdot q) n_+^\mu,$$

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

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

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

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



Partonic subprocess : virtual photon-gluon fusion

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

Use TMD factorization

PRODUCTION OF J/Ψ IN NRQCD

In NRQCD the heavy quark pair is produced in the hard process either in color octet or in color singlet configuration

Then they hadronize to form a color singlet quarkonium state of given quantum numbers through soft gluon emission

Hard process is calculated perturbatively and soft process is given in terms of long distance matrix elements (LDMEs) that are determined from data

The LDMEs are categorized by performing an expansion in terms of the relative velocity of the heavy quark v in the limit $v \ll 1$

The theoretical predictions are arranged as double expansions in terms of v as well as α_s.

C. E. Carlson and R. Suaya, Phys. Rev. D 14, 3115 (1976).
E. L. Berger and D. L. Jones, Phys. Rev. D 23, 1521 (1981).
R. Baier and R. Ruckl, Phys. Lett. B 102B, 364 (1981).
R. Baier and R. Ruckl, Nucl. Phys. B201, 1 (1982).
E. Braaten and S. Fleming, Phys. Rev. Lett. 74, 3327 (1995).
P. L. Cho and A. K. Leibovich, Phys. Rev. D 53, 150 (1996).

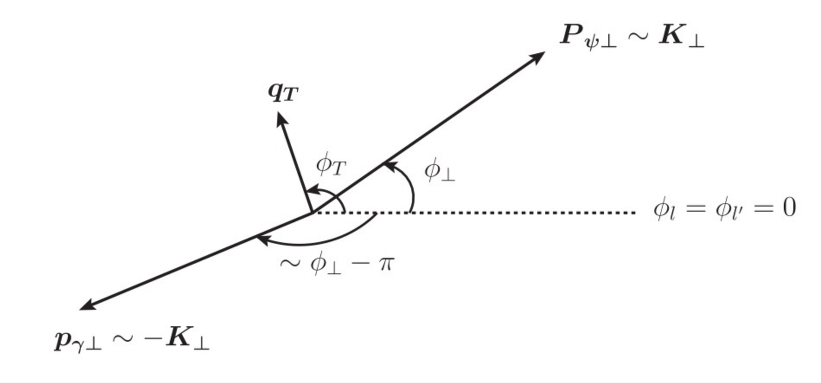
G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D 51, 1125 (1995); 55, 5853(E) (1997).

GLUON TMDS IN J/ψ AND PHOTON PRODUCTION

J/ψ and photon almost back to back

$$q_T \equiv P_{\psi\perp} + p_{\gamma\perp}, \qquad K_\perp \equiv \frac{P_{\psi\perp} - p_{\gamma\perp}}{2}.$$

$$q_T \ll K_\perp$$



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

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

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

In the back-to-back kinematics, we approximate

$$P_{\psi\perp} \simeq -p_{\gamma\perp} \simeq K_\perp.$$

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

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 $\langle q_T^2\rangle = 1\ \text{GeV}^2$

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

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)

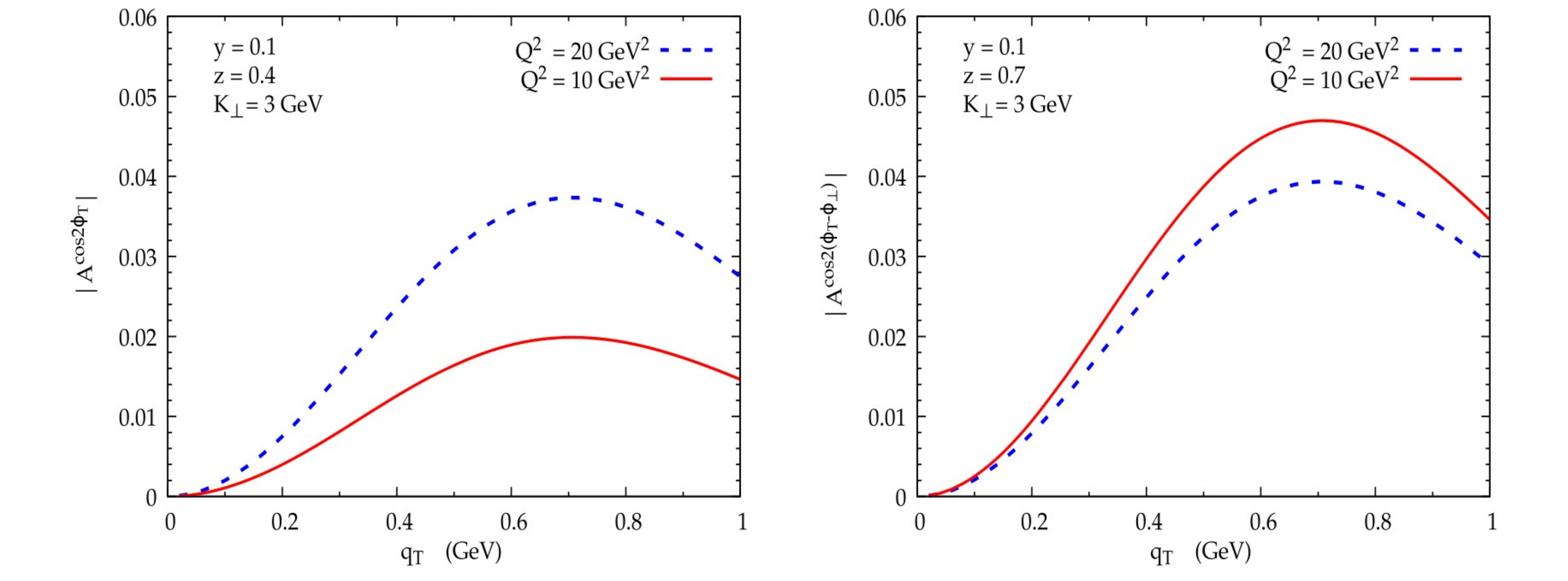
$$\Delta^N f_{g/p^\uparrow}(x, q_T) = \left(-\frac{2|\boldsymbol{q}_T|}{M_P}\right) f_{1T}^{\perp g}(x, q_T)$$
$$= 2\frac{\sqrt{2e}}{\pi}\mathcal{N}_g(x) f_{g/p}(x)\sqrt{\frac{1-\rho}{\rho}}\, q_T \frac{e^{-\boldsymbol{q}_T^2/\rho\langle q_T^2\rangle}}{\langle q_T^2\rangle^{3/2}}$$

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

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

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

ASYMMETRY WITH GAUSSIAN PARAMETRIZATION OF TMDS



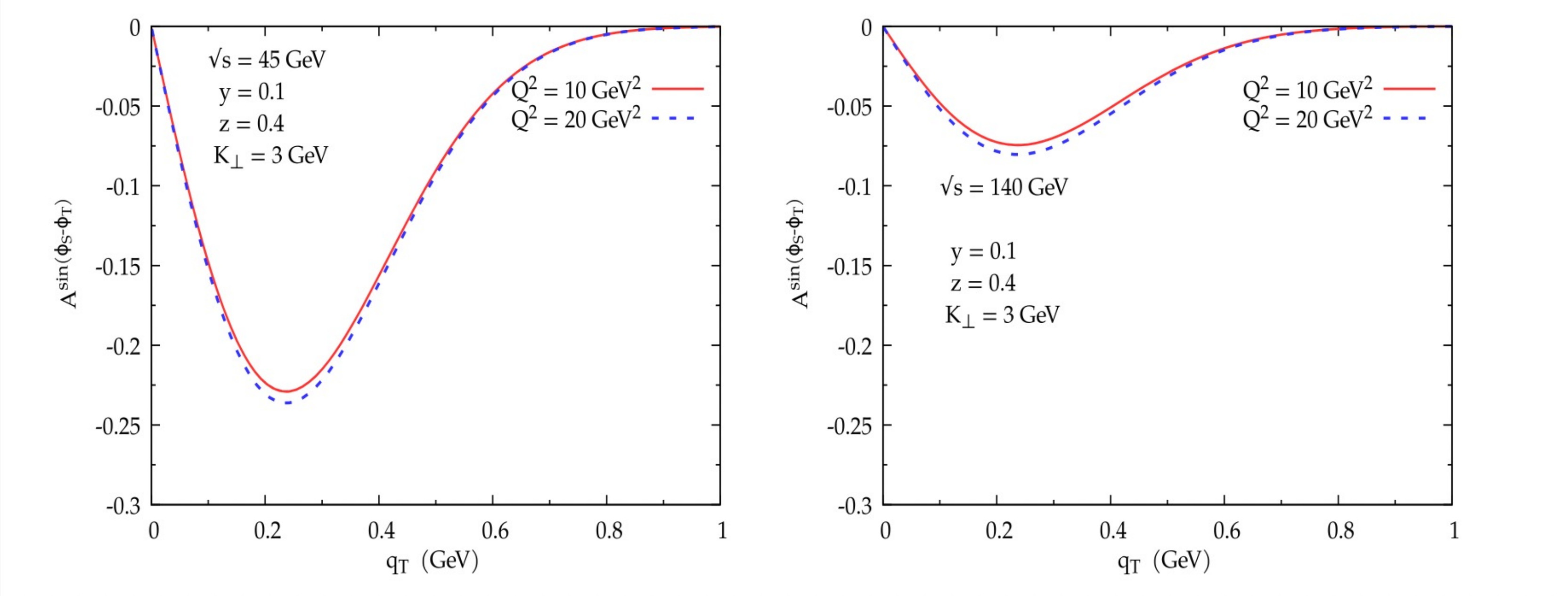
Asymmetry does not depend that much on CMS energy

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

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

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

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

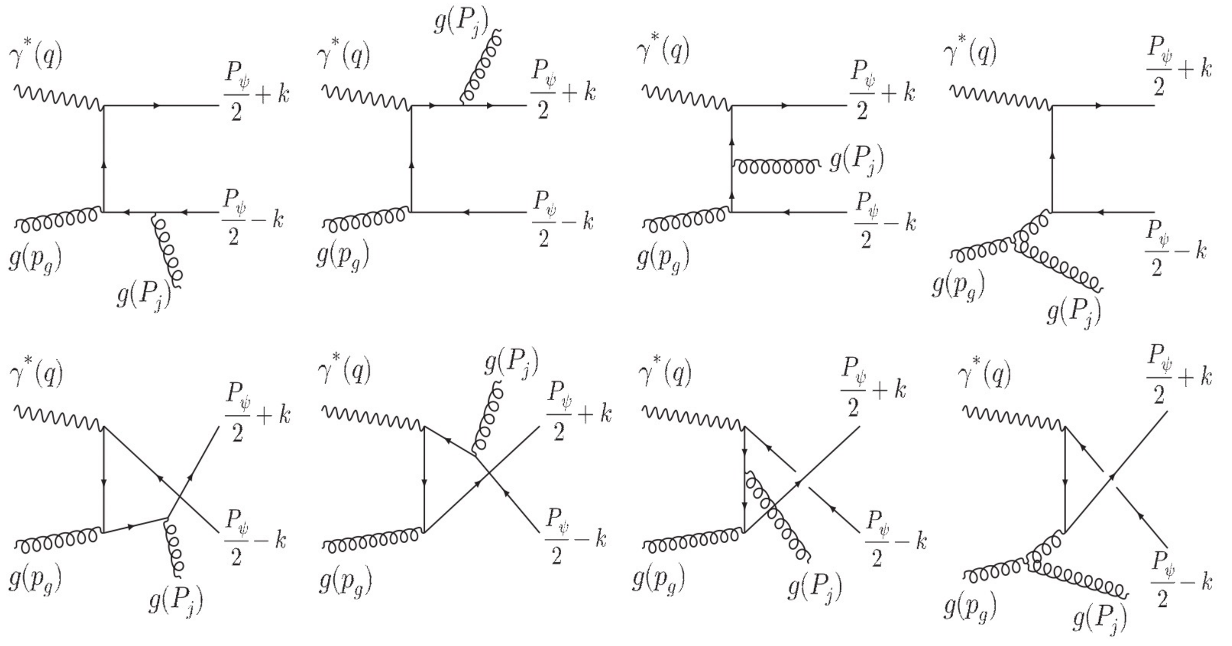


FIG. 1. Feynman diagrams for the partonic process $\gamma^*(q) + g(p_g) \rightarrow J/\psi(\mathrm{P}_\psi) + g(\mathrm{P}_j)$.

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

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

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

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

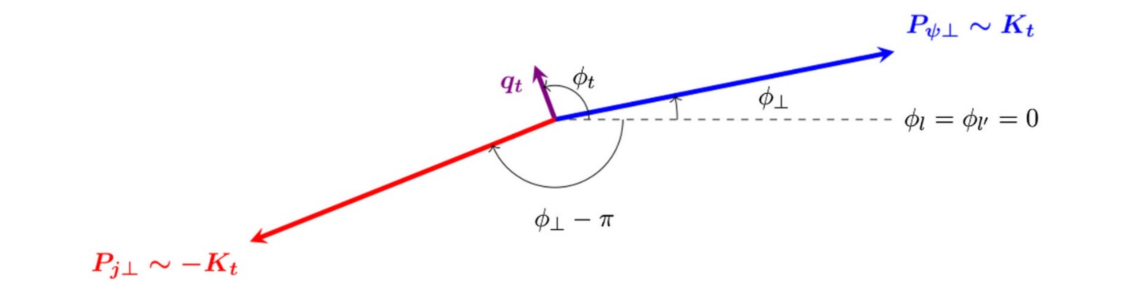
$$\mathcal{M}(\gamma^* g \to Q\bar{Q}[^{2S+1}L_J^{(1,8)}]g) = \sum_{L_z S_z}\int \frac{d^3\mathbf{k}}{(2\pi)^3}\Psi_{LL_z}(\mathbf{k})\langle LL_z; SS_z|JJ_z\rangle \times \mathrm{Tr}[O(q,p_g,P_\psi,k)\mathcal{P}_{SS_z}(P_\psi,k)],$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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)

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

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

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

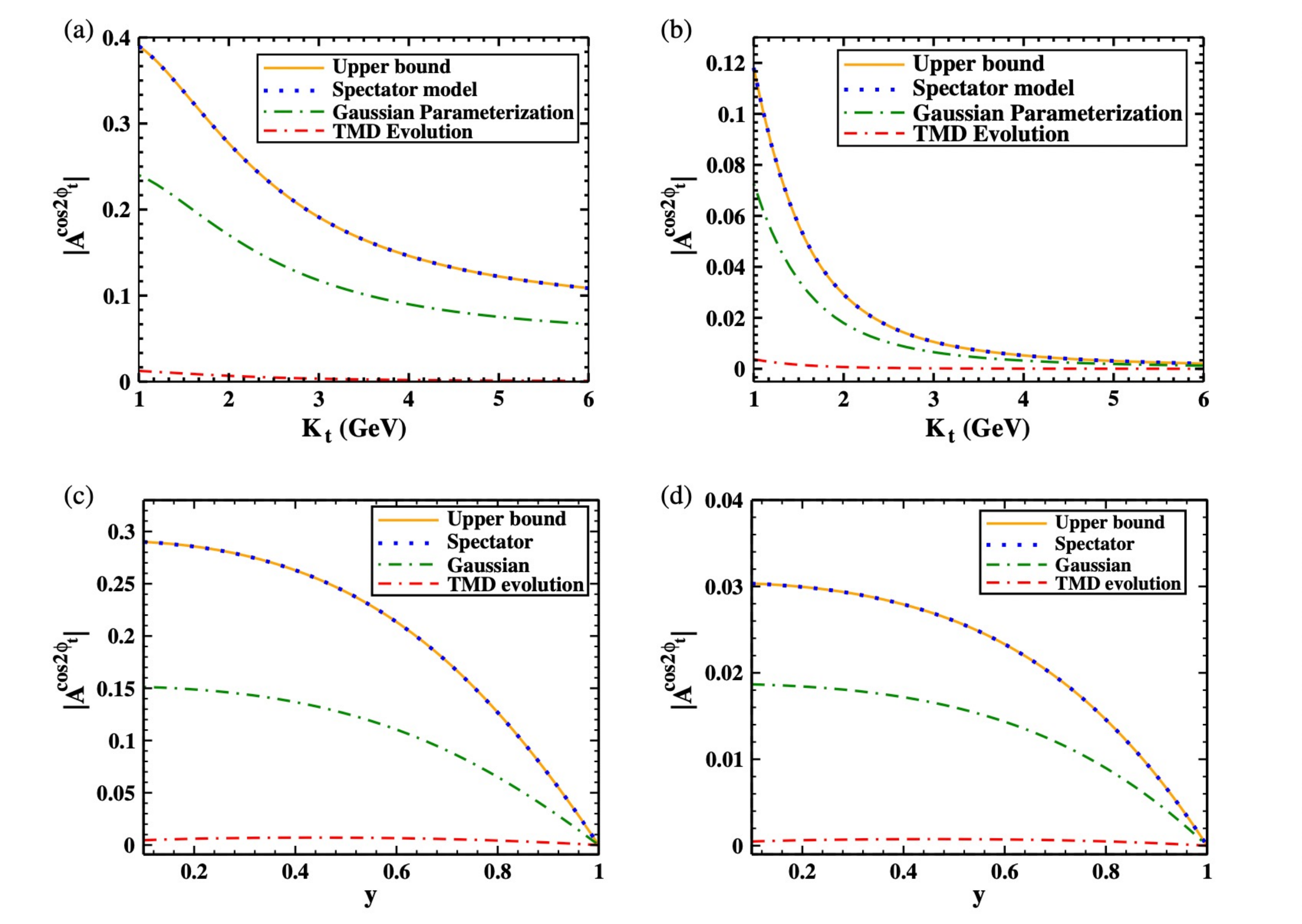
Used b_{t*} prescription to prevent Q_i larger than Q_f for low b_t

Final expressions are :

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

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

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

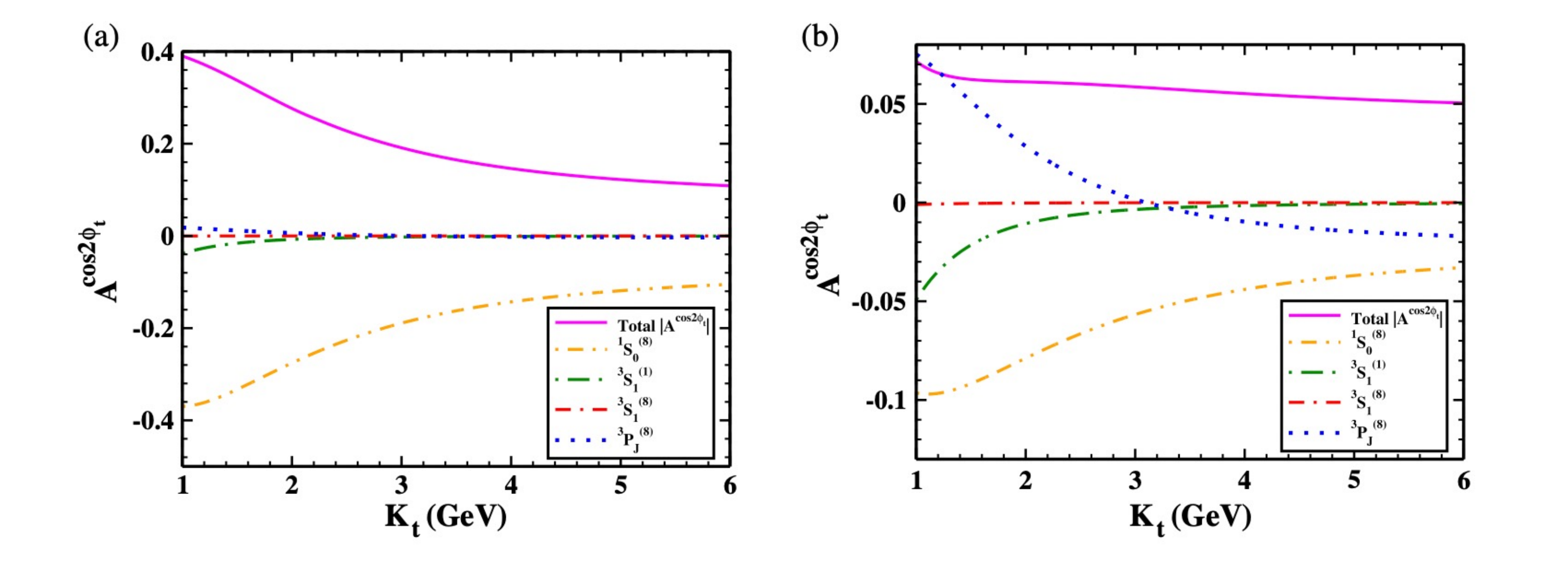
Result in spectator model in the kinematics considered overlaps with the upper bound saturating the positivity bound

Result is Gaussian parametrization lower than in spectator model

Asymmetries in CS smaller than in NRQCD

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

CONTRIBUTION TO ASYMMETRY FROM DIFFERENT STATES



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

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

y=0.3

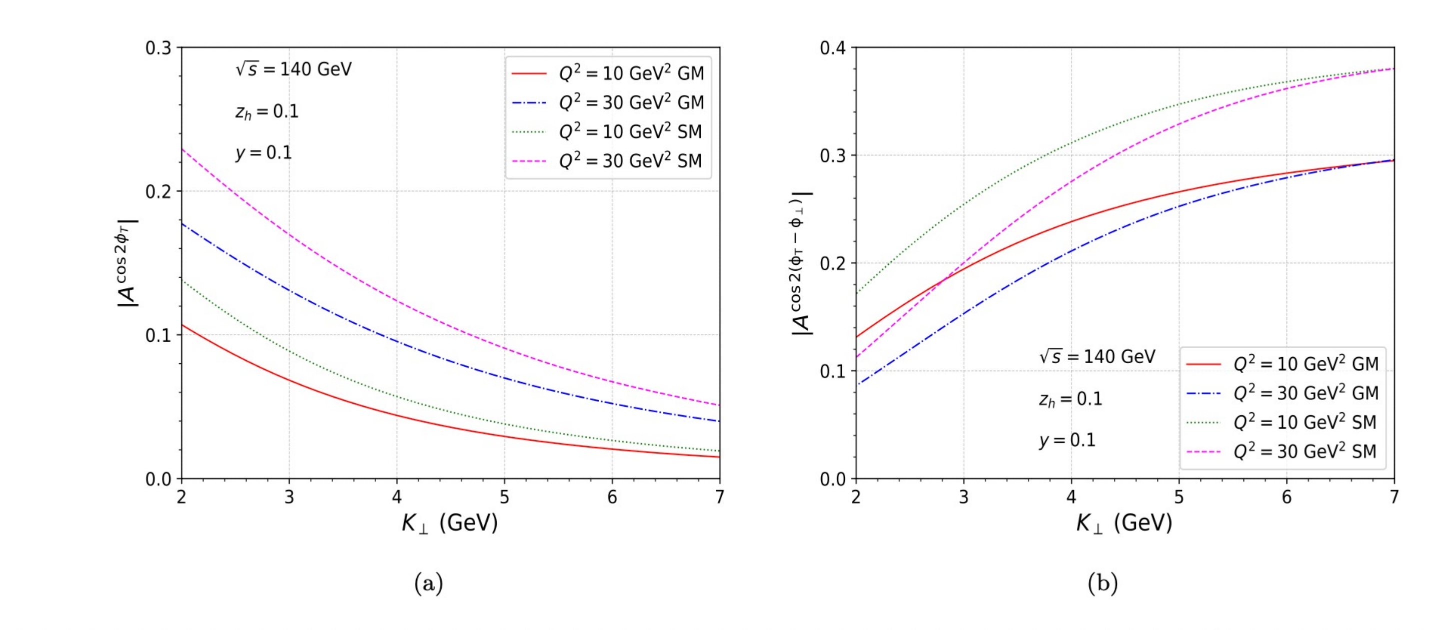
(a) LDMEs from K.T. Chao et al, Phys. Rev. Lett. 108, 242004 (2012).

(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

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

J/Ψ AND PION PRODUCTION



Fragmentation of the outgoing gluon into pion

Spectator model for gluon TMDs

D. Chakrabarti, P. Choudhary, B. Gurjar, R. Kishore, T. Maji, C. Mondal, and AM Phys. Rev. D 108, 014009 (2023)

Treated fragmentation as collinear

Comparison of Gaussian parametrization and Spectator model for the $A_{\cos 2\phi T}$ (left panel) and $A_{\cos 2(\phi T - \phi \perp)}$ (right panel) azimuthal asymmetries are shown as functions of $K_\perp$ in the process ep → e+J/ψ+π+X . Integration of kinematic variables z and q_T occurs over the intervals [0,1] and $0.3 < z_1 < 0.9$, $0.1 < z_2 < 0.9$, respectively.

Khatiza Sheikh, Amol Pawar, AM, Sangem Rajesh, work in progress

SUMMARY AND CONCLUSION

Upcoming EIC can probe the nucleons in three dimensions in terms of TMDs. In particular gluon TMDs can be probed in J/ψ production processes.

Discussed theoretical estimates of azimuthal asymmetries in back-to-back production of J/ψ –photon, J/ψ-jet and J/ψ-pion production 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.

In J/ψ-jet production, significant contribution to cos 2ϕ asymmetry in NRQCD, smaller in CSM. Also considered effect of TMD evolution. The asymmetry is also sizable if one observes back-to-back J/ψ-pion.

Asymmetry depends on LDME sets chosen, as well as the parametrization of gluon TMDs.