Pseudo-scalar Higgs form factor at 3 loops and QCD N^3LO threshold corrections to its production at the LHC

V. Ravindran
Institute of Mathematical Sciences,
Chennai, India

In collaboration with Ahmed, Gehrmann, Mathews, Rana

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Plan

- Computation of Pseudo-scalar Higgs boson form factor at three loops in QCD
- Discuss UV and IR poles structure using K+G equation
- How IR can be used to obtain UV renormalisation constant
- Applications to 1.N3LO threshold corrections and 2. N-independent part of N3LL and 3. Matching coefficient in SCET
- Leading Transcendentality Principle
- Scale dependence has been studied.

CP Odd Higgs boson

CP even Higgs boson Production cross section at N^3LO

[Anastasiou, Duhr, Dulat, Furlan, Herzog, Mistlberger]

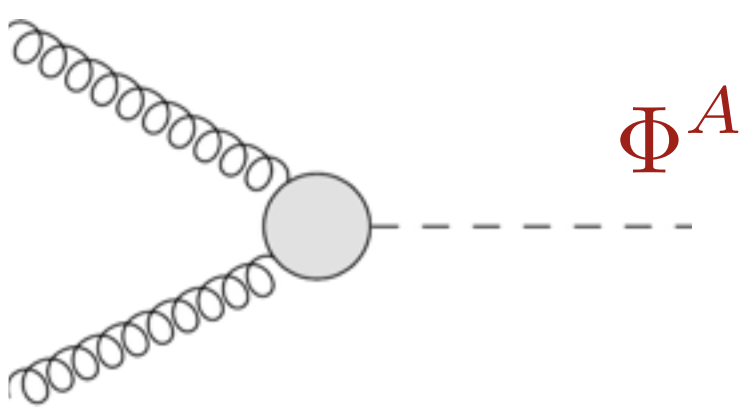
CP odd Higgs boson Production cross section at N^2LO

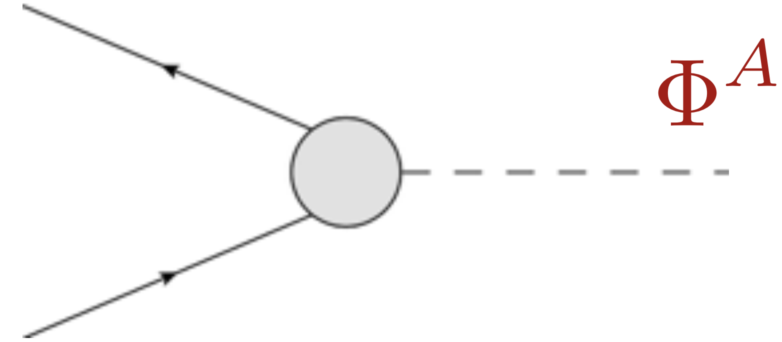
[Harlander, Kilgore; Anastasiou, Melnikov; VR, Smith, Neerven]

CP odd Higgs boson production at N^3LO

1. Virtual Corrections
2. Real Emission Corrections

Three Loop Virtual Contributions





Yukawa Interaction

$$\mathcal{L}^A = -i\frac{g_c}{v}\Phi^A\left(m_t\bar{\psi}_t\gamma_5\psi_t + \sum_{i=1}^{n_l} m_i\bar{\psi}_i\gamma_5\psi_i\right)$$

$m_t =$ top quark mass

$g_c =$ coupling constant

$v =$ vev = $2^{-\frac{1}{4}}G_F^{-\frac{1}{2}}$

$g_c = \cot\beta$ in MSSM

$\Phi^A =$ pseudo scalar field

$\psi_t =$ top quark field

$n_l =$ no of light quarks = 5

Effective Theory

[Chetyrkin, Kniehl, Steinhauser and Bardeen]

Integrating top quark fields:

$$\mathcal{L}^A_{\rm eff} = \Phi^A \Big[-\frac{1}{8} C_G O_G - \frac{1}{2} C_J O_J \Big]$$

Effective Operators $\mathcal{O}_G$ & $\mathcal{O}_J$

$$O_G(x) = G_a^{\mu\nu} \tilde{G}_{a,\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$$

$$O_J(x) = \partial_\mu \left(\bar{\psi} \gamma^\mu \gamma_5 \psi \right)$$

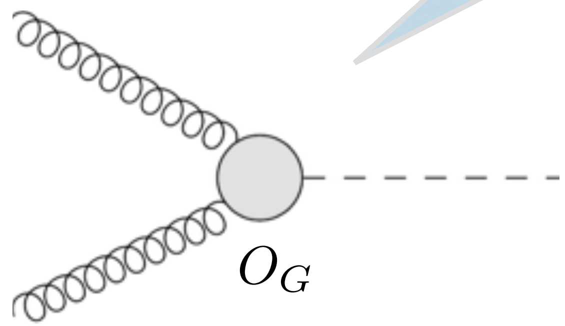
$$C_G = -a_s 2^{\frac{5}{4}} G_F^{\frac{1}{2}} \cot\beta$$

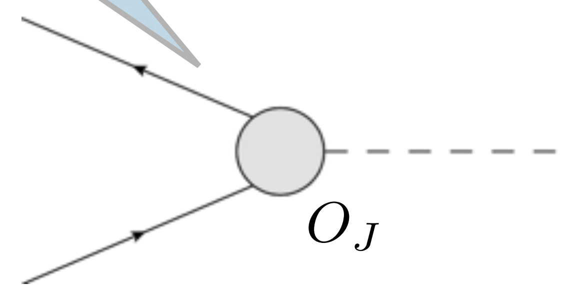
$$C_J = -\left[a_s C_F \left(\frac{3}{2} - 3 \ln \frac{\mu_R^2}{m_t^2} \right) + a_s^2 C_J^{(2)} + \cdots \right] C_G$$

- C_G and C_J are Wilson Coefficients
- C_G is exact to all orders due to Adler-Bardeen theorem
- C_J is known to a_s only

Effective Couplings

$$\mathcal{L}^{A}_{\rm eff} = \Phi^{A}\left[-\frac{1}{8}C_G O_G - \frac{1}{2}C_J O_J\right]$$

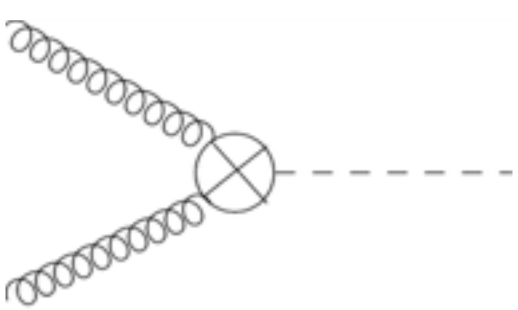


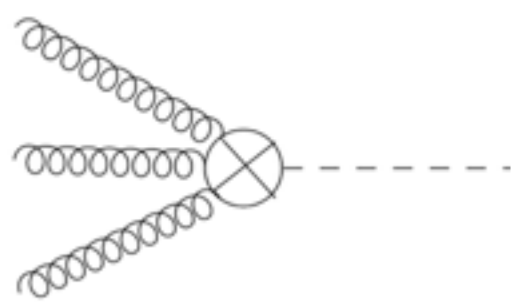


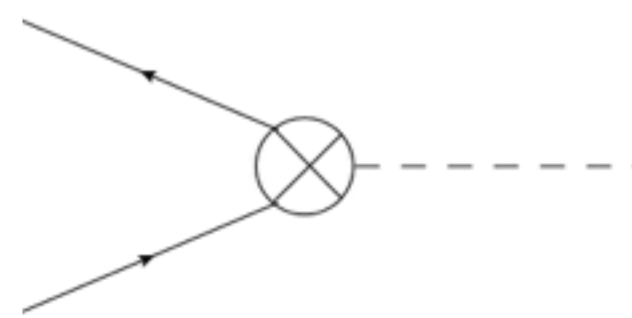
$$O_G(x) = G^{\mu\nu}_a \tilde{G}_{a,\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma} G^{\mu\nu}_a G^{\rho\sigma}_a$$

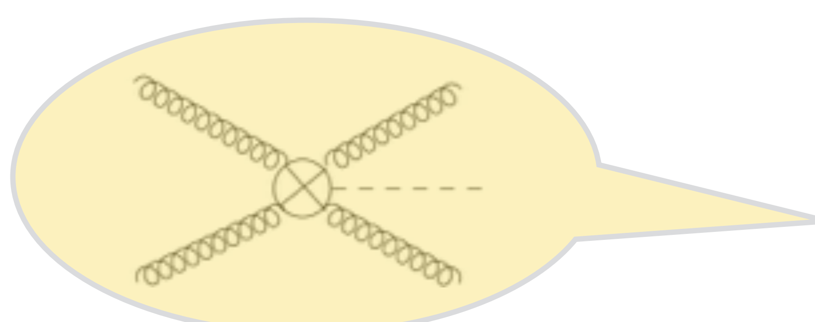
$$O_J(x) = \partial_\mu \left(\bar{\psi}\gamma^\mu \gamma_5 \psi\right)$$

Feynman Rules:







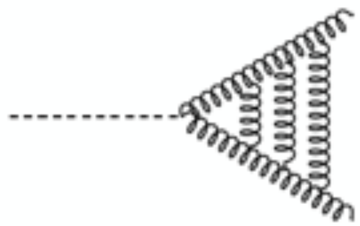
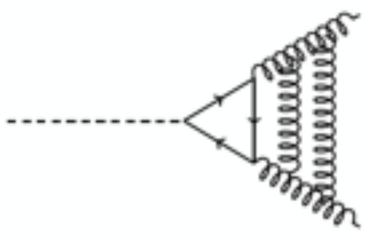
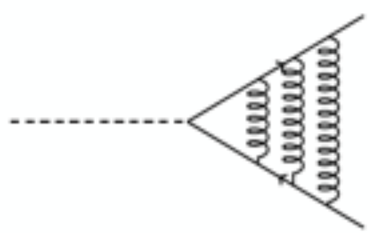
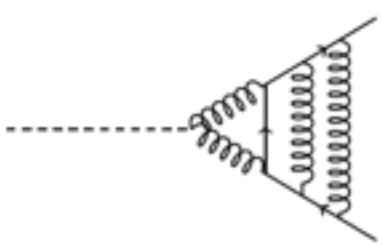


Vanishes

Qgraf and FORM …

[Nogueira,Vermaseren]

Form Factors at Three loops in QCD

1. 
2. 
3. 
4. 

# of diagrams
1586
447
244
400

Qgraf

Diagram generation

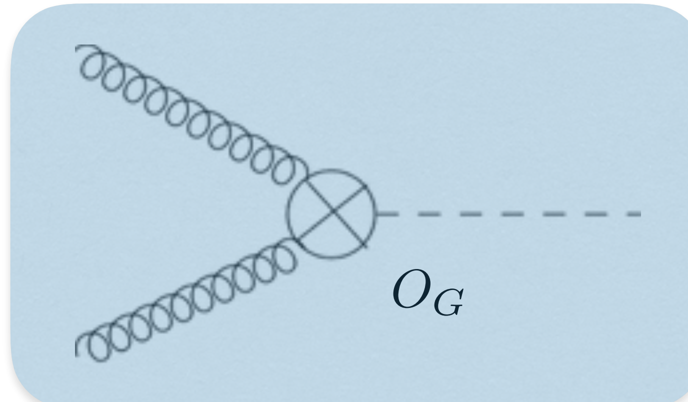
FORM

Feynman rules
SU(N) color algebra
Lorentz contraction

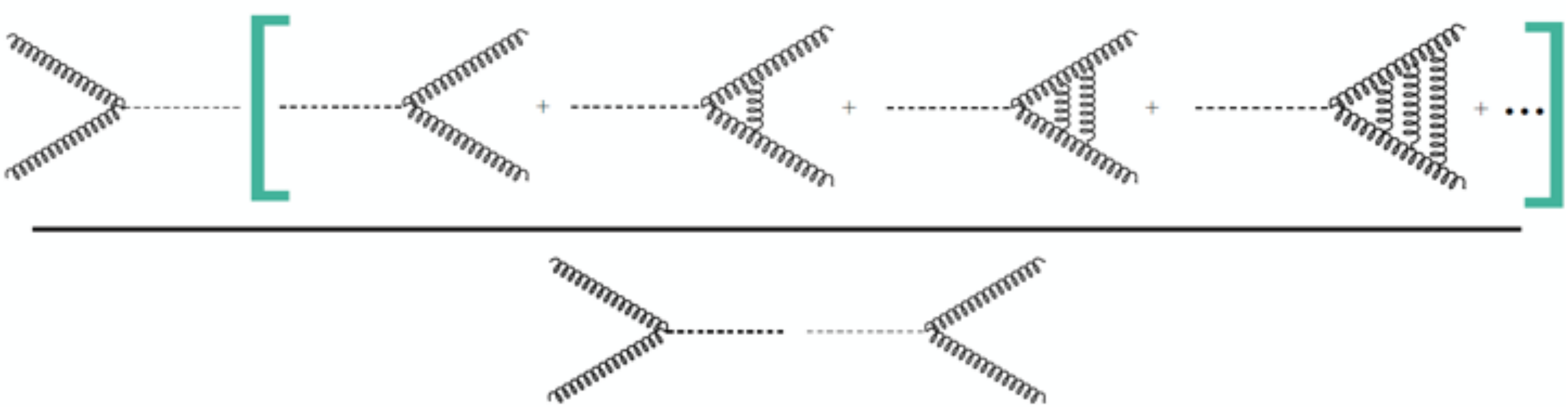
Mathematica

IBP reductions

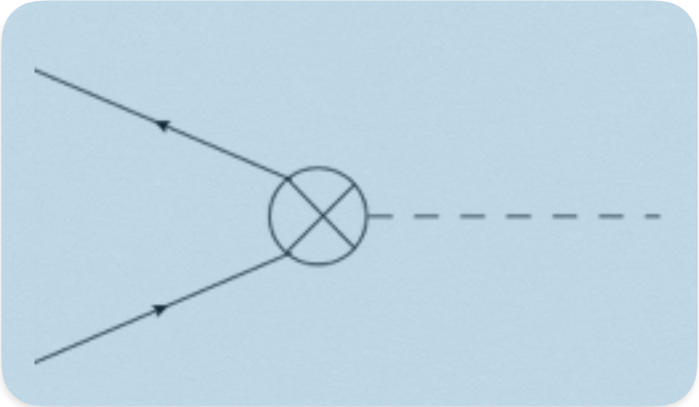
$\mathcal{F}_g^G$ at Three loops



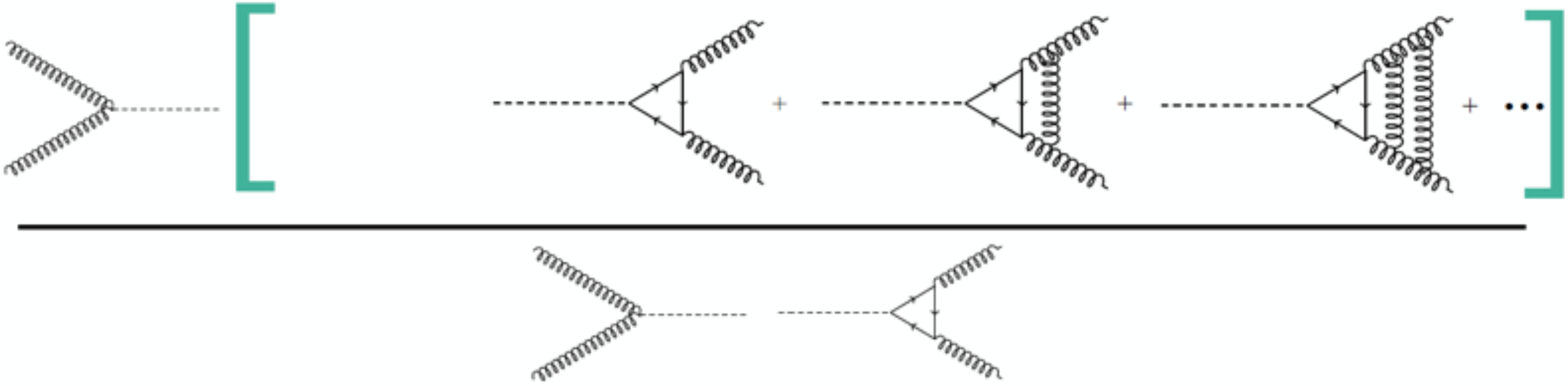
$$\mathcal{F}_g^G = 1 + \hat{a}_s \left(\frac{Q^2}{\mu^2}\right)^{\frac{\epsilon}{2}} S_\epsilon \hat{\mathcal{F}}_g^{G,(1)} + \hat{a}_s^2 \left(\frac{Q^2}{\mu^2}\right)^{2\frac{\epsilon}{2}} S_\epsilon^2 \hat{\mathcal{F}}_g^{G,(2)} + \hat{a}_s^3 \left(\frac{Q^2}{\mu^2}\right)^{3\frac{\epsilon}{2}} S_\epsilon^3 \hat{\mathcal{F}}_g^{G,(3)} + \cdots$$



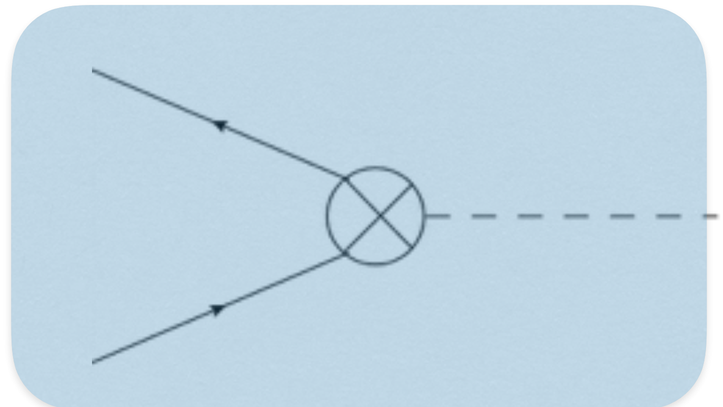
$\mathcal{F}_g^J$ at Three loops



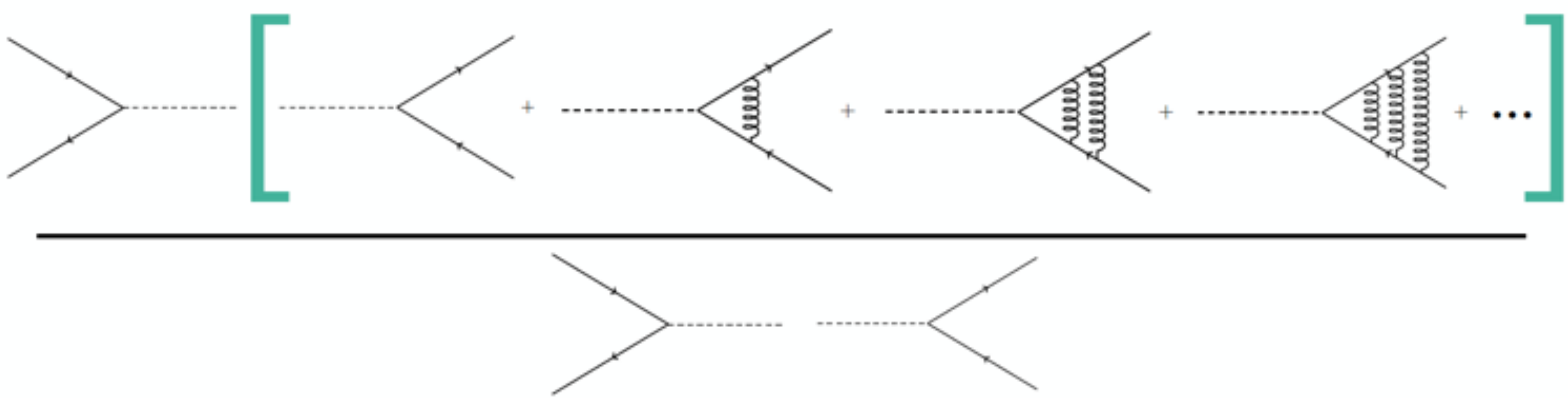
$$\mathcal{F}_g^J = 1 + \hat{a}_s \left(\frac{Q^2}{\mu^2}\right)^{\frac{\epsilon}{2}} S_\epsilon \hat{\mathcal{F}}_g^{J,(1)} + \hat{a}_s^2 \left(\frac{Q^2}{\mu^2}\right)^{2\frac{\epsilon}{2}} S_\epsilon^2 \hat{\mathcal{F}}_g^{J,(2)} + \cdots$$



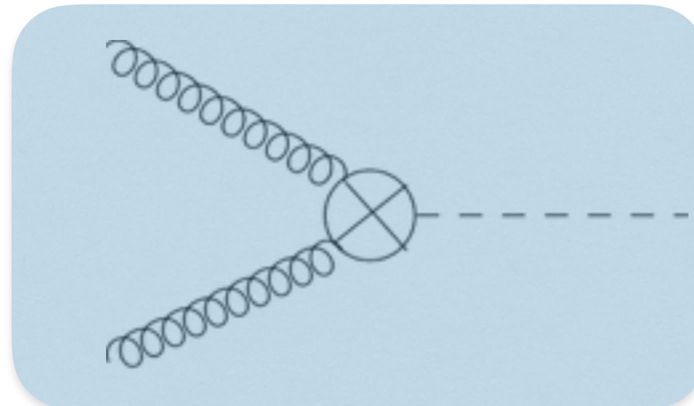
$\mathcal{F}_q^J$ at Three loops



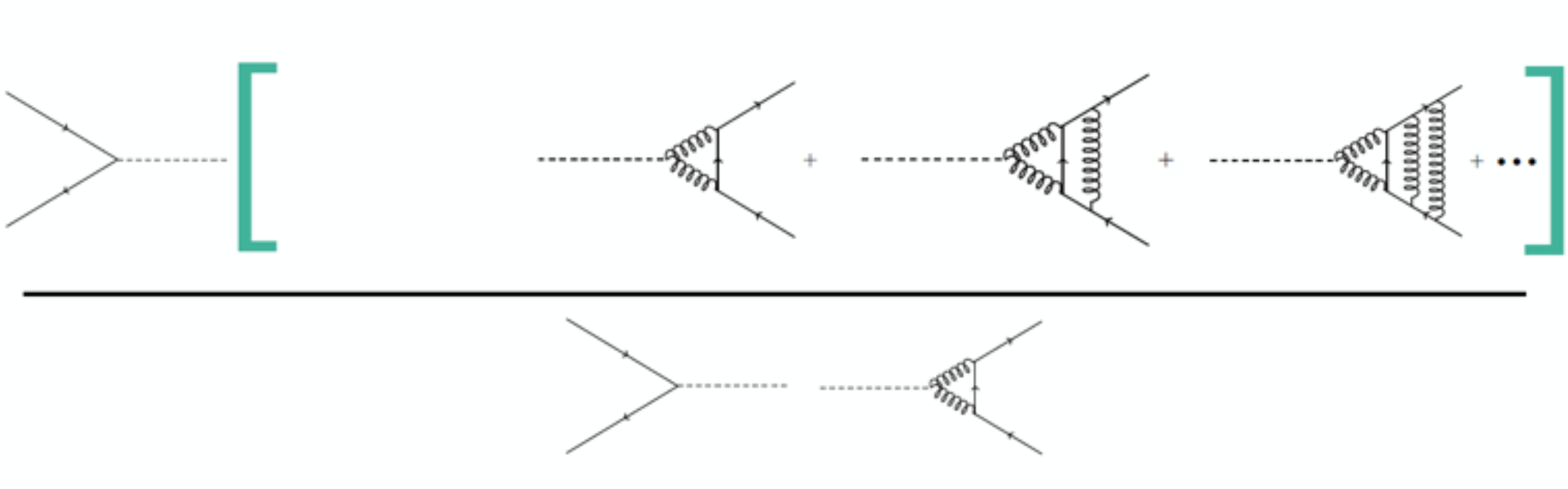
$$\mathcal{F}_q^J = 1 + \hat{a}_s \left(\frac{Q^2}{\mu^2}\right)^{\frac{\epsilon}{2}} S_\epsilon \hat{\mathcal{F}}_q^{J,(1)} + \hat{a}_s^2 \left(\frac{Q^2}{\mu^2}\right)^{2\frac{\epsilon}{2}} S_\epsilon^2 \hat{\mathcal{F}}_q^{J,(2)} + \hat{a}_s^3 \left(\frac{Q^2}{\mu^2}\right)^{3\frac{\epsilon}{2}} S_\epsilon^3 \hat{\mathcal{F}}_q^{J,(3)} + \cdots$$



$\mathcal{F}_q^G$ at Two loops



$$\mathcal{F}_q^G = 1 + \hat{a}_s \left(\frac{Q^2}{\mu^2}\right)^{\frac{\epsilon}{2}} S_\epsilon \hat{\mathcal{F}}_q^{G,(1)} + \hat{a}_s^2 \left(\frac{Q^2}{\mu^2}\right)^{2\frac{\epsilon}{2}} S_\epsilon^2 \hat{\mathcal{F}}_q^{G,(2)} + \cdots$$



γ_5 & $\epsilon_{\mu\nu\lambda\sigma}$ in n-dimensions

Defining γ_5 & $\epsilon_{\mu\nu\lambda\sigma}$ in $n \neq 4$ dimension ?

Many Prescriptions exist $\{\gamma_5, \gamma^\mu\} \neq 0$ $n \neq 4$

['t Hooft and Veltman]

We follow:

$$\gamma_5 = \frac{i}{4!}\epsilon_{\mu_1\mu_2\mu_3\mu_4}\gamma^{\mu_1}\gamma^{\mu_2}\gamma^{\mu_3}\gamma^{\mu_4}$$

n-dim

$$\epsilon_{\mu_1\mu_2\mu_3\mu_4}\epsilon^{\nu_1\nu_2\nu_3\nu_4} = 4!\ \delta^{\nu_1\cdots\nu_4}_{[\mu_1\cdots\mu_4]}$$

[Larin]

Breaks Chiral Ward identity !

Remedy: Finite renormalisation

Method

Unphysical degrees of Freedom of gluons:

1. Feynman Gauge for internal gluons
2. Physical Polarisation for external gluons

Large number of 3- loop Integrals:

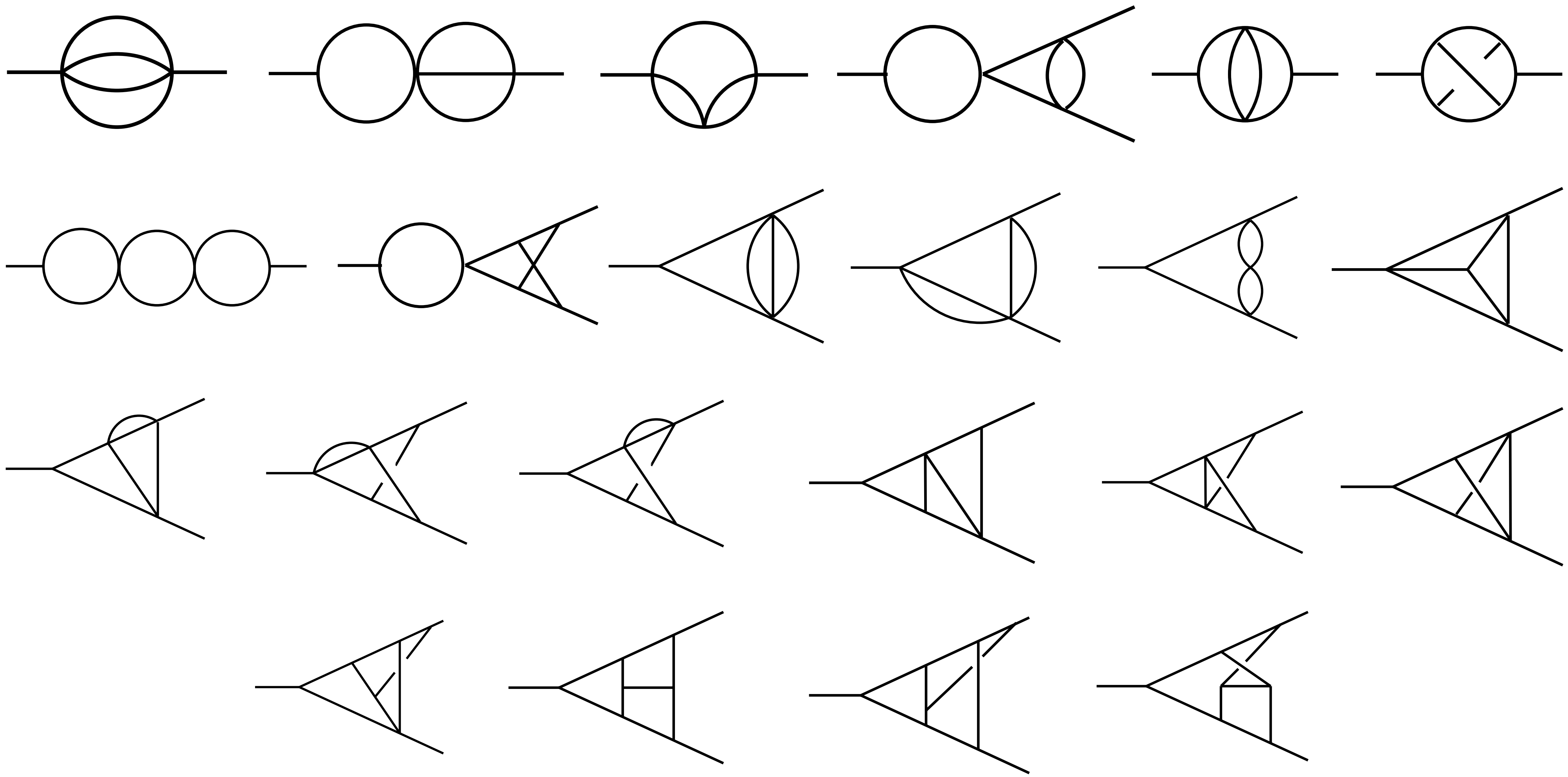
[Chetyrkin, Tkachov; Gehrmann, Remiddi]

1. IBP reduction
2. Lorentz Invariant (LI) Identities

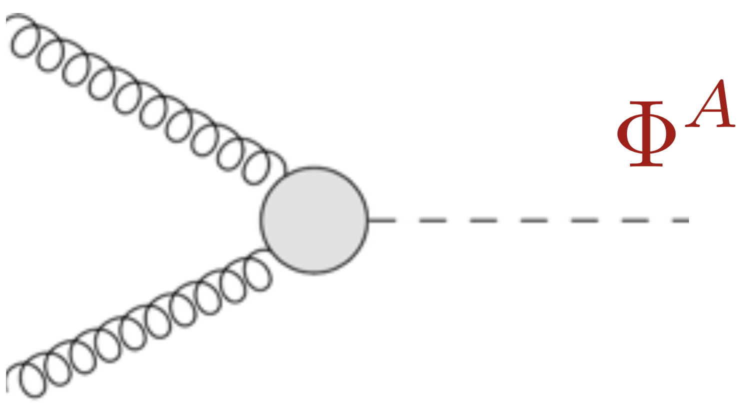
*Reduze2 and **LiteRed*** → *22 Master Integrals*

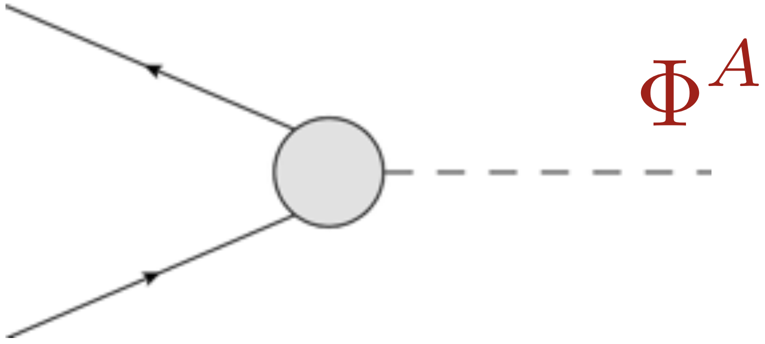
Master Integrals

[T.Gehrmann,T.Huber,D.Maitre,G.Heinrich,C.Studerus,D.A.Kosower,V.A.Smirnov,A.V.Smirnov, R.N.Lee]



UV Renormalisation Z_{IJ}





UV renormalisation

[Larin]

- O_G mixes under renorm with O_J

Renormalised

Bare

$$[O_G]_R = Z_{GG}\,[O_G]_B + Z_{GJ}\,[O_J]_B$$

O_J needs finite renormalisation Z_5^s

$$[O_J]_R = Z_5^s Z^s_{\overline{MS}}\,[O_J]_B$$

needs finite renormalisation

On-shell matrix elements

$$[O_G]_R = Z_{GG}\,[O_G]_B + Z_{GJ}\,[O_J]_B$$

Matrix elements between quark and gluon fields :

$$\mathcal{S}_g^G \equiv Z_{GG}\langle\hat{\mathcal{M}}_g^{G,(0)}|\mathcal{M}_g^G\rangle + Z_{GJ}\langle\hat{\mathcal{M}}_g^{G,(0)}|\mathcal{M}_g^J\rangle$$

$$\mathcal{S}_q^G \equiv Z_{GG}\langle\hat{\mathcal{M}}_q^{J,(0)}|\mathcal{M}_q^G\rangle + Z_{GJ}\langle\hat{\mathcal{M}}_q^{J,(0)}|\mathcal{M}_q^J\rangle$$

Form Factors :

$$\left[\mathcal{F}_g^G\right]_R \equiv \frac{\mathcal{S}_g^G}{\mathcal{S}_g^{G,(0)}} \equiv 1 + \sum_{n=1}^{\infty} a_s^n \left[\mathcal{F}_g^{G,(n)}\right]_R \qquad n = 3$$

$$\left[\mathcal{F}_q^G\right]_R \equiv \frac{\mathcal{S}_q^G}{a_s \mathcal{S}_q^{G,(1)}} \equiv 1 + \sum_{n=1}^{\infty} a_s^n \left[\mathcal{F}_q^{G,(n)}\right]_R \qquad n = 2$$

On-shell matrix elements

$$[O_J]_R = Z_5^s Z_{\overline{MS}}^s [O_J]_B$$

Matrix elements between quark and gluon fields :

$$\mathcal{S}_g^J \equiv Z_5^s Z_{\overline{MS}}^s \langle \hat{\mathcal{M}}_g^{G,(0)} | \mathcal{M}_g^J \rangle$$

Form Factors :

$$\left[\mathcal{F}_g^J\right]_R \equiv \frac{\mathcal{S}_g^J}{a_s \mathcal{S}_g^{J,(1)}} \equiv 1 + \sum_{n=1}^{\infty} a_s^n \left[\mathcal{F}_g^{J,(n)}\right]_R \qquad n = 2$$

$$\left[\mathcal{F}_q^J\right]_R \equiv \frac{\mathcal{S}_q^J}{\mathcal{S}_q^{J,(0)}} \equiv 1 + \sum_{n=1}^{\infty} a_s^n \left[\mathcal{F}_q^{J,(n)}\right]_R \qquad n = 3$$

UV and IR poles mix

On-shell matrix elements between quark and gluon fields :

$$< \hat{\mathcal{M}}_i^{I,(0)} | \mathcal{M}_i^{K,(n)} >$$

$$I, K = G, J$$
$$i = g, q$$

UV and IR poles mix in n-dimensions

Trick!

Exploit Univerality of IR poles → UV poles

Sudakov Equation (K+G Eqn.)

[Moch, Vogt, Vermaseren; Ravindran; Magnea]

$$Q^2 \frac{d}{dQ^2} \ln \mathcal{F}^\lambda_\beta(\hat{a}_s, Q^2, \mu^2, \epsilon) = \frac{1}{2}\left[K^\lambda_\beta(\hat{a}_s, \frac{\mu_R^2}{\mu^2}, \epsilon) + G^\lambda_\beta(\hat{a}_s, \frac{Q^2}{\mu_R^2}, \frac{\mu_R^2}{\mu^2}, \epsilon)\right]$$

poles

No poles

RG invariance

$$\mu_R^2 \frac{d}{d\mu_R^2} K^\lambda_\beta(\hat{a}_s, \frac{\mu_R^2}{\mu^2}, \epsilon) = -\mu_R^2 \frac{d}{d\mu_R^2} G^\lambda_\beta(\hat{a}_s, \frac{Q^2}{\mu_R^2}, \frac{\mu_R^2}{\mu^2}, \epsilon) = -A^\lambda_\beta(a_s(\mu_R^2))$$

Cusp Anomalous dim.

$$A^g_\beta = \frac{C_A}{C_F} A^q_\beta$$

UV + IR Anomalous dim.

$$G^\lambda_{\beta,i}(\epsilon) = 2\left(B^\lambda_{\beta,i} - \gamma^\lambda_{\beta,i}\right) + f^\lambda_{\beta,i} + C^\lambda_{\beta,i} + \sum_{k=1}^{\infty} \epsilon^k g^{\lambda,k}_{\beta,i}$$

Solution in n-dimensions

[Moch, Vogt, Vermaseren; Ravindran; Magnea]

Solution in $4+\epsilon$ dim:

$$\ln \mathcal{F}^\lambda_\beta(\hat{a}_s, Q^2, \mu^2, \epsilon) = \sum_{i=1}^{\infty} \hat{a}_s^i \left(\frac{Q^2}{\mu^2}\right)^{i\frac{\epsilon}{2}} S_\epsilon^i \hat{\mathcal{L}}^\lambda_{\beta,i}(\epsilon)$$

with

$$\hat{\mathcal{L}}^\lambda_{\beta,1}(\epsilon) = \frac{1}{\epsilon^2}\Big\{-2A^\lambda_{\beta,1}\Big\} + \frac{1}{\epsilon}\Big\{G^\lambda_{\beta,1}(\epsilon)\Big\}$$

$$\hat{\mathcal{L}}^\lambda_{\beta,2}(\epsilon) = \frac{1}{\epsilon^3}\Big\{\beta_0 A^\lambda_{\beta,1}\Big\} + \frac{1}{\epsilon^2}\Big\{-\frac{1}{2}A^\lambda_{\beta,2} - \beta_0 G^\lambda_{\beta,1}(\epsilon)\Big\} + \frac{1}{\epsilon}\Big\{\frac{1}{2}G^\lambda_{\beta,2}(\epsilon)\Big\}$$

$$\hat{\mathcal{L}}^\lambda_{\beta,3}(\epsilon) = \frac{1}{\epsilon^4}\Big\{-\frac{8}{9}\beta_0^2 A^\lambda_{\beta,1}\Big\} + \frac{1}{\epsilon^3}\Big\{\frac{2}{9}\beta_1 A^\lambda_{\beta,1} + \frac{8}{9}\beta_0 A^\lambda_{\beta,2} + \frac{4}{3}\beta_0^2 G^\lambda_{\beta,1}(\epsilon)\Big\} + \frac{1}{\epsilon^2}\Big\{-\frac{2}{9}A^\lambda_{\beta,3} - \frac{1}{3}\beta_1 G^\lambda_{\beta,1}(\epsilon) - \frac{4}{3}\beta_0 G^\lambda_{\beta,2}(\epsilon)\Big\} + \frac{1}{\epsilon}\Big\{\frac{1}{3}G^\lambda_{\beta,3}(\epsilon)\Big\}$$

Cusp Anomalous dim.

$$G^\lambda_{\beta,i}(\epsilon) = 2\left(B^\lambda_{\beta,i} - \gamma^\lambda_{\beta,i}\right) + f^\lambda_{\beta,i} + C^\lambda_{\beta,i} + \sum_{k=1}^{\infty} \epsilon^k g^{\lambda,k}_{\beta,i}$$

Single Pole term & UV from IR

[Ravindran, Smith, van Neerven; Moch et. al.]

UV Anomalous dim.

$$C^{\lambda}_{\beta,i} = \sum_j s_j C^{\lambda}_{\beta,j}, j < i$$

$$G^{\lambda}_{\beta,i}(\epsilon) = 2\left(B^{\lambda}_{\beta,i} - \gamma^{\lambda}_{\beta,i}\right) + f^{\lambda}_{\beta,i} + C^{\lambda}_{\beta,i} + \sum_{k=1}^{\infty} \epsilon^k g^{\lambda,k}_{\beta,i}$$

Collinear Anomalous dim.

Soft Anomalous dim.

$$f^g_\beta = \frac{C_A}{C_F} f^q_\beta$$

- Computation of $G^{\lambda}_{\beta,i}$, $C^{\lambda}_{\beta,i} = C^{\lambda}_{\beta,j}, j < i$
- Knowledge of $B^{q,g}_{\beta,i}, f^{q,g}_{\beta,i}$

$\gamma^{\lambda}_{\beta,i}$ → $Z^{\lambda}_{\beta,i}$

UV Renormalisation Constant

$$\mu_R^2 \frac{d}{d\mu_R^2} \ln Z^\lambda(a_s, \mu_R^2, \epsilon) = \sum_{i=1}^{\infty} a_s^i \gamma_i^\lambda$$

Solution to third order

$$Z^\lambda = 1 + a_s\left[\frac{1}{\epsilon}2\gamma_1^\lambda\right] + a_s^2\left[\frac{1}{\epsilon^2}\left\{2\beta_0\gamma_1^\lambda + 2(\gamma_1^\lambda)^2\right\} + \frac{1}{\epsilon}\gamma_2^\lambda\right] + a_s^3\left[\frac{1}{\epsilon^3}\left\{8\beta_0^2\gamma_1^\lambda + 4\beta_0(\gamma_1^\lambda)^2 + \frac{4(\gamma_1^\lambda)^3}{3}\right\} + \frac{1}{\epsilon^2}\left\{\frac{4\beta_1\gamma_1^\lambda}{3} + \frac{4\beta_0\gamma_2^\lambda}{3} + 2\gamma_1^\lambda\gamma_2^\lambda\right\} + \frac{1}{\epsilon}\left\{\frac{2\gamma_3^\lambda}{3}\right\}\right].$$

$$[O_J]_R = Z_5^s Z_{\overline{MS}}^s [O_J]_B$$

[Larin,Zoller]

$$Z_5^s = 1 + a_s\{-4C_F\} + a_s^2\left\{22C_F^2 - \frac{107}{9}C_AC_F + \frac{31}{18}C_Fn_f\right\}$$

All UV Z_{IK} agree with those in the literature

Adler-Bell-Jackie Anomaly

CP odd operators

$O_J(x) = \partial_\mu \left(\bar\psi \gamma^\mu \gamma_5 \psi\right)$ and $O_G(x) = G_a^{\mu\nu} \tilde{G}_{a,\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$

related by

ABJ Anomaly

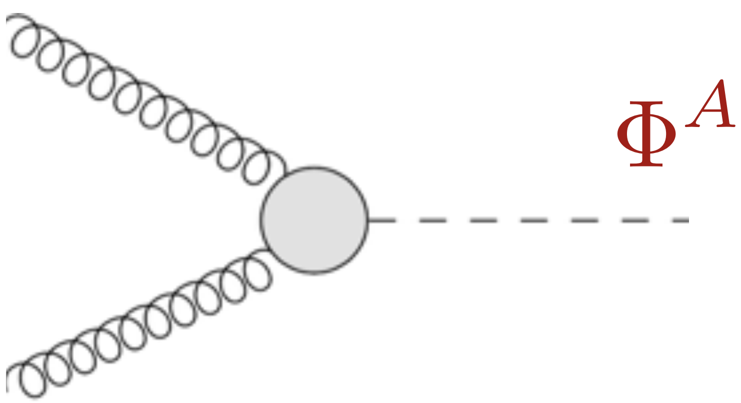
$$[O_J]_R = a_s \frac{n_f}{2} [O_G]_R$$

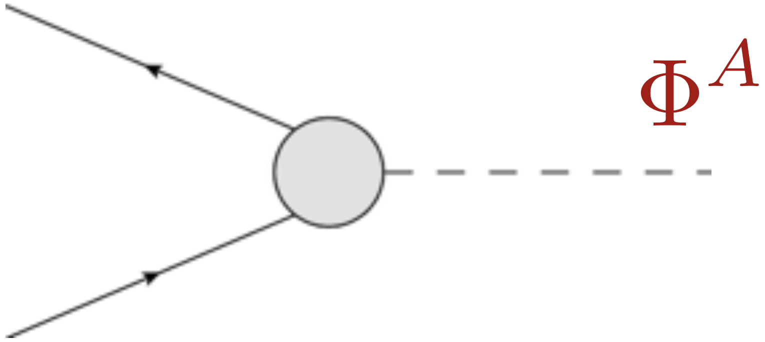
Renormalisation Group Invariance

$$\gamma_{JJ} = \frac{\beta}{a_s} + \gamma_{GG} + a_s \frac{n_f}{2} \gamma_{GJ}$$

Check !

N3LO Soft+Virtual Cross section





Soft+Virtual at N3LO

Inclusive cross section:

$$\sigma^A(\tau, m_A^2) = \sigma^{A,(0)}(\mu_R^2) \sum_{a,b=q,\bar{q},g} \int_\tau^1 dy\, \Phi_{ab}(y, \mu_F^2) \Delta_{ab}^A \left(\frac{\tau}{y}, m_A^2, \mu_R^2, \mu_F^2\right)$$

Born cross section:

$$\sigma^{A,(0)}(\mu_R^2) = \frac{\pi\sqrt{2}G_F}{16} a_s^2 \cot^2\beta\, |\tau_A f(\tau_A)|^2.$$

Partonic Flux:

$$\Phi_{ab}(y, \mu_F^2) = \int_y^1 \frac{dx}{x} f_a(x, \mu_F^2) f_b\left(\frac{y}{x}, \mu_F^2\right),$$

Partonic Cross section:

$$\Delta_{ab}^A(z, q^2, \mu_R^2, \mu_F^2) = \Delta_{ab}^{A,\mathrm{SV}}(z, q^2, \mu_R^2, \mu_F^2) + \Delta_{ab}^{A,\mathrm{hard}}(z, q^2, \mu_R^2, \mu_F^2)$$

Soft+Virtual:

$$\Delta_g^{A,\mathrm{SV}}(z, q^2, \mu_R^2, \mu_F^2) = \sum_{i=0}^{\infty} a_s^i \Delta_{g,i}^{A,\mathrm{SV}}(z, q^2, \mu_R^2, \mu_F^2)$$

New!

SV part to N3LO

Hard part to NNLO

Soft+Virtual at N3LO

Soft+Virtual:

$$\Delta_{g,i}^{A,\mathrm{SV}} = \Delta_{g,i}^{A,\mathrm{SV}}|_{\delta}\delta(1-z) + \sum_{j=0}^{2i-1} \Delta_{g,i}^{A,\mathrm{SV}}|_{\mathcal{D}_j}\mathcal{D}_j\,.$$

Plus distributions:

$$\mathcal{D}_i \equiv \left[\frac{\ln^i(1-z)}{1-z}\right]_+$$

z-space exponentiation of SV cross section:

$$\Delta_g^{A,\mathrm{SV}}(z,q^2,\mu_R^2,\mu_F^2) = \mathcal{C}\exp\left(\Psi_g^A\left(z,q^2,\mu_R^2,\mu_F^2,\epsilon\right)\right)\Big|_{\epsilon=0}$$

Mellin Convolution in z-space:

$$\mathcal{C}e^{f(z)} = \delta(1-z) + \frac{1}{1!}f(z) + \frac{1}{2!}f(z)\otimes f(z) + \cdots\,.$$

z-space Exponent at α_s^3

[V.Ravindran]

RG invariance, K+G equation, Mass factorisation:

$$\Delta_g^{A,\mathrm{SV}}(z, q^2, \mu_R^2, \mu_F^2) = \mathcal{C} \exp\left(\Psi_g^A\left(z, q^2, \mu_R^2, \mu_F^2, \epsilon\right)\right)\Big|_{\epsilon=0}$$

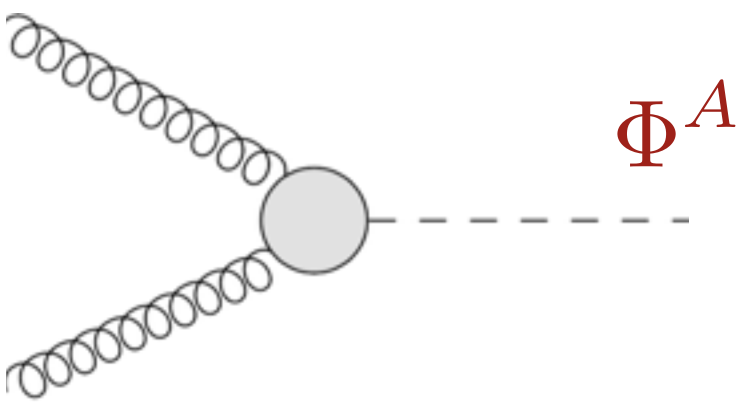
$$\Psi_g^A\left(z, q^2, \mu_R^2, \mu_F^2, \epsilon\right) = \left(\ln\left[Z_g^A(\hat{a}_s, \mu_R^2, \mu^2, \epsilon)\right]^2 + \ln\left|\mathcal{F}_g^A(\hat{a}_s, Q^2, \mu^2, \epsilon)\right|^2\right)\delta(1-z)$$
$$+ 2\Phi_g^A(\hat{a}_s, q^2, \mu^2, z, \epsilon) - 2\mathcal{C}\ln\Gamma_{gg}(\hat{a}_s, \mu_F^2, \mu^2, z, \epsilon)\,.$$

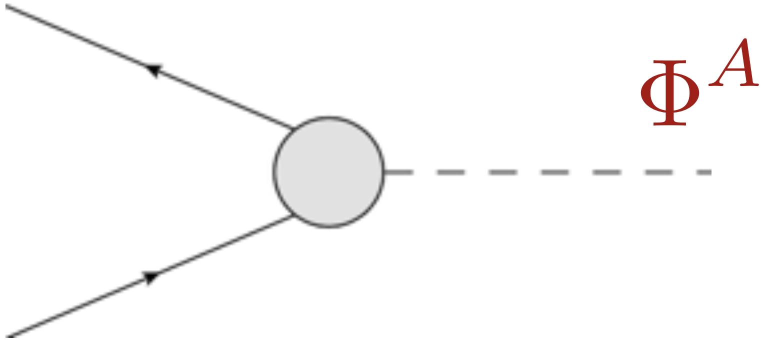
α_s^3

- Z_g^A is operator renormalisation → Checked
- $\mathcal{F}_g^A$ is the Form Factor → New !
- Φ_g^A is the Soft distribution function → Known
- Γ_{gg} is the Altarelli Parisi kernel → Known

N3LO $\Delta_{g,3}^{A,SV}(z, q^2)$ New

N3LL Resumed Cross section





Constant part at N3LL

[S.Catani, L.Trentadue, G.F.Sterman]

Resumed Cross section

$$\Delta_{g,N}^{A,\mathrm{res}}(q^2,\mu_R^2,\mu_F^2) = C_g^{A,\mathrm{th}}(q^2,\mu_R^2,\mu_F^2)\Delta_{g,N}(q^2)\,.$$

$$\Delta_{g,N} = \exp\left[\int_0^1 dz\,\frac{z^{N-1}-1}{1-z}\left\{2\int_{q^2}^{q^2(1-z)^2}\frac{d\lambda^2}{\lambda^2}A_g\left(a_s(\lambda^2)\right)+D_g\left(a_s(q^2(1-z)^2)\right)\right\}\right]$$

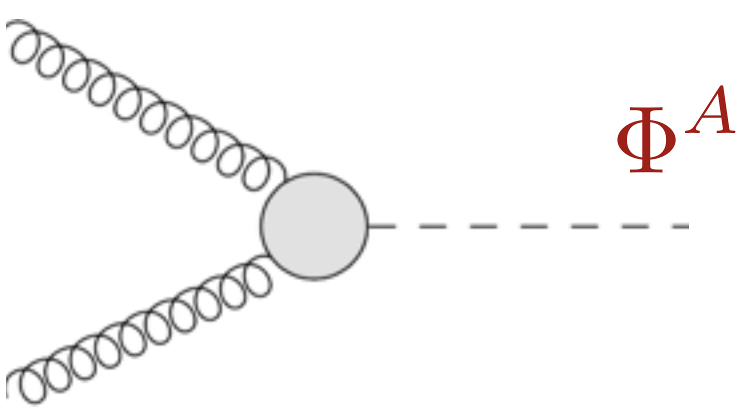
$$C_g^{A,\mathrm{th}} = 1 + \sum_{j=1}^{\infty} a_s^j\, C_{g,j}^{A,\mathrm{th}}\,,$$

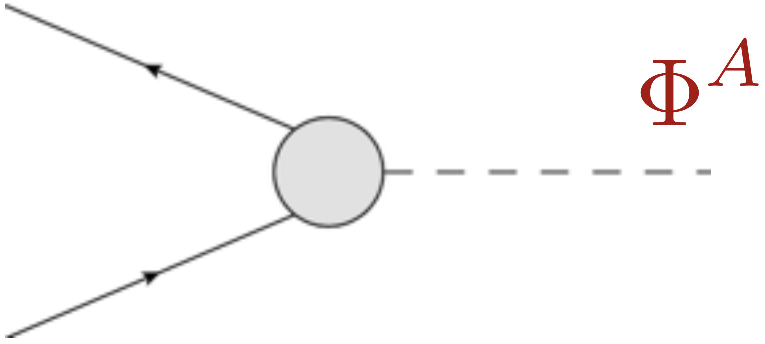
N3LL

$$\begin{aligned}
C_{g,3}^{A,\mathrm{th}} = {} & n_f C_J^{(2)}\left\{-4\right\} + C_F n_f^2\left\{\frac{1498}{9} - \frac{40}{9}\zeta_2 - \frac{32}{45}\zeta_2^2 - \frac{224}{3}\zeta_3\right\} + C_F^2 n_f\left\{\frac{457}{3} + 208\zeta_3\right. \\
& \left. - 320\zeta_5\right\} + C_A^2 n_f\left\{-\frac{113366}{81} - \frac{10888}{81}\zeta_2 + \frac{17192}{135}\zeta_2^2 + \frac{584}{3}\zeta_3 - \frac{464}{3}\zeta_2\zeta_3 + \frac{808}{9}\zeta_5\right\} \\
& + C_A^3\left\{\frac{114568}{27} + \frac{137756}{81}\zeta_2 - \frac{4468}{27}\zeta_2^2 - \frac{32}{5}\zeta_2^3 - \frac{80308}{27}\zeta_3 - \frac{616}{3}\zeta_2\zeta_3 + 96\zeta_3^2\right. \\
& \left. + \frac{3476}{9}\zeta_5\right\} + C_A n_f^2\left\{\frac{6914}{81} - \frac{1696}{81}\zeta_2 - \frac{608}{45}\zeta_2^2 + \frac{688}{27}\zeta_3\right\} + C_A C_F n_f\left\{-1797\right. \\
& + 96\ln\left(\frac{q^2}{m_t^2}\right) - \frac{4160}{9}\zeta_2 + 96\ln\left(\frac{q^2}{m_t^2}\right)\zeta_2 + \frac{176}{45}\zeta_2^2 + \frac{1856}{3}\zeta_3 + 192\zeta_2\zeta_3 \\
& \left. + 160\zeta_5\right\}.
\end{aligned}$$

New!

N3LO Matching Coefficient in SCET





Matching Coefficient in SCET

IR finite Matching Coefficient

[T.Becher, M.Neubert]

$$C_g^{A,\text{eff}}\,(Q^2,\mu_h^2) \equiv \lim_{\epsilon\to 0} (Z_g^{A,h})^{-1}(\epsilon,Q^2,\mu_h^2)\,[\mathcal{F}_g^A]_R\,(\epsilon,Q^2)$$

$$Z_g^{A,h}(\epsilon,Q^2,\mu_h^2) = 1 + \sum_{i=1}^{\infty} a_s^i(\mu_h^2) Z_{g,i}^{A,h}(\epsilon,Q^2,\mu_h^2)\,,$$

$$C_g^{A,\text{eff}}\,(Q^2,\mu_h^2) = 1 + \sum_{i=1}^{\infty} a_s^i(\mu_h^2) C_{g,i}^{A,\text{eff}}\,(Q^2,\mu_h^2)$$

N3LL

$$\mu_h^2 \frac{d}{d\mu_h^2} \ln C_{g,i}^{A,\text{eff}} = \frac{1}{2} A_{g,i} L - \left(B_{g,i} + \frac{1}{2} f_{g,i}\right)$$

$$\begin{aligned}
C_{g,3}^{A,\text{eff}} = {} & n_f C_J^{(2)}\Big\{-2\Big\} + C_F n_f^2\Big\{L\Big(-\frac{320}{9} + 8\ln\Big(\frac{\mu_h^2}{m_t^2}\Big) + \frac{32}{3}\zeta_3\Big) + \frac{749}{9} - \frac{20}{9}\zeta_2 - \frac{16}{45}\zeta_2^2 \\
& - \frac{112}{3}\zeta_3\Big\} + C_F^2 n_f\Big\{\frac{457}{6} + 104\zeta_3 - 160\zeta_5\Big\} + C_A^2 n_f\Big\{\frac{2}{9}L^5 - \frac{8}{27}L^4 + L^3\Big(-\frac{752}{81} \\
& - \frac{2}{3}\zeta_2\Big) + L^2\Big(\frac{512}{27} - \frac{103}{9}\zeta_2 + \frac{118}{9}\zeta_3\Big) + L\Big(\frac{129283}{729} + \frac{4198}{81}\zeta_2 - \frac{48}{5}\zeta_2^2 + \frac{28}{9}\zeta_3\Big) \\
& - \frac{7946273}{13122} - \frac{19292}{729}\zeta_2 + \frac{73}{45}\zeta_2^2 - \frac{2764}{81}\zeta_3 - \frac{82}{9}\zeta_2\zeta_3 + \frac{428}{9}\zeta_5\Big\} + C_A^3\Big\{-\frac{1}{6}L^6 - \frac{11}{9}L^5 \\
& + L^4\Big(\frac{389}{54} - \frac{3}{2}\zeta_2\Big) + L^3\Big(\frac{2206}{81} + \frac{11}{3}\zeta_2 + 2\zeta_3\Big) + L^2\Big(-\frac{20833}{162} + \frac{757}{18}\zeta_2 - \frac{73}{10}\zeta_2^2 \\
& + \frac{143}{9}\zeta_3\Big) + \frac{2222}{9}\zeta_5 + L\Big(-\frac{500011}{1458} - \frac{16066}{81}\zeta_2 + \frac{176}{5}\zeta_2^2 + \frac{1832}{27}\zeta_3 + \frac{34}{3}\zeta_2\zeta_3 \\
& + 16\zeta_5\Big) + \frac{41091539}{26244} + \frac{316939}{1458}\zeta_2 - \frac{1399}{270}\zeta_2^2 - \frac{24389}{1890}\zeta_2^3 - \frac{176584}{243}\zeta_3 - \frac{605}{9}\zeta_2\zeta_3 \\
& - \frac{104}{9}\zeta_3^2\Big\} + C_A n_f^2\Big\{-\frac{2}{27}L^4 + \frac{40}{81}L^3 + L^2\Big(\frac{80}{81} + \frac{8}{9}\zeta_2\Big) + L\Big(-\frac{12248}{729} - \frac{80}{27}\zeta_2 \\
& - \frac{128}{27}\zeta_3\Big) + \frac{280145}{6561} + \frac{4}{9}\zeta_2 + \frac{4}{27}\zeta_2^2 + \frac{4576}{243}\zeta_3\Big\} + C_A C_F n_f\Big\{-\frac{2}{3}L^3 + L^2\Big(\frac{215}{6} \\
& - 6\ln\Big(\frac{\mu_h^2}{m_t^2}\Big) - 16\zeta_3\Big) + L\Big(\frac{9173}{54} - 44\ln\Big(\frac{\mu_h^2}{m_t^2}\Big) + 4\zeta_2 + \frac{16}{5}\zeta_2^2 - \frac{376}{9}\zeta_3\Big) \\
& + 24\ln\Big(\frac{\mu_h^2}{m_t^2}\Big) - \frac{726935}{972} - \frac{415}{18}\zeta_2 + 6\ln\Big(\frac{\mu_h^2}{m_t^2}\Big)\zeta_2 - \frac{64}{45}\zeta_2^2 + \frac{20180}{81}\zeta_3 + \frac{64}{3}\zeta_2\zeta_3 \\
& + \frac{608}{9}\zeta_5\Big\}.
\end{aligned}$$

New!

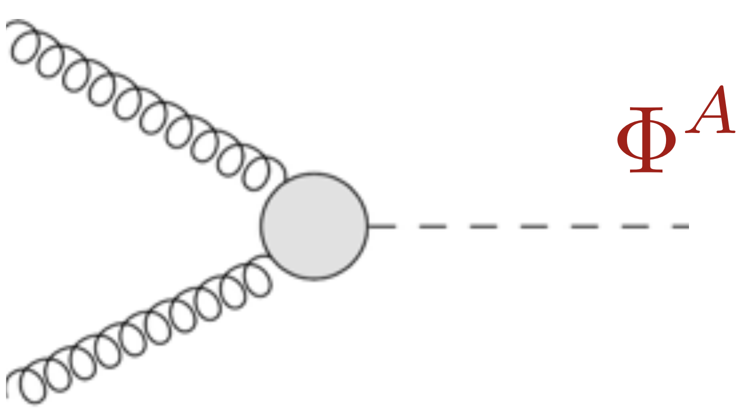
Relations in $\mathcal{N}=4$ SYM

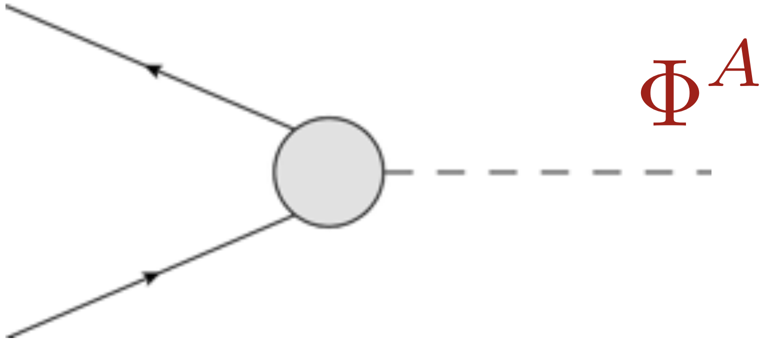
[A.V.Kotikov,L.N.Lipatov,A.I.Onishchenko,V.N.Velizhanin,T. Gehrmann,J. Henn]

Leading Transcendentality Principle

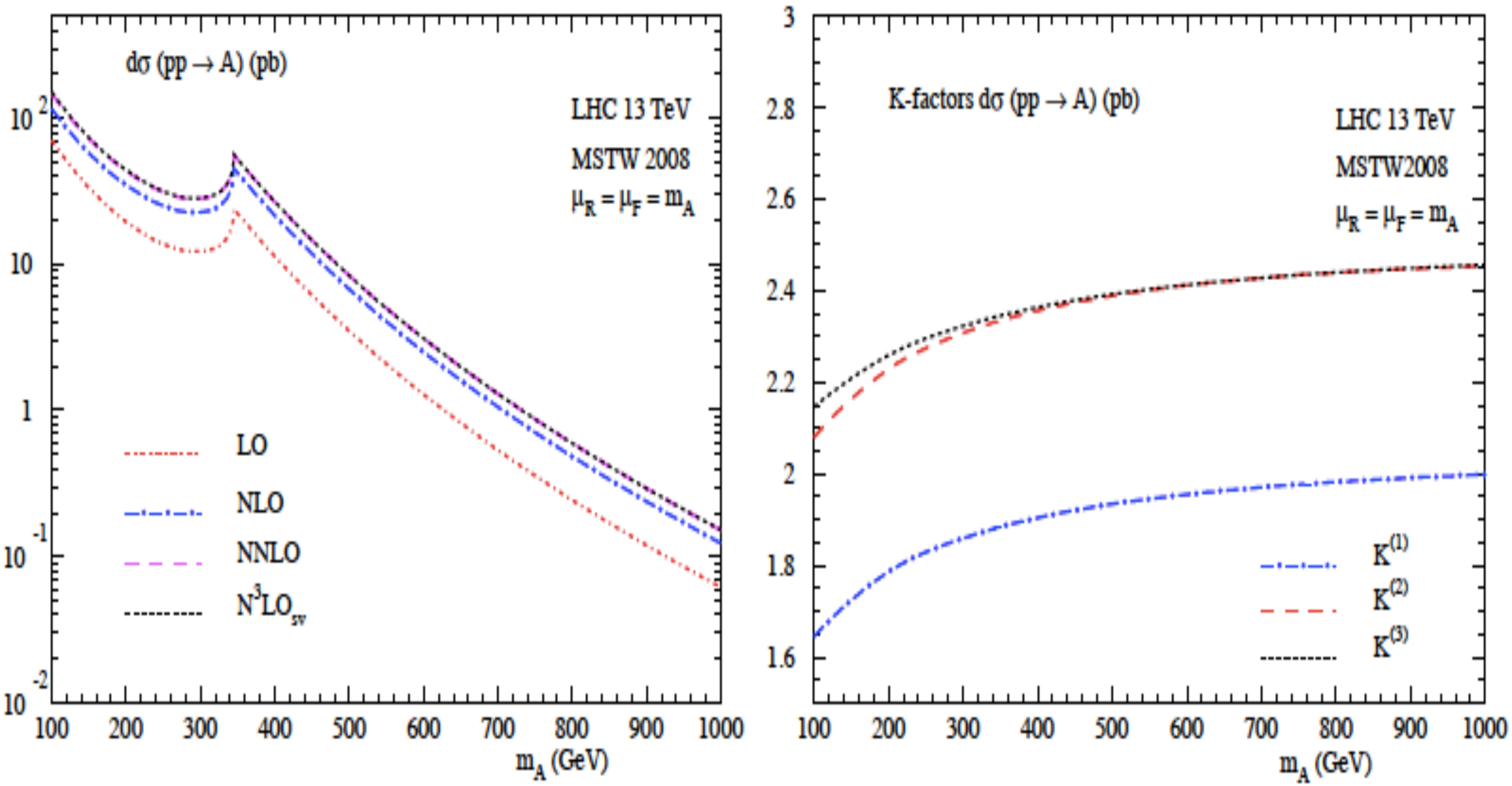
- Set $C_A = C_F = N, T_f n_f = N/2$ for $SU(N)$
- Leading Transcendental (LT) parts of quark and gluon form factors in QCD are equal upto a factor 2^l
- LT part of quark and gluon form factors are identical to the scalar form factor in $\mathcal{N}=4$ SYM
- LT part of pseudo scalar form factor is identical to quark and gluon form factors in QCD upto a factor 2^l also to scalar form factor in $\mathcal{N}=4$ SYM

N3LO Phenomenology

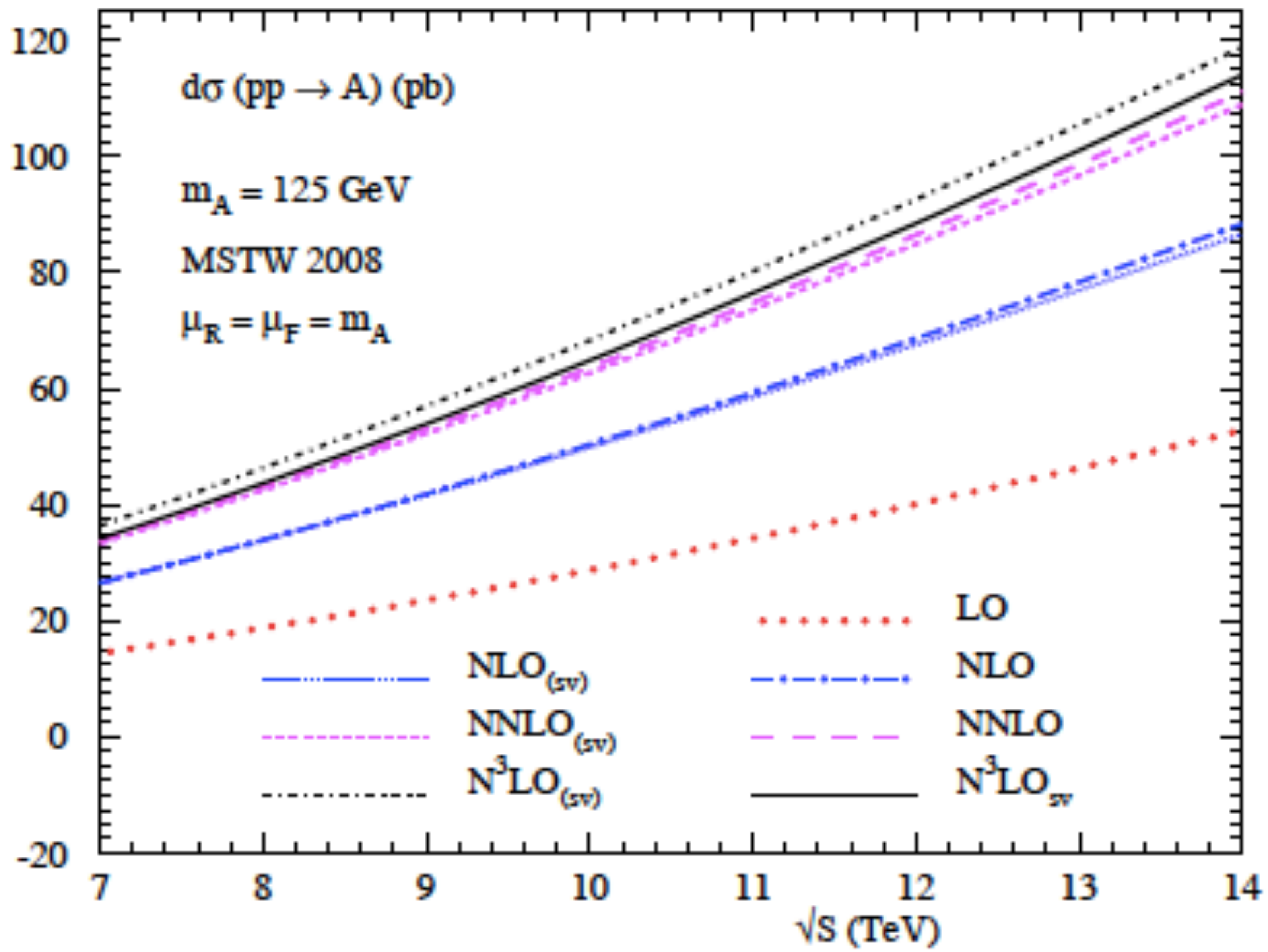




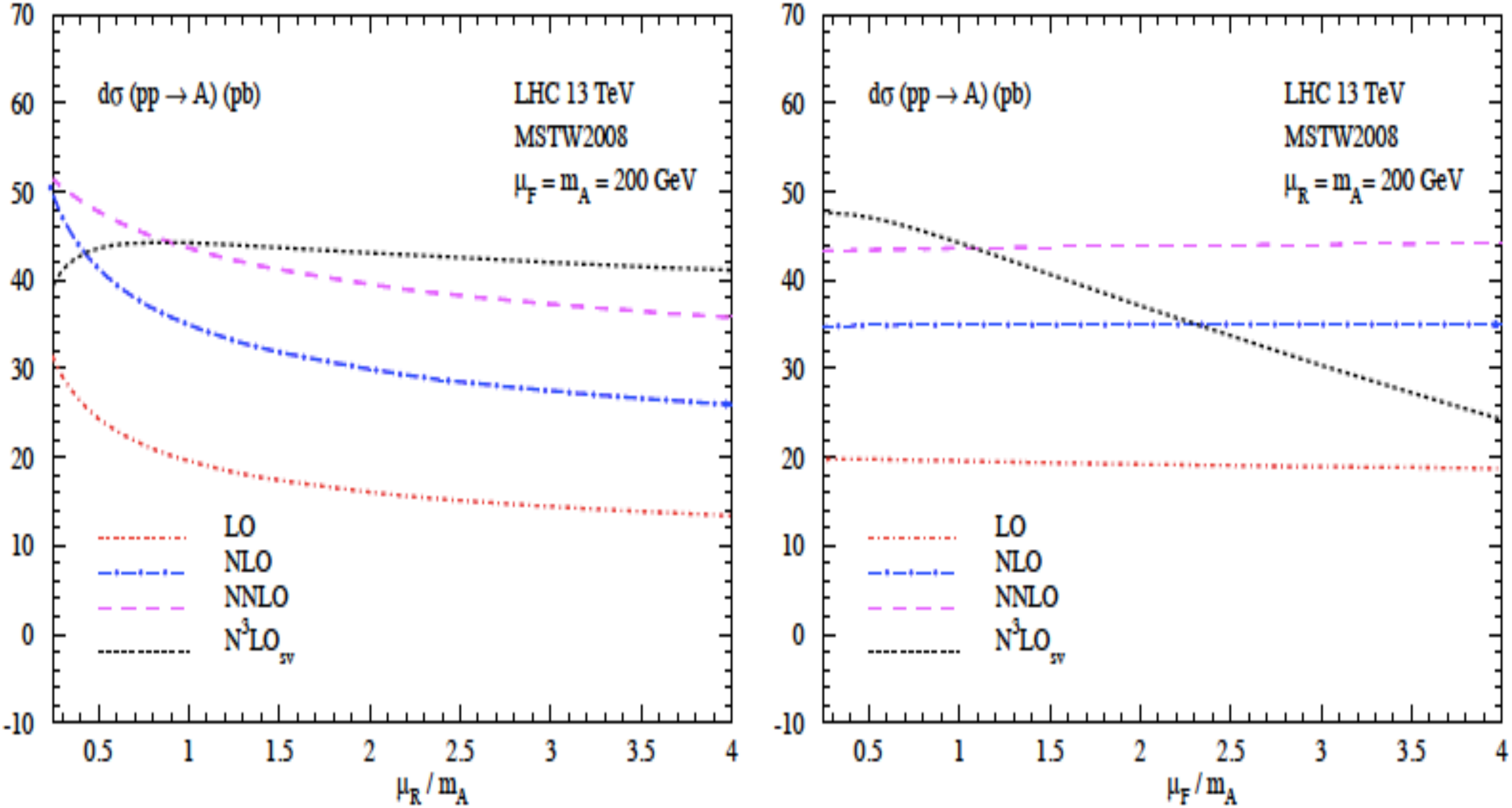
Cross section at N3LO sv



$\sqrt{S}$ dependence at N3LO (sv)



Scale dependence at N3LO sv



PDF dependence at N3LO sv

PDF set	SM Higgs			Pseudo-scalar		
	NLO	NNLO	N^3LO_{SV}	NLO	NNLO	N^3LO_{SV}
ABM11	33.19	39.59	41.99	77.42	92.66	94.64
CT10	31.79	41.84	44.67	74.15	97.94	100.44
MSTW2008	33.59	42.13	44.92	78.35	98.61	101.06
NNPDF 23	33.55	43.01	45.87	78.26	100.70	103.19

Conclusions

- Pseudo-scalar Higgs form factor at three loops in QCD
- UV and IR poles structure using K+G equation
- Subtraction of IR poles results in UV renormalisation constant
- N3LO threshold corrections and N-independent part of resumed cross section at N3LL, Matching coefficients at N3LO in SCET are available
- Scale dependence has been studied.