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Parton tomography: Wigner distributions in nucleon and nuclear targets

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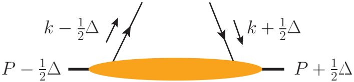
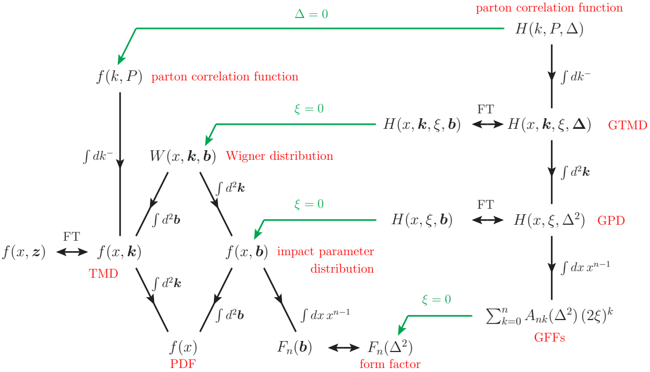
Parton correlator and distributions

Markus Diehl 1512.01328

$$H(k,P,\Delta) = (2\pi)^{-4} \int d^4z\, e^{iz\cdot k}$$
$$\times \left\langle p(P+\frac{1}{2}\Delta) \middle| \bar{q}(-\frac{1}{2}z)\Gamma q(\frac{1}{2}z) \middle| p(P-\frac{1}{2}\Delta) \right\rangle$$





Quark Wigner distribution

$$W(x,\vec{k}_\perp,\vec{b}_\perp)=\frac{1}{2}\int\frac{d^2\vec{b}_\perp}{(2\pi)^2}e^{i\vec{\Delta}_\perp\cdot\vec{b}_\perp}\int\frac{dz^-}{2\pi}e^{iz^-xP^+}\int\frac{d^2\vec{z}_\perp}{(2\pi)^2}e^{-i\vec{z}_\perp\cdot\vec{k}_\perp}$$
$$\times\left\langle p(P+\frac{\Delta_\perp}{2})|\bar{q}(-\frac{z}{2})\Gamma q(\frac{z}{2})|p(P-\frac{\Delta_\perp}{2})\right\rangle$$

- Five dimensional distribution.
- Most complete information for on-shell partons in a Lorentz contracted nucleus.
- Orbital angular momentum introduces correlations between $\vec{k}$ and $\vec{b}_\perp$:

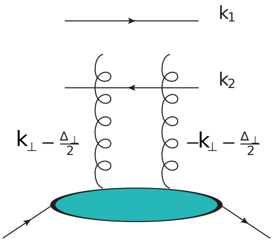
$$L_z == \int dx\, d^2\vec{k}_\perp\, d^2\vec{b}_\perp(\vec{b}_\perp\times\vec{k}_\perp)W(x,\vec{k}_\perp,\vec{b}_\perp)$$

- These correlations can contribute to elliptic flow.

Gluon Wigner distribution at small x from the dipole cross section

$$S(\vec{k},\vec{\Delta}_\perp) = \int \frac{d^2\vec{r}_\perp\, d^2\vec{b}_\perp}{(2\pi)^4} e^{i\vec{\Delta}_\perp\cdot\vec{b}_\perp + i\vec{k}_\perp\cdot\vec{r}_\perp} \left\langle \frac{1}{N_c}\mathrm{Tr}\,U\left(\vec{b}_\perp + \frac{\vec{r}_\perp}{2}\right) U^\dagger\left(\vec{b}_\perp - \frac{\vec{r}_\perp}{2}\right)\right\rangle$$

- The dipole S-matrix provides information on correlations in impact parameter space
- During scattering, dipole size does not change.
- Extra propagator and coupling.

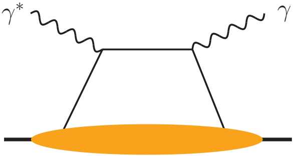


In the small-x limit, the dipole S-matrix is related to the the Fourier transform of the gluon Wigner distribution (or directly to the GTMD) in diffractive dijet production (Hatta, Xiao, Yuan, PRL 116, 202301, 2016).

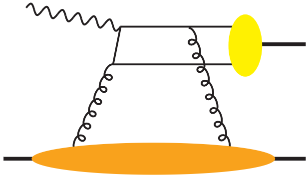
$$xG(\vec{k}_\perp,\vec{\Delta}_\perp) \overset{x\to 0}{\approx} \frac{2N_c}{\alpha_s}\left(k_\perp^2 - \frac{\Delta_\perp^2}{4}\right) S(\vec{k}_\perp,\vec{\Delta}_\perp)\,,$$

Observables

Deeply Virtual Compton Scattering

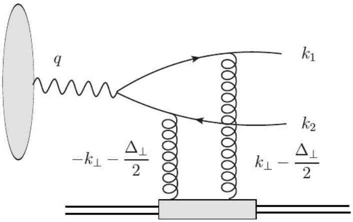


Vector meson production



Exclusive dijets in UPC

Hagiwara, Hatta, Pasechnik, Tasevsky, Teryaev, PRD 96, 034009 (2017).



- Exclusive dijets in UPC are a way to probe the GTMDs.
- The convolution involving the dipole S-matrix components and the light-cone wave function can be analytically inverted in the back to back limit.
- Problem 1: at low transverse momentum there is no hard scale.
- Problem 2: Measuring jets coming from light quarks is very hard at relatively low transverse momentum.

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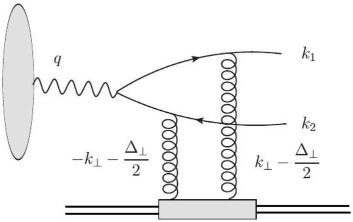

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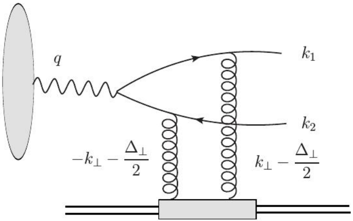
- Problem 1: at low transverse momentum there is no hard scale.
- Problem 2: Measuring jets coming from light quarks is very hard at relatively low transverse momentum.
- What if we use heavy quarks?

Exclusive heavy quark photoproduction in UPC



- Ultraperipheral collisions (UPC), photon is real and has comes from the projectile (nucleus) with Weizsäcker–Williams flux:

$$\frac{dN_\gamma}{d\omega} = \frac{2Z^2\alpha}{\pi\omega}\left[\xi_{jA}K_0(\xi_{jA})K_1(\xi_{jA}) - \frac{\xi_{ja}^2}{2}\left(K_1^2(\xi_{jA}) - K_0^2(\xi_{jA})\right)\right].$$

  with $\xi_{jA} = \omega(R_j + R_A)/\gamma$
- The Z^2 enhancement in the photon flux makes the process much more efficient in probing the Wigner distribution then pp collisions.
- We study the forward direction, such that the contribution to the longitudinal quark momentum is small.

Light-cone Feynman rules

- To calculate the interaction among the photon and the two gluons light-cone Feynman rules.
- The rule for particles on-shell are as in usual Feynman rules (spinors and polarization vectors).
- Each intermediate state denotes a factor

$$\frac{1}{\sum_{\rm in} k^- - \sum_{\rm int} k^- + i\epsilon}$$

  where in denotes initial states and int intermediary ones.
- For each internal line include a factor $\theta(k^+)/k^+$.
- Vertices are changed by a normalization factor, for instance, quark-gluon vertice: $-g\gamma^\mu t^a_{ij}$.
- Each independent momentum must be integrated with a measure

$$\int \frac{dk^+ d^2 k_\perp}{2(2\pi)^3}.$$

Dipole T matrix

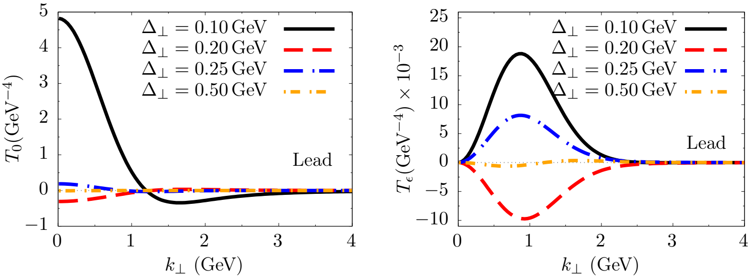
- As a final step, we need the probability of having two gluons from the target.
- It will be given by the Wigner distribution (a.k.a. dipole scattering amplitude) squared.
- Focusing on the first harmonic, we can expand $T = 1 - S$ as:

$$T(\vec{k}_\perp, \vec{\Delta}_\perp) = T_0(k_\perp, \Delta_\perp) + T_\epsilon(k_\perp, \Delta_\perp)\cos 2(\phi_k - \phi_\Delta) + \cdots$$

- The elliptic part is the one that will produce correlations, which can be solely responsible for observed final state asymmetries
- If $|\vec{k}_\perp| \gg |\vec{\Delta}_\perp|$, the isotropic component will be the largest and we can neglect terms with order higher than the elliptic one.

MV model

- For the dipole T-matrix we use the MV model improved for an inhomogeneous target in the transverse plane by Iancu and Rezaeian, Phys. Rev. D 95, 094003, 2017.
- With a large gluon occupation number at small x, the color field is treated as a classical one in the presence of sources.
- The saturation scale Q_s grows with $A^{1/3}$.



- The larger the Δ, the more important the elliptic part is.

Putting it all together

Hadron level cross section:

$$\frac{d\sigma^{Aj}}{d\mathcal{PS}} = \frac{d\sigma^{Aj}}{dy_1\, dy_2\, d^2\vec{P}_\perp\, d^2\vec{\Delta}_\perp}$$
$$= \omega \frac{dN}{d\omega} 2(2\pi)^2 N_c \alpha_{em} e_q^2 z(1-z) \frac{1}{P_\perp^2}$$
$$\times \Big\{ (z^2 + (1-z)^2)\ [A(P_\perp, \Delta_\perp) + B(P_\perp, \Delta_\perp) \cos 2(\phi_P - \phi_\Delta)]^2$$
$$+ \frac{m_f^2}{P_\perp^2}\ [C(P_\perp, \Delta_\perp) + D(P_\perp, \Delta_\perp) \cos 2(\phi_P - \phi_\Delta)]^2 \Big\}\ .$$

where $2\vec{P}_\perp = \vec{k}_{1\perp} - \vec{k}_{2\perp}$.
The above can be thought as the photon to quark pair wavefunction convoluted with target structure functions.

Mass-corrected A and B structure functions

$$A(P_\perp,\Delta_\perp) = \int_0^\infty k_\perp dk_\perp \frac{P_\perp^2}{k_\perp^2 + P_\perp^2 + m_Q^2 + \sqrt{(k_\perp^2 + P_\perp^2 + m_Q^2)^2 - 4P_\perp^2 k_\perp^2}} \times \left[1 + \frac{P_\perp^2 + m_Q^2 - k_\perp^2}{\sqrt{(k_\perp^2 + P_\perp^2 + m_Q^2)^2 - 4P_\perp^2 k_\perp^2}}\right] T_0(k_\perp,\Delta_\perp),$$

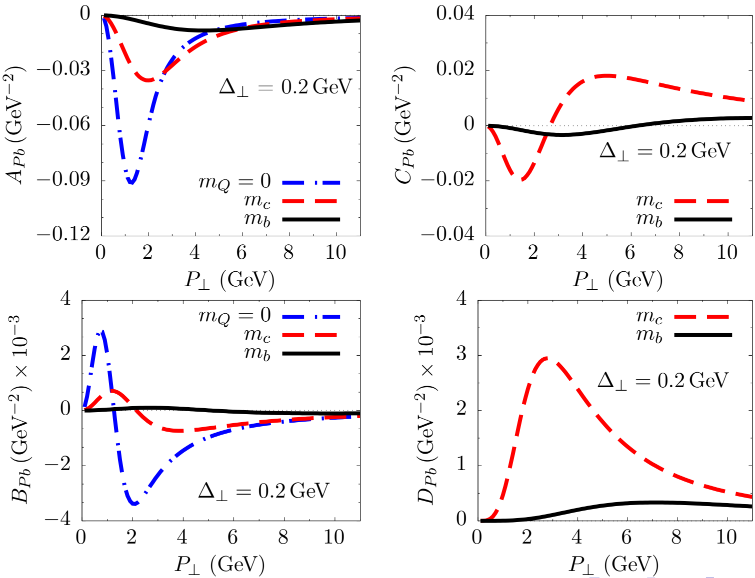
$$B(P_\perp,\Delta_\perp) = \frac{1}{2P_\perp^2}\int_0^\infty \frac{dk_\perp}{k_\perp}(P_\perp^2 - k_\perp^2 - m_Q^2) T_\epsilon(k_\perp,\Delta_\perp) \times \left[\frac{(k_\perp^2 + P_\perp^2 + m_Q^2)^2 - 2k_\perp^2 P_\perp^2}{\sqrt{(k_\perp^2 + P_\perp^2 + m_Q^2)^2 - 4P_\perp^2 k_\perp^2}} - (P_\perp^2 + k_\perp^2 + m_Q^2)\right].$$

New C and D structure functions

$$C(P_\perp, \Delta_\perp) = \int_0^\infty k_\perp dk_\perp \frac{P_\perp^2}{\sqrt{(k_\perp^2 + P_\perp^2 + m_Q^2)^2 - 4P_\perp^2 k_\perp^2}} T_0(k_\perp, \Delta_\perp),$$

$$D(P_\perp, \Delta_\perp) = \int_0^\infty \frac{dk_\perp}{k_\perp} \left[k_\perp^2 + P_\perp^2 + m_Q^2 - \frac{(k_\perp^2 + P_\perp^2 + m_Q^2)^2 - 2P_\perp^2 k_\perp^2}{\sqrt{(k_\perp^2 + P_\perp^2 + m_Q^2)^2 - 4P_\perp^2 k_\perp^2}} \right] \times T_\epsilon(k_\perp, \Delta_\perp).$$

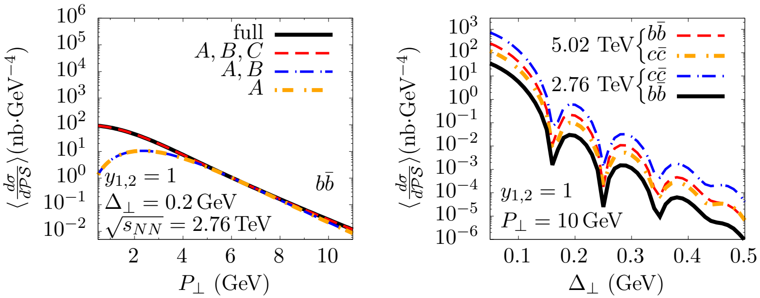
Nuclear structure functions from MV model



Angle-integrated results

- We focus on lead as the target.
- To present our results, we integrate in azimuthal angle.
- We calculate the hadron cross section integrated in angle with exact kinematics.
- However, in the limit $k_{1,2\perp} \to P_\perp$, azimuthal integration produces terms proportional to $2A^2 + B^2$ or $2C^2 + D^2$.
- Since B and D are small compared to A and C this is a measure of the isotropic component.
- We numerically investigated this approximation and found that it has negligible impact on the final result for our choice of small $\Delta_\perp$.

Angle-integrated results



- The A structure function is the dominant one, but where $P_\perp \lesssim 4$ GeV and $P_\perp \gtrsim 7$ GeV, C has a non negligible contribution, and can be measured with an appropriate choice of kinematical cuts.
- By fixing $P_\perp$ we see the dips present in the cross section, as expected in the small-x region.
- The dips (minima) are not affected by changing the c.m. energy; they are a feature of the nucleus structure.

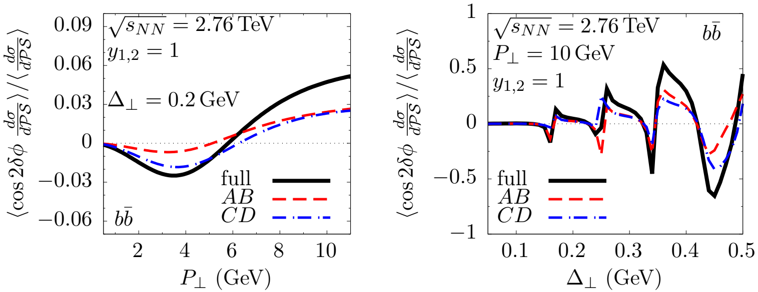
Cosine-weighted angular average

- As seen above, the angular-integrated cross sections discussed above are not very convenient for getting any physics information about the elliptic part.
- Therefore, instead we would like use the cosine-weighted angle average determined as follows:

$$\left\langle \frac{d\sigma^{pA}}{d\mathcal{PS}} \cos 2(\phi_P - \phi_\Delta) \right\rangle = \int_0^{2\pi} d\phi_{P_\perp} \int_0^{2\pi} d\phi_{\Delta_\perp} \cos 2(\phi_P - \phi_\Delta) \frac{d\sigma^{pA}}{dy_1 dy_2\, d^2\vec{P}_\perp\, d^2\vec{\Delta}_\perp}$$

- Roughly speaking, the more positive this observable is, the more $P_\perp$ and $\Delta_\perp$ are parallel (or antiparallel); the negative case correlates with perpendicular vectors.
- If we integrate the cross section averaged by $\cos 2\delta\phi$, only crossed terms (AB and CD) appear in the limit $k_{1,2\perp} \to P_\perp$, allowing us to obtain information on the elliptic component.

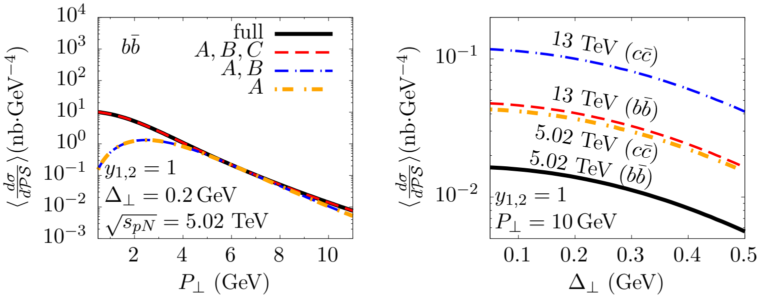
Cosine-weighted angular average results



- The azimuthal angle distribution is easy to measure and is not affected by fragmentation. Also, the ratio is less affected by experimental uncertainties. It is not possible to disentangle the AB and CD contribution, so the measurement is of both B and D simultaneously.
- In the right, we see the rise of the elliptic contribution with $\Delta_\perp$, which occurs due to the rapidly falling of T_0.

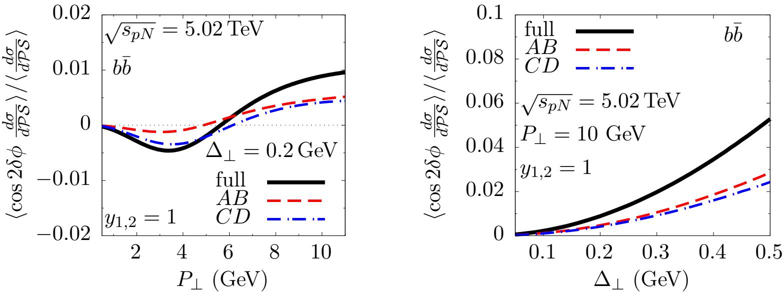
Proton target

- What would change if the target were a proton?
- Smaller cross section.
- The dependence on $\Delta_\perp$ does not show oscillations for the ranges studied.



Proton target – cosine-weighted average

- The dependence on $P_\perp$ is pretty much the same as in the nuclear case.
- Again no oscillations.
- The cosine-weighted average increases steadily with $\Delta_\perp$.



Conclusion

- We derived the analytic expressions at leading order for the calculation of the exclusive heavy quark photoproduction. These are of definite importance to understand the angular correlations between the transverse momenta $k_\perp$ and $\Delta_\perp$ in the GTMD, and can be related to elliptic flow in hadron and/or nuclei collisions.

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- The study of heavy-quark di-jets is relevant in comparison to its light quark equivalent, since it is less affected by fragmentation effects and has a cleaner QCD background.
- Also, it has much smaller theoretical uncertainties w.r.t. higher order terms, as light quark jets suffer from potentially huge corrections.

Future work

- To have some precision predictions for comparison with experimental measurements it is necessary to include fragmentation functions (FF) for the $q\bar{q}$ pair.
- In the case of the charm quark, FFs for D mesons also should be included to know which range of transverse momentum should be looked.
- As for light quarks, it is interesting to include FFs for charged pions, which have a high impact in the cross section.
- Also it is important to study a range of models for the dipole cross section, including some x dependence.

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