Low-x DIS at NLO with massive quarks and mass renormalization in LFPT

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Outline

- Low-x DIS at NLO: from massless to massive quarks
  - Massless quarks case:
    G.B., PRD94 (2016) & PRD96 (2017)
    Hänninen, Lappi and Paatelainen, Annals Phys. 393 (2018)
    See next talk by Hänninen
  - Massive quarks case:
    G.B., Lappi and Paatelainen, *in preparation*
- Quark and gluon mass renormalization in light-front perturbation theory (LFPT)

DIS and gluon saturation : towards NLO

At low x_{Bj}, many DIS observables can be expressed within dipole factorization, including gluon saturation $\rightarrow$ rich phenomenology.

In particular: Dipole amplitude obtained from fits of HERA data for DIS structure functions in the dipole factorization at LO+LL with rcBK
Albacete *et al.*, PRD80 (2009); EPJC71 (2011)
Kuokkanen *et al.*, NPA875 (2012);
Lappi, Mäntysaari, PRD88 (2013)

$\Rightarrow$ The fitted dipole amplitude can then be used for pp, pA, AA, as well as other DIS observables.

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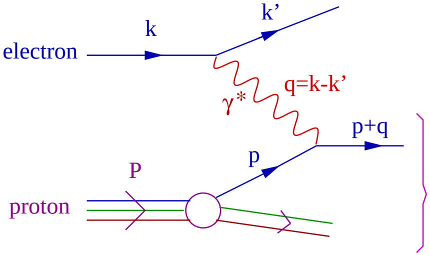
In the last 10 years, many theoretical (including numerical) progresses towards NLO/NLL accuracy for gluon saturation/CGC.

Obviously, DIS structure functions at NLO in the dipole factorization are required to push the fits beyond LO+LL accuracy.
$\rightarrow$ Precision gluon saturation physics both at HERA and at future ep/eA colliders

Kinematics for Deep Inelastic Scattering (DIS)



$$\frac{d\sigma^{ep\to e+X}}{dx_{Bj}\,d^2Q} = \frac{\alpha_{em}}{\pi x_{Bj} Q^2}\left[\left(1-y+\frac{y^2}{2}\right)\sigma_T^{\gamma}(x_{Bj},Q^2)+(1-y)\,\sigma_L^{\gamma}(x_{Bj},Q^2)\right]$$

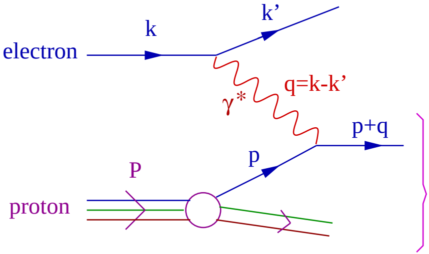
Photon virtuality: $Q^2 \equiv -q^2 > 0$

Bjorken x variable: $x_{Bj} \equiv \frac{Q^2}{2P\cdot q} \in [0,1]$

Inelasticity: $y \equiv \frac{2P\cdot q}{(P+k)^2} = \frac{2P\cdot q}{s} \in [0,1]$

$x_{Bj}\, y\, s = Q^2$

Kinematics for Deep Inelastic Scattering (DIS)



$$\frac{d\sigma^{ep\to e+X}}{dx_{Bj}\, d^2Q} = \frac{\alpha_{em}}{\pi x_{Bj} Q^2}\left[\left(1-y+\frac{y^2}{2}\right)\sigma_T^{\gamma}(x_{Bj},Q^2)+(1-y)\,\sigma_L^{\gamma}(x_{Bj},Q^2)\right]$$

Other equivalent parametrization: structure functions F_i

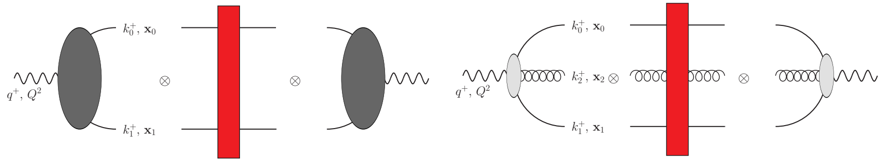
$$\sigma^{\gamma}_{T,L}(x_{Bj},Q^2) = \frac{(2\pi)^2\alpha_{em}}{Q^2}\, F_{T,L}(x_{Bj},Q^2)$$

$$F_2 = F_T + F_L \quad \text{and} \quad 2x_{Bj}\, F_1 = F_T$$

Dipole factorization for eikonal DIS

Total cross section for (virtual) photon eikonal scattering on a shockwave target, in LFPT:

$$\sigma^{\gamma}_{\lambda} = 2N_c \widetilde{\sum_{q_0\bar{q}_1 \text{ F. states}}} \frac{2\pi\delta(k_0^+ + k_1^+ - q^+)}{2q^+} \left|\widetilde{\psi}_{\gamma_\lambda \to q_0\bar{q}_1}\right|^2 \mathrm{Re}\left[1 - \mathcal{S}_{01}\right]$$
$$+ 2N_c C_F \widetilde{\sum_{q_0\bar{q}_1 g_2 \text{ F. states}}} \frac{2\pi\delta(k_0^+ + k_1^+ + k_2^+ - q^+)}{2q^+}$$
$$\times \left|\widetilde{\psi}_{\gamma_\lambda \to q_0\bar{q}_1 g_2}\right|^2 \mathrm{Re}\left[1 - \mathcal{S}^{(3)}_{012}\right] + O(\alpha_{em}\, \alpha_s^2)$$



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$\widetilde{\psi}_{\gamma_\lambda\to f}$: color-stripped light-front wavefunctions of the incoming photon for the Fock-state decomposition in mixed-space $(k^+, \mathbf{x})$

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$$+ \; 2N_c C_F \widetilde{\sum_{q_0\bar{q}_1 g_2 \text{ F. states}}} \frac{2\pi\delta(k_0^+ + k_1^+ + k_2^+ - q^+)}{2q^+}$$
$$\times \left|\widetilde{\psi}_{\gamma_\lambda \to q_0\bar{q}_1 g_2}\right|^2 \mathrm{Re}\left[1 - \mathcal{S}_{012}^{(3)}\right] \; + O(\alpha_{em}\,\alpha_s^2)$$

Dipole operator: $\mathcal{S}_{01} \equiv \frac{1}{N_c} \mathrm{Tr}\left(U_F(\mathbf{x}_0)\, U_F^\dagger(\mathbf{x}_1)\right)$

"Tripole" operator: $\mathcal{S}_{012}^{(3)} \equiv \frac{1}{N_c\, C_F} \mathrm{Tr}\left(t^b\, U_F(\mathbf{x}_0)\, t^a\, U_F^\dagger(\mathbf{x}_1)\right) U_A(\mathbf{x}_2)_{ba}$

NLO DIS calculation in the massless quark case

- LFWFs for $\gamma_{T,L} \to q\bar{q}$ and $\gamma_{T,L} \to q\bar{q}g$ can be calculated separately in LFPT for QCD+QED
- No UV renormalization at this order in the massless quark case.
- But both $q\bar{q}$ and $q\bar{q}g$ contributions to the cross-section have UV divergences, which cancel each other

  $\Rightarrow$ Use Dim. Reg. for the $\mathbf{k}_\perp$ integrations
- Cut-off k^+_{min} introduced to regulate the small k^+ divergences

  $\Rightarrow$ associated with low-x leading logs to be resummed with BK/JIMWLK evolution at the end

NLO DIS with massive quarks

Charm and bottom contributions are sizable at HERA

$\Rightarrow$ Need to calculate as well NLO DIS with massive quarks in the dipole factorization

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Features/complications appearing in the massive case:

- New contributions induced by quark LF helicity flip vertices
  $\Rightarrow$ More algebra, extra finite terms: still ok! Does not affect UV cancelations.
- Loop or Fourier transform integrals not fully doable analytically anymore
  $\Rightarrow$ Final results for the extra contributions given as integrals over Feynman/Schwinger parameters.
- Quark mass renormalization has to be performed, since the LO result depends on m
  $\rightarrow$ Focus of the rest of the talk

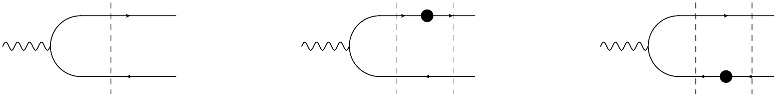
From bare to renormalized LFPT: kinetic mass c.t.

For the LO $\gamma \to q\bar{q}$ LFWF, the energy denominator with bare mass $m_0 = m\, Z_m$ writes

$$(ED_{LO})_{m_0} \equiv q^- - \frac{\mathbf{k}_0{}^2 + m_0{}^2}{2k_0^+} - \frac{\mathbf{k}_1{}^2 + m_0{}^2}{2k_1^+} = (ED_{LO}) + \frac{m^2 - m_0{}^2}{2k_0^+} + \frac{m^2 - m_0{}^2}{2k_1^+}$$

Kinetic mass counter-terms are then obtained from the bare LO graph as

$$\Rightarrow \frac{1}{(ED_{LO})_{m_0}} = \frac{1}{(ED_{LO})} + \frac{(Z_m - 1)m^2}{k_0^+ (ED_{LO})^2} + \frac{(Z_m - 1)m^2}{k_1^+ (ED_{LO})^2} + O(\alpha_s^2)$$



On-shell mass renormalization scheme: Choose Z_m such that all terms with an extra $1/(ED_{LO})$ factor cancel between counter-terms and one-loop graphs.

From bare to renormalized LFPT: vertex mass

On the LF, the *good* components of the spinors are independent of m, and the *bad* components are constrained as

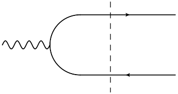
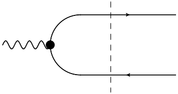
$$u_B(k,h) = \frac{\gamma^+}{2k^+}\left(\mathbf{k}^j\gamma^j + m\right)\, u_G(k^+,h)$$
$$v_B(k,h) = \frac{\gamma^+}{2k^+}\left(\mathbf{k}^j\gamma^j - m\right)\, v_G(k^+,h)$$

Hence, the $\gamma_L \to q\bar{q}$ vertex is mass independent:

$$\overline{u}(k_0,h_0)\,\gamma^+\, v(k_1,h_1) = \overline{u_G}(k_0^+,h_0)\,\gamma^+\, v_G(k_1^+,h_1)$$

And the $\gamma_T \to q\bar{q}$ vertex depends on the mass as

$$\left[\overline{u}(k_0,h_0)\,\not\epsilon_\lambda(q)\, v(k_1,h_1)\right]\Big|_{m_0} = \left[\overline{u}(k_0,h_0)\,\not\epsilon_\lambda(q)\, v(k_1,h_1)\right]\Big|_{m}$$
$$+\,(Z_m-1)m\,\frac{q^+}{2k_0^+k_1^+}\left[\overline{u}(k_0,h_0)\,\gamma^+\,\not\epsilon_\lambda(q)\, v(k_1,h_1)\right]\Big|_{m}$$

Earlier results on mass renormalization on the light-front

UV divergent one-loop corrections in QED and QCD on the light-front first calculated long ago
Mustaki, Pinsky, Shigemitsu and Wilson, PRD43 (1991)
Harindranath and Zhang, PRD48 (1993)

$\rightarrow$ Puzzling results:

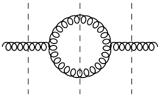
- Same result for the quark vertex mass correction as in covariant PT
- But different result for the quark kinetic mass correction

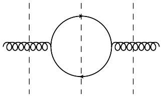
  $\Rightarrow$ Do vertex mass and kinetic mass become different objects on the light front, with different counter-terms and different anomalous dimensions?

- Non-zero correction to the gluon mass

  $\Rightarrow$ Can the bare and the renormalized gluon masses vanish simultaneously in light-front quantization?

Standard one-loop graphs for the gluon mass on the LF





Inserting a gluon or quark loop on an internal gluon line within any LFPT graph amounts to multiply this graph by

$$-\frac{(\mu^2)^{2-\frac{D}{2}}}{k_0^+(ED_{LO})}\int\frac{d^{D-2}\mathbf{K}}{(2\pi)^{D-2}}\int_0^1 d\xi\left\{\alpha_s C_A\left[\frac{1}{\xi^2}+\frac{1}{(1-\xi)^2}+\frac{(D_s-2)}{(D-2)}\right]\right.$$
$$\left.+\alpha_s T_F N_f\left[\frac{1}{\xi}+\frac{1}{(1-\xi)}-\frac{4}{(D-2)}+\frac{4}{(D-2)}\frac{m^2}{(\mathbf{K}^2+m^2)}\right]\right\}+O(1)$$

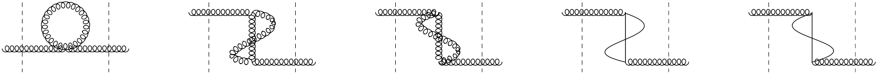
for $ED_{LO}\to 0$

ED_{LO} : Energy Denominator of the Fock state containing the parent gluon ($\rightsquigarrow$ off-shellness of the parent gluon)

- Nonzero result: need for gluon mass counter-term?
- Both quadratic and log UV divergences in the $\mathbf{K}$ integral
- Power and log divergences in the ξ momentum fraction integral

Normal-ordering graphs for the gluon mass on the LF

Some 2-points vertices are obtained in LFPT as leftover after extracting the 4-points vertices by normal ordering of the LF Hamiltonian $\hat{P}^-$



$$\frac{(\mu^2)^{2-\frac{D}{2}}}{k_0^+(ED_{LO})}\int\frac{d^{D-2}\mathbf{K}}{(2\pi)^{D-2}}\Bigg\{\alpha_s C_A\Bigg[\int_0^1 d\xi\left(\frac{1}{\xi^2}+\frac{1}{(1-\xi)^2}\right) + \frac{(D_s-2)}{2}\int_0^{+\infty}\frac{dk^+}{k^+}\Bigg] + \alpha_s T_F N_f\left[\int_0^1 d\xi\left(\frac{1}{\xi}+\frac{1}{(1-\xi)}\right)-2\int_0^{+\infty}\frac{dk^+}{k^+}\right]\Bigg\}$$

- Only quadratic UV divergence w.r.t. $\mathbf{K}$
- New type of contributions with unbounded k^+ integration
- Needs new regulator for $k^+ \to +\infty$

Full one-loop terms for the gluon mass on the LF

Adding the two types of loop diagrams (non-instantaneous and instantaneous)

$$\frac{(\mu^2)^{2-\frac{D}{2}}}{k_0^+(ED_{LO})}\int\frac{d^{D-2}\mathbf{K}}{(2\pi)^{D-2}}\Bigg\{\alpha_s C_A\frac{(D_s-2)}{(D-2)}\left[-1+\frac{(D-2)}{2}\int_0^{+\infty}\frac{dk^+}{k^+}\right]$$
$$-\alpha_s T_F N_f\frac{4}{(D-2)}\left[\frac{m^2}{(\mathbf{K}^2+m^2)}-1+\frac{(D-2)}{2}\int_0^{+\infty}\frac{dk^+}{k^+}\right]\Bigg\}+O(1)$$

for $ED_{LO}\to 0$

Can the $\alpha_s C_A$ and the $\alpha_s T_F N_f$ terms both vanish, to ensure a zero gluon mass?

One-body phase space integral

The terms with unbounded k^+ integration correspond to one-body phase space integrals

$$\int \frac{d^D k}{(2\pi)^D}\,\theta(k^0)\,2\pi\delta(k^2-m_i^2) = \int \frac{d^{D-2}\mathbf{k}}{(2\pi)^{D-2}}\int_0^{+\infty}\frac{dk^+}{(2\pi)(2k^+)}$$

But this light-cone expression a bit awkward and badly defined:

- Parton mass m_i dependence lost
- Divergences at $k^+ \to +\infty$ and at $k^+ \to 0$ (as $k^- \to +\infty$) are of the UV type, not regularized by transverse dim. reg.
- Anywhere else in LFPT, UV divergences come only from **K** integration

One-body phase space integral

Calculation in cartesian coordinates, with full dim. reg. (using an IBP relation):

$$\int \frac{d^D k}{(2\pi)^D}\,\theta(k^0)\,2\pi\delta(k^2-m_i^2) = \int \frac{d^{D-2}\mathbf{k}}{(2\pi)^{D-2}} \int \frac{dk_L}{2\pi} \frac{1}{2\sqrt{{k_L}^2+\mathbf{k}^2+m_i^2}}$$

$$= \frac{1}{2\pi(D-2)} \int \frac{d^{D-2}\mathbf{k}}{(2\pi)^{D-2}} \left[1-\frac{m_i^2}{\mathbf{k}^2+m_i^2}\right]$$

In this way:

- No need for an extra regulator
- No breaking of Poincaré symmetry by the UV regulator
- Depends on the mass of the parton

Prescription to deal with the unbounded k^+ integrals

1. Split the instantaneous loop contributions into 1-body phase space integrals and integrals with internal k^+s bounded by the parent k_0^+
2. Replace the 1-body phase space integral with unbounded k^+ by its better defined expression

$$\int \frac{d^{D-2}\mathbf{k}}{(2\pi)^{D-2}} \int_0^{+\infty} \frac{dk^+}{k^+} \mapsto \frac{2}{(D-2)} \int \frac{d^{D-2}\mathbf{k}}{(2\pi)^{D-2}} \left[1 - \frac{m_i^2}{\mathbf{k}^2 + m_i^2}\right],$$

with the appropriate mass m_i for the corresponding parton.

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with the appropriate mass m_i for the corresponding parton.

In the gluon loop contribution (taking $m_i = 0$):

$$\alpha_s C_A \int \frac{d^{D-2}\mathbf{K}}{(2\pi)^{D-2}} \left[-1 + \frac{(D-2)}{2} \int_0^{+\infty} \frac{dk^+}{k^+}\right] \mapsto 0$$

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with the appropriate mass m_i for the corresponding parton.

In the quark loop contribution (taking $m_i = m$):

$$\alpha_s T_F N_f \int \frac{d^{D-2}\mathbf{K}}{(2\pi)^{D-2}} \left[\frac{m^2}{(\mathbf{K}^2 + m^2)} - 1 + \frac{(D-2)}{2} \int_0^{+\infty} \frac{dk^+}{k^+}\right] \mapsto 0$$

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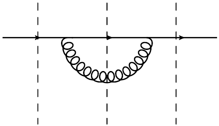
with the appropriate mass m_i for the corresponding parton.

- Cancelation of both the $\alpha_s C_A$ and the $\alpha_s T_F N_f$ corrections to the gluon mass, both in CDR and FDH
- Both the bare mass and the on-shell mass for the gluon can now be zero !
- Also applies to QED: massless photon on the light-front

Standard one-loop graphs for the quark mass on the LF



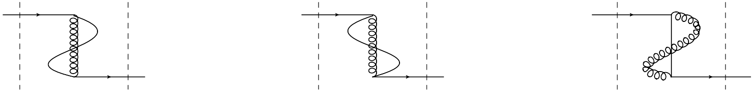
Inserting a gluon or quark loop on an internal quark line within any LFPT graph amounts to multiply this graph by

$$\alpha_s C_F \frac{(\mu^2)^{2-\frac{D}{2}}}{k_0^+(ED_{LO})} \int \frac{d^{D-2}\mathbf{K}}{(2\pi)^{D-2}} \int_0^1 d\xi \left\{ -\frac{2}{\xi^2} - \frac{(D_s-2)}{2(1-\xi)} + \frac{2m^2}{(\mathbf{K}^2+\xi^2 m^2)} \right\} + O(1)$$

for $ED_{LO} \to 0$

Normal-ordering graphs for the quark mass on the LF

Contribution of the 2-points quark vertices obtained in LFPT as leftover after normal ordering of the LF Hamiltonian $\hat{P}^-$:



$$\alpha_s C_F \frac{(\mu^2)^{2-\frac{D}{2}}}{k_0^+(ED_{LO})} \int \frac{d^{D-2}\mathbf{K}}{(2\pi)^{D-2}} \left\{ \int_0^1 d\xi \left(\frac{2}{\xi^2} + \frac{(D_s-2)}{2(1-\xi)} \right) + \frac{(D_s-2)}{2} \int dk_2^+ \left(\frac{\theta(k_2^+)}{k_2^+} - \frac{\theta(k_2^+ - k_0^+)}{k_2^+ - k_0^+} \right) \right\}$$

- k_2^+ corresponds to the gluon line in the loop
- $k_0^+ - k_2^+$ or $k_2^+ - k_0^+$ corresponds to the quark line in the loop

The 2 terms with unbounded k_2^+ integrations would naively cancel
$\rightarrow$ but not when using the previous prescription with different masses.

Full one-loop terms for the quark mass on the LF

Sum of the one loop graphs for the quark mass correction, after applying the prescription:

$$\alpha_s C_F \frac{(\mu^2)^{2-\frac{D}{2}}}{k_0^+(ED_{LO})} \int \frac{d^{D-2}\mathbf{K}}{(2\pi)^{D-2}} \left\{ \int_0^1 d\xi \, \frac{2m^2}{(\mathbf{K}^2+\xi^2 m^2)} + \frac{(D_s-2)}{(D-2)} \left[1 - \left(1 - \frac{m^2}{(\mathbf{K}^2+m^2)} \right) \right] \right\} + O(1)$$

for $ED_{LO} \to 0$

- Quadratic UV divergences cancel
- But leave a new log UV divergent term as leftover

That result should be combined with the (kinetic) quark mass counterterm

Quark mass counter-term

Kinetic quark mass counter-term insertion: multiplication of LO graph by

$$\frac{(Z_m - 1)m^2}{k_0^+(ED_{LO})}$$

In the on-shell mass scheme

$$(Z_m^{OS} - 1) = -\,\alpha_s C_F\,(\mu^2)^{2-\frac{D}{2}} \int \frac{d^{D-2}\mathbf{K}}{(2\pi)^{D-2}} \left\{ 2\int_0^1 d\xi\, \frac{1}{(\mathbf{K}^2 + \xi^2 m^2)} + \frac{(D_s - 2)}{(D-2)} \frac{1}{(\mathbf{K}^2 + m^2)} \right\}$$

in order to cancel the $1/(ED_{LO})$ contributions from the one-loop graphs.

Quark mass counter-term

Taking $D_s = D$ in CDR or $D_s = 4$ in FDH, and then expanding in $\epsilon = 2 - \frac{D}{2}$:

$$\left.(Z_m^{OS} - 1)\right|_{CDR} = -\frac{\alpha_s C_F}{\pi}\left\{\frac{3}{4}\left[\frac{1}{\overline{\epsilon}} - \log\left(\frac{m^2}{\mu^2}\right)\right] + 1 + O(\epsilon)\right\}$$

$$\left.(Z_m^{OS} - 1)\right|_{FDH} = -\frac{\alpha_s C_F}{\pi}\left\{\frac{3}{4}\left[\frac{1}{\overline{\epsilon}} - \log\left(\frac{m^2}{\mu^2}\right)\right] + \frac{5}{4} + O(\epsilon)\right\}$$

- Consistent with the vertex mass renormalization
  $\Rightarrow$ Only one quark mass parameter
- Consistent with the results in covariant PT, including the finite term both for CDR and FDH

Conclusion

- NLO corrections to inclusive DIS structure functions at low x in dipole factorization:
  - Results available in the massless quark case
  - Calculations being finalized in the massive quark case

  $\rightarrow$ Critical input for gluon saturation/CGC phenomenology beyond LO

- Longstanding issues with mass renormalization in LFPT finally resolved
  $\rightarrow$ Expected results finally obtained:
  - The gluon mass stays zero without needing a counter-term
  - The quark mass stays the same in the energy denominators and in the vertices
  - The quark mass renormalization constant is the same as in covariant PT, including the finite terms in the on-shell scheme