QCD Radiative Corrections To Higgs Physics

Taushif Ahmed

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Talk to Defend My Thesis

Thesis Advisor: Prof. V. Ravindran

The Institute of Mathematical Sciences

Motivations

- It is an interesting era for High energy physics

  2012's Discovery of SM-Higgs-like particle

  ~~Excess in 750 GeV~~

- Is it new physics or the SM?

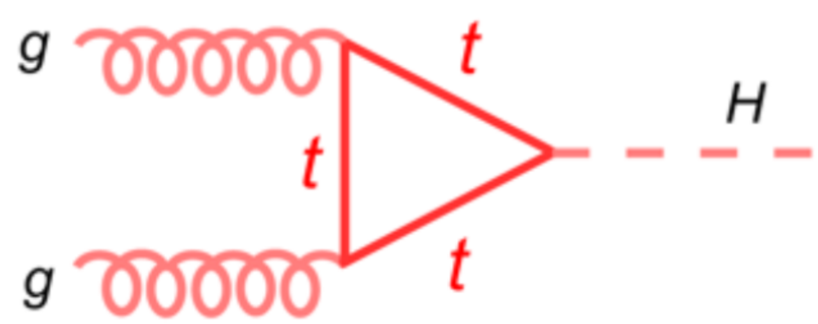
- Confirming these demand more data at LHC and precise theoretical predictions

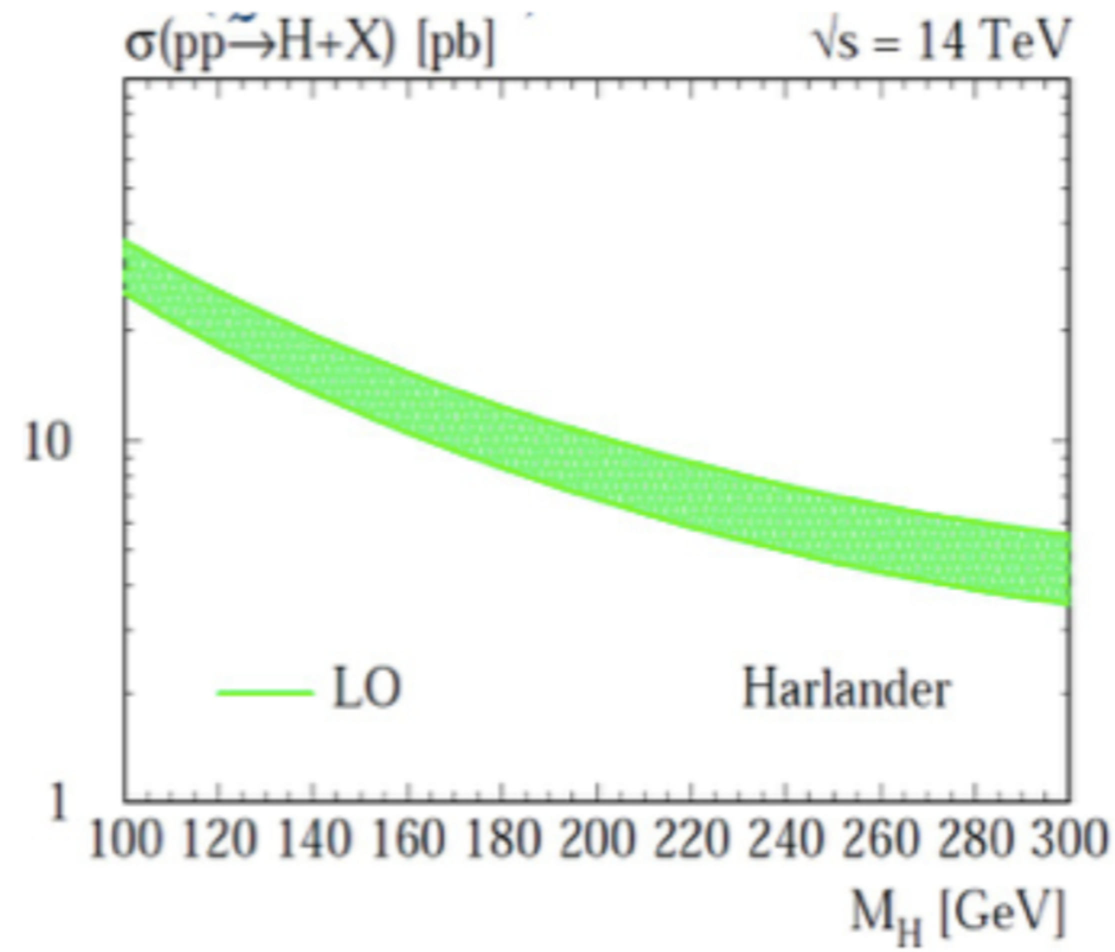
- QCD radiative corrections are crucial

Motivations

LO is a crude approximation

$$2S\sigma^H(x, m_H) = \int_x^1 \frac{dz}{z} \Phi_{gg}^{(0)}(z, \mu_F) 2\hat{s}\hat{\sigma}_{gg}^{(0)}\left(\frac{x}{z}, m_H^2, \mu_R\right) + \cdots$$

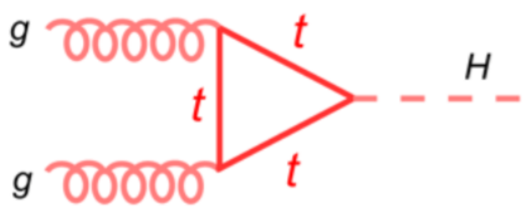


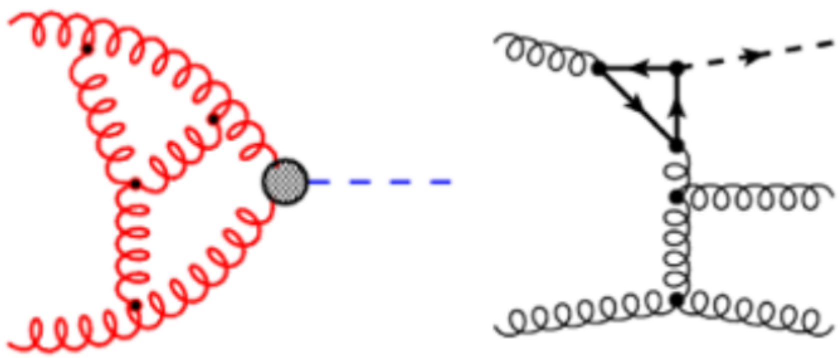


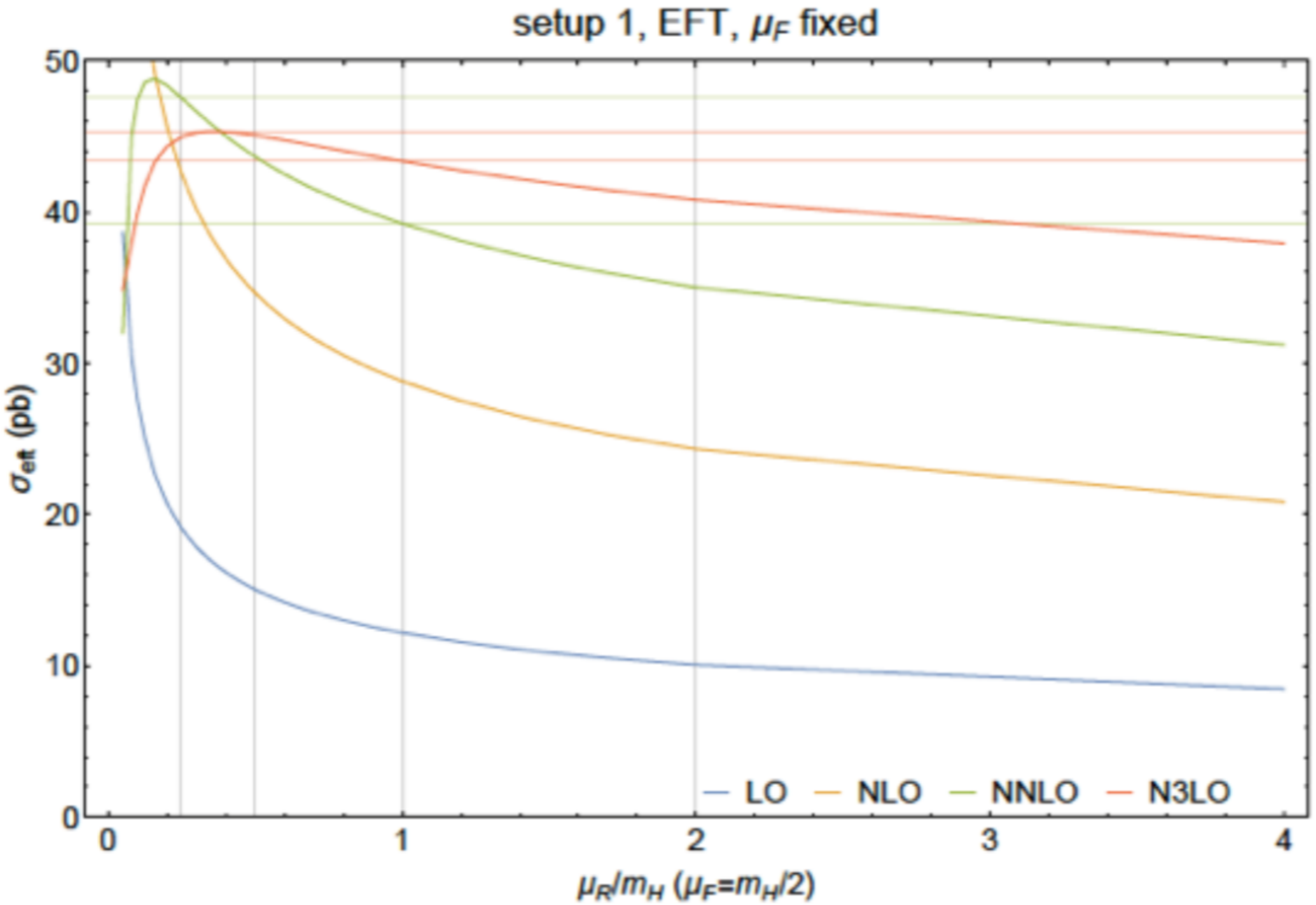
$$2\hat{s}\hat{\sigma}_{gg}^{(0)}\left(\frac{x}{z}, m_H^2, \mu_R\right) = \alpha_s^2(\mu_R) G_F F(m_t, m_H)$$

LO prediction is unreliable: **Huge** scale uncertainty

Reliable Result at N^3LO







$\Delta^{scale}_{EFT,k}$ $(\mu_F = m_H/2)$		
LO	$(k=0)$	$\pm 22.0\%$
NLO	$(k=1)$	$\pm 19.2\%$
NNLO	$(k=2)$	$\pm 9.5\%$
N^3LO	$(k=3)$	$\pm 2.2\%$

$\Delta^{scale}_{EFT,k}$		
LO	$(k=0)$	$\pm 14.8\%$
NLO	$(k=1)$	$\pm 16.6\%$
NNLO	$(k=2)$	$\pm 8.8\%$
N^3LO	$(k=3)$	$\pm 1.9\%$

What Is Next?

This thesis arises in this context

↓

Precise predictions in Higgs, pseudo-Higgs & DY production channels

Publications

1. **Higgs Boson Production Through $b\bar{b}$ Annihilation At Threshold $\mathrm{N^3LO}$ QCD**

   TA, Rana & Ravindran
   JHEP 1410, 139 (2014)

2. **Rapidity Distribution In Drell-Yan & Higgs Productions at Threshold $\mathrm{N^3LO}$ QCD**

   TA, Mandal, Rana & Ravindran
   Phys.Rev.Lett. 113, 212003 (2014)

3. **Pseudo Scalar Form Factors At 3-Loop QCD**

   TA, Gehrmann, Mathews, Rana & Ravindran
   JHEP 1511, 169 (2015)

4. **Pseudo-scalar Higgs Boson Production at Threshold $\mathrm{N^3LO}$ and $\mathrm{N^3LL}$ QCD**

   TA, Kumar, Mathews, Rana & Ravindran
   Eur. Phys. J. C (2016) 76:355

Publications (Not Included In Thesis)

5. Two-Loop QCD Correction to massive spin-2 resonance $\rightarrow$ 3-gluons

JHEP 1405, 107 (2014) TA, Mahakhud, Mathews, Rana & Ravindran

6. Drell-Yan Production at Threshold to Third Order in QCD

Phys.Rev.Lett. 113, 112002 (2014) TA, Mahakhud, Rana & Ravindran

7. Two-loop QCD corrections to Higgs $\rightarrow b + \bar{b} + g$ amplitude

JHEP 1408, 075 (2014) TA, Mahakhud, Mathews, Rana & Ravindran

8. Higgs Rapidity Distribution in $b\bar{b}$ Annihilation at Threshold in N^3LO QCD

JHEP 1502, 131 (2015) TA, Mandal, Rana & Ravindran

9. Spin-2 Form Factors at Three Loop in QCD

JHEP 1512, 084 (2015) TA, Das, Mathews, Rana & Ravindran

10. Pseudo-scalar Higgs boson production at $N^3LO_A + N^3LL'$

Eur.Phys.J. C76 (2016) no.12, 663 TA, Bonvini, Kumar, Mathews, Rottoli, Rana & Ravindran

11. NNLO QCD Corrections to the Drell-Yan Cross Section in Models of TeV- Scale Gravity

Eur.Phys.J. C77 (2017) no.1, 22 TA, Banerjee, Dhani, Kumar, Mathews, Rana & Ravindran

12. The two-loop QCD correction to massive spin-2 resonance $\rightarrow q\bar{q}g$

Eur.Phys.J. C76 (2016) no.12, 667 TA, Das, Mathews, Rana & Ravindran

13. Konishi Form Factor at Three Loop in $\mathcal{N} = 4$ SYM

arXiv:1610.05317 [hep-th] (Under consideration in PRL) TA, Banerjee, Dhani, Rana, Ravindran & Seth

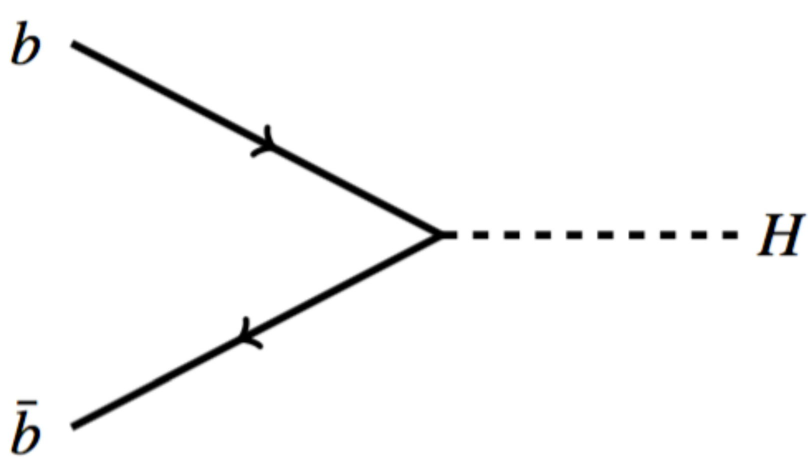
14. Three loop form factors of a massive spin-2 with non-universal coupling

arXiv:1612.00024 [hep-ph] (Appeared to be in PRD) TA, Banerjee, Dhani, Mathews, Rana & Ravindran

15. RG improved Higgs boson production to N3LO in QCD

arXiv:1505.07422 [hep-ph] TA, Das, Kumar, Mathews, Rana & Ravindran

Higgs Boson Production Through $b\bar{b}$ Annihilation At Threshold $\mathrm{N^3LO}$ QCD



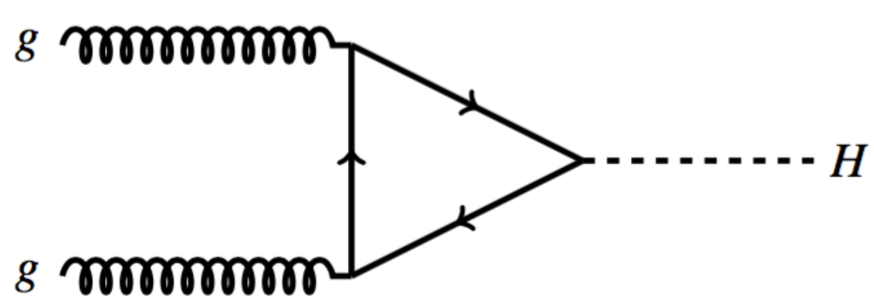
TA, Rana & Ravindran
JHEP 1410, 139 (2014)

MOTIVATIONS: $b\bar{b} \to H$

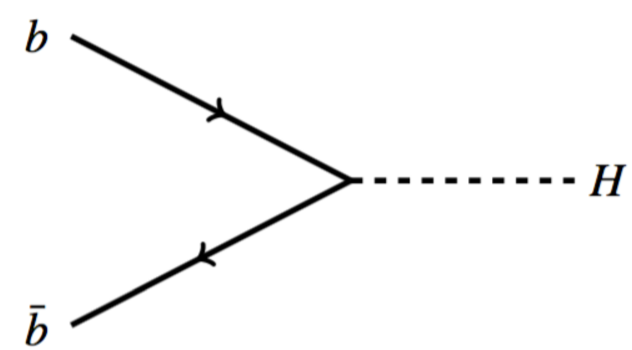
Give % of bB channel contribution

Higgs boson production

Dominant



Sub-dominant



- Yukawa coupling: small in SM, can be enhanced in MSSM
- Measurements of Higgs couplings are underway at LHC
- In precision studies nothing is unimportant

QCD RADIATIVE CORRECTIONS ARE CRUCIAL

Motivations: SV

- Going beyond LO: challenging → large no of diagrams; Loop integrals; Phase space integrals

- Often fail to compute complete fixed order result

- Alternative approach to catch dominant contributions

virtual & soft gluons

↓

Soft-virtual corrections

Partonic X-section

$$\Delta(z) = \Delta^{\text{sing}}(z) + \Delta^{\text{hard}}(z)$$

$$z = \frac{q^2}{\hat{s}}$$

$$\mathcal{D}_j \equiv \left(\frac{\ln^j(1-z)}{1-z} \right)_+$$

$$\Delta^{\text{sing}}(z) \equiv \Delta^{\text{SV}}(z) = \Delta^{\text{SV}}_{\delta}\,\delta(1-z) + \sum_{j=0}^{\infty} \Delta^{\text{SV}}_{j}\,\mathcal{D}_j$$

Leading in $z \to 1$ (threshold limit)

$\Delta^{\text{hard}}(z)$: polynomial in $\ln(1-z)$ → sub-leading

Motivations: SV

Partonic X-section: expand around $z \to 1$ (threshold limit)

$$\Delta(z) = \Delta^{\text{sing}}(z) + \Delta^{\text{hard}}(z)$$

$$z = \frac{q^2}{\hat{s}}$$

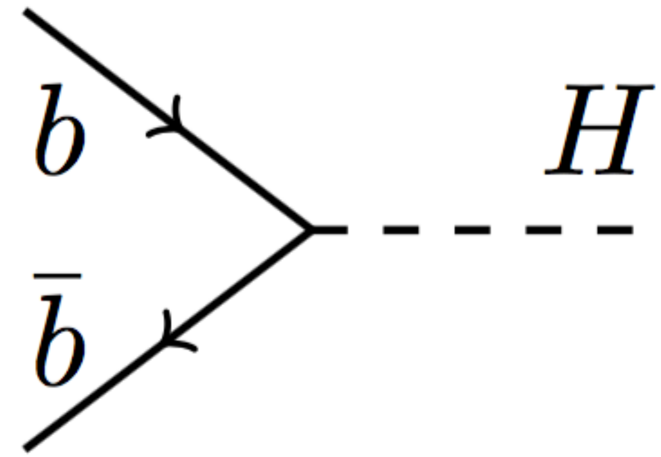
$$\mathcal{D}_j \equiv \left(\frac{\ln^j(1-z)}{1-z}\right)_+$$

$$\Delta^{\text{sing}}(z) \equiv \Delta^{\text{SV}}(z) = \Delta_\delta^{\text{SV}}\delta(1-z) + \sum_{j=0}^{\infty} \Delta_j^{\text{SV}} \mathcal{D}_j$$

Leading in $z \to 1$

$\Delta^{\text{hard}}(z)$: polynomial in $\ln(1-z)$ → sub-leading

Our focus



Existing result: NNLO and partial SV N^3LO ['03, '06]

Next obvious and necessary extension

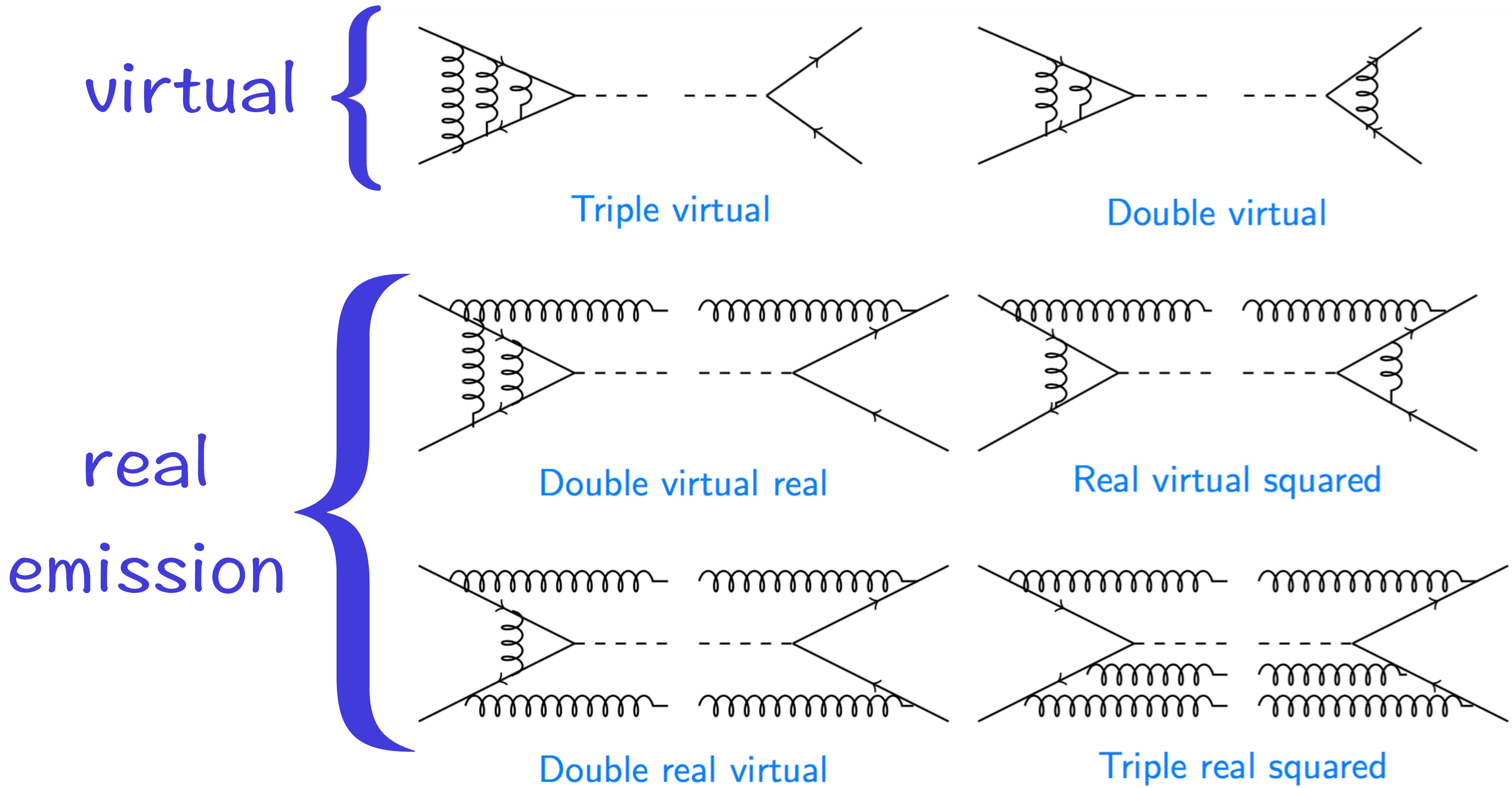
SV corrections to $b\bar{b} \to H$ cross section at N^3LO QCD

Many methods

1. Direct evaluation of diagrams

Many methods

1. Direct evaluation of diagrams



Many methods

1. Direct evaluation of diagrams

2. Use factorisation, RGE & Sudakov resum

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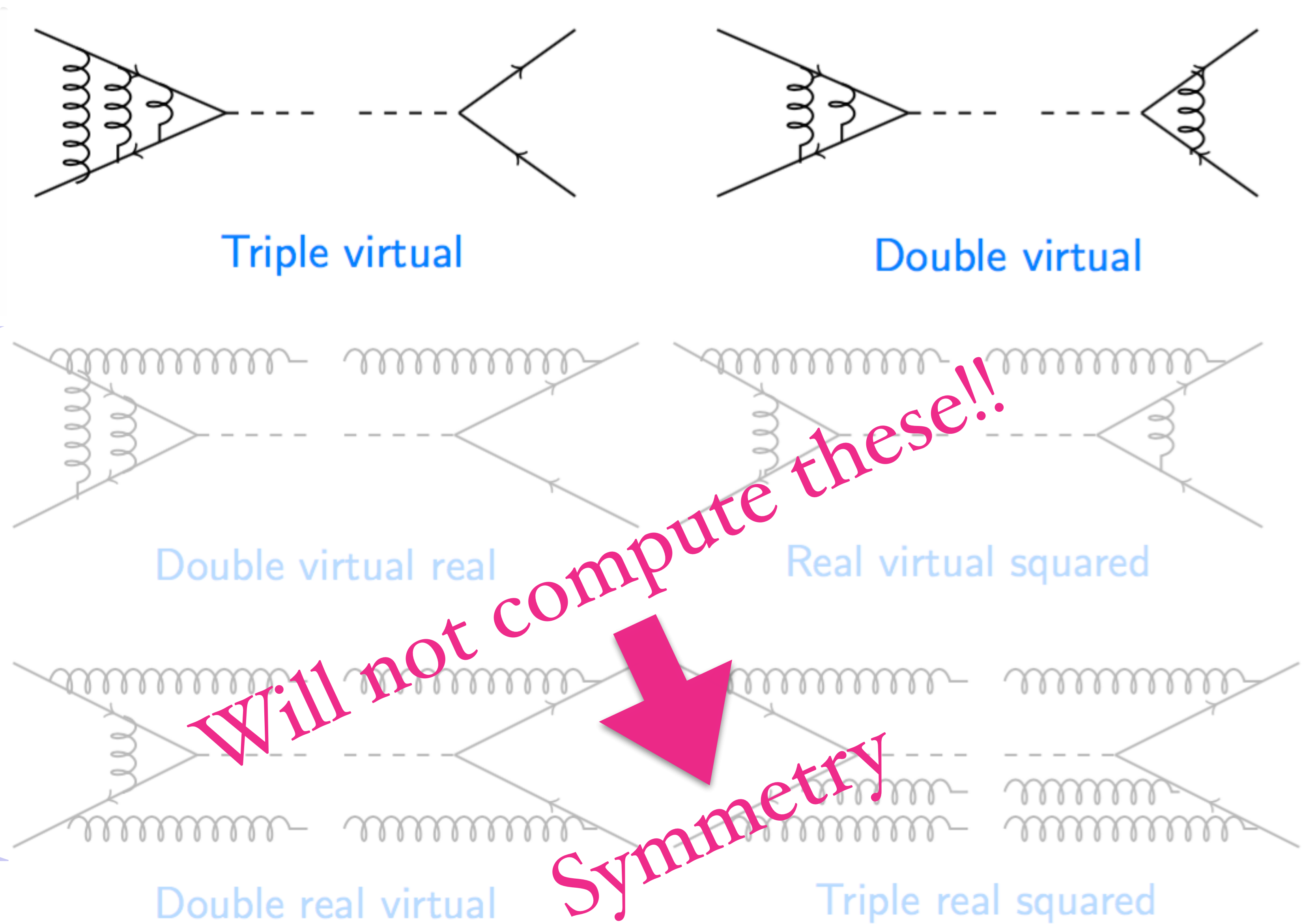
virtual

real emission



Master Formula

$$\Delta^{\mathrm{SV},I}\left(z,q^2,\mu_R^2,\mu_F^2\right)=\mathcal{C}\exp\left(\Psi^I\left(z,q^2,\mu_R^2,\mu_F^2,\epsilon\right)\right)\big|_{\epsilon=0}$$

[Ravindran]

with

$$\Psi^I=\left(\ln\left[Z^I(\hat{a}_s,\mu_R^2,\mu^2,\epsilon)\right]^2+\ln\left|\hat{F}^I(\hat{a}_s,Q^2,\mu^2,\epsilon)\right|^2\right)\delta(1-z)$$
$$+2\Phi^I\left(\hat{a}_s,q^2,\mu^2,z,\epsilon\right)-2\mathcal{C}\ln\Gamma_{II}\left(\hat{a}_s,\mu^2,\mu_F^2,z,\epsilon\right)$$

Required up to N^{3}LO

- Operator renormalisation
- Form factors
- Soft-collinear distribution
- Mass factorisation kernel

Master Formula

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

[Ravindran]

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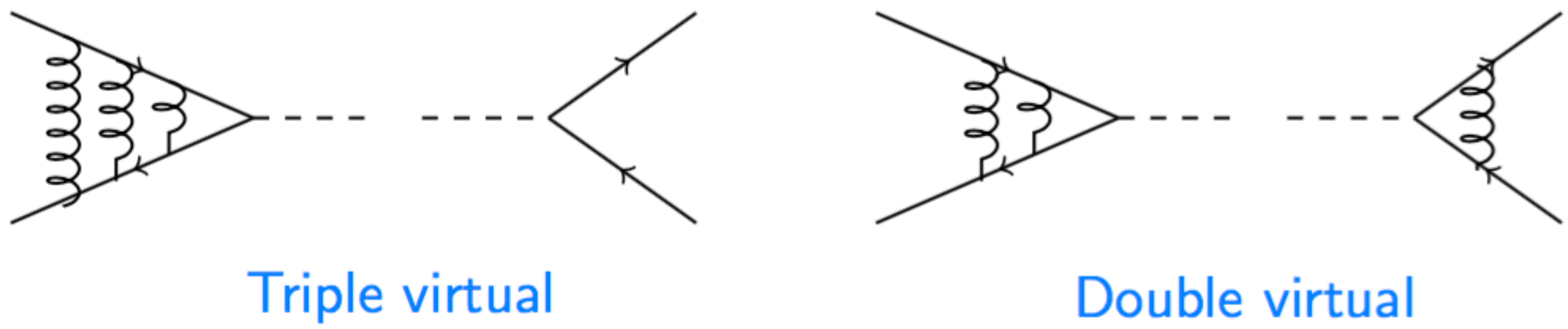
$$\Psi^I = \left(\ln\left[Z^I(\hat{a}_s, \mu_R^2, \mu^2, \epsilon)\right]^2 + \ln\left|\hat{F}^I(\hat{a}_s, Q^2, \mu^2, \epsilon)\right|^2\right)\delta(1-z) + 2\Phi^I\left(\hat{a}_s, q^2, \mu^2, z, \epsilon\right) - 2\mathcal{C}\ln\Gamma_{II}\left(\hat{a}_s, \mu^2, \mu_F^2, z, \epsilon\right)$$

- ✓ Operator renormalisation
- ✓ Form factors — Recently computed [Gehrmann, Kara '14]
- ✓ Soft-collinear distribution — Recently computed [TA, Mahakhud, Rana, Ravindran '14]
- ✓ Mass factorisation kernel

Form Factors



[Gehrmann, Kara '14]

Soft-Collinear Distr

$$\text{Real emission diagrams}|_{gg\to H} \Leftrightarrow \text{Real emission diagrams}|_{b\bar{b}\to H}$$

$$\Phi|_{gg\to H} = \frac{C_A}{C_F}\Phi|_{b\bar{b}\to H}$$

- Established up to NNLO [Ravindran '06]
- We postulated the relation even at N^3LO [TA, Mahakhud, Rana, Ravindran '14]
- Verified in case of Drell-Yan [Catani et. al., von Monteuffel et. al. '14]

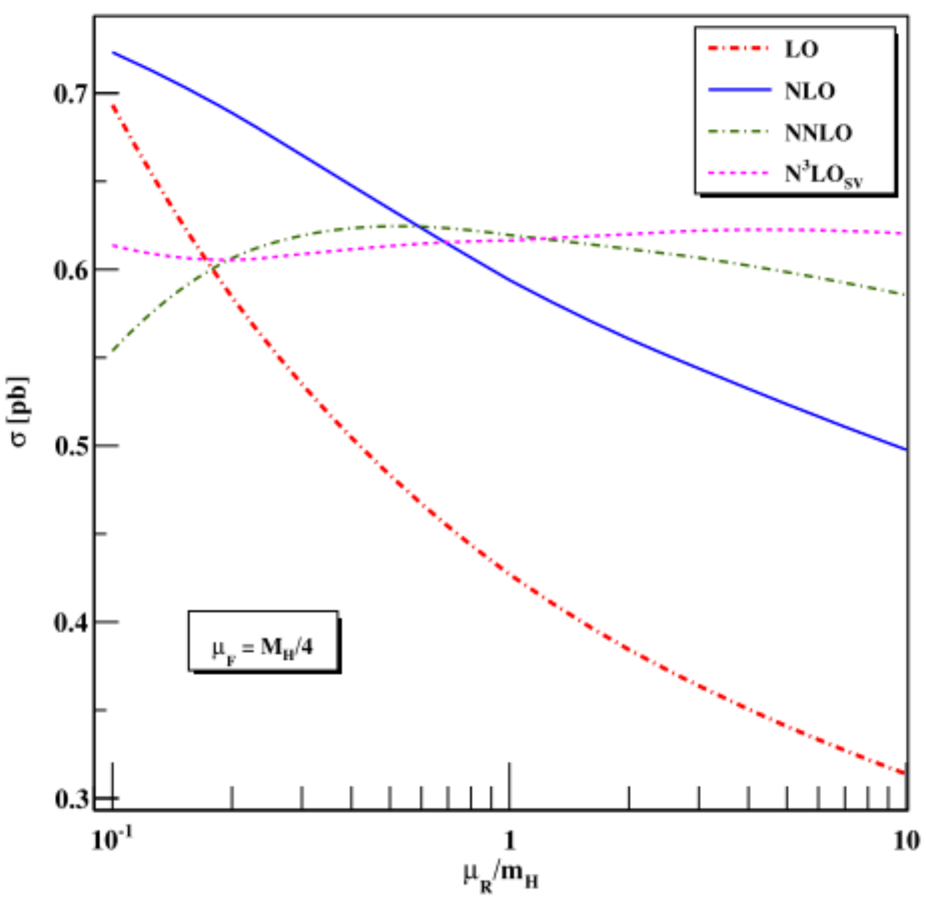
Results

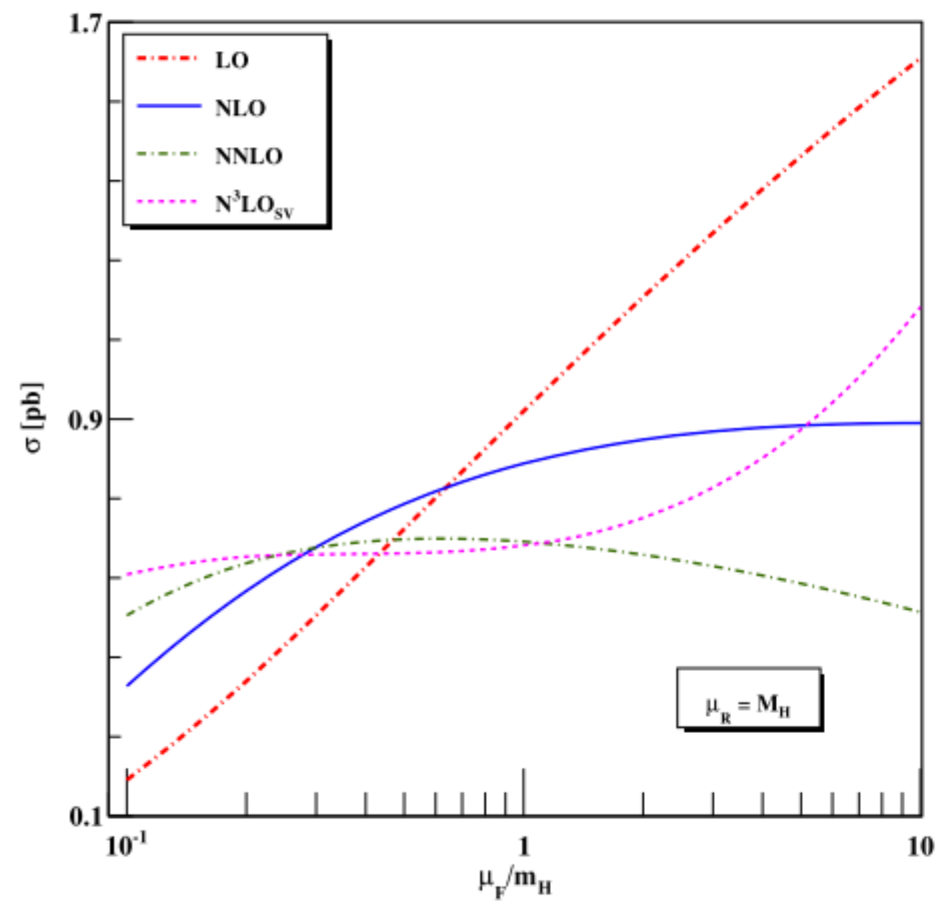
Analytical results at $\mathrm{N}^3\mathrm{LO}$

- $\Delta^{\mathrm{SV}}|_\delta$ is the new result
- Uplift the theoretical precision
- Reduces scale uncertainties

$$\Delta_b^{sv,(3)} = \delta(1-z)\Big\{C_A{}^2C_F\Big(\frac{13264}{315}\zeta_2{}^3 + \frac{2528}{27}\zeta_2{}^2 - \frac{1064}{3}\zeta_2\zeta_3 - 272\zeta_2 - \frac{400}{3}\zeta_3{}^2 - \frac{14212}{81}\zeta_3$$
$$- 84\zeta_5 + \frac{68990}{81}\Big) + C_AC_F{}^2\Big(-\frac{20816}{315}\zeta_2{}^3 - \frac{62468}{135}\zeta_2{}^2 + \frac{27872}{9}\zeta_2\zeta_3 + \frac{22106}{27}\zeta_2$$
$$+ \frac{3280}{3}\zeta_3{}^2 - \frac{10940}{9}\zeta_3 - \frac{37144}{9}\zeta_5 - \frac{982}{3}\Big) + C_AC_Fn_f\Big(-\frac{6728}{135}\zeta_2{}^2 + \frac{208}{3}\zeta_2\zeta_3$$
$$+ \frac{3368}{81}\zeta_2 + \frac{2552}{81}\zeta_3 - 8\zeta_5 - \frac{11540}{81}\Big) + C_F{}^3\Big(-\frac{184736}{315}\zeta_2{}^3 + \frac{152}{5}\zeta_2{}^2 - 64\zeta_2\zeta_3$$
$$- \frac{550}{3}\zeta_2 + \frac{10336}{3}\zeta_3{}^2 - 1188\zeta_3 + 848\zeta_5 + \frac{1078}{3}\Big) + C_F{}^2n_f\Big(\frac{12152}{135}\zeta_2{}^2 - \frac{5504}{9}\zeta_2\zeta_3$$
$$- \frac{2600}{27}\zeta_2 + \frac{4088}{9}\zeta_3 + \frac{5536}{9}\zeta_5 - \frac{70}{9}\Big) + C_Fn_f{}^2\Big(\frac{128}{27}\zeta_2{}^2 - \frac{32}{81}\zeta_2 - \frac{1120}{81}\zeta_3 + \frac{16}{27}\Big)\Big\}$$
$$+ \mathcal{D}_0\Big\{C_A{}^2C_F\Big(-\frac{2992}{15}\zeta_2{}^2 - \frac{352}{3}\zeta_2\zeta_3 + \frac{98224}{81}\zeta_2 + \frac{40144}{27}\zeta_3 - 384\zeta_5 - \frac{594058}{729}\Big)$$
$$+ C_AC_F{}^2\Big(\frac{1408}{\cdots}\zeta_2{}^2 - 1472\zeta_2\zeta_3 + \frac{6592}{\cdots}\zeta_2 + \frac{32288}{\cdots}\zeta_3 + \frac{6464}{\cdots}\Big) + C_AC_Fn_f\Big(\frac{736}{\cdots}\zeta_2{}^2$$

LHC13



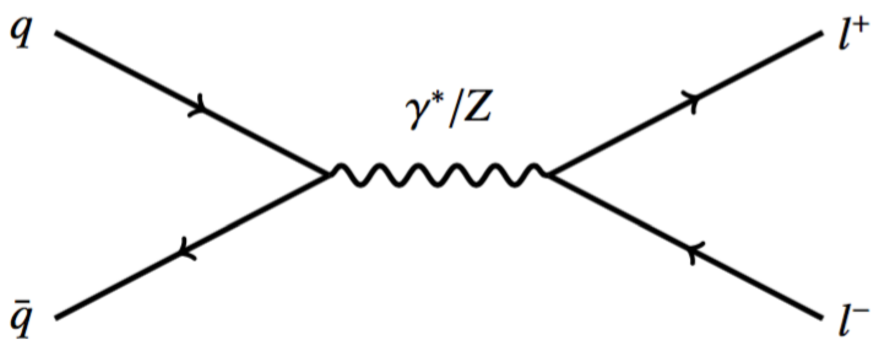


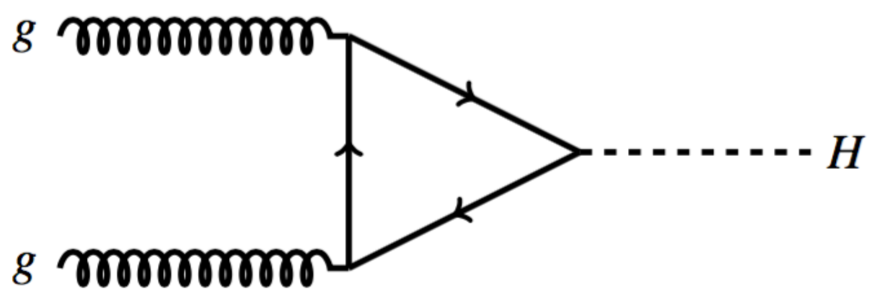
Most accurate result till date!

Rapidity Distribution In Drell-Yan & Higgs Productions at Threshold $\mathrm{N^3LO}$ QCD

TA, Mandal, Rana & Ravindran

Phys.Rev.Lett. 113, 212003 (2014)





MOTIVATIONS

- DY & Higgs: very important processes
- DY: 1. One of the cleanest processes
  2. Crucial role in determining PDF
- Higgs: Yet to confirm the identities of 2012's particle

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Catch dominant contributions through SV approx

Rapidity Distribution

$$\Delta_Y(z_1, z_2) = \Delta_Y^{\text{sing}}(z_1, z_2) + \Delta_Y^{\text{hard}}(z_1, z_2)$$

$$Y \equiv \frac{1}{2} \log\left(\frac{x_1^0}{x_2^0}\right) \qquad \tau \equiv x_1^0 x_2^0$$

$$z_i = \frac{x_i^0}{x_i}$$

$$\Delta_Y^{\text{SV}} = \Delta_Y^{\text{SV}}|_{\delta\delta}\delta(1-z_1)\delta(1-z_2) + \sum_{j=0}^{2j-1} \Delta_Y^{\text{SV}}|_{\delta\mathcal{D}_j}\delta(1-z_2)\mathcal{D}_j$$
$$+ \sum_{j=0}^{2j-1} \Delta_Y^{\text{SV}}|_{\delta\overline{\mathcal{D}}_j}\delta(1-z_2)\overline{\mathcal{D}}_j + \sum_{j,l} \Delta_Y^{\text{SV}}|_{\mathcal{D}_j\overline{\mathcal{D}}_l}\mathcal{D}_j\overline{\mathcal{D}}_l\,.$$

Leading in $z_1 \to 1, z_2 \to 1$ (threshold limit)

$\Delta_Y^{\text{hard}}(z_1, z_2)$: polynomial in $\ln(1-z_i)$ → sub-leading

Goal

Existing result: NNLO and partial SV N^3LO ['03, '07]

Next obvious and necessary extension

SV corrections to rapidity for

1. Higgs in $gg \to H$
2. Leptonic pair in DY

at N^3LO QCD

Many methods

1. Direct evaluation of diagrams

Many methods

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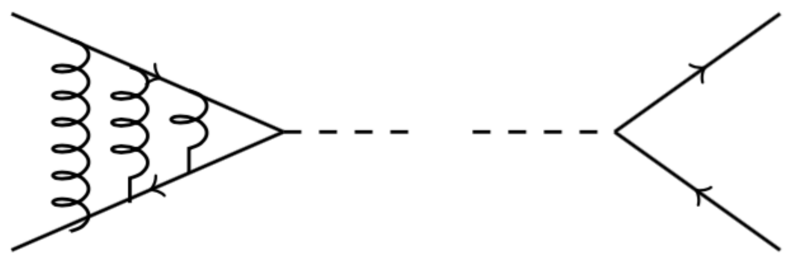
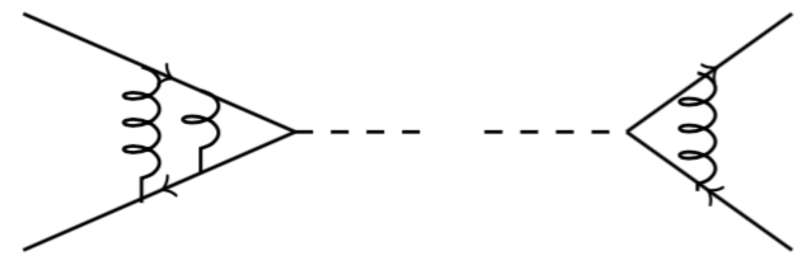
virtual

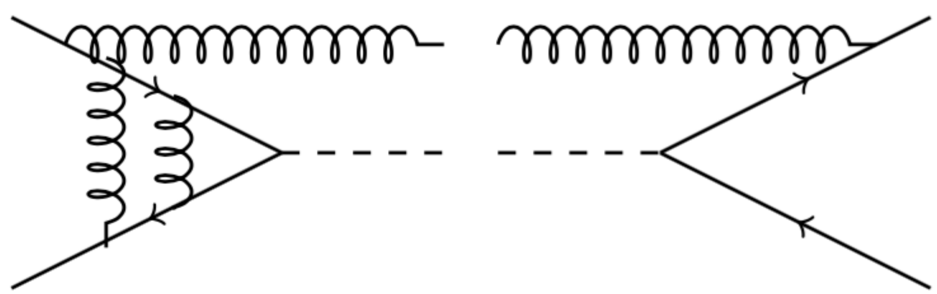


Triple virtual

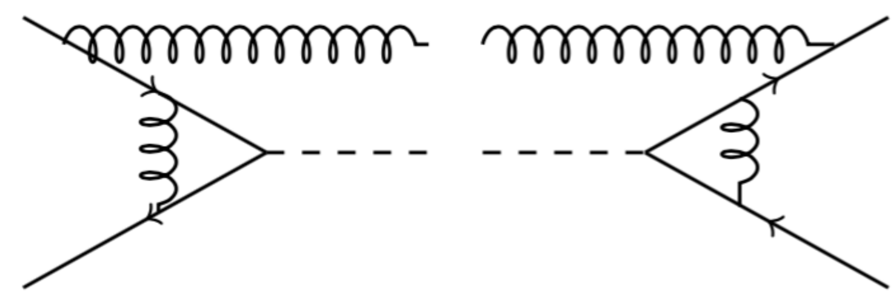


Double virtual

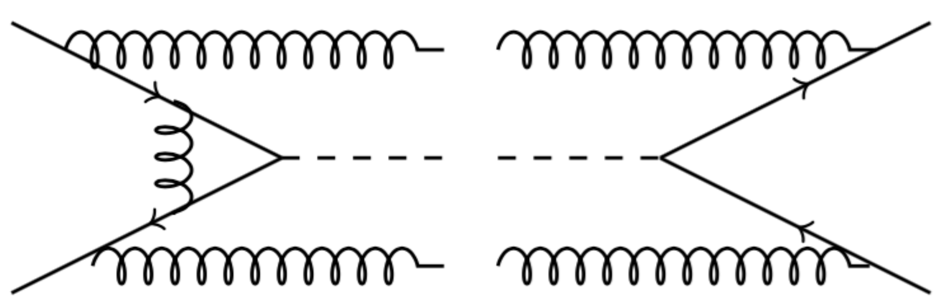
real emission



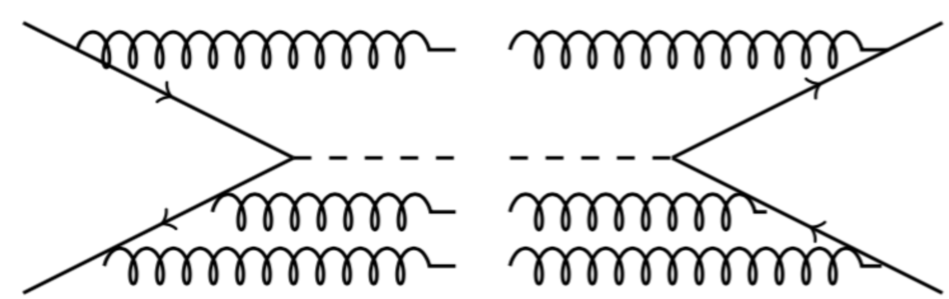
Double virtual real



Real virtual squared



Double real virtual



Triple real squared

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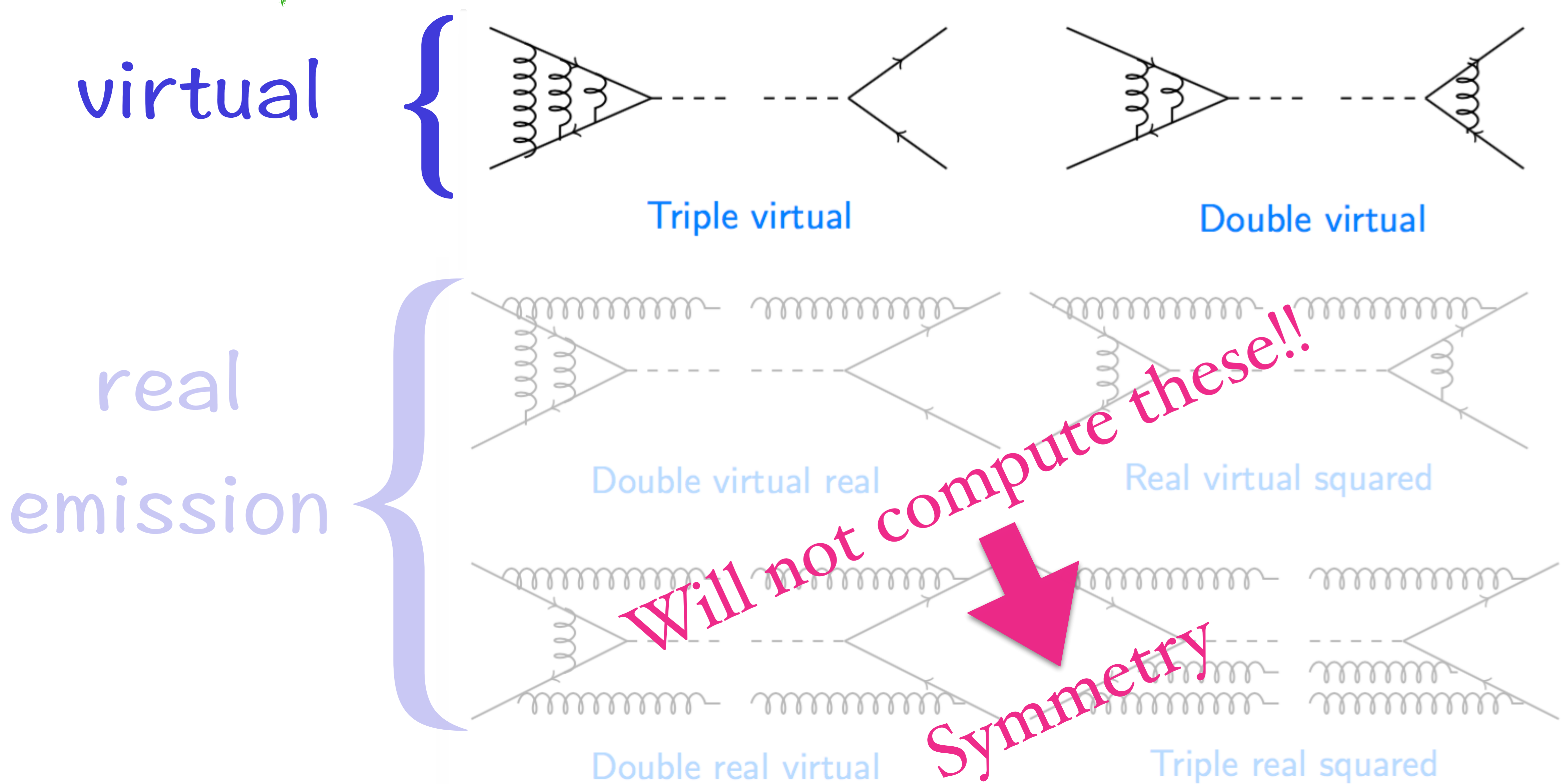

Master Formula

$$\Delta_Y^{\mathrm{SM}}(z_1, z_2, q^2, \mu_R^2, \mu_F^2) = \mathcal{C} \exp\left(\Psi_Y\left(z_1, z_2, q^2, \mu_R^2, \mu_F^2, \epsilon\right) \right)\Big|_{\epsilon=0}$$

[Ravindran]

$$\Psi_Y = \left(\ln\left[Z(\hat{a}_s, \mu_R^2, \mu^2, \epsilon)\right]^2 + \ln\left|\mathcal{F}(\hat{a}_s, Q^2, \mu^2, \epsilon)\right|^2 \right) \delta(1-z_1)\delta(1-z_2)$$
$$+ 2\Phi_Y(\hat{a}_s, q^2, \mu^2, z_1, z_2, \epsilon) - \mathcal{C} \ln\Gamma(\hat{a}_s, \mu^2, \mu_F^2, z_1, \epsilon)\delta(1-z_2)$$
$$- \mathcal{C} \ln\Gamma(\hat{a}_s, \mu^2, \mu_F^2, z_2, \epsilon)\delta(1-z_1)\,.$$

- Operator renormalisation
- Form factors
- Soft-collinear distribution
- Mass factorisation kernel

Required up to N^{3}LO

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$$\Delta_Y^{\rm SM}(z_1, z_2, q^2, \mu_R^2, \mu_F^2) = \mathcal{C} \exp\Big(\Psi_Y\left(z_1, z_2, q^2, \mu_R^2, \mu_F^2, \epsilon\right)\Big)\Big|_{\epsilon=0}$$

[Ravindran]

$$\Psi_Y = \left(\ln\Big[Z(\hat{a}_s, \mu_R^2, \mu^2, \epsilon)\Big]^2 + \ln\Big|\mathcal{F}(\hat{a}_s, Q^2, \mu^2, \epsilon)\Big|^2\right)\delta(1-z_1)\delta(1-z_2)$$
$$+ 2\Phi_Y(\hat{a}_s, q^2, \mu^2, z_1, z_2, \epsilon) - \mathcal{C}\ln\Gamma(\hat{a}_s, \mu^2, \mu_F^2, z_1, \epsilon)\delta(1-z_2)$$
$$- \mathcal{C}\ln\Gamma(\hat{a}_s, \mu^2, \mu_F^2, z_2, \epsilon)\delta(1-z_1)\,.$$

- ✓ Operator renormalisation
- ✓ Form factors
- Soft-collinear distribution — Unavailable
- ✓ Mass factorisation kernel

SOFT-COLLINEAR DISTRIBUTION

- Demanding finiteness of rapidity & RG invariance

  → poles of SCD

- Determining finite part

  → requires explicit computations

- However, it has been found $\Phi_Y \Leftrightarrow \Phi_{\text{Xsection}}$

[Ravindran, van Neerven, Smith]

- SCD for Xsection is used to obtain Φ_Y at N^3LO

[TA, Mandal, Rana, Ravindran]

Analytical results at $\mathrm{N^3LO}$

- $\Delta_Y^{\mathrm{SV}}|_{\delta\delta}$ is the new result
- Uplift the theoretical precision
- Reduces scale uncertainties

$$\Delta^{H,\mathrm{SV}}_{Y,gg,3} = \delta(1-z_1)\delta(1-z_2)\Bigg[C_A^3\Bigg\{\frac{215131}{81} + \frac{1364}{9}\zeta_5 - \frac{54820}{27}\zeta_3 + \frac{1600}{3}\zeta_3^2 + \frac{41914}{27}\zeta_2$$
$$- 88\zeta_2\zeta_3 + \frac{40432}{135}\zeta_2^2 + \frac{12032}{105}\zeta_2^3\Bigg\} + n_f C_A^2\Bigg\{-\frac{98059}{81} + \frac{1192}{9}\zeta_5 + \frac{2536}{27}\zeta_3$$
$$- \frac{7108}{27}\zeta_2 - 272\zeta_2\zeta_3 + \frac{1240}{27}\zeta_2^2\Bigg\} + n_f C_F C_A\Bigg\{-\frac{63991}{81} + 160\zeta_5 + 400\zeta_3 - \frac{2270}{9}\zeta_2$$
$$+ 288\zeta_2\zeta_3 + \frac{176}{45}\zeta_2^2\Bigg\} + n_f C_F^2\Bigg\{\frac{608}{9} - 320\zeta_5 + \frac{592}{3}\zeta_3\Bigg\} + n_f^2 C_A\Bigg\{\frac{2515}{27} + \frac{112}{3}\zeta_3$$
$$- \frac{64}{3}\zeta_2 - \frac{208}{15}\zeta_2^2\Bigg\} + n_f^2 C_F\Bigg\{\frac{8962}{81} - \frac{224}{3}\zeta_3 - \frac{184}{9}\zeta_2 - \frac{32}{45}\zeta_2^2\Bigg\}$$
$$+ \log\left(\frac{q^2}{\mu_F^2}\right) C_A^3\Bigg\{-\frac{8284}{9} + 224\zeta_5 + \frac{10408}{9}\zeta_3 - \frac{22528}{27}\zeta_2 - 224\zeta_2\zeta_3 - \frac{1276}{3}\zeta_2^2\Bigg\}$$
$$+ \log\left(\frac{q^2}{\mu_F^2}\right) n_f C_A^2\Bigg\{\frac{4058}{9} - \frac{1120}{9}\zeta_3 + \frac{8488}{27}\zeta_2 + \frac{232}{3}\zeta_2^2\Bigg\}$$
$$+ \log\left(\frac{q^2}{\ldots}\right) n_f C_F C_A\Bigg\{\frac{616}{\ldots} - \frac{352}{\ldots}\zeta_3 + 72\zeta_2\Bigg\} + \log\left(\frac{q^2}{\ldots}\right) n_f C_F^2\Bigg\{-4\Bigg\}$$

Numerical Impacts for Higgs

	$\delta\delta$	$\delta\overline{\mathcal{D}}_0$	$\delta\overline{\mathcal{D}}_1$	$\delta\overline{\mathcal{D}}_2$	$\delta\overline{\mathcal{D}}_3$	$\delta\overline{\mathcal{D}}_4$	$\delta\overline{\mathcal{D}}_5$	$\mathcal{D}_0\overline{\mathcal{D}}_0$	$\mathcal{D}_0\overline{\mathcal{D}}_1$
%	73.3	16.0	9.1	31.4	1.0	-9.9	-23.1	-13.7	-10.7

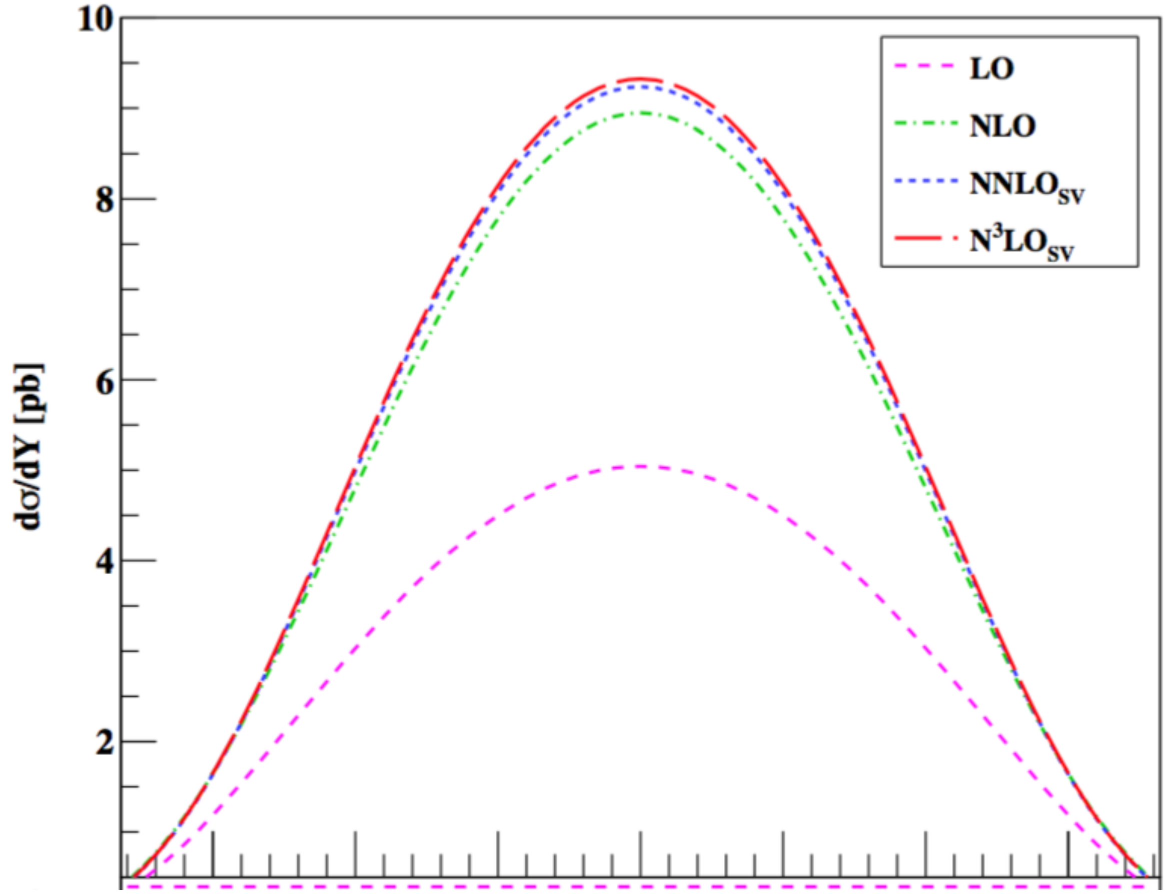
	$\mathcal{D}_0\overline{\mathcal{D}}_2$	$\mathcal{D}_0\overline{\mathcal{D}}_3$	$\mathcal{D}_0\overline{\mathcal{D}}_4$	$\mathcal{D}_1\overline{\mathcal{D}}_1$	$\mathcal{D}_1\overline{\mathcal{D}}_2$	$\mathcal{D}_1\overline{\mathcal{D}}_3$	$\mathcal{D}_2\overline{\mathcal{D}}_2$
%	-0.3	3.1	7.3	-0.2	3.8	8.6	4.2

→ $\Delta_Y^{\mathrm{SV}}|_{\delta\delta}$ has the largest contribution!

RESULTS

Y	0.0	0.4	0.8	1.2	1.6
NNLO	11.21	10.96	10.70	9.13	7.80
$\mathrm{NNLO_{SV}}$	9.81	9.61	8.99	8.00	6.71
$\mathrm{NNLO_{SV}(A)}$	10.67	10.46	9.84	8.82	7.48
$\mathrm{N^3LO_{SV}}$	11.62	11.36	11.07	9.44	8.04
$\mathrm{N^3LO_{SV}(A)}$	11.88	11.62	11.33	9.70	8.30
$K3$	2.31	2.29	2.36	2.21	2.17

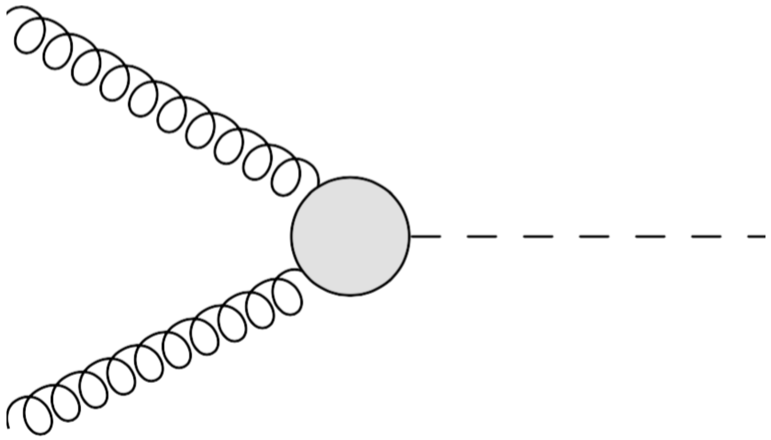
Most accurate results till date!

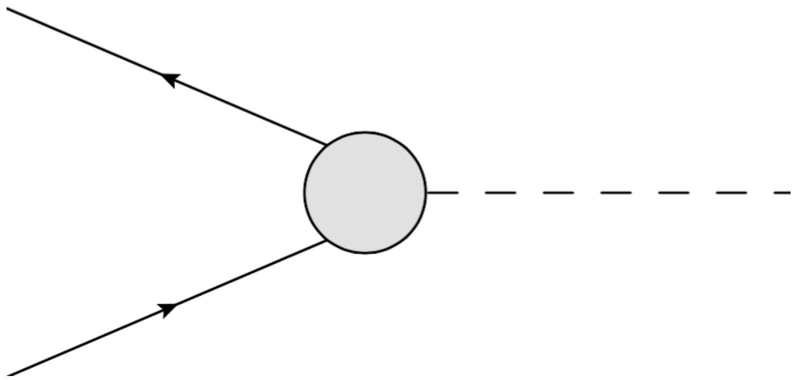


Pseudo Scalar Form Factors At 3-Loop QCD

TA, Gehrmann, Mathews, Rana & Ravindran
JHEP 1511, 169 (2015)

TA, Kumar, Mathews, Rana & Ravindran
Eur. Phys. J. C (2016) 76:355





- MSSM has richer Higgs sector

  → 5 physical Higgs bosons → neutral h, H, A ; charged $H^{\pm}$

  h, H : CP even
  A : CP odd

- Pseudo-scalar: important at the LHC

  → similar to scalar Higgs

- ~~New resonance at 750 GeV~~

  → ~~New scalar / Spin-2 / Pseudo-scalar?~~

- Searches at the LHC demands precise theoretical predictions

Motivations

CP even

Inclusive production cross section at N^3LO QCD

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

CP odd

Inclusive production cross section at NNLO QCD

[Harlander, Kilgore; Anastasiou, Melnikov]

What is next?

Go beyond NNLO for CP odd!

requires →

1. Virtual correction at 3-loop
2. Real corrections at N^3LO

GOAL

CP even

Inclusive production cross section at N^3LO QCD

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

CP odd

Inclusive production cross section at NNLO QCD

[Harlander, Kilgore; Anastasiou, Melnikov]

What is next?

Go beyond NNLO for CP odd!

requires →

1. Virtual correction at 3-loop — Our GOAL
2. Real corrections at N^3LO

Original Theory

Pseudo scalar couples to quarks through Yukawa

Effective Theory

[Chetyrkin, Kniehl, Steinhauser and Bardeen]

Simplifications occur if $m_A << 2m_t$

→ effective theory by int out top loop

→ massless QCD

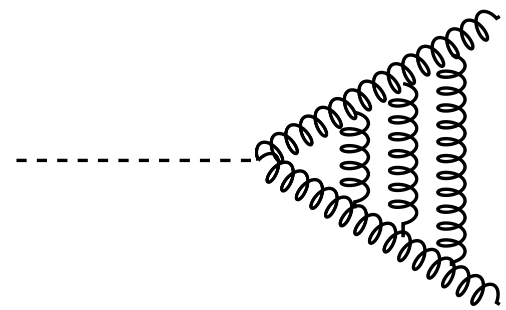
$$\mathcal{L}_{\rm eff}^{A} = \Phi^A \Big[-\frac{1}{8} C_G O_G - \frac{1}{2} C_J O_J \Big]$$

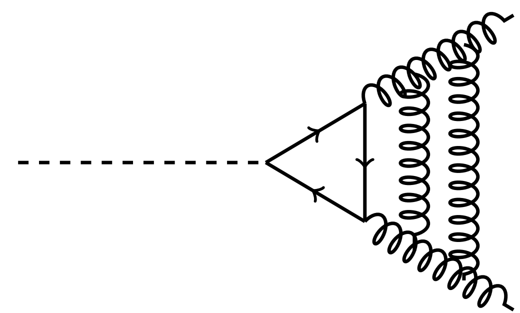
$$O_G(x) = G_a^{\mu\nu} \tilde{G}_{a,\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma} \qquad O_J(x) = \partial_\mu \left(\bar{\psi} \gamma^\mu \gamma_5 \psi \right)$$

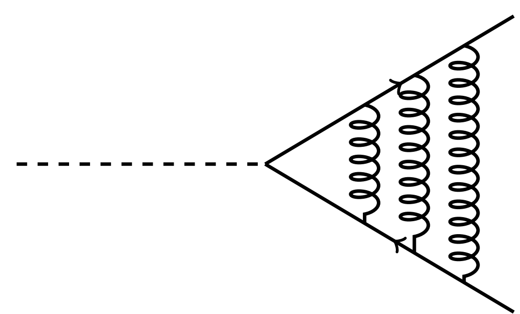
$$C_G = -a_s 2^{\frac{5}{4}} G_F^{\frac{1}{2}} \cot\beta \qquad C_J = -\left[a_s C_F \left(\frac{3}{2} - 3 \ln \frac{\mu_R^2}{m_t^2} \right) + a_s^2 C_J^{(2)} + \cdots \right] C_G$$

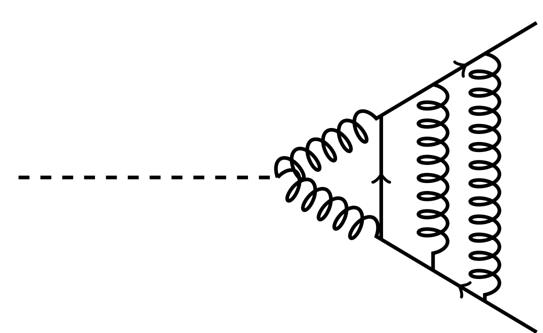
Qgraf

[P. Nogueira]

1586  type

447  type

244  type

400  type

- Color simplification in SU(N) theory
- Lorentz & Dirac algebra in d-dimensions

} in-house codes

- What about γ_5 & $\varepsilon_{\mu\nu\rho\sigma}$?

→ inherently 4-dimensional

→ problem of defining in d $(\neq 4)$ dimensions

Prescription

$$\gamma_5 = i\frac{1}{4!}\varepsilon_{\nu_1\nu_2\nu_3\nu_4}\gamma^{\nu_1}\gamma^{\nu_2}\gamma^{\nu_3}\gamma^{\nu_4}$$

$$\{\gamma_5, \gamma^\mu\} \neq 0$$

['t Hooft and Veltman]

$$\varepsilon_{\mu_1\nu_1\lambda_1\sigma_1}\,\varepsilon^{\mu_2\nu_2\lambda_2\sigma_2} = 4!\,\delta^{\mu_2}_{[\mu_1}\cdots\delta^{\sigma_2}_{\sigma_1]}$$

Treat in d-dimensions

IBP & LI

- Removing unphysical DOF of gluons

  1. Internal: Ghost loops

  2. External: Polarization sum in axial gauge

- Results

Thousands of 3-loop scalar integrals!

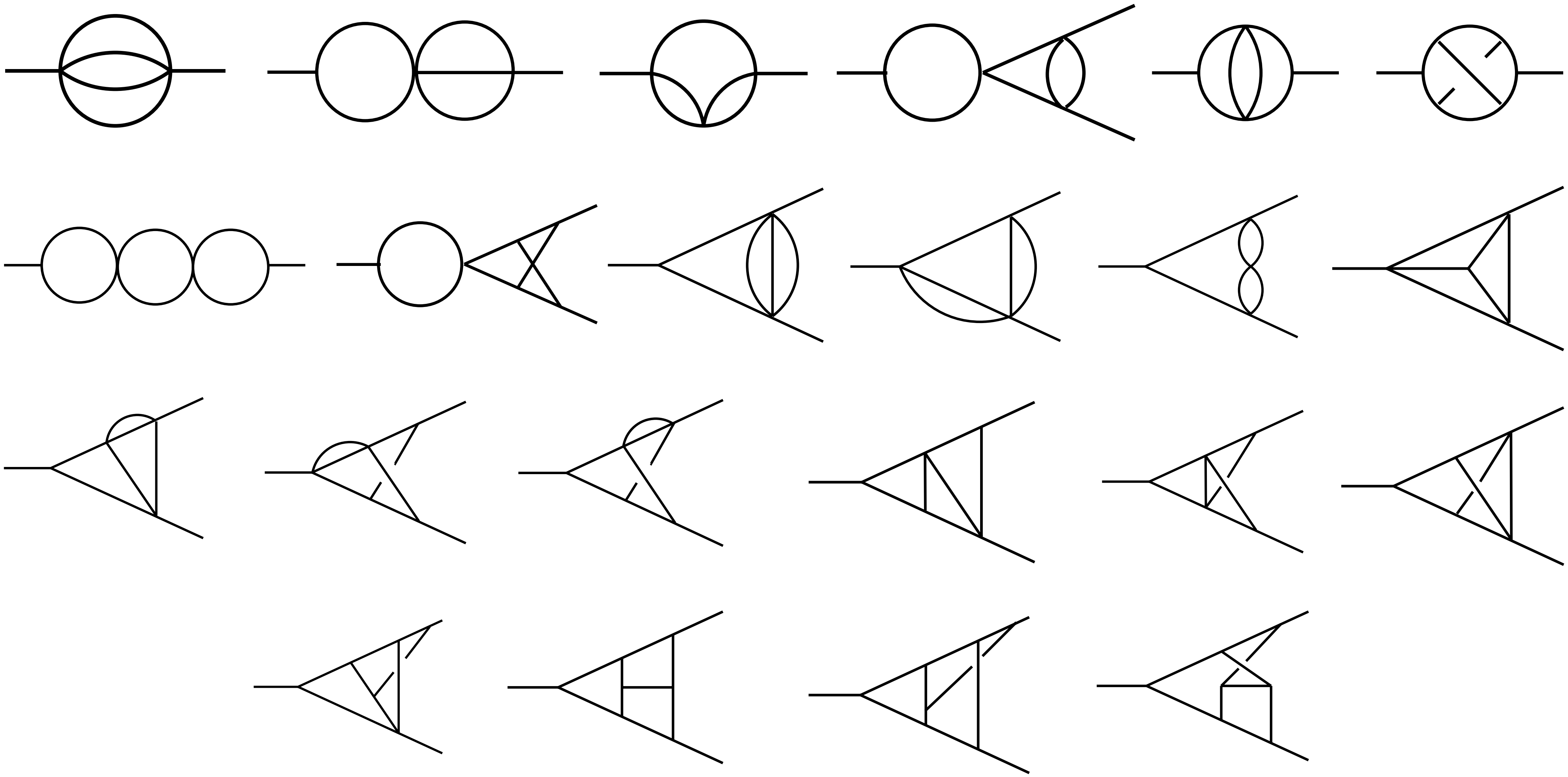
↓ IBP & LI identities

[Chetyrkin,Tkachov; Gehrmann, Remeddy]

22 Master Integrals (topologically different)

Master Integrals

[Gehrmann, Huber & Maitre '05;
Gehrmann, Heinrich, Huber & Studerus '06;
Heinrich, Huber & Maitre '08;
Heinrich, Huber, Kosower & Smirnov '09;
Lee, Smirnov & Smirnov '10]



Results

Unrenormalized 3-loop FF in power series of ϵ $(d = 4 + \epsilon)$

- Dimensional Regularization

$$d = 4 + \epsilon$$

- Coupling Constant Renorm

$$\hat{a}_s S_\epsilon = \left(\frac{\mu^2}{\mu_R^2}\right)^{\epsilon/2} Z_{a_s} a_s$$

$$Z_{a_s} = 1 + a_s \left[\frac{2}{\epsilon}\beta_0\right] + a_s^2 \left[\frac{4}{\epsilon^2}\beta_0^2 + \frac{1}{\epsilon}\beta_1\right] + a_s^3 \left[\frac{8}{\epsilon^3}\beta_0^3 + \frac{14}{3\epsilon^2}\beta_0\beta_1 + \frac{2}{3\epsilon}\beta_2\right] + \cdots$$

β_i QCD beta functions

- Overall Operator Renorm

O_G & O_J requires additional renorm

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

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

- O_G mixes under renorm
- Finite renorm Z_5^s ⟷ γ_5 prescription
- Universal IR pole structure ⟶ Z_{ij}

⟶ New methodology

Results

- 3-loop pseudo-scalar FF
- Operator renormalisation constants
- Corresponding anomalous dimensions

$$\mu_R^2 \frac{d}{d\mu_R^2} Z_{ij} \equiv \gamma_{ik} Z_{kj}$$

- Using these, we obtain renormalised FF

Most accurate results till date!

Axial Anomaly Relation

Axial Anomaly

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

↓ RG Invariance

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

Our results are in agreement with this in $\epsilon \to 0$

→ Crucial check

- Soft-virtual cross section at $\mathrm{N^3LO}$

  and

  Threshold resum cross section at $\mathrm{N^3LL}$

[TA, Kumar, Mathews, Rana & Ravindran]

- Approximate $\mathrm{N^3LO} + \mathrm{N^3LL'}$ cross section using SCET

[TA, Bonvini, Kumar, Mathews, Rottoli, Rana & Ravindran]

- For total inclusive production cross section, it is an important ingredient.

Conclusions

Most precise predictions for

1. Xsection of Higgs production in bottom annihilation
2. Rapidity of Higgs and DY pair
3. Pseudo-scalar Form Factors at 3-loop

Scale dependence is under control

These will play important role at the LHC

Thank you

ধন্যবাদ