Multi-Loop Feynman Integrals and Conformal Quantum Mechanics

(New algebraic approach to analytical calculations of Feynman diagrams)

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Nucl. Phys. **B662** *(2003) 461*
(hep-th/0303056)

Plan

1. **Motivation**
2. **The diagrams** $\leftrightarrow$ Perturbative integrals
   - Which kind of Feynman diagrams (F.D.) we consider
3. **Operator formalism**
   - Algebraic reformulation of integrals for F.D.: manipulations with integrals $\rightarrow$ manipulations with operators
4. **Application**
   - Ladder diagrams for ϕ^3-theory in $D = 4$; relations to conformal quantum mechanics

Physics

- In perturbative QFT physical data are extracted from multiple integrals (perturbative integrals) associated to F.D.
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2. The diagrams

The F.D. (considered here) are graphs with vertices connected by lines labeled by numbers (indeces).

To each vertex of the graph we associate the point in D-dimensional Euclidean space $\mathbf{R}^D$, while the lines (edges) of the graph (with index α) are propagators of massless particles

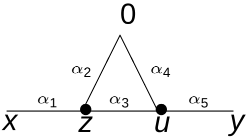
$$x \overset{\alpha}{\text{———}} y \quad = \quad 1/(x-y)^{2\alpha}$$

where $(x-y)^{2\alpha} := (\sum_{i=1}^{D}(x_i - y_i)(x_i - y_i))^{\alpha}$, $\alpha \in \mathbf{C}$, $x, y \in \mathbf{R}^D$. We have 2 types of vertices: the boldface vertices • denote the integration over $\mathbf{R}^D$. These F.D. are called F.D. in the configuration space.

2. The diagrams

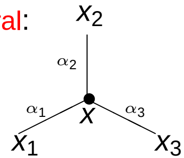
Examples (F.D. in configuration space):

a. 3-point function (graph with 5 vertices and 5 edges):



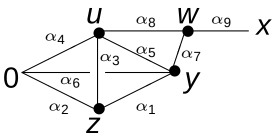
$$= \int \frac{d^D z \, d^D u}{(z-y)^{2\alpha_1} \, z^{2\alpha_2} \, y^{2\alpha_3} \, u^{2\alpha_4} \, (u-y)^{2\alpha_5}}$$

b. Star integral:



$$= \int \frac{d^D x}{(x-x_1)^{2\alpha_1} \, (x-x_2)^{2\alpha_2} \, (x-x_3)^{2\alpha_3}}$$

c. Propagator-type diagram:



$$= \int \frac{d^D z \, d^D u \, d^D y \, d^D w}{(x-z)^{2\alpha_1} \, z^{2\alpha_2} \, (z-u)^{2\alpha_3} \, u^{2\alpha_4} \, (u-y)^{2\alpha_5} \, y^{2\alpha_6} \ldots (w-x)^{2\alpha_9}}$$

Analytical calc. of F.D. $\rightarrow$ reconstruction of graphs to reduce no. of $\bullet$.

3. Operator formalism

Consider D-dimensional Euclidean space $\mathbf{R}^D$ with coordinates x_i, $(i = 1, 2, \dots, D)$. We use notation: $\boxed{x^{2\alpha} = (\sum_{i=1}^D x_i^2)^\alpha}$. Let $\hat{q}_i = \hat{q}_i^\dagger$ and $\hat{p}_i = \hat{p}_i^\dagger$ be operators of coordinate and momentum

$$\boxed{[\hat{q}_k, \hat{p}_j] = \mathrm{i}\, \delta_{kj}} \; .$$

Introduce states $|x\rangle \equiv |\{x_i\}\rangle$, $|k\rangle \equiv |\{k_i\}\rangle$: $\hat{q}_i|x\rangle = x_i\,|x\rangle$, $\hat{p}_i|k\rangle = k_i\,|k\rangle$, and normalize these states as:

$$\langle x|k\rangle = \frac{1}{(2\pi)^{D/2}} \exp(\mathrm{i}\, k_j\, x_j) \; , \quad \int d^D k\, |k\rangle\,\langle k| = \hat{1} = \int d^D x\, |x\rangle\,\langle x| \; .$$

"Matrix representation" of $\hat{p}^{-2\beta}$ (propagator of massless particle) is:

$$\underline{\langle x|\frac{1}{\hat{p}^{2\beta}}|y\rangle = a(\beta)\,\frac{1}{(x-y)^{2\beta'}}} \; , \quad \left(a(\beta) = \frac{\Gamma(\beta')}{\pi^{D/2}\, 2^{2\beta}\, \Gamma(\beta)} \right) .$$

where $\boxed{\beta' = D/2 - \beta}$ and $\Gamma(\beta)$ is the Euler gamma-function.

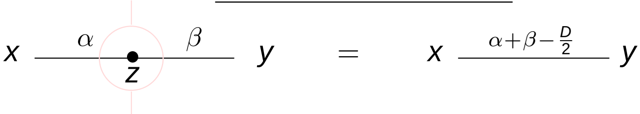
For $\hat{q}^{2\alpha}$ the "matrix representation" is: $\quad \langle x|\hat{q}^{2\alpha}|y\rangle = x^{2\alpha}\,\delta^D(x-y)$.

Algebraic relations (a,b,c) which are helpful for analytical calculations of perturbative integrals for multi-loop F.D. $\Rightarrow$ reconstruction of graphs

a. Group relation. Consider a convolution product of two propagators:

$$\int \frac{d^D z}{(x-z)^{2\alpha}\,(z-y)^{2\beta}} = \frac{G(\alpha',\beta')}{(x-y)^{2(\alpha+\beta-D/2)}}\,, \quad \left(G(\alpha,\beta) = \frac{a(\alpha+\beta)}{a(\alpha)\,a(\beta)} \right),$$

which leads to the reconstruction of graph:



This is the "matrix representation" of the operator relation

$$\boxed{\hat{p}^{-2\alpha'}\,\hat{p}^{-2\beta'} = \hat{p}^{-2(\alpha'+\beta')}.} \quad !!!$$

Proof.

$$\int d^D z\, \langle x|\hat{p}^{-2\alpha'}|z\rangle\, \langle z|\hat{p}^{-2\beta'}|y\rangle = \langle x|\hat{p}^{-2(\alpha'+\beta')}|y\rangle \qquad \square$$

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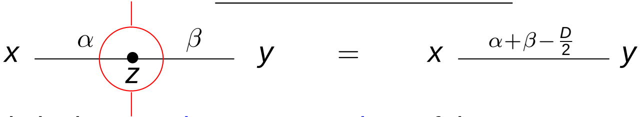

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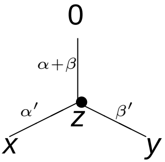
□

b. Star-triangle relation

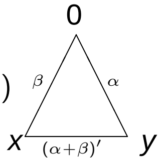
The "Method Of Uniqueness" (D.Kazakov, 1983) (Yang-Baxter equation)

$$\int \frac{d^D z}{(x-z)^{2\alpha'}\, z^{2(\alpha+\beta)}\, (z-y)^{2\beta'}} = \frac{G(\alpha,\beta)}{(x)^{2\beta}\, (x-y)^{2(\frac{D}{2}-\alpha-\beta)}\, (y)^{2\alpha}} \,.$$

Reconstruction of graph:



$= G(\alpha,\beta)$



$$\boxed{\alpha' = \frac{D}{2} - \alpha}$$

Operator version:

$$\boxed{\hat{p}^{-2\alpha}\hat{q}^{-2(\alpha+\beta)}\hat{p}^{-2\beta} = \hat{q}^{-2\beta}\hat{p}^{-2(\alpha+\beta)}\hat{q}^{-2\alpha}}$$!!!

Compare with Yang-Baxter equation:

$$S(\alpha)\,\widetilde{S}(\alpha+\beta)\,S(\beta) = \widetilde{S}(\beta)\,S(\alpha+\beta)\,\widetilde{S}(\alpha)$$

3. Operator formalism

Remarks on star-triangle relation:

1. STR is a commutativity condition for the set of operators $H_\alpha = \hat{p}^{2\alpha}\hat{q}^{2\alpha}$:

$$\hat{p}^{2\gamma}\hat{q}^{2\gamma}\,\hat{p}^{2\alpha}\hat{q}^{2\alpha} = \hat{p}^{2\alpha}\hat{q}^{2\alpha}\,\hat{p}^{2\gamma}\hat{q}^{2\gamma} \Rightarrow$$

$$\hat{p}^{2(\gamma-\alpha)}\hat{q}^{2\gamma}\,\hat{p}^{2\alpha} = \hat{q}^{2\alpha}\,\hat{p}^{2\gamma}\hat{q}^{2(\gamma-\alpha)} \Rightarrow \text{STR for } \gamma = \alpha+\beta\,.$$

2. Algebraic proof of the STR. Introduce inversion operator R:

$$R^2 = 1\,, \quad \langle x_i|R = \langle \tfrac{x_i}{x^2}|$$

$$R\hat{q}_iR = \hat{q}_i\,/\,\hat{q}^2\,, \quad R\hat{p}_iR = \hat{q}^2\,\hat{p}_i - 2\,\hat{q}_i\,(\hat{q}\,\hat{p}) =: K_i\,,$$

$$\boxed{R\,\hat{p}^{2\beta}\,R = \hat{q}^{2(\beta+\frac{D}{2})}\,\hat{p}^{2\beta}\,\hat{q}^{2(\beta-\frac{D}{2})}}\,.$$

Proof.

$$\underset{\substack{\Uparrow\\ R^2}}{R\,\hat{p}^{2\alpha}\,\hat{p}^{2\beta}\,R} = R\,\hat{p}^{2(\alpha+\beta)}\,R \;\Rightarrow\; \hat{p}^{2\alpha}\hat{q}^{2(\alpha+\beta)}\,\hat{p}^{2\beta} = \hat{q}^{2\beta}\,\hat{p}^{2(\alpha+\beta)}\hat{q}^{2\alpha}$$

3. Operator formalism

3. One can deduce "local" STR which is related to the α-representation for FD (*R.Kashaev, 1996*)

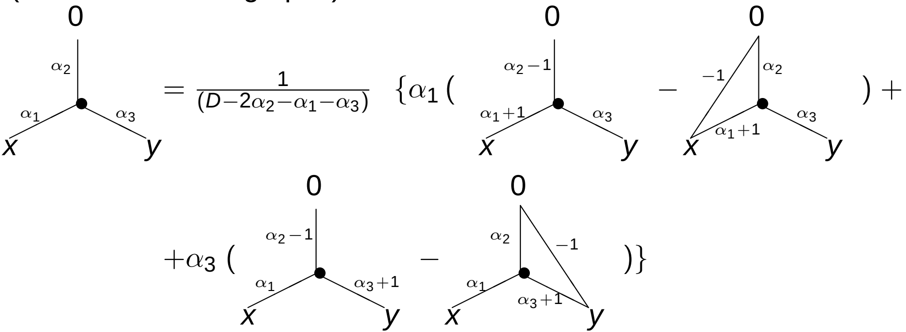
$$W(x^2|\alpha) = \exp\left(-\frac{x^2}{2\alpha}\right)$$

$$W(\hat{q}^2|\alpha_1)\,W(\hat{p}^2|\,\tfrac{1}{\alpha_2})\,W(\hat{q}^2|\alpha_3) = W(\hat{p}^2|\,\tfrac{1}{\beta_3})\,W(\hat{q}^2|\beta_2)\,W(\hat{p}^2|\,\tfrac{1}{\beta_1})$$

where $\alpha_i = \frac{\beta_1\beta_2+\beta_1\beta_3+\beta_2\beta_3}{\beta_i}$ is a star-triangle transformation for resistances in electric networks

c. Integration by parts rule. (*F. Tkachov, K. Chetyrkin, 1981*)

(reconstruction of graphs)



It can be represented in the operator form:

$$(2\gamma-\alpha-\beta)\,\hat{p}^{2\alpha}\hat{q}^{2\gamma}\hat{p}^{2\beta} = \frac{[\hat{q}^2,\,\hat{p}^{2(\alpha+1)}]}{4(\alpha+1)}\,\hat{q}^{2\gamma}\,\hat{p}^{2\beta} - \hat{p}^{2\alpha}\hat{q}^{2\gamma}\frac{[\hat{q}^2,\,\hat{p}^{2(\beta+1)}]}{4(\beta+1)}\;!!$$

where $\alpha=-\alpha_1'$, $\gamma=-\alpha_2$ and $\beta=-\alpha_3'$.

The integration by parts identity

$$(2\gamma-\alpha-\beta)\,\hat{p}^{2\alpha}\hat{q}^{2\gamma}\hat{p}^{2\beta} = \frac{[\hat{q}^2,\,\hat{p}^{2(\alpha+1)}]}{4(\alpha+1)}\,\hat{q}^{2\gamma}\,\hat{p}^{2\beta} - \hat{p}^{2\alpha}\hat{q}^{2\gamma}\,\frac{[\hat{q}^2,\,\hat{p}^{2(\beta+1)}]}{4(\beta+1)}\,,$$

can be proved by using relations for Heisenberg algebra

$$[\hat{q}^2,\,\hat{p}^{2(\alpha+1)}] = 4\,(\alpha+1)\,(H+\alpha)\,\hat{p}^{2\alpha}\,,$$

$$H\,\hat{q}^{2\alpha} = \hat{q}^{2\alpha}\,(H+2\alpha)\,, \quad H\,\hat{p}^{2\alpha} = \hat{p}^{2\alpha}\,(H-2\alpha)\,,$$

where $H := \frac{\mathrm{i}}{2}(\hat{p}_i\hat{q}_i + \hat{q}_i\hat{p}_i)$ is the dilatation operator.

The set of operators $\{\hat{q}^2, \hat{p}^2, H\}$ generates the algebra $sl(2)$.

3. Operator formalism

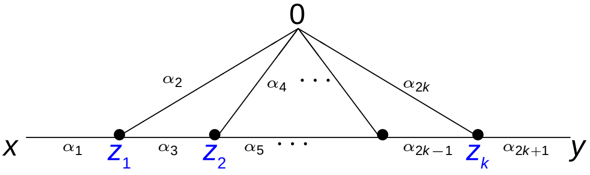
An example of the operator representation for F.D.

Consider an operator:

$$\Psi(\alpha_i) = \hat{p}^{-2\alpha'_1}\,\hat{q}^{-2\alpha_2}\,\hat{p}^{-2\alpha'_3}\,\hat{q}^{-2\alpha_4}\,\hat{p}^{-2\alpha'_5}\cdots\hat{q}^{-2\alpha_{2k}}\,\hat{p}^{-2\alpha'_{2k+1}}\,.$$

This operator is the algebraic version of 3-point function:

$\langle x|\Psi(\alpha_i)|y\rangle \sim$



Indeed,

$$\langle x|\Psi(\alpha_i)|y\rangle = \langle x|\hat{p}^{-2\alpha'_1}\,\underset{\Uparrow}{\hat{q}}^{-2\alpha_2}\,\hat{p}^{-2\alpha'_3}\,\underset{\Uparrow}{\hat{q}}^{-2\alpha_4}\,\hat{p}^{-2\alpha'_5}\cdots\underset{\Uparrow}{\hat{q}}^{-2\alpha_{2k}}\,\hat{p}^{-2\alpha'_{2k+1}}|y\rangle$$

$$\int d^D z_1 |z_1\rangle\langle z_1| \qquad \int d^D z_2 |z_2\rangle\langle z_2| \qquad \int d^D z_k |z_k\rangle\langle z_k|$$

Remark. $\langle x|\Psi(\alpha_i)|x\rangle$ represents the propagator-type diagrams.

3. Operator formalism

The advantage: we change the manipulations with integrals by the manipulations with elements of the algebra generated by $\hat{p}^{2\alpha}, \hat{q}^{2\beta}$.

Is it possible to define the trace for this algebra?

$$\mathrm{Tr}\,(\Psi(\alpha_i)) = \int d^D x \, \langle x | \hat{p}^{-2\alpha'_1} \, \hat{q}^{-2\alpha_2} \, \hat{p}^{-2\alpha'_3} \cdots \hat{q}^{-2\alpha_{2k}} \, \hat{p}^{-2\alpha'_{2k+1}} | x \rangle = c(\alpha_i) \int \frac{d^D x}{x^{2\beta}} \, .$$

($\beta = \sum_i \alpha_i$; $c(\alpha_i)$- coeff. function). The dim. reg. procedure requires:

$$\int \frac{d^D x}{x^{2(D/2+\alpha)}} = 0 \quad \forall \alpha \neq 0 \, .$$

The extension of the definition of this integral is (S.Gorishnii, A.Isaev, 1985)

$$\boxed{\int \frac{d^D x}{x^{2(D/2+\alpha)}} = \pi \Omega_D \delta(|\alpha|) \, ,} \quad \textbf{!!!}$$

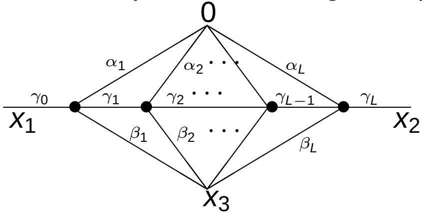
where $\Omega_D = 2\pi^{D/2}/\Gamma(D/2)$, $\alpha = |\alpha| e^{i \arg(\alpha)}$. Then, the cyclic property of "Tr" can be checked. "Tr": propagators $\Rightarrow$ vacuum diagrams.

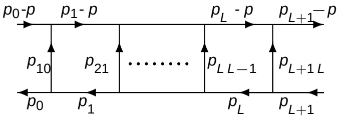
L-loop ladder diagrams for ϕ^3 FT $\Leftrightarrow$ D-dimensional conformal QM

Consider dimensionally and analytically regularized massless integrals

$$D_L(p_0, p_{L+1}, p; \vec{\alpha}, \vec{\beta}, \vec{\gamma}) = \left[\prod_{k=1}^{L} \int \frac{d^D p_k}{p_k^{2\alpha_k} (p_k - p)^{2\beta_k}}\right] \prod_{m=0}^{L} \frac{1}{(p_{m+1} - p_m)^{2\gamma_m}}$$

which correspond to the diagrams ($x_1 = p_0$, $x_2 = p_{L+1}$, $x_3 = p$):





$(p_{mk} = p_m - p_k)$

The diagrams (in config. and moment. spaces) are dual to each other (the boldface vertices correspond to the loops). The operator version is

$$D_L(x_a; \vec{\alpha}, \vec{\beta}, \vec{\gamma}) \sim \langle x_1 | \hat{p}^{-2\gamma_0'} \left(\prod_{k=1}^{L} \hat{q}^{-2\alpha_k} (\hat{q} - x_3)^{-2\beta_k} \hat{p}^{-2\gamma_k'} \right) | x_2 \rangle \ .$$

4. Application

For simplicity we put $\boxed{\alpha_i = \alpha, \beta_i = \beta, \gamma_i = \gamma}$ and consider the generating function for D_L:

$$D_g(x_a; \alpha, \beta, \gamma) = \sum_{L=0}^{\infty} g^L \, D_L(x_a; \alpha, \beta, \gamma) \sim \langle x_1 \,|\left(\hat{p}^{2\gamma'} - \frac{\bar{g}}{\hat{q}^{2\alpha}(\hat{q} - x_3)^{2\beta}}\right)^{-1} |\, x_2\rangle$$

where $\bar{g} = g/a(\gamma')$ is the renormalized coupling constant. For the case $\boxed{\alpha + \beta = 2\gamma'}$, using inversions, etc. we obtain

$$D_g \sim \langle u \,|\, \left(\hat{p}^{2\gamma'} - \frac{g_x}{\hat{q}^{2\beta}}\right)^{-1} \,|\, v\rangle \; ,$$

where $g_x = \bar{g}(x_3)^{-2\beta}$, $u_i = \frac{(x_1)_i}{(x_1)^2} - \frac{(x_3)_i}{(x_3)^2}$, $v_i = \frac{(x_2)_i}{(x_2)^2} - \frac{(x_3)_i}{(x_3)^2}$.

The ϕ^3-theory for $D = 4$ is related to $\gamma' = 1 = \beta$ and we obtain the Green's function for conformal QM:

$$D_g \sim \langle u \,|\, \left(\hat{p}^2 - \frac{g_x}{\hat{q}^2}\right)^{-1} \,|\, v\rangle \; ,$$

For $D \neq 4$ this GF $\Rightarrow$ ladder diagrams for $\alpha = \beta = 1, \gamma = \frac{D}{2} - 1$.

Our method is based on the identity:

$$\frac{1}{\hat{p}^2 - g/\hat{q}^2} = \sum_{L=0}^{\infty} \left(-\frac{g}{4}\right)^L \left[\hat{q}^{2\alpha} \frac{(H-1)}{(H-1+\alpha)^{L+1}} \frac{1}{\hat{p}^2} \hat{q}^{-2\alpha}\right]_{\alpha^L}$$

where we denote $[\dots]_{\alpha^L} = \frac{1}{L!} \left(\partial_\alpha^L [\dots]\right)_{\alpha=0}$. Taking into account

$$\frac{(H-1)}{(H-1+\alpha)^{L+1}} = \frac{(-1)^{L+1}}{L!} \int_0^\infty dt\, t^L\, e^{t\alpha}\, \partial_t \left(e^{t\,(H-1)}\right)$$

and $e^{t(H+\frac{D}{2})}\,|x\rangle = |e^{-t}x\rangle$ the Green's function D_g is written in the form

$$\langle u| \frac{1}{(\hat{p}^2 - g_x/\hat{q}^2)} |v\rangle = \sum_{L=0}^{\infty} \frac{1}{L!} \left(\frac{g_x}{4}\right)^L \Phi_L(u,v)\,,$$

$$\Phi_L(u,v) = -a(1) \int_0^\infty dt\, t^L \left[\left(\frac{u^2}{v^2}\right)^\alpha e^{t\alpha}\right]_{\alpha^L} \partial_t \left(\frac{e^{-t}}{(u-e^{-t}v)^2}\right)^{(\frac{D}{2}-1)}$$

4. Application

For $D = 4 - 2\epsilon$ one can expand $\Phi_L(u,v)$ over small ϵ:

$$\Phi_L(u,v) = \frac{\Gamma(1-\epsilon)}{4\pi^{2-\epsilon}u^{2(1-\epsilon)}} \sum_{k=0}^{\infty} \frac{\epsilon^k}{k!} \Phi_L^{(k)}(z_1,z_2) \, .$$

where $z_1 + z_2 = 2(uv)/u^2$ and $z_1 z_2 = v^2/u^2$. The coeff. functions $\Phi_L^{(k)}$ are expressed in terms of multiple polylogarithms. The first one is (N.I. Ussyukina and A.I. Davydychev; D.J. Broadhurst; 1993)

$$\Phi_L^{(0)}(z_1,z_2) = \frac{1}{z_1 - z_2} \sum_{f=0}^{L} \frac{(-)^f \, (2L-f)!}{f! \, (L-f)!} \ln^f(z_1 z_2) \left[\mathrm{Li}_{2L-f}(z_1) - \mathrm{Li}_{2L-f}(z_2) \right] .$$

where polylogs are

$$\mathrm{Li}_m(w) = \sum_{n=1}^{\infty} \frac{w^n}{n^m} \, .$$

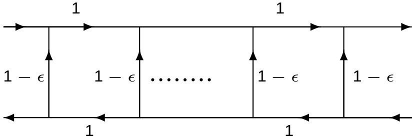
The next coefficient is: $\Phi_L^{(1)}(z_1, z_2) =$

$$= \sum_{n=L}^{2L} \frac{n!\ \ln^{2L-n}(z_1 z_2)\left[(n\mathrm{Li}_{n+1}(z_1) - \mathrm{Li}_{n,1}(z_1,1) - \mathrm{Li}_{n,1}(z_1,\frac{z_2}{z_1})) - (z_1 \leftrightarrow z_2)\right]}{(-1)^n\,(2L-n)!\,(n-L)!\ \ (z_1 - z_2)},$$

where multiple polylogarithms are

$$\mathrm{Li}_{m_0,m_1,\ldots,m_r}(w_0, w_1, \ldots, w_r) = \sum_{n_0>n_1>\cdots>n_r>0} \frac{w_0^{n_0} w_1^{n_1} \ldots w_r^{n_r}}{n_0^{m_0} n_1^{m_1} \ldots n_r^{m_r}}\ .$$

The function $\Phi_L^{(1)}(z_1, z_2)$ gives the first term in the expansion over ϵ of the L-loop ladder diagram (with special indices on the lines)



Summary

- Applications of the coefficients $\Phi_L(u,v)$ for the avaluations of 4-point functions in $N=4$ SYM theory.
- Lipatov's integrable model – describes high energy scattering of hadrons in QCD.
- Generalizations to massive case and to supersymmetric case. In massive case it is tempting to calculate the Green's function

$$\langle u| \frac{1}{(\hat{p}^2 - g/\hat{q}^2 + m^2)} |v\rangle = \sum_{L=0}^{\infty} g^L \, \Phi_L(u,v;m^2) \; ,$$

- It seems that the approach is not universal even for massless FDs. We should add something new.

For Further Reading I

A.P. Isaev,
Nucl. Phys. **B662** *(2003) 461 (hep-th/0303056)*
Multi-Loop Feynman Integrals and Conformal Quantum Mechanics