TOWARDS HIGHER-ORDER ACCURACY IN LCPT

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Work in progress
see also T. Lappi, RP **Annals of Physics** (2017) 379, 34-66

Initial Stages, September 20, 2017

Outline of the talk

European Research Council
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Motivation

Develop an approach to automatize higher-order LCPT computations in CGC framework

A test bench

Full NLO correction to the (DIS) $\gamma^*_{\mathrm{T/L}} \to q\bar{q}$ LC wave-functions

DIS cross-section at NLO

Example: full result for γ^*_{L} case

Outlook

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- LCPT[1] computations of small-x scattering processes in the CGC picture slowly approaching the NLO
  - The inclusive DIS cross-section (Beuf: arXiv:1606.00777)
  - Small-x evolution equations (Balitsky, Chirilli: arXiv:0710.4330)
  - ...

[1] Hamiltonian perturbation theory in the light-cone form (LCPT)

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- Problem in LCPT approach
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- Solution: a new formulation for LCPT computations
  - Easy to implement and can be fully automatized (in all orders!)

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- Full perturbative Fock state decomposition for γ^*

$$|\gamma^*\rangle_i = \sqrt{Z_{\gamma^*}}\left[|\gamma^*\rangle_b + PS_{(2)}\psi^{\gamma^*\to q\bar{q}}|q\bar{q}\rangle + PS_{(3)}\psi^{\gamma^*\to q\bar{q}g}|q\bar{q}g\rangle + \dots\right]$$

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- Compute the NLO i.e. $\mathcal{O}(eg^2)$ QCD corrections to $|\gamma^*\rangle_i$ in momentum $(p^+, \mathbf{p})$-space
  - $q\bar{q}$-sector: one-loop virtual corrections
  - $q\bar{q}g$-sector: radiative corrections

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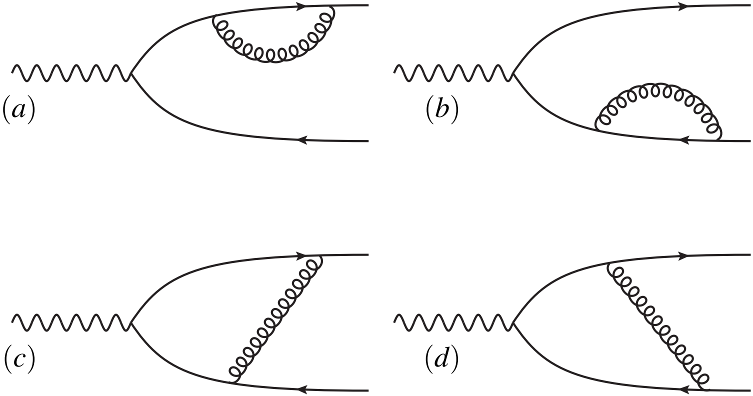
  - $q\bar{q}$-sector: one-loop virtual corrections
  - $q\bar{q}g$-sector: radiative corrections
- Note: no UV renormalization at this order $\Rightarrow \sigma^{\gamma^*_{\mathrm{T/L}}}$ is scheme independent!

- $q\bar{q}$-sector: LC diagrams contributing to γ_{T}^{*} LCWF at NLO



Computation of (a)-(d) in practice:

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Computation of (a)-(d) in practice:

- Construct the LCWF using LCPT rules
- Handle the UV-divergent $\mathbf{k}$-integrals and numerator γ-algebra
  - **Conventional Dim. Reg.** (CDR) scheme: both observed and unobserved particles and momenta are continued to d dimension
  - **Four Dimensional Helicity** (FDH) scheme: momenta of unobserved particles[2] are continued to $d > 4$ and observed particles are kept in 4d

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- Regulate the longitudinal k^+-integrals with the momentum cut-off

$$k^+ > \alpha q^+, \quad \text{where} \quad \alpha > 0$$

[2]Unobserved states are treated as $d_s > d$. Once the tensoral algebra is done the limit $d_s \to 4$ can be taken!

Standard "covariant style" computation (Beuf. arXiv:1606.00777):

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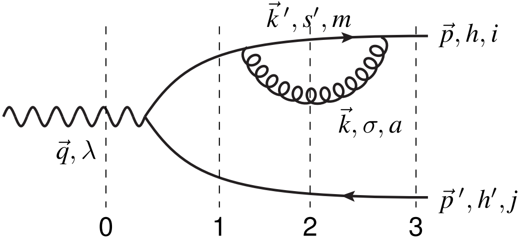
$$k^+/q^+ = z'$$

$$p^+/q^+ = z$$

$$p'^+ = (1-z)q^+$$

$$\overline{Q}^2 = z(1-z)Q^2$$



$$\psi_{(a)}^{\gamma_T^* \to q\bar{q}} = \frac{-ee_f g^2 C_F \delta^{ij}}{16\pi (q^+)^2} \int_\alpha^z \frac{\mathrm{d}z'}{zz'(z-z')} \int \frac{\mathrm{d}^{d-2}\mathbf{k}}{(2\pi)^{d-2}} \frac{\mathrm{num}|_a}{\Delta_{01}^- \Delta_{02}^- \Delta_{03}^-}$$

- The LC energy denominators

$$\Delta_{01}^- = \Delta_{03}^- = \frac{1}{(-2q^+)z(1-z)} \left(\mathbf{p}^2 + \overline{Q}^2\right)$$

$$\Delta_{02}^- = \frac{z}{(-2q^+)z'(z-z')} \left[\mathbf{m}^2 + \frac{z'(z-z')}{z^2(1-z)} (\mathbf{p}^2 + \overline{Q}^2)\right]$$

- The numerator

$$\mathrm{num}|_a = \sum_{\sigma,s',s} \varepsilon^{\mu}_{\sigma}(k)\varepsilon^{*\nu}_{\sigma}(k)\left[\bar{u}_h(p)\gamma_\mu \underbrace{u_{s'}(k')\bar{u}_{s'}(k')}_{=\not{k}'}\gamma_\nu \underbrace{u_s(p)\bar{u}_s(p)}_{=\not{p}}\not{\varepsilon}_\lambda(q)v_{h'}(p')\right]$$

- 4-momentum not conserved $\Rightarrow \not{k}' = \not{p} - \not{k} + (k^- + k'^- - p^+)\gamma^+$
- Light-cone γ-algebra is difficult to automatize

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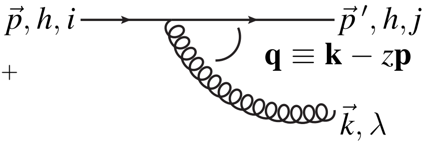
- 4-momentum not conserved $\Rightarrow \not{k}' = \not{p} - \not{k} + (k^- + k'^- - p^+)\gamma^+$
- Light-cone γ-algebra is difficult to automatize
  - $\Rightarrow$ Full "(a) + (b) + (c) + (d)": long and complicated "brute force" calculation

Urgent need for a simpler approach!

- Systematic approach to automatise LCPT computations
  - Decompose the vertices to symmetric and anti-symmetric part:

$$k^+ = zp^+$$

$$p'^+ = (1-z)p^+$$



$$\bar{u}_h(p')\not{\epsilon}^*_\lambda(k)u_h(p) \overset{d=4}{=} \frac{2}{z\sqrt{1-z}}\left[\left(1-\frac{z}{2}\right)\delta^{ij} + ih\frac{z}{2}\epsilon^{ij}\right]\mathbf{q}^i\epsilon^{*j}_\lambda \qquad (1)$$

$$\bar{u}_h(p')\not{\epsilon}^*_\lambda(k)u_h(p) \overset{d\neq 4}{=} \left[a(z)\bar{u}_h\gamma^+u_h\delta^{ij} + b(z)\bar{u}_h\gamma^+[\gamma^i,\gamma^j]u_h\right]\mathbf{q}^i\epsilon^{*j}_\lambda \qquad (2)$$

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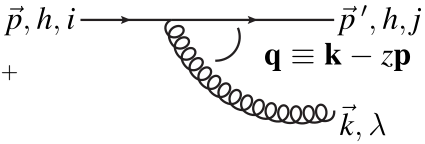

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    - Step1: Compute $d=4$ part with (1)

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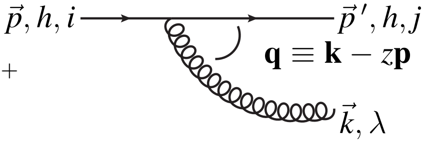

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  - Step1: Compute $d=4$ part with (1)
  - Step2: Compute $d\neq 4$ rational parts with (2)

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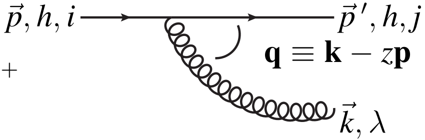

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  - Step1: Compute $d=4$ part with (1)
  - Step2: Compute $d \neq 4$ rational parts with (2)
  - Step3: After Step2 use $[\gamma^i,\gamma^j]u_h(p) \overset{d=4}{=} -2ih\epsilon^{ij}u_h(p)$

Results: "(a) + (b) + (c) + (d)" for γ_{T}^{*} in FDH and CDR schemes

erc

$$\psi_{(\mathrm{NLO})}^{\gamma_{\mathrm{T}}^{*}\to q\bar{q}}\Big|_{\mathrm{FDH}} = \psi_{\mathrm{LO}}^{\gamma_{\mathrm{T}}^{*}\to q\bar{q}}(\mathbf{p},z)\left(\frac{g_{\mathrm{R}}^{2}C_{\mathrm{F}}}{8\pi^{2}}\right)\left\{\left[\frac{3}{2}+\log\left(\frac{\alpha}{z}\right)+\log\left(\frac{\alpha}{1-z}\right)\right]C_{\mathrm{full}} + \frac{1}{2}\log^{2}\left(\frac{z}{1-z}\right)-\frac{\pi^{2}}{3}+\frac{5}{2}\right\}+\mathcal{O}(\varepsilon)$$

$$C_{\mathrm{full}} = \frac{1}{\varepsilon_{\overline{\mathrm{MS}}}}+\log\left(\frac{\mu^{2}}{\overline{Q}^{2}}\right)+\left(\frac{\overline{Q}^{2}-\mathbf{p}^{2}}{\mathbf{p}^{2}}\right)\log\left(\frac{\mathbf{p}^{2}+\overline{Q}^{2}}{\overline{Q}^{2}}\right)$$

$$\psi_{(\mathrm{NLO})}^{\gamma_{\mathrm{T}}^{*}\to q\bar{q}}\Big|_{\mathrm{CDR}} = \psi_{\mathrm{LO}}^{\gamma_{\mathrm{T}}^{*}\to q\bar{q}}(\mathbf{p},z)\left(\frac{g_{\mathrm{R}}^{2}C_{\mathrm{F}}}{8\pi^{2}}\right)\left\{\left[\frac{3}{2}+\log\left(\frac{\alpha}{z}\right)+\log\left(\frac{\alpha}{1-z}\right)\right]C_{\mathrm{full}} + \frac{1}{2}\log^{2}\left(\frac{z}{1-z}\right)-\frac{\pi^{2}}{3}+\frac{5}{2}+\frac{1}{2}\right\}+\mathcal{O}(\varepsilon)$$

Consistent with Beuf: arXiv:1606.00777

- $q\bar{q}g$-sector: straightforward computation for $\psi^{\gamma^*_{\mathrm{T/L}} \to q\bar{q}g}$
  - Example: full result for γ^*_{L} (in FDH scheme)

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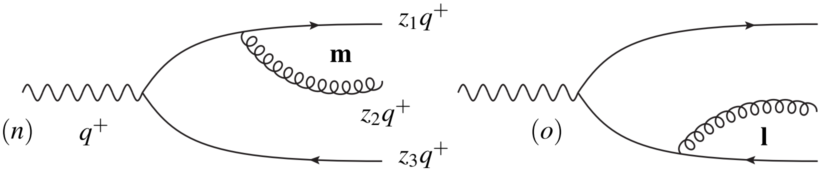

$$\psi^{\gamma^*_{\mathrm{L}} \to q\bar{q}g}_{\mathrm{NLO}}\Big|_{\mathrm{FDH}} = 8q^+ ee_f Q g^2 t^a_{\alpha\beta} z_1 z_3 \Bigg[\Sigma^{ij}_{(n)} \frac{\mathbf{m}^i}{\left[\mathbf{p}'^2 + \overline{Q}^2_{(n)}\right]\left[\mathbf{m}^2 + \omega_{(n)}\left(\mathbf{p}'^2 + \overline{Q}^2_{(n)}\right)\right]} - \Sigma^{ij}_{(o)} \frac{\mathbf{l}^i}{\left[\mathbf{p}^2 + \overline{Q}^2_{(o)}\right]\left[\mathbf{l}^2 + \omega_{(o)}\left(\mathbf{p}^2 + \overline{Q}^2_{(o)}\right)\right]} \Bigg] \varepsilon^{*j}_{\sigma}$$

where

$$\Sigma^{ij}_{(n)} = (z_1 + z_2)\left(\frac{z_3}{z_1}\right)^{1/2} \left[\left(1 - \frac{1}{2}\left(\frac{z_2}{z_1 + z_2}\right)\right)\delta^{ij} + ih\frac{1}{2}\left(\frac{z_2}{z_1 + z_2}\right)\epsilon^{ij}\right]$$

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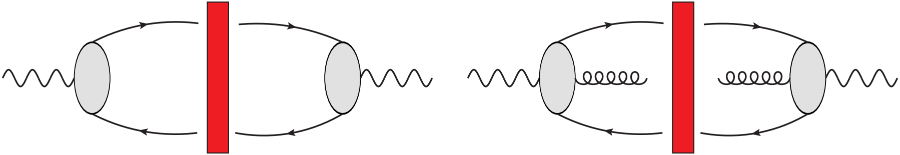

The total cross-section for γ^* scattering from a classical gluon field:

$$\sigma^{\gamma^*_{\mathrm{T/L}}}[A] = \frac{2}{2q^+(2\pi)\delta(q'^+ - q^+)} \left\{ {}_{q\bar{q}}\langle\gamma^*|1-\hat{S}_E|\gamma^*\rangle_{q\bar{q}} + {}_{q\bar{q}g}\langle\gamma^*|1-\hat{S}_E|\gamma^*\rangle_{q\bar{q}g} \right\}$$

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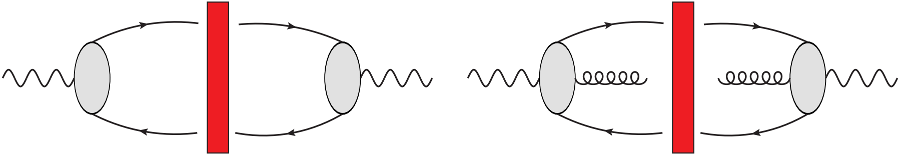

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- Step1: Fourier transform $|\gamma^*\rangle_{q\bar{q}}$ and $|\gamma^*\rangle_{q\bar{q}g}$ into the mixed $(p^+, \mathbf{x})$-space

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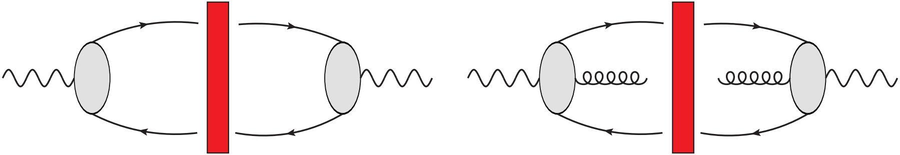

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- Step2: compute the amplitude square with eikonal target $(1 - \hat{S}_E)|\gamma^*\rangle_{q\bar{q}}$

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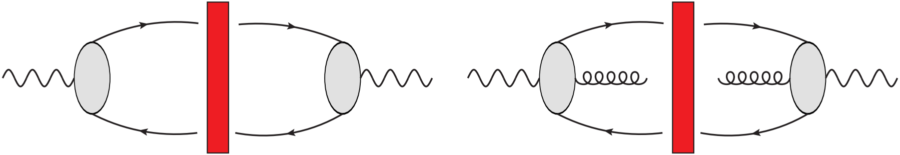

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- Step2: compute the amplitude square with eikonal target $(1 - \hat{S}_E)|\gamma^*\rangle_{q\bar{q}}$
- Step3: UV subtraction between $q\bar{q}$ and $q\bar{q}g$ sectors

- Example: full result for γ_{L}^{*} (similar result for γ_{T}^{*})

$$\sigma^{\gamma_{\mathrm{L}}^{*}}\Big|_{q\bar{q}} = 4N_c \frac{4\alpha_{em} e_f^2 Q^2}{(2\pi)^2} \int \mathrm{d}^2\mathbf{x} \int \mathrm{d}^2\mathbf{y} \int_0^1 \mathrm{d}z z^2 (1-z)^2 [K_0\left(Q\sqrt{z(1-z)}|\mathbf{r}_{xy}|\right)]^2$$
$$\times \left\{1 + \left(\frac{\alpha_s C_F}{\pi}\right)\left[\frac{1}{2}\log^2\left(\frac{z}{1-z}\right) - \frac{\pi^2}{6} + \frac{5}{2}\right]\right\}(1 - \mathcal{S}_{xy})$$

- Example: full result for $\gamma_{\rm L}^*$ (similar result for $\gamma_{\rm T}^*$)

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$$\sigma^{\gamma_{\rm L}^*}\Big|_{q\bar{q}} = 4N_c \frac{4\alpha_{em} e_f^2 Q^2}{(2\pi)^2} \int \mathrm{d}^2\mathbf{x} \int \mathrm{d}^2\mathbf{y} \int_0^1 \mathrm{d}z z^2 (1-z)^2 [K_0\left(Q\sqrt{z(1-z)}|\mathbf{r}_{xy}|\right)]^2 \times \left\{1 + \left(\frac{\alpha_s C_F}{\pi}\right)\left[\frac{1}{2}\log^2\left(\frac{z}{1-z}\right) - \frac{\pi^2}{6} + \frac{5}{2}\right]\right\}(1-\mathcal{S}_{xy})$$

$$\sigma^{\gamma_{\rm L}^*}\Big|_{q\bar{q}g} = 4N_c \frac{4\alpha_{em} e_f^2 Q^2}{(2\pi)^3}\left(\frac{\alpha_s C_F}{\pi}\right) \int \mathrm{d}^2\mathbf{x} \int \mathrm{d}^2\mathbf{y} \int \mathrm{d}^2\mathbf{z} \int_0^1 \mathrm{d}z_1 \int_0^{1-z_1} \frac{\mathrm{d}z_2}{z_2} \Big\{ z_3^2\left(2z_1(z_1+z_2)+z_2^2\right)\frac{1}{\mathbf{r}_{zx}^2}\left([K_0(Q|\mathbf{R}|)]^2(1-\mathcal{S}_{xyz}) - [K_0(\overline{Q}_{(n)}|\mathbf{r}_{xy}|)]^2 e^{-\mathbf{r}_{zx}^2/(\mathbf{r}_{xy}^2 e^{\gamma_E})}(1-\mathcal{S}_{xy})\right) + z_1^2\left(2z_3(z_2+z_3)+z_2^2\right)\frac{1}{\mathbf{r}_{zy}^2}\left([K_0(Q|\mathbf{R}|)]^2(1-\mathcal{S}_{xyz}) - [K_0(\overline{Q}_{(o)}|\mathbf{r}_{xy}|)]^2 e^{-\mathbf{r}_{zy}^2/(\mathbf{r}_{xy}^2 e^{\gamma_E})}(1-\mathcal{S}_{xy})\right) - 2\left((z_1+z_2)z_1z_3^2 + (z_2+z_3)z_3z_1^2\right)\frac{\mathbf{r}_{zx}\cdot\mathbf{r}_{zy}}{(\mathbf{r}_{zx}^2)(\mathbf{r}_{zy}^2)}[K_0(Q|\mathbf{R}|)]^2(1-\mathcal{S}_{xyz})\Big\}$$

- Cancellation of UV reg. scheme dependence
- Result numerically consistent with Beuf arXiv:1708.06557

Outlook

- Automatization of higher-order LCPT computation for QCD/QED
  - replace the complicated light-cone γ-algebra and spin sums by simple tensor algebra (easy to implement - FORM)
  - Test bench: Computation of massless DIS cross-sections at NLO accuracy (results fully agree with Beuf arXiv:1708.06557)
- To-Do List:
  - DIS: include the mass corrections
  - NLO computations for other processes
  - Higher-order (NNLO) corrections