Dijet Azimuthal Anisotropy in High Energy DIS

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March 10, 2016

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Phys.Rev.Lett. 115 (2015) 25, 252301

Weizsäcker-Williams gluon distribution: linearly polarized gluons in unpolarized target

P. Mulders and J. Ridrigues Phys.Rev. D63 (2001) 094021
D. Boer, P. Mulders, C. Pisano Phys.Rev. D80 (2009) 094017
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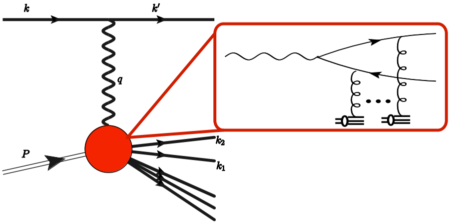
F. Dominguez, C. Marquet, B.-W. Xiao, F. Yuan Phys.Rev. D83 (2011) 105005
F. Dominguez, J.-W. Qiu , B.-W. Xiao, F. Yuan Phys.Rev. D85 (2012) 045003

- WW Linearly polarized gluons are present even in upolarized hadrons
- Linarly polarized gluon distribution originates as interference of different helicity states
- It is present only at a non-zero transverse momentum: transverse momentum dependent dictribution
- Small x behaviour of polarization is largely unknown
- JIMWLK-B renormalization group equation to analyze the magnitude of azimuthal anisotropy
- WW Linearly polarized gluons can be probed in DIS dijet production



- DIS dijet production: $\gamma^* A \quad \to \quad q\,\bar{q}\;\; X$
- Multiple scatterings of (anti) quark are accounted for by ressumation:

$$U(\mathbf{x}) = \mathbb{P}\exp\left\{ ig \int dx^- A^+(x^-, \mathbf{x}_\perp) \right\}$$

- In color dipole model this process corresponds to

$$\frac{d\sigma^{\gamma^* A \to q\bar{q}X}}{d^3k_1 d^3k_2} =$$

$$N_c \alpha_{em} e_q^2 \delta(p^+ - k_1^+ - k_2^+) \int \frac{d^2x_1}{(2\pi)^2}\frac{d^2x_2}{(2\pi)^2}\frac{d^2y_1}{(2\pi)^2}\frac{d^2y_2}{(2\pi)^2} \exp\left(-i\mathbf{k}_1(\mathbf{x}_1 - \mathbf{y}_1) - i\mathbf{k}_2(\mathbf{x}_2 - \mathbf{y}_2)\right)$$

$$\sum_{\gamma\alpha\beta} \psi^{\mathrm{T,L}\gamma}_{\alpha\beta}(\mathbf{x}_1 - \mathbf{x}_2)\psi^{\mathrm{T,L}\gamma *}_{\alpha\beta}(\mathbf{y}_1 - \mathbf{y}_2)\left[1 + \frac{1}{N_c}\Big(\langle \mathrm{Tr}\; U(\mathbf{x}_1)U^\dagger(\mathbf{y}_1)U(\mathbf{y}_2)U^\dagger(\mathbf{x}_2)\rangle\right.$$

$$\left. - \langle \mathrm{Tr}\; U(\mathbf{x}_1)U^\dagger(\mathbf{x}_2)\rangle - \langle \mathrm{Tr}\; U(\mathbf{y}_1)U^\dagger(\mathbf{y}_2)\rangle\Big)\right]$$

↑ Quadrupole contribution

- Splitting wave function of $\gamma^\star$ with longitudinal momentum p^+ and virtuality Q^2
- This expression can be computed without any further simplifications with quadrupole, but no direct relation to TMD

Dijet production in DIS

- In correlation limit (almost back-to-back jets) $\mathbf{P} = (\mathbf{k}_1 - \mathbf{k}_2)/2$ is much larger than $\mathbf{q} = \mathbf{k}_1 + \mathbf{k}_2$, for conjugate variables, $u \ll v$, where $\mathbf{u} = \mathbf{x}_1 - \mathbf{x}_2$ and $\mathbf{v} = (\mathbf{x}_1 + \mathbf{x}_2)/2$. Expand in u.
- Expansion of quadrupole brings gradients of Wilson lines.
- Allows to reduce to 2 point functions

$$xG^{ij}_{WW}(\mathbf{k}) = \frac{8\pi}{S_\perp} \int \frac{d^2x}{(2\pi)^2} \frac{d^2y}{(2\pi)^2} e^{-\mathbf{k}\ (\mathbf{x}-\mathbf{y})} \langle A^i_a(\mathbf{x}) A^j_a(\mathbf{y}) \rangle, \qquad A^i(\mathbf{x}) = \frac{1}{ig} U^\dagger(\mathbf{x}) \partial_i U(\mathbf{x})$$

WW Color Electric field ↑

- Decomposition to conventional and traceless contribution

$$xG^{ij}_{WW} = \frac{1}{2}\delta^{ij} x\, G^{(1)} - \frac{1}{2}\left(\delta^{ij} - 2\frac{q^i q^j}{q^2}\right) x\, h^{(1)}_\perp$$

- Contribution to azimuthal anisotropy of dijet production

$$E_1 E_2 \frac{d\sigma^{\gamma_L^* A \to q\bar{q}X}}{d^3k_1 d^3k_2 d^2b} = \alpha_{em} e_q^2 \alpha_s \delta\left(x_{\gamma^*} - 1\right) z^2(1-z)^2 \frac{8\epsilon_f^2 P_\perp^2}{(P_\perp^2 + \epsilon_f^2)^4}$$

$$\times \left[xG^{(1)}(x, q_\perp) + \underline{\cos(2\phi)}\; xh_\perp^{(1)}(x, q_\perp) \right].$$

$$E_1 E_2 \frac{d\sigma^{\gamma_T^* A \to q\bar{q}X}}{d^3k_1 d^3k_2 d^2b} = \alpha_{em} e_q^2 \alpha_s \delta\left(x_{\gamma^*} - 1\right) z(1-z)(z^2 + (1-z)^2) \frac{\epsilon_f^4 + P_\perp^4}{(P_\perp^2 + \epsilon_f^2)^4}$$

$$\times \left[xG^{(1)}(x, q_\perp) - \frac{2\epsilon_f^2 P_\perp^2}{P_\perp^4 + \epsilon_f^4}\; \underline{\cos(2\phi)}\; xh_\perp^{(1)}(x, q_\perp) \right].$$

z is long. momentum fraction of photon carried by quark $\qquad \epsilon_f^2 = z(1-z)Q^2$

Several useful limits

- Scattering of real photon $Q = 0$

$$E_1 E_2 \frac{d\sigma^{\gamma_L^* A \to q\bar{q}X}}{d^3k_1 d^3k_2 d^2b} = 0$$

$$E_1 E_2 \frac{d\sigma^{\gamma_T^* A \to q\bar{q}X}}{d^3k_1 d^3k_2 d^2b} = \alpha_{em} e_q^2 \alpha_s \delta\left(x_{\gamma^*} - 1\right) z(1-z)(z^2 + (1-z)^2) \frac{1}{P_\perp^4} \; xG^{(1)}(x, q_\perp)$$

- Real photon does not give $\cos(2\phi)$ transverse spin correltion that can match with spin correlation genrated by $h_\perp^{(1)}(x, q_\perp)$

Several useful limits

- $Q \gg P_\perp$

$$E_1 E_2 \frac{d\sigma^{\gamma_L^* A \to q\bar{q}X}}{d^3k_1 d^3k_2 d^2b} = \alpha_{em} e_q^2 \alpha_s \delta\left(x_{\gamma^*} - 1\right) z^2(1-z)^2 \frac{8P_\perp^2}{\epsilon_f^6}$$
$$\times \left[xG^{(1)}(x, q_\perp) \; + \; \underline{\cos(2\phi)} \; xh_\perp^{(1)}(x, q_\perp) \right] .$$
$$E_1 E_2 \frac{d\sigma^{\gamma_T^* A \to q\bar{q}X}}{d^3k_1 d^3k_2 d^2b} = \alpha_{em} e_q^2 \alpha_s \delta\left(x_{\gamma^*} - 1\right) z(1-z)(z^2 + (1-z)^2) \frac{1}{\epsilon_f^4}$$
$$\times \left[xG^{(1)}(x, q_\perp) \; - \; \frac{2P_\perp^2}{\epsilon_f^2} \; \underline{\cos(2\phi)} \; xh_\perp^{(1)}(x, q_\perp) \right] .$$

- Relative anisotropy is larger for longitudinal photon

Physical interpretation

- Conventional WW: probability distribution

$$\delta_{ij} = \varepsilon_+^{*i}\varepsilon_+^j + \varepsilon_-^{*i}\varepsilon_-^j$$

- Gluon helicity: difference of probability distributions

$$i\epsilon_{ij} = \varepsilon_+^{*i}\varepsilon_+^j - \varepsilon_-^{*i}\varepsilon_-^j$$

- $h^{(1)}$: transverse spin correlation function of gluons in two orthogonal polarization states

$$2\frac{q^i q^j}{q^2} - \delta^{ij} = i(\varepsilon_+^{*i}\varepsilon_-^j - \varepsilon_-^{*i}\varepsilon_+^j)$$

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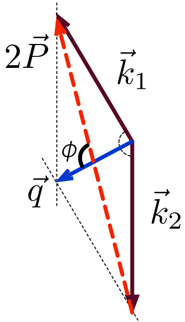
$$E_1E_2\frac{d\sigma^{\gamma_L^* A\to q\bar{q}X}}{d^3k_1d^3k_2d^2b} = \alpha_{em}e_q^2\alpha_s\delta\left(x_{\gamma^*}-1\right)z^2(1-z)^2\frac{8\epsilon_f^2P_\perp^2}{(P_\perp^2+\epsilon_f^2)^4}\times\left[xG^{(1)}(x,q_\perp)+\underline{\cos(2\phi)}\ xh_\perp^{(1)}(x,q_\perp)\right]$$

$$E_1E_2\frac{d\sigma^{\gamma_T^* A\to q\bar{q}X}}{d^3k_1d^3k_2d^2b} = \alpha_{em}e_q^2\alpha_s\delta\left(x_{\gamma^*}-1\right)z(1-z)\left(z^2+(1-z)^2\right)\frac{\epsilon_f^4+P_\perp^4}{(P_\perp^2+\epsilon_f^2)^4}$$
$$\times\left[xG^{(1)}(x,q_\perp)-\frac{2\epsilon_f^2P_\perp^2}{\epsilon_f^4+P_\perp^4}\underline{\cos(2\phi)}\ xh_\perp^{(1)}(x,q_\perp)\right]$$

- Jets are almost back-to-back. Note: this is not about supression of back-to-back peak, but rather about the structure of back to back correlation.
- **Azimuthal anisotropy is in angle between P and q, denoted by ϕ.**
- Is $h_\perp^{(1)}$ important at small x?



$$2\vec{P}=\vec{k}_1-\vec{k}_2$$
$$\vec{q}=\vec{k}_1+\vec{k}_2$$

NUMERICS

- MV initial conditions at $Y = \ln x_0/x = 0$

$$S_{\text{eff}}[\rho^a] = \int dx^- d^2x_\perp \, \frac{\rho^a(x^-, x_\perp)\,\rho^a(x^-, x_\perp)}{2\mu^2}$$

for

$$U(x_\perp) = \mathbb{P}\exp\left\{ig^2 \int dx^- \frac{1}{\nabla_\perp^2} t^a \rho^a(x^-, x_\perp)\right\}$$

- Quantum evolution at $Y > 0$ is accounted for by solving JIMWLK-B using Langevin method

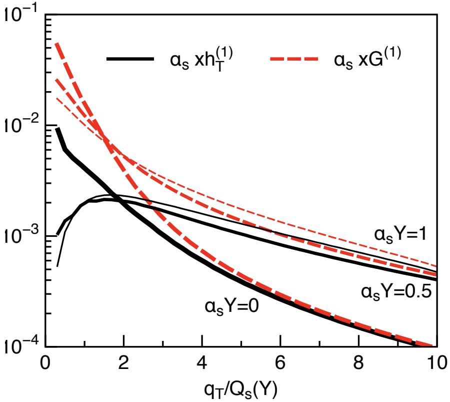
$$\partial_Y U(z) = U(z)\frac{i}{\pi}\int d^2u \frac{(z-u)^i \eta^i(u)}{(z-u)^2} - \frac{i}{\pi}\int d^2v\, U(v)\frac{(z-v)^i\eta^i(v)}{(z-v)^2}U^\dagger(v)U(z)\,.$$

The Gaussian white noise $\eta^i = \eta_a^i t^a$ satisfies $\langle \eta_i^a(z)\rangle = 0$ and

$$\langle \eta_i^a(z)\ \eta_j^b(y)\rangle = \alpha_s\, \delta^{ab}\delta_{ij}\delta^{(2)}(z-y).$$

L. D. McLerran and R. Venugopalan, Phys. Rev. D49, 2233 (1994)
J.-P. Blaizot, E. Iancu and H. Weigert, Nucl. Phys. A713, 441 (2003)
T. Lappi and H. Mäntysaari, Eur. Phys. J. C73, 2307 (2013)

Small x evolution



MV model results

$$xh_\perp^{(1)} = \frac{S_\perp}{2\pi^3\alpha_s}\frac{N_c^2-1}{N_c}\int_0^\infty drr\frac{J_2(q_\perp r)}{r^2\ln\frac{1}{r^2\Lambda^2}}\left(1-\exp\left(-\frac{1}{4}r^2Q_s^2\right)\right)$$

$$xG^{(1)} = \frac{S_\perp}{2\pi^3\alpha_s}\frac{N_c^2-1}{N_c}\int_0^\infty drr\frac{J_2(q_\perp r)}{r^2}\left(1-\exp\left(-\frac{1}{4}r^2Q_s^2\right)\right)$$

Large $q_\perp \gg Q_s$: $xh_\perp^{(1)} = xG^{(1)} \propto 1/q_\perp^2$

Small $q_\perp \ll Q_s$: $xh_\perp^{(1)} \propto q_\perp^0 \quad xG^{(1)} \propto \ln\frac{Q_s^2}{q_\perp^2}$

- at large $q_\perp$, saturation of positivity bound $h_\perp^{(1)} \to G^{(1)}$, as also was found in pert. twist 2 calculations of small x field of fast quark
- at small $q_\perp$, $h_\perp^{(1)}/G^{(1)} \to 0$
- both functions decrease fast as functions of $q_\perp$ ($q_\perp^{-2}$ in MV): best measured when $q_\perp \approx Q_s$. Nuclear target!

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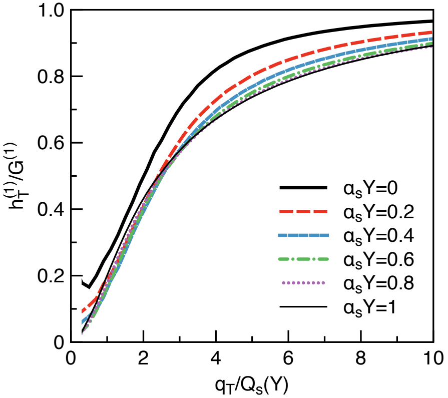
Small x evolition II



- Fast departure from MV ($\alpha_s Y = 0$)
- Slow evolution towards smaller x
- $h_\perp^{(1)}$ is large at small x
- Note: $q_\perp$ is scaled by exponentially growing $Q_s(Y)$: ratio at fixed $q_\perp$ decreases with rapidity.
  Emission of small x gluons reduces degree of polarization.
- Approximate geometric scaling at small x: can be fit with polynomial $\times$ tanh

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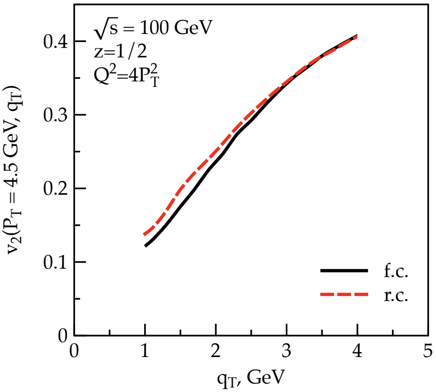
SECOND HARMONICS OF AZIMUTHAL ANISOTROPY: $q_\perp$-DEPENDENCE

- By analogy to HIC

$$v_2(P_\perp, q_\perp) = \langle \cos 2\phi \rangle$$

- Fixed coupling results ("f.c.") are for $\alpha_s = 0.15$
- At this fixed $P_\perp$ not very significant dependence on prescription for α_s
- Increase of v_2 is due to increasing $h_\perp^{(1)}(q_\perp)/G^{(1)}(q_\perp)$



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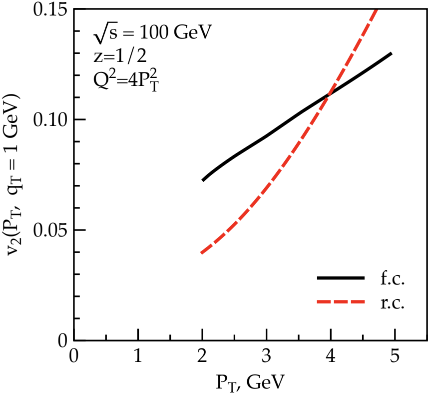
Second harmonics of azimuthal anisotropy: $P_\perp$-dependence



- Fixed coupling results significantly different from running coupling
- Large azimuthal anisotropy in both cases
- Increasing $P_\perp$ increases x and suppresses evolution effects driving v_2 towards its MV value

$$x = \frac{1}{s}\left(q_\perp^2 + \frac{1}{z(1-z)}P_\perp^2\right)$$

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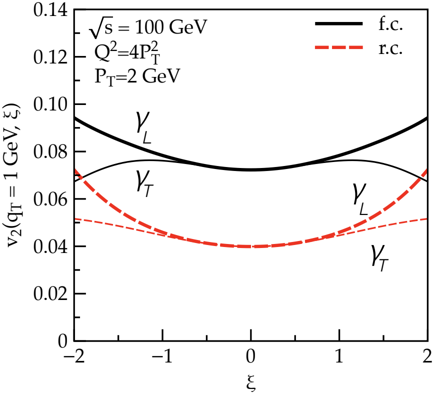
Dependence on longitudinal momentum

- To probe longitudinal structure

$$\xi = \ln \frac{1-z}{z}$$

- Long-range "rapidity" correlation
- Mild increase for large ξ because asymmetric dijets probe target at larger values of x



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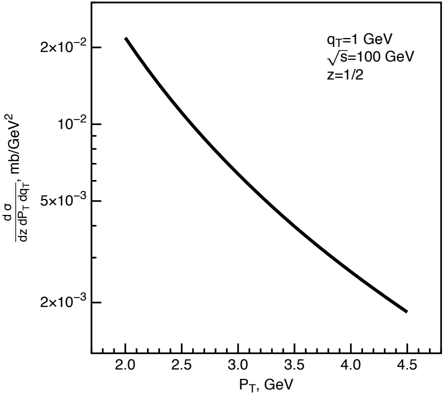
Cross-section for signal

- Cross-section summed with respect to γ^* polarizations and integrated over angles
- $\sqrt{s}$ is given for $\gamma^* A$ CM



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Monte Carlo Event generator

- DIS event with random Q^2, W^2, photon polarization, as well as $P_\perp$ and $q_\perp$
- Input: $\sqrt{s}$ and A
- Q_s and target area are adjusted according to A
- Output: Parton 4-momentum etc
- Pythia afterburner → particles
- This does not account for background

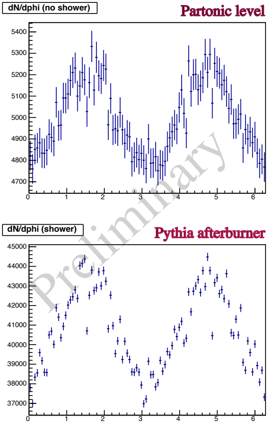

Fig. by T. Ulrich

A. Dumitru, V. S. and T. Ulrich work in progress

Conclusions

- In correlations limit, DIS dijets to probe WW gluon distribution
- Gluon distribution has two distinct contributions: isotropic conventional WW $xG^{(1)}$ and $\cos(2\phi)$ anisotropic with amplitude $xh^{(1)}$ – interference of gluons in orthogonal polarizations
- MV model gives large relative anisotropy at large momentum, both $G^{(1)}$ and $h_\perp^{(1)}$ are proportional to $1/q_\perp^2$
- JIMWLK-B: $h^{(1)}$ grows as fast as $G^{(1)}$
- Not significant dependence on prescription for α_s
- Long-range in “rapidity”
- Survives in MC events summed over polarization and different distributions of q, z, $P_\perp$, $q_\perp$ etc.