Di-Scalar production in $q\bar{q}$ annihilation at 2-loops in perturbative QCD

Surabhi Tiwari

The Institute of Mathematical Sciences, India
In collaboration with: Taushif Ahmed, V. Ravindran and Aparna Sankar

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Motivation

- Precision study at Standard Model (SM) and exploring physics beyond the SM (BSM)
- To better understand the Higgs Sector, the shape of the potential and the electroweak symmetry breaking mechanism
- Form of the Higgs potential plays an important part
- Independent measurements on Higgs trilinear and quartic couplings become essential
- At the LHC measuring the quartic coupling via triple Higgs production is very hard
- Higgs trilinear coupling can be probed via di-higgs boson production at high luminosities
- Future hadron colliders will increase the importance of such processes

Higgs Sector

- Thanks to large amounts of high precision data, available from two runs at the LHC

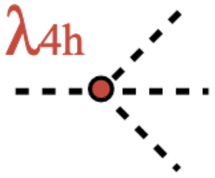
  Precise measurements of mass of the Higgs and its spin properties are possible

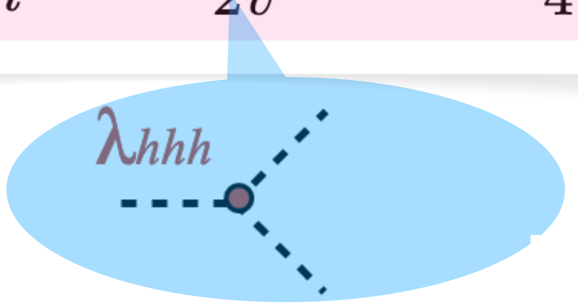
  Independent measurement of self coupling to be probed to understand EWSB

- Higgs potential:

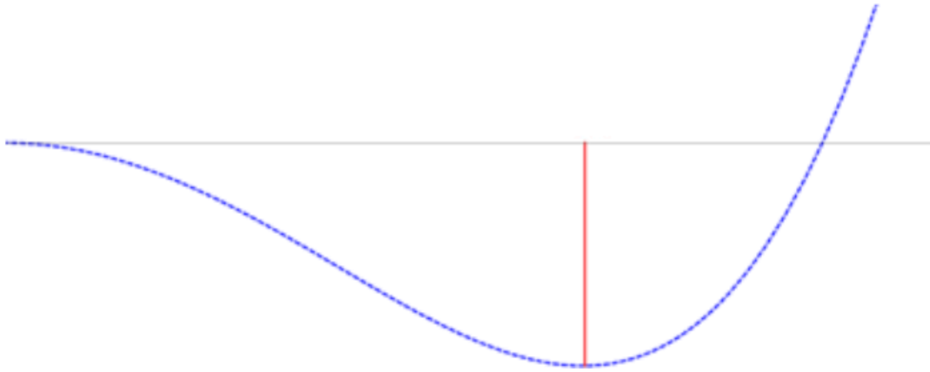
$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

$$= V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4$$





Measure shape of the potential through these coupling



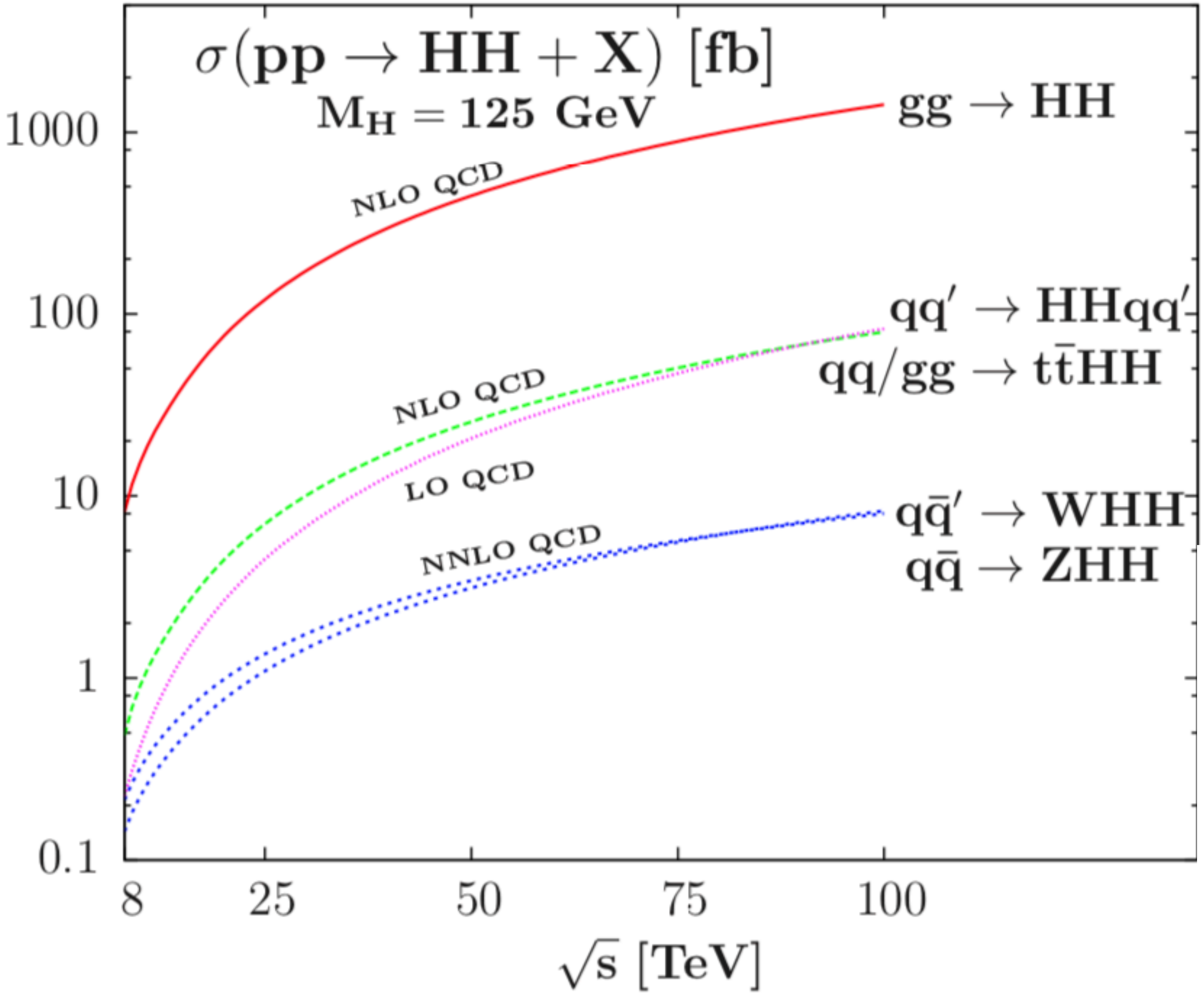
Di-Higgs production

[Boudjema, Chopin]

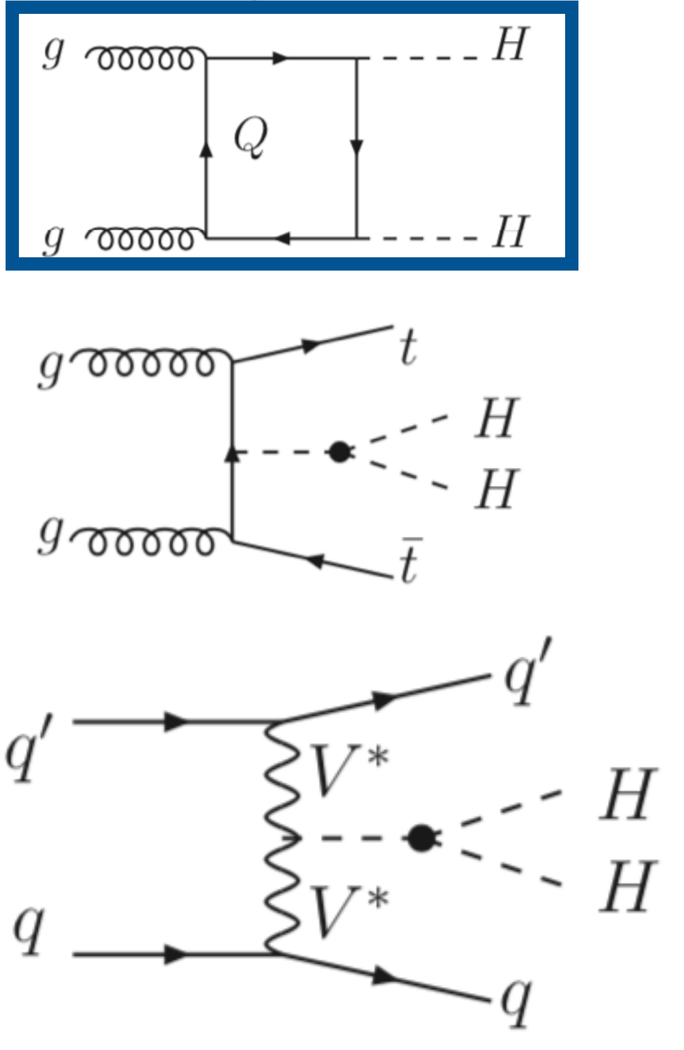
[Asakawa, Harada, Kanemura]

[Osland, Pandita]

- Triple Higgs production sensitive to trilinear coupling
- Xsecn ~$\mathcal{O}(\text{ab})$ Not feasible at the LHC at present!
- Possible with high luminosities, Xsecn~ $\mathcal{O}(\text{fb})$
- Still small: Xsecn ~1000 times smaller than single Higgs



[Baglio et. al.]



Developments

- **gg -> HH :** calculation with top mass effect has been achieved till NLO

  A. Xsection is ~14% less than born improved HEFT($\sqrt{s} = 13\,\mathrm{TeV}$)

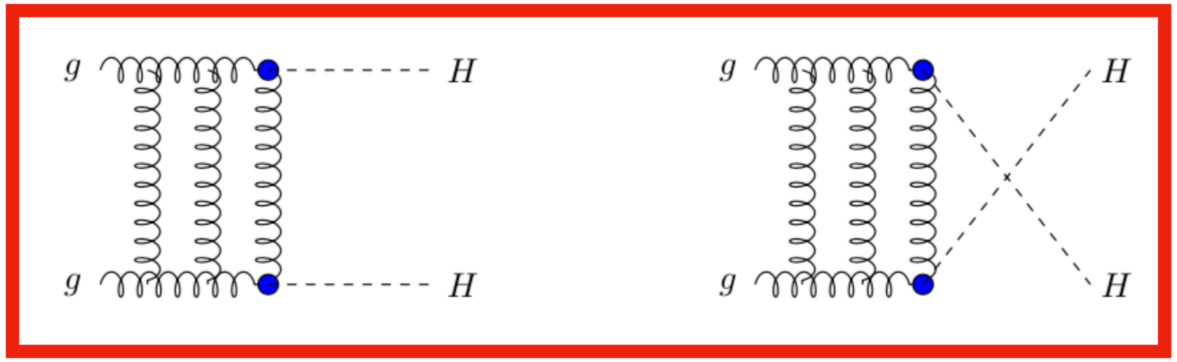
  B. NLO top mass effects ~ -15%

  C. Top mass scheme uncertainties $\lesssim$ 30%

S. Borowka et al.,
J. Baglio et al.,
J. Davies et al.

- Going beyond NLO with top mass effects is very hard
- **Alternate approach - Effective Field Theory**

Banerjee, Borowka, Dhani, TGehrmann, Ravindran

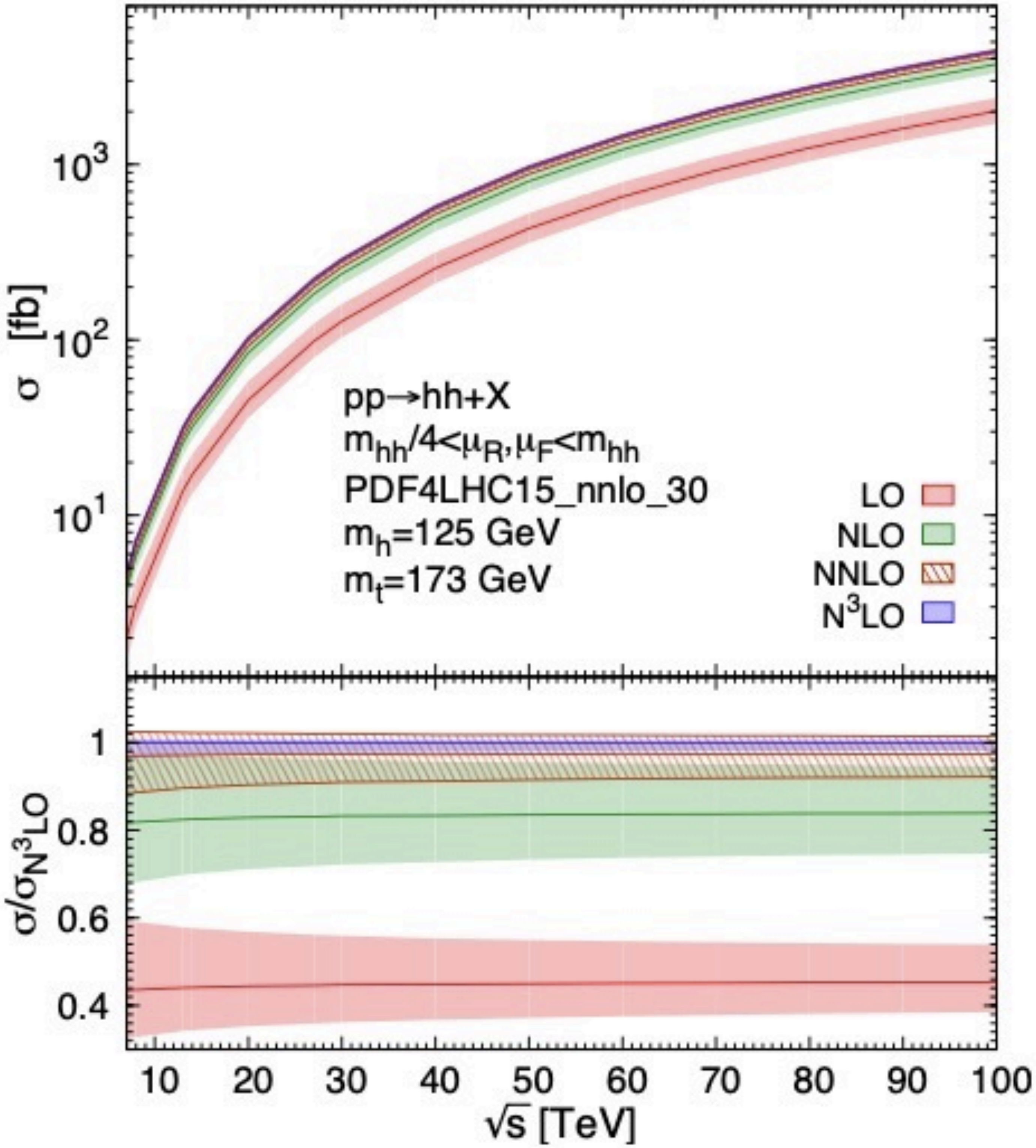


- Calculations done in the infinite top-quark mass limit till N^3LO for $g + g \rightarrow H + H$

Chen, Hai Tao, Hua-Sheng, Wang

State of the Art! at N3LO

- $g + g \to H + H$ at N^3LO in QCD in EFT



Chen, Hai Tao, Hua-Sheng, Wang

Improvements

- Soft gluon resummation at NNLL

[Shao, Li, Li, Wang]
[de Florian, Mazzitelli]

[Q.Li, Q.-S. Yan, X. Zhao]

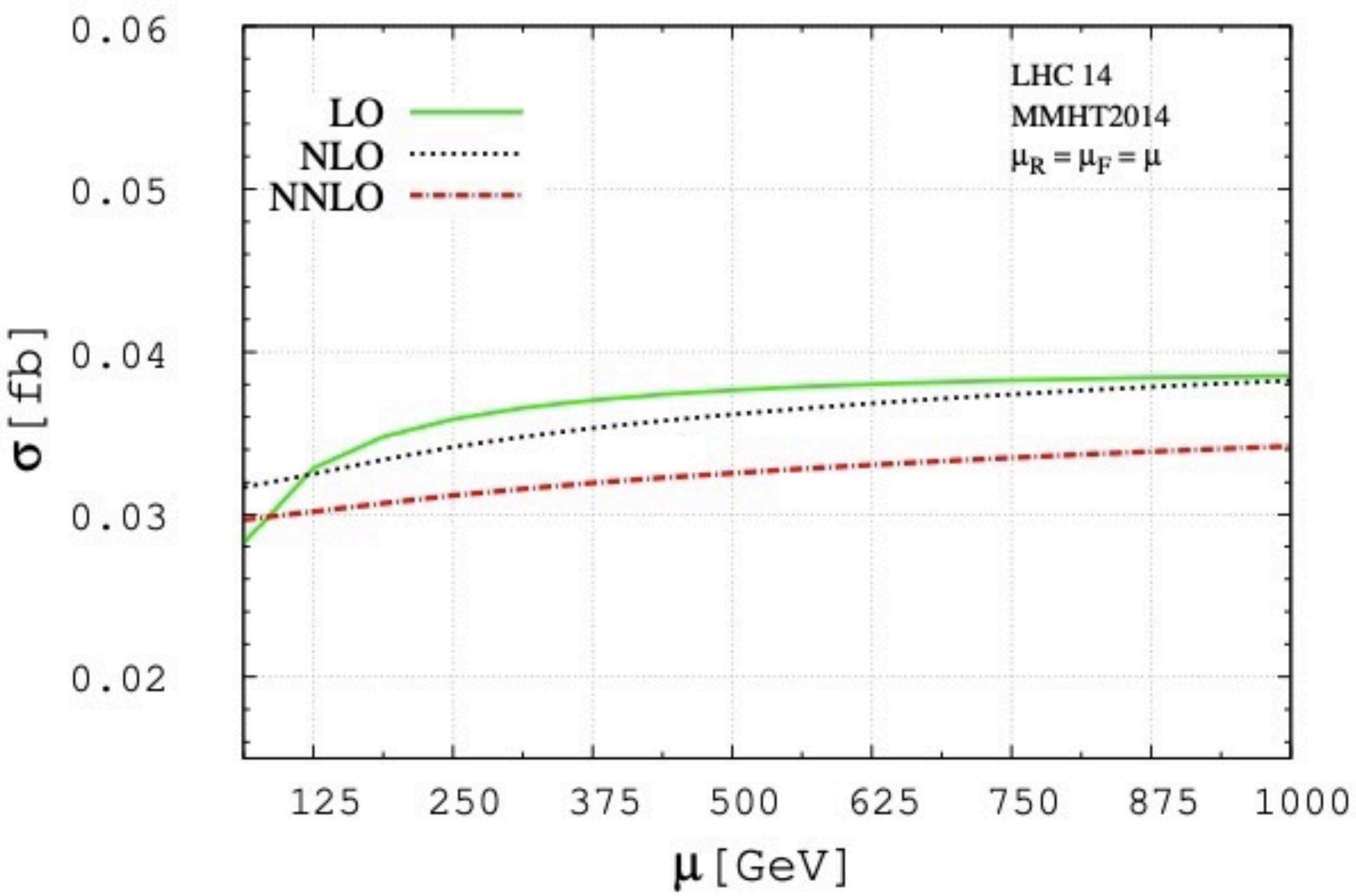
- Differential Distribution

[Maierhofer, Papaefstathiou]

- Inclusion of sub-leading partonic channels b+B -> HH (Important in MSSM)

- $b + \bar{b} \rightarrow H + H$ at NNLO

Ajjath, Ahmed ,Dhani, Banerjee, Mukherjee, Ravindran



Goal of present work

- A lot of work has been done in past two decades on $g+g \to H+H$ and $b+\bar{b} \to H+H$
- We are in the era of 'Ultra-Precision' so we want to quantify even the smaller contributions
- Sub-leading channels do play important role in some kinematic regions

Light Quark contributions to Di-Higgs in EFT

$$q+\bar{q} \to H+H$$

- Role of light quarks in other production channels:

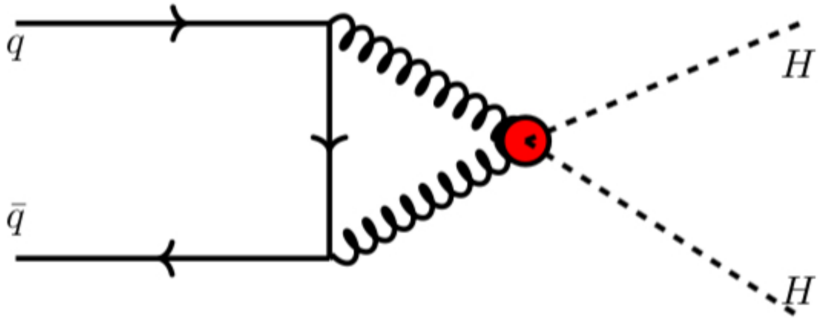
$q+\bar{q} \to A+A$ and $q+\bar{q} \to H+A$

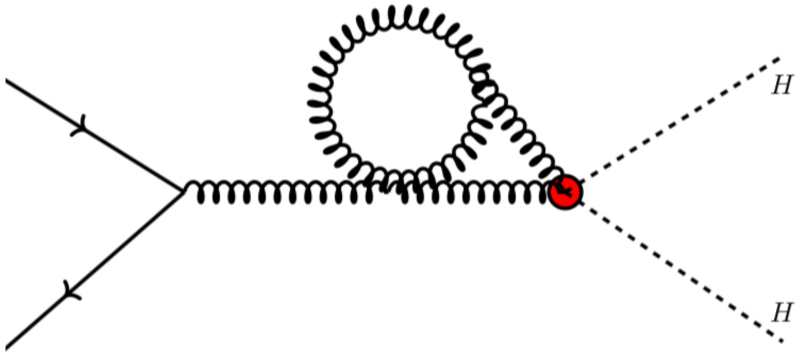
WHAT WE COMPUTE…

- Diagrams : In EFT (large top limit) in powers of a_s

• LO **• NLO**

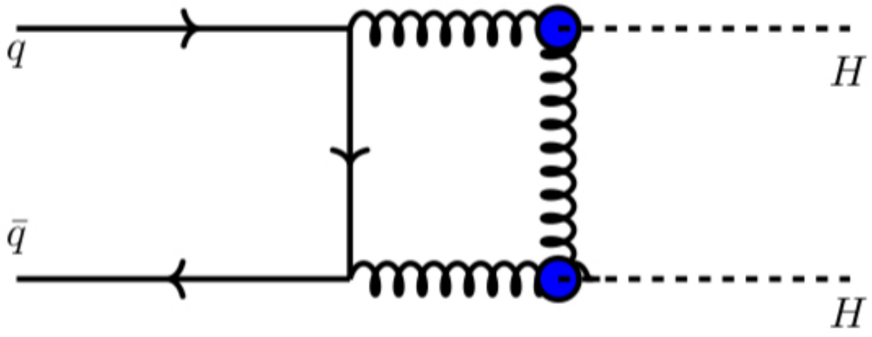
- Class A

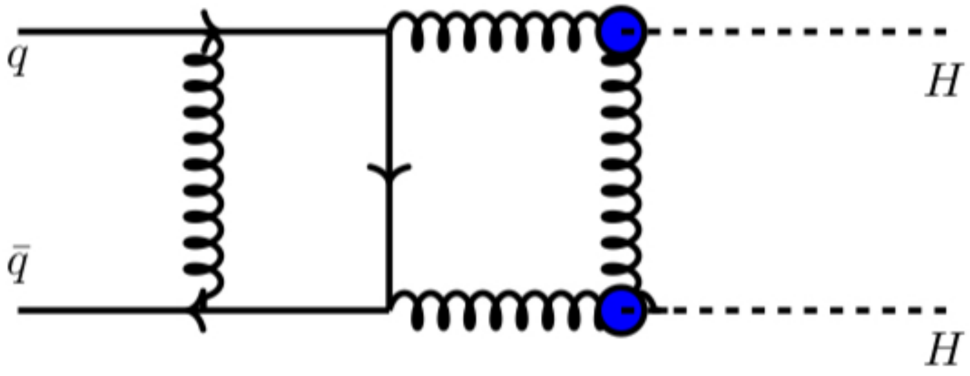




Contains diagrams proportional to C_{HH}

- Class B



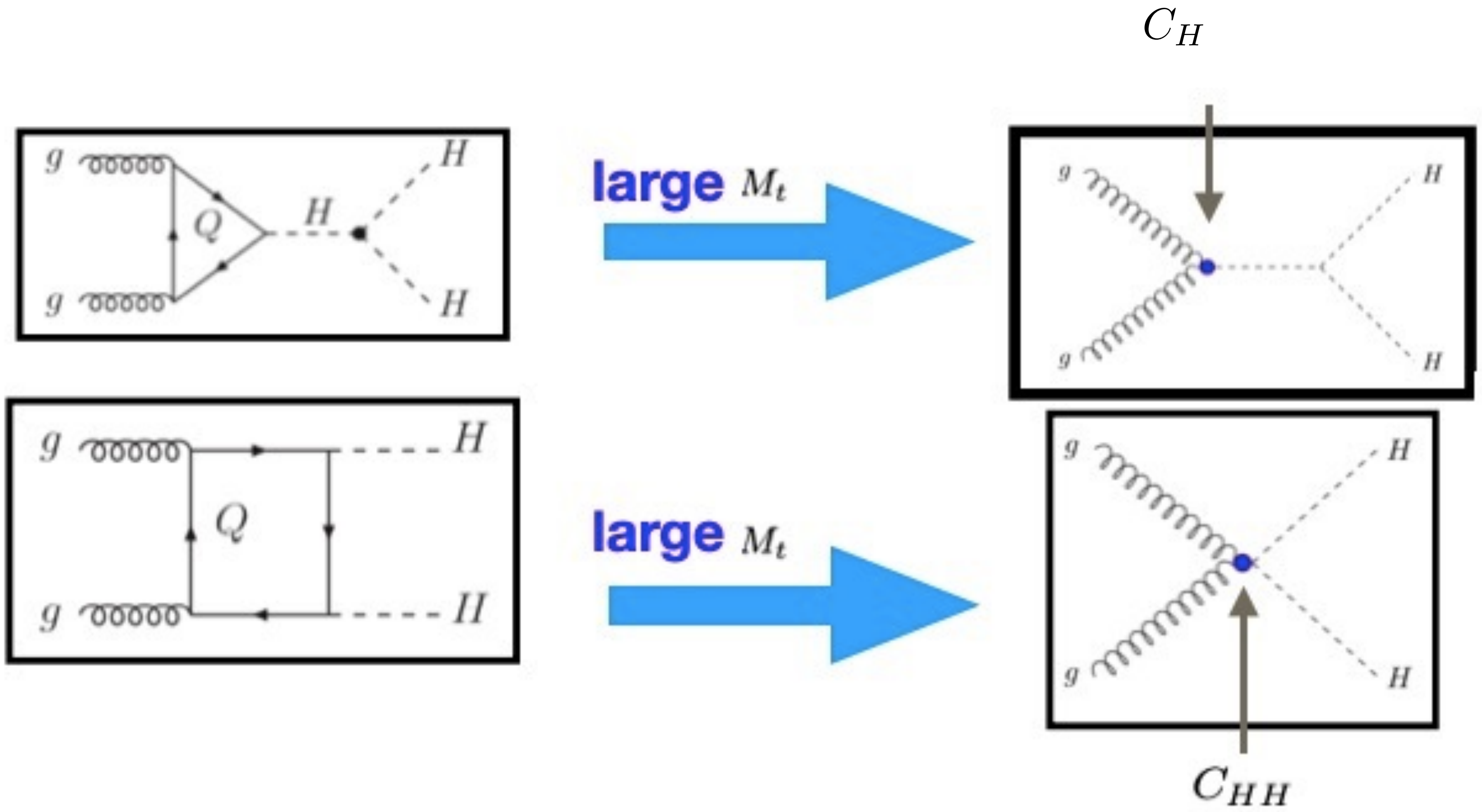


Contains diagrams proportional to C_H^2

OUR COMPUTATION !

WHAT WE COMPUTE…

- We work in effective field theory where large M_t limit (EFT)



- Class A diagrams give zero contribution to all orders!

- Higgs trilinear coupling diagrams included in Class A are zero

- Only Class B diagrams give non-zero contribution

Matching Coefficients in EFT

- Wilson coefficients C_H and C_{HH} determined by matching the effective theory to full theory, are given as,

$$\begin{aligned}
C_H(a_s) = -\frac{4a_s}{3}\Bigg[&1 + a_s\Big(11\Big) \\
&+a_s^2\left(\left\{\frac{2777}{18} + 19\log\left(\frac{\mu_R^2}{m_t^2}\right)\right\} + n_f\left\{-\frac{67}{6} + \frac{16}{3}\log\left(\frac{\mu_R^2}{m_t^2}\right)\right\}\right) \\
&+a_s^3\left(-\frac{2892659}{648} + \frac{3466}{9}\log\left(\frac{\mu_R^2}{m_t^2}\right) + 209\log^2\left(\frac{\mu_R^2}{m_t^2}\right) + \frac{897943}{144}\zeta_3\right. \\
&+n_f\left\{\frac{40291}{324} + \frac{1760}{27}\log\left(\frac{\mu_R^2}{m_t^2}\right) + 46\log^2\left(\frac{\mu_R^2}{m_t^2}\right) - \frac{110779}{216}\zeta_3\right\} \\
&\left.+n_f^2\left\{-\frac{6865}{486} + \frac{77}{27}\log\left(\frac{\mu_R^2}{m_t^2}\right) - \frac{32}{9}\log^2\left(\frac{\mu_R^2}{m_t^2}\right)\right\}\right)\Bigg], \\
C_{HH}(a_s) = -\frac{4a_s}{3}\Bigg[&1 + a_s\Big(11\Big) \\
&+a_s^2\left(\frac{3197}{18} + 19\log\left(\frac{\mu_R^2}{m_t^2}\right) + n_f\left\{-\frac{1}{2} + \frac{16}{3}\log\left(\frac{\mu_R^2}{m_t^2}\right)\right\}\right)\Bigg],
\end{aligned}$$

Computation of Class B diagrams

$$q(p_1) + \bar{q}(p_2) \to H(p_3) + H(p_4)$$

- Diagram generation by QGRAF: 5 diagrams @LO, 143 diagrams @NLO [Nogueira]

- Kinematics: $s = (p_1 + p_2)^2, \quad t = (p_1 - p_3)^2, \quad u = (p_2 - p_3)^2$

$$s + t + u = 2m_{\mathrm{h}}^2$$

$$s = m_{\mathrm{h}}^2 \frac{(1+x)^2}{x}, \quad t = -m_{\mathrm{h}}^2 y, \quad u = -m_{\mathrm{h}}^2 z.$$

- Amplitude:

$$A_{ij} = \bar{v}(p_2)\Big(C\, \not{p}_3\Big)u(p_1)\delta_{ij}$$

i,j are the incoming quarks

- The coefficients C can be determined from the amplitude A_{ij} by using appropriate projection operators

Computation of Class B diagrams

$$\mathcal{C} = \frac{1}{N} \sum \mathcal{P}(\mathcal{C}) \mathcal{A}_{ij} \delta_{ij}$$

$d = 4 + \epsilon$

- The sum includes spin, flavors and colors of the external fermions.

- N is the number of colors in $SU(N)$ gauge theory.

- The projector that satisfy $\sum P(C)T = 1,$ is found to be

$$\mathcal{P}(\mathcal{C}) = \frac{\bar{u}(p_1)\left(\not{p}_3\right)v(p_2)}{2(u\,t - m_h^4)} \qquad T = \bar{v}(p_2)\left(\not{p}_3\right)u(p_1)$$

- We expand the amplitude A_{ij} as well as the coefficient C in powers of the strong coupling constant defined by $a_s = g_s^2(\mu_R^2)/16\pi^2$

Computation of Class B diagrams

- So the task : $$\mathcal{A}_{ij}^{(l)} = \left(\mathcal{C}^{(l)}\mathcal{T}\right)\delta_{ij}$$
- Up to 2-Loop

- Complexity in computing the coefficients $\mathcal{C}^{(l)}$ becomes involved due to the number of diagrams.

● Computational Details :

- These coefficients were calculated using in-house routines in FORM.

[Vermaseren]

- At each stage, simplification was done to ensure the expressions remain compact.

- Reduze 2 : Shift propagators to transform diagrams to different basis.

[von Manteuffel, Studerus]

Computation of Class B diagrams

- Reduction of huge number of scalar Feynman integrals to Master Integrals; done independently in LiteRed and REDUZE 2.

  [Lee] **[von Manteuffel, Studerus]**

- 149 Master integrals.

- Integrals calculated for the process $q\bar{q} \to VV$

  [Gehrmann, von Manteuffel, Tancredi, Weihs] **[Gehrmann, Tancredi, Weihs]**

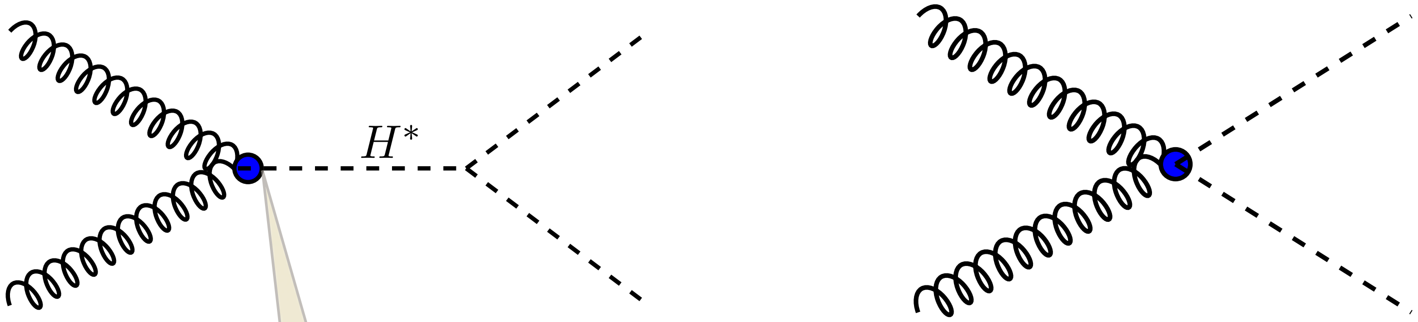
- Using the integrals, we compute the UV and IR divergent amplitudes.

UV renormalization

- Coupling constant renormalization:

$$\hat{a}_s \mu^{2\epsilon} S_\epsilon = a_s \mu_R^{2\epsilon}\left[1 - a_s\left(\frac{\beta_0}{\epsilon}\right) + a_s^2\left(\frac{\beta_0^2}{\epsilon^2} - \frac{\beta_1}{2\epsilon}\right) + \mathcal{O}(a_s^3)\right]$$

- Effective vertices

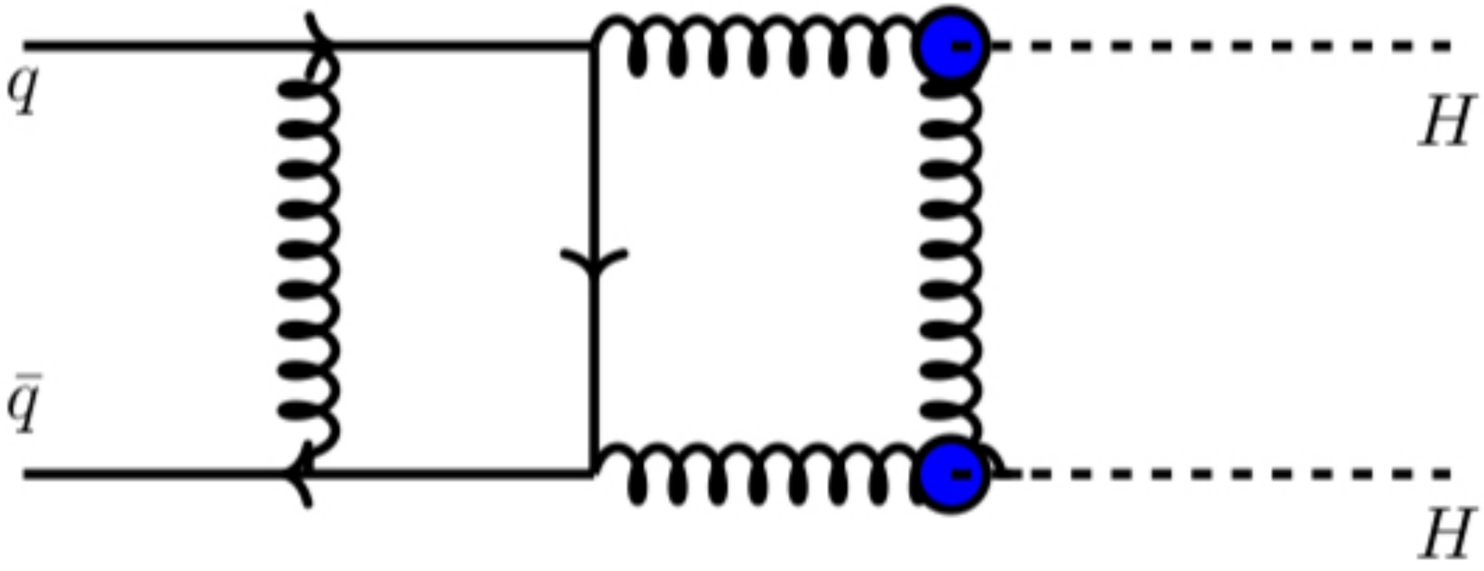


Effective vertex

Multiply overall renormalisation constant $Z_{\mathcal{O}}$

[Nielsen] [Spiridonov, Chetyrkin]
[Kataev, Krasnikov, Pivovarov]

$$Z_{\mathcal{O}} = 1 - a_s\left(\frac{1}{\epsilon}\beta_0\right) + a_s^2\left(\frac{1}{\epsilon^2}\beta_0^2 - \frac{1}{\epsilon}\beta_1\right) + \mathcal{O}(a_s^3)$$



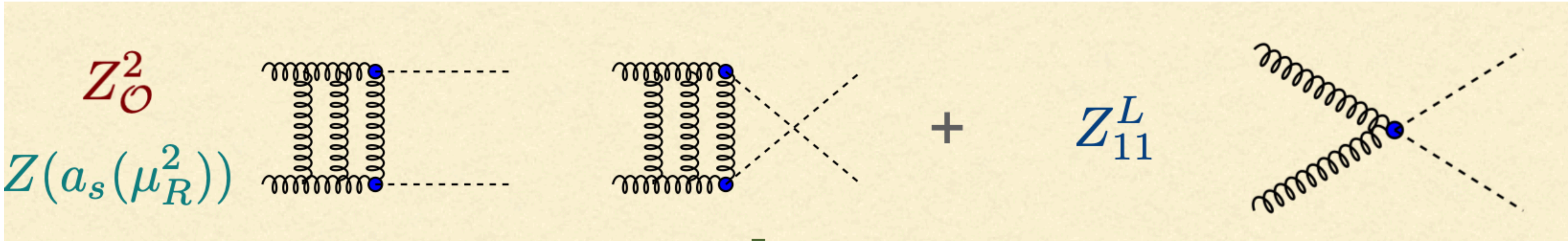
Multiply $Z_{\mathcal{O}}^2$

Operator Renormalisation

- For $gg \rightarrow HH$ it was observed that a new renormalization constant , Z^L_{11} , was required at two loop.

- Due to presence of two composite operators: $G_{\mu\nu}G^{\mu\nu}\phi$

Zoller

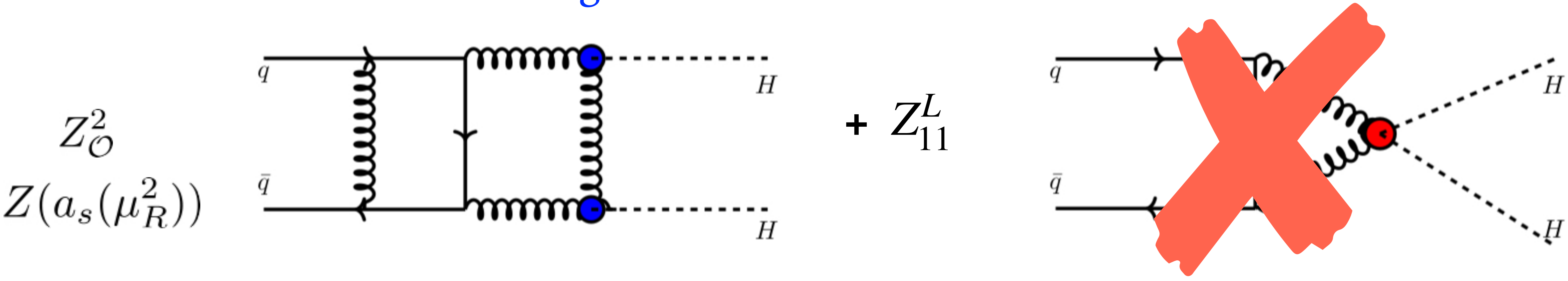


$Z^2_{\mathcal{O}}$ $Z(a_s(\mu_R^2))$ $+$ Z^L_{11}

UV finite

$$\boxed{Z^L_{11} = a_s^2 \frac{2\beta_1}{\epsilon} + \mathcal{O}(a_s^3)}$$

- For $q\bar{q} \rightarrow HH$ we observe that no additional renormalization is required due to the absence of Class A diagram.



$Z^2_{\mathcal{O}}$ $Z(a_s(\mu_R^2))$ $+$ Z^L_{11}

IR factorization

- UV finite and IR divergent projected amplitudes: [Catani]

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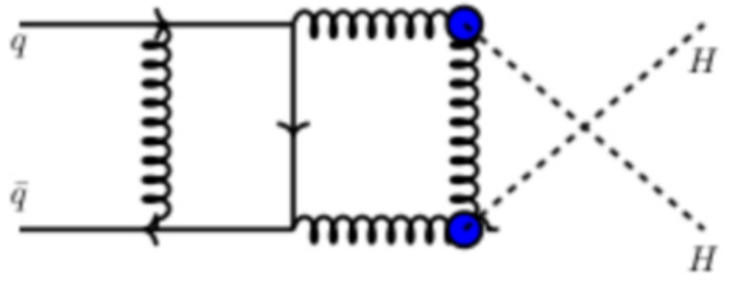

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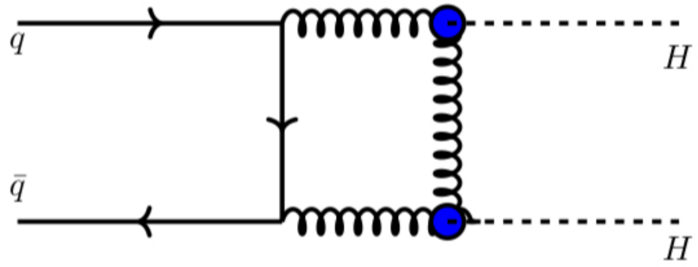
UV finite,
IR singular

= $2I_q^{(1)}(\epsilon)$



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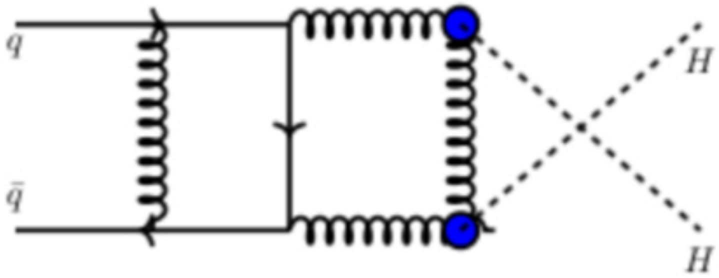

$\Bigg)$

UV finite,
IR finite

where ,

$$\mathcal{I}_q^{(1)}(\epsilon) = \frac{e^{-\frac{\epsilon}{2}\gamma_E}}{\Gamma(1+\epsilon/2)}\left(-\frac{4C_F}{\epsilon^2}+\frac{3C_F}{\epsilon}\right)\left(-\frac{s}{\mu_R^2}\right)^{\frac{\epsilon}{2}}$$

Conclusion

- We have computed light quark initiated processes at two loops amplitude in HEFT framework for HH pair production.

- This amplitude will contribute to inclusive cross sections at N3LO and differential ones at N2LO for di-Higgs production in the effective theory.

- Combine these amplitudes into fully differential calculation will require more work.

- Study of light quark initiated processes at two loops in QCD to,   A+A and A+H productions is underway

Thank You