QCD Radiative Corrections To Higgs Physics

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Feb 21, 2017
Talk to Defend My Thesis

Thesis Advisor: Prof. V. Ravindran
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
LO is a crude approximation

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

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

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

Reliable Result at $N^3LO$
This thesis arises in this context

Precise predictions in Higgs, pseudo-Higgs & DY production channels
1. Higgs Boson Production Through $b\bar{b}$ Annihilation At Threshold $N^3$LO QCD

TA, Rana & Ravindran

JHEP 1410, 139 (2014)

2. Rapidity Distribution In Drell-Yan & Higgs Productions at Threshold $N^3$LO 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 $N^3$LO and $N^3$LL QCD

TA, Kumar, Mathews, Rana & Ravindran

Eur. Phys. J. C (2016) 76:355
5. Two-Loop QCD Correction to massive spin-2 resonance → 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 → $b + \bar{b} + g$ 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 → $q\bar{q}g$
    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 $N^3LO$ in QCD
    arXiv:1505.07422 [hep-ph] TA, Das, Kumar, Mathews, Rana & Ravindran
Higgs Boson Production Through $b\bar{b}$ Annihilation At Threshold $N^3$LO QCD

$H \rightarrow b\bar{b}$

TA, Rana & Ravindran
JHEP 1410, 139 (2014)
MOTIVATIONS: $b\bar{b} \to H$

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
- 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

\[ \Delta(\zeta) = \Delta^{\text{sing}}(\zeta) + \Delta^{\text{hard}}(\zeta) \]

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

\[ z = \frac{q^2}{\hat{s}} \]

\[ \mathcal{D}_j = \left( \frac{\ln^j(1 - \zeta)}{1 - \zeta} \right)_+ \]

Leading in \( \zeta \to 1 \) (threshold limit)

\[ \Delta^{\text{hard}}(\zeta) : \text{polynomial in} \ \ln(1 - \zeta) \]

\( \Rightarrow \) sub-leading
**Motivations: SV**

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

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

\[
\Delta^{\text{sing}}(z) \equiv \Delta^{\text{SV}}(z) = \Delta^{\text{SV}}_\delta \delta(1 - z) + \sum_{j=0}^{\infty} \Delta^{\text{SV}}_j D_j
\]

*Leading in \( z \to 1 \)*

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

**Our focus**

\[
z = \frac{q^2}{\hat{s}}
\]

\[
D_j \equiv \left( \frac{\ln^j(1 - z)}{1 - z} \right)_+
\]
Goal

Existing result: NNLO and partial SV N^3\text{LO} \ [’03, ’06]

Next obvious and necessary extension

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

1. Direct evaluation of diagrams
Many methods

1. Direct evaluation of diagrams

**virtual**

- Triple virtual
- Double virtual

**real emission**

- Double virtual real
- Real virtual squared
- Double real virtual
- Triple real squared
The Prescription

Many methods

1. Direct evaluation of diagrams

2. Use factorisation, RGE & Sudakov resum
Many methods

1. Direct evaluation of diagrams

2. Use factorisation, RGE & Sudakov resum

[Diagrams of virtual and real emission processes]

Will not compute these!! Symmetry
**Master Formula**

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

with

\[
\Psi^I = \left( \ln \left[ Z^I (\hat{a}_s, \mu_R^2, \mu^2, \epsilon) \right]^2 + \ln \left| \hat{F}^I (\hat{a}_s, Q^2, \mu^2, \epsilon) \right|^2 \right) \delta (1 - z)
\]

\[
+ 2 \Phi^I (\hat{a}_s, q^2, \mu^2, z, \epsilon) - 2 \mathcal{C} \ln \Gamma_{II} (\hat{a}_s, \mu^2, \mu_F^2, z, \epsilon)
\]

Required up to $N^3\text{LO}$

- Operator renormalisation
- Form factors
- Soft-collinear distribution
- Mass factorisation kernel
\[ \Delta^{SV,I} (z, q^2, \mu_R^2, \mu_F^2) = C \exp \left( \Psi^I (z, q^2, \mu_R^2, \mu_F^2, \epsilon) \right) \bigg|_{\epsilon=0} \]

with

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

Recently computed

[Gehrmann, Kara '14]

Recently computed

[TA, Mahakhud, Rana, Ravindran '14]

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

Real emission diagrams $gg \rightarrow H \Leftrightarrow$ Real emission diagrams $b\bar{b} \rightarrow H$

$\Phi\big|_{gg \rightarrow H} = \frac{CA}{CF} \Phi\big|_{b\bar{b} \rightarrow H}$

- Established up to NNLO
- We postulated the relation even at $N^3$LO
- Verified in case of Drell-Yan

[Form Factors & Soft-Collinear Distr]

[Gerkmann, Kara '14]

[Soft-Collinear Distr]

[Ravindran '06]

[TA, Mahakhud, Rana, Ravindran '14]

[Catani et. al., von Monteuffel et. al. '14]
RESULTS

Analytical results at $N^3$LO

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

LHC13

Most accurate result till date!
Rapidity Distribution In Drell-Yan & Higgs Productions at Threshold $\text{N}^3\text{LO QCD}$

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
**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**

  - **Differential rapidity distributions:** important observable
  - **Will be measured at the LHC**
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

  • Differential rapidity distributions: important observable
  • Will be measured at the LHC

• Call for more precise theoretical results
• Going beyond LO: challenging
• Often fail to compute complete fixed order result
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• Call for more precise theoretical results
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Catch dominant contributions through SV approx
Rapidity Distribution

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

\[ \Delta_Y^{\text{SV}} = \Delta_Y^{\text{SV}} \big|_{\delta \delta (1-z_1) \delta (1-z_2)} + \sum_{j=0}^{2j-1} \Delta_Y^{\text{SV}} |_{\delta D_j \delta (1-z_2) D_j} \]

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

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

\[ \Delta_Y^{\text{hard}}(z_1, z_2): \text{polynomial in } \ln(1-z_i) \]

\[ Y = \frac{1}{2} \log \left( \frac{x_1^0}{x_2^0} \right) \quad \tau \equiv x_1^0 x_2^0 \]

\[ z_i = \frac{x_i^0}{x_i} \]
GOAL

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

Next obvious and necessary extension

SV corrections to rapidity for
1. Higgs in \( gg \rightarrow H \)
2. Leptonic pair in DY

at \( N^3LO \) QCD
Many methods

1. Direct evaluation of diagrams
THE PRESCRIPTION

Many methods

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virtual

real emission

Triple virtual

Double virtual

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Many methods

1. Direct evaluation of diagrams
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Virtual

Real emission

Will not compute these!!

Symmetry
\[ \Delta_{Y}^{\text{SM}}(z_1, z_2, q^2, \mu_R^2, \mu_F^2) = C \exp \left( \Psi_Y (z_1, z_2, q^2, \mu_R^2, \mu_F^2, \epsilon) \right) \bigg|_{\epsilon=0} \]

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

**Master Formula**

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

Required up to \( N^3\text{LO} \)
\[ \Delta_{Y}^{\text{SM}}(z_1, z_2, q^2, \mu_R^2, \mu_F^2) = \mathcal{C} \exp \left( \Psi_Y \left( z_1, z_2, q^2, \mu_R^2, \mu_F^2, \epsilon \right) \right) \bigg|_{\epsilon=0} \]

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

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

Unavailable
**Soft-Collinear Distribution**

- Demanding finiteness of rapidity & RG invariance
  
  **poles of SCD**

- Determining finite part
  
  **requires explicit computations**

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

- SCD for Xsection is used to obtain $\Phi_Y$ at $N^3LO$

  [Ravindran, van Neerven, Smith]

  [TA, Mandal, Rana, Ravindran]
RESULTS

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

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

Numerical Impacts for Higgs

| $\delta\delta$ | $\delta D_0$ | $\delta D_1$ | $\delta D_2$ | $\delta D_3$ | $\delta D_4$ | $\delta D_5$ | $D_0 D_0$ | $D_0 D_1$ |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|-----------|-----------|
| %              | 73.3        | 16.0        | 9.1         | 31.4        | 1.0         | -9.9        | -23.1     | -13.7     | -10.7     |

| $D_0 D_2$ | $D_0 D_3$ | $D_0 D_4$ | $D_1 D_1$ | $D_0 D_2$ | $D_1 D_2$ | $D_0 D_3$ | $D_2 D_2$ |
|------------|------------|------------|------------|------------|------------|------------|------------|
| %          | -0.3       | 3.1        | 7.3        | -0.2       | 3.8        | 8.6        | 4.2        |

$\Delta_Y^{\text{SV}}|_{\delta\delta}$ has the largest contribution!
Most accurate results till date!

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

- **MSSM** has richer Higgs sector
  - 5 physical Higgs bosons
    - \( h, H : \text{CP even} \)
    - \( A : \text{CP odd} \)
  - neutral \( h, H, A \)
  - charged \( H^\pm \)

- 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 $N^3\text{LO}$ QCD

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

**CP odd**

Inclusive production cross section at $\text{NNLO}$ 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 $N^3\text{LO}$
**GOAL**

CP even

Inclusive production cross section at $N^3\text{LO }\text{QCD}$

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

CP odd

Inclusive production cross section at $\text{NNLO }\text{QCD}$

[Harlander, Kilgore; Anastasiou, Melnikov]

What is next?

Go beyond $\text{NNLO}$ for CP odd!

requires

1. Virtual correction at 3-loop

2. Real corrections at $N^3\text{LO}$

Our GOAL
**Effective Lagrangian**

**Original Theory**

Pseudo scalar couples to quarks through **Yukawa**

**Effective Theory**

Simplifications occur if $m_A << 2m_t$

Effective theory by int out top loop

Massless QCD

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

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

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

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

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

[Chetyrkin, Kniehl, Steinhauser and Bardeen]
Feynman Diagrams

Qgraf

1586

447

244

400

type

type

type

type

[P. Nogueira]
**γ5 Prescription**

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

in-house codes

- What about $\gamma_5 \text{ & } \varepsilon_{\mu\nu\rho\sigma}$?

  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]

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

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

Results

Unrenormalized 3-loop FF in power series of $\epsilon$ ($d = 4 + \epsilon$)
**Coupling Constant Renorm**

- **Dimensional Regularization**

\[ d = 4 + \epsilon \]

- **Coupling Constant Renorm**

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

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

\[ \beta_i \text{ QCD beta functions} \]
**Operator Renorm**

- **Overall Operator Renorm**

\[ O_G \ & \ O_J \text{ requires additional renorm} \]

\[
\begin{align*}
[O_G]_R &= Z_{GG} [O_G]_B + Z_{GJ} [O_J]_B \\
[O_J]_R &= Z_5^s Z_{MS}^s [O_J]_B
\end{align*}
\]

- **\( O_G \) mixes under renorm**
- **Finite renorm** \( Z_5^s \) \( \leftrightarrow \) \( \gamma_5 \) prescription
- **Universal IR pole structure** \( Z_{ij} \)
- **New methodology**
Results

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

\[ \mu^2 R \frac{d}{d\mu^2} Z_{ij} \equiv \gamma_{ik} Z_{kj} \]

- Using these, we obtain renormalised FF

Most accurate results till date!
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
Applications

- Soft-virtual cross section at $N^3\text{LO}$ and Threshold resum cross section at $N^3\text{LL}$
  
  [TA, Kumar, Mathews, Rana & Ravindran]

- Approximate $N^3\text{LO} + N^3\text{LL}'$ 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