Impact factors: *Current status and future*

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GRUPPO COLLEGATO DI COSENZA

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DIPARTIMENTO DI FISICA

Outline

Introduction

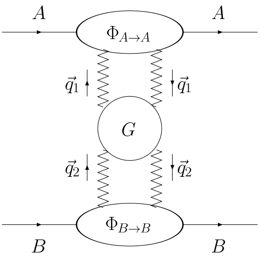
- hadronic scattering processes with a hard scale $Q^2 \gg \Lambda^2_{\rm QCD}$ described within pQCD
- in high-energy limit $s \gg Q^2$: $\Rightarrow \alpha_s(Q)\ln s/Q^2 \sim 1$ need to be resummed

- **BFKL resummation**:

  leading logarithmic approximation (LLA): $\alpha_s^n (\ln s)^n$

  next-to-leading logarithmic approximation (NLA): $\alpha_s^{n+1} (\ln s)^n$

[Ya.Ya. Balitsky, V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975)]
[V.S. Fadin,L.N. Lipatov, D. Ciafaloni, G. Gamici (1998)]



BFKL factorization:

$$\sigma_{AB}(s) = \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \int \frac{d^2 q_2}{2\pi \vec{q}_2^{\,2}} \int \frac{d^2 q_1}{2\pi \vec{q}_1^{\,2}} \left(\frac{s}{s_0}\right)^{\omega}$$
$$\times \Phi_A(\vec{q}_1, s_0) \quad G_\omega(\vec{q}_1, \vec{q}_2) \quad \Phi_B(-\vec{q}_2, s_0)$$

- **Green's function** is **process-independent**

  $\longrightarrow$ determined through the **BFKL equation**

- **Impact factors** are **process-dependent**

  $\longrightarrow$ known in the NLA just for limited cases.

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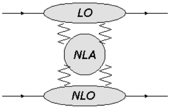
▽ Partial inclusion of NLA effects: by using the two impact factors in the leading-order (LO), along with the NLA BFKL Green's function:



- Full NLA:

(mn-jets)[B. Ducloué, L. Szymanowski, S. Wallon (2014)]
[F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa (2014)]
[F.G. Celiberto, D.Yu. Ivanov, B. Murdaca, A.Papa (2015)]

(di-hadron)[F.G. Celiberto, D.Yu. Ivanov, B. Murdaca, A.Papa (2016,2017)]

(hadron-jet)[A.D. Bolognino, F.G. Celiberto, D.Yu. Ivanov, M.M.A.M, A.Papa (2018)]

- Partial NLA:

(four-jet)[F. Caporale, G. Chachamis, B. Murdaca, A. Sabio Vera (2016)]
[F. Caporale, F.G. Celiberto, G. Chachamis, A. Sabio Vera (2016)]

(multi-jet)[F. Caporale, F.G. Celiberto, G. Chachamis, D.G. Gomez, A. Sabio Vera (2016,2017)]

(J/ψ-jet production)[R. Boussarie, B. Ducloué, L. Szymanowski, S. Wallon (2018)]

(Drell-Yan pair -jet)[K. Golec-Biernat, L. Motyka, T. Stebel (2018)]

(photoproduction)[F.G. Celiberto, D.Yu. Ivanov, B. Murdaca, A. Papa,(2018)]
[A.D. Bolognino, F.G. Celiberto, M. Fucilla, D.Yu. Ivanov, B. Murdaca, A. Papa,(2019)]
(hadroproduction) [A.D. Bolognino, F.G. Celiberto, M. Fucilla, D.Yu. Ivanov, B. Murdaca, A. Papa, (2019).]

(Higgs-jet) [F.G Celiberto's talk]

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- why do we need NLO Impact factors:

NLO corrections generally found to be large → need to calculate them

  - Reduce scale uncertainties due to (μ_R, μ_F, s_0).
  - Understand: the main physical effects of the radiative corrections in BFKL.
  - Check the validation of the Reggeization beyond LLA.
  - Match realistic cases (jet with more than one parton).
  - Complete and open the door for more phenomenological studies beyond LLA.
- tools and methods:
  - Lipatov's high energy effective action.

    [L.N. Lipatov,(1995)]
  - Standard (Feynman diagrams), Reggezed gluone is an external gluon with the "nonsense" polarization.
  - Operator product expansion "OPE" .

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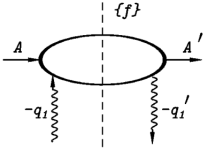
Impact factor definition

- **Impact factors:** account for the coupling of the Pomeron to the hadrons.



Universal property: $\Phi(k,q)|_{k\to 0}^{k-q\to 0} \to 0,$

which guarantees the infra-red finiteness of the BFKL amplitudes.

LLA

$$\Phi_{AA'}(\vec{q}) = \sum_{\{f\}} \int \frac{dM_{AR}}{2\pi} \Gamma^{(0)c}_{\{f\}A} [\Gamma^{(0)c'}_{\{f\}A'}]^* d\rho_f$$

[V.S. Fadin ,R. Fiore (1998)]

- **Phase space**
- particle-Reggeon squared **invariant mass**
- **Effective vertices**

$$d\rho_f = (2\pi)^D \delta^{(D)}\left(P_A - q_1 - \sum_{\{f\}} l_f\right) \prod_{\{f\}} \frac{d^{D-1} l_f}{2\epsilon_f (2\pi)^{D-1}}$$

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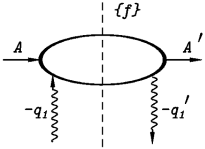

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$$M_{AR} = (P_A - q_1)^2 = (P_{A'} - q_1')^2$$

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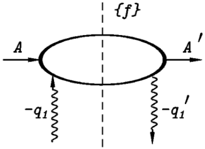

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Evaluated in the LLA or Born approximation

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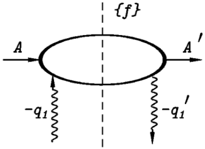

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- Phase space
- particle-Reggeon squared invariant mass
- Effective vertices

Remark:In the LLA impact factors do not depend ons_0

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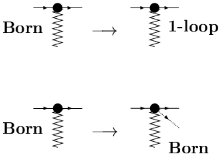
- In the NLA, modification needed..
  - Higher order corrections to $\Gamma_{AA'} \to \Gamma^{(0)}_{AA'} + \Gamma^{(1)}_{AA'}$
  - Extra gluons:
    - fragmentation region
    - central region



NLA

$$\Phi_{AA'}(\vec{q}, s_0) = \sum_{\{f\}} \int \frac{dM_{AR} d\rho_f}{2\pi} \Gamma^{c}_{\{f\}A} [\Gamma^{c'}_{\{f\}A'}]^* \theta(M_\Lambda - M_{AR})$$

$$- \frac{1}{2} \int \frac{d^{D-2}q'}{\vec{q}'^2 (\vec{q}' - \vec{q})^2} \Phi^{(B)}_{A'A}(\vec{q}', \vec{q}) \mathcal{K}^{(B)}_r(\vec{q}', \vec{q}_R) \ln \left(\frac{s_\Lambda^2}{(\vec{q}' - \vec{q}_R) s_0} \right)$$

[V.S. Fadin ,R. Fior (1998)]

- Two more remarks:
  - ✓ s_0-dependence of the BFKL amplitude is canceled.
  - ✓ NLO impact factors for colorless particles are IR finite.

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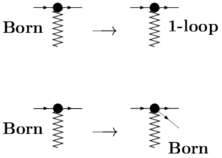

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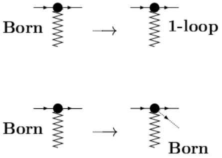

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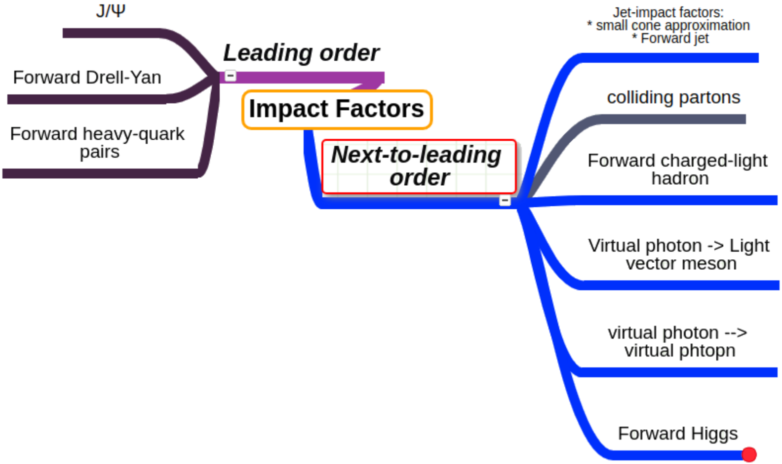
Impact factors map

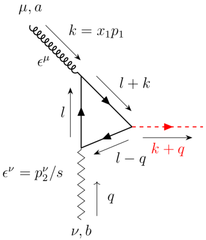


Review of Higgs IF calculation

- Leading-order
  - Calculating $\mathcal{M}(gg^* \to H)$....
  - Use QCD collinear factorization

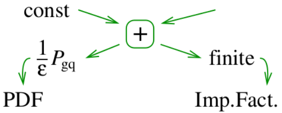
$$f_g \otimes \text{[Higgs vertex]}$$

  - $\int P.S^{(1)} \to 2\pi\delta(s_{gR} - M_H^2)$
  - Simple result projected into $(\nu, n = 0)$-space.



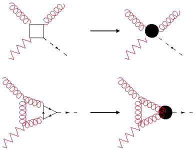
$$\frac{dV^{(0)}_{gg\to H}(\nu, n=0)}{dx_1 d^2\overrightarrow{P_H}} = \frac{\alpha_s^2}{v^2}\frac{|\mathcal{F}(|q_\perp^2|)|^2}{128\pi^3\sqrt{2(N_c^2-1)}}\left(\overrightarrow{P_H}^2\right)^{i\nu-1/2} f_g(x_1).$$

- NLO: part of **virtual** **real**



NL contribution

large top quark mass limit :$m_t \to \infty$



- features of HEFT

$$\mathcal{L}_{eff} = -\frac{A}{4} h G^a_{\mu\nu} G^{\mu\nu}_a, \quad A = \frac{\alpha_s}{3\pi v}\left(1 + \frac{11}{4}\frac{\alpha_s}{\pi}\right)$$

- Reduces calculations by one loop order.
- Turns a two-scale problem into two one-scale problems

▷ **NLA recipe...**

⋆ Pick a regularization scheme (dimensional regularization for us)

⋆ Get the tree-level result.

⋆ Calculate 1-loop diagrams as a series in ϵ

⋆ Perform the ultraviolet renormalization.

⋆ Calculate the real emission diagrams, extract singularities that appear in soft/collinear regions of phase space.

⋆ Absorb initial-state collinear singularities into PDFs

⋆ Get a finite result

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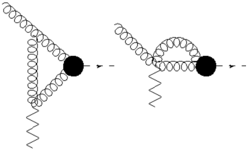
Virtual correction

- non-zero contributions to $gg^* \to H$ at one-loop in the HEFT



  - Born in $(d = 4 - 2\epsilon)$ dimensions:

$$|\mathcal{M}^{(B)}|^2 = \frac{\alpha_s^2}{72\pi^2} \frac{|q_\perp^2|}{v^2} \frac{1}{(1-\epsilon)}$$

- tensor integrals appearing in the amplitudes so to express the results in terms
  - triangle diagram

$$\mu^{2\epsilon} \int \frac{d^d z}{(2\pi)^d} \frac{1}{(k-z)^2 z^2 (q+z)^2} = \frac{-i}{(4\pi)^2} \frac{G(\epsilon)}{\epsilon^2} \frac{\left(\mu^2/q_\perp^2\right)^\epsilon}{2k \cdot q} \left[1 + \left(\frac{M_H^2}{q_\perp^2}\right)^{-\epsilon}\right],$$

  - bubble diagram

$$\mu^{2\epsilon} \int \frac{d^d z}{(2\pi)^d} \frac{1}{z^2 (P_H + z)^2} = \frac{i}{16\pi^2} \frac{G(\epsilon)}{\epsilon} \frac{\left(-\mu^2/P_H^2\right)^\epsilon}{(1-2\epsilon)}$$

$$G(\epsilon) = (4\pi)^\epsilon \frac{\Gamma(1+\epsilon)\Gamma^2(1-\epsilon)}{\Gamma(1-2\epsilon)}$$

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- Taking into our account the QCD charge renormalization, LO dependence on α_S gives the counterterm

$$V^{(0)}_{g\to H}(\vec{q}^{\,2}) \to V^{(0)}_{g\to H}(\vec{q}^{\,2})\left[1-\frac{\alpha_s}{2\pi}G(\epsilon)\left(\frac{\mu^2}{\mu_R^2}\right)^{\epsilon}\frac{2\beta_0}{\epsilon}\right],$$

- Using the NLO IF definition and $\omega(-\vec{q}^{\,2})$ in the 1-loop approximation

$$\omega(-\vec{q}^{\,2}) = \frac{g^2 C_A}{2}\mu^{2\epsilon}\int\frac{d^{d-2}k}{(2\pi)^{d-1}}\frac{(-\vec{q}^{\,2})}{\vec{k}^{\,2}(\vec{q}-\vec{k})^2} = -\frac{\alpha_s}{2\pi}G(\epsilon)\frac{C_A}{2}\left(\frac{\mu^2}{q_\perp^2}\right)^{\epsilon}$$

- result

$$V^{(1)virt}_{g\to H}(\vec{q}^{\,2},s_0) = V^{(0)}_{g\to H}(\vec{q}^{\,2})\left(\frac{\alpha_s}{2\pi}\right)G(\epsilon)\left(\frac{\mu^2}{q_\perp^2}\right)^{\epsilon}\left\{\frac{-2C_A}{\epsilon^2}+\frac{C_A}{\epsilon}\left(\ln\frac{M_H^2}{q_\perp^2}-\ln\frac{s_0}{\vec{q}^{2}}-2\beta_0\right)\right.$$
$$\left.+C_A\left(\frac{2\beta_0}{C_A}\ln\frac{q_\perp^2}{\mu_R^2}-\frac{5}{3}\right)+\ldots\right\}$$

- apart from the notation, this coincides with what has been computed two years ago

[Bo-Wen; Yuan, Feng (2018), Physics Letters B, 782(), 28-33.]

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Real correction

- imply the calculation of $2 \to 2$ tree-level amplitudes and integration over part of the phase space in d-dimensions

$$PS = \frac{1}{8\pi}\left(\frac{4\pi}{M_H^2}\right)^{\epsilon}\frac{(1-z)^{1-2\epsilon}}{\Gamma(1-\epsilon)}\int_0^1 \omega^{-\epsilon}(1-\omega)^{-\epsilon}d\omega, \quad z=\frac{M_H^2}{s}, \quad \omega=\frac{1+\cos(\theta)}{2}$$

- When we combine matrix elements and phase space, get terms of the following form:

$$(1-z)^{1-2\epsilon}(1-\omega)^{-\epsilon}$$

- The integrals over ω can be done in terms of $\Gamma(\epsilon)$, while the soft singularities as can be extracted using $[\quad]_+$:

$$(1-z)^{1-2\epsilon} = \left[\frac{1}{1-z}\right]_+ - 2\epsilon\left[\frac{\ln(1-z)}{1-z}\right]_+ - \frac{1}{2\epsilon}\delta(1-z)$$

- up to he following contribution to IF

$$\simeq \left\{\frac{6}{\epsilon^2}\delta(1-z) + \frac{18z(z^2-z+2)}{\epsilon} + 12\left[\frac{\ln(1-z)}{1-z}\right]_+ + ...\right\}$$

- remaining initial-state collinear singularities $\to$ PDFs.

Conclusions

- BFKL NLL corrections are large and must be taken into account.
- For the colorless particles the IR safety of the impact factors is guaranteed by their definition within the spirit of BFKL factorization
- It is important to have an indepentent calculation of NL IF for forward Higgs.

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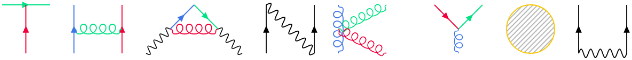
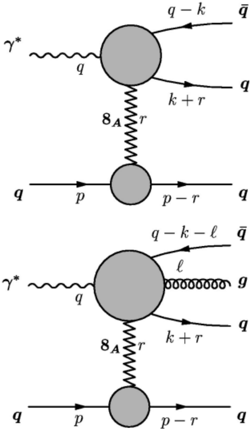


BACKUP slides

A brief history of NLO γ^* impact factor

- one-loop correction $\Gamma^c_{q\bar{q}}$.
- real corrections:$\gamma^* + q \to (q\bar{q}g) + q$.
- Combining real and virtual corrections.
- possibility for simplification.
- 1st numerical results for the real corrections γ^*_L.
- Wilson lines:



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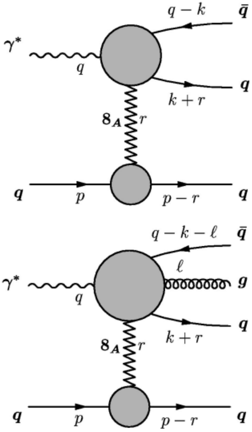

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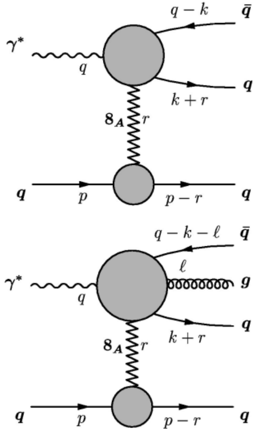

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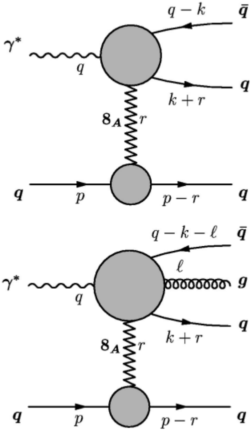

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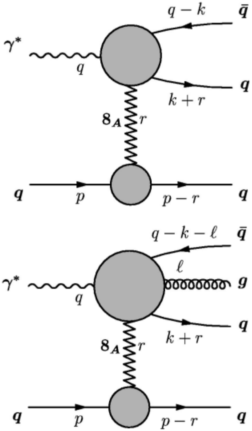

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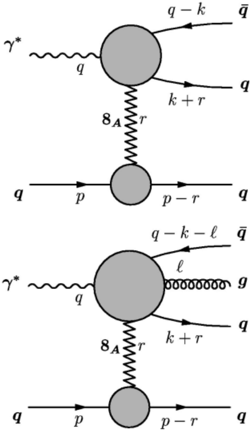
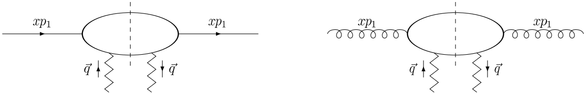


Yesterday

- Impact factors for colliding parton

[V.S. Fadin, R. Fiore, M.I. Kotsky, A. Papa (2000)]
[M. Ciafaloni and G. Rodrigo (2000)]



- ⋆ LLA → leading-order (LO) impact factor → one-particle intermediate state.
- ⋆ NLA → next-to-LO (NLO) impact factor:
  virtual corrections → one-particle intermediate state
  real particle production → two-particle intermediate state

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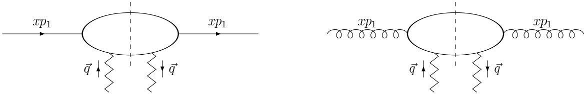

- ⋆ LLA → leading-order (LO) impact factor → one-particle intermediate state.
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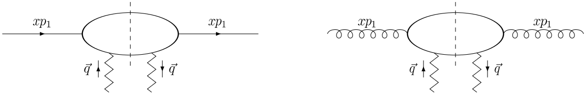

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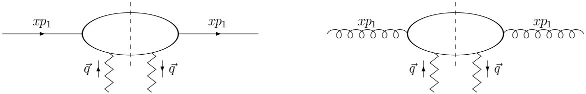

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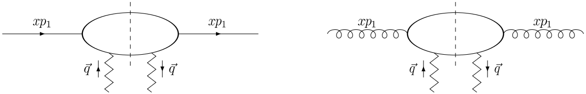

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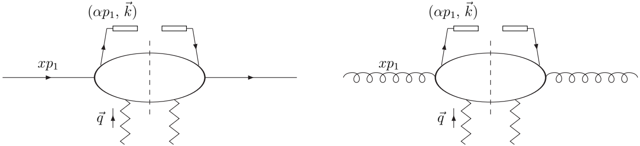
Forward jet / Identified hadron impact factors

- To allow one parton to produce jet (or hadron), open one of the integrations over the phase space of the intermediate state.



- use QCD collinear factorization:
  - $\sum_{a=q,\bar{q}} f_a \otimes (quark\ jet\ vertex) + f_g \otimes (gluon\ jet\ vertex).$

    [J. Bartels, D. Colferai, G.P. Vacca (2003)]
    [F. Caporale, D.Yu. Ivanov, B. Murdaca, A.Papa, A. Perri (2011)]
    [D.Yu. Ivanov, A.Papa. (2012)](small-cone approximation)
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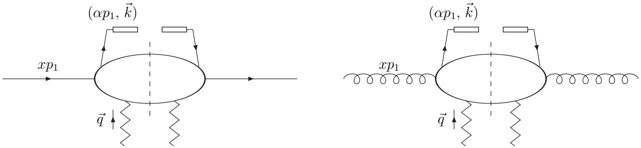

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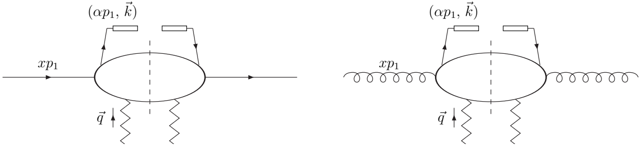

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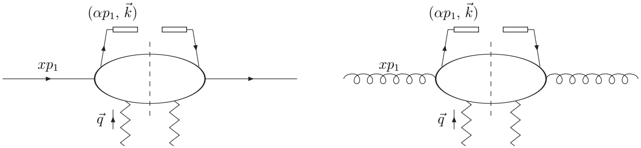

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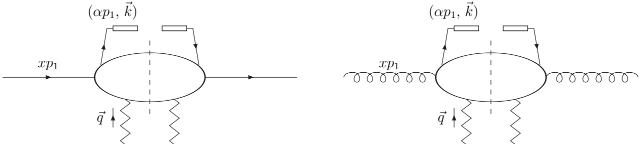

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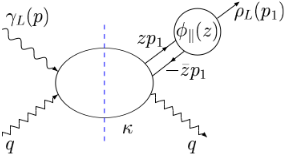
$\gamma^* \to VLM$

$$\Phi_{1,2}(\vec{q}) = \alpha_s D_{1,2}\left[C^{(0)}_{1,2}(\vec{q}^2) + \bar{\alpha}_s C^{(1)}_{1,2}(\vec{q}^2)\right]$$

$$D_{1,2} = -\frac{4\pi e_q f_V}{N_c Q_{1,2}}\sqrt{N_c^2 - 1}$$



[D.Yu. Ivanov, M.I. Kotsky, A.P. (2004)]

- Leading order (photon virtuality Q^2):

$$C^{(0)}_{1,2}(\vec{q}^2) = \int_0^1 \frac{\vec{q}^2}{\vec{q}^2 + z\bar{z}Q^2}\phi_{||}(z,\mu_F)dz$$

- Next-to-leading order:

$$C^{(1)}_{1,2}(\vec{q}^2) = \frac{1}{4N_c}\int_0^1 \frac{\vec{q}^2}{\vec{q}^2 + z\bar{z}Q^2}\left[\tau(z) + \tau(1-z)\right]\phi_{||}(z,\mu_F)dz$$

- Collinear factoraization reduces complexity.