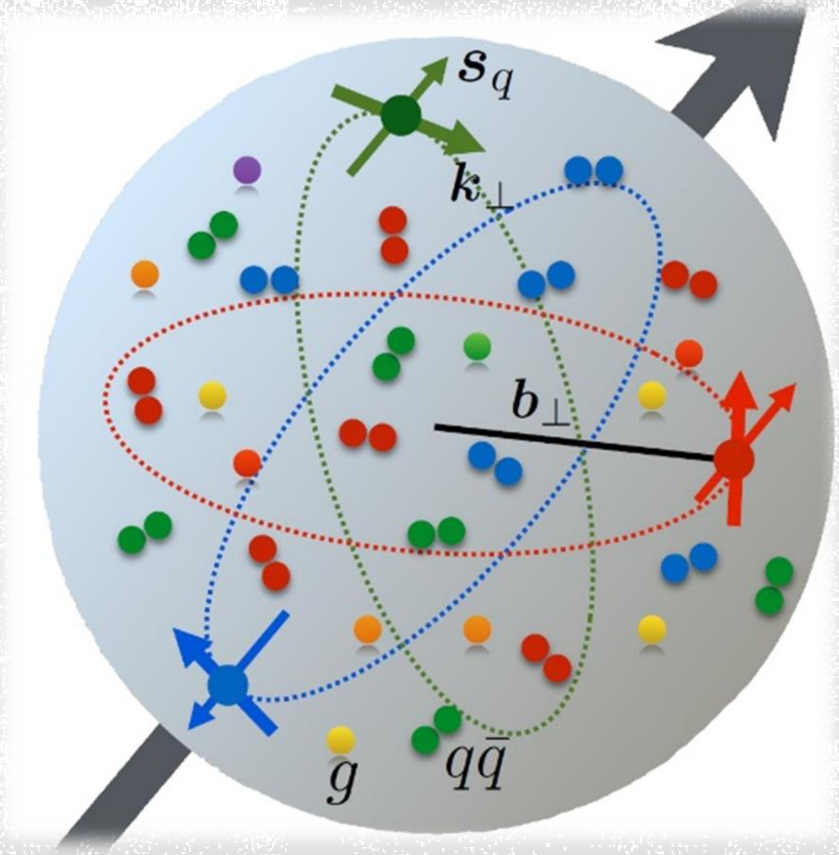

AZIMUTHAL ASYMMETRY IN J/ψ PRODUCTION IN ELECTRON-PROTON COLLISION AT EIC

The 3-D nucleon structure in momentum space is still not known yet!

Parton intrinsic transverse momentum?

Spin and $k_\perp$ correlations?

Angular momentum of partons?

Spatial distribution?

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HRZZ Croatian Science Foundation

ACHT-2023 Workshop
27-29 September, Leibnitz

PLAN OF TALK

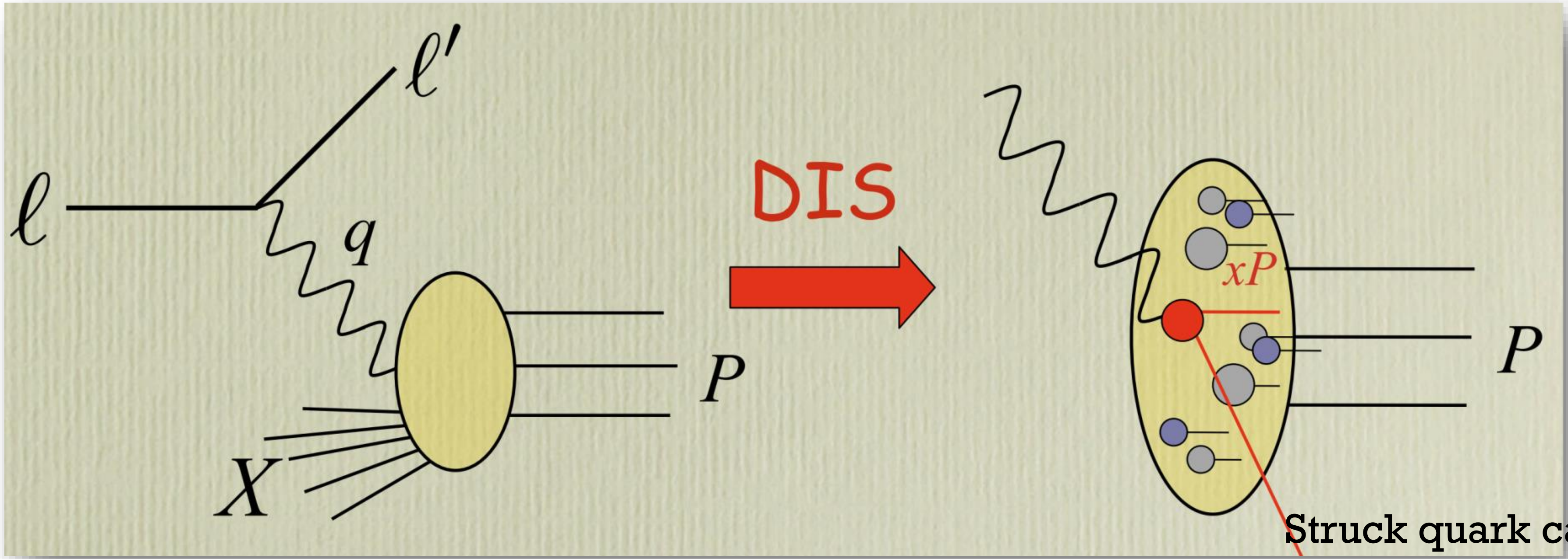
Parton Distribution function: PDFs, TMDs (Gluon TMDs)

Azimuthal asymmetries in $J/\psi - jet$ and $J/\psi - \gamma$ pair production in ep scattering at EIC

Numerical estimates

Conclusion

DIS process: usual way of exploring the proton structure



Struck quark carry a momenta fraction "x"

Scale: $Q^2 = -q^2$

Naïve parton model: $d\sigma^{lp\to l'X} = \sum_q f_q(x) \otimes d\sigma^{lq\to l'q}$

Within the Parton model of nucleons we defined parton distribution functions (PDFs).

- Collinear parton distribution functions, $f_a(x, Q^2)$, gives the number density of partons with momentum fraction x and that depends on scale Q^2 , gives the 1-D picture of a nucleon.

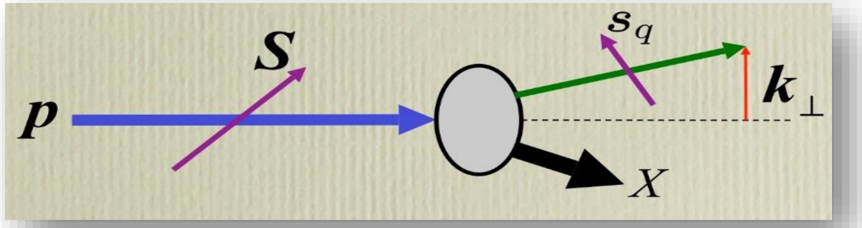
Transverse momentum-dependent distribution and fragmentation functions

- Introducing a new concept: Transverse momentum dependent, distribution functions (TMD-PDFs) and fragmentation functions (TMD-FFs).

- TMD-PDFs (Transverse Momentum Dependent Parton Distribution Functions): $f(x, k_\perp, Q^2)$ gives the number density of partons , with their intrinsic transverse motion and spin, inside a nucleon.

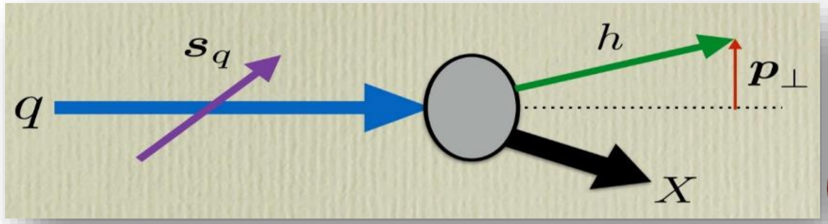
$\boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp)$: **Sivers effect**

$\boldsymbol{s}_q \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp)$: **Boer-Mulders effect**



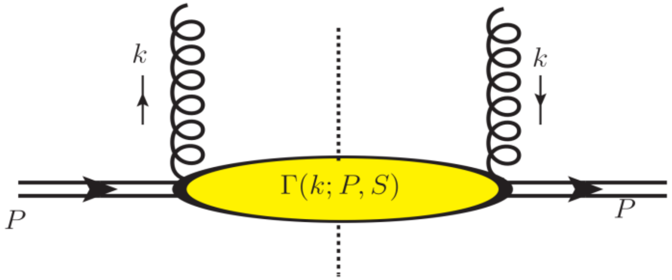
- TMD-FFs (Transverse Momentum Dependent Fragmentation Functions): $D(z, p_\perp)$ gives the number density of hadrons , with their momentum, originated in the fragmentation of a parton.

$\boldsymbol{s}_q \cdot (\boldsymbol{p}_q \times \boldsymbol{p}_\perp)$: **Collins effect**



Gluon TMDs

❑ Gluon-gluon correlator at leading twist



Gluon field tensor

$$\Gamma^{+i;+j}(x,\boldsymbol{k}_T;P,S)=\int\frac{d\xi^- d^2\xi_\perp}{(2\pi)^3}e^{ik\cdot\xi}\langle P,S|\mathrm{Tr}[F^{+i}(0)W_{[0,\xi]}F^{+j}(\xi)W_{[\xi,0]}]|P,S\rangle_{|\xi^+=0}$$

Gauge links

$$W_{[0,\xi]}=\mathcal{P}\exp\left(-\iota g\int_0^{\xi}dz_\mu A^\mu(z)\right)$$

- Parameterizations: for the unpolarized (U) and transversely polarized (T) target

$$\Gamma_U^{ij}(x,\boldsymbol{k}_T^2)=\frac{x}{2}\left\{-g_T^{ij}f_1^g(x,\boldsymbol{k}_T^2)+\left(\frac{k_T^i k_T^j}{M_P^2}+g_T^{ij}\frac{\boldsymbol{k}_T^2}{2M_P^2}\right)h_1^{\perp g}(x,\boldsymbol{k}_T^2)\right\}$$

$$\Gamma_T^{ij}(x,\boldsymbol{k}_T^2)=\frac{x}{2}\left\{-g_T^{ij}\frac{\epsilon_T^{\rho\sigma}k_{T\rho}S_{T\sigma}}{M_p}f_{1T}^{\perp g}(x,\boldsymbol{k}_T^2)+\dots\right\}$$

Hadron Pol. \ Gluon Polarization	U	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	$h_{1T}^g,\ h_{1T}^{\perp g}$

BOER-MULDERS

KOTZINIAN-MULDERS

SIVERS HELICITY WORM-GEAR PRETZELOSITY

Mulders and Rodrigues PRD 63 094021(2001)

GLUON TMDS: (BOER-MULDERS) $h_1^{\perp g}(x,k_T^2)$ AND (GSF) $\Delta^N f_{g/P^\uparrow}(x,k_T^2)$

- Gluon Boer-Mulders function is associated with a symmetric tensor structure

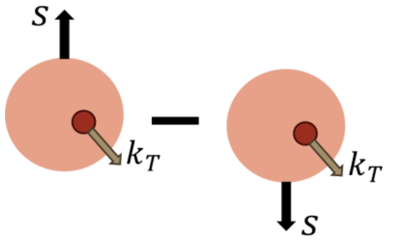
$$\frac{1}{2}\left(\frac{2k_T^i k_T^j}{k_T^2}-\delta^{ij}\right)=\frac{1}{2}\begin{pmatrix} cos2\phi & sin2\phi \\ sin2\phi & -cos2\phi \end{pmatrix}$$

- Interpret $h_1^{\perp g}(x,k_T^2)$ as "azimuthal correlated" gluon distribution function.

- It affects the unpolarized cross section and cause **azimuthal asymmetries**: $\langle\cos(2\phi)\rangle, \langle\cos(4\phi)\rangle$

- GSF describes the number density of unpolarized gluon inside a transversely polarized nucleon.

$$\Delta^N f_{g/P^\uparrow}(x,\boldsymbol{k}_T)=\widehat{f}_g(x,\boldsymbol{k}_T;\boldsymbol{S}_T)-\widehat{f}_g(x,\boldsymbol{k}_T;-\boldsymbol{S}_T)\equiv\Delta^N f_g(x,k_T)(\widehat{\boldsymbol{P}}\times\widehat{\boldsymbol{k}}_T)\cdot\widehat{\boldsymbol{S}}_T$$

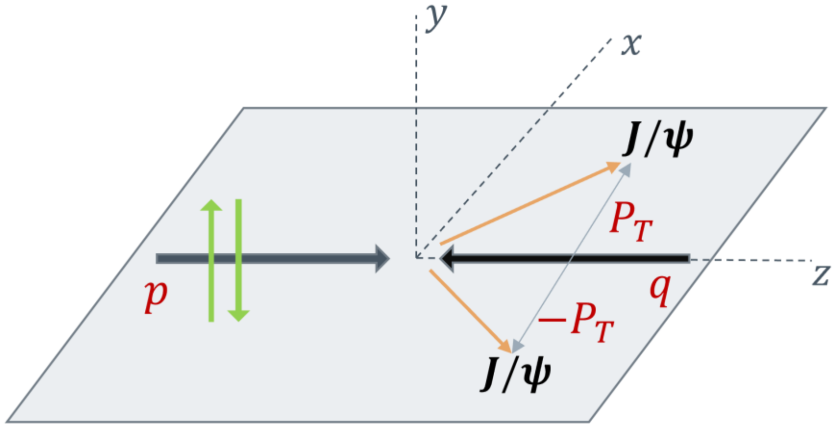


SINGLE SPIN ASYMMETRY (SSA) AND AZIMUTHAL ASYMMETRY

The TMDs can be studied in Drell-Yan (DY) $(pp \to ll')$, semi-inclusive deep inelastic scattering (SIDIS) $(ep \to e'hX)$ and electron-positron $(e^+e^- \to h)$ annihilation processes.

➢ Transverse SSA in a hadronic scattering process: $A + B^{\uparrow} \to C + X$

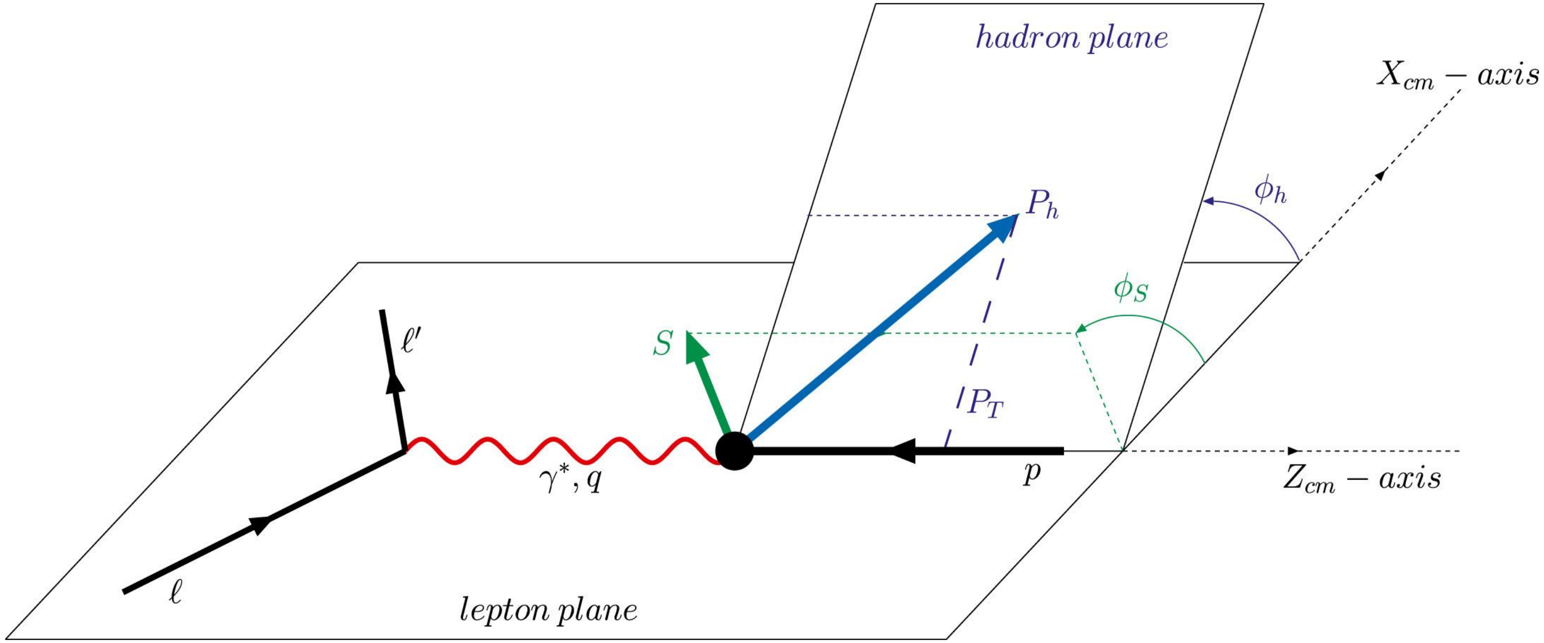
$$A_N = \frac{d\sigma^{\uparrow}(\boldsymbol{P}_T) - d\sigma^{\downarrow}(\boldsymbol{P}_T)}{d\sigma^{\uparrow}(\boldsymbol{P}_T) + d\sigma^{\downarrow}(\boldsymbol{P}_T)} \equiv \frac{d\sigma^{\uparrow}(\boldsymbol{P}_T) - d\sigma^{\uparrow}(-\boldsymbol{P}_T)}{2d\sigma^{\mathrm{unp}}(P_T)}$$



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

J/ψ PRODUCTION IN ep SCATTERING

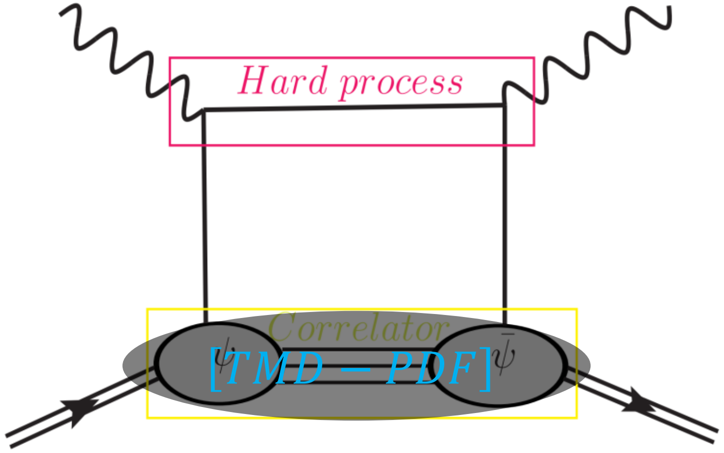
➢ Consider the electroproduction processes: $\boldsymbol{e(l) + p(P) \to e(l') + J/\psi(P_\psi) + X}$



$\gamma^* - p$ c.m. frame

$$z\left(= \frac{P\cdot P_\psi}{P\cdot q}\right) = 1 \text{ (LO)}$$

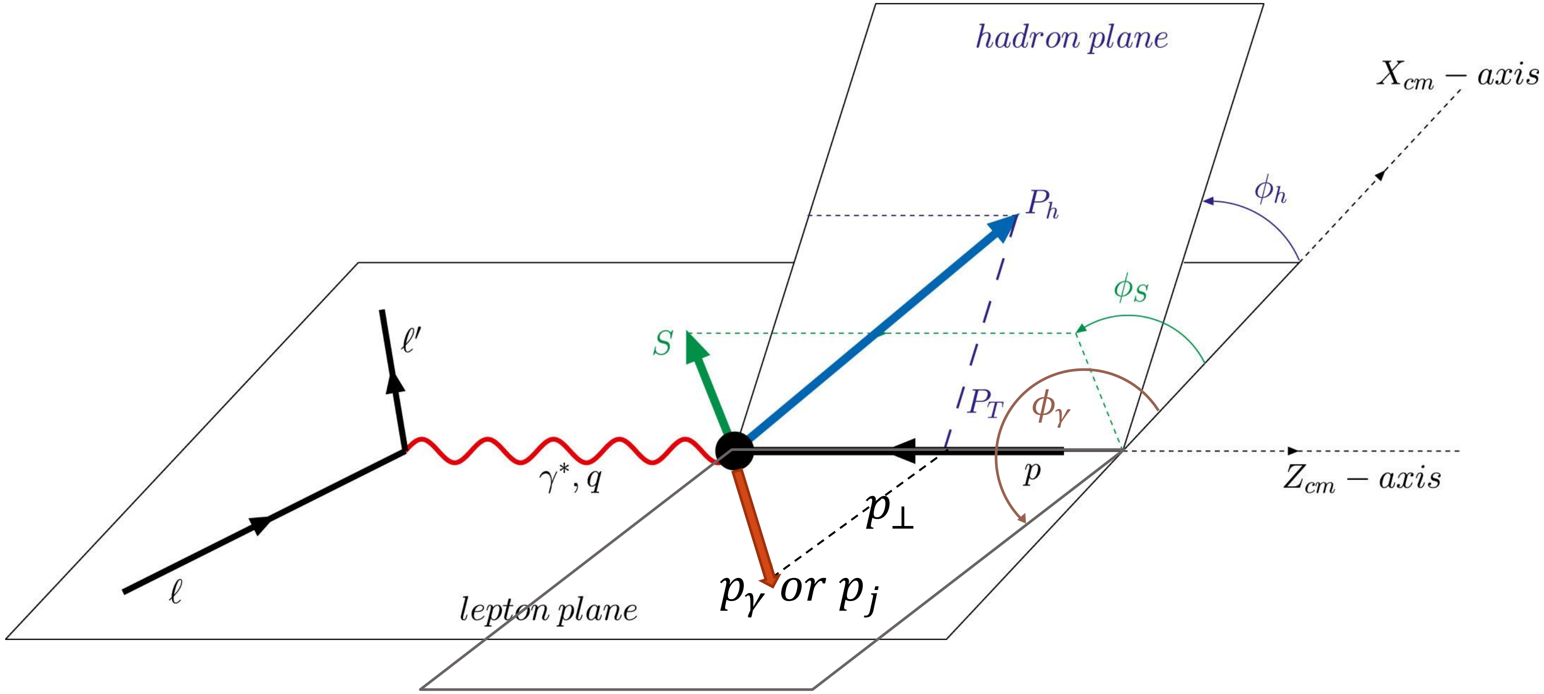
z is fraction of virtual photon energy carried by J/ψ in proton rest frame.



$$d\sigma \propto [TMD - PDF] \otimes d\hat{\sigma} \otimes [Hadronization]$$

A BACK-TO-BACK $J/\psi - jet$ AND $J/\psi - \gamma$ PRODUCTION IN ep SCATTERING

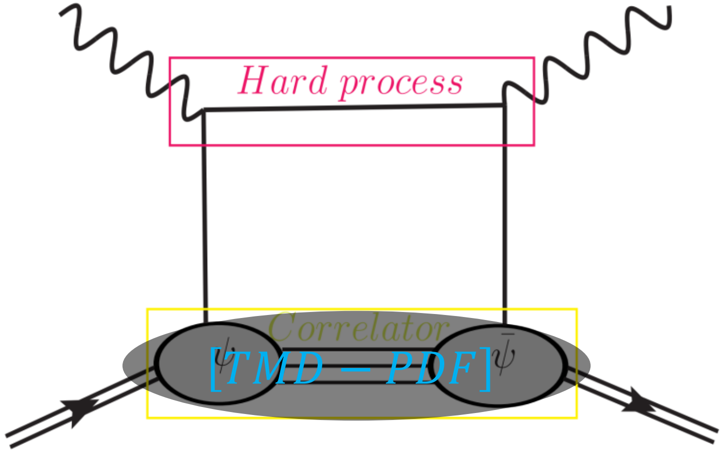
- Consider the electroproduction processes: $\boldsymbol{e(l) + p(P) \to e(l') + J/\psi(P_\psi) + \gamma(p_\gamma) + X}$
  $\boldsymbol{e(l) + p(P) \to e(l') + J/\psi(P_\psi) + jet(p_j) + X}$



$\gamma^* - p$ c.m. frame

$$z \left(= \frac{P \cdot P_\psi}{P \cdot q} \right) < 1 \text{ (LO)}$$

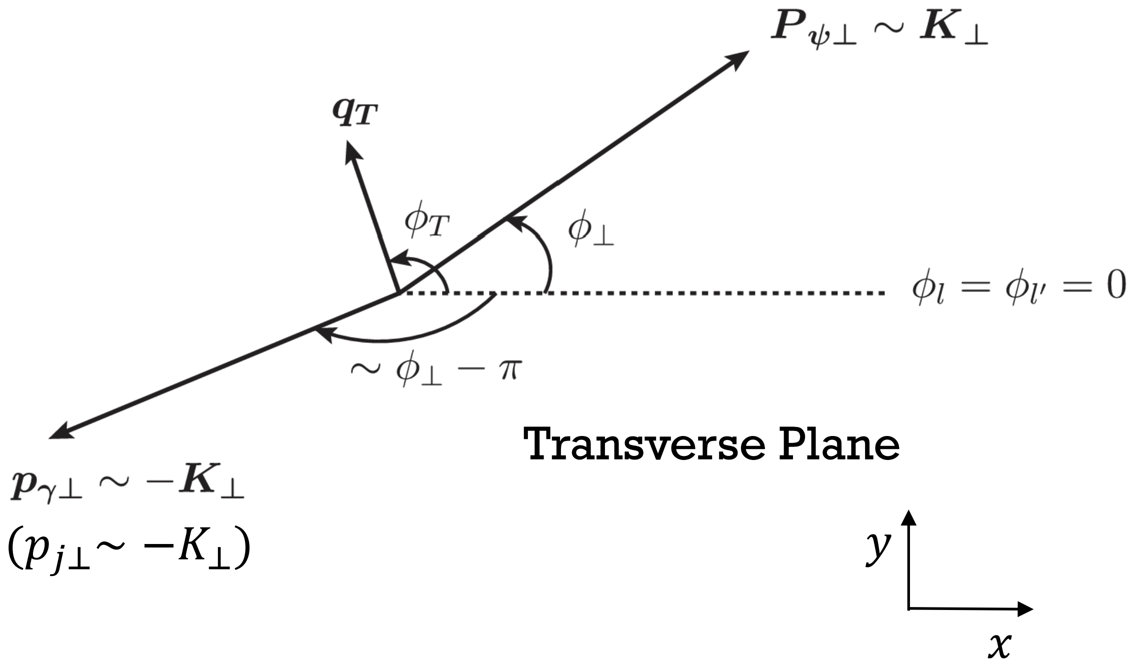
z is fraction of virtual photon energy carried by J/ψ in proton rest frame.



$$d\sigma \propto [TMD - PDF] \otimes d\hat{\sigma} \otimes [Hadronization]$$

A BACK-TO-BACK $J/\psi - jet$ AND $J/\psi - \gamma$ PRODUCTION IN ep SCATTERING

- Assume TMD factorization.
- $p - \gamma^*$ center of mass frame which move along z direction
- $\boldsymbol{P}_{\psi\perp}$ and $\boldsymbol{P}_{j\perp}$ are transverse momentum of J/ψ and jet respectively in the plane orthogonal to the proton momentum.
- We define sum and difference of transverse momenta



$$\boldsymbol{q}_T = \boldsymbol{P}_{\psi\perp} + \boldsymbol{P}_{j\perp} \quad , \qquad \boldsymbol{K}_\perp = \frac{\boldsymbol{P}_{\psi\perp} - \boldsymbol{P}_{j\perp}}{2}$$

ϕ_T denotes azimuthal angle of $\boldsymbol{q}_T$

- In the case where $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$, the J/ψ and jet are almost back-to-back in the transverse plane.

TMD Factorization

CROSS SECTION: $ep \to e + J/\psi + jet + X$

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

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

Parameterization of gluon correlator for **unpolarized proton** target at 'Leading Twist'

$$\Phi_g^{\nu\nu'}\left(x,\boldsymbol{p}_T^2\right) = \frac{1}{2x}\left[-g_\perp^{\nu\nu'} f_1^g\left(x,\boldsymbol{p}_T^2\right) + \left(\frac{p_T^\nu p_T^{\nu'}}{M_p^2} + g_\perp^{\nu\nu'}\frac{\boldsymbol{p}_T^2}{2M_p^2}\right) h_1^{\perp g}\left(x,\boldsymbol{p}_T^2\right)\right]$$

Unpolarized gluon distribution

Linearly polarized gluon distribution

QUARKONIUM PRODUCTION

- Quarkonium is a bound state of heavy quark and anti-quark ($Q\bar{Q}$)

NRQCD factorization

Describes conversion of $Q\bar{Q}[n]$ states into final quarkonium state.

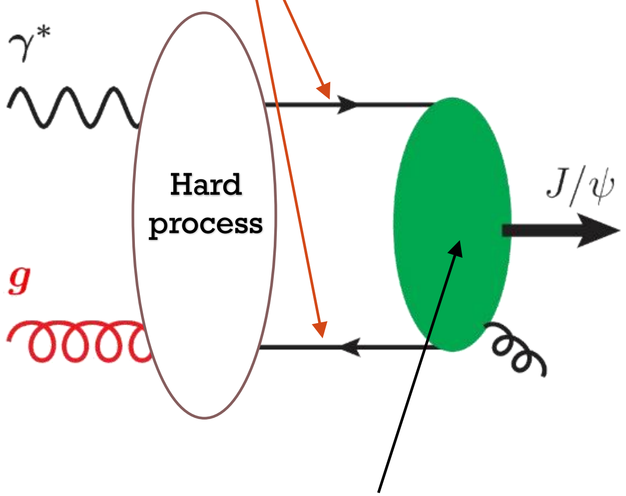
Non-perturbative; long distance matrix elements (LDMEs)

$$d\sigma^{ab\to J/\psi} = \sum_n d\hat{\sigma}[ab \to c\bar{c}(n)]\langle 0 \mid \mathcal{O}_n^{J/\psi} \mid 0\rangle$$

Perturbative short distance coefficient

Cross section in particular color, angular momentum and spin state "n" : ${}^{2S+1}L_J$, calculated by perturbative QCD

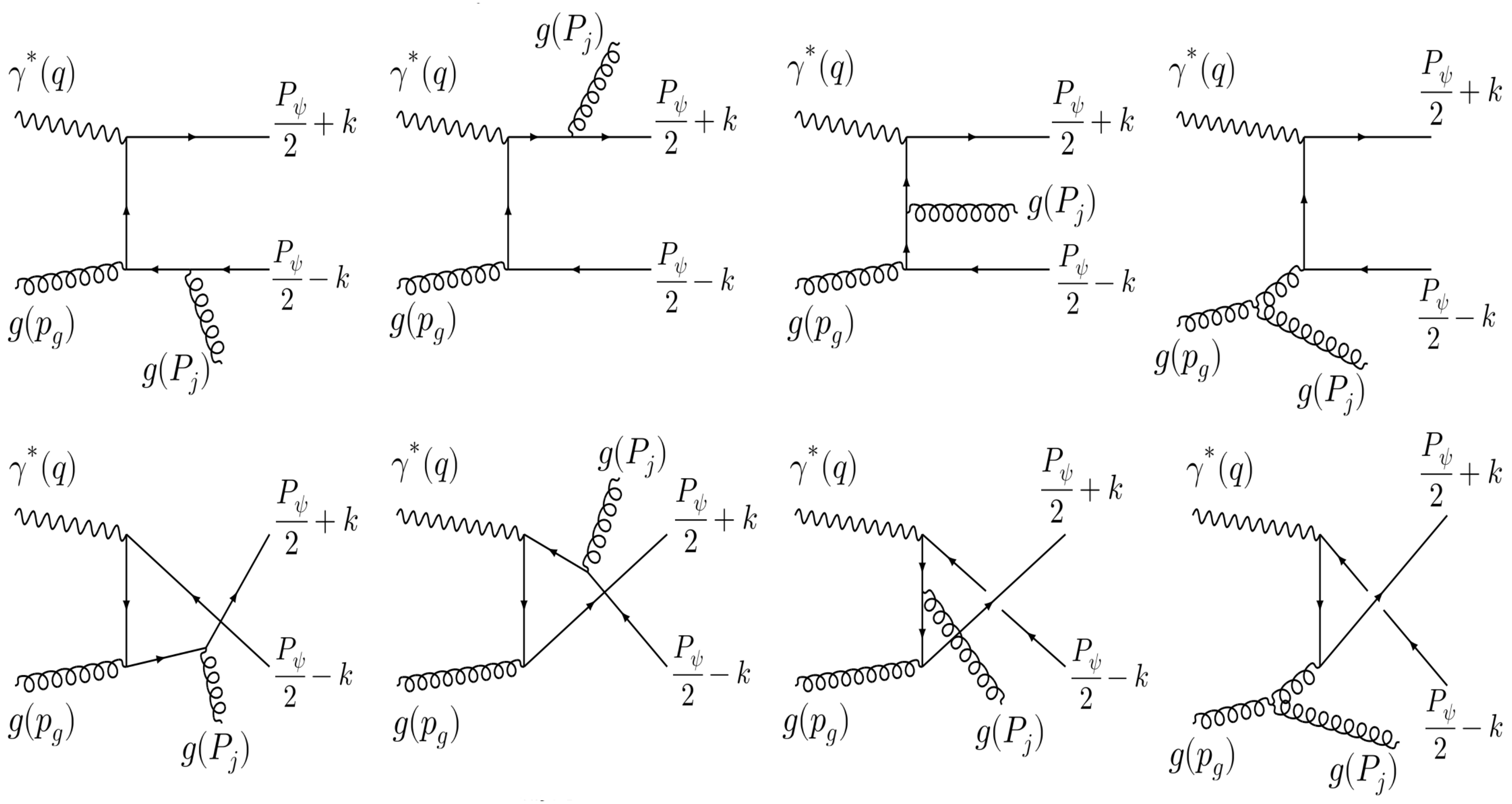
$Q\bar{Q}$ pair with $[{}^{2S+1}L_J^{(1,8)}]$ quantum number



G. T. Bodwin et al, PRD51 (1995), Lepage 95

FEYNMAN DIAGRAMS

Gluon initiated hard process: $\gamma^* g \to Q\bar{Q}\ g$, contributes significantly over the quark(anti-quark) initiated hard process: $\gamma^* q(\bar{q}) \to Q\bar{Q}\ q(\bar{q})$, in the small$-x$ domain.



Tree level Feynman diagrams for the hard process: $\gamma^* + g \to c + \bar{c} + g$

AMPLITUDE CALCULATIONS USING NRQCD

The amplitude can be written as

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

D. Boer and C. Pisano (2012)

$\mathcal{O}(q,p,P_\psi,k)$: amplitude for production of $Q\bar{Q}$ pair.

$$\mathcal{O}(q,p,P_\psi,k) = \sum_{m=1}^{8} C_m \mathcal{O}_m(q,p,P_\psi,k)$$

The spin projection operator, $\mathcal{P}_{SS_z}(P_\psi,k)$, projects the spin triplet and spin singlet states of $Q\bar{Q}$ pair

$$\mathcal{P}_{SS_z}(P_\psi,k) = \sum_{s_1 s_2} \left\langle \frac{1}{2} s_1 ; \frac{1}{2} s_2 \middle| SS_z \right\rangle v\left(\frac{P_\psi}{2} - k, s_1\right) \bar{u}\left(\frac{P_\psi}{2} + k, s_2\right)$$
$$= \frac{1}{4M_\psi^{3/2}} (-\not{P}_\psi + 2\not{k} + M_\psi) \Pi_{SS_z} (\not{P}_\psi + 2\not{k} + M_\psi) + O(k^2)$$

$\Pi_{SS_z} = \gamma^5$ for spin singlet ($S = 0$)

$\Pi_{SS_z} = \epsilon^{\mu}_{S_z}(P_\psi)\gamma_\mu$ for spin triplet ($S = 1$)

Amplitude Calculations

Since, $k \ll P_h$, amplitude expanded in Taylor series about $k = 0$

First term in the expansion gives the S-states $(L = 0, J = 0,1)$. The linear term in k gives the P-states $(L = 1, J = 0,1,2)$.

The S-states amplitude :

$$M[{}^{2S+1}S_J^{(1,8)}](P_\psi, k) = \frac{1}{\sqrt{4\pi}} R_0(0) \mathrm{Tr}[\mathcal{O}(q,p,P_\psi,k)\mathcal{P}_{SS_z}(P_\psi,k)\Big|_{k=0}$$

The P-states amplitude :

$$M[{}^{2S+1}P_J^{(1,8)}](P_\psi, k) = -i\sqrt{\frac{3}{4\pi}} R_1'(0) \sum_L \epsilon_{L_z}^{\alpha}(P_\psi)\langle LL_z; SS_z|JJ_z\rangle \mathrm{Tr}[\mathcal{O}_\alpha(0)\mathcal{P}_{SS_z}(0) + \mathcal{O}(0)\mathcal{P}_{SS_z\alpha}(0)]$$

$$\mathcal{O}_\alpha(0) = \frac{\partial}{\partial k^\alpha}\mathcal{O}(q,p,P_\psi,k)\Big|_{k=0} \qquad \mathcal{P}_{SS_z\alpha}(0) = \frac{\partial}{\partial k^\alpha}\mathcal{P}_{SS_z}(q,p,P_\psi,k)\Big|_{k=0}$$

Contribution: ${}^3S_1^{(1)}$, ${}^3S_1^{(8)}$, ${}^1S_0^{(8)}$, ${}^3P_{j(=0,1,2)}^{(8)}$

R_0 and R_1' are related with the LDMEs

FINAL CROSS SECTION: $ep \to e + J/\psi + jet + X$ OR $ep \to e + J/\psi + \gamma + X$

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

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

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

Coefficients: $A_i \sim A_i^{\gamma g\to c\bar{c}[n]g}\langle 0|O_n^{J/\psi}|0\rangle$ and $B_i \sim B_i^{\gamma g\to c\bar{c}[n]g}\langle 0|O_n^{J/\psi}|0\rangle$ comes from partonic processes.

ASYMMETRY CALCULATIONS

Weighted azimuthal asymmetry:

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

U. D'Alesio (2019)

Azimuthal modulations probe Boer-Mulder gluon TMD:

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

Azimuthal modulations which can be exploited to extract polarized TMDs $f_{1T}^{\perp g}$, h_1^g and $h_{1T}^{\perp g}$

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

$$A^{\sin(\phi_S-3\phi_T)} = -\frac{|\boldsymbol{q}_T|^3}{2M_p^3}\frac{\mathcal{B}_0}{\mathcal{A}_0}\frac{h_{1T}^{\perp g}(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)} \qquad A^{\sin(\phi_S+\phi_T)} = \frac{|\boldsymbol{q}_T|}{M_p}\frac{\mathcal{B}_0}{\mathcal{A}_0}\frac{h_1^g(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)}$$

GAUSSIAN PARAMETERIZATION (GP)

$f_1^g(x, \boldsymbol{q}_T^2)$ and $h_1^{\perp g}(x, \boldsymbol{q}_T^2)$ are assumed to be factorized as function of x, i.e. collinear PDFs and a Gaussian function of the transverse momentum q_T.

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

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

r $(0 < r < 1)$ and $\langle q_T^2 \rangle$ are parameters

We took, $r = 1/3$ and $\langle q_T^2 \rangle = 0.25$

$$\Delta^N f_{g/p^\uparrow}(x, q_T) = \left(-\frac{2|\boldsymbol{q}_T|}{M_P}\right) f_{1T}^{\perp g}(x, q_T)$$

$$= 2\frac{\sqrt{2e}}{\pi} \mathcal{N}_g(x) f_{g/p}(x) \sqrt{\frac{1-\rho}{\rho}} q_T \frac{e^{-q_T^2/\rho \langle q_T^2 \rangle}}{\langle q_T^2 \rangle^{3/2}}$$

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

$$N_g = 0.25, \quad \alpha = 0.6, \quad \beta = 0.6, \quad \rho = 0.1$$

U. D'Alesio (2019)

Gluon TMDs satisfy positivity bounds:

$$\frac{\boldsymbol{q}_T^2}{2M_P} \left| h_1^{\perp g}(x, \boldsymbol{q}_T^2) \right| \leq f_1^g(x, \boldsymbol{q}_T^2)$$

$$\frac{|\boldsymbol{q}_T|}{M_P} \left| f_{1T}^{\perp g}(x, \boldsymbol{q}_T^2) \right| \leq f_1^g(x, \boldsymbol{q}_T^2)$$

D. Boer and C. Pisano (2012)

PARAMETERIZATION: SPECTATOR MODEL (SM)

A. Bacchetta, F. G. Celiberto, M. Radici, and P. Taels (2020)

Nucleon is assumed to emit a gluon and the remaining is treated as a single on-shell particle called spectator particle.

Mass of the spectator particle is allowed to take a continuous values described by a spectral function, $\rho_X(M_X)$

Gluon TMDs: $F^g\left(x, q_t^2\right) = \int_M^\infty \mathrm{d}M_X \rho_X(M_X) \hat{F}^g(x, q_t^2; M_X)$

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

where, A, B, C, D, a, b, σ are free parameters

At leading-twist, T-even unpolarized and linearly polarized gluon TMDs can be written as

$$\hat{f}_1^g(x, \boldsymbol{q}_t^2; M_X) = \left[(2Mxg_1 - x(M+M_X)g_2)^2\left[\left(M_X - M(1-x)\right)^2 + \boldsymbol{q}_t^2\right] + 2\boldsymbol{q}_t^2\left(\boldsymbol{q}_t^2 + xM_X^2\right)g_2^2 + 2\boldsymbol{q}_t^2 M^2(1-x)\left(4g_1^2 - xg_2^2\right)\right] \times \left[(2\pi)^3 4xM^2\left(L_X^2(0) + \boldsymbol{q}_t^2\right)^2\right]^{-1}$$

$$\hat{h}_1^{\perp g}(x, \boldsymbol{q}_t^2; M_X) = \left[4M^2(1-x)g_1^2 + \left(L_X^2(0) + \boldsymbol{q}_t^2\right)g_2^2\right] \times \left[(2\pi)^3 x\left(L_X^2(0) + \boldsymbol{q}_t^2\right)^2\right]^{-1}$$

Where $g_{1,2}(p^2)$ are model-dependent form factors, given as: $g_{1,2}(p^2) = \kappa_{1,2}\frac{p^2(1-x)^2}{(q_t^2 + L_X^2(\Lambda_X^2))^2}$

p^2 is gluon momentum, $\kappa_{1,2}$ and Λ_X are normalization and cut-off parameters respectively, and $L_X^2(\Lambda_X^2) = xM_X^2 + (1-x)\Lambda_X^2 - x(1-x)M^2$

RESULTS: $J/\psi - jet$ PRODUCTION

PRD 106.034009

$\cos 2\phi_t$ azimuthal asymmetry in
(A) Gaussian Parameterization
(B) Spectator Model

Kinematics: $\sqrt{s} = 140$ GeV
$0.1 < y < 1, \ \ 0 < q_t < 1$ GeV
$$Q = \sqrt{M_\psi^2 + K_t^2}$$

Plots as function of K_t and y are at fixed $z = 0.7$

Significant contribution to $A^{\cos 2\phi_t}$ coming from color octet states.

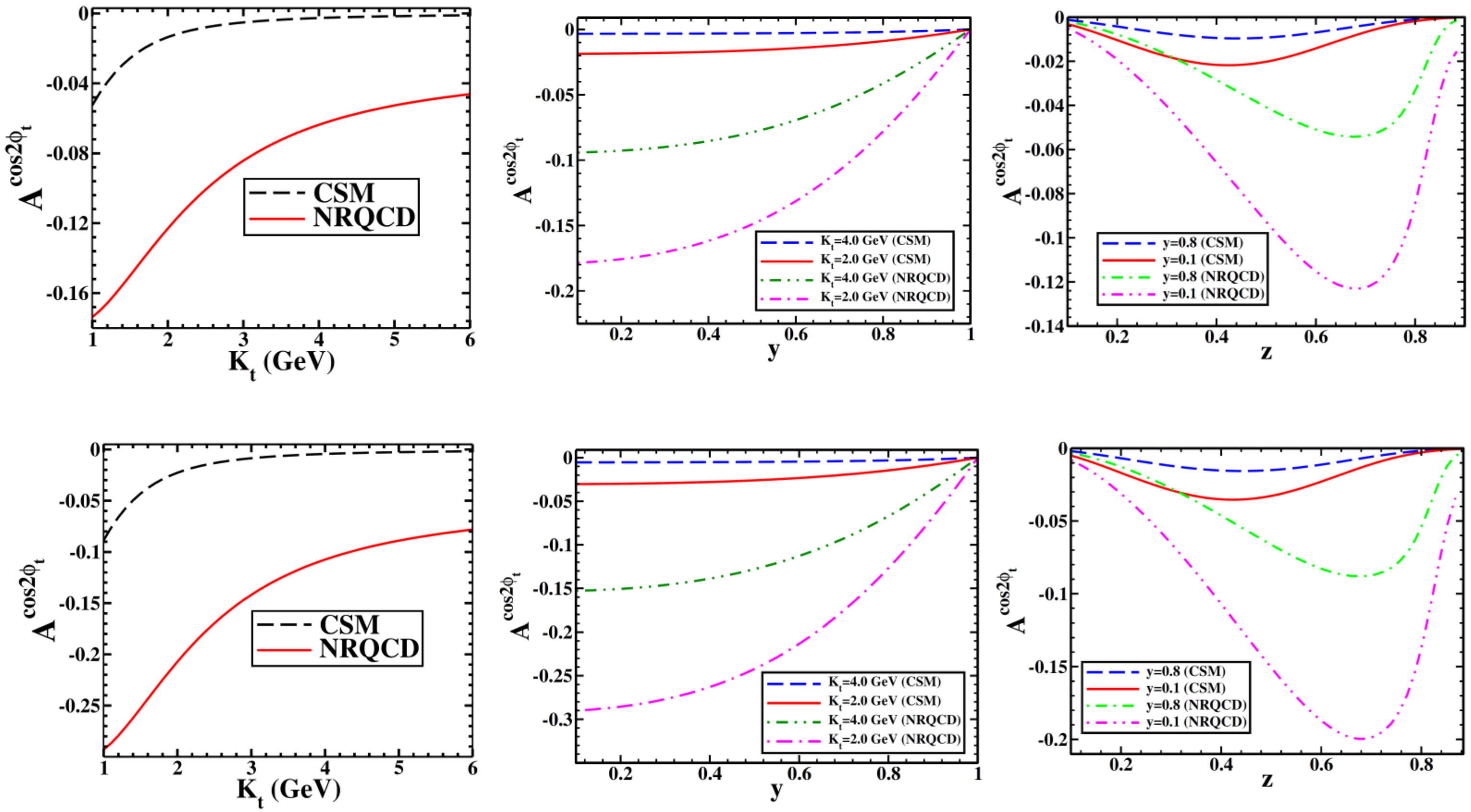
Asymmetry hardly change with $\sqrt{s}$

We used CSMWZ set of LDME

Chao (2012)

(A)

(B)

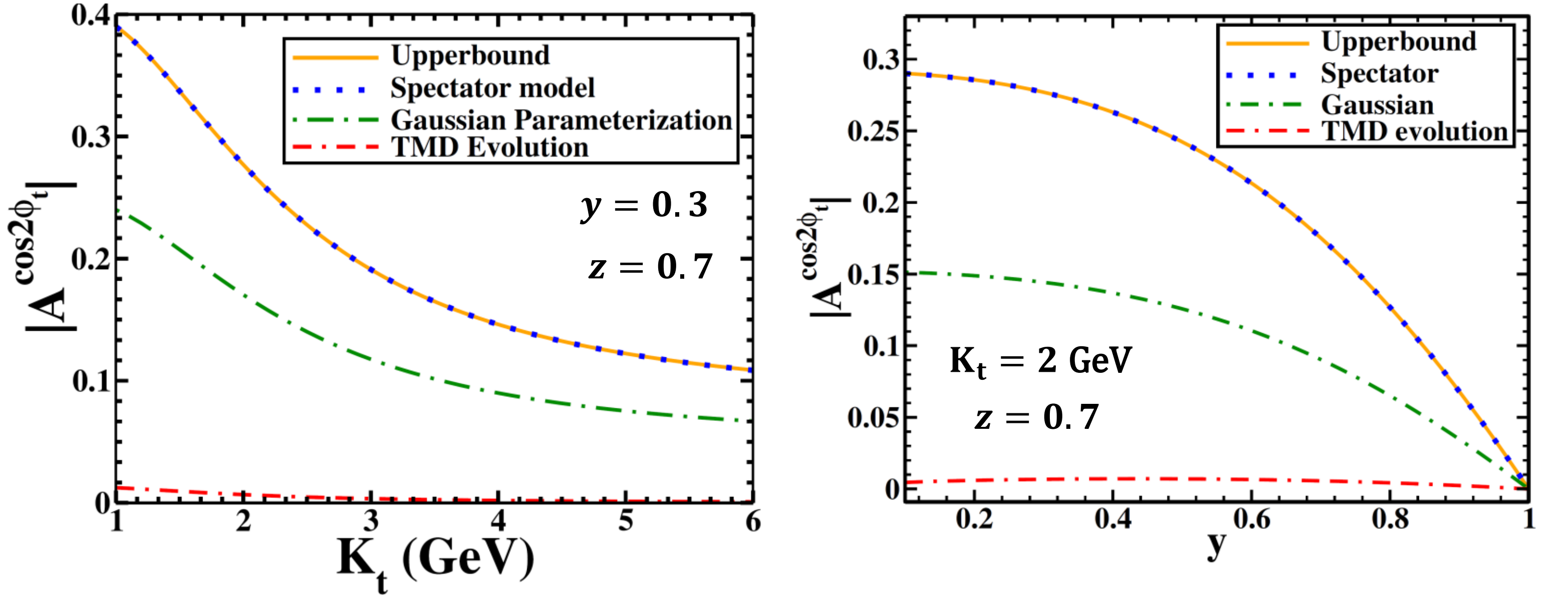


RESULTS: $J/\psi - jet$ PRODUCTION

PRD 106.034009

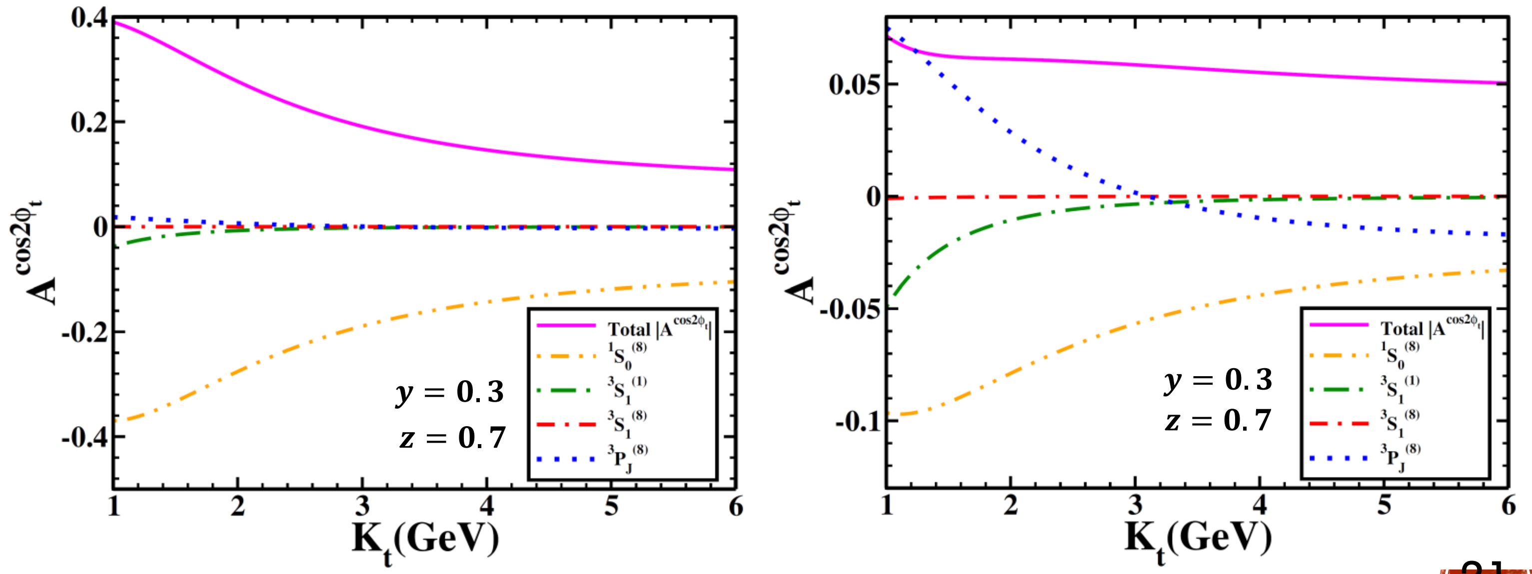
(A) Comparing $|A^{\cos 2\phi_t}|$ calculated in SM, GP and TMD evolution with the upper bound on the asymmetry.

(A)



(B) Contribution to $|A^{\cos 2\phi_t}|$ from all the color singlet and color octet states for two sets of LDMEs, CMSWZ (left) and SV (right).

(B)

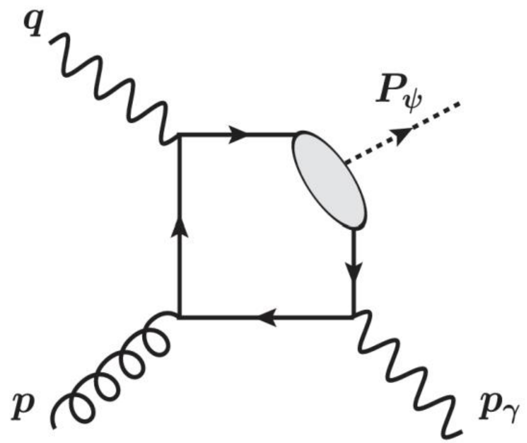


Chao (2012)

Sharma (2013)

AMPLITUDE CALCULATIONS USING NRQCD

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



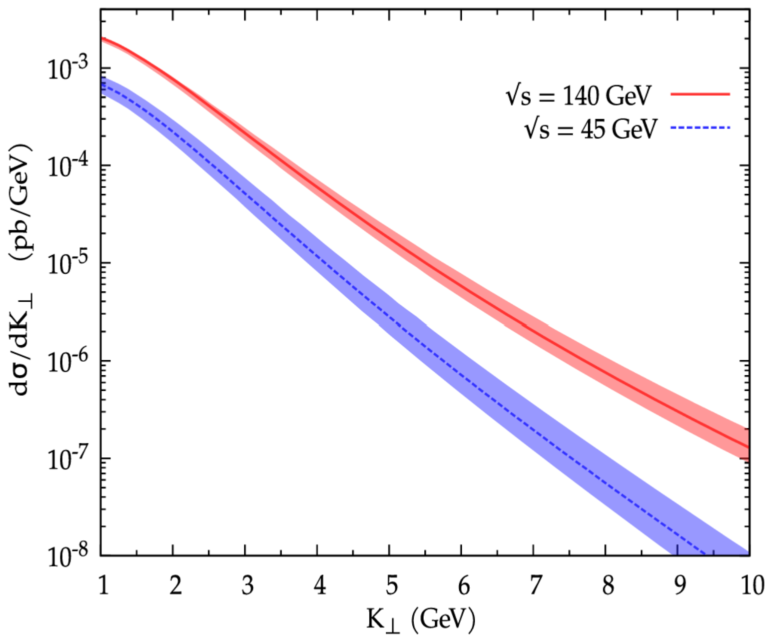
The amplitude can be written as

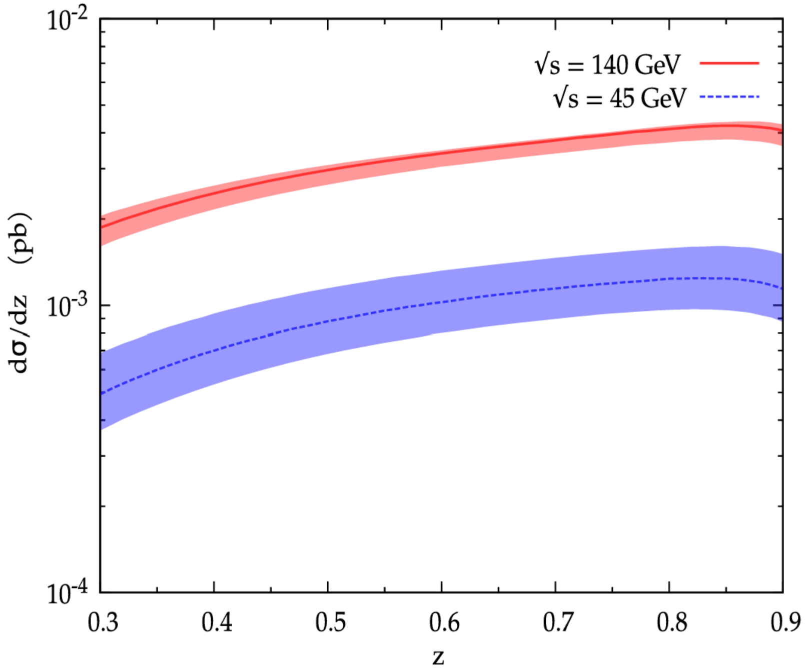
$$M(\gamma^* g \to Q\bar{Q}[^{2S+1}L_J^{(1,8)}](P_\psi) + \gamma(p_\gamma))$$
$$= \sum_{L_z S_z} \int \frac{d^3k}{(2\pi)^3} \Psi_{LL_z}(k) \langle LL_z ; SS_z | JJ_z \rangle \mathrm{Tr}[\mathcal{O}(q, p, P_\psi, k) \mathcal{P}_{SS_z}(P_\psi, k)]$$

D. Boer and C. Pisano (2012)

Contribution: $^3S_1^{(8)}$

UNPOLARIZED CROSS SECTION: $J/\psi - \gamma$ PRODUCTION





$Z < 0.9$: avoid contribution from diffractive process and prevents hitting ultraviolet divergences.

$0.3 < Z$: avoid contribution via resolved-photon channel

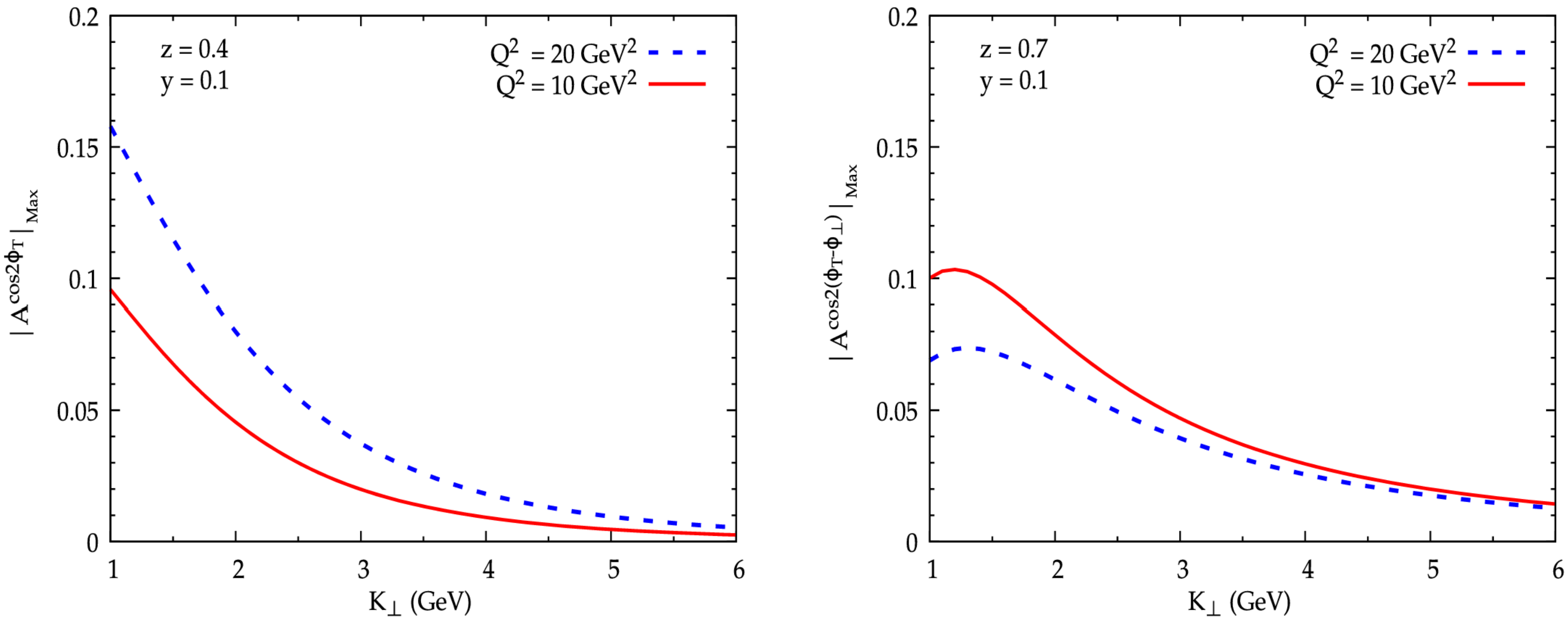
A sizable cross section, expected to be detected at upcoming EIC.

Its measurement can provide a clean probe CO mechanism within NRQCD framework.

Provide clean extraction of a CO LDME

D. Chakrabarti,RK,A. Mukherjee,R.Sangem,PRD.107.014008

ASYMMETRY AT EIC: $J/\psi - \gamma$ PRODUCTION



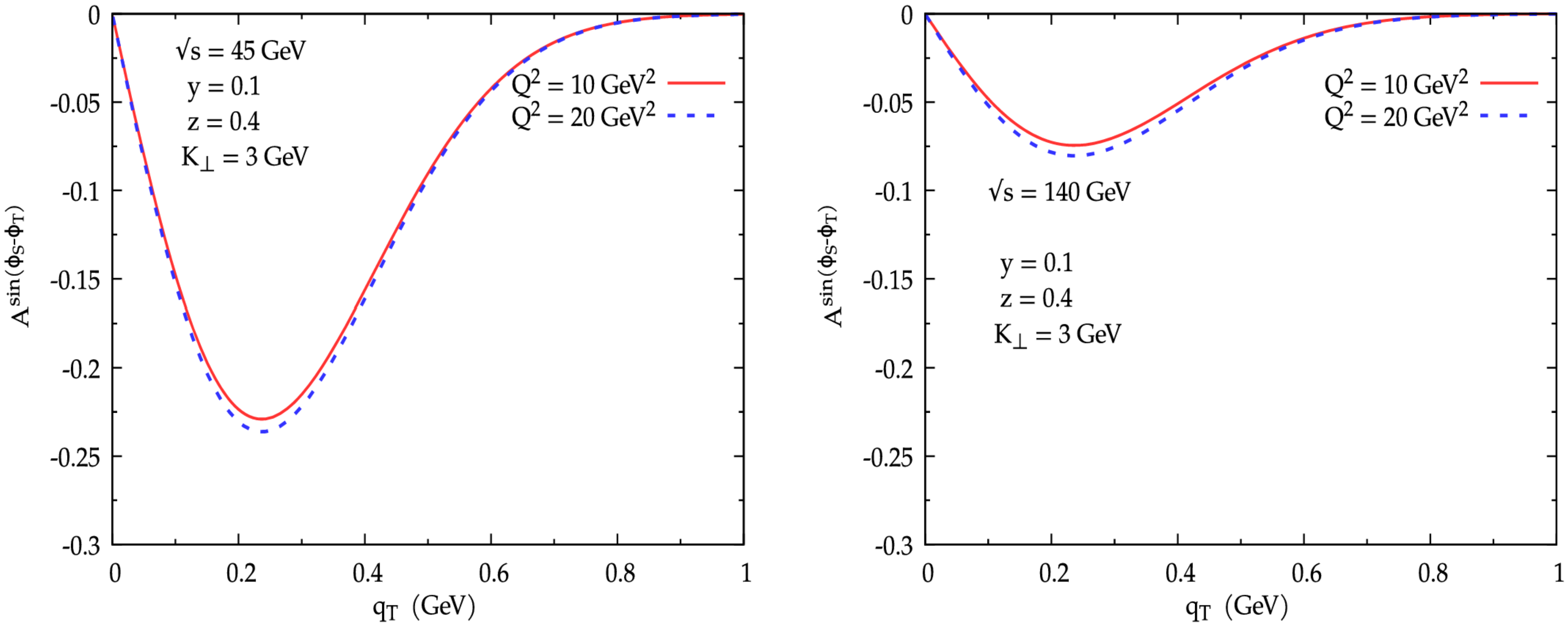
Model independent Upper bounds on the asymmetries: $|A^{\cos 2\phi_T}| \leq 2\frac{|\mathcal{B}_0|}{\mathcal{A}_0}, \qquad |A^{\cos 2(\phi_T-\phi_\perp)}| \leq 2\frac{|\mathcal{B}_2|}{\mathcal{A}_0}$

Asymmetries are independent of center of mass energy.

Asymmetries are independent of LDMEs.

D. Chakrabarti,RK,A. Mukherjee,R.Sangem,PRD.107.014008

ASYMMETRY AT EIC: $J/\psi - \gamma$ PRODUCTION



Upper bounds on the Sivers asymmetry is 1.

q_T dependent of Sivers asymmetry is obtained using Gaussian parameterization. Asymmetry depends on center of mass energy. Asymmetry hardly depends on virtuality.

D. Chakrabarti,RK,A. Mukherjee,R.Sangem,PRD.107.014008

CONCLUSION

We calculated the azimuthal asymmetry in $J/\psi - jet$ and $J/\psi - \gamma$ electroproductions where the pair produced in a almost back-to-back in the transverse plane.

We used NRQCD framework for J/ψ production.

$A^{\cos(2\phi_T)}$ and $A^{\cos 2(\phi_T - \phi_\perp)}$ azimuthal asymmetries probes the linearly polarized gluon TMD, where as the $A^{\sin(\phi_S - \phi_T)}$ can probe gluon Sivers function.

We show the numerical estimates of the asymmetries in a *model dependent parameterizations of the TMDs* and *model independent upper bounds on these asymmetries using the positivity bounds on TMDs* . ***We found a sizable azimuthal asymmetries both in $J/\psi - jet$ and $J/\psi - \gamma$ productions.***

Back-to-back $J/\psi - jet$ and $J/\psi - \gamma$ electroproduction could be a promising channel to probe poorly known gluon TMDs at the future proposed EIC.

Thank You