Azimuthal anisotropy in small-x DIS dijet production

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A. Dumitru, T. Lappi and V. S. Phys.Rev.Lett. 115 (2015) 25, 252301

A. Dumitru and V. S., arXiv:1605.02739

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

Talk by Daniël Boer on Monday; ArXiv 1611.06089

At small x, there are two different unintegrated gluon distributions (UGD):

- Dipole gluon distribution ($G^{(2)}$) + linearly polarized partner ($h^{(2)}$).
  Appears in many processes. Small x evolution is well understood.
  Maximal polarization $xh^{(2)} = xG^{(2)}$
- Weizsäcker-Williams (WW) gluon distribution ($G^{(1)}$) + linearly polarized partner ($h^{(1)}$).
  Degree of polarization is x- and transverse momentum dependent

	DIS	DY	SIDIS	$pA \to \gamma\,\mathrm{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$	$pA \to j_1 j_2 X$
$G^{(1)}$ (WW)	×	×	×	×	√	√	√	√
$G^{(2)}$ (DP)	√	√	√	√	×	×	×	√

	$pp \to \gamma\,\gamma\,X$	$pA \to \gamma^*\,\mathrm{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$h^{(1)}$ (WW)	√	×	√	√	√
$h^{(2)}$ (DP)	×	√	×	×	×

Talk by Daniël Boer on Monday

Talk by Elke Aschenauer on Tuesday

Dijets in DIS: saturation $\rightsquigarrow$ decrease of back-to-back dihadron correlation as a probe of $G^{(1)}$

L. Zheng, E. C. Aschenauer, J. H. Lee and B. W. Xia Phys. Rev. D **89***, 7, 074037 (2014)*

In this talk: structure of back-to-back peak as a probe of $h_g^{(1)}$

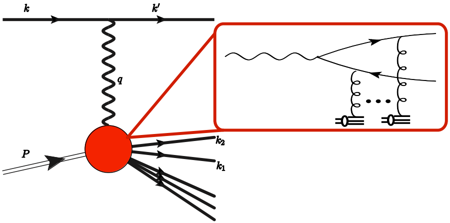
Weizsäcker-Williams gluon distribution: linearly polarized gluons in unpolarized target

P. Mulders and J. Ridrigues Phys.Rev. D63 (2001) 094021
D. Boer, P. Mulders, C. Pisano Phys.Rev. D80 (2009) 094017
A. Metz and J. Zhou Phys.Rev. D84 (2011) 051503
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

Talk by Daniël Bohr on Monday

- WW Linearly polarized gluons are present even in unpolarized hadrons
- Origin: averaged quantum interference of different helicity states between scattering amplitude and its complex conjugate
- It is present only at non-zero transverse momentum: transverse momentum-dependent distribution
- Small x behaviour of WW linearly polarized gluon distribution was largely unknown and is addressed in this talk

Dijet production in DIS at small x

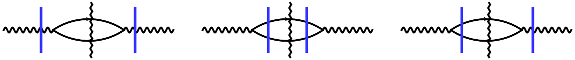


- DIS dijet production: $\gamma^* A \quad \rightarrow \quad q\, \bar{q}\,\ X$
- Multiple scatterings of (anti) quark are accounted for by ressumation:

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

- In color dipole model this process corresponds to

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



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

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

$$- \langle \mathrm{Tr}\ U(\mathbf{x}_1) U^\dagger(\mathbf{x}_2) \rangle - \langle \mathrm{Tr}\ U(\mathbf{y}_1) U^\dagger(\mathbf{y}_2) \rangle \Big) \Bigg] \quad \uparrow \text{Quadrupole contribution}$$

- 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 WW distribution function

Dijet production in DIS

- For almost back-to-back jets (so-called correlation limit):
  Total momentum $\mathbf{P} = (\mathbf{k}_1 - \mathbf{k}_2)/2 \gg$ momentum imbalance $\mathbf{q} = \mathbf{k}_1 + \mathbf{k}_2$;
  For conjugate variables, $u \ll v$, where $\mathbf{u} = \mathbf{x}_1 - \mathbf{x}_2$ and $\mathbf{v} = (\mathbf{x}_1 + \mathbf{x}_2)/2$.
- Expansion of quadrupole about $\mathbf{x}_1 \approx \mathbf{x}_2$ and $\mathbf{y}_1 \approx \mathbf{y}_2$ results in gradients of Wilson lines
- Allows to reduce to 2-point functions

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

WW Color Electric field ↑

- Decomposition to conventional (unpolarized) and traceless (linearly polarized) contributions

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

- Beyond leading order in gradient expansion $\mathcal{O}(\mathbf{u}^4)$ to probe non-local structure of quadrupole: 2-nd part of talk

MV model results

- $G^{(1)}$ and $h_\perp^{(1)}$ can be analytically computed in Gaussian approximation.
- In particular, using McLerran-Venugopalan (MV) model

$$g^2\langle A^{-a}(z_1^+, z_1)\, A^{-b}(z_2^+, z_2)\rangle = \delta^{ab}\, \delta(z_1^+ - z_2^+)\, \mu^2(z^+)\, L_{z_1 z_2}\ ,$$

It was obtained

$$xh^{(1)}(x,q^2) = \frac{N_c S_\perp}{2\pi^3\alpha_s}\int d|r|\,|r| J_2(|r|\,|q|)\left[1-\exp\left(-\frac{Q_s^2 r^2}{4}\log\frac{1}{r^2\Lambda_{\rm IR}^2}\right)\right]\frac{1}{r^2 \log\frac{1}{r^2\Lambda_{\rm IR}^2}}$$

$$xG^{(1)}(x,q^2) = \frac{N_c S_\perp}{2\pi^3\alpha_s}\int d|r|\,|r| J_0(|r|\,|q|)\left[1-\exp\left(-\frac{Q_s^2 r^2}{4}\log\frac{1}{r^2\Lambda_{\rm IR}^2}\right)\right]\frac{1}{r^2}$$

A. Metz and J. Zhou Phys.Rev. D84 (2011) 051503

F. Dominguez, J.-W. Qiu , B.-W. Xiao, F. Yuan Phys.Rev. D85 (2012) 045003

- Limiting cases:
  - $\Lambda_{IR} \ll q \ll Q_s$, $xh^{(1)} \propto q^0$ and $xG^{(1)} \propto \ln\frac{Q_s^2}{q^2} \rightsquigarrow$ suppression of polarization
  - $q \gg Q_s$, $xh^{(1)} \approx xG^{(1)} \propto 1/q^2 \rightsquigarrow$ maximal polarization
  - first correction to $q \gg Q_s$, $xh^{(1)} \sim \frac{1}{\alpha_s}\left(\frac{g^4\mu^2}{q^2} - \#\frac{g^8\mu^4}{q^4}\right)$, $xG^{(1)} \sim \frac{1}{\alpha_s}\left(\frac{g^4\mu^2}{q^2} + \#\frac{g^8\mu^4}{q^4}\right)$

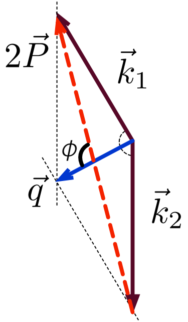
Correlations limit results for $\gamma^*_{\|,\perp}$

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

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

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

- Jets are almost back-to-back. Note: this is not about suppression 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?



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

$$\mathbf{k}_{1,2} = \mathbf{P} \pm \tfrac{1}{2}\mathbf{q}$$

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

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

for

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

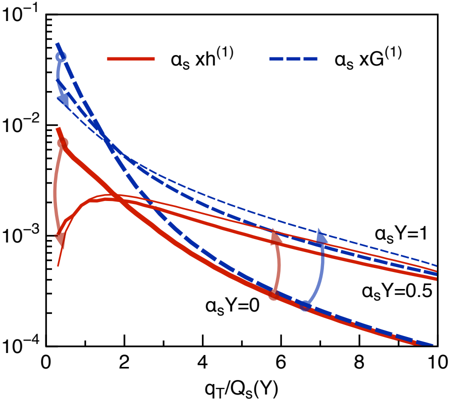
- Quantum evolution at $Y > 0$ is accounted for by solving JIMWLK-B using Langevin method

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

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

$$\langle \eta^a_i(z)\; \eta^b_j(y)\rangle = \alpha_s\, \delta^{ab}\delta_{ij}\delta^{(2)}(z-y).$$

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)



Reminder of McLerran-Venugopalan model results

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

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

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

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

$xh^{(1)} \sim \frac{1}{\alpha_s}\left(\frac{g^4\mu^2}{q^2} - \#\frac{g^8\mu^4}{q^4}\right)$, $xG^{(1)} \sim \frac{1}{\alpha_s}\left(\frac{g^4\mu^2}{q^2} + \#\frac{g^8\mu^4}{q^4}\right)$

Definition of $Q_S(Y)$: $\langle \mathrm{tr} V^\dagger(0)V(r=\sqrt{2}/Q_s)\rangle = N_c e^{-1/2}$

- 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 $q_\perp$, $h_\perp^{(1)}/G^{(1)} \to 0$

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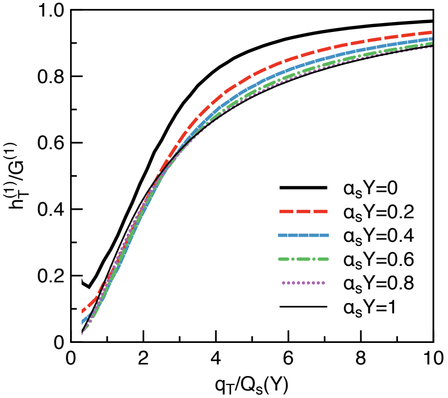

- Fast departure from MV ($\alpha_s Y = 0$)
- Slow evolution towards smaller x
- Emission of small x gluons reduces degree of polarization.
  $q_\perp$ is scaled by exponentially growing $Q_s(Y)$: ratio at fixed $q_\perp$ decreases with rapidity.
- Approximate scaling at small x.

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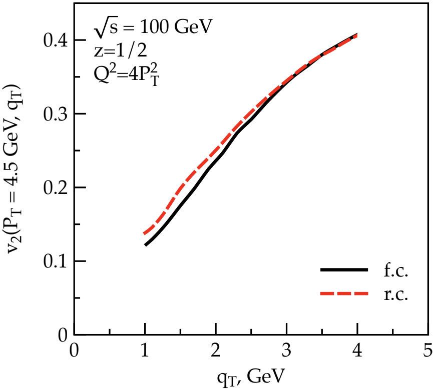
- By analogy to HIC

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

- Fixed coupling results ("f.c."): $\alpha_s = 0.15$
- At a fixed $P_\perp$ no 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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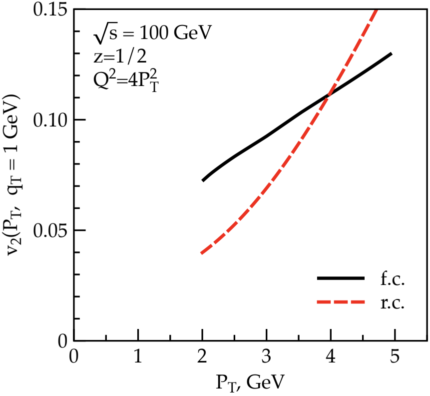

- Fixed coupling results significantly different from running coupling
- Large azimuthal anisotropy in both cases
- Increasing $P_\perp$ increases x and suppresses evolution effects driving v_2 towards its MV value

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

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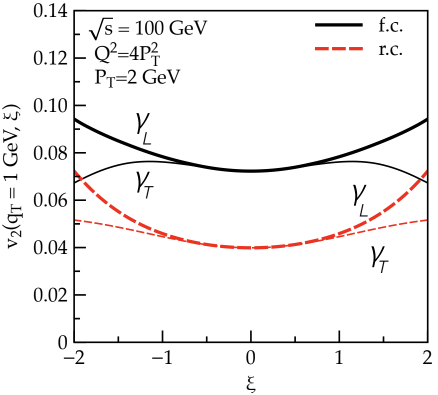
- To probe longitudinal structure

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

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



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- General small x expression for dijet cross section

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

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

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

$$- \langle \mathrm{Tr}\, U(\mathbf{x}_1) U^\dagger(\mathbf{x}_2) \rangle - \langle \mathrm{Tr}\, U(\mathbf{y}_1) U^\dagger(\mathbf{y}_2) \rangle \Big) \Bigg] \quad \uparrow \text{Quadrupole contribution}$$

- For arbitrary $\mathbf{k}_1$ and $\mathbf{k}_2$, one expects presence of non-trivial $\langle \cos 2n\phi \rangle, n \in Z$
- First correction to correlation limit (suppressed by $1/P^2$) includes terms $\propto (\mathbf{q} \cdot \mathbf{P})^4$ and thus results in $\langle \cos 4\phi \rangle \neq 0$

First correction to correlation limit at small x II

- Derivation is tedious but straight forward (see details in 1605.02739)
- Expectation of Wilson lines

$$Q(\mathbf{x}_1, \mathbf{x}_2; \mathbf{x}_2', \mathbf{x}_1') = 1 + \frac{\langle \mathrm{Tr}\, U(\mathbf{x}_1)U^\dagger(\mathbf{x}_1')U(\mathbf{x}_2')U^\dagger(\mathbf{x}_2)\rangle - \langle \mathrm{Tr}\, U(\mathbf{x}_1)U^\dagger(\mathbf{x}_2)\rangle - \langle \mathrm{Tr}\, U(\mathbf{x}_1')U^\dagger(\mathbf{x}_2')\rangle}{N_c}$$

is expanded in series wrt $\mathbf{u} = \mathbf{x}_1 - \mathbf{x}_2$ and $u' = \mathbf{x}_1' - \mathbf{x}_2'$:

$$Q = u_i u_j' \mathcal{G}^{i,j}(v, v') + u_i u_j' u_k' u_l' \mathcal{G}^{i,jkl}(v, v') + u_i u_j u_k u_l' \mathcal{G}^{ijk,l}(v, v') + u_i u_j u_k' u_l' \mathcal{G}^{ij,kl}(v, v') + \cdots$$

- Following combination is relevant (momentum space)

$$\mathcal{G}^{ijmn}(x, q^2) = \mathcal{G}^{i,jmn}(x, q^2) + \mathcal{G}^{ijm,n}(x, q^2) - \frac{2}{3}\mathcal{G}^{ij,mn}(x, q^2)$$

- $\mathcal{G}^{ijmn}(x, q^2)$ results in corrections to isotropic and $\langle \cos 2\phi \rangle$, as well as non-trivial $\langle cos 4\phi \rangle$. I will focus on $\langle \cos 4\phi \rangle$.

- The amplitude of $\cos 4\phi$ is determined by

$$\Phi_2(x,q^2) = -\frac{2N_c}{\alpha_s}\mathfrak{P}_3^{ijmn}\mathcal{G}^{ijmn}(x,q^2)\,.$$

where $\mathfrak{P}_3^{ijmn}$ is projector extracting $\propto \cos 4\phi$

$$\mathfrak{P}_3^{ijmn} = -\frac{1}{6\sqrt{2}}\Big(\delta_{ij}\delta_{mn}+\delta_{im}\delta_{jn}+\delta_{jm}\delta_{in}-2(\Pi_{ij}\Pi_{mn}+\Pi_{im}\Pi_{jn}+\Pi_{jm}\Pi_{in})\Big)\,; \quad \Pi_{ij} = \delta_{ij}-\frac{2q_iq_j}{q^2}$$

- For MV model

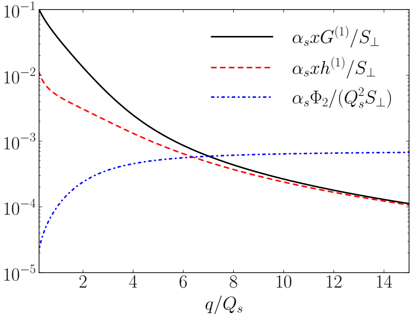
$$\Phi_2(q^2) = \frac{N_c}{\sqrt{2}\,3\pi\alpha_s}\frac{S_\perp}{(2\pi)^2}\int\frac{d|r|}{|r|^3}J_4(|r|\,|q|)\Bigg[\frac{2}{\ln\frac{1}{r^2\Lambda_{\rm IR}^2}}\left\{1-\exp\left(-\frac{Q_s^2r^2}{4}\log\frac{1}{r^2\Lambda_{\rm IR}^2}\right)\right\}$$
$$+\frac{5}{\ln^2\frac{1}{r^2\Lambda_{\rm IR}^2}}\left\{1-\exp\left(-\frac{Q_s^2r^2}{4}\log\frac{1}{r^2\Lambda_{\rm IR}^2}\right)\left[1+\frac{Q_s^2r^2}{4}\log\frac{1}{r^2\Lambda_{\rm IR}^2}\right]\right\}\Bigg]$$

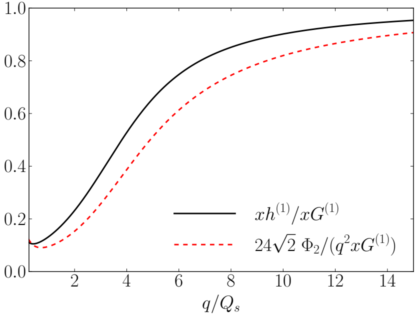
- $\Phi_2(q^2)$ is positive-definite function
- Limiting cases:

$\Lambda_{\rm IR} \ll q \ll Q_s \quad \Phi_2(q^2) \sim (N_c/\alpha_s \log Q_s^2/\Lambda_{\rm IR}^2)\, S_\perp q^2$

$q \gg Q_s, \quad \Phi_2(q^2) \to (N_c/\sqrt{2}\,24\pi\alpha_s)\,(S_\perp/4\pi^2)\,Q_s^2$

MV RESULTS





These functions determine amplitudes of $\cos 2n\phi$ contributions to dijet angular distributions for $n = 0, 1, 2$, respectively.

A. Dumitru and V. S., arXiv:1605.02739

Dijet cross section to this order

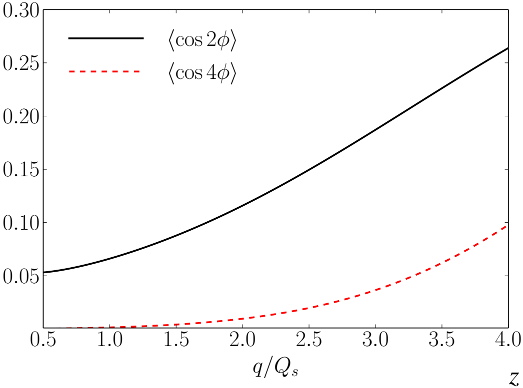
$$\frac{d\sigma^{\gamma_T^* A\to q\bar{q}X}}{d^2k_1 dz_1 d^2k_2 dz_2} = \alpha_s \alpha_{em} e_q^2 \left(z_1^2 + z_2^2\right)\left[\frac{P^4+\epsilon_f^4}{(P^2+\epsilon_f^2)^4}\left(xG^{(1)}(x,q^2) - \frac{2\epsilon_f^2 P^2}{P^4+\epsilon_f^4} xh^{(1)}(x,q^2)\cos 2\phi + \mathcal{O}\left(\frac{1}{P^2}\right)\right) - \frac{48\epsilon_f^2 P^4}{\sqrt{2}\,(P^2+\epsilon_f^2)^6}\Phi_2(x,q^2)\cos 4\phi\right]$$

$$\frac{d\sigma^{\gamma_L^* A\to q\bar{q}X}}{d^2k_1 dz_1 d^2k_2 dz_2} = 8\alpha_s \alpha_{em} e_q^2 z_1 z_2 \epsilon_f^2 \left[\frac{P^2}{(P^2+\epsilon_f^2)^4}\left(xG^{(1)}(x,q^2) + xh^{(1)}(x,q^2)\cos 2\phi + \mathcal{O}\left(\frac{1}{P^2}\right)\right) + \frac{48 P^4}{\sqrt{2}\,(P^2+\epsilon_f^2)^6}\Phi_2(x,q^2)\cos 4\phi\right].$$

A. Dumitru and V. S., arXiv:1605.02739

MV results

$\langle \cos 2\phi \rangle$ and $\langle \cos 4\phi \rangle$ in $\gamma_L^* + A \to q + \bar{q}$ dijet production from MV model:



$z = 1/2$, $P = 4.5 Q_s$

$\langle \cos 4\phi \rangle$ can be safely neglected in first approximation

A. Dumitru and V. S., arXiv:1605.02739

Monte-Carlo Event generator

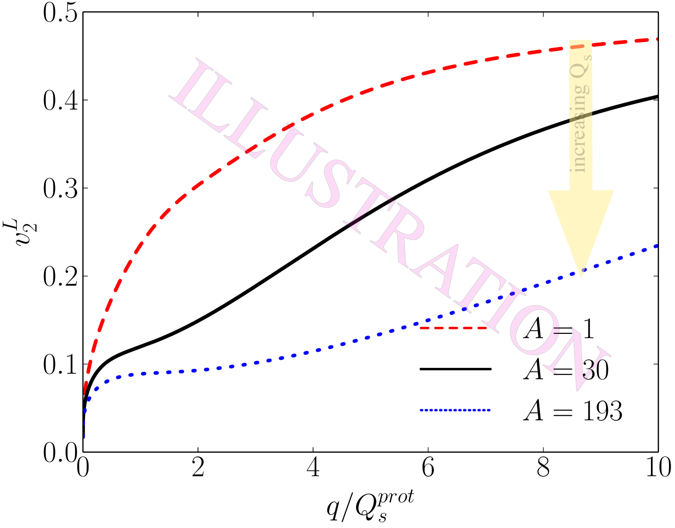
- McDijet: Dijet in DIS event generator
  https://github.com/vskokov/McDijet
- Input: collision energy $\sqrt{s}$ and atomic number A
- Q_s and target area are adjusted according to A
- Output: partons' 4-momentum etc
- Pythia afterburner: partons $\rightarrow$ particles
- Jet reconstruction

Goal is to study feasibility of extracting signal and its dependence on atomic number, A, and collision energy, $\sqrt{s}$

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

A-DEPENDENCE

MV model



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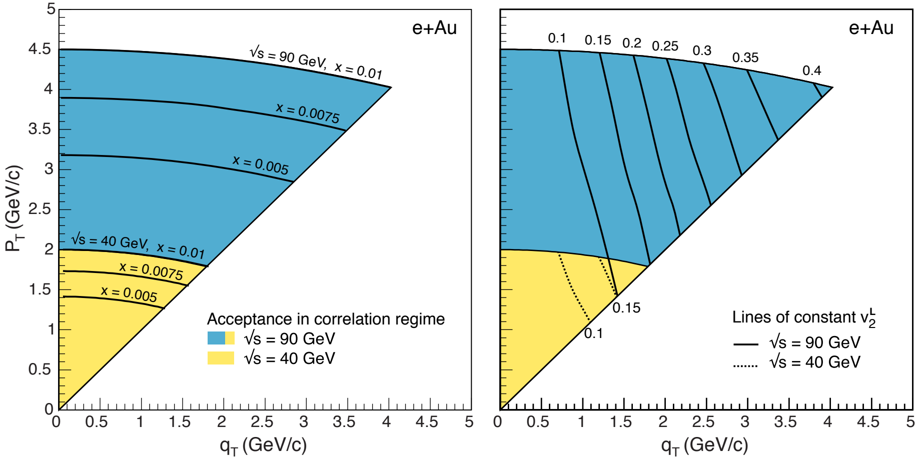
Kinematic range for EIC



- Substantial effect can only be observed at largest energy.
- Magnitude of $P_\perp$ must be sufficiently large to allow jet reconstruction.
- To probe $h^{(1)}$ wide range of $q_\perp$ and $P_\perp$ is required.

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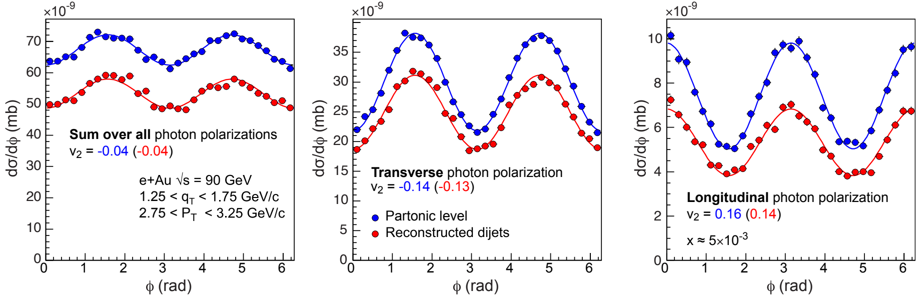
Simulations for eRHIC: no background



- Reconstructed jets reproduce original correlations surprisingly well.
- Amplitude of azimuthal asymmetry is largest if polarization of γ^* is known.
- Sum over all polarizations reduced signal drastically, due to $\pi/2$ phase shift between T and L polarizations

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

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

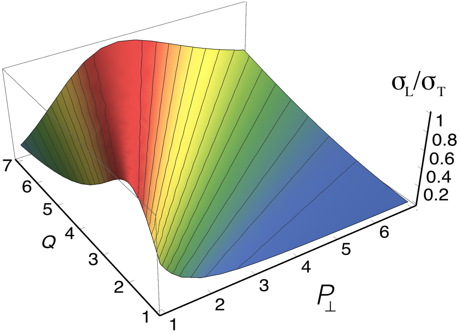
- Selecting dijets within certain range of $P_\perp$ and Q biases T over L

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

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

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

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



- Q and $P_\perp$ provide sufficient leverage to disentangle L and T

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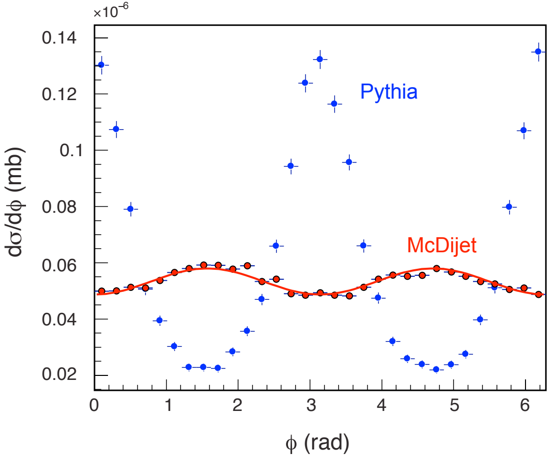

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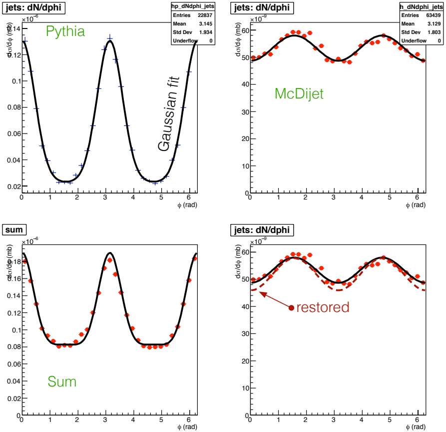

- Pythia background contaminates signal.
- Background contribution is overwhelming.
- Removing background with double Gaussian fit is possible.

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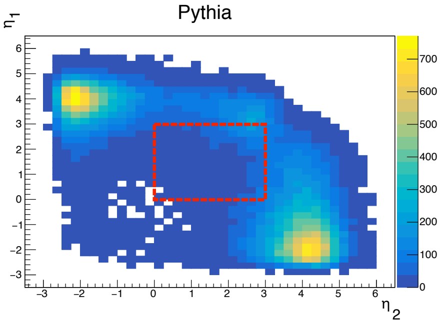
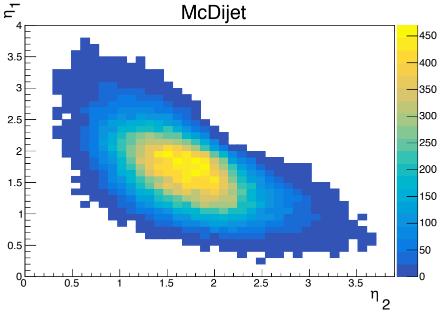
Going more differential I





- Kinematic cuts in rapidity of two jets allow to suppress background contribution

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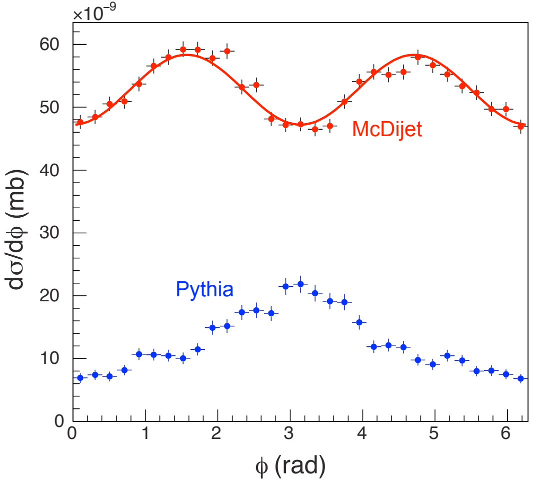
Going more differential II



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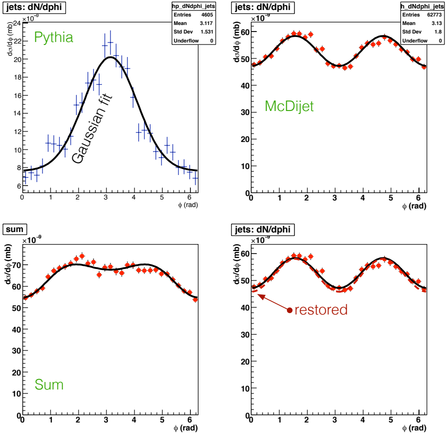
Going more differential III



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Conclusions

In correlation limit:

- DIS dijets to probe WW linearly polarized gluon distribution
- Classical McLerran-Venugopalan model: large relative anisotropy at large momentum, both $G^{(1)}$ and $h_\perp^{(1)}$ are proportional to $1/q_\perp^2$
- Small x evolution in JIMWLK-B: $h^{(1)}$ grows as fast as $G^{(1)}$
- No significant dependence on prescription for α_s
- Simulations and backgrounds: anisotropy is present in MC events summed over polarization and different distributions of q, z, $P_\perp$, $q_\perp$ etc. It is also present after Pythia shower; survives removing Pythia background

First correction to correlations limit:

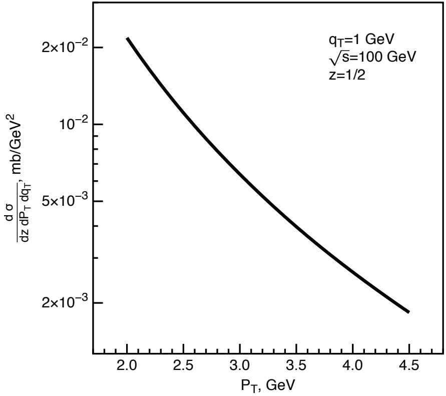
- Nontrivial contribution to $\langle \cos 4\phi \rangle$
- Corresponding amplitude has distinct dependence on q: constant at large q, proportional to q^2 at small q.
- As expected this contribution is suppressed by $1/P^2$ at nearly correlation limit.

Outlook:

- Sudakov factors
- Dijet production from low to moderate x (A. Tarasov and V.S. work in progress)

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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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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D. Boer, P. Mulders, C. Pisano Phys.Rev. D80 (2009) 094017
A. Metz and J. Zhou Phys.Rev. D84 (2011) 051503
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

Weizsäcker-Williams gluon distribution

- Contribution to azimuthal anisotropy of dijet production

$$E_1E_2\frac{d\sigma^{\gamma_L^* A\to q\bar{q}X}}{d^3k_1d^3k_2d^2b} = \alpha_{em}e_q^2\alpha_s\delta\left(x_{\gamma^*}-1\right)z^2(1-z)^2\frac{8\epsilon_f^2P_\perp^2}{(P_\perp^2+\epsilon_f^2)^4}$$

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

$$E_1E_2\frac{d\sigma^{\gamma_T^* A\to q\bar{q}X}}{d^3k_1d^3k_2d^2b} = \alpha_{em}e_q^2\alpha_s\delta\left(x_{\gamma^*}-1\right)z(1-z)(z^2+(1-z)^2)\frac{\epsilon_f^4+P_\perp^4}{(P_\perp^2+\epsilon_f^2)^4}$$

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

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