LINEARLY POLARIZED GLUON DISTRIBUTION IN J/ψ AND J/ψ PLUS JET PRODUCTION AT EIC

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PLAN OF THE TALK

TMD gluon distributions

Linearly polarized gluon distributions

Probing linearly polarized gluon distribution in J/Ψ production in ep collision

Cos 2 ϕ asymmetry

Numerical results

Ongoing work on J/Ψ and jet

Summary and conclusion

GLUON TMDS

Very little known about gluon TMDs, satisfy positivity bound

Unpolarized gluon TMDs have been extracted from LHCb data

Lansberg, Pisano, Scarpa, Schlegel, PLB 784, 217 (2018)

Like quark TMDs, gluon TMDpdfs are process dependent due to the presence of gauge links.
Each gluon TMD contains two gauge links : process dependence more involved than quark TMDs

Simplest possible configurations are ++ or - - and +- or -+

In the literature related to small-x physics, these are known as Weizsacker-Williams (WW) and Dipole distributions, respectively

Kovchegov and Mueller, Nucl. Phys. B 529, 451 (1998)
McLerran and Venugopalan, PRD 59, 094002 (1999)
Dominguez, Qiu, Xiao, Yuan, PRD 85, 045003 (2012)
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LINEARLY POLARIZED GLUON DISTRIBUTIONS

Unpolarized WW gluon distributions can be interpreted as number density of gluons in a nucleon in light cone gauge; can be accessed in processes for example in dijet production in DIS
Dipole distributions are the Fourier transform of color dipole amplitudes and appear in many processes for example in photon-jet and dijet production in pA collision

Operator structure of these two unintegrated gluon distributions are different : studied extensively in the literature

Linearly polarized gluon distributions were first introduced in

Mulders and Rodrigues, PRD 63, 094021 (2001)

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

LINEARLY POLARIZED GLUON DISTRIBUTION

T-even; can be WW type or dipole type depending on gauge link

Has not been extracted from data yet, although a lot of theoretical studies has been done

Can be probed in dijet imbalance in unpolarized hadronic collision; heavy quark pair production in ep and pp collision , Quarkonium pair production in pp collision Associated production of dilepton and J/Ψ

eA collision: dijet imbalance; Transverse momentum distribution of Higgs boson and heavy quarkonium in unpolarized pp collision

J/Ψ production and back to back production of J/Ψ and a jet in ep collision

An incomplete list of references :

Lansberg, Pisano, Scarpa, Schlegel (2018) Lansberg, Pisano, Schlegel (2017) Dumitru, Skokov, Ulrich (2018)

Marquret, Roisnel, Taels (2018); Pisano, Boer, Brodsky, Buffing, Mulders (2013); Efremov, Evanov, Teryaev (2018)

Sun, Xiao, Yuan (2011); Boer, Dunnen, Pisano, Schlegel, Vogelsang (2012); Boer and Pisano (2012); AM and Rajesh (2016,2017), AM and Kishore (2019); D'Alesio, Murgia, Pisano, Taels (2019); Bacchetta, Boer, Pisano, Taels (2020); Boer, D'Alesio, Murgia, Pisano, Taels (2020).

LINEARLY POLARIZED GLUON DISTRIBUTION IN J/Ψ PRODUCTION

Initial and final state interaction may affect the generalized factorization. Such effects are less complicated in ep collision compared to pp and pA collision

J/Ψ production in ep collision probes $h_{1g}^{\perp}$ through the LO process $\gamma^* + g \to c + \bar{c}$

AM and Rajesh, EPJC 77, 854 (2017)

Contributes at z=1, where z is the energy fraction of the photon carried by J/Ψ in the proton rest frame

Extended to the region z<1 keeping only CS contributions Kishore and AM, PRD (2019)

Also included CO contributions in NRQCD Kishore, AM, Siddiqah 2103.09070 [hep-ph]

Investigated gluon distributions at small x (gluon contribution dominant)

Basic assumption : factorization of amplitude into a hard part with the heavy quark pair produced in the process $\gamma^* + g \to c + \bar{c} + g$

Heavy quark pair then hadronizes to form J/Ψ. Hadronization is described in terms of long distance matrix elements (LDMEs).

LINEARLY POLARIZED GLUON DISTRIBUTION IN J/Ψ PRODUCTION

LDMEs have scaling property wrt the velocity parameter v (small)

Cross section is expressed as a double expansion in terms of α_s and v. For J/Ψ $v \approx 0.3$

In NRQCD, the heavy quark pair in the hard process can be produced in color singlet (CS) state or in color octet (CO) state

With the assumption of generalized TMD factorization it was shown that low p_T RHIC data can be reasonably described by NRQCD based CS model; although high p_T data needs inclusion of CO states

D'Alesio, Murgia, Pisano, Taels, PRD 036011 (2017)

Both CS and CO states are needed to describe the HERA data

Rajesh, Kishore, AM, PRD 98, 014007 (2018)

J/Ψ PRODUCTION IN EP COLLISION

We present a calculation of cos 2ϕ asymmetry in the process $e(l) + p(P) \rightarrow e(l') + J/\psi(P_h) + X$

In the kinematical region z < 1 in NRQCD, took into account both CS and CO contributions

The corresponding hard process is $\gamma^* + g \rightarrow c + \bar{c} + g$ Final state gluon not detected

$z = P \cdot P_h / P \cdot q$ energy fraction of J/Ψ in rest frame of proton

$$q = l - l'; Q^2 = -q^2; s = (l+P)^2 \qquad Q^2 = s x_B y; \quad x_B = \frac{Q^2}{2P \cdot q}; \quad y = P \cdot q / P \cdot l$$

Incoming and outgoing leptons form the lepton plane. Azimuthal angles are measured wrt this plane

We use a framework based on generalized parton model approach with the inclusion of intrinsic transverse momentum effects, and assume TMD factorization.

J/Ψ PRODUCTION IN EP COLLISION

Diff. cross section

$$d\sigma = \frac{1}{2s}\frac{d^3l'}{(2\pi)^3 2E_{l'}}\frac{d^3P_h}{(2\pi)^3 2E_{P_h}}\int\frac{d^3p_g}{(2\pi)^3 2E_g}\int dx d^2k_\perp (2\pi)^4\delta(q+k-P_h-p_g)$$
$$\times\frac{1}{Q^4}L^{\mu\mu'}(l,q)\Phi^{\nu\nu'}(x,k_\perp)\mathcal{M}_{\mu\nu}^{\gamma^*+g\to J/\psi+g}\mathcal{M}_{\mu'\nu'}^{*\gamma^*+g\to J/\psi+g}$$

Leptonic tensor $$L^{\mu\mu'}(l,q) = e^2(-g^{\mu\mu'}Q^2 + 2(l^\mu l'^{\mu'} + l^{\mu'}l'^{\mu}))$$

Gluon correlator for unpolarized hadron

$$\phi_g^{\nu\nu'}(x,\mathbf{k}_\perp) = \frac{1}{2x}[-g_\perp^{\nu\nu'}f_1^g(x,\mathbf{k}_\perp^2) + (\frac{k_\perp^\nu k_\perp^{\nu'}}{M_p^2} + g_\perp^{\nu\nu'}\frac{\mathbf{k}_\perp^2}{2M_p^2})h_1^{\perp g}(x,\mathbf{k}_\perp^2)]$$

↑ Unpol. gluon distribution

↑ Linearly polarized gluon distribution

$$g_\perp^{\nu\nu'} = g^{\nu\nu'} - P^\nu n^{\nu'}/P\cdot n - P^{\nu'}n^\nu/P\cdot n$$

FEYNMAN DIAGRAMS CONTRIBUTING

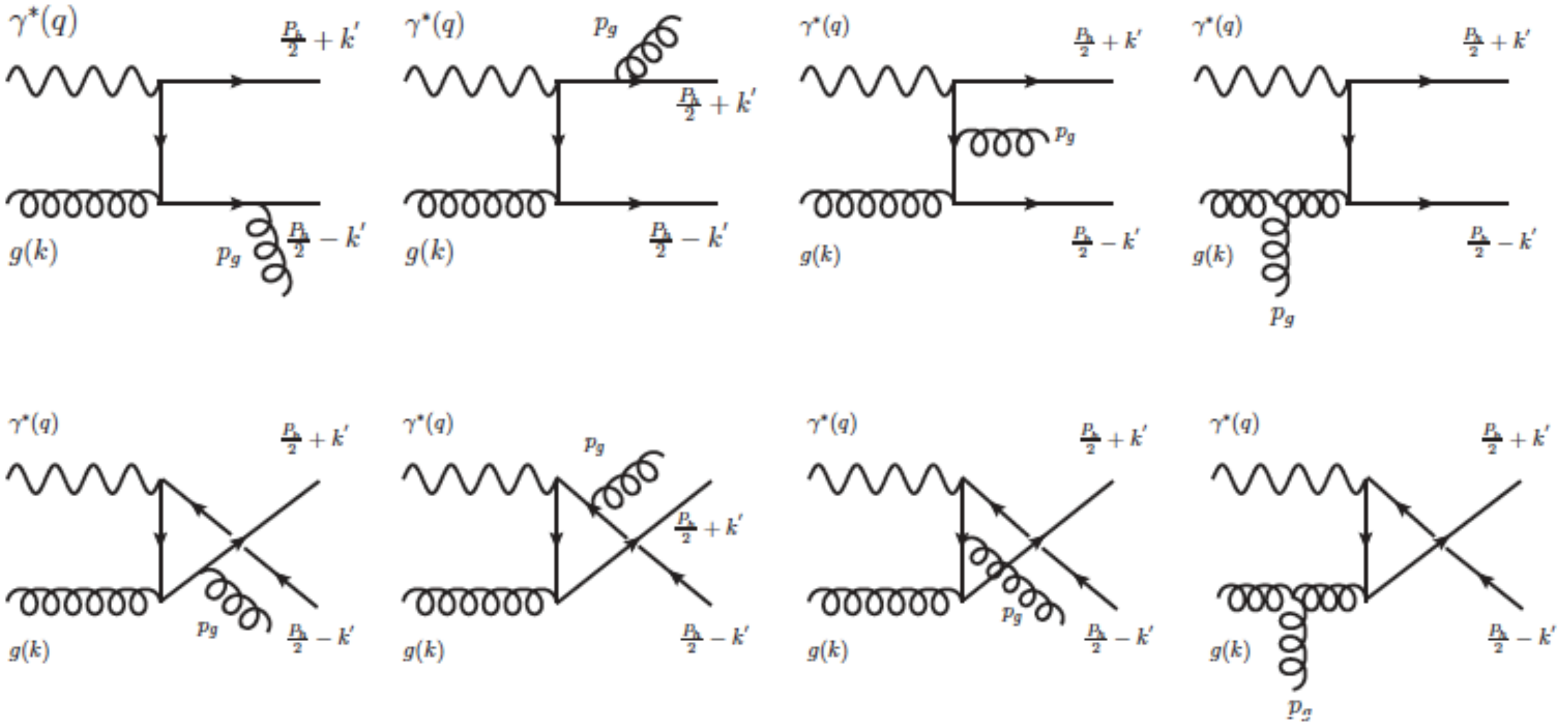

FIG. 1. Feynman diagrams for the partonic subprocess $\gamma^* + g \to J/\psi + g$.

CALCULATION OF THE AMPLITUDE

Virtual diagrams not there, cutoff z< 0.9

Approach of Boer and Pisano, PRD (2012)

The amplitude can be written as,

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

The operators $O(q,k,P_h,k')$ are calculated from the Feynman diagrams

$$O(q,k,P_h,k') = \sum_{m=1}^{8} \mathcal{C}_m O_m(q,k,P_h,k').$$

$\mathcal{P}_{SS_z}(P_h,k')$ Is the projection operator that projects the spin triplet and singlet states

$$\mathcal{P}_{SS_z}(P_h,k') = \sum_{s_1 s_2} \langle \frac{1}{2}s_1; \frac{1}{2}s_2 | SS_z \rangle v(\frac{P_h}{2} - k', s_1) \bar{u}(\frac{P_h}{2} + k', s_2)$$
$$= \frac{1}{4M^{3/2}} (-\not{P}_h + 2\not{k}' + M) \Pi_{SS_z} (\not{P}_h + 2\not{k}' + M) + \mathcal{O}(k'^2)$$

Generic structure of the TMD cross section

$$L^{\mu\mu'}(l,q) \Phi^{\nu\nu'}(x,\boldsymbol{k}_\perp) \mathcal{M}_{\mu\nu}^{\gamma^*+g\to J/\psi+g} \mathcal{M}_{\mu'\nu'}^{*\gamma^*+g\to J/\psi+g}$$

CALCULATION OF THE AMPLITUDE

$$\mathcal{M}[^3S_1^{(8)}](P_h,k) = \frac{1}{4\sqrt{\pi M}} R_0(0) \frac{\sqrt{2}}{2} d_{abc} \mathrm{Tr}\left[\sum_{m=1}^{3} O_m(0)(-\not{P}_h + M)\not{\epsilon}_{s_z}\right],$$

$$k' << P_h$$

Amplitude expanded in Taylor series about k'=0

$$\mathcal{M}[^1S_0^{(8)}](P_h,k) = \frac{R_0(0)}{4\sqrt{\pi M}} \frac{\sqrt{2}}{2} i f_{abc} \mathrm{Tr}\left[(O_1(0) - O_2(0) - O_3(0) + 2O_4(0))(-\not{P}_h + M)\gamma^5\right]$$

$$\mathcal{M}[^3P_J^{(8)}](P_h,k) = \frac{\sqrt{2}}{2} f_{abc} \sqrt{\frac{3}{4\pi}} R_1'(0) \sum_{L_z S_z} \varepsilon^{\alpha}_{L_z}(P_h) \langle 1L_z; 1S_z | JJ_z \rangle$$
$$\mathrm{Tr}\Big[(O_{1\alpha}(0) - O_{2\alpha}(0) - O_{3\alpha}(0) + 2O_{4\alpha}(0)) \mathcal{P}_{SS_z}(0)$$
$$+ (O_1(0) - O_2(0) - O_3(0) + 2O_4(0)) \mathcal{P}_{SS_z\alpha}(0) \Big].$$

$$O(0) = O(q,k,P_h,k')\Big|_{k'=0}, \qquad \mathcal{P}_{SS_z}(0) = \mathcal{P}_{SS_z}(P_h,k')\Big|_{k'=0}$$

$$\langle 0|\mathcal{O}_1^{J/\psi}(^{2S+1}S_J)|0\rangle = \frac{N_c}{2\pi}(2J+1)|R_0(0)|^2,$$

$$\langle 0|\mathcal{O}_8^{J/\psi}(^{2S+1}S_J)|0\rangle = \frac{2}{\pi}(2J+1)|R_0(0)|^2,$$

$$\langle 0|\mathcal{O}_8^{J/\psi}(^3P_J)|0\rangle = \frac{2N_c}{\pi}(2J+1)|R_1'(0)|^2.$$

First term in the expansion gives the S wave states (L=0, J=0,1). Terms linear in k' give the P wave states (L=1, J=0,1,2).

CALCULATION OF THE ASYMMETRY

* We use a framework based on generalized parton model with the inclusion of intrinsic transverse momentum

* Keep terms upto $\mathcal{O}(P_{h\perp}^2/M^2)$. M is the mass of J/Ψ

* Impose cutoff z < 0.9 to keep outgoing gluon hard ,
  Upper limit on $P_{h\perp}$ reduces fragmentation contribution from heavy quark

* 0.3 < z to eliminate fragmentation of hard gluon into J/Ψ

Final expression of the diff cross section

$$\frac{d\sigma}{dy\,dx_B\,dz\,d^2\mathbf{P}_{h\perp}} = \frac{1}{256\pi^4}\frac{1}{x_B^2 s^3 y^2 z(1-z)}\int k_\perp dk_\perp |\, M' \,|^2$$

$$|\, M' \,|^2 = \int d\phi |\, M \,|^2,$$

We are interested in small x, we neglect terms with higher powers of x_B

When CO contributions are included contribution come from all the diagrams

CALCULATION OF THE ASYMMETRY

With only CS, contributions came only from one Feynman diagram in the numerator and it was possible to disentangle linearly polarized gluon distribution from the unpolarized distribution in the asymmetry.

R. Kishore and AM; PRD 99 (2019), no. 5, 054012

$$\langle cos(2\phi_h)\rangle = \frac{\int d\phi_h cos(2\phi_h) d\sigma}{\int d\phi_h d\sigma}$$

Including the CO contributions in NRQCD, the asymmetry is of the form

$$\langle cos(2\phi_h)\rangle \propto \frac{\int k_\perp dk_\perp \left(A_2\ f_1^g(x,\mathbf{k}_\perp^2) + \frac{k_\perp^2}{M_p^2}\ B_2\ h_1^{\perp g}(x,\mathbf{k}_\perp^2)\right)}{\int k_\perp dk_\perp \left(A_0\ f_1^g(x,\mathbf{k}_\perp^2) + \frac{k_\perp^2}{M_p^2}\ B_0\ h_1^{\perp g}(x,\mathbf{k}_\perp^2)\right)}.$$

Kishore, AM, Siddiqah 2103.09070 [hep-ph]

Analytic expressions of the coefficients are too lengthy to be given here.

PARAMETRIZATION OF THE TMDS

Linearly polarized gluon distribution satisfies the positivity bound

Upper limit of asymmetry obtained when this bound is saturated

$$\frac{\mathbf{k}_\perp^2}{2M_p^2}\left|h_1^{\perp g}(x,\mathbf{k}_\perp^2)\right| \leq f_1^g(x,\mathbf{k}_\perp^2)$$

Gaussian parametrization satisfy positivity bound but does not saturate it

Boer and Pisano (2012)

$$f_1^g(x,\mathbf{k}_\perp^2) = f_1^g(x,\mu)\frac{1}{\pi\langle k_\perp^2\rangle}e^{-k_\perp^2/\langle k_\perp^2\rangle}$$

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

We took r=1/3 $\langle k_\perp^2\rangle = 0.25\ \mathrm{GeV}^2.$

In small x region the WW gluon distributions are calculated in McLerran-Venugopalan (MV) model

$S_\perp$ is the transverse size of the proton

Q_{sg} Is the saturation scale

$$f_1^g(x,\mathbf{k}_\perp^2) = \frac{S_\perp C_F}{\alpha_s\pi^3}\int dr\frac{J_0(k_\perp r)}{r}\left(1-e^{-\frac{r^2}{4}Q_{sg}^2(r)}\right)$$

$$h_1^{\perp g}(x,\mathbf{k}_\perp^2) = \frac{S_\perp C_F}{\alpha_s\pi^3}\frac{2M_p^2}{k_\perp^2}\int dr\frac{J_2(k_\perp r)}{r\log(\frac{1}{r^2\Lambda_{QCD}^2})}\left(1-e^{-\frac{r^2}{4}Q_{sg}^2(r)}\right)$$

$$Q_{sg}^2 = \alpha_s N_c \mu_A \ln\frac{1}{r^2\Lambda_{QCD}^2} \qquad \mu_A S_\perp = \alpha_s 2\pi A.$$

For proton A=1

McLerran and Venugopalan, PRD (1994)

PARAMETRIZATION OF THE TMDS

MV model calculation for WW gluon distributions in small x region : for large nucleus or energetic proton

We use a regulated version of MV model

Bacchetta, Boer, Pisano, Taels (2018)

$$\frac{\mathbf{k}_\perp^2}{2M_p^2}\frac{h_1^{\perp g}(x,\mathbf{k}_\perp^2)}{f_1^g(x,\mathbf{k}_\perp^2)} = \frac{\int dr \frac{J_2(k_\perp r)}{r\log(\frac{1}{r^2\Lambda_{QCD}^2})}\left(1-e^{-\frac{r^2}{4}Q_{sg0}^2\log(\frac{1}{r^2\Lambda_{QCD}^2})}\right)}{\int dr \frac{J_0(k_\perp r)}{r}\left(1-e^{-\frac{r^2}{4}Q_{sg0}^2\log(\frac{1}{r^2\Lambda_{QCD}^2})}\right)}$$

A regulator is added to the exponent and the log for numerical convergence

$Q_{sg0}^2 = (N_c/C_F)\times Q_{s0}^2$; $Q_{s0}^2 = 0.35\ \mathrm{GeV}^2$ at $x = 0.01$ and $\Lambda_{QCD} = 0.2\ \mathrm{GeV}$

From the fits to HERA data

The ratio is less than 1 for all values of transverse momentum

PARAMETRIZATION OF THE TMDS

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From the fits to HERA data

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NUMERICAL RESULTS

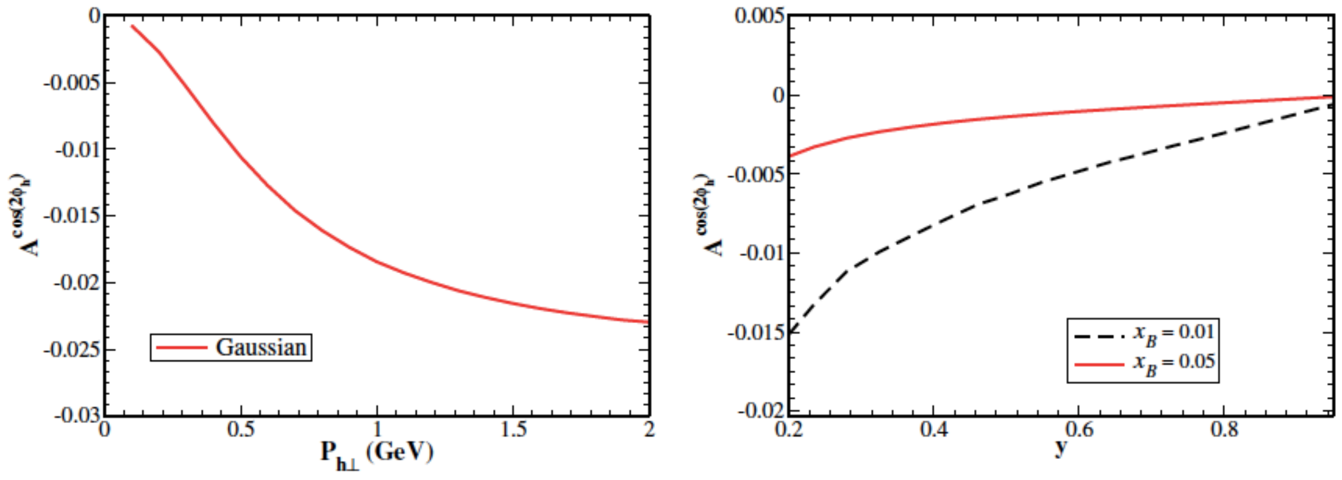

FIG. 2. $cos(2\phi_h)$ asymmetry in $e + p \to e + J/\psi + X$ process. Left: As a function of $P_{h\perp}$ at $\sqrt{s} = 100$ GeV and $Q^2 = 15$ GeV^2. The integration ranges are $0.0015 < x_B < 0.1$, $0.1 < z < 0.9$ and y is set by the values of Q^2, s and x_B. Right: As a function of y at $\sqrt{s} = 120$ GeV and at fixed x_B. The integration ranges are $0 < P_{h\perp} < 2$, $0.1 < z < 0.9$. For both plots CMSWZ set of LDMEs [48] is used.

LDME set : PRL 108,242004 (2012)

Asymmetry calculated using Gaussian parametrization

Included both CS and CO contributions

Negative asymmetry consistent with LO calculations

Kishore, AM, Siddiqah 2103.09070 [hep-ph]

NUMERICAL RESULTS

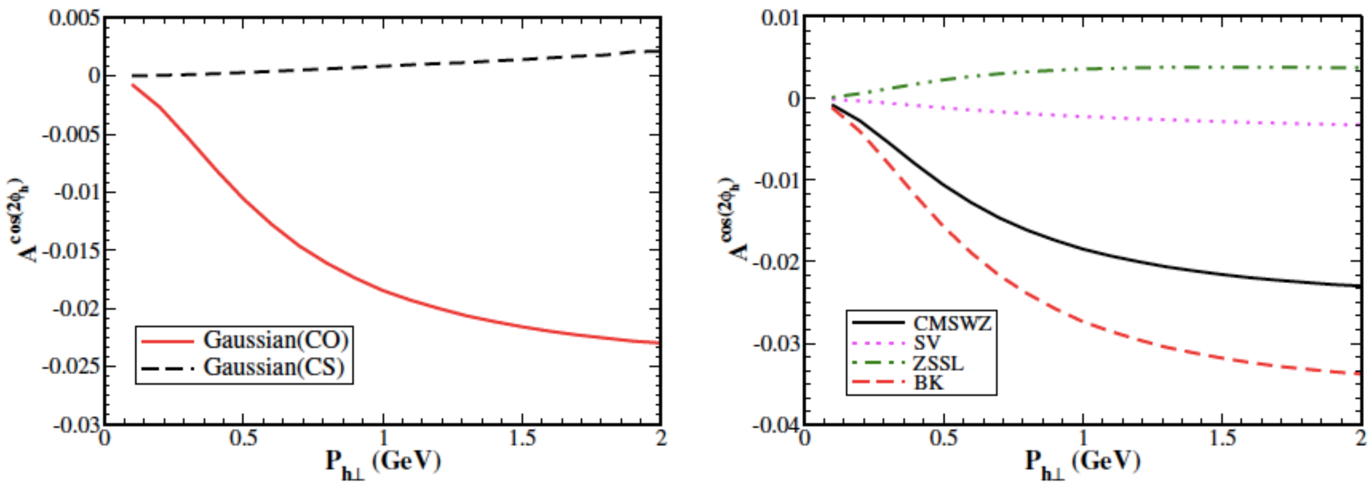

FIG. 3. $cos(2\phi_h)$ asymmetry in $e + p \to e + J/\psi + X$ process as function of $P_{h\perp}$ at $\sqrt{s} = 100$ GeV and $Q^2 = 15$ GeV^2. The integration ranges are $0.0015 < x_B < 0.1$, $0.1 < z < 0.9$ and y is set by the values of Q^2, s and x_B. Left: contributions from color singlet and color octet states using the LDMEs set CMSWZ [48]. Right: comparing the asymmetry for different LDMEs sets: CMSWZ [48], SV [59], ZSSL [60], BK [61].

CMSWZ : PRL 108,242004 (2012)

SV : PRC 87, 044905 (2013)

ZSSL : PRL 114, 092006 (2015)

BK : PRD 84, 051501 (2011).

CO states contribute significantly

Asymmetry depends on the set of LDMEs used

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CONTRIBUTION FROM DIFFERENT STATES

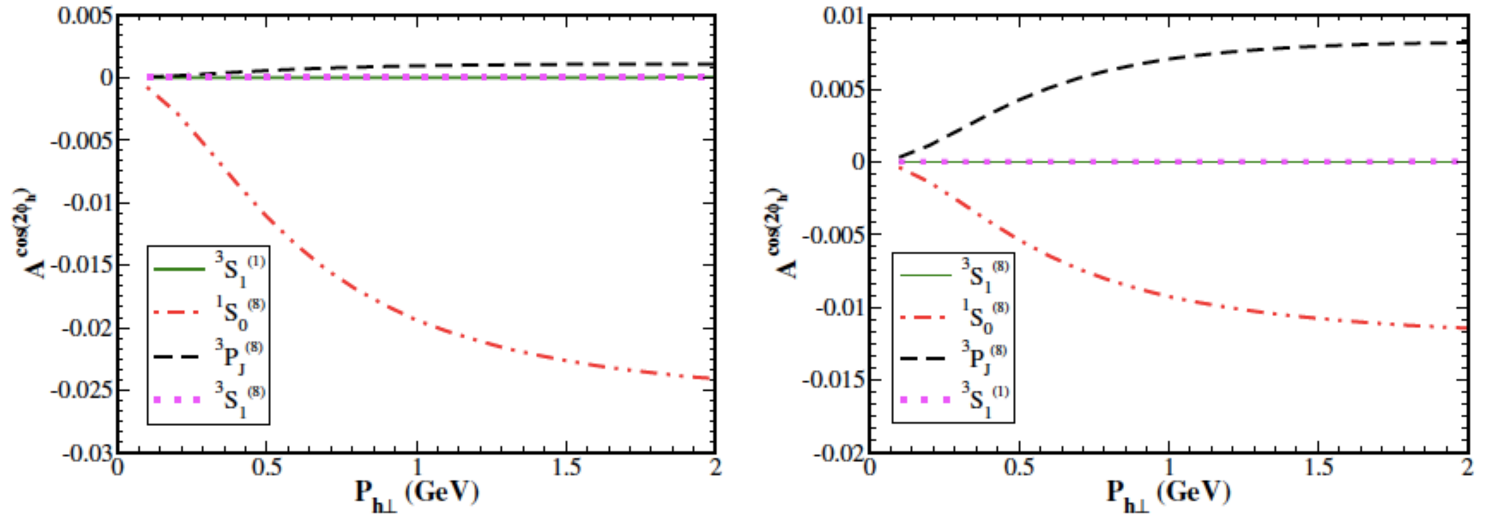


FIG. 4. $cos(2\phi_h)$ asymmetry in $e + p \to e + J/\psi + X$ process as function of $P_{h\perp}$ at $\sqrt{s} = 100$ GeV and $Q^2 = 15$ GeV^2. The integration ranges are $0.0015 < x_B < 0.1$, $0.1 < z < 0.9$ and y is set by the values of Q^2, s and x_B. Left: asymmetry for the set of LDMEs, CMSWZ [48]. Right: asymmetry for the set of LDMEs SV [59]

Different states contribute in. a different way depending on set of LDME

In CMSWZ dominating contribution comes from $^1S_0^{(8)}$ state

In SV set two states give approximately equal contribution, one positive and one negative, to the asymmetry

Kishore, AM, Siddiqah 2103.09070 [hep-ph]

PARAMETER DEPENDENCE

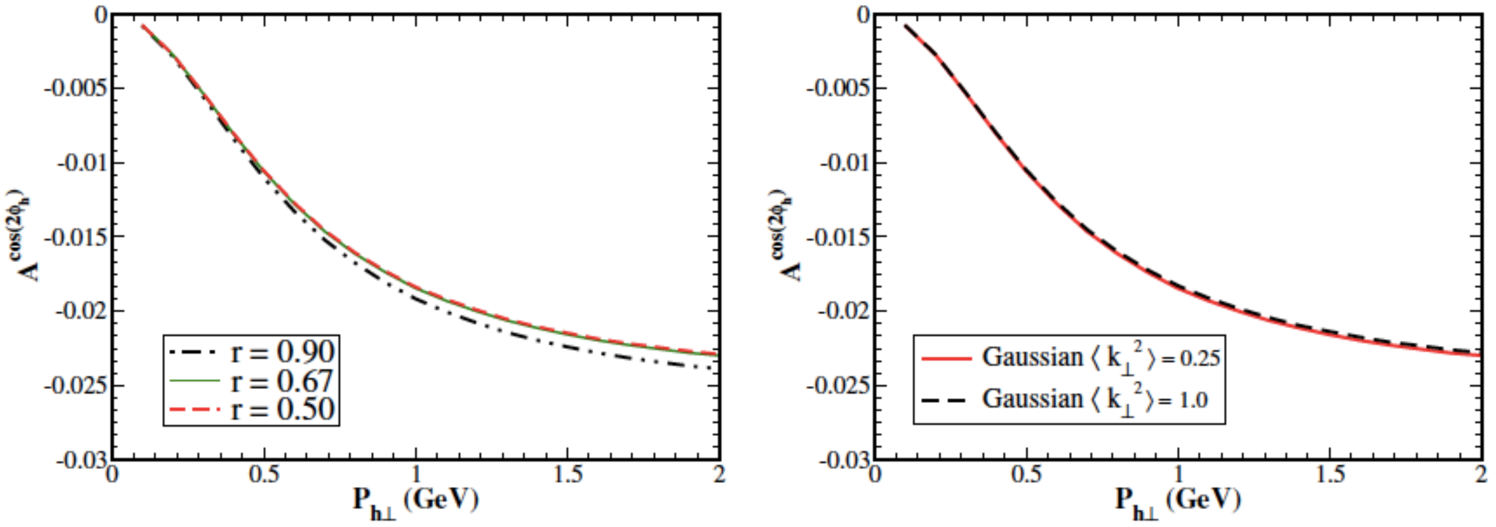


FIG. 5. $cos(2\phi_h)$ asymmetry in $e+p \to e+J/\psi+X$ process as function of $P_{h\perp}$ at $\sqrt{s} = 100$ GeV and $Q^2 = 15$ GeV^2. The integration ranges are $0.0015 < x_B < 0.1$, $0.1 < z < 0.9$ and y is set by the values of Q^2, s and x_B. Left: asymmetry for three different values of r. Right: asymmetry for two different values of Gaussian width parameter. For both plots CMSWZ set of LDMEs [48] is used.

Kishore, AM, Siddiqah 2103.09070 [hep-ph]

ASYMMETRY IN MV MODEL

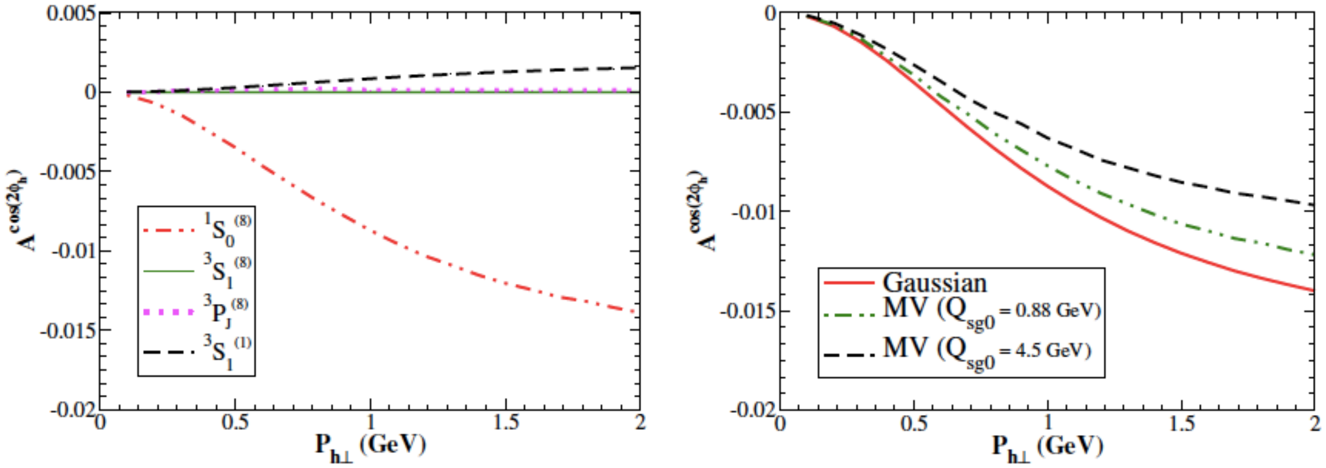


FIG. 6. $cos(2\phi_h)$ asymmetry in $e + p \to e + J/\psi + X$ process as function of $P_{h\perp}$ at $\sqrt{s} = 150$ GeV, $x = 0.01$ and $z = 0.7$. Left: contribution to the $cos(2\phi)$ asymmetry coming from the individual states, as a function of $P_{h\perp}$ in the NRQCD framework using color octet model. Right: comparison of the Gaussian and MV model (with two different values of Q_{sg0}). For both plots, CMSWZ set of LDMEs [48] is used.

Saturation scale at $x=x_0=0.01$

$$Q_{s0}^2 = 0.35 \text{ GeV}^2$$

Regulated version of MV model

Bacchetta, Boer, Pisano, Taels (2018)

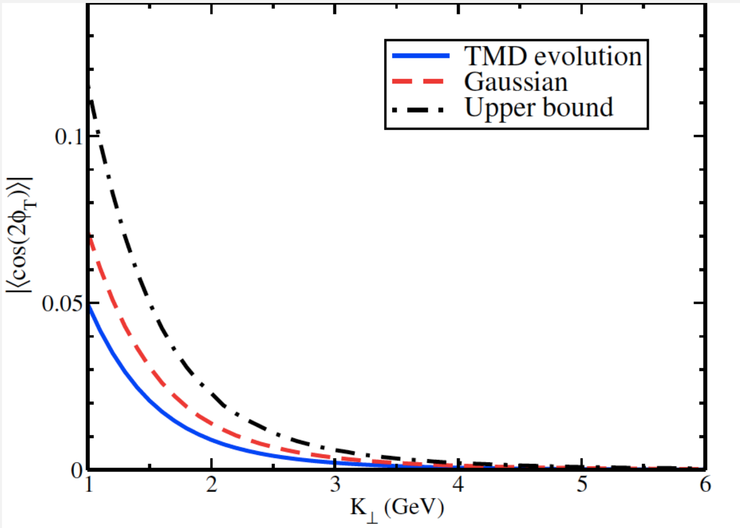
Integration range 0.2<y<0.9

Showed contribution from different states

Gaussian parametrization gives larger asymmetry

Kishore, AM, Siddiqah 2103.09070 [hep-ph]

COS(2ϕ) ASYMMETRY IN BACK-TO-BACK PRODUCTION OF J/Ψ AND A JET (PRELIMINARY)



Total transverse momentum of the J/Ψ and jet smaller than the invariant mass

Relative transverse momentum large (back-to-back) : asymmetry can be accessed at a range of scales by varying the invariant mass of the pair

Upper bound of the asymmetry as well as calculations at small x

D'Alesio, Murgia, Pisano, Taels PRD 100, 094016 (2019)

We present results using Gaussian parametrization and incorporating TMD evolution of gluon TMDs : only CS contributions included : asymmetry large

Work under progress : asymmetry using the parametrization in Bacchetta, Celiberto, Radici, Taels EPJC 2020

SUMMARY AND CONCLUSION

A calculation of Cos 2 ϕ asymmetry in J/Ψ production in eP collision is presented in NRQCD

Both CS and CO contributions included, can probe ratio of linearly polarized gluon distribution and unpolarized distribution in small x kinematics .
Negative asymmetry consistent with LO estimate

AM and Rajesh, EPJC (2017)

Asymmetry depends on the parametrization of the gluon TMDs : we presented results for Gaussian parametrization and MV model at small x

Asymmetry depends significantly on the choice of LDMEs : can help to shed light on the LDMEs ?

Cos 2 ϕ asymmetry in back-to-back production of J/Ψ and jet: upper limit large even with only CS contributions

Gaussian parametrization of TMDs, also included TMD evolution. Good channel to probe linearly polarized gluon TMDs at EIC.