QCD–Gravity Duality and Discrete BFKL Evolution in Multi-Regge Kinematics

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QCD summer school, 2026

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Outline

1. Double copy structure
   - QCD process
   - Gravity process
   - Double-copy structure in the MRK
2. Discrete BFKL
   - Introduction to the discrete BFKL
   - Walk expansion and Reggeization
   - Anomalous dimension
3. Conclusions and outlook

Procedure - Mathematica libraries

- FeynArts draws the Feynman Diagrams[1]

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[2] Shtabovenko et al. 2025.
[3] Latosh 2025.

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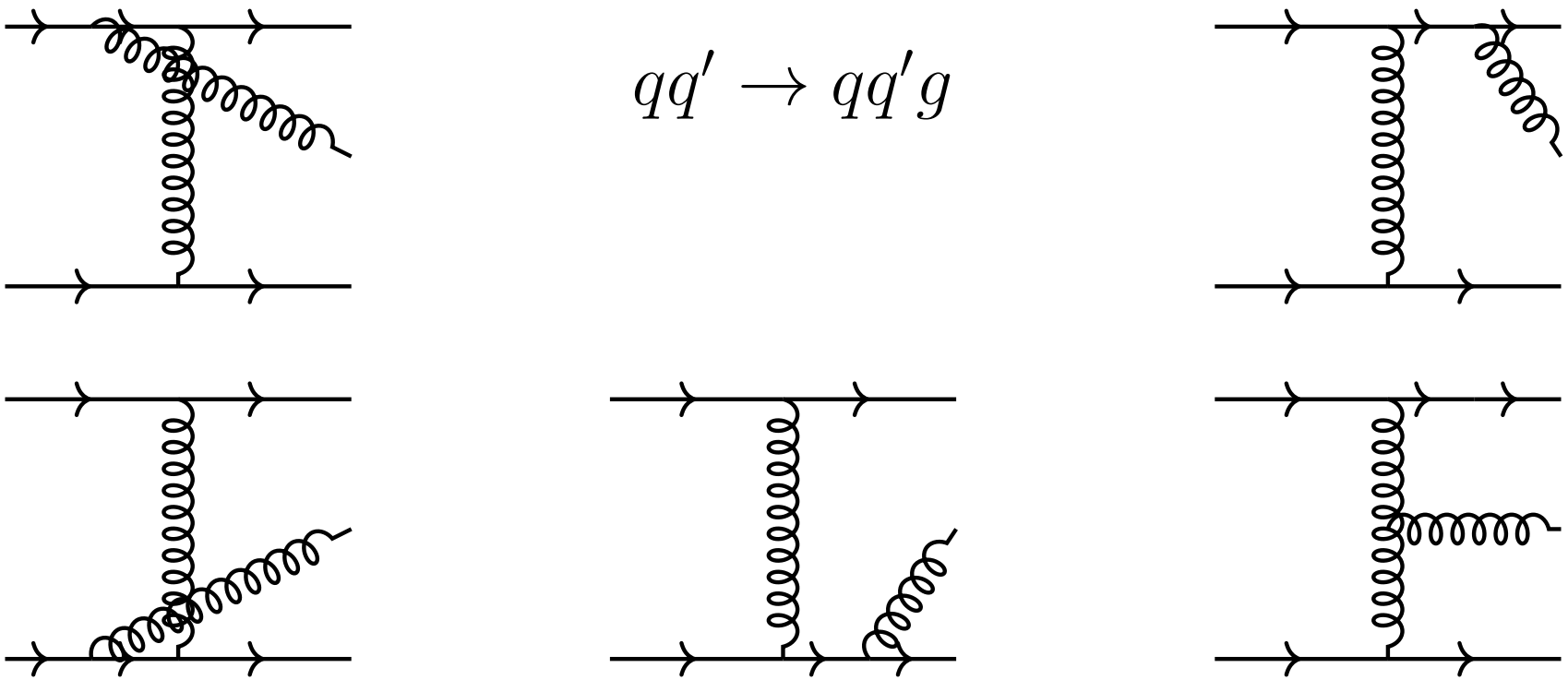

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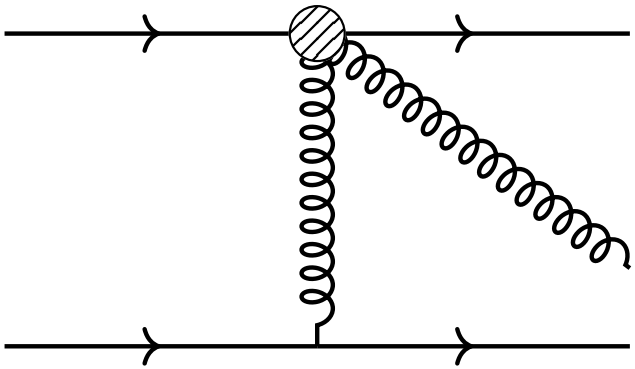
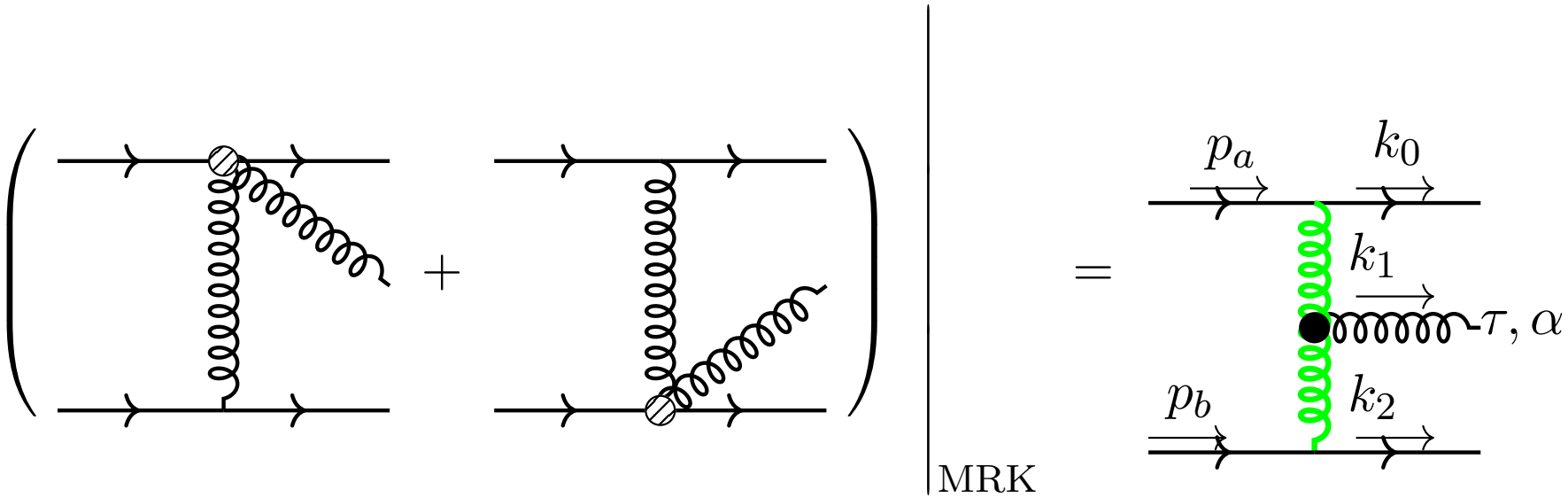
And with them, an effective vertex pops up



$$\propto \qquad \bar{u}\gamma u \bar{u}\Lambda u$$

By combining the two GI vertices one obtains the full amplitude



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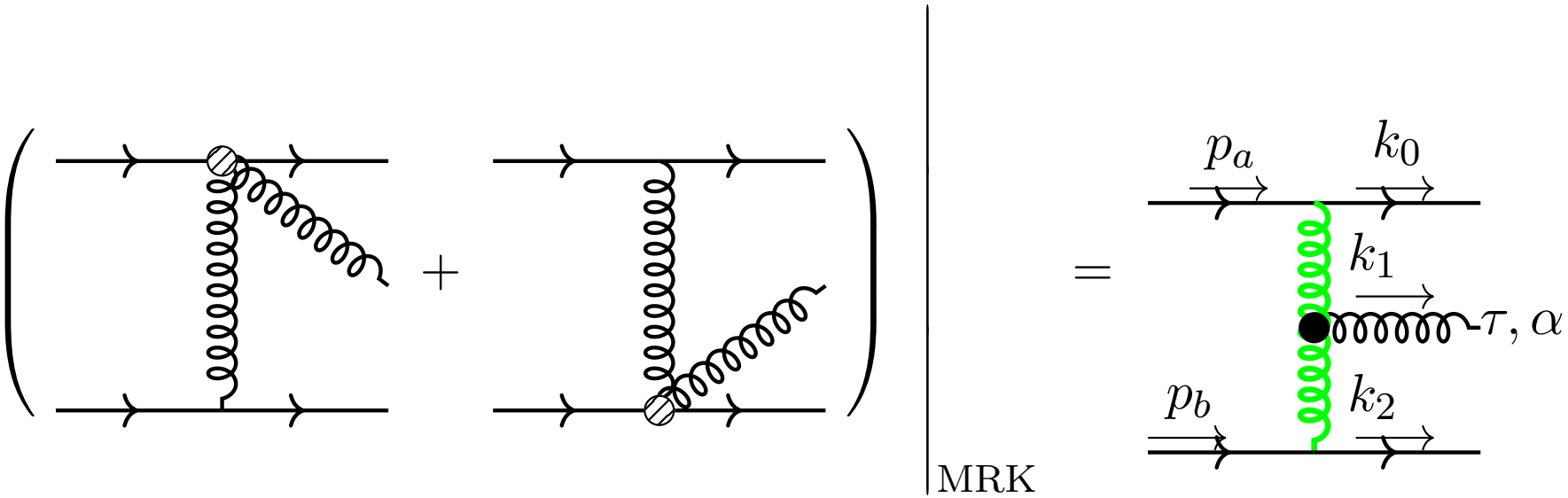

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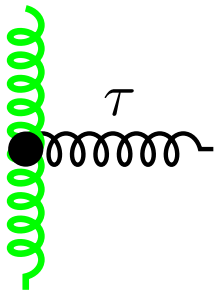

$$\propto \qquad \Gamma^{\tau}_{\chi\sigma} = i\alpha_s g_{\chi\sigma}\Omega^{\tau}$$

Gravitational diagrams

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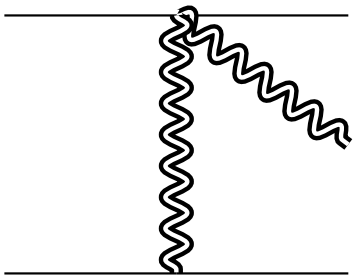
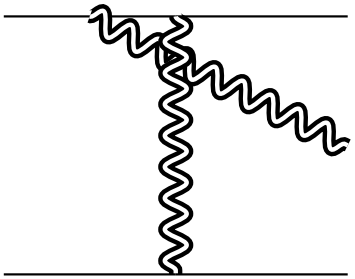
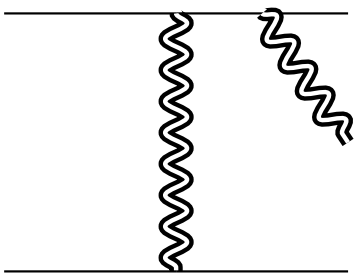

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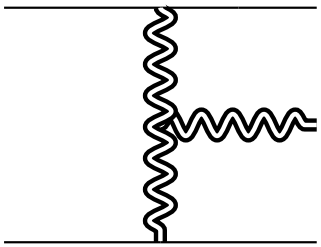
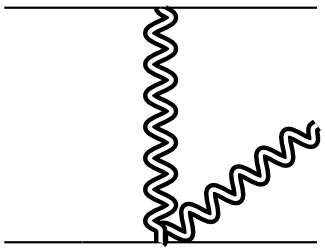
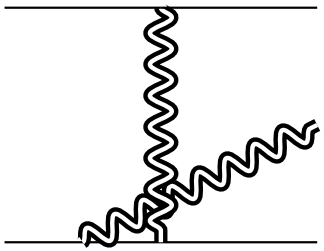
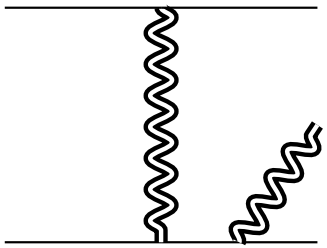

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We obtain the total amplitude

$$\mathcal{M} = \mathcal{M}^{\mu\nu}\epsilon_{\mu\nu}$$

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By checking the Steinmann relations we can see that this should not be valid, and we need to use[5]

$$\mathcal{M}^{\mu\nu} = \Omega^{\mu}\Omega^{\nu} - \mathcal{N}^{\mu}\mathcal{N}^{\nu}.$$

[5] Lipatov 1982.

The structure for the QCD term is given by

$$\Omega^{\mu} = p_a^{\mu}\left(\alpha_1 - 2\frac{t}{\beta_2 s}\right) + p_b^{\mu}\left(\beta_2 - 2\frac{t'}{\alpha_1 s}\right) - (q_1 - q_2)_{\perp}^{\mu}$$

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And the one from gravity is given by

$$\mathcal{M}^{\mu\nu} = p_a^{\mu}p_a^{\nu}\frac{(\alpha_1\beta_2 - 2\beta_1)^2 + 4\alpha_2\beta_1}{\beta_2^2} + (p_a^{\mu}p_b^{\nu} + p_a^{\nu}p_a^{\mu})(\alpha_1\beta_2 + 2\alpha_2 - 2\beta_1)$$
$$+ q_{\perp}^{\mu}q_{\perp}^{\nu} + p_b^{\mu}p_b^{\nu}\frac{(\alpha_1\beta_2 + 2\alpha_2)^2 + 4\alpha_2\beta_1}{\alpha_1^2}$$
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And finally

$$\mathcal{N}^{\mu} = -2i\sqrt{\beta_1\alpha_2}\left(\frac{p_a^{\mu}}{\beta_1} + \frac{p_b^{\mu}}{\alpha_2}\right)$$

Discrete Hamiltonian

As shown in the BFKL equation for forward scattering, i.e.,

$$\frac{\partial\phi(Q^2,Y)}{\alpha\partial Y} = \int_0^\infty \frac{dq^2}{|q^2-Q^2|}\left(\phi(q^2,Y) - \frac{2\min(q^2,Q^2)}{q^2+Q^2}\phi(Q^2,Y)\right)$$

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$$\frac{\partial}{\alpha\partial Y}|\phi^{(N)}\rangle=\hat{\mathcal{H}}_N|\phi^{(N)}\rangle;\qquad \hat{\mathcal{H}}_N=A-2D,$$

where

$$A_{ij}=\begin{cases}1/|i-j|, & i\neq j,\\ 0, & i=j\end{cases}\qquad D_{ij}=H_{i-1}\delta_{ij}$$

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Norm bounds and Rayleigh quotient

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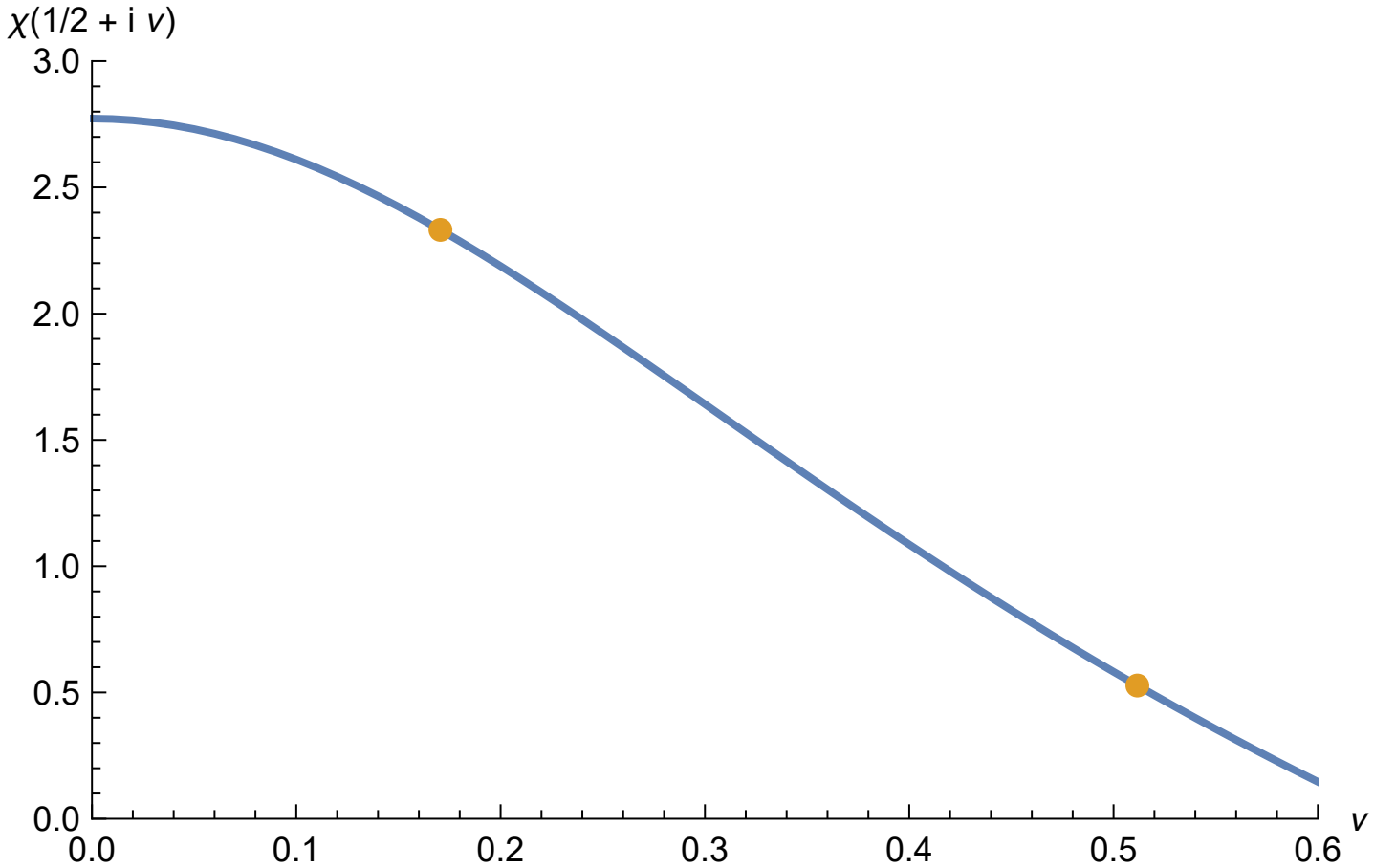
By imposing hard-wall conditions on the boundary we obtain

$$\lambda_n(\hat{\mathcal{H}}_N) \approx 4\log(2) - 14\zeta(3)\left(\frac{n\pi}{L}\right)^2$$


χ(1/2 + i ν)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
ν

Vertex-dressed resolvent

To obtain the evolution we now want to compute

$$|\phi^{(N)}(Y)\rangle = e^{\alpha Y \hat{\mathcal{H}}_N} |\phi^{(N)}(0)\rangle$$
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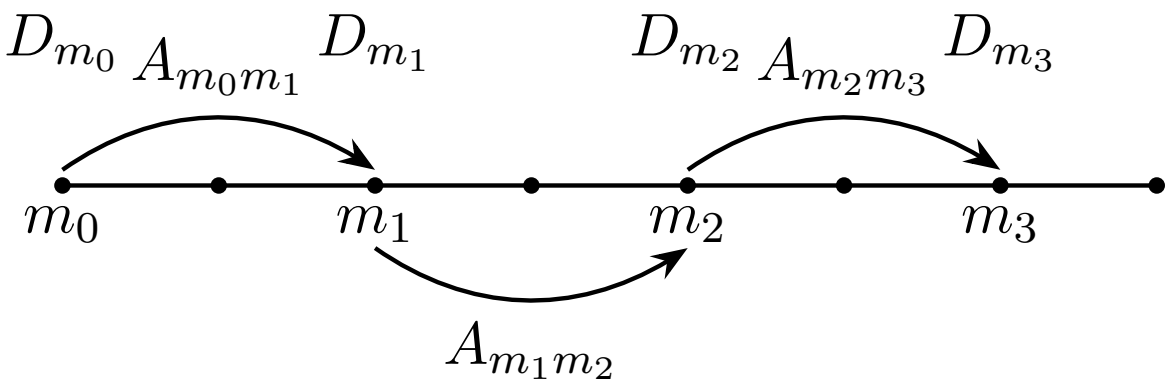

Reggeization

With this, we obtain

$$d_n^{(r)} = \sum_{j=0}^{r} (-2)^{r-j} \sum_{(m_0,\ldots,m_j)} \left[h_{r-j}(H_{m_0-1},\ldots,H_{m_j-1}) \prod_{i=0}^{j-1} \frac{1}{|m_i - m_{i+1}|} \right]$$

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When the sum over m's means for all the paths connecting n and N_0. By introducing a generating function, we can write

$$\mathcal{G}_n(z) = \sum_{j=0}^{\infty} z^j \sum_{(m_0,\ldots,m_j)} \left(\prod_{i=0}^{j-1} \frac{1}{|m_i - m_{i+1}|} \right) \left(\prod_{l=0}^{j} \frac{1}{1 + 2z H_{m_i-1}} \right)$$

From discrete to continuum

Instead of writting

$$d_n^{(r)} = (A - 2D)d^{(r-1)}; \qquad \mathcal{G}^{(r)}(m/n; x) = \frac{d_m^{(r)}}{n(m/n - x)}$$

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$$\mathcal{G}^{(r+1)}(1; x) = \frac{1}{x}\int_0^x \frac{\mathcal{G}^{(r)}(y; x)}{y}dy + \frac{1}{1-x}\int_x^1 \frac{\mathcal{G}^{(r)}(y; x)}{1-y}dy$$

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And from this, one can obtain the differential equation

$$\frac{d}{dx}\mathcal{F}^{(r+1)}(x) = \left(\frac{A_0}{x} + \frac{A_1}{1-x}\right)\mathcal{F}^{(r)}(x),$$

where $\mathcal{G}^{(r)}(1; x) \equiv \mathcal{F}^{(r)}(x)$.

Single log structure

Following the HPL structure, we can write

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[7] Del Duca et al. 2014.

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The Gluon's green function can be written as

$$\tilde{\phi}_n(\omega) = \sum_{r\geq 0} \frac{\alpha^r}{\omega^{r+1}} d_n^{(r)} \qquad \tilde{\phi}_n(\omega) \propto \sum_{r\geq 0} \sum_{|\omega|=r-1} \frac{\alpha^r}{\omega^{r+1}} c_\omega^{(r)} H_\omega(x)$$

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The single-log and single-valued[7] version is given by

$$\Pi_{SV}(\tilde{\phi}_n) \propto \log(x).$$

[7] Del Duca et al. 2014.

Anomalous dimension coefficients

By writting the anomalous dimension expansion as

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one finds the following coefficients

n	c_1^{n+1}
0	1
1	0
2	0
3	$2\zeta_3$
4	0
5	$2\zeta_5$
$\vdots$	$\vdots$

Results and conclusions

- Double copy structure
  1. Correct amplitudes with Mathematica
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- Discrete BFKL
  1. Pomeron intercept
  2. Evolution and Reggeization
  3. Knizhnik–Zamolodchikov and Harmonic Polylogarithms
  4. Anomalous dimension expansion

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Thank you for your attention!

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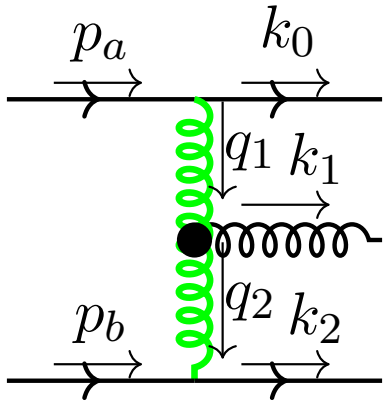
More on the MRK limit

By setting



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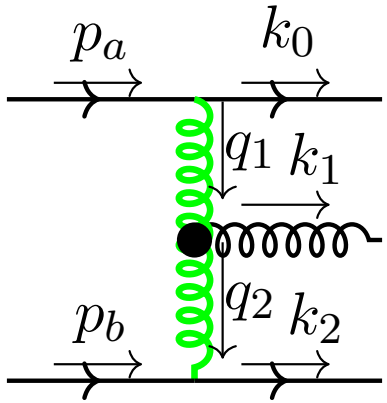

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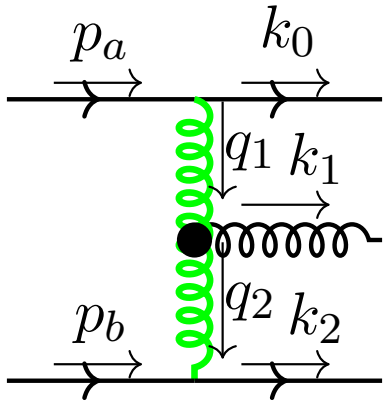

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And the generalized Mandestav variables as

$$\hat{s} = x_A x_B s; \qquad \hat{s}_{ai} = -2p_a k_i; \qquad \hat{s}_{bi} = -2p_b k_i; \qquad \hat{s}_{ij} = 2k_i k_j,$$

we can obtain the following relations

More on the MRK limit

$$\hat{s}_{01} = -\hat{s}(\alpha_2 + \beta_2); \qquad \hat{s}_{21} = \hat{s}(\alpha_1 + \beta_1); \qquad \hat{s}_{a0} = -t = -\hat{s}\beta_1;$$

$$\hat{s}_{b2} = -t' = \hat{s}\alpha_2; \qquad \hat{s}_{a1} = \hat{s}(\beta_1 - \beta_2); \qquad \hat{s}_{b1} = \hat{s}(\alpha_1 - \alpha_2);$$

$$\hat{s}_{a2} = \hat{s}(1 + \beta_2); \qquad \hat{s}_{b0} = \hat{s}(1 - \alpha_1);$$
$$\hat{s}_{02} = \hat{s}(1 - \alpha_1 + \alpha_2 - \beta_1 + \beta_2).$$

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- No double poles
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I have not found yet a reference that is able to explain them in English.

More on duality relations

There are other works in the duality relation[8]

$$A = \sum_i \frac{n_i c_i}{d_i}; \qquad \tilde{A} = \sum_i \frac{\tilde{n}_i c_i}{d_i}$$

$$n_i - n_j = n_k; \qquad c_i - c_j = c_k;$$

$$A_{\text{grav}} = \sum_i \frac{n_i \tilde{n}_i}{d_i}$$

[8] Bern et al. 2019.

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With this, and being careful on the end points regularization, we obtain the BFKL characteristic function

$$\chi(\gamma) = 2\psi(1) - \psi(\gamma) - \psi(1-\gamma).$$

Hard-wall boundary

Define the logarithmic coordiantes

$$t = \log(i); \qquad [T_-, T_+] = [\log(\epsilon N), \log((1-\epsilon)N)]; \qquad L = T_+ - T_-.$$

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Imposing boundary conditions means

$$\nu_n L + \delta(\nu) = \pi \left(\frac{1}{n} + n \right)$$

and the wave function becomes

$$\psi_i^{(n)} = 2Bi^{-1/2} \cos(\nu(t - T_\pm))$$

Single Valued HPLS

The map from the HPLs to the SVHPLs reads, for the first ones

$$\mathcal{L}_0(z) = H_0 + \overline{H}_0; \qquad \mathcal{L}(z) = H_1 + \overline{H}_1.$$

For the next weight two we have

$$\mathcal{L}_{0,0}(z) = H_{0,0} + \overline{H}_{0,0} + H_0\overline{H}_0; \qquad \mathcal{L}_{0,1}(z) = H_{0,1} + \overline{H}_{1,0} + H_0\overline{H}_1;$$
$$\mathcal{L}_{1,0}(z) = H_{1,0} + \overline{H}_{0,1} + H_1\overline{H}_0; \qquad \mathcal{L}_{1,1}(z) = H_{1,1} + \overline{H}_{1,1} + H_1\overline{H}_1;$$

Anomalous dimension

We know that the Gluon Green Function can be written in Mellin momenta space as

$$f(\omega,\gamma) = \frac{\tilde{f}^0(\omega,\gamma)}{1-(\overline{\alpha}_s/\omega)\chi(\gamma),}$$

where $t \to M$ and $\xi \to N$. There is a singularity around $\omega/\overline{\alpha}_s = \chi(\overline{\gamma})$. Inverting this we obtain

$$\overline{\gamma} = \frac{\overline{\alpha}_s}{\omega} + 2\zeta(3)\left(\frac{\overline{\alpha}_s}{\omega}\right)^4 + 2\zeta(5)\left(\frac{\overline{\alpha}_s}{\omega}\right)^6 + \mathcal{O}\left(\frac{\overline{\alpha}_s}{\omega}\right)^7$$

Gravity BFKL

There are works for the Gravity BFKL equation[9]

- We can ask if we can do something similar
- Would the KZ structure also appear?
- Work in progress

[9] Raj et al. 2025.