Electroweak logarithms at 2 loops

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- Introduction
- Electroweak logarithmic corrections to $g \to f\bar{f}$
- Algorithm for next-to-leading logarithms

Introduction

- High-energy asymptotic expansion

$$s \gg M_{\mathrm{W}}^2$$

- tower of electroweak logs $L = \log(s/M_{\mathrm{W}}^2)$

$$\alpha^N \left[C_{2N} \underbrace{L^{2N}}_{\mathrm{LL}} + C_{2N-1} \underbrace{L^{2N-1}}_{\mathrm{NLL}} + \dots \right]$$

- origin: UV and mass singularities

- large electroweak corrections at TeV colliders

$$\boxed{\text{Typical size at } \sqrt{s} \simeq 1 \text{ TeV}}$$

1-Loop: $\mathcal{O}(10\%)$ corrections

$$\left(\frac{\delta\sigma_1}{\sigma_0}\right)_{\mathrm{LL}} \simeq -\frac{\alpha}{\pi s_{\mathrm{W}}^2}\log^2\frac{s}{M_{\mathrm{W}}^2} \simeq -26.4\%$$
$$\left(\frac{\delta\sigma_1}{\sigma_0}\right)_{\mathrm{NLL}} \simeq +\frac{3\alpha}{\pi s_{\mathrm{W}}^2}\log\frac{s}{M_{\mathrm{W}}^2} \simeq +15.6\%$$

2-Loop: $\mathcal{O}(1\%)$ corrections

$$\left(\frac{\delta\sigma_2}{\sigma_0}\right)_{\mathrm{LL}} \simeq +\frac{\alpha^2}{2\pi^2 s_{\mathrm{W}}^4}\log^4\frac{s}{M_{\mathrm{W}}^2} \simeq 3.5\%$$
$$\left(\frac{\delta\sigma_2}{\sigma_0}\right)_{\mathrm{NLL}} \simeq -\frac{3\alpha^2}{\pi^2 s_{\mathrm{W}}^4}\log^3\frac{s}{M_{\mathrm{W}}^2} \simeq -4.1\%$$

Resummation in **symmetric gauge theories**

Factorization of mass singularities in QCD

- evolution equations ($F =$ form factor)

$$\frac{\partial}{\partial Q^2} F = \int_{M^2}^{Q^2} \frac{\mathrm{d}x}{x} K(\alpha(x), x) F$$

- integration

$$F = F_0 \exp \left[\int_{M^2}^{Q^2} \frac{\mathrm{d}x}{x} \int_{M^2}^{x} \frac{\mathrm{d}x'}{x'} K(\alpha(x'), x') \right]$$

Sen (1981)

Perturbative expansion

$$F = 1 + \frac{\alpha}{4\pi} F^{(1)} + \left(\frac{\alpha}{4\pi}\right)^2 F^{(2)} + \dots$$

To NLL accuracy

$$F^{(1)} = C_F \left[\ln^2\left(\frac{Q^2}{M^2}\right) - 3 \ln\left(\frac{Q^2}{M^2}\right) \right]$$

$$F^{(2)} = \frac{1}{2}\left[F^{(1)}\right]^2 - \frac{1}{3}\beta_0 \ln^3\left(\frac{Q^2}{M^2}\right)$$

$$\boxed{\text{Mass gap: } M_A = 0 \ll M_{\mathrm{Z}} \sim M_{\mathrm{W}}}$$

General form of mass singularities

$$\left(\frac{1}{\epsilon}\right)^k \log^j\left(\frac{s}{M_{\mathrm{W}}^2}\right)$$

$$\boxed{\text{InfraRed Evolution Equation (IREE)}}$$

Transverse-momentum cut-off μ_{T}

$$\frac{\partial F}{\partial \log(\mu_{\mathrm{T}})} = K(\mu_{\mathrm{T}})F$$

2 regimes with **exact gauge symmetry**

- $\mu_{\mathrm{T}} \geq M_{\mathrm{W}}$: $M_A = M_{\mathrm{Z}} = M_{\mathrm{W}}$: $\mathrm{SU}(2) \times \mathrm{U}(1)$

$$F(M_{\mathrm{W}}) = \exp\left\{\int_{M_{\mathrm{W}}}^{\sqrt{s}} \frac{\mathrm{d}\mu_{\mathrm{T}}}{\mu_{\mathrm{T}}} K_1(\mu_{\mathrm{T}})\right\} F^{(0)}$$

- $\mu_{\mathrm{T}} \leq M_{\mathrm{W}}$: $M_{\mathrm{Z}} = M_{\mathrm{W}} = \infty$: QED

$$F(\mu_0) = \exp\left\{\int_{\mu_0}^{M_{\mathrm{W}}} \frac{\mathrm{d}\mu_{\mathrm{T}}}{\mu_{\mathrm{T}}} K_2(\mu_{\mathrm{T}})\right\} F(M_{\mathrm{W}})$$

Fadin, Lipatov, Martin, Melles (2000)

2-loop results: resummations

→ LL for **arbitrary processes**

Fadin, Lipatov, Martin, Melles (2000)

→ NLL for **arbitrary processes**

Melles (2001,2002)

→ NNLL for massless $f\bar{f} \to f'\bar{f}'$

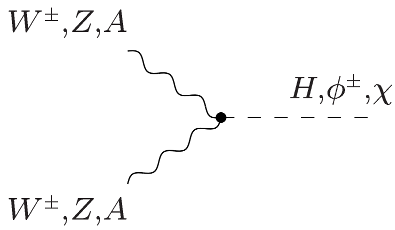
Kühn, Moch, Penin, Smirnov (2000,2001)

Assumptions

Various aspects of **symmetry breaking** are **neglected** in the limit

$$M_\mathrm{W}^2/s \to 0$$

(i) couplings with mass dimension



$$\sim \; \mathrm{i}e^2 \mathbf{v} \; \to \; 0$$

(ii) mass splittings

$$\frac{M_\mathrm{Z}}{M_\mathrm{W}} \to 1, \qquad \frac{M_\mathrm{H}}{M_\mathrm{W}} \to 1, \qquad \frac{m_\mathrm{t}}{M_\mathrm{W}} \to 1$$

(iii) mixing in the **gauge sector**

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} c_\mathrm{W} & s_\mathrm{W} \\ -s_\mathrm{W} & c_\mathrm{W} \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} \to \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix}$$

2-loop results: diagrammatic calculations

For **arbitrary processes**

$\rightarrow$ LL (Coulomb gauge)

Beenakker and Werthenbach (2000,2002)

$\rightarrow$ LL + ang-dep-NLL ($\xi = 1$ gauge)

Denner, Melles and P. (2003)

For the **massless fermionic form factor** $g \rightarrow f\bar{f}$

$\rightarrow$ LL (EW theory)

Melles (2000); Hori, Kodaira and Kawamura (2000)

$\rightarrow$ LL+NLL (EW theory)

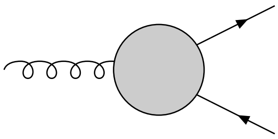
S.P. (hep-ph/0401087)

$\rightarrow$ LL+NLL+...+NNNNLL (abelian theory)

Feucht, Kühn, Penin and Smirnov (hep-ph/0404082)

2-loop fermionic form factor to NLL accuracy

S.P. (hep-ph/0401087)



$$= \mathrm{i}\bar{u}(p_1)F^\mu v(p_2)$$

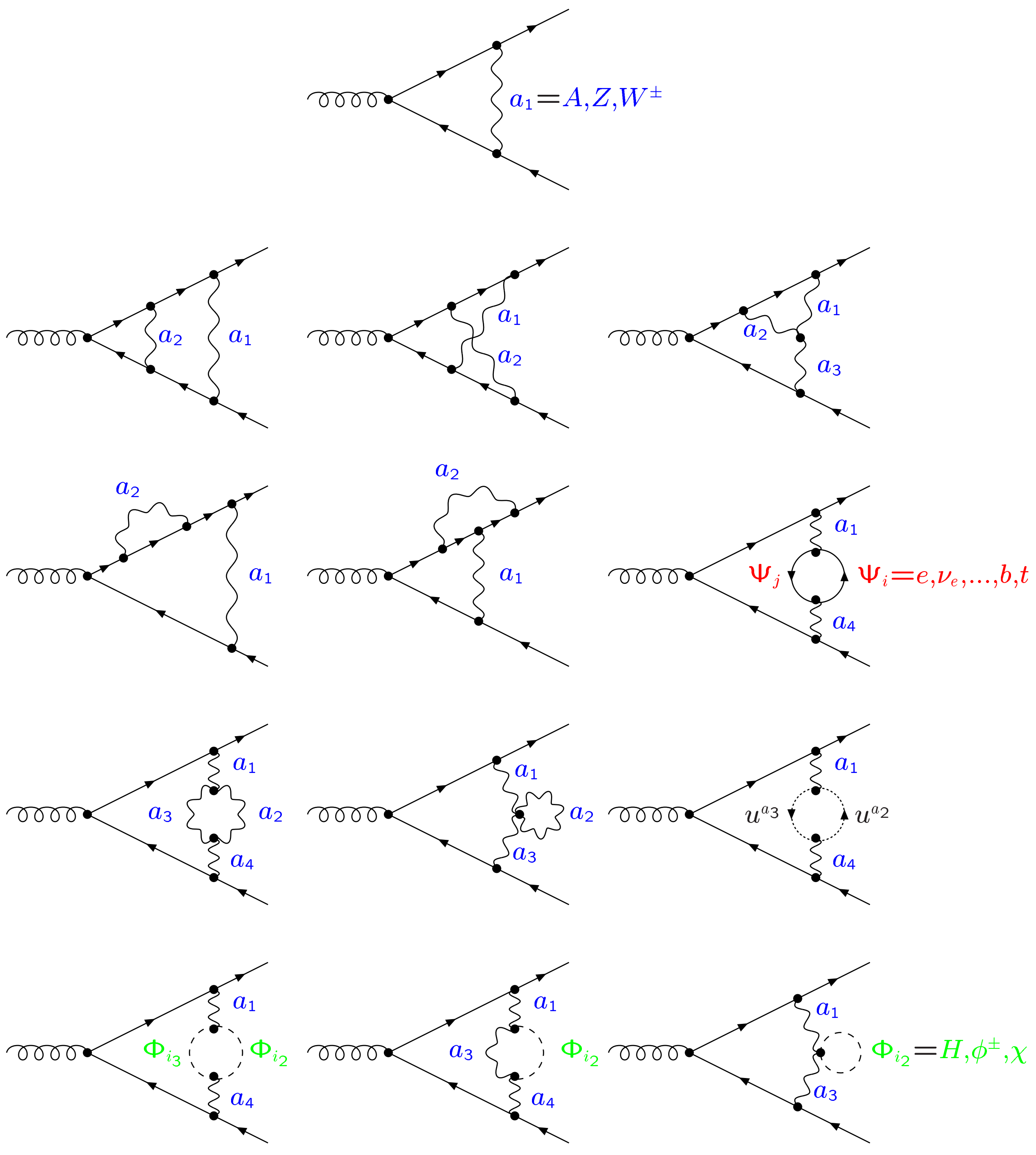
- chiral fermions: massless and on-shell

$$F^\mu = \gamma^\mu \sum_{\sigma=\pm} F_\sigma \, \omega_\sigma, \qquad \omega_\pm = \frac{1}{2}(1 \pm \gamma^5)$$

using $\{\gamma^5, \gamma^\mu\} = 0$ in $D = 4 - 2\epsilon$

- gauge boson (for instance a gluon)
  - external SU(2)xU(1) singlet: no interactions with virtual EW gauge bosons
  - parity-violating couplings: $F_+ \neq F_-$

1-loop and 2-loop Feynman diagrams



Masses

massless particles: γ, light fermions

heavy particles: $M_\mathrm{Z} \sim M_\mathrm{W} \sim m_\mathrm{t} \sim M_\mathrm{H}$

$$\boxed{\text{Asymptotic expansion for } L = \log\left(\frac{-s}{M_\mathrm{W}^2}\right) \gg 1}$$

$$F = \sum_{N=0}^{\infty} \left(\frac{\alpha}{4\pi}\right)^N \sum_{j=2N-1}^{2N} \sum_{k=0}^{j} F_{jk}^{(N)}\, \epsilon^{-k} L^{j-k}$$

NLL approximation

1-loop

$$F^{(1)} \overset{\mathrm{NLL}}{=} \underbrace{F_{22}^{(1)}\,\epsilon^{-2} + F_{21}^{(1)}\,\epsilon^{-1} L^1 + F_{20}^{(1)}\, L^2}_{j=2:\mathrm{LL's}} + \underbrace{F_{11}^{(1)}\,\epsilon^{-1} + F_{10}^{(1)}\, L^1}_{j=1:\mathrm{NLL's}}$$

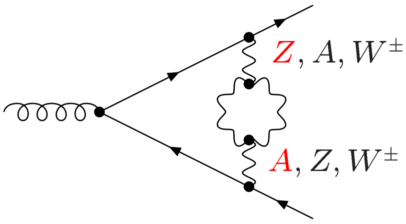
2-loop

$$F^{(2)} \overset{\mathrm{NLL}}{=} \underbrace{F_{44}^{(2)}\,\epsilon^{-4} + F_{43}^{(2)}\,\epsilon^{-3} L^1 + F_{42}^{(2)}\,\epsilon^{-2} L^2 + F_{41}^{(2)}\,\epsilon^{-1} L^3 + F_{40}^{(2)}\, L^4}_{\mathrm{j=4:LL's}}$$
$$+ \underbrace{F_{33}^{(2)}\,\epsilon^{-3} + F_{32}^{(2)}\,\epsilon^{-2} L^1 + F_{31}^{(2)}\,\epsilon^{-1} L^2 + F_{30}^{(2)}\, L^3}_{\mathrm{j=3:NLL's}}$$

$$\boxed{\text{mass-gap dependence}}$$

$$F_{jk}^{(N)} \equiv F_{jk}^{(N)}\left(\frac{M_\mathrm{Z}}{M_\mathrm{W}}, \frac{M_\mathrm{H}}{M_\mathrm{W}}, \frac{m_\mathrm{t}}{M_\mathrm{W}}\right)$$

Example 1



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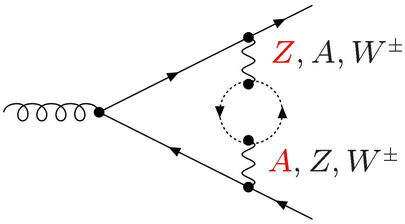


$$
\begin{aligned}
= &-\frac{1}{2} g_2^4 C_A C_\sigma\, D_6(M_\mathrm{W}, M_\mathrm{W}, M_\mathrm{W}, M_\mathrm{W}) \\
&- e^2 g_2^2 s_\mathrm{W} c_\mathrm{W} C_A Q I_\sigma^Z\, \Delta D_6(0, M_\mathrm{W}, M_\mathrm{W}, M_\mathrm{Z}) \\
&- \frac{1}{2} e^2 g_2^2 s_\mathrm{W}^2 C_A Q^2\, \Delta D_6(0, M_\mathrm{W}, M_\mathrm{W}, 0)
\end{aligned}
$$

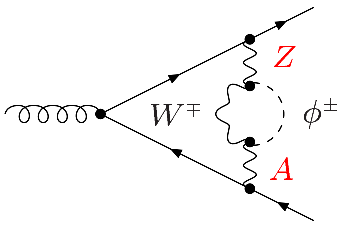
loop integrals

$$
\begin{aligned}
D_6(M_\mathrm{W},M_\mathrm{W},M_\mathrm{W},M_\mathrm{W}) &\overset{\mathrm{NLL}}{=} \tfrac{10}{3} L^2 \epsilon^{-1} + \tfrac{40}{9} L^3 \\
\Delta D_6(0,M_\mathrm{W},M_\mathrm{W},M_\mathrm{Z}) &\overset{\mathrm{NLL}}{=} \left(\frac{M_\mathrm{W}}{M_\mathrm{Z}}\right)^2 \left[-16\epsilon^{-3} - 16 L \epsilon^{-2} + \tfrac{32}{3} L^3\right] \\
\Delta D_6(0,M_\mathrm{W},M_\mathrm{W},0) &\overset{\mathrm{NLL}}{=} \tfrac{20}{3}\epsilon^{-3} + \tfrac{20}{3} L \epsilon^{-2} - \tfrac{40}{9} L^3
\end{aligned}
$$

linear dependence on the ratio $(M_\mathrm{W}/M_\mathrm{Z})^2$!

- $\log(M_\mathrm{W}/M_\mathrm{Z}) \to 0$ no problem
- $(M_\mathrm{W}/M_\mathrm{Z})^2 \to 1$ would destroy cancellations

Example 2



$$= -\frac{1}{2}e^2 g_2^4 \frac{s_{\mathrm{W}}}{c_{\mathrm{W}}} \mathbf{v}^2 Q I_\sigma^Z \left[C_A - (d_2-1)c_{\mathrm{W}}^2\right] \Delta D_8(0, M_{\mathrm{W}}, M_{\mathrm{W}}, M_{\mathrm{Z}})$$

loop integral

$$\Delta D_8(0, M_{\mathrm{W}}, M_{\mathrm{W}}, M_{\mathrm{Z}}) \overset{\underline{\mathrm{NLL}}}{=} \left(\frac{1}{M_{\mathrm{Z}}}\right)^2 \left[-2\epsilon^{-3} - 2L\epsilon^{-2} + \frac{4}{3}L^3\right]$$

inversely proportional to M_{Z}^2!

- $\mathbf{v}^2/s \to 0$ at high energies
- $\mathbf{v}^2/M_{\mathrm{Z}}^2$ non suppressed

One-loop result

$$e^2\delta F_\sigma^{(1)} \overset{\text{NLL}}{=} \left[g_1^2\left(\frac{Y_\sigma}{2}\right)^2+g_2^2C_\sigma\right]I(\epsilon,M_\text{W})+\left(I_\sigma^Z\right)^2\Delta I(\epsilon,M_\text{Z})$$
$$+e^2Q^2\Delta I(\epsilon,0)$$

expanding up to $\mathcal{O}(\epsilon^2)$:

$$I(\epsilon,M_\text{W}) \overset{\text{NLL}}{=} -L^2+3L-\epsilon\left(\frac{2}{3}L^3-\frac{3}{2}L^2\right)-\epsilon^2\left(\frac{1}{4}L^4-\frac{1}{2}L^3\right)$$
$$\Delta I(\epsilon,M_\text{Z}) \overset{\text{NLL}}{=} \left(2L+2L^2\epsilon+L^3\epsilon^2\right)\log\left(\frac{M_\text{Z}^2}{M_\text{W}^2}\right)$$
$$\Delta I(\epsilon,0) \overset{\text{NLL}}{=} -2\epsilon^{-2}-3\epsilon^{-1}-I(\epsilon,M_\text{W})$$

Two-loop result

$$e^4\delta F_\sigma^{(2)} \overset{\text{NLL}}{=} \frac{1}{2}\left[e^2\delta F_\sigma^{(1)}\right]^2+e^2\left[g_1^2b_1^{(1)}\left(\frac{Y_\sigma}{2}\right)^2+g_2^2b_2^{(1)}C_\sigma\right]$$
$$\times J(\epsilon,M_\text{W},M_\text{W})+e^4b_\text{QED}^{(1)}Q^2\Delta J(\epsilon,0,M_\text{W})$$

exponentiated 1-loop + NLL's prop. to β!

$$J(\epsilon,m,\mu) := \frac{1}{\epsilon}\left[I(2\epsilon,m)-\left(\frac{s}{\mu^2}\right)^\epsilon I(\epsilon,m)\right]$$

analogous to Catani's formula for $1/\epsilon$ poles in massless gauge theories!

ϵ-expansions

1-loop

$$I(\epsilon,M_{\mathrm{W}}) \overset{\mathrm{NLL}}{=} -L^2+3L-\epsilon\left(\frac{2}{3}L^3-\frac{3}{2}L^2\right)-\epsilon^2\left(\frac{1}{4}L^4-\frac{1}{2}L^3\right),$$

$$\Delta I(\epsilon,M_{\mathrm{Z}}) \overset{\mathrm{NLL}}{=} \left(2L+2L^2\epsilon+L^3\epsilon^2\right)\log\left(\frac{M_{\mathrm{Z}}^2}{M_{\mathrm{W}}^2}\right),$$

$$\Delta I(\epsilon,0) \overset{\mathrm{NLL}}{=} -2\epsilon^{-2}-3\epsilon^{-1}-I(\epsilon,M_{\mathrm{W}}).$$

2-loop

$$[I(\epsilon,M_{\mathrm{W}})]^2 \overset{\mathrm{NLL}}{=} L^4-6L^3,$$

$$[\Delta I(\epsilon,0)]^2 \overset{\mathrm{NLL}}{=} 4\epsilon^{-4}-4L^2\epsilon^{-2}-\frac{8}{3}L^3\epsilon^{-1}+12\epsilon^{-3}$$
$$+12L\epsilon^{-2}-8L^3,$$

$$I(\epsilon,M_{\mathrm{W}})\Delta I(\epsilon,0) \overset{\mathrm{NLL}}{=} 2L^2\epsilon^{-2}+\frac{4}{3}L^3\epsilon^{-1}-\frac{1}{2}L^4-6L\epsilon^{-2}+7L^3,$$

$$I(\epsilon,M_{\mathrm{W}})\Delta I(\epsilon,M_{\mathrm{Z}}) \overset{\mathrm{NLL}}{=} -2L^3\log\left(\frac{M_{\mathrm{Z}}^2}{M_{\mathrm{W}}^2}\right),$$

$$\Delta I(\epsilon,M_{\mathrm{Z}})\Delta I(\epsilon,0) \overset{\mathrm{NLL}}{=} -4\left[L\epsilon^{-2}+L^2\epsilon^{-1}\right]\log\left(\frac{M_{\mathrm{Z}}^2}{M_{\mathrm{W}}^2}\right),$$

$$J(\epsilon,M_{\mathrm{W}},M_{\mathrm{W}}) \overset{\mathrm{NLL}}{=} \frac{1}{3}L^3,$$

$$\Delta J(\epsilon,0,M_{\mathrm{W}}) \overset{\mathrm{NLL}}{=} \frac{3}{2}\epsilon^{-3}+2L\epsilon^{-2}+L^2\epsilon^{-1}.$$

Normalization of α in $D=4-2\epsilon$

$$\alpha=\frac{1}{\Gamma(1-\epsilon)}\left(\frac{4\pi\mu_0^2}{-s}\right)^{\epsilon}\frac{e^2}{4\pi}$$

One-loop result

$$e^2\delta F_\sigma^{(1)} \overset{\text{NLL}}{=} \left[g_1^2\left(\frac{Y_\sigma}{2}\right)^2+g_2^2C_\sigma\right]I(\epsilon,M_\text{W})+\left(I_\sigma^Z\right)^2\Delta I(\epsilon,M_\text{Z})$$
$$+e^2Q^2\Delta I(\epsilon,0)$$

Two-loop result

$$e^4\delta F_\sigma^{(2)} \overset{\text{NLL}}{=} \frac{1}{2}\left[e^2\delta F_\sigma^{(1)}\right]^2+e^2\left[g_1^2b_1^{(1)}\left(\frac{Y_\sigma}{2}\right)^2+g_2^2b_2^{(1)}C_\sigma\right]$$
$$\times J(\epsilon,M_\text{W},M_\text{W})+e^4b^{(1)}_\text{QED}Q^2\Delta J(\epsilon,0,M_\text{W})$$

As predicted by (IREE-like) resummations:

- $(M_A=M_\text{Z}=M_\text{W})$-part SU(2)xU(1)-symmetric
- $(M_A\ll M_\text{Z}=M_\text{W})$-effects of QED nature

Kühn, Penin, Smirnov (2000); Melles (2001)

Additional $(M_\text{Z}\neq M_\text{W})$-effects exponentiate

$$\Delta I(\epsilon,M_\text{Z}) \overset{\text{NLL}}{=} \left(2L+2L^2\epsilon+L^3\epsilon^2\right)\log\left(\frac{M_\text{Z}^2}{M_\text{W}^2}\right)$$

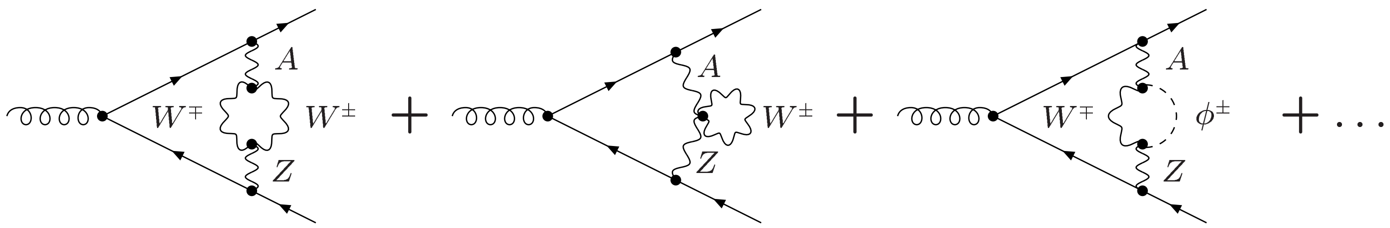
Equivalence to a SU(2)xU(1) theory

(i) **unbroken** ($\mathrm{v} = 0$)

(ii) **with** $M_Z = M_W$

(iii) **unmixed** ($s_W = 0$)

Mixing cancellations



$$= 8e^2 g_2^2 s_W c_W Q I_\sigma^Z \underbrace{\left[\left(\frac{M_W}{M_Z}\right)^2 + s_W^2\left(\frac{g_2 \mathrm{v}}{2c_W M_Z}\right)^2 - 1\right]}_{=0}\left(\epsilon^{-3} + L\epsilon^{-2} - \frac{2}{3}L^3\right)$$

based on

$$M_W = \frac{1}{2} g_2 \mathrm{v}, \qquad M_Z = \frac{1}{2c_W} g_2 \mathrm{v}$$

- details of spontaneous symmetry breaking relevant!

- **different weak-boson masses**, $M_W = c_W M_Z$, in the propagators!

Sector-decomposition algorithm

- arbitrary L-loop diagrams
- UV and IR singularities in $D = 4 - 2\epsilon$
- multi-scale problem

$$s_0 \sim s_1 \sim \cdots \sim s_K \gg M_0^2 \sim M_1^2 \sim \cdots \sim M_J^2$$

- Completely automatized to NLL accuracy

$$\Rightarrow A_{r_0,r_1}\left(\frac{s_i}{s_0},\frac{M_i}{M_0}\right)\left(\frac{1}{\epsilon}\right)^{r_0}\log^{r_1}\left(\frac{s_0}{M_0^2}\right)$$

with $r_0 + r_1 = 2L$ and $2L - 1$

- Can be extended to subleading logarithms

Denner and P. (to be published)

Sector decomposition (example)

1) Massive L-loop integral with $s \gg M^2$

$$I = \int \frac{\mathrm{d}^d q_1}{(2\pi)^d} \cdots \int \frac{\mathrm{d}^d q_L}{(2\pi)^d} \frac{N(\{q_j\},\{p_l\})}{\prod_{i=1}^{n+1}(k_i^2 - m_i^2 + \mathrm{i}\epsilon)}$$

2) Feynman parametrization

$$I = \int_{[0,1]^n} \mathrm{d}^n \vec{x} \frac{s^e f(\vec{x})}{\left[sP(\vec{x}) + M^2 Q(\vec{x})\right]^e}$$

- **mass singularities** from **zeros** of type

$$P(\vec{x}) = 0 \qquad \text{at} \quad x_1 = \cdots = x_m = 0$$

3) Sector decomposition

- partition of $[0,1]^n$ into sectors $\Omega_1, \ldots, \Omega_N$

- $\vec{x} \to \vec{y}$: $\Omega_j \to [0,1]^n$

such that **Feynman parameters are factorized**

$$P(\vec{x}) = \underbrace{P_j(\vec{y})}_{\neq 0} \prod_{k=1}^{m_j} y_k$$

4) Structure of resulting integrals

$$I_j = \int_0^1 \mathrm{d}^K \vec{z} \underbrace{\int_0^1 \mathrm{d}^{2L} \vec{y} \frac{s^e f(\vec{y},\vec{z}) \prod y_i{}^{e-1}}{\left[sP(\vec{y},\vec{z}) \prod y_i + M^2 Q(\vec{y},\vec{z}) \right]^e}}_{g_j(\vec{z})}$$

$\Rightarrow$ simple counting of logarithmic singularities

$$g_j(\vec{z}) = \sum_{k=0}^{2L} \frac{a_k(\vec{z})}{k!} \log^k \left(\frac{s}{M^2} \right)$$

5) Singular integrations to NLL accuracy

$$a_{2L}(\vec{z}) = \frac{f(\vec{0},\vec{z})}{\left[P(\vec{0},\vec{z}) \right]^e},$$

$$a_{2L-1}(\vec{z}) = \frac{f(\vec{0},\vec{z})}{\left[P(\vec{0},\vec{z}) \right]^e} \left[\log \left(\frac{P(\vec{0},\vec{z})}{Q(\vec{0},\vec{z})} \right) - \Psi(e) - \gamma_{\mathrm{E}} \right]$$

$$+ \sum_{k=1}^{2L} \int_0^1 \frac{\mathrm{d}y_k}{y_k} \left\{ \frac{f(0,\ldots,y_k,\ldots,0,\vec{z})}{[P(0,\ldots,y_k,\ldots,0,\vec{z})]^e} - \frac{f(\vec{0},\vec{z})}{\left[P(\vec{0},\vec{z}) \right]^e} \right\}$$

6) Non-singular integrations

- $K = I - 2L$ integrations

  ($K \leq 3$ for 2-loop 4-point functions)

- are done automatically by Mathematica

Conclusions

The computation of the EW logarithms

$$\alpha^L \epsilon^{-J} \log^{K-J}(s/M_{\mathrm{W}}^2) \quad \text{for} \quad s \gg M_{\mathrm{W}}^2$$

has been automatized with an algorithm

- based on the sector-decomposition method
- for arbitrary multi-loop diagrams
- to NLL accuracy (K=2L, 2L-1)

Application: 2-loop form factor $g \to f\bar{f}$

- computed with EW Feynman rules
  vev$\neq$ 0, $\sin(\theta_W) \neq 0$, $M_Z \neq M_W$, $M_A = 0$
- **resummations** based on the unbroken phase of the $SU(2) \times U(1)$ theory **confirmed**
- effects from vev, W-Z mass gap and mixing cancel as a result of relations based on spontaneous symmetry breaking