Three-loop cusp anomalous dimension in QCD

A. Grozin, J. Henn, G. Korchemsky, P. Marquard

Heavy electron effective theory

Single electron of mass M + soft photons
Ground state — electron at rest
Mass shell

$$\varepsilon(\vec{p}) = \frac{\vec{p}^{\,2}}{2M}$$
$$\vec{v} = \frac{\partial \varepsilon(\vec{p})}{\partial \vec{p}} = \frac{\vec{p}}{M}$$

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Leading order in $1/M$

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Leading order in $1/M$
Lagrangian

$$L = h^{+} i\partial_0 h$$
$$\partial_0 h = 0$$

External field

$$\varepsilon(\vec{p}) = -eA_0$$
$$D_0 h = 0 \qquad D_\mu = \partial_\mu - ieA_\mu$$
$$L = h^+ D_0 h$$

Gauge invariant

$$h \to he^{ie\alpha(x)}h \qquad A_\mu \to A_\mu + \partial_\mu \alpha(x)$$

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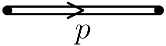
$+$ Lagramgian of electromagnetic field

$$\partial_\mu F^{\mu\nu} = j^\nu \qquad j^0 = -eh^+ h$$

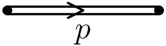
Interaction Lagrangian $-j^\mu A_\mu$

Propagator



$$= iS_0(p) \qquad S_0(p) = \frac{1}{p_0 + i0}$$

Propagator



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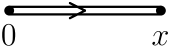
Coordinate space



$$= iS_0(x) \qquad S_0(x) = S_0(x_0)\delta(\vec{x}\,) \qquad S_0(t) = -i\theta(t)$$

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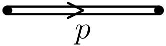

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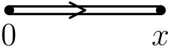

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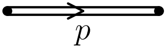
Solving the equation

$$i\partial_0 S_0(x) = \delta(x)$$

Propagator



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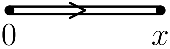
Coordinate space



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Solving the equation

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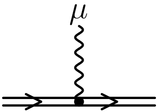
Interaction eh^+hA_0 — vertex



$$= ie_0 v^\mu \qquad v^\mu = (1, \vec{0}\,)$$

Wilson line

$$iD_0 S(x,x') = (i\partial_0 + eA_0(x))S(x,x') = \delta(x-x')$$

$$S(x,x') = S(x_0,x_0')\delta(\vec{x}-\vec{x}\,')$$

$$S(x_0,x_0') = S_0(x_0-x_0')W(x_0,x_0')$$

$$W(x_0,x_0') = \exp ie\int_{x_0'}^{x_0} A^\mu(t,\vec{x}\,)v_\mu dt$$

Covariant notation

HEET lowest-energy state ("vacuum")
— single electron at rest $\varepsilon = 0$

QED $E = M$

For any state containing the electron

$$E = M + \varepsilon$$

ε — residual energy

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For any state containing the electron

$$E = M + \varepsilon$$

ε — residual energy

$$P^\mu = M v^\mu + p^\mu$$

$$p^\mu \ll M \qquad p_i^\mu \ll M$$

p — residiual momentum
p_i — light particles' (photons') momenta

Covariant notation

$$L = h^+ iv \cdot Dh$$

$$S(p) = \frac{1}{p \cdot v + i0}$$

Mass shell

$$p \cdot v = 0$$

Covariant notation

$$L = \bar{h} \;\; iv \cdot Dh$$

$$S(p) = \frac{1}{p \cdot v + i0} \frac{1 + \not{v}}{2}$$

Mass shell

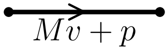
$$p \cdot v = 0$$

Electron spin $\not{v}h = h$

Full theory and effective theory

Propagator

$$S_0(Mv+p) = \frac{M + M\not{v} + \not{p}}{(Mv+p)^2 - M^2 + i0} = \frac{1}{p\cdot v + i0}\,\frac{1+\not{v}}{2} + \mathcal{O}\left(\frac{p}{M}\right)$$



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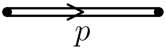

$+\,\mathcal{O}\left(\frac{p}{M}\right)$

Full theory and effective theory

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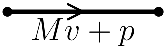
$$S_0(Mv+p) = \frac{M + M\not{v} + \not{p}}{(Mv+p)^2 - M^2 + i0} = \frac{1}{p\cdot v + i0}\,\frac{1+\not{v}}{2} + \mathcal{O}\left(\frac{p}{M}\right)$$



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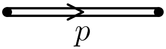


$+\,\mathcal{O}\left(\frac{p}{M}\right)$

Vertex

$$\frac{1+\not{v}}{2}\gamma^\mu\frac{1+\not{v}}{2} = \frac{1+\not{v}}{2}v^\mu\frac{1+\not{v}}{2}$$

Why

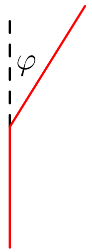
IR behavior of scattering amplitudes $\rightarrow$ Wilson lines

Why

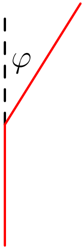
IR behavior of scattering amplitudes $\to$ Wilson lines

- $t\bar{t}$ production at LHC and ILC
- $t \to bW$
- $b \to c$
- $\dots$

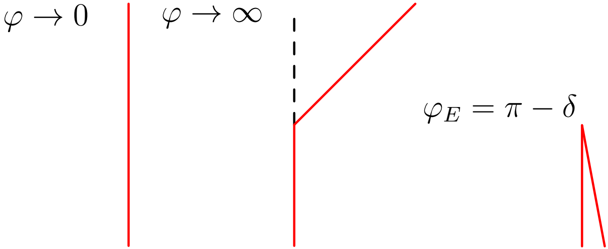
Wilson lines



Wilson lines



Limiting cases



HQET heavy-to-heavy current

$$J = h_{v'}^{+} h_v = Z_J(\alpha_s(\mu); \varphi) J_r(\mu)$$
$$h_v = Z_h^{1/2}(\alpha_s(\mu)) h_{vr}(\mu)$$
$$\cosh \varphi = v \cdot v'$$

Green functions

$$-i\langle h_v(x)h_v^+(0)\rangle = \delta(x_\perp)W(t) = Z_h\delta(x_\perp)W_r(t;\mu)$$

Green functions

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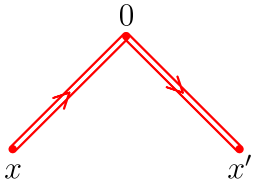


$$(-i)^2 \langle h_{v'}(x') J(0) h_v^+(x)\rangle = \delta(x_\perp)\delta(x'_{\perp'}) W(t,t';\varphi)$$
$$= Z_h Z_J \delta(x_\perp)\delta(x'_{\perp'}) W_r(t,t';\varphi;\mu)$$

Renormalization

$$W(t,t';0) = W(t+t')$$

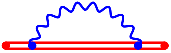
$$\log \frac{W(t,t';\varphi)}{W(t,t';0)} = \log Z_J + \text{finite}$$

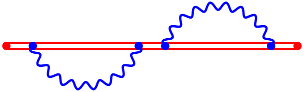
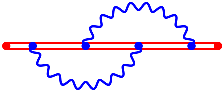
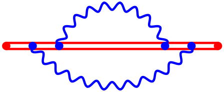
$$\Gamma(\alpha_s,\varphi) = \frac{d\log Z_J}{d\log\mu}$$

$$\Gamma(\alpha_s,0) = 0$$

Exponentiation in QED

Coordinate space, Wilson line of any shape ($n_f = 0$)

$W(t) =$  $+$ 

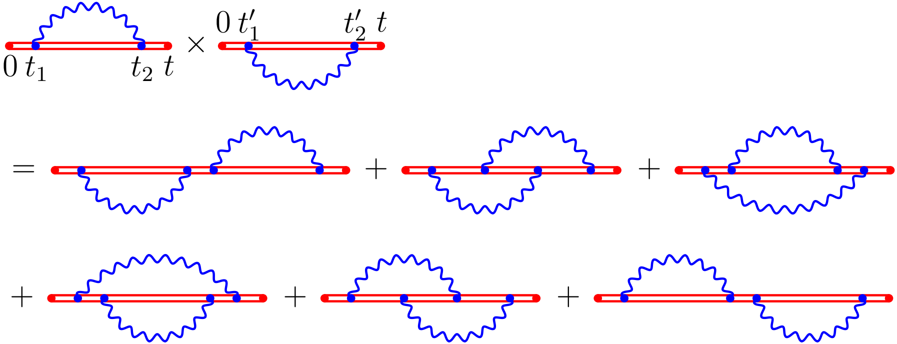
$+$  $+$  $+$ 

$+ \cdots$

$\log W(t) = ?$

Exponentiation in QED

$$0 < t_1 < t_2 < t,\ 0 < t'_1 < t'_2 < t$$



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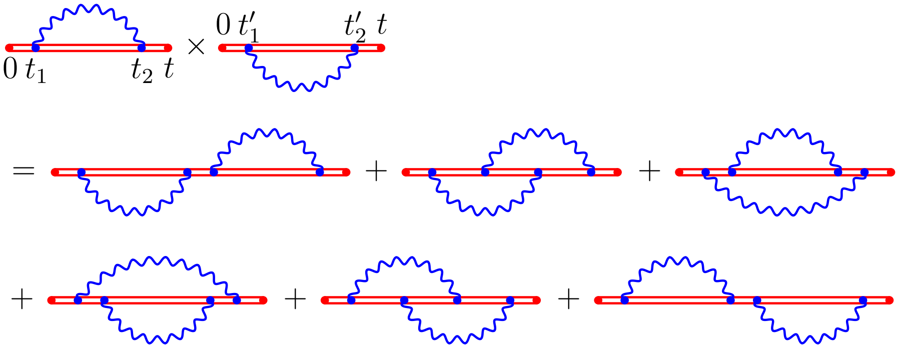
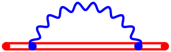
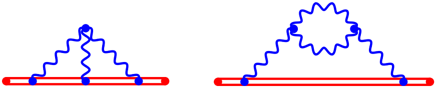
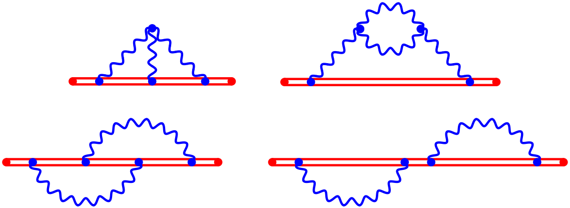


$\log W(t) =$ 

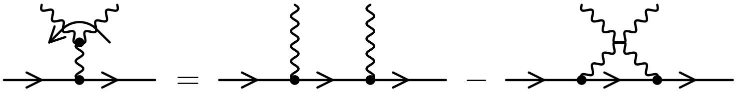
Exponentiation in QCD



Exponentiation in QCD

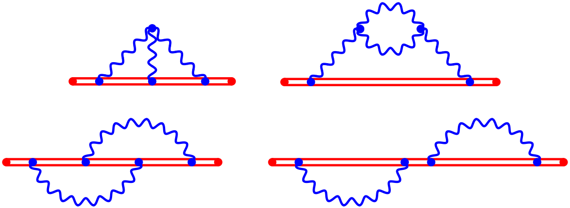


$[t^a, t^b] = i f^{abc} t^c$



Gatheral (1983); Frenkel, Taylor (1984)

Exponentiation in QCD



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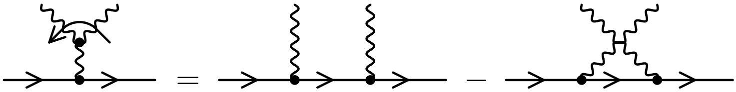

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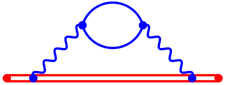

$T_F n_f \Rightarrow$ all color structures allowed

Exponentiation in QCD

$$\log W = C_F \frac{g_0^2}{(4\pi)^{d/2}} \left[w + \left(C_A w_A + T_F n_f w_f \right) \frac{g_0^2}{(4\pi)^{d/2}} \right.$$

$$\left. + \left(C_A^2 w_{AA} + C_F T_F n_f w_{Ff} + C_A T_F n_f w_{Af} + \left(T_F n_f \right)^2 w_{ff} \right) \left(\frac{g_0^2}{(4\pi)^{d/2}} \right)^2 \right]$$

Exponentiation in QCD

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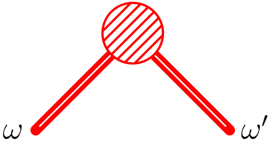
$$\Gamma = C_F \frac{\alpha_s}{\pi} \left[\gamma + \left(C_A \gamma_A + T_F n_f \gamma_f \right) \frac{\alpha_s}{\pi} + \left(C_A^2 \gamma_{AA} + C_F T_F n_f \gamma_{Ff} + C_A T_F n_f \gamma_{Af} + \left(T_F n_f \right)^2 \gamma_{ff} \right) \left(\frac{\alpha_s}{\pi} \right)^2 \right]$$

Momentum space



Vertex function V: 1PI, without external-leg propagators

$$G(\omega, \omega'; \varphi) = V(\omega, \omega'; \varphi) S_v(\omega) S_{v'}(\omega')$$
$$V(\omega, \omega'; \varphi) = Z_J Z_h^{-1} V_r(\omega, \omega'; \varphi; \mu)$$
$$\log V(\omega, \omega'; \varphi) - \log V(\omega, \omega'; 0) = \log Z_J + \text{finite}$$

Convenient to set $\omega' = \omega$

$\varphi = 0$

$$V(\omega, \omega'; 0) = \frac{S^{-1}(\omega') - S^{-1}(\omega)}{\omega' - \omega} = Z_h^{-1} V_r(\omega, \omega'; 0; \mu)$$

$$\log V(\omega, \omega'; 0) = -\log Z_h + \text{finite}$$

Z_h is gauge dependent; Z_J is gauge invariant

History

1 loop

$$\Gamma(\alpha_s, \varphi) = C_F \frac{\alpha_s}{\pi} (\varphi \coth \varphi - 1)$$

Follows from the soft radiation function in classical electrodynamics

The Guinness Book of Records The anomalous dimension known for a longest time (> 100 years)

2 loops Korchemsky, Radyushkin (1987)
Kidonakis (2009)

3 loops here

History

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3 loops here

γ_h at 3 loops — Chetyrkin, Grozin (2003)

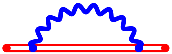
Abelian large n_f structures

$C_F(T_F n_f)^{L-1}\alpha_s^L$ and $C_F^2(T_F n_f)^{L-2}\alpha_s^L$ $(L \geq 3)$

Abelian large n_f structures

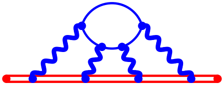
$C_F(T_F n_f)^{L-1}\alpha_s^L$ and $C_F^2(T_F n_f)^{L-2}\alpha_s^L$ $(L \geq 3)$

QED with n_f flavors $C_F = 1$, $C_A = 0$, $T_F = 1$, $\beta_0 = -\frac{4}{3}n_f$
At Lβ_0 and NLβ_0, the Wilson line of any shape

$\log W =$ 

with

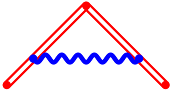
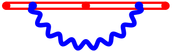
up to NLβ_0. First broken at NNLβ_0



$n_f^{L-3}\alpha^L$ $(L \geq 4)$

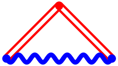
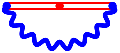
Abelian large n_f structures

$$\log W(t, t'; \varphi) - \log W(t, t'; 0)$$

$=$  $-$  $= \log Z_J + \text{finite}$

(external-leg corrections cancel). Momentum space

$$\log V(\omega, \omega; \varphi) - \log V(\omega, \omega; 0)$$

$=$  $-$  $= \log Z_J + \text{finite}$

Abelian large n_f structures

$$\Gamma = C_F \frac{\alpha_s}{6\pi} \frac{\varphi \coth \varphi - 1}{B(2+b, 2+b)\Gamma(1+b)\Gamma(1-b)}$$

$$= C_F \frac{\alpha_s}{\pi} \left[1 + \frac{5}{3} b - \frac{1}{3} b^2 + \left(2\zeta_3 - \frac{1}{3} \right) b^3 + \cdots \right] (\varphi \coth \varphi - 1)$$

$b = \beta_0 \frac{\alpha_s}{4\pi}$ Beneke, Braun (1995)

Abelian large n_f structures

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$$= C_F \frac{\alpha_s}{\pi} \left[1 + \frac{5}{3} b - \frac{1}{3} b^2 + \left(2\zeta_3 - \frac{1}{3} \right) b^3 + \cdots \right] (\varphi \coth \varphi - 1)$$

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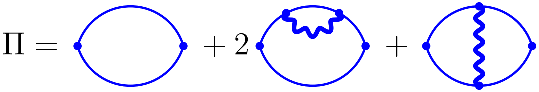
NLβ_0

- NL photon self energy



- NL Z_α

$C_F C_A T_F n_f$

$$\log Z_J = \cdots + C_F \left(\frac{\alpha_s}{\pi}\right)^3 \left[C_A^2 z_{AA} + T_F n_f (C_F z_{Ff} + C_A z_{Af}) + (T_F n_f)^2 z_{ff}\right]$$

$C_F C_A T_F n_f$

$$\log Z_J = \cdots + C_F \left(\frac{\alpha_s}{\pi}\right)^3$$
$$\left[C_A^2 z_{AA} + T_F n_f (C_F z_{Ff} + C_A z_{Af}) + (T_F n_f)^2 z_{ff}\right]$$

$$N_c \to \infty \qquad N_c \left(\frac{z_{Ff}}{2} + z_{Af}\right)$$

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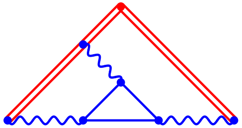
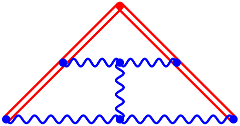


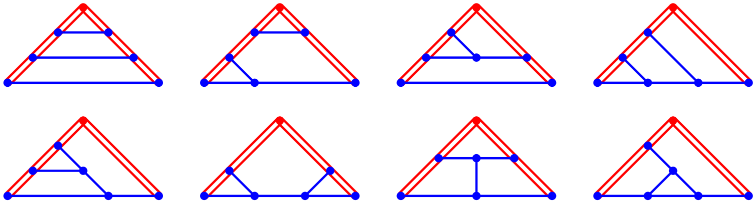
$C_F C_A^2$

$N_c \to \infty \qquad N_c^2 z_{AA}$

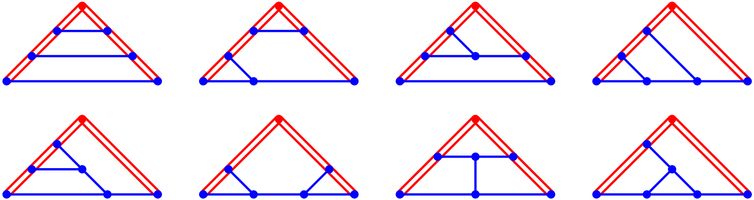


Only topologies surviving at $N_c \to \infty$

Topologies and master integrals



Topologies and master integrals



71 master integrals

- 7 straight-line [Grozin (2000)]
- 8 products of lower loops
- 10 generalized triangles [Grozin, Kotikov (2011)]
- 46 nontrivial

Differential equations

$$x = e^{-\varphi}$$

Symmetry $x \to 1/x$
Differentiate in x and reduce to masters
Initial values at $x = 1$

Differential equations

$$x = e^{-\varphi}$$

Symmetry $x \to 1/x$
Differentiate in x and reduce to masters
Initial values at $x = 1$
Canonical basis $\vec{f}$ [Henn (2013)]

$$\partial_x \vec{f}(x,\epsilon) = \epsilon \left[\frac{a}{x} + \frac{b}{x+1} + \frac{c}{x-1} \right] \vec{f}(x,\epsilon)$$

4 singular points

- $x = 1$ $(\varphi \to 0)$
- $x = 0, \infty$ $(\varphi \to \pm\infty)$
- $x = -1$ $(\varphi_E \to \pi)$

Harmonic polylogarithms $H_{n_1 \dots n_k}(x)$ $(n_i = 0, \pm 1)$
[Remiddi,Vermaseren (2000)]
Uniform weight functions

Result

$$
\begin{aligned}
\Gamma(\alpha_s, x) = C_F \frac{\alpha_s}{\pi} \Bigg\{ & \tilde{A}_1 \\
& + \left[\frac{1}{2} C_A \left(\tilde{A}_3 + \tilde{A}_2 \right) + \frac{1}{9} \left(\frac{67}{4} C_A - 5 T_F n_f \right) \tilde{A}_1 \right] \frac{\alpha_s}{\pi} \\
& + \Bigg\{ \Bigg[\frac{1}{4} \left(\tilde{A}_5 + \tilde{A}_4 + \tilde{B}_5 + \tilde{B}_3 \right) + \frac{67}{36} \tilde{A}_3 + \frac{29}{18} \tilde{A}_2 \\
& \qquad + \frac{1}{24} \left(11 \zeta_3 + \frac{245}{4} \right) \tilde{A}_1 \Bigg] C_A^2 \\
& \quad - \left[\frac{5}{9} \left(\tilde{A}_3 + \tilde{A}_2 \right) + \frac{1}{6} \left(7 \zeta_3 + \frac{209}{36} \right) \tilde{A}_1 \right] C_A T_F n_f \\
& \quad + \left(\zeta_3 - \frac{55}{48} \right) \tilde{A}_1 C_F T_F n_f - \frac{1}{27} \tilde{A}_1 \left(T_F n_f \right)^2 \Bigg\} \left(\frac{\alpha_s}{\pi} \right)^2 \Bigg\}
\end{aligned}
$$

Result

$$\tilde{A}_i(x) = A_i(x) - A_i(1)$$
$$A_1(x) = \frac{\xi}{2} H_1(y)$$
$$A_2(x) = \frac{1}{2} H_{1,1}(y) + \frac{\pi^2}{3} - \xi \left[\frac{1}{2} H_{1,1}(y) - H_{1,0}(y) \right]$$
$$A_3(x) = -\xi \left[\frac{1}{4} H_{1,1,1}(y) + \frac{\pi^2}{6} H_1(y) \right] + \xi^2 \left[\frac{1}{4} H_{1,1,1}(y) + \frac{1}{2} H_{1,0,1}(y) \right]$$
$$\dots$$
$$y = 1 - x^2 \qquad \xi = \frac{1 + x^2}{1 - x^2}$$

Uniform weight i

$\varphi \to \infty$

$x \to 0$

$$\Gamma(\alpha_s, x) = K(\alpha_s)\varphi + \mathcal{O}(1)$$

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$$P_{q\to q}(z) = K(\alpha_s)\left(\frac{1}{1-z}\right)_+ + \cdots$$

Korchemsky (1989); Korchemsky, Marchesini (1993)

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$$K(\alpha_s) = C_F\frac{\alpha_s}{\pi}\left\{1 + \left[\frac{1}{12}\left(\pi^2 - \frac{67}{3}\right)C_A + \frac{5}{9}T_F n_f\right]\frac{\alpha_s}{\pi}\right.$$
$$+ \left[\frac{1}{24}\left(\frac{11}{30}\pi^4 + 11\zeta_3 - \frac{67}{9}\pi^2 + \frac{245}{4}\right)C_A^2\right.$$
$$- \frac{1}{6}\left(7\zeta_3 - \frac{5}{9}\pi^2 + \frac{209}{36}\right)C_A T_F n_f$$
$$\left.\left. + \left(\zeta_3 - \frac{55}{48}\right)C_F T_F n_f - \frac{1}{27}(T_F n_f)^2\right]\left(\frac{\alpha_s}{\pi}\right)^2\right\}$$

Moch, Vermaseren, Vogt (2004)

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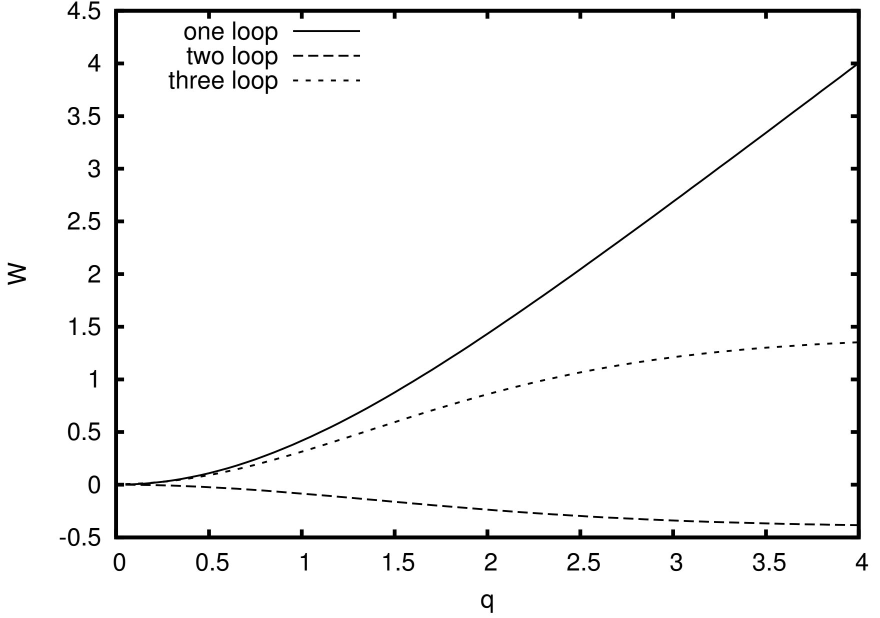
Moch, Vermaseren, Vogt (2004)

$$\Gamma(\alpha_s, x) = \Omega(a, x)$$

$$\Omega(a,x) = C_F \frac{a}{\pi}\left[\tilde{A}_1 + \frac{1}{2}\left(\tilde{A}_3 + \tilde{A}_2 + \frac{\pi^2}{6}\tilde{A}_1\right) C_A \frac{a}{\pi} + \frac{1}{4}\left(\tilde{A}_5 + \tilde{A}_4 - \tilde{A}_2 + \tilde{B}_5 + \tilde{B}_3 + \frac{\pi^2}{3}\tilde{A}_3 + \frac{\pi^2}{3}\tilde{A}_2 - \frac{\pi^4}{180}\tilde{A}_1\right) C_A^2 \left(\frac{a}{\pi}\right)^2\right]$$

Does not contain n_f!


one loop
two loop
three loop
W
q
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4

$\varphi_E \to \pi$

Euclidean $\varphi_E = \pi - \delta$

$$\Gamma = \frac{rV(r)}{\delta}$$

Kilian, Mannel, Ohl (1993)

Conformal symmetry

Euclidean space

$$ds^2 = dx_0^2 + d\vec{x}^2$$

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Spherical coordinates

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$$ds^2 = dr^2 + r^2(d\delta^2 + \sin^2\delta\, d\vec{n}^2)$$

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$\delta \ll 1$

$$r = e^{y_0} \qquad \vec{y} = \delta\vec{n}$$
$$ds^2 = e^{2y_0}\left(dy_0^2 + d\vec{y}^2\right)$$

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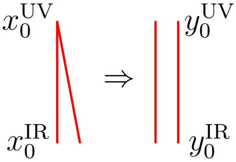

Conformal symmetry

$$\log W = \Gamma \log \frac{x_0^{\mathrm{IR}}}{x_0^{\mathrm{UV}}} = V(\vec{y})\left(y_0^{\mathrm{IR}} - y_0^{\mathrm{UV}}\right)$$

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In QCD conformal symmetry is anomalous $\Rightarrow$ β function
2 loops

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$$\delta\Gamma(\alpha_s, \pi - \delta) - rV(r, \alpha_s(\mu)) = C(\mu)\beta_0\alpha_s^2$$

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In QCD conformal symmetry is anomalous $\Rightarrow$ β function
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At 3 loops $\delta\Gamma(\pi - \delta)$ differs from $rV(r)$ by a term $\sim \beta_0 \alpha_s^3$

Conclusion

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- $\Omega(a, x)$ does not contain n_f: only 1 gluonic color structure at each L (1 structure at 2 loops and 3 structures at 3 loops disappear)
- $\varphi_E = \pi - \delta$: the relation to $V(r)$ which follows from conformal invariance is violated at 3 loops by a term $\sim \beta_0 \alpha_s^3$