Precision studies for Higgs-Strahlung process at hadron collider

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Outline

Introduction

- VH Production process has importance in the observation of the Higgs decay $H \to b\bar{b}$
- It is very well suited to constrain anomalous couplings of the Higgs boson in both the Yukawa and the gauge boson sector.
- Higgs production in association with weak boson have a great relevance to probe the coupling between weak boson.
- Probing new physics (NP) from the coupling of the Higgs boson with the gauge boson.

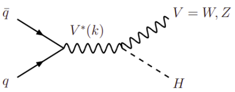
Importance of the Process

Higgs Strahlung process in Hadron level at the LHC

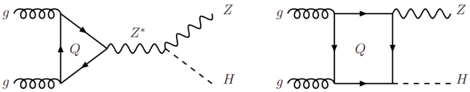
$$pp \to VH + X \qquad\qquad (V = Z, W)$$

Higgs Strahlung process in Parton level at the LHC

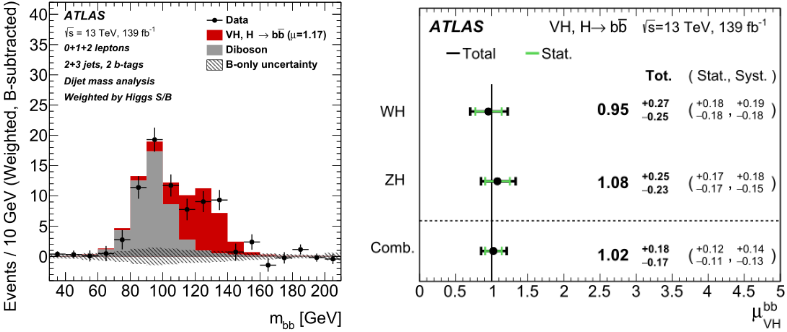
$$q\bar{q} \to VH \qquad\qquad\qquad gg \to ZH$$



(a) $q\bar{q}$-channel



(b) gg-channel



(c) Experimental status for VH production [ATLAS Collaboration, 2021]

Hadron level Cross-section

Hadron level cross-section can be factorized as

$$\sigma(Q^2) = \sum_{a,b=q,\overline{q},g} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \; f_a(x_1,\mu_F^2) \; f_b(x_2,\mu_F^2) \int_0^1 \mathrm{d}z \; \hat{\sigma}_{ab}(z,Q^2,\mu_F^2)\delta(\tau - zx_1x_2)$$

$\sigma(Q^2)$, the hadronic and partonic threshold variables τ and z are defined as

$$\sigma(Q^2) \equiv Q^2 \frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}, \qquad \tau = \frac{Q^2}{S}, \qquad z = \frac{Q^2}{\hat{s}}.$$

They are thus related by $\tau = x_1 x_2 z$, $f_{a,b}(x_i,\mu_F)$ are the partonic distribution function (PDF) for the incoming partons.

Higgs Strahlung process in $q\bar{q}$-channel

For VH production, the partonic cross section can be written as

$$\frac{d\hat{\sigma}}{dQ^2}\left(ab \to VH\right) = \hat{\sigma}\left(ab \to V^*\right)\frac{d\Gamma\left(V^* \to VH\right)}{dQ^2}$$

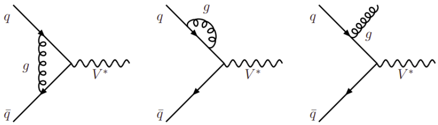
$$\hat{\sigma}_{ab}(z, Q^2, \mu_F) = \sigma^{(0)}_{VH}\Big(\Delta_{ab}(z, \mu_F)\Big),$$

The general structure of n-th order perturbative partonic coefficient is

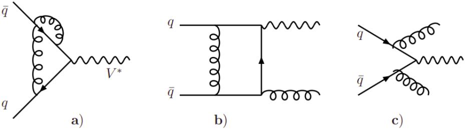
$$\Delta^{(n)}_{ab}(z; Q^2/\mu_R^2; Q^2/\mu_F^2) = C^{(n)}_{\delta}\delta(1-z) + \sum_{i=0}^{2n-1} A^{(n)}_i \mathcal{D}_i(z) + C^{(n)}_{reg} R^{(n)}_{ab}(z)$$

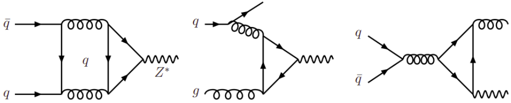
$\mathcal{D}_i = \left[\frac{\ln^i(1-z)}{1-z}\right]_+$ $\quad R^{(n)}_{ab}(z) =$ Regular Piece $\quad z = \frac{Q^2}{\hat{s}}$ $\quad \tau = \frac{Q^2}{S}$

Higgs Strahlung process in $q\bar{q}$-channel



(d) NLO diagrams for $q\bar{q} \to V^*$





(e) NNLO diagrams for $q\bar{q} \to Z^*$

ZH production

- LO 0.6199 pb at 13 TeV LHC.
- NLO in QCD [Tao Han, et al., 1991] gives 26.12% correction.
- NNLO in QCD [O.Brein, et al., 2012] gives 2.63% correction.
- N^3LO_{sv} in QCD [M. C. Kumar, et al., 2015] gives 0.11% correction.
- N^3LO in QCD [J. Baglio, et al., 2022] gives -0.73% correction.
- NLO in EW [A. Denner, et al., 2012] gives -5.28% correction.

Threshold Resummation

The n-th order partonic coefficient term is

$$\Delta_{ab}^{(n)}(z;Q^2/\mu_R^2;Q^2/\mu_F^2) = C_\delta^{(n)}\delta(1-z) + \sum_{i=0}^{2n-1} A_i^{(n)}\mathcal{D}_i(z) + C_{reg}^{(n)}R_{ab}^{(n)}(z)$$

$\mathcal{D}_i = \left[\frac{\ln^i(1-z)}{1-z}\right]_+$ $\quad R_{ab}^{(n)}(z) =$ Regular Piece $\quad z = \frac{Q^2}{\hat{s}}$ $\quad \tau = \frac{Q^2}{S}$

When $z \to 1$ this $\mathcal{D}_i$ becomes large.

$n=1$ $A_1^{(1)}\mathcal{D}_1(LL), A_0^{(1)}\mathcal{D}_0(NLL)$

$n=2$ $A_3^{(2)}\mathcal{D}_3(LL), A_2^{(2)}\mathcal{D}_2(NLL), A_1^{(2)}\mathcal{D}_1(NNLL), A_0^{(2)}\mathcal{D}_0(N^3LL)$

$n=3$ $A_5^{(3)}\mathcal{D}_5(LL), A_4^{(3)}\mathcal{D}_4(NLL), A_3^{(3)}\mathcal{D}_3(NNLL), A_2^{(3)}\mathcal{D}_2(N^3LL), A_1^{(3)}\mathcal{D}_1 N^4LL, \ldots .$

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Threshold Resummation in Mellin Space

- The Mellin transformation with respect to τ is defined as
  $\sigma_N(Q^2) = \int_0^1 d\tau \tau^{N-1} \sigma(s, Q^2)$ $\qquad z \to 1 \equiv N \to \infty$
- In Mellin space, all order resum partonic coefficient function can be written as

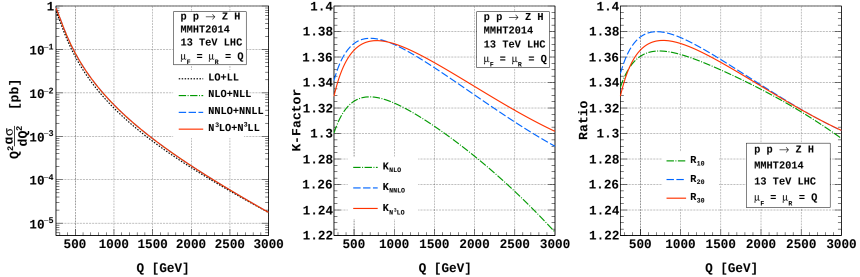
$$\Delta^{(res)}_{ab,N}(\alpha_s(\mu_R^2), Q^2/\mu_R^2; Q^2/\mu_F^2) = C_{ab}(\alpha_s(\mu_R^2), Q^2/\mu_R^2; Q^2/\mu_F^2) \times \exp\{\mathcal{G}_N(\alpha_s(\mu_R^2), \ln N; Q^2/\mu_R^2, Q^2/\mu_F^2)\}.$$

$$\mathcal{G}_N(\alpha_s(\mu_R^2), \ln N; \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) = \ln N g_N^{(1)}(b_0 \alpha_s(\mu_R^2) \ln N) + g_N^{(2)}(b_0 \alpha_s(\mu_R^2) \ln N, \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) + \alpha_s(\mu_R^2) g_N^{(3)}(b_0 \alpha_s(\mu_R^2) \ln N, \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) + \ldots$$

- Mellin inversion and matching

$$\sigma^{\mathrm{N^nLO+N^nLL}} = \sigma^{\mathrm{N^nLO}} + \sigma^{(0)} \sum_{a,b \in \{q,\bar{q}\}} \int_{c-i\infty}^{c+i\infty} \frac{\mathrm{d}N}{2\pi i} \tau^{-N} f_{a,N}(\mu_F) f_{b,N}(\mu_F) \times \left(\hat{\sigma}_N^{\mathrm{N^nLL}} - \hat{\sigma}_N^{\mathrm{N^nLL}} \Big|_{\mathrm{tr}} \right)$$

ZH Production for $q\bar{q}$-channel



(f) The resummed Invariant mass k-factor for ZH [Chinmoy Dey et al. 2022].

FO k-factor at $Q = 3000$GeV

$$K_{NLO} = 1.22$$
$$K_{NNLO} = 1.29$$
$$K_{N^3LO} = 1.30$$

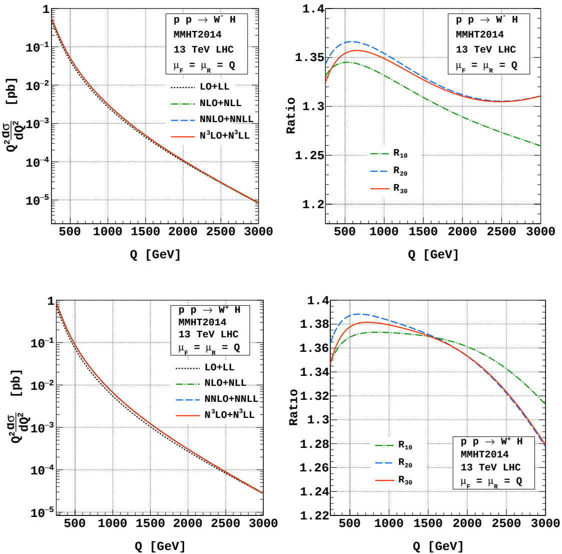
Resummed k-factor at $Q = 3000$GeV

$$R_{10} = 1.295$$
$$R_{20} = 1.30$$
$$R_{30} = 1.30$$

$$K_{N^nLO} = \frac{(d\sigma/dQ)_{N^nLO}}{(d\sigma/dQ)_{LO}}$$

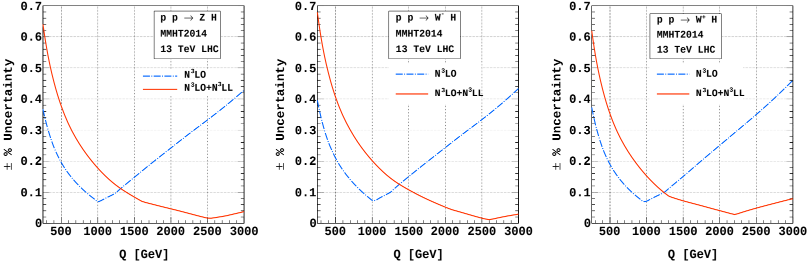
$$R_{ij} = \frac{(d\sigma/dQ)_{N^iLO+N^iLL}}{(d\sigma/dQ)_{N^jLO}}$$

WH Production for $q\bar{q}$-channel



(h) Invariant mass distribution and k-factor [Chinmoy Dey et al. 2022].

7-points scale uncertainty in VH production



(i) 7-point scale comparison between FO and resummed [Chinmoy Dey et al. 2022]

$\sqrt{S}$ (TeV)	13.0	13.6	100.0
NLO	$0.7754 \pm 1.36\%$	$0.8245 \pm 1.36\%$	$9.1445 \pm 4.40\%$
NNLO	$0.8005 \pm 0.35\%$	$0.8508 \pm 0.36\%$	$9.1215 \pm 0.94\%$
N^3LO	$0.7943 \pm 0.32\%$	$0.8441 \pm 0.33\%$	$8.9790 \pm 0.49\%$
NLO+NLL	$0.7966 \pm 4.31\%$	$0.8469 \pm 4.31\%$	$9.3550 \pm 5.39\%$
NNLO+NNLL	$0.8036 \pm 1.53\%$	$0.8542 \pm 1.53\%$	$9.1500 \pm 1.77\%$
N^3LO+N^3LL	$0.7943 \pm 0.57\%$	$0.8441 \pm 0.58\%$	$8.9795 \pm 0.75\%$

Table: ZH production cross section (in pb) with 7-point scale uncertainty [Chinmoy Dey et al. 2022].

Central scale $\mu_R = \mu_F = Q$

7-point scale variation

$|\ln(\mu_R/\mu_F)| < \ln 4$

ZH inclusive Production

$\sqrt{S}$ (TeV)	LO (fb)	NLO (fb)
13.0	$51.5775 \pm 25.02\%$	$106.9756 \pm 15.56\%$
13.6	$57.1041 \pm 24.52\%$	$118.2644 \pm 15.32\%$
100.0	$2019.4491 \pm 19.13\%$	$3975.6576 \pm 14.59\%$

Table: ZH production cross-section in gg channel with 7-point scale uncertainty [R. V. Harlander, et al., 2018].

$\sqrt{S}$ (TeV)	$\sigma^{DY,ZH}_{\mathrm{N^3LO}}$	$\sigma^{DY,ZH}_{\mathrm{N^3LO+N^3LL}}$	$\sigma^{tot,ZH}_{\mathrm{N^3LO}}$	$\sigma^{tot,ZH}_{\mathrm{N^3LO+N^3LL}}$
13.0	$0.7943 \pm 0.32\%$	$0.7943 \pm 0.57\%$	$0.9112 \pm 1.79\%$	$0.9112 \pm 1.67\%$
13.6	$0.8441 \pm 0.33\%$	$0.8441 \pm 0.58\%$	$0.9728 \pm 1.86\%$	$0.9728 \pm 1.75\%$
100.0	$8.9790 \pm 0.49\%$	$8.9795 \pm 0.75\%$	$13.2674 \pm 4.57\%$	$13.2678 \pm 4.39\%$

Table: ZH production cross-section (in pb) [Chinmoy Dey, et al., 2022]

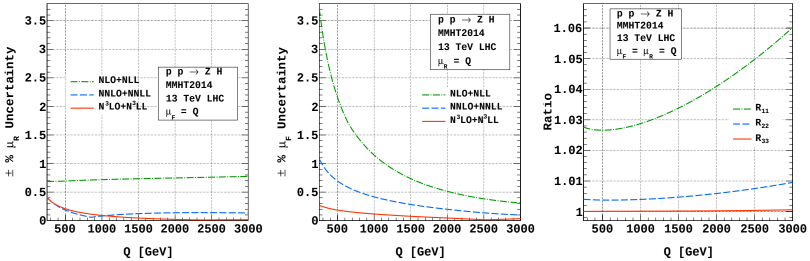
$$\sigma^{tot,ZH}_{\mathrm{N^3LO}} = \sigma^{\mathrm{DY,ZH}}_{\mathrm{N^3LO}} + \sigma^{gg}(\alpha_S^3) + \sigma^{\mathrm{top}}(\alpha_S^2) + \sigma^{b\bar{b}}$$

$$\sigma^{tot,ZH}_{\mathrm{N^3LO+N^3LL}} = \sigma^{\mathrm{DY,ZH}}_{\mathrm{N^3LO+N^3LL}} + \sigma^{gg}(\alpha_S^3) + \sigma^{\mathrm{top}}(\alpha_S^2) + \sigma^{b\bar{b}}$$

Summary

- Threshold resummation for $q\bar{q}$-channel is shown up to $\text{N}^3\text{LO}+\text{N}^3\text{LL}$ for total production cross-section of VH.
- Invariant mass distribution is shown up to $\text{N}^3\text{LO}+\text{N}^3\text{LL}$ for VH production.
- The 7-points scale uncertainty reduced to less then 0.1% at high Q.
- Gluon initiated process fixed order calculation is done at LO in exact for total cross-section and NLO by considering infinite top mass.
- Inclusive cross section for ZH production shown for $q\bar{q}$-channel up to $\text{N}^3\text{LO}+\text{N}^3\text{LL}$, gg-channel NLO in EFT, top-loops effect and $b\bar{b} \to ZH$.

Thank you



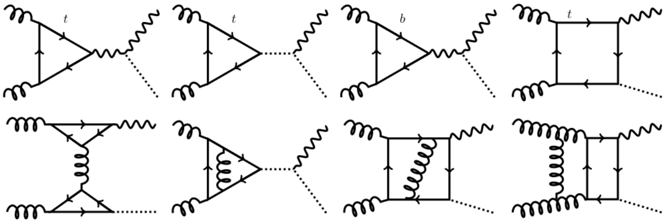
(j) μ_R scale uncertainty for fixed order[FO] (left panel), after resummation (middle panel) resummed effect (right panel)

$$\frac{d\Gamma(V^* \to VH)}{dQ^2} = \frac{G_F M_V^4}{2\sqrt{2}\pi^2} \frac{\lambda(M_V^2, M_H^2; Q^2)}{(Q^2 - M_V^2)^2} \left(1 + \frac{\lambda(M_V^2, M_H^2; Q^2)}{12 M_V^2/Q^2}\right)$$

$$\sigma_{VH}^{(0)}(Q) = \frac{\pi}{n_c} \frac{\alpha^2}{S} \left[\frac{M_V^2 Q^2 \lambda^{1/2}(M_V^2, M_H^2, Q^2)\left(1 + \frac{\lambda(M_V^2, M_H^2, Q^2)}{12 M_V^2/Q^2}\right)}{(Q^2 - M_V^2)^2 c_w^4 s_w^4} \left((g_{q,V}^v)^2 + (g_{q,V}^a)^2\right) \right]$$

The function λ is defined as $\lambda(x, y, z) = \left(1 - \frac{x}{z} - \frac{y}{z}\right)^2 - 4\frac{xy}{z^2}$

Higgs Strahlung process in gg-channel

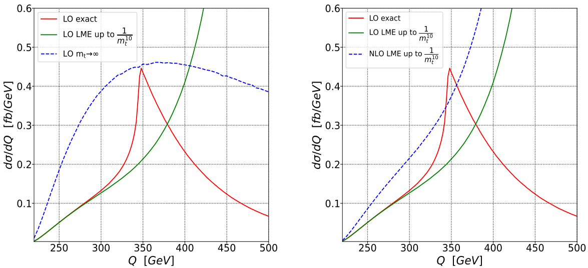


(k) Fixed order LO and NLO diagrams contributiong to $gg \to ZH$

- ZH production at LO 51.5775 fb at 13 TeV LHC in exact theory[B. A. Kniehl, et al., 1990].
- ZH production at LO 27.13% additional contribution in effective field theory (EFT) approach i.e. $m_t \to \infty$ limit.
- ZH production at NLO in QCD in EFT gives 107.41% correction [R. V. Harlander, et al., 2018] [O, Brein, et al., 2013].
- ZH production at NLO in QCD in large mass expansion (LME) [A. Hasselhuhn, et al., 2017] gives 136.92% correction.

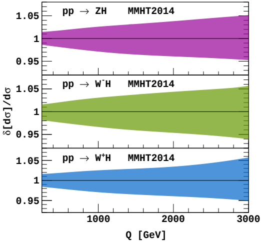
LO and NLO Large mass expansion (LME) and EFT Results

Plus Distribution $\int_0^1 dz f(z)[g(z)]_+ = \int_0^1 dz \Big[f(z) - f(1) \Big] g(z)$



(I) Fixed order LO and NLO results in EFT, LME and exact LO. [On going work]

PDF uncertainty



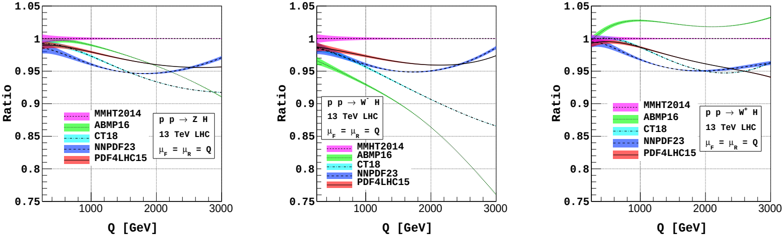
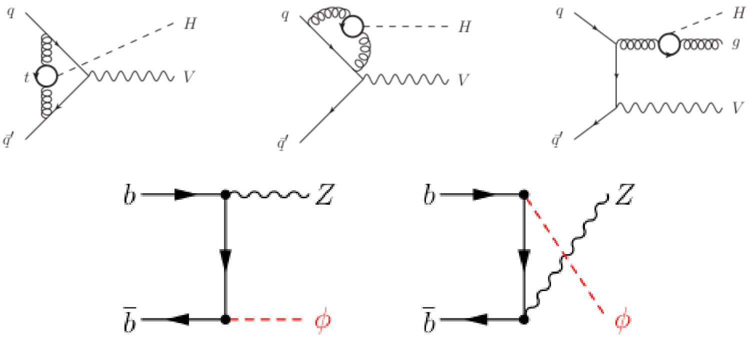


Figure: Intrinsic and group variation for PDF normalized to MMHT2014 central value

Top-loop and $b\bar{b}$ subprocess



(a) ZH production through top-loop and $b\bar{b}$ subprocess [R. V. Harlander, et al., 2018].

Matching in Mellin space

$$\sigma^{\mathrm{N^nLO+N^nLL}} = \sigma^{\mathrm{N^nLO}} + \sigma^{(0)} \sum_{a,b\in\{q,\bar{q}\}} \int_{c-i\infty}^{c+i\infty} \frac{\mathrm{d}N}{2\pi i} \tau^{-N} f_{a,N}(\mu_F) f_{b,N}(\mu_F) \times \left(\hat{\sigma}_N^{\mathrm{N^nLL}} - \hat{\sigma}_N^{\mathrm{N^nLL}}\Big|_{\mathrm{tr}} \right) \quad (1)$$

$$\frac{d\sigma^{\mathrm{match}}}{dQ^2} = \frac{1}{2\pi i} \int_{C_N} dN\, \tau^{-N} \sum_{i,j} \left[(N-1)\, f_{1/P_1}(N,\mu_F) \right] \left[(N-1)\, f_{b/P_2}(N,\mu_F) \right] \frac{\hat{\sigma}_{ij}^{\mathrm{match}}(N,Q,\mu,\mu_F)}{(N-1)^2}$$

$$\frac{1}{2\pi i} \int_{C_N} dN\, x^{-N}\, (N-1)\, f_{i/H}(N,\mu_F) = -\frac{d}{dx}\Big[x\, \tilde{f}_i(x,\mu_F) \Big] \equiv \mathcal{F}(x,\mu_F)\,.$$

$$\mathcal{S}_{ab}^{match} = \sum_{ab\in\{q,\bar{q}\}} \int_{c-i\infty}^{c+i\infty} \frac{dN}{2\pi i} (\tau)^{-N} \left(\hat{\sigma}_N \Big|_{N^n LL} - \hat{\sigma}_N \Big|_{trN^n LO} \right).$$

$$\frac{d\sigma^{\mathrm{match}}}{dQ^2} \equiv \sum_{i,j} \int_{\tau}^{\infty} \frac{dz}{z} \int_{\tau/z}^{1} \frac{dy}{y}\, \mathcal{F}_a(y,\mu_F)\, \mathcal{F}_b\left(\frac{\tau}{yz}, \mu_F \right) \mathcal{S}_{ab}^{\mathrm{match}}(z,Q,\mu,\mu_F)$$

Sudakov factor

- The all-order resummation formula can be written in terms of the Sudakov radiative factor (Δ_N^H)

Sudakov Factor

$$\Delta_N^H\left(\alpha_s(\mu_R^2), Q^2/\mu_R^2; Q^2/\mu_f^2\right) = \exp\left\{\int_0^1 dz\,\frac{z^{N-1}-1}{1-z} \times \left[2\int_{\mu_f^2}^{(1-z)^2Q^2} \frac{dq^2}{q^2} A(\alpha_s(q^2)) + D(\alpha_s((1-z)^2Q^2))\right]\right\},$$

- $A(\alpha_s)$ is coming from the collinear and soft gluon contribution.
- $D(\alpha_s)$ is coming from non-colinear and soft gluon contribution.
- This coefficients $A(\alpha)$ and $D(\alpha_s)$ are perturbatively computed using fixed order calculation at different order.

Anomalous Dimensions

$$A_1 = \Big[C_F \, \Big(4 \Big) \Big],$$

$$A_2 = \Big[C_F \, N_F \, \Big(- \frac{40}{9} \Big) + C_F \, C_A \, \Big(\frac{268}{9} - 8 \, \zeta_2 \Big) \Big],$$

$$A_3 = \Big[C_F \, N_F^2 \, \Big(- \frac{16}{27} \Big) + C_F \, C_A \, N_F \, \Big(- \frac{836}{27} - \frac{112}{3} \, \zeta_3 + \frac{160}{9} \, \zeta_2 \Big) + C_F \, C_A^2 \, \Big(\frac{490}{3} + \frac{88}{3} \, \zeta_3 - \frac{1072}{9} \, \zeta_2 + \frac{176}{5} \, \zeta_2^2 \Big) + C_F^2 \, N_F \, \Big(- \frac{110}{3} + 32 \, \zeta_3 \Big) \Big].$$

$$D_1 = C_F \Big[0 \Big],$$

$$D_2 = C_F \Big[n_f \Big(\frac{224}{27} - \frac{32}{3} \zeta_2 \Big) + C_A \Big(- \frac{1616}{27} + 56 \zeta_3 + \frac{176}{3} \zeta_2 \Big) \Big].$$