DIS dijet production beyond eikonal accuracy

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for Heavy Ion collisions in the QCD phase diagram

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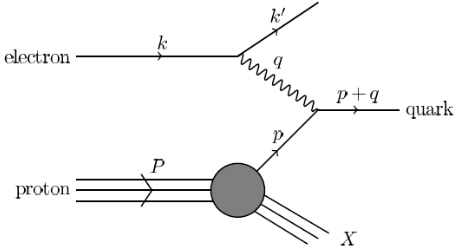
Work in progress in collaboration with Tolga Altinoluk, Guillaume Beuf and Alina Czajka

DIS in QCD

We have three Lorentz invariant quatities

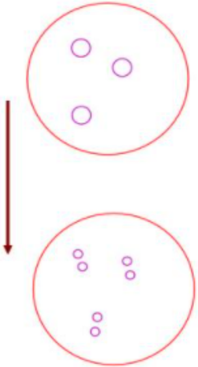
- $q^2 = -Q^2$: virtuality of the incoming photon
- $x = \frac{Q^2}{2PQ}$:longitudinal momentum fraction carried by the parton
- $s \simeq 2PQ$: energy of the colliding system $s = \frac{Q^2}{x}$



Two different ways to go to high energies

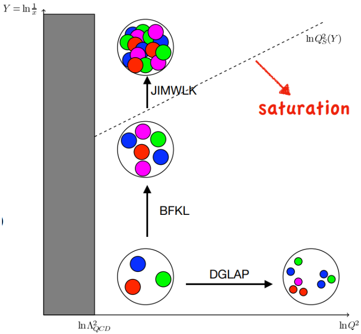
Bjorken limit

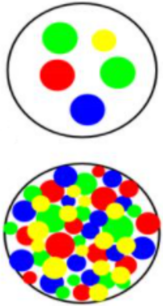
- We take a fixed x and $Q^2 \to \infty$
- Density of partons decreases
- System becomes more dilute
- Evolution given by DGLAP



Regge-Gribov limit

- We take a fixed Q^2 and $x \to 0$
- Density of partons increases
- System becomes more dense
- Causes saturation





Color Glass Condensate (I)

- Regge-Gribov limit: $x \to 0$
- At small $x \to$ saturation
- In this regime we use the Color Glass Condensate to describe a scattering process

The interaction between projectile and the target: each parton coming from the projectile picks up a Wilson line during the interaction

$$\mathcal{U}_R(x) = \mathcal{P}_+ exp\left[ig \int dx^+ T_R^a A_a^-(x^+, x_\perp)\right]$$

Color Glass Condensate (II)

CGC formalism used for dilute-dense scattering so we apply Semi-classical approximation

- Dense target: classical background field $A_a^\mu(x)$
- Dilute projectile: virtual photon treated in perturbation theory

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We also adopt Eikonal approximation which amount to taking the high energy limit $s \to \infty$. Beyond eikonal limit give corrections of order $1/s$. We can obtain this limit boosting the target in following way:

$$A_a^\mu(x) \to \begin{cases} \gamma_t A_a^-\left(\gamma_t x^+, \frac{1}{\gamma_t} x^-, x_\perp\right) \\ \frac{1}{\gamma_t} A_a^+\left(\gamma_t x^+, \frac{1}{\gamma_t} x^-, x_\perp\right) \\ A_a^i\left(\gamma_t x^+, \frac{1}{\gamma_t} x^-, x_\perp\right) \end{cases}$$

Eikonal approximation

The Eikonal approximation is given by:

- $A_a^\mu(x) \propto \delta(x^+)$

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  T. Altinoluk, G. Beuf. A.Czajka, A.Tymowska (2021) [arXiv:2012.03886] see also G.A.Chirilli [arXiv:1807.11435], [arxiv:2101.12744]

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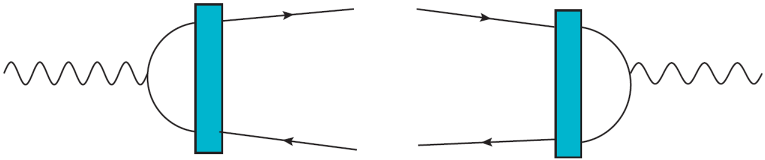
- Taking into account x^- -dependence
  T. Altinoluk, G. Beuf (2021) [arXiv:2109.01620]

Inclusive DIS dijet production

We want to calculate DIS dijet production at next-to eikonal order for the inclusive case

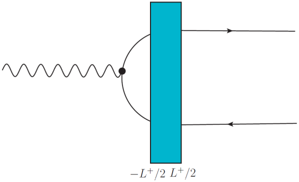


The process will be one of the focus for future EIC experiments.

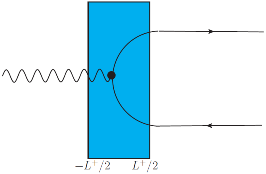
Lower energies at EIC compared to LHC $\rightarrow$ NEik corrections

Diagrams for DIS dijet production at NEik

We need contributions from photon splitting into quark-antiquark pair
First diagrams contributes at both eikonal and next-to eikonal order



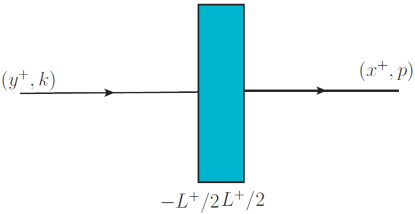
Second diagram contributes only at next-to eikonal order and vanishes when taking the longitudinal polarization of the photon.



Quark propagator at NEik order

The quark propagator through the whole medium is given by:

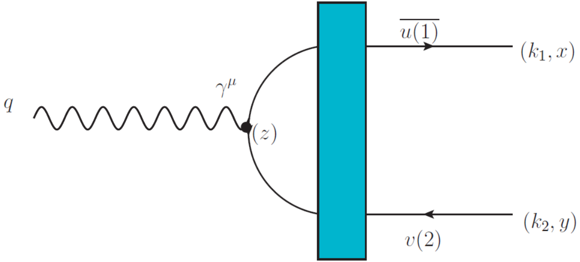
$$
\begin{aligned}
S_F(x,y) = & \int \frac{d^3\underline{p}}{(2\pi)^3} \int \frac{d^3\underline{k}}{(2\pi)^3}\, \theta(p^+)\theta(k^+) e^{-ix\cdot\check{p}}\, e^{iy\cdot\check{k}} \int dz^-\, e^{iz^-(p^+-k^+)} \int d^2\mathbf{z}\, e^{-i\mathbf{z}\cdot(\mathbf{p}-\mathbf{k})} \times \frac{(\check{\not{p}}+m)}{2p^+}\gamma^+ \Bigg\{ \mathcal{U}_F\Big(\frac{L^+}{2}, -\frac{L^+}{2}; \mathbf{z}, z^-\Big) \\
& - \frac{(\mathbf{p}^j+\mathbf{k}^j)}{2(p^+ + k^+)} \int_{-\frac{L^+}{2}}^{\frac{L^+}{2}} dz^+ \Big[\mathcal{U}_F\Big(\frac{L^+}{2}, z^+; \mathbf{z}, z^-\Big) \overleftrightarrow{\mathcal{D}_{\mathbf{z}^j}}\, \mathcal{U}_F\Big(z^+, -\frac{L^+}{2}; \mathbf{z}, z^-\Big) \Big] \\
& - \frac{i}{(p^+ + k^+)} \int_{-\frac{L^+}{2}}^{\frac{L^+}{2}} dz^+ \Big[\mathcal{U}_F\Big(\frac{L^+}{2}, z^+; \mathbf{z}, z^-\Big) \overleftarrow{\mathcal{D}_{\mathbf{z}^j}}\, \overrightarrow{\mathcal{D}_{\mathbf{z}^j}}\, \mathcal{U}_F\Big(z^+, -\frac{L^+}{2}; \mathbf{z}, z^-\Big) \Big] \\
& + \frac{[\gamma^i, \gamma^j]}{4(p^+ + k^+)} \int_{-\frac{L^+}{2}}^{\frac{L^+}{2}} dz^+\, \mathcal{U}_F\Big(\frac{L^+}{2}, z^+; \mathbf{z}, z^-\Big)\, gt\cdot\mathcal{F}_{ij}(\mathbf{z})\, \mathcal{U}_F\Big(z^+, -\frac{L^+}{2}; \mathbf{z}, z^-\Big) \Bigg\} \frac{(\check{\not{k}}+m)}{2k^+}
\end{aligned}
$$



LSZ reduction formula

S-matrix element for the virtual photon splitting into a quark-antiquark pair is

$$S_{q_1\bar{q}_2\leftarrow\gamma*} = -iee_f \frac{Q}{q^+} g^+_\mu \lim_{x^+,y^+\to\infty} \int d^2\mathrm{x} \int dx^- \int d^2\mathrm{y} \int dy^- \int d^4z$$
$$\times\, e^{-iq\cdot z} e^{ik_1\cdot x} e^{ik_2\cdot y}\ \bar{u}(1)\gamma^+ S_F(x,z)_{\beta\alpha}(-\gamma^\mu) S_F(z,y)_{\alpha\delta}\gamma^+ v(2)$$



Amplitudes

We can write the amplitude divided in two contributions.
First the generalized Eikonal contribution where we don't have momentum conservation compared to Eikonal because of common b^- in the Wilson lines

$$\mathcal{S}^{\mathrm{L-Eik}}_{q_1\bar{q}_2\leftarrow\gamma*} = -\frac{ee_f\, Q}{2\pi}\delta_{h_2,-h_1}\theta\Big(q^+ + k_1^+ - k_2^+\Big)\theta\Big(q^+ - k_1^+ + k_2^+\Big)\int db^-\, e^{ib^-(k_1^+ + k_2^+ - q^+)}$$

$$\times \int_{v,w} e^{-i\mathrm{v}\cdot\mathbf{k_1}}\, e^{-i\mathrm{w}\cdot\mathbf{k_2}}\, \frac{\sqrt{k_1^+ k_2^+}}{(q^+)^2}(q^+ + k_1^+ - k_2^+)(q^+ - k_1^+ + k_2^+)K_0(\hat{Q}|\mathrm{v}-\mathrm{w}|)\Big(\mathcal{U}_F(\mathrm{v},b^-)\mathcal{U}_F^\dagger(\mathrm{w},b^-) - 1\Big)$$

where we have

$$\hat{Q} = \sqrt{m^2 + Q^2\frac{(q^+ + k_1^+ - k_2^+)(q^+ - k_1^+ + k_2^+)}{4(q^+)^2}}$$

$$\bar{Q} = \sqrt{m^2 + Q^2\frac{k_1^+ k_2^+}{(q^+)^2}}$$

Amplitudes

$$i\mathcal{M}^{\mathrm{L-NEik}}_{q_1\bar{q}_2\leftarrow\gamma*} = -\frac{iee_f\, Q}{2\pi}\delta_{h_2,-h_1}2\pi\delta(k_2^+ + k_1^+ - q^+)\theta(k_1^+)\theta(k_2^+)\int d^2\mathrm{v}\int d^2\mathrm{w}\, e^{-i\mathrm{v}\cdot\mathbf{k_1}}\, e^{-i\mathrm{w}\cdot\mathbf{k_2}}\, \frac{4\sqrt{k_1^+k_2^+}k_1^+k_2^+}{(k_1^+ + k_2^+)^2}$$

$$\times\Bigg\{K_0(\bar{Q}|\mathrm{w}-\mathrm{v}|)$$

$$\times\Bigg[\frac{1}{2k_1^+}\int_{-\frac{L^+}{2}}^{\frac{L^+}{2}} dv^+\,\mathcal{U}_F\Big(\frac{L^+}{2},v^+;\mathrm{v}\Big)\Big(-ih_1\epsilon^{ij}gt\cdot\mathcal{F}_{ij}(v) - \frac{\mathrm{k}_1^j}{2}\overleftrightarrow{\mathcal{D}_{\mathrm{v}j}} - i\overleftarrow{\mathcal{D}_{\mathrm{v}j}}\,\overrightarrow{\mathcal{D}_{\mathrm{v}j}}\Big)\mathcal{U}_F\Big(v^+,-\frac{L^+}{2};\mathrm{v}\Big)\mathcal{U}_F^\dagger(\mathrm{w})$$

$$+\frac{1}{2k_2^+}\int_{-\frac{L^+}{2}}^{\frac{L^+}{2}} dw^+\,\mathcal{U}_F(\mathrm{v})\mathcal{U}_F^\dagger\Big(w^+,-\frac{L^+}{2};\mathrm{w}\Big)\Big(-ih_1\epsilon^{ij}gt\cdot\mathcal{F}_{ij}(w) + \frac{\mathrm{k}_2^j}{2}\overleftrightarrow{\mathcal{D}_{\mathrm{w}j}} - i\overleftarrow{\mathcal{D}_{\mathrm{w}j}}\,\overrightarrow{\mathcal{D}_{\mathrm{w}j}}\Big)\mathcal{U}_F^\dagger\Big(\frac{L^+}{2},w^+;\mathrm{w}\Big)\Bigg]$$

$$+\frac{i}{2}\frac{\mathrm{w}^j-\mathrm{v}^j}{|\mathrm{w}-\mathrm{v}|}\,\bar{Q}K_1(\bar{Q}|\mathrm{w}-\mathrm{v}|)$$

$$\times\Bigg[\frac{1}{2k_1^+}\int_{-\frac{L^+}{2}}^{\frac{L^+}{2}} dv^+\,\mathcal{U}_F\Big(\frac{L^+}{2},v^+;\mathrm{v}\Big)\overleftrightarrow{\mathcal{D}_{\mathrm{v}j}}\mathcal{U}_F\Big(v^+,-\frac{L^+}{2};\mathrm{v}\Big)\mathcal{U}_F^\dagger(\mathrm{w})$$

$$+\frac{1}{2k_2^+}\int_{-\frac{L^+}{2}}^{\frac{L^+}{2}} dw^+\,\mathcal{U}_F(\mathrm{v})\mathcal{U}_F^\dagger\Big(w^+,-\frac{L^+}{2};\mathrm{w}\Big)\overleftrightarrow{\mathcal{D}_{\mathrm{w}j}}\mathcal{U}_F^\dagger\Big(\frac{L^+}{2},w^+;\mathrm{w}\Big)\Bigg]\Bigg\}$$

$$i\mathcal{M}^{\mathrm{L-Eik-corr}}_{q_1\bar{q}_2\leftarrow\gamma*} = -\frac{iee_f\, Q}{2\pi}\delta_{h_2,-h_1}2\pi\delta(k_1^+ + k_2^+ - q^+)\theta(k_1^+)\theta(k_2^+)$$

$$\times\int d^2\mathrm{v}\int d^2\mathrm{w}\, e^{-i\mathrm{v}\cdot\mathbf{k_1}}\, e^{-i\mathrm{w}\cdot\mathbf{k_2}}\,\frac{2\sqrt{k_1^+k_2^+}}{(q^+)^2}(k_2^+ - k_1^+)$$

$$\times\Bigg[K_0(\bar{Q}|\mathrm{w}-\mathrm{v}|) - 2k_1^+k_2^+\frac{Q^2|\mathrm{w}-\mathrm{v}|}{(q^+)^2}K_1(\bar{Q}|\mathrm{w}-\mathrm{v}|)\Bigg]\Big(\mathcal{U}_F(\mathrm{v},b^-)\overleftrightarrow{\partial_-}\mathcal{U}_F^\dagger(\mathrm{w},b^-)\Big)\Big|_{b^-=0}$$

Amplitude for transverse polarization

$$i\mathcal{M}^{\mathrm{T-Eik-Gen}}_{q_1\bar{q}_2\leftarrow\gamma*} = -\frac{iee_f\,\epsilon^n_\lambda}{2\pi}\theta(q^+ + k_1^+ - k_2^+)\theta(q^+ - k_1^+ + k_2^+)\int db^-\, e^{ib^-(k_1^+ + k_2^+ - q^+)}\int_{\mathrm{v,w}} e^{-i\mathrm{v}\cdot\mathbf{k_1}}\, e^{-i\mathrm{w}\cdot\mathbf{k_2}}$$

$$\frac{i}{2q^+}\bar{u}(1)\gamma^+\Big[2\gamma^n mq^+ K_0(\hat{Q}|\mathrm{w}-\mathrm{v}|) - \Big(4ih_1\epsilon^{mn}q^+ - 2\delta^{mn}(k_1^+ - k_2^+)\Big)\frac{i\hat{Q}(\mathrm{w}^m - \mathrm{v}^m)}{|\mathrm{w}-\mathrm{v}|}K_1(\hat{Q}|\mathrm{w}-\mathrm{v}|)\Big]$$

$$\times\Big(\mathcal{U}_F(\mathrm{v},b^-)\mathcal{U}_F^\dagger(\mathrm{w},b^-) - 1\Big)v(2)$$

with

$$\hat{Q} = \sqrt{m^2 + Q^2\frac{(q^+ + k_1^+ - k_2^+)(q^+ - k_1^+ + k_2^+)}{4(q^+)^2}}$$

$$\begin{aligned}\epsilon_T^+ &= 0\\ \epsilon_T^- &= \frac{\mathrm{q}^k}{q^+}\epsilon^k_\lambda = 0\\ \epsilon_T^k &= \epsilon^k_\lambda\end{aligned}$$

Amplitude for transverse polarization: NEik corrections

$$
\begin{aligned}
i\mathcal{M}^{\mathrm{bessel-T-NEik}}_{q_1\bar{q}_2\leftarrow\gamma^*} &= \frac{ee_f\,\epsilon^n_\lambda}{2\pi}\theta(k_1^+)\theta(k_2^+)2\pi\delta(k_1^++k_2^+-q^+)\int d^2\mathrm{v}\int d^2\mathrm{w}\, e^{-i\mathrm{v}\cdot\mathrm{k_1}}\, e^{-i\mathrm{w}\cdot\mathrm{k_2}}\;\bar{u}(1)\gamma^+\\
&\times\Bigg\{\Bigg[\gamma^n mK_0(\bar{Q}|\mathrm{w}-\mathrm{v}|)-\Big(2ih_1\epsilon^{mn}-\delta^{mn}\frac{(k_1^+-k_2^+)}{q^+}\Big)\frac{i\bar{Q}(\mathrm{w}^m-\mathrm{v}^m)}{|\mathrm{w}-\mathrm{v}|}K_1(\bar{Q}|\mathrm{w}-\mathrm{v}|)\Bigg]\\
&\times\Bigg[\frac{1}{2k_1^+}\int_{-\frac{L^+}{2}}^{\frac{L^+}{2}}dv^+\,\mathcal{U}_F\Big(\frac{L^+}{2},v^+;\mathrm{v}\Big)\\
&\qquad\times\Big(-ih_1\epsilon^{ij}gt\cdot\mathcal{F}_{ij}(v)-\frac{\mathrm{k}_1^j}{2}\overleftrightarrow{\mathcal{D}_{\mathrm{v}^j}}-i\overleftarrow{\mathcal{D}_{\mathrm{v}^j}}\,\overrightarrow{\mathcal{D}_{\mathrm{v}^j}}\Big)\mathcal{U}_F\Big(v^+,-\frac{L^+}{2};\mathrm{v}\Big)\mathcal{U}_F^\dagger(\mathrm{w})\\
&+\frac{1}{2k_2^+}\int_{-\frac{L^+}{2}}^{\frac{L^+}{2}}dw^+\,\mathcal{U}_F(\mathrm{v})\mathcal{U}_F^\dagger\Big(w^+,-\frac{L^+}{2};\mathrm{w}\Big)\\
&\qquad\times\Big(ih_2\epsilon^{ij}gt\cdot\mathcal{F}_{ij}(w)+\frac{\mathrm{k}_2^j}{2}\overleftrightarrow{\mathcal{D}_{\mathrm{w}^j}}-i\overleftarrow{\mathcal{D}_{\mathrm{w}^j}}\,\overrightarrow{\mathcal{D}_{\mathrm{w}^j}}\Big)\mathcal{U}_F^\dagger\Big(\frac{L^+}{2},w^+;\mathrm{w}\Big)\Bigg]\\
&+\Bigg[\frac{i\bar{Q}(\mathrm{w}^j-\mathrm{v}^j)}{2|\mathrm{w}-\mathrm{v}|}K_1(\bar{Q}|\mathrm{w}-\mathrm{v}|)\gamma^n m\\
&-\frac{1}{2}\Big(2ih_1\epsilon^{mn}-\delta^{mn}\frac{(k_1^+-k_2^+)}{q^+}\Big)\Bigg(\frac{\bar{Q}}{|\mathrm{w}-\mathrm{v}|}\Big(\delta^{mj}-\frac{2(\mathrm{w}^m-\mathrm{v}^m)(\mathrm{w}^j-\mathrm{v}^j)}{(\mathrm{w}-\mathrm{v})^2}\Big)K_1(\bar{Q}|\mathrm{w}-\mathrm{v}|)\\
&-\frac{\bar{Q}^2(\mathrm{w}^m-\mathrm{v}^m)(\mathrm{w}^j-\mathrm{v}^j)}{(\mathrm{w}-\mathrm{v})^2}K_0(\bar{Q}|\mathrm{w}-\mathrm{v}|)\Bigg)\Bigg]\\
&\times\Bigg[\frac{1}{2k_1^+}\int_{-\frac{L^+}{2}}^{\frac{L^+}{2}}dv^+\,\mathcal{U}_F\Big(\frac{L^+}{2},v^+;\mathrm{v}\Big)\overleftrightarrow{\mathcal{D}_{\mathrm{v}^j}}\mathcal{U}_F\Big(v^+,-\frac{L^+}{2};\mathrm{v}\Big)\mathcal{U}_F^\dagger(\mathrm{w})\\
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\end{aligned}
$$

Amplitude for transverse polarization: NEik corrections

$$i\mathcal{M}^{\text{bef}}_{q_1\bar{q}_2\leftarrow\gamma*} = -iee_f\,\epsilon^n_\lambda\theta(k_1^+)\theta(k_2^+)2\pi\delta(k_1^++k_2^+-q^+)\frac{L^+}{2}\frac{(-i)}{4k_1^+k_2^+}$$
$$\times\int d^2\mathrm{v}e^{-i\mathrm{v}\cdot(\mathbf{k_1}+\mathbf{k_2})}\bar{u}(1)\gamma^+v(2)\Big[2ih_1\epsilon^{mn}(k_1^++k_2^+)-\delta^{mn}(k_1^+-k_2^+)\Big]\Big(\mathcal{U}_F(\mathrm{v})\overleftrightarrow{\partial_{\mathrm{v}^m}}\mathcal{U}_F^\dagger(\mathrm{v})\Big)$$

$$i\mathcal{M}^{\text{bef}-\text{T}-\text{Eik}-\text{corr}}_{q_1\bar{q}_2\leftarrow\gamma*} = -\frac{iee_f\,\epsilon^n_\lambda}{2\pi}\theta(q^++k_1^+-k_2^+)\theta(q^+-k_1^++k_2^+)\int db^-\,e^{ib^-(k_1^++k_2^+-q^+)}$$
$$\times\int d^2\mathrm{v}\int d^2\mathrm{w}\,e^{-i\mathrm{v}\cdot\mathbf{k_1}}\,e^{-i\mathrm{w}\cdot\mathbf{k_2}}\,\frac{i}{2q^+}\bar{u}(1)\gamma^+\Bigg\{\Bigg[i\gamma^n mq^+(k_1^+-k_2^+)\frac{2Q^2}{(q^+)^2}|\mathrm{v}-\mathrm{w}|K_1(\hat{Q}|\mathrm{v}-\mathrm{w}|)$$
$$+2\frac{(\mathrm{v}^n-\mathrm{w}^n)}{|\mathrm{v}-\mathrm{w}|}\hat{Q}K_1(\hat{Q}|\mathrm{v}-\mathrm{w}|)-\Big(2ih_1\epsilon^{mn}q^+-\delta^{mn}(k_1^+-k_2^+)\Big)(\mathrm{v}^m-\mathrm{w}^m)\frac{Q^2(k_1^+-k_2^+)}{2(q^+)^2}K_0(\hat{Q}|\mathrm{v}-\mathrm{w}|)\Bigg]$$
$$\times\,\mathcal{U}_F(\mathrm{v},b^-)\overleftrightarrow{\partial_-}\mathcal{U}_F^\dagger(\mathrm{w},b^-)\Bigg\}_{\delta\beta}v(2)$$

$$i\mathcal{M}^{T(in)}_{q_1\bar{q}_2\leftarrow\gamma*} = -ee_f\,\epsilon^n_\lambda(q)\theta(k_1^+)\theta(k_2^+)2\pi\delta(k_1^++k_2^+-q^+)\int d^2\mathrm{z}\int_{-L^+/2}^{L^+/2}dz^+e^{-i\mathrm{z}\cdot(\mathbf{k_1}+\mathbf{k_2})}e^{-iz^+(q^--k_1^--k_2^-)}$$
$$\times\,2\sqrt{k_1^+k_2^+}\delta_{h_1,-h_2}\Bigg\{\mathcal{U}_F\Big(\frac{L^+}{2},z^+;\mathrm{z}\Big)\Bigg(2i\epsilon^{in}\Big(h_1\frac{\overleftarrow{D}_{\mathrm{z}^i}}{2k_1^+}+h_2\frac{\overrightarrow{D}_{\mathrm{z}^i}}{2k_2^+}\Big)+\Big(\frac{\overleftarrow{D}_{\mathrm{z}^n}}{2k_1^+}+\frac{\overrightarrow{D}_{\mathrm{z}^n}}{2k_2^+}\Big)\Bigg)\mathcal{U}_F^\dagger\Big(\frac{L^+}{2},z^+;\mathrm{z}\Big)\Bigg\}$$

Outlook

- We computed the amplitudes for the case of photon longitudinal and transverse polarization for DIS dijet production at full NEik order from the gluon background field
- Next-to eikonal corrections include:
  - Relaxing the shockwave approximation → transverse motion through the target
  - Including interactions with transverse component of the background field
  - Taking into account z^--dependence → effects of longitudinal momentum exchange with the target
- Computation of the cross section for longitudinal and transverse polarization of the photon (in progress)
- NEik effect from the quark background field not yet included

Thank you for your attention