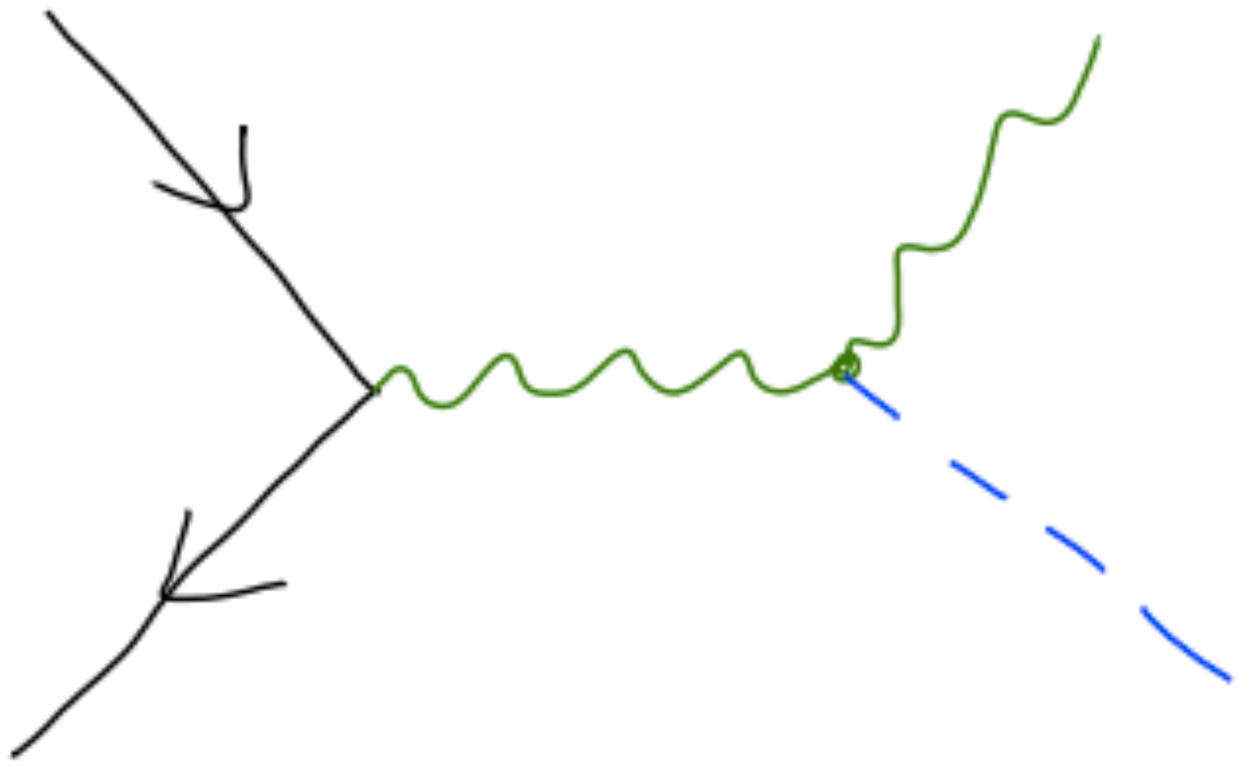
Project A1b

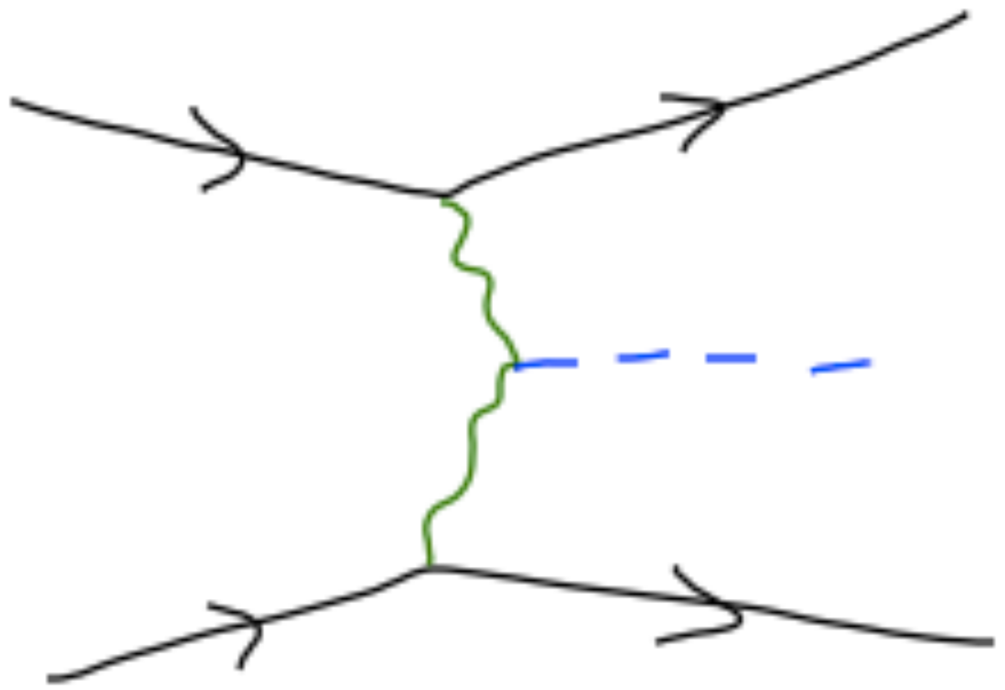
Higgs boson physics with higher order QCD corrections within the Higgs Effective Theory

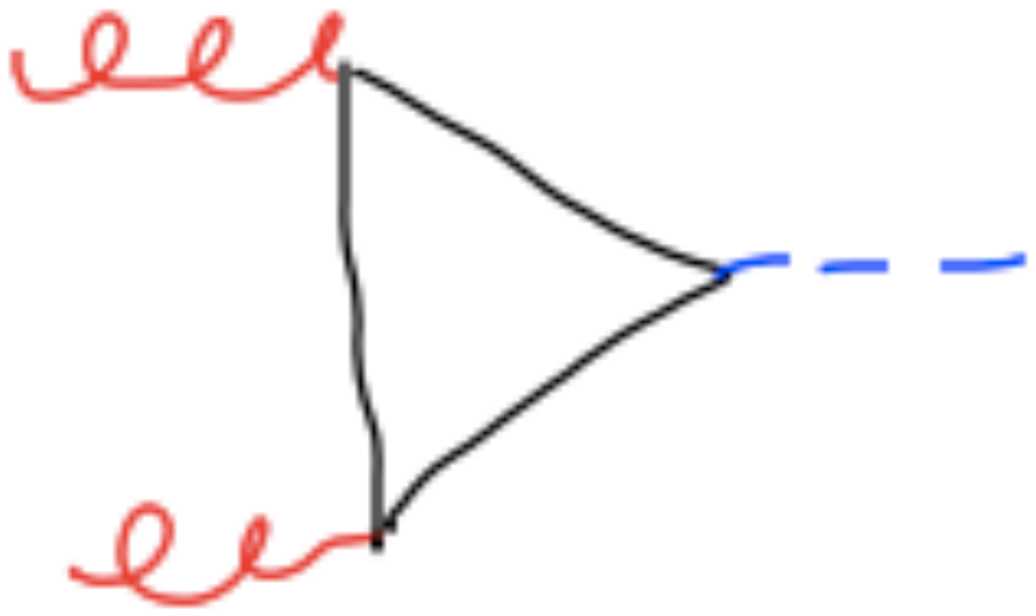
PIs: Harlander/Melnikov

Goal:

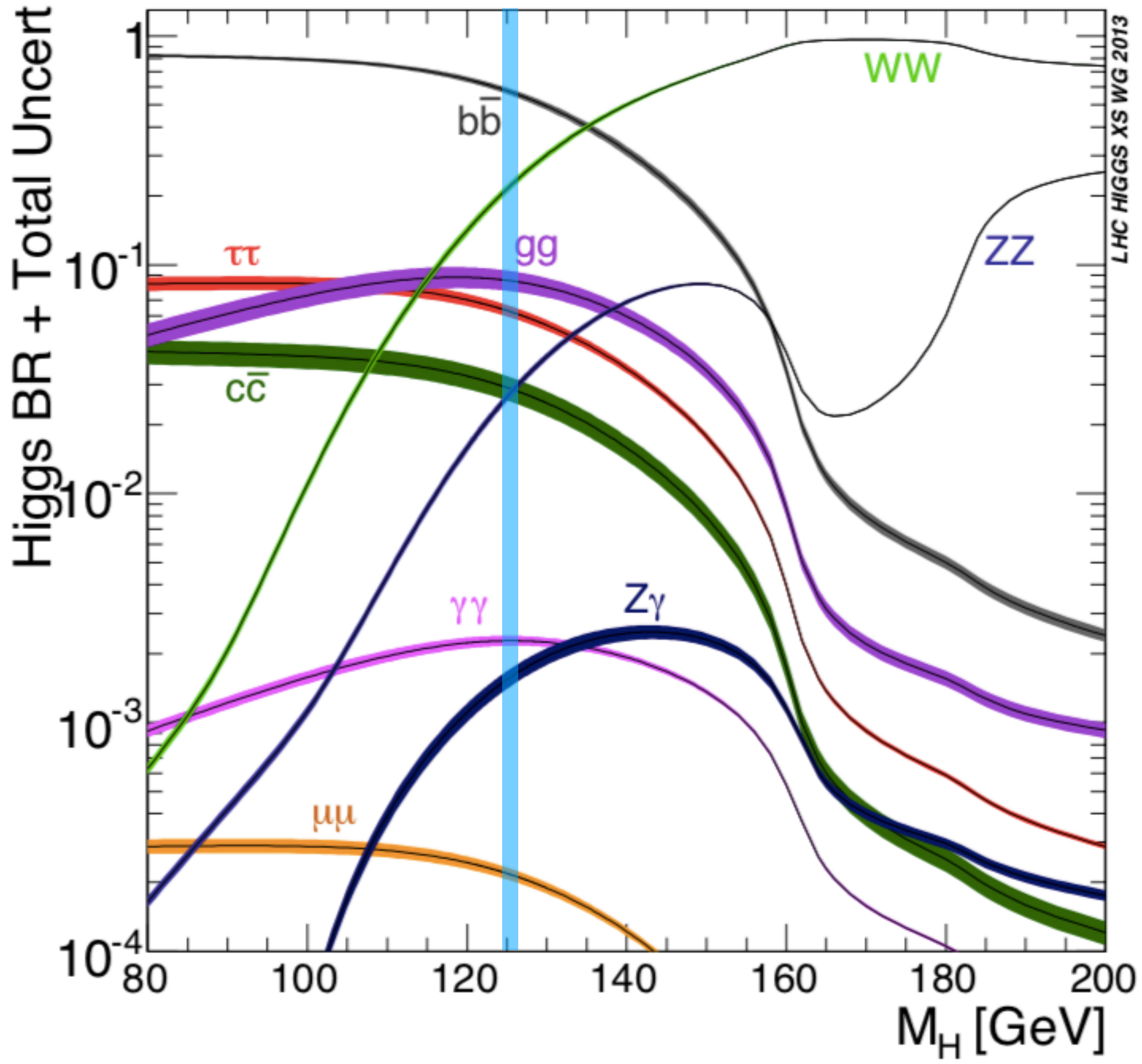
Public tool to calculate differential Higgs cross sections at NNLO QCD within SMEFT.

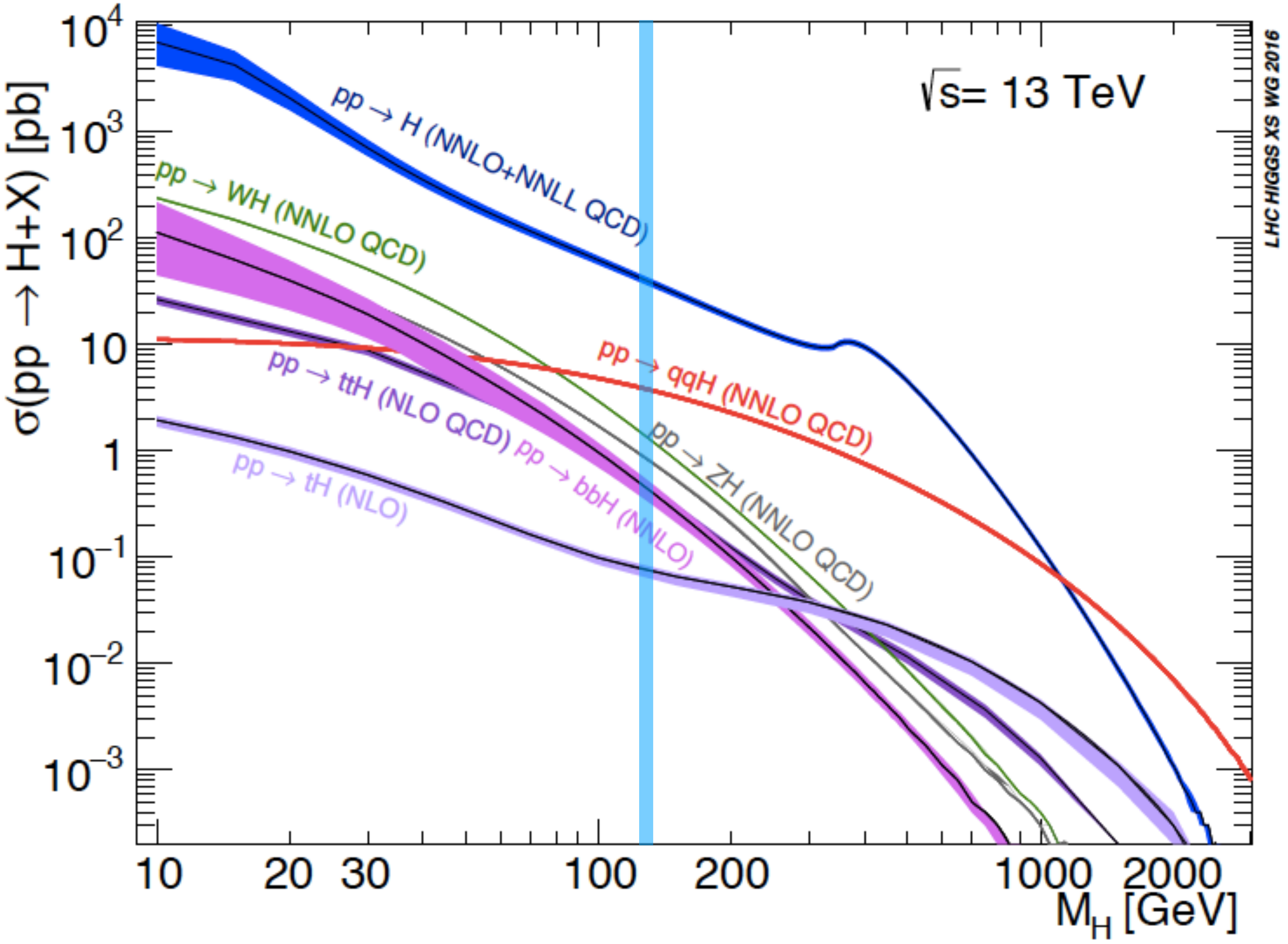




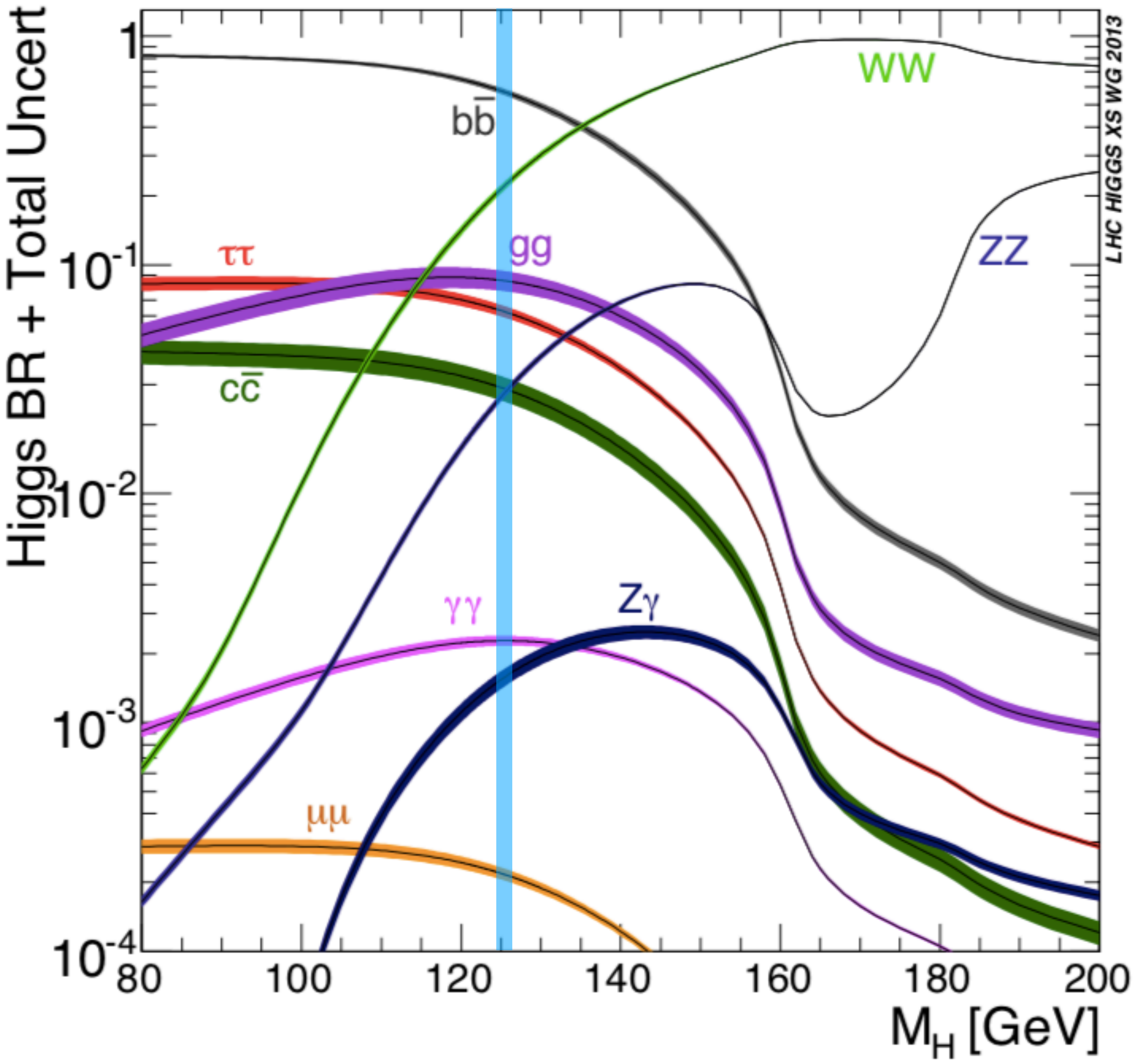


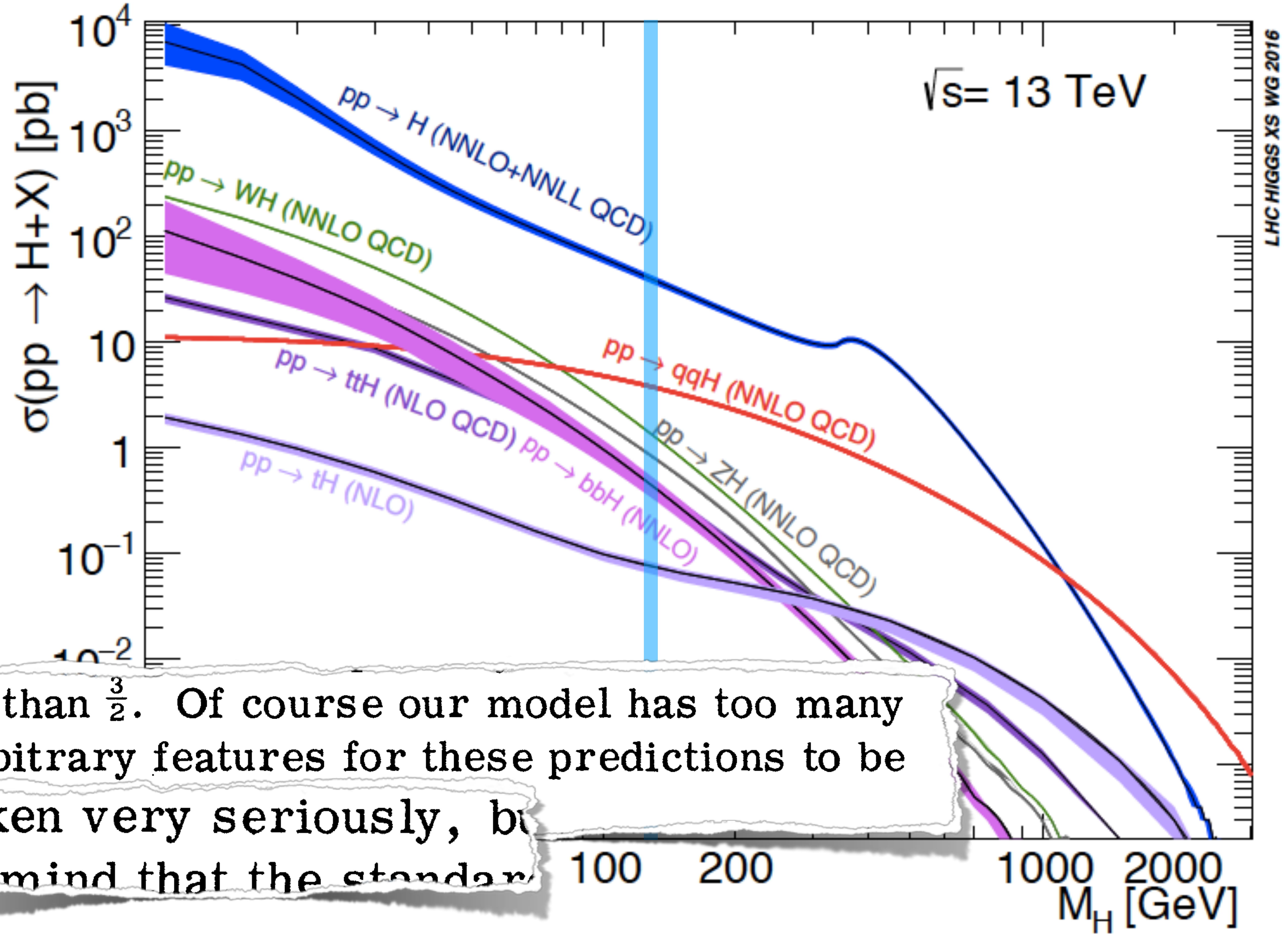
Plenty of options to study the Higgs





Plenty of options to study the Higgs



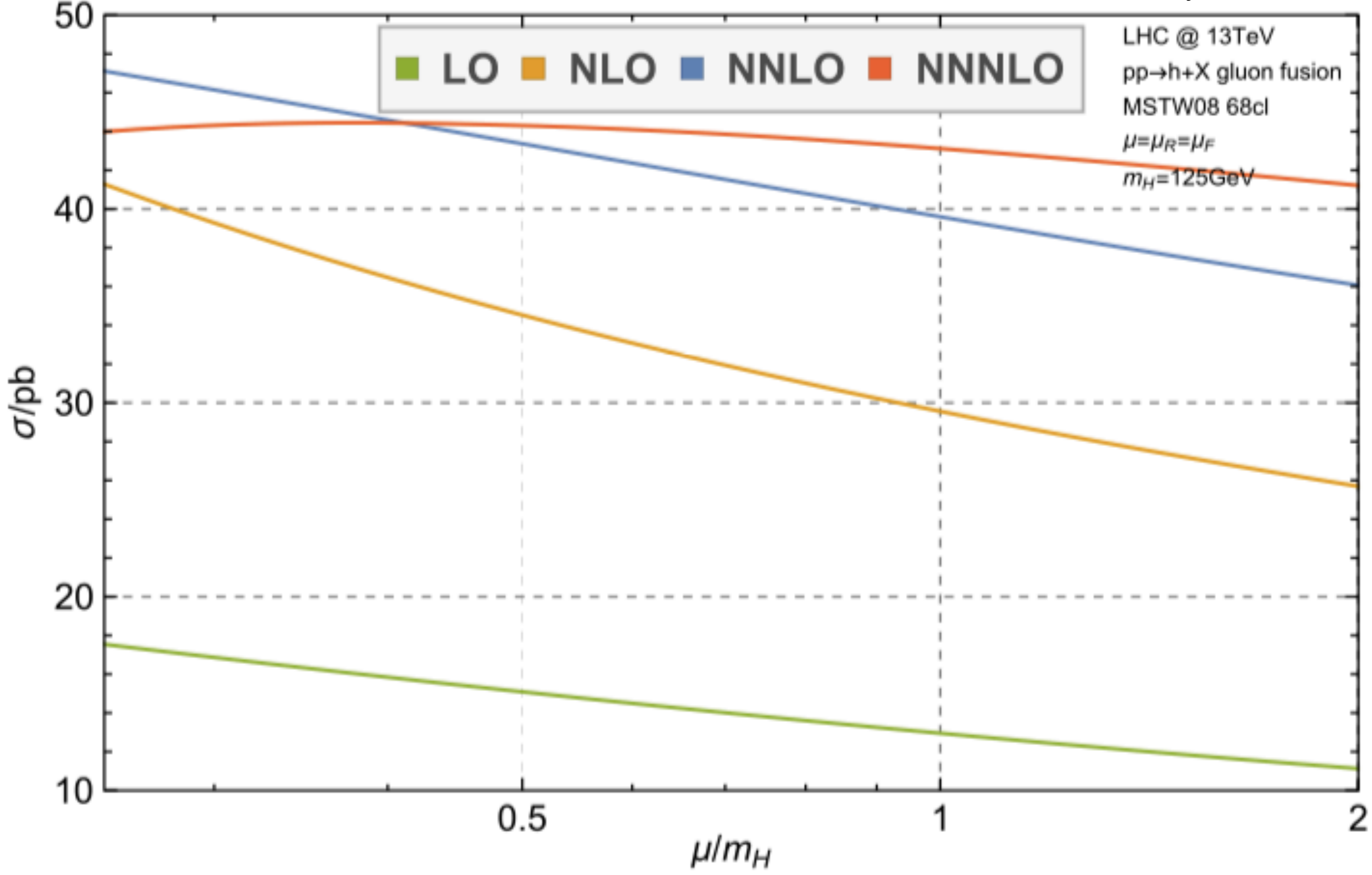


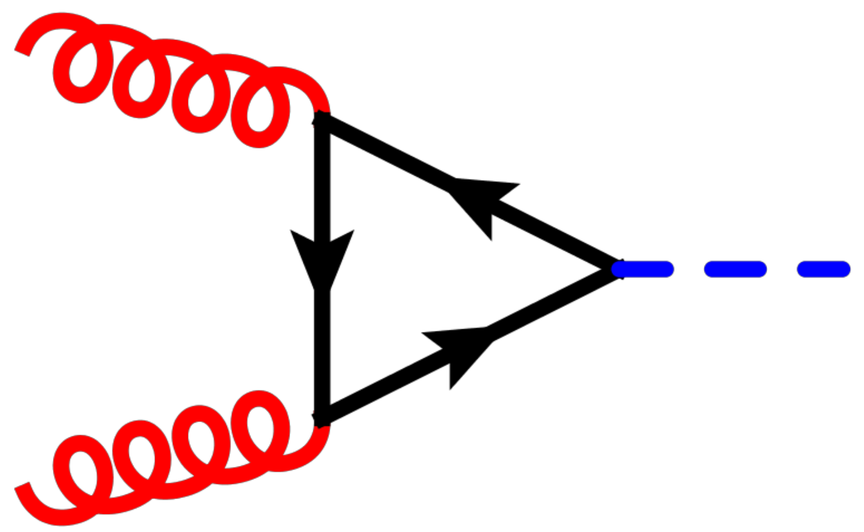
er than $\frac{3}{2}$. Of course our model has too many arbitrary features for these predictions to be taken very seriously, bu
in mind that the standar

S. Weinberg '67

Radiative corrections can be large

$m_t \to \infty$





Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger '14

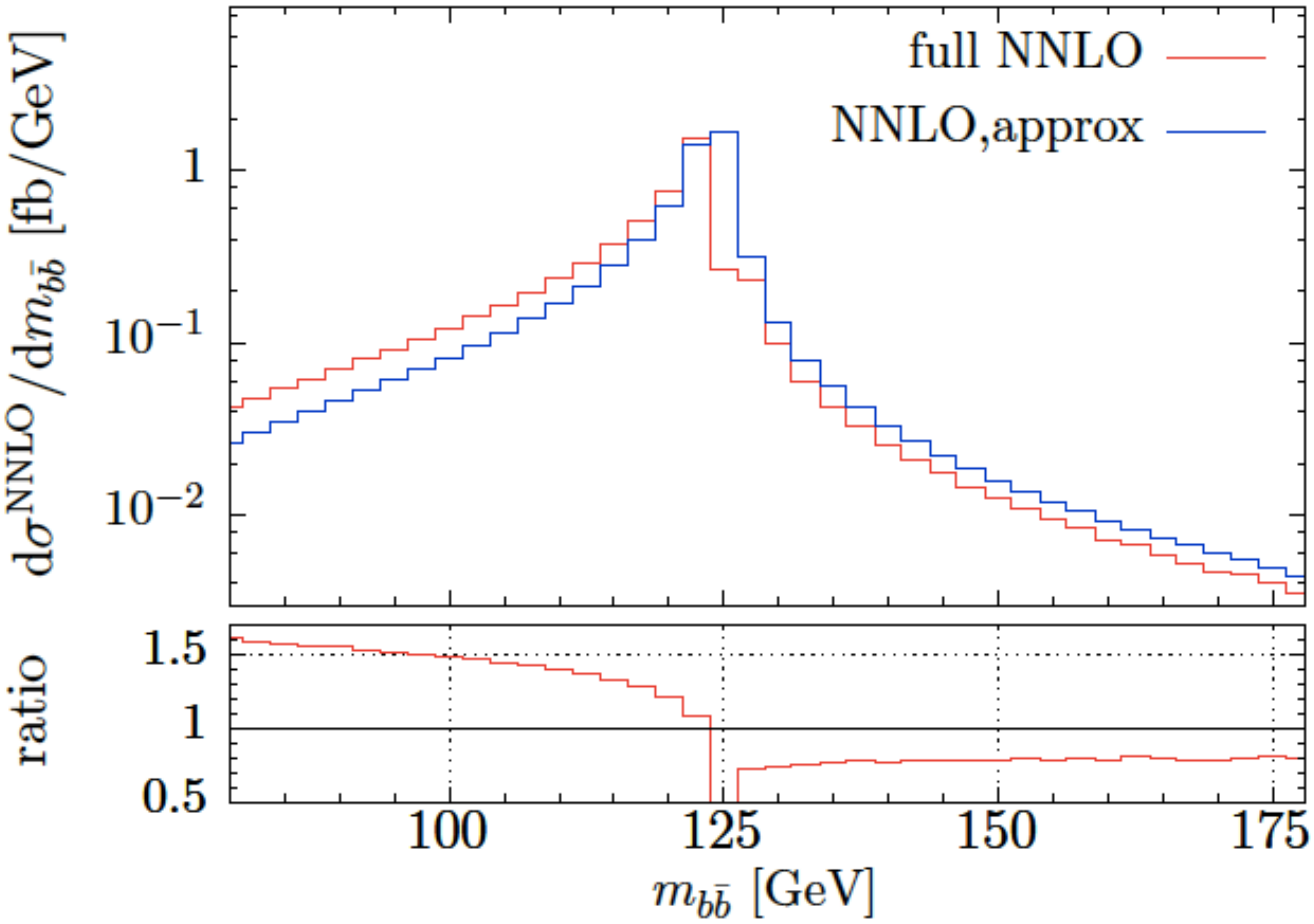
Find deviations from SM@NNLO: New Physics.

Framework for New Physics analysis: SMEFT

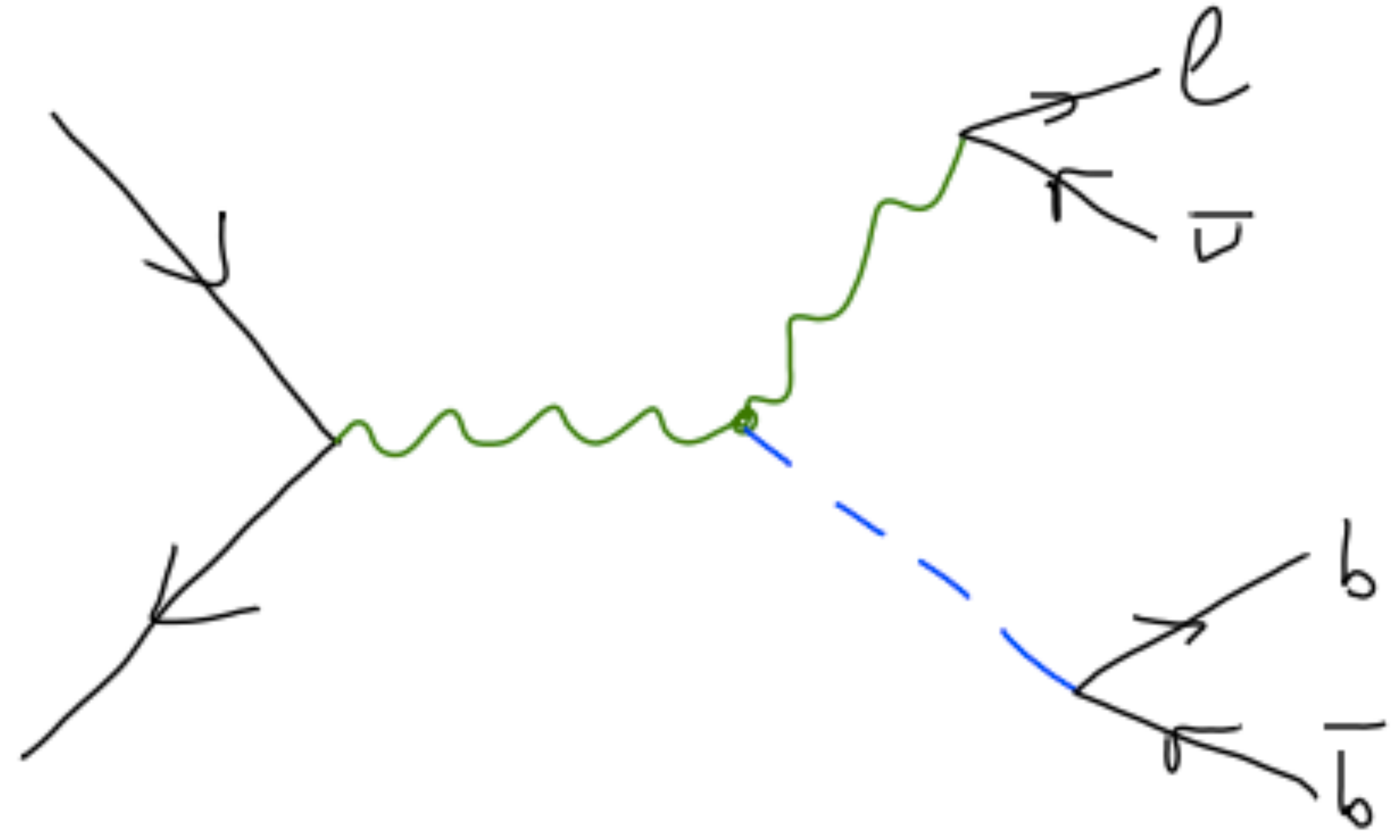
$$\mathscr{L} = \mathscr{L}_{SM} + \sum_x \frac{f_x}{\Lambda^2}\mathscr{O}_x^{(6)} + \ldots$$

Proper analysis requires inclusion of radiative corrections: SMEFT@NNLO.
We restrict ourselves to QCD.

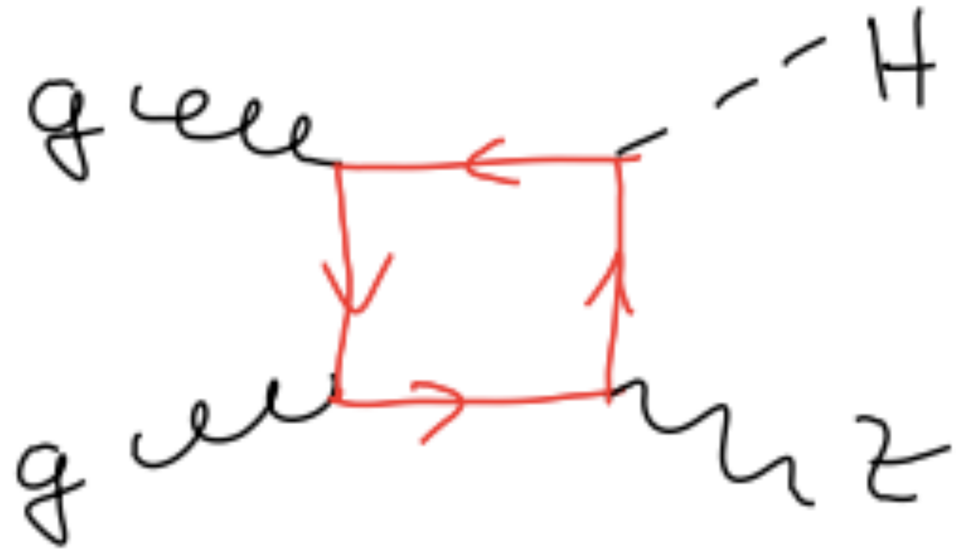
In A1b, we start with the simplest case: *HW* production

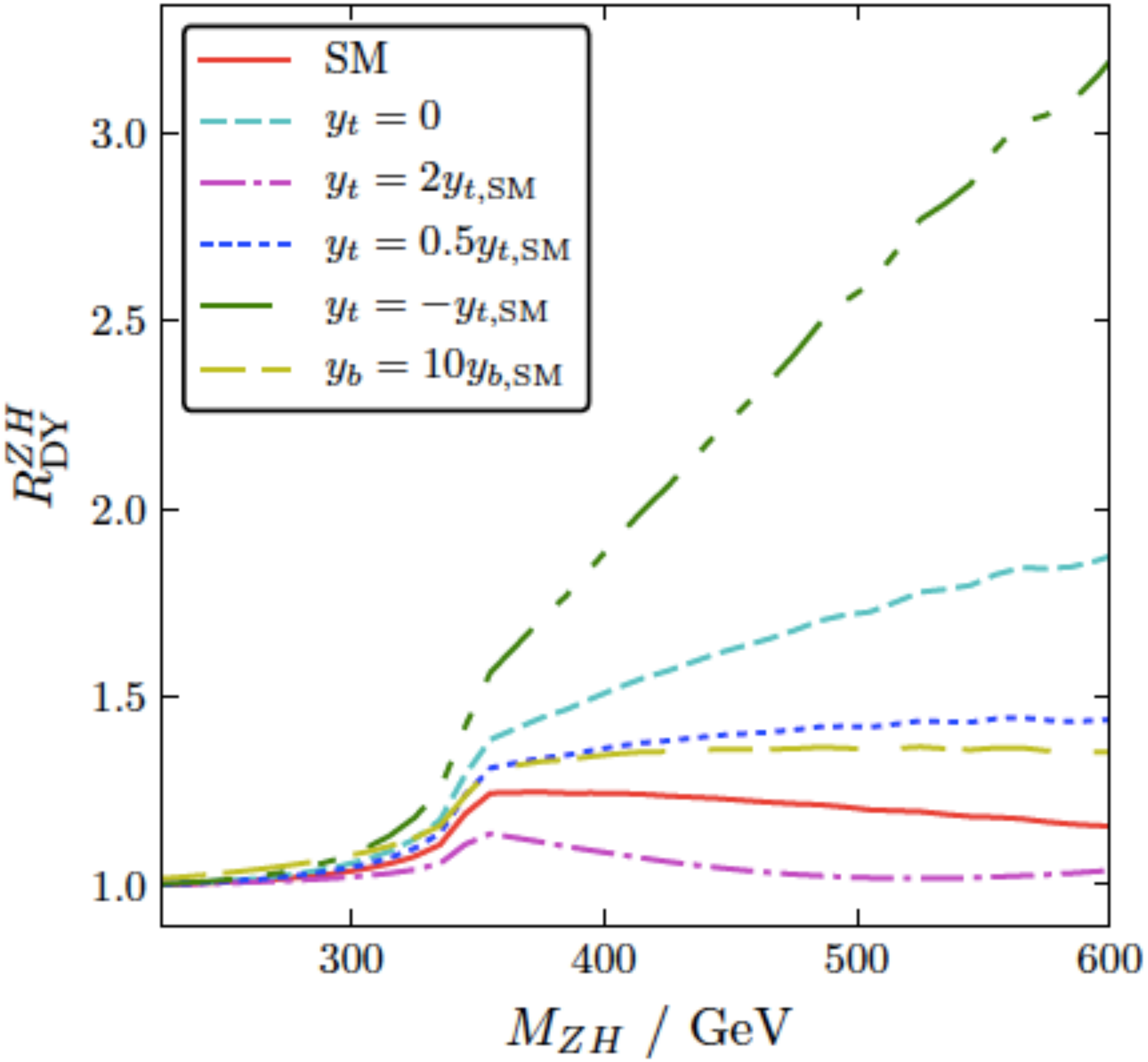


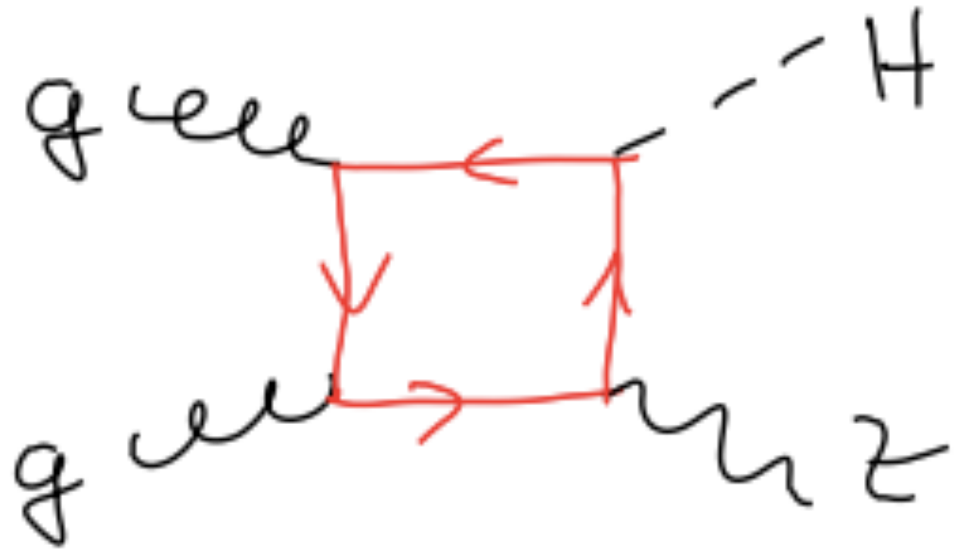
Caola, Luisoni, Melnikov, Röntsch ‘18



- up to now, the only channel to see $H \to bb$
- *HW*/*HZ* ratio sensitive to new physics







RH, Klappert, Pandini, Papaefstathiou '18

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{f_i}{\Lambda^2} \mathscr{O}_i^{(6)} + \ldots$$

$1 : X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2 : H^6$	
Q_H	$(H^\dagger H)^3$

$3 : H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5 : \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4 : X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6 : \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7 : \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8 : (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8 : (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8 : (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8 : (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

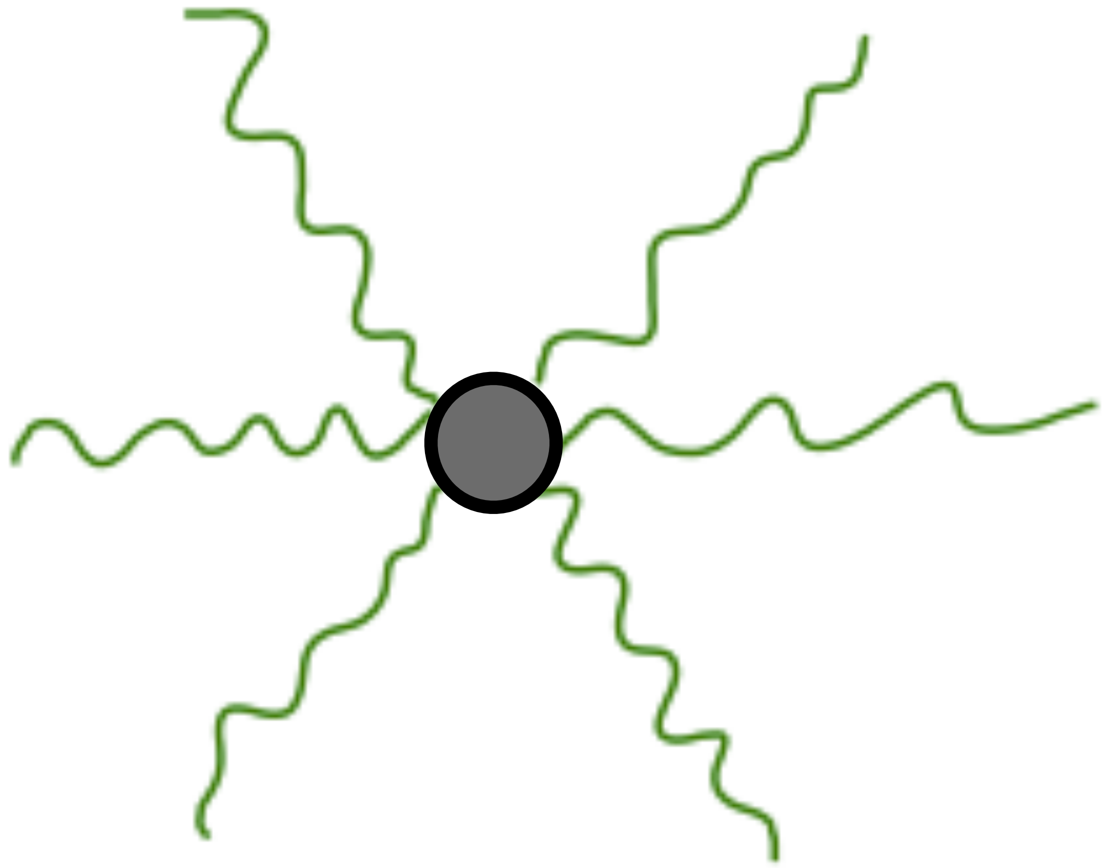
$8 : (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

 B_μ, W^i_μ dim 1

 A^a_μ dim 1

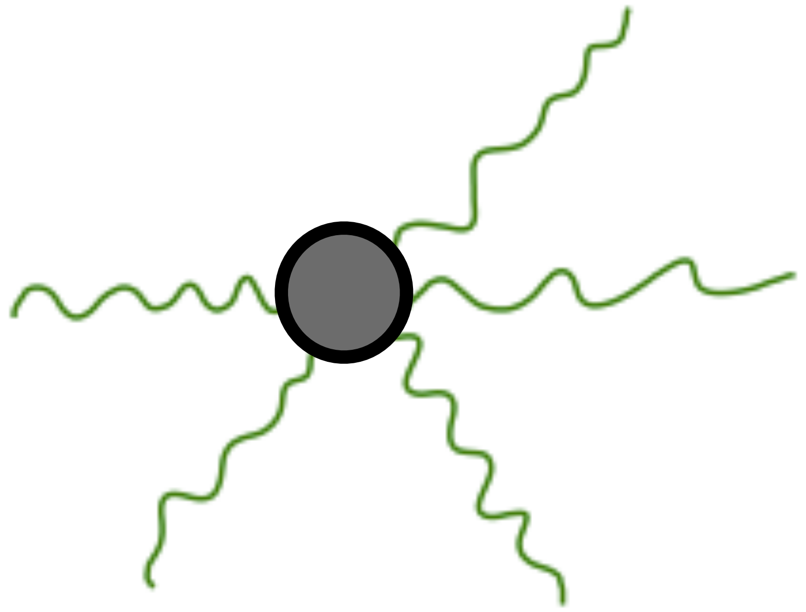
} appear as D_μ *or* $W_{\mu\nu}$, $B_{\mu\nu}$, $G_{\mu\nu}$

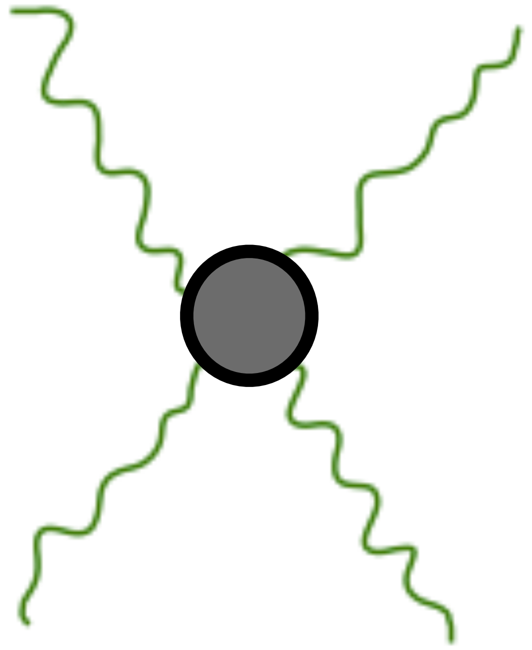
 ψ dim 3/2

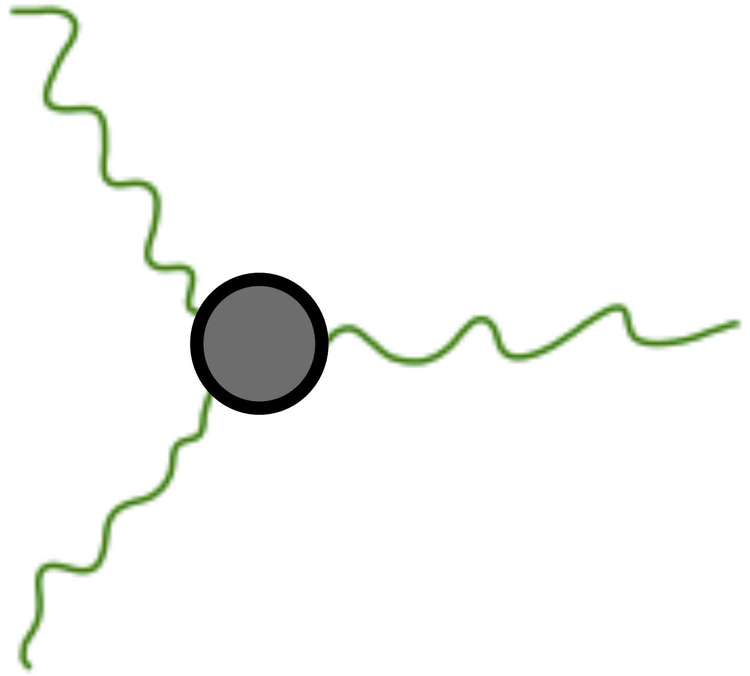


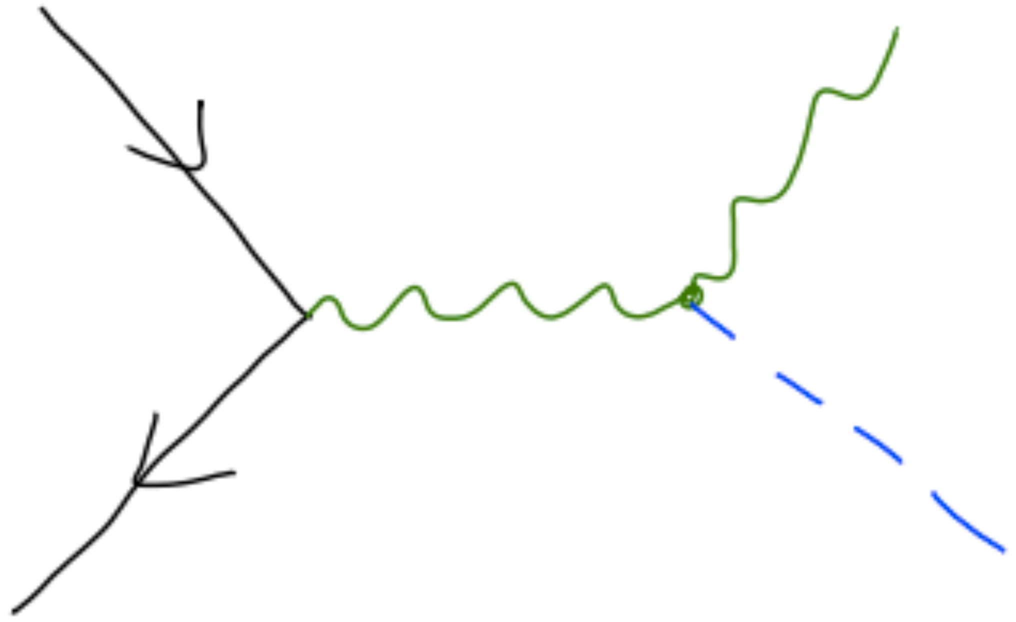
$$Q_W \sim \epsilon_{ijk} W_\mu^{i,\nu} W_\nu^{j,\rho} W_\rho^{k,\mu}$$

$$W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g_2 \epsilon^{ijk} W_\mu^j W_\nu^k$$

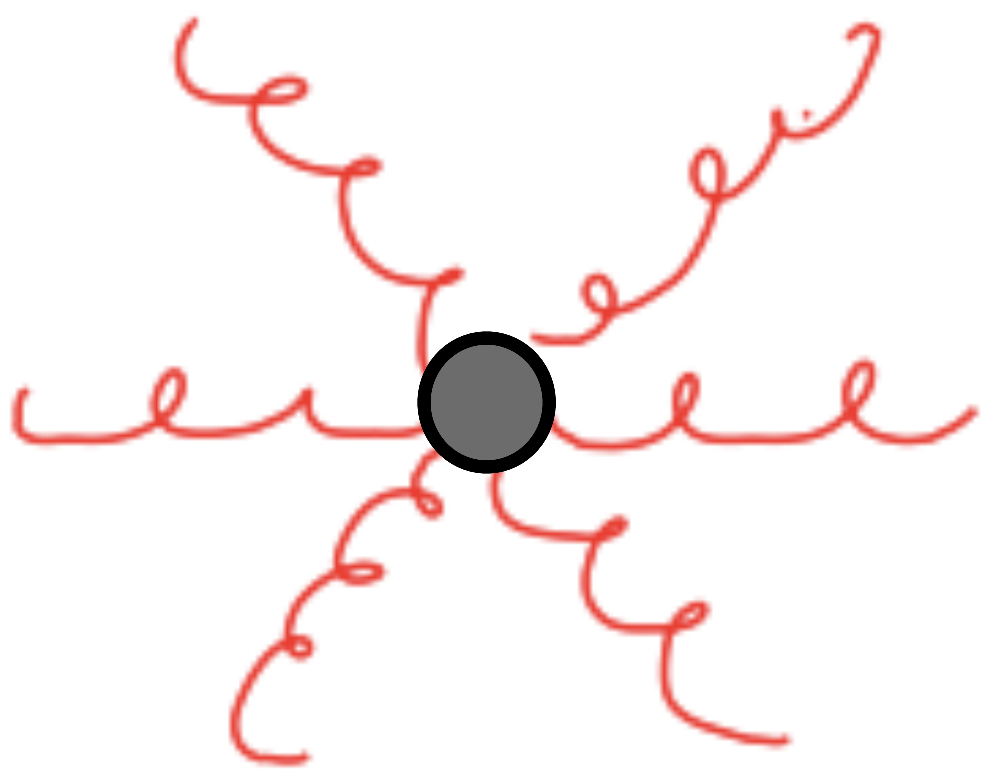






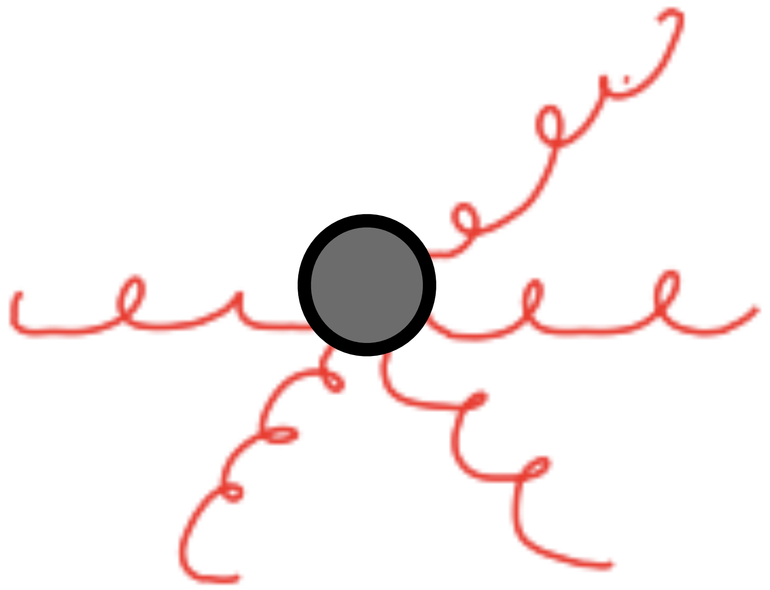


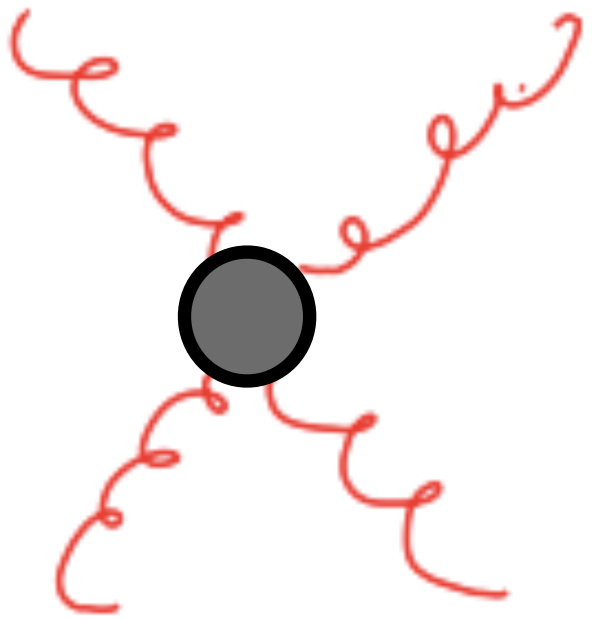
No contribution
to *WH* production

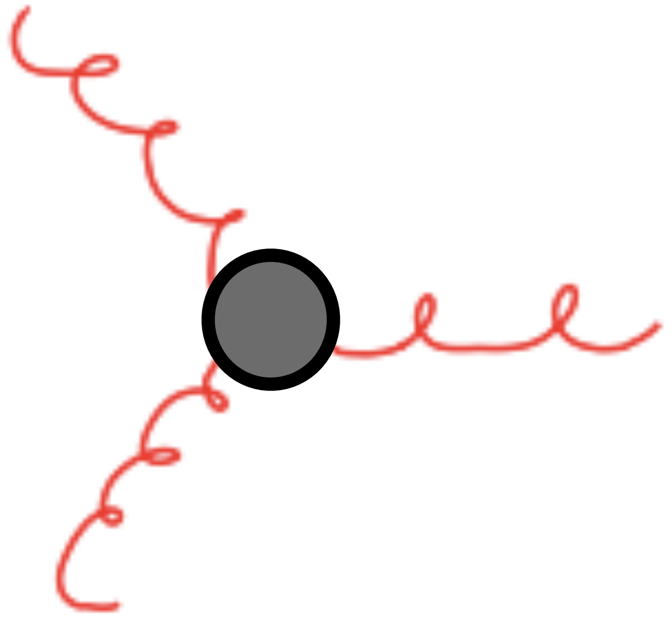


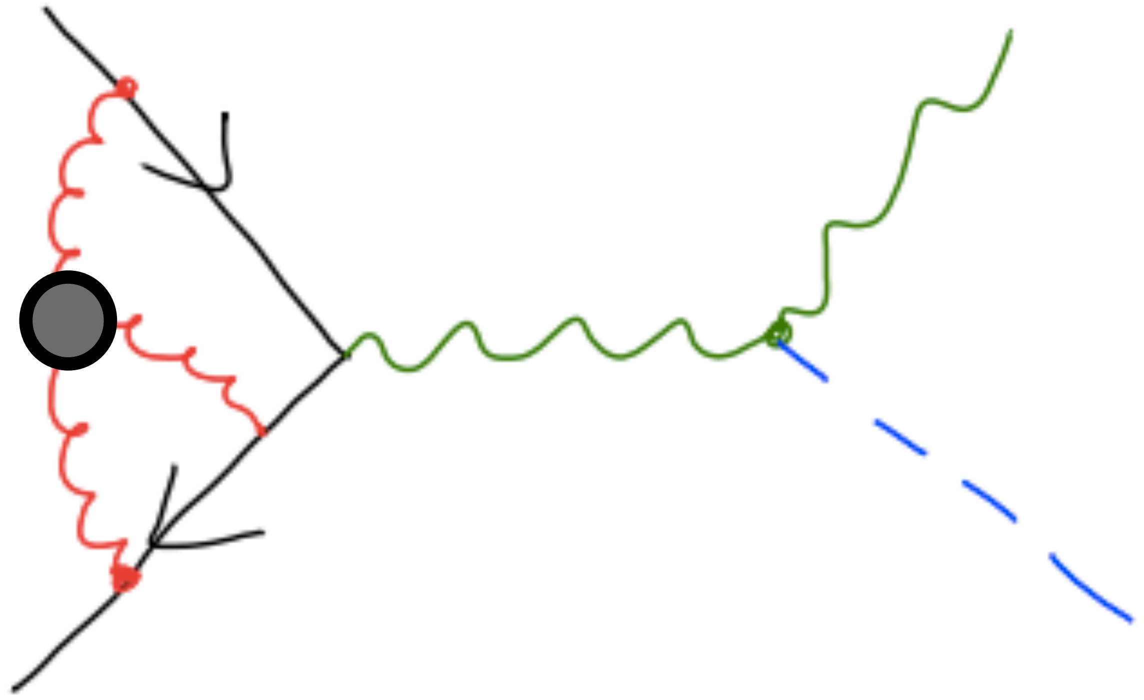
$$Q_G \sim f_{abc} G_{\mu}^{a,\nu} G_{\nu}^{b,\rho} G_{\rho}^{c,\mu}$$

$$G_{\mu\nu}^{a} = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_3 f^{abc} G_\mu^b G_\nu^c$$

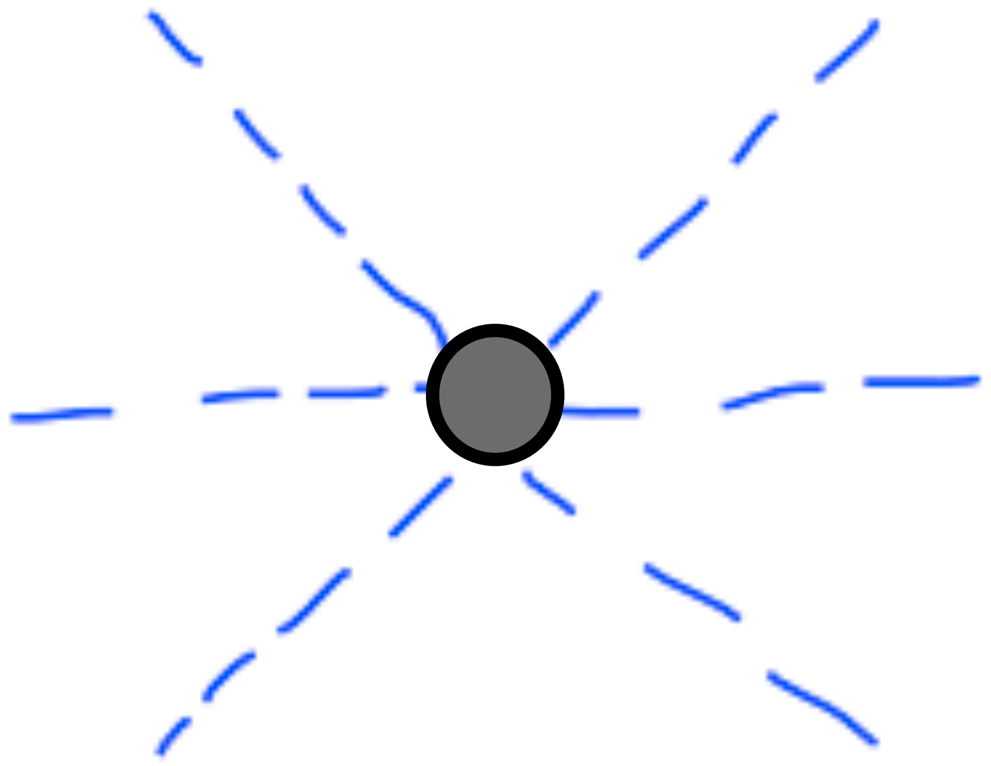






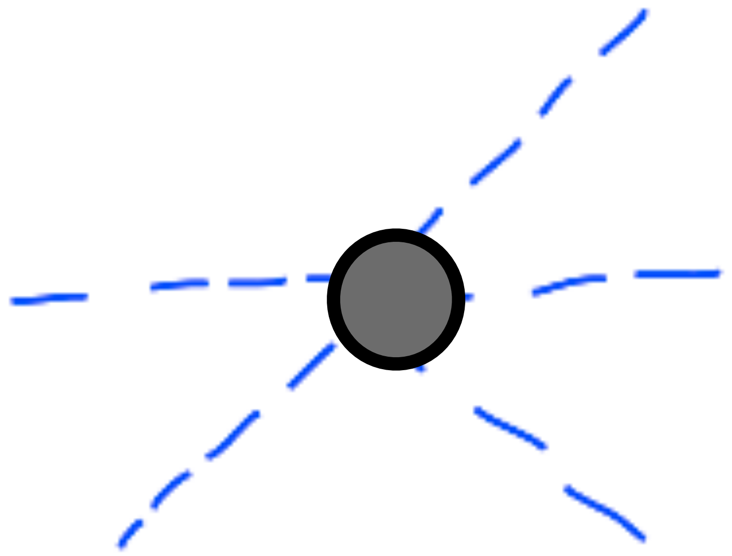


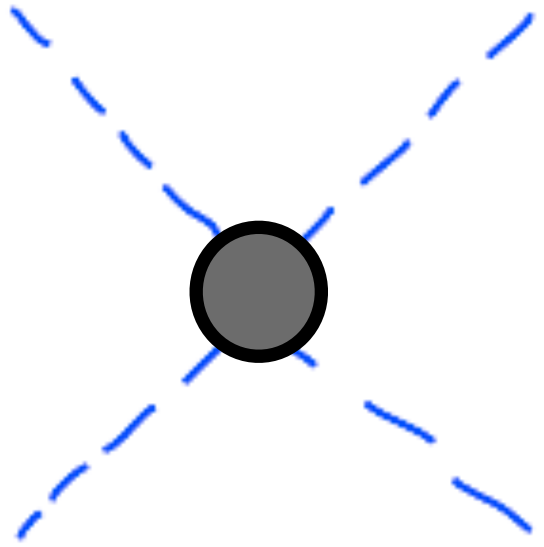
contributes at NNLO,
no renormalization required

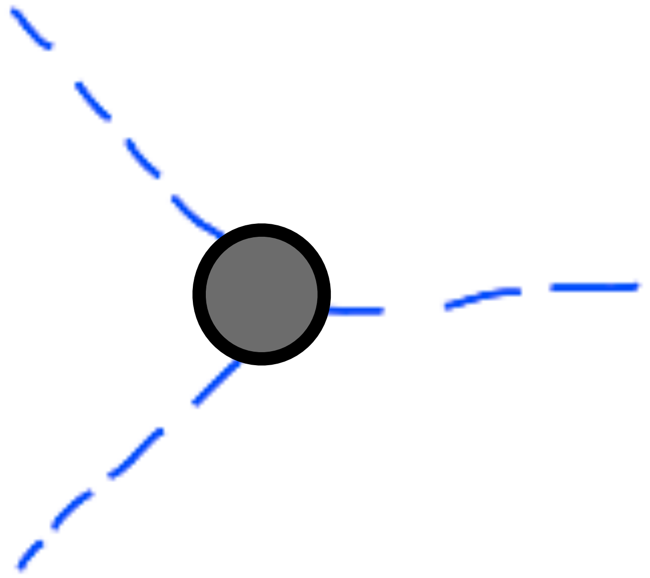


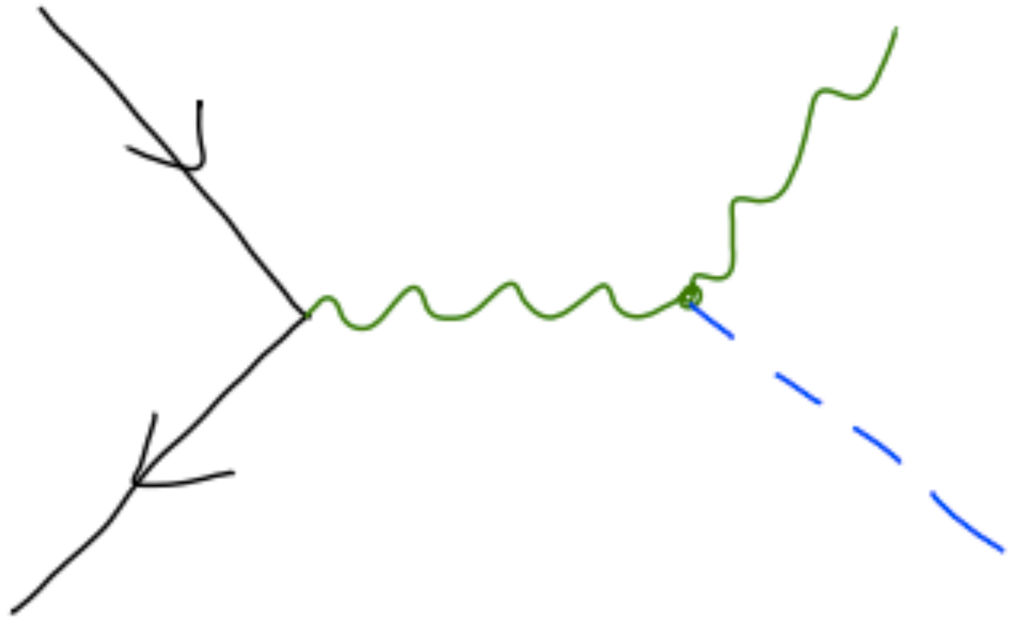
$$Q_H \sim (H^\dagger H)^3$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$



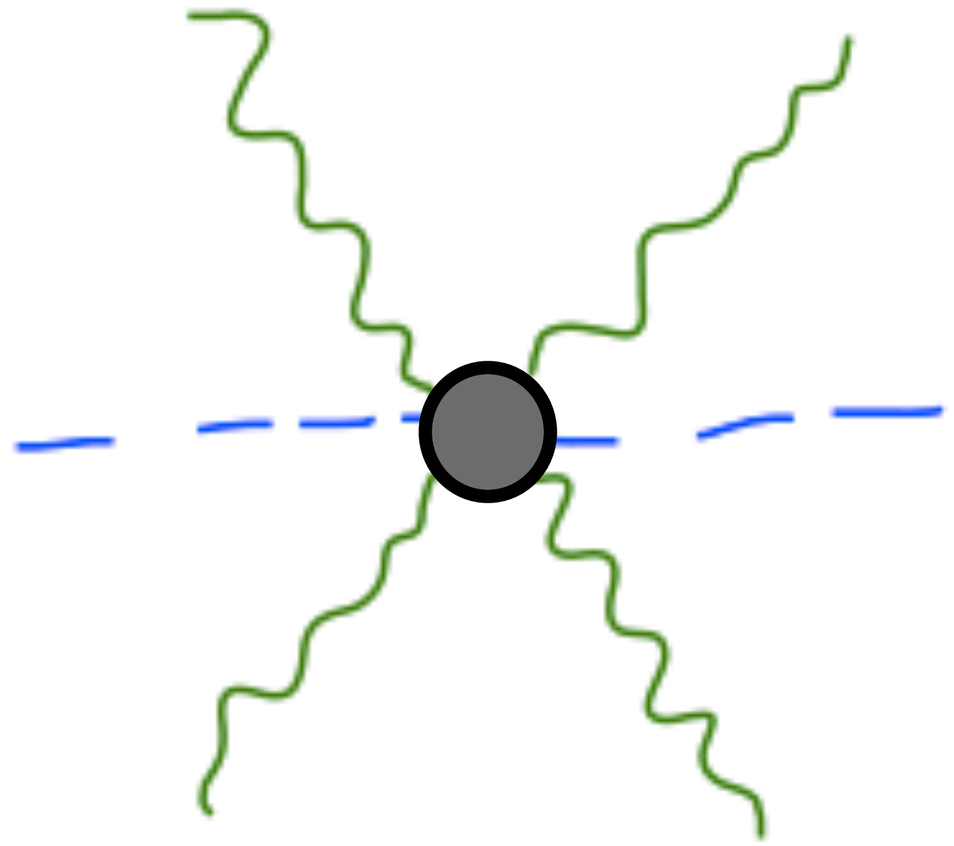




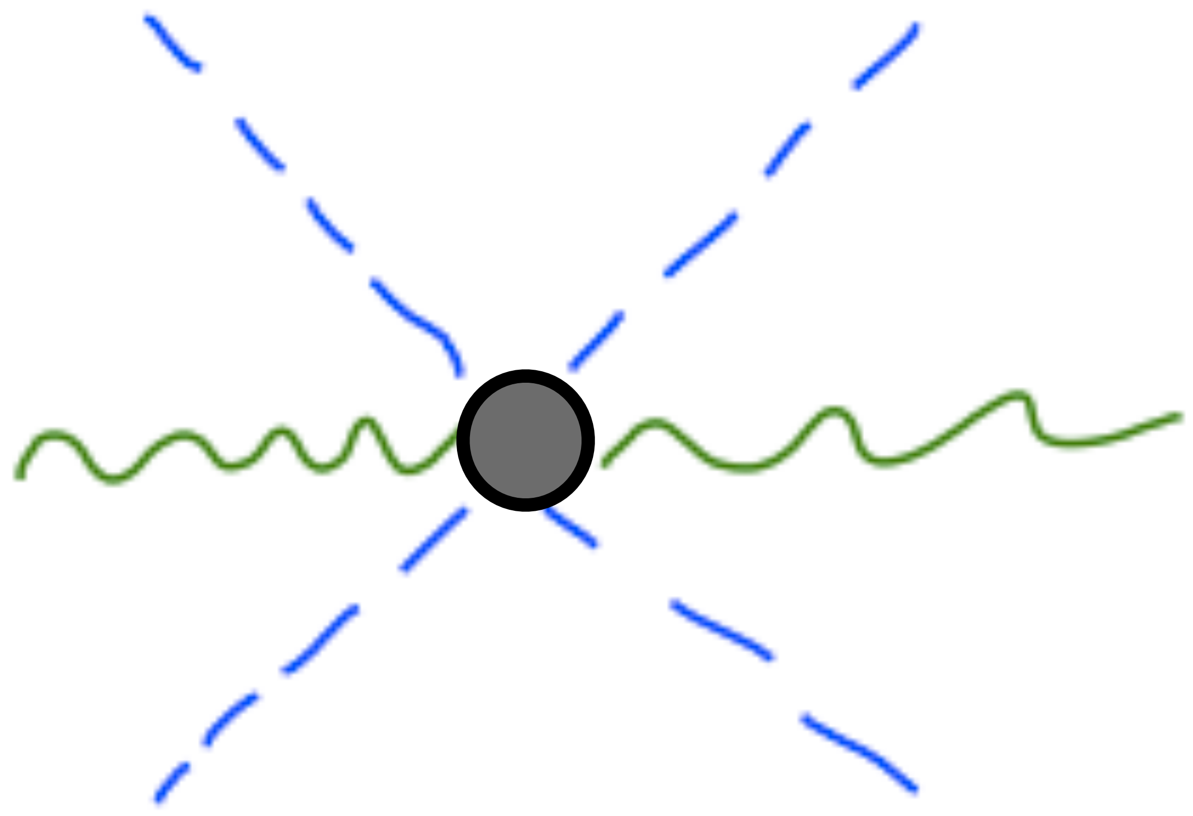


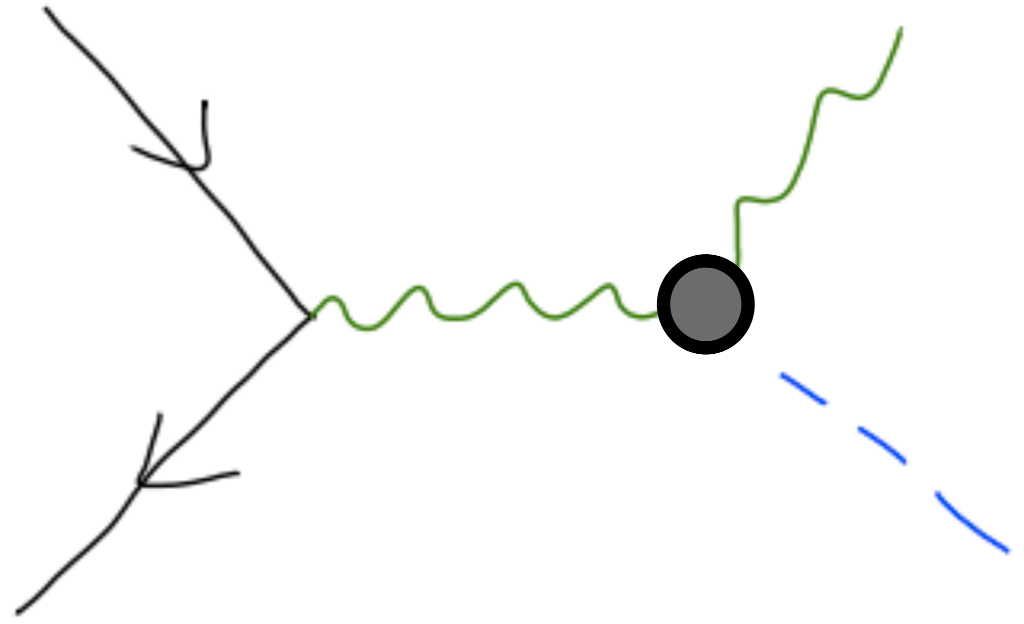
No contribution to *WH* production

$$Q_{HW} \sim H^\dagger H\, W_{i,\mu\nu} W^{i,\mu\nu}$$

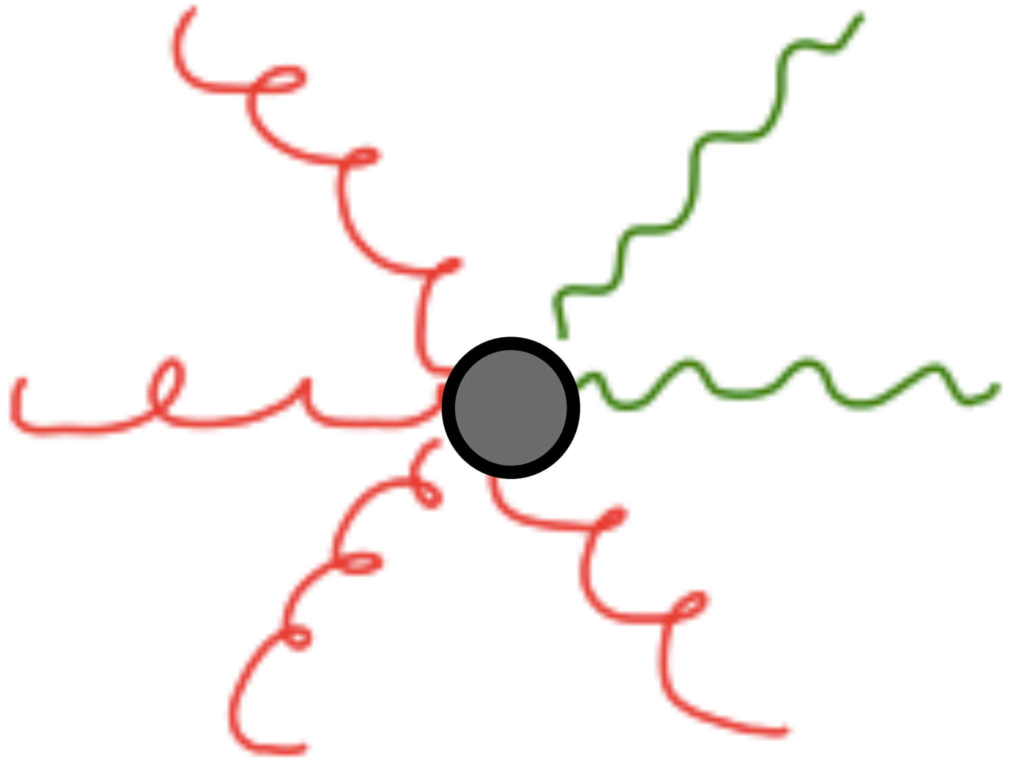


$$Q_{HD} \sim (H^\dagger D_\mu H)^* (H^\dagger D^\mu H)$$



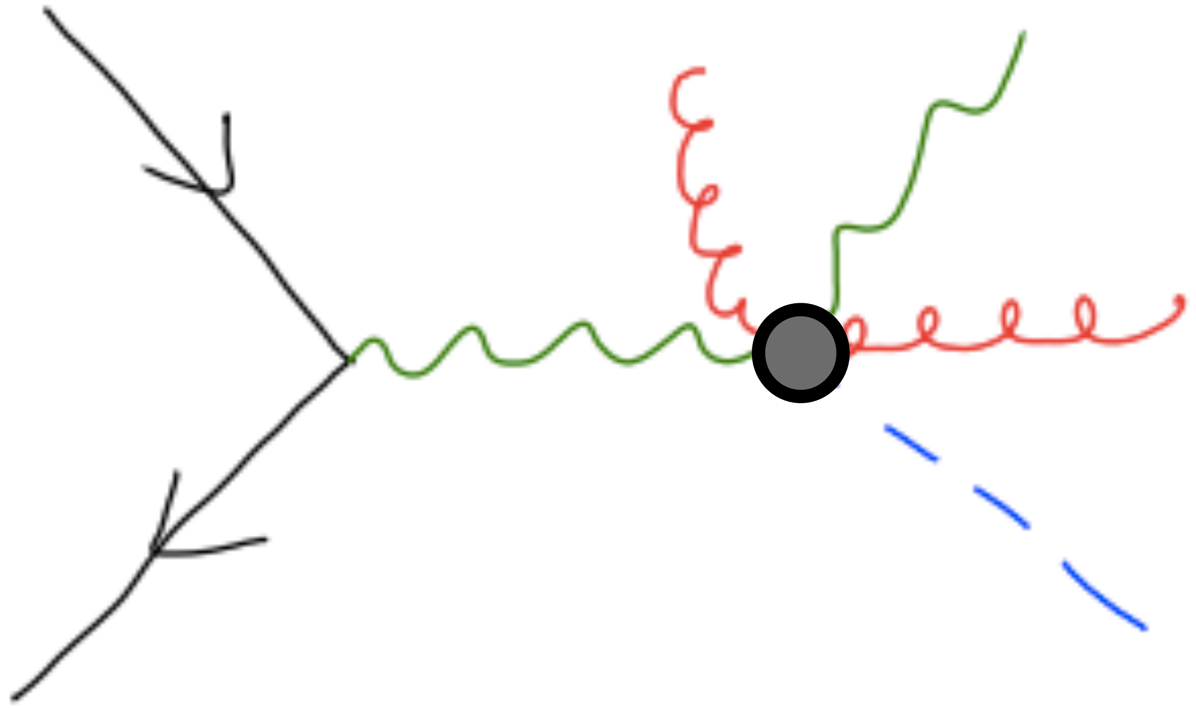


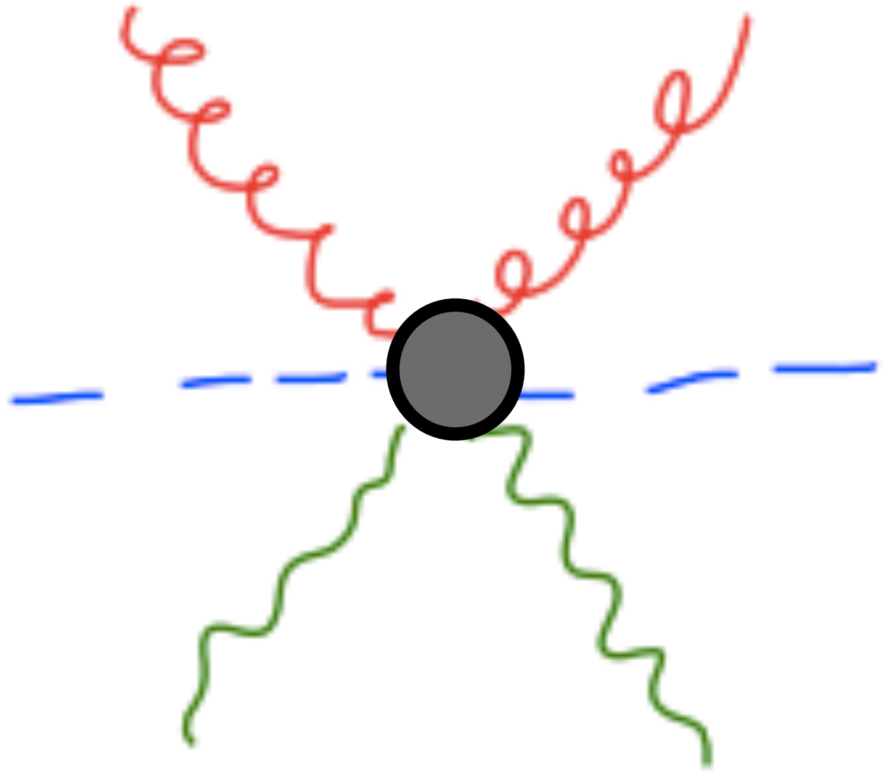
Contribute at LO, but no renormalization required



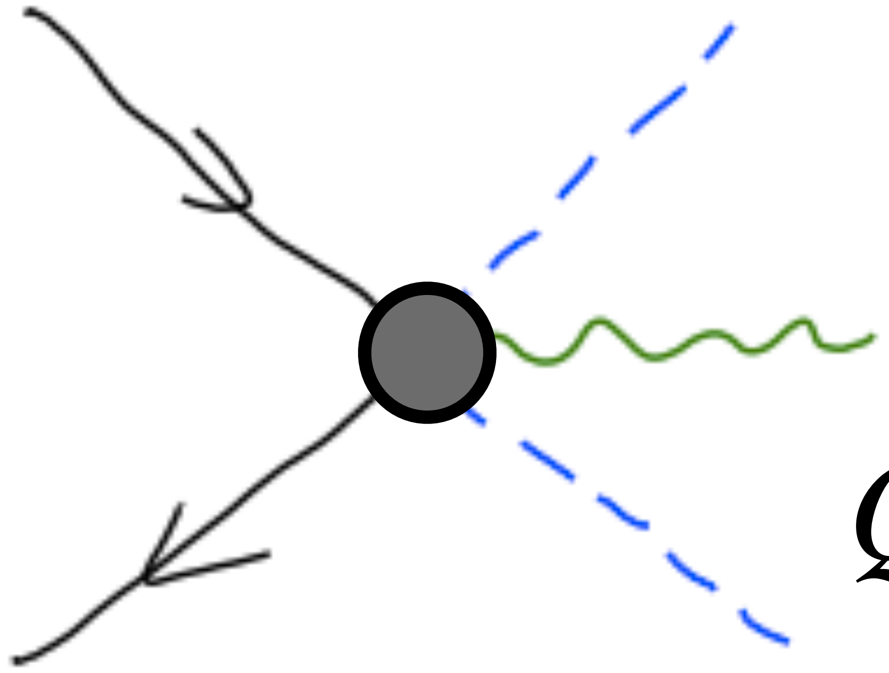
$$G_{\mu}^{a,\nu} G_{\nu}^{b,\rho} W_{\rho}^{i,\mu}$$

no!

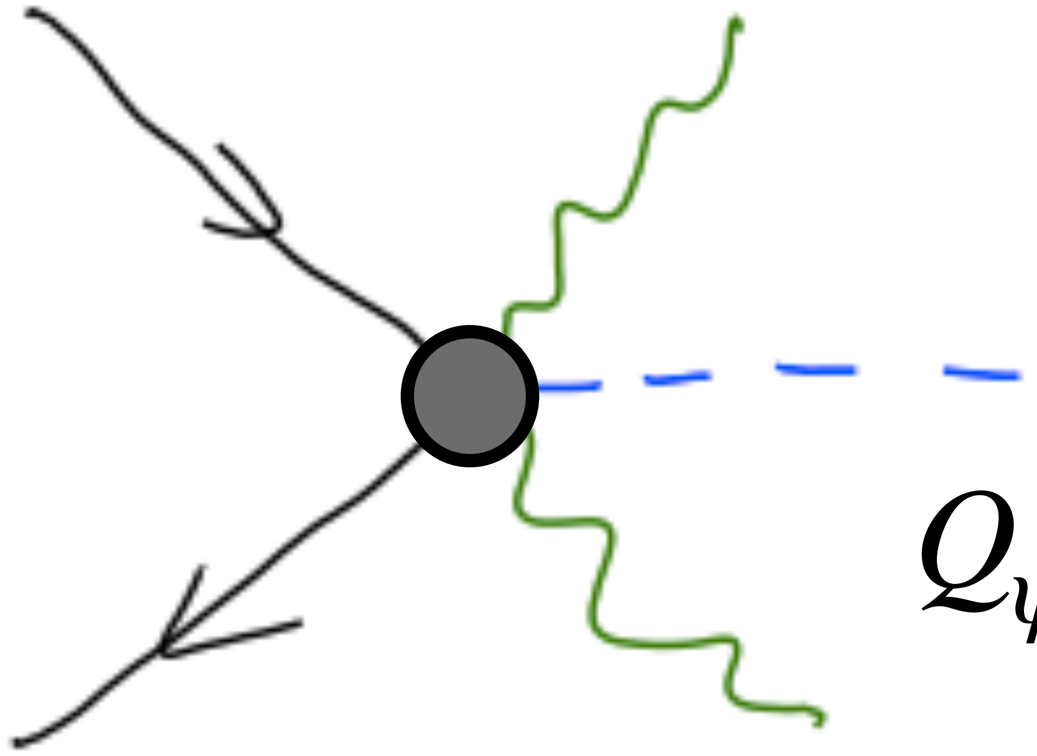




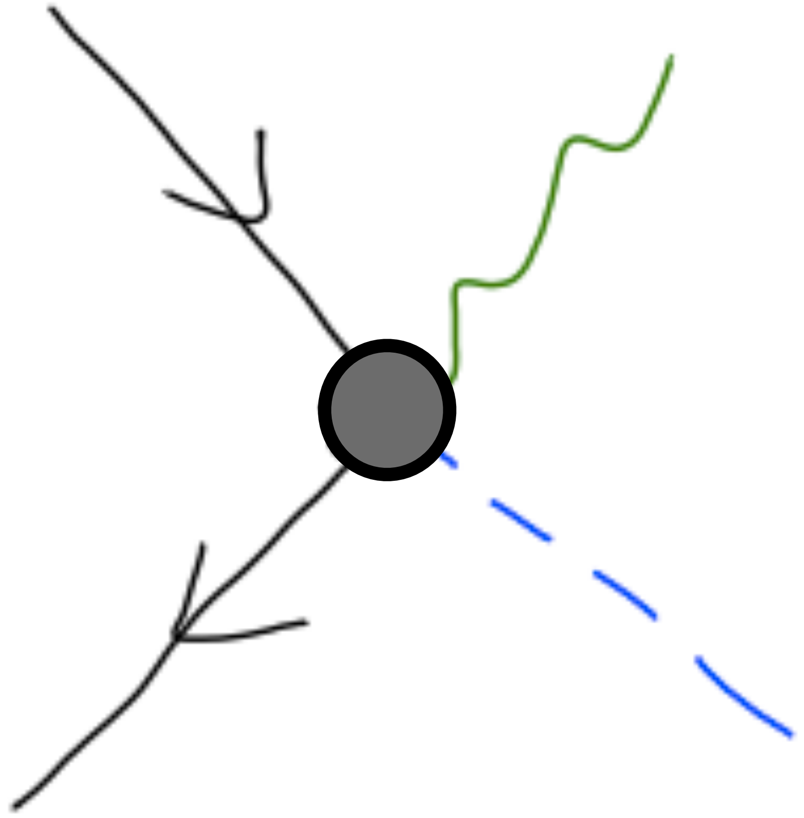
$$(H^{\dagger}H) G_{\mu\nu}^{a} W^{i,\mu\nu}$$

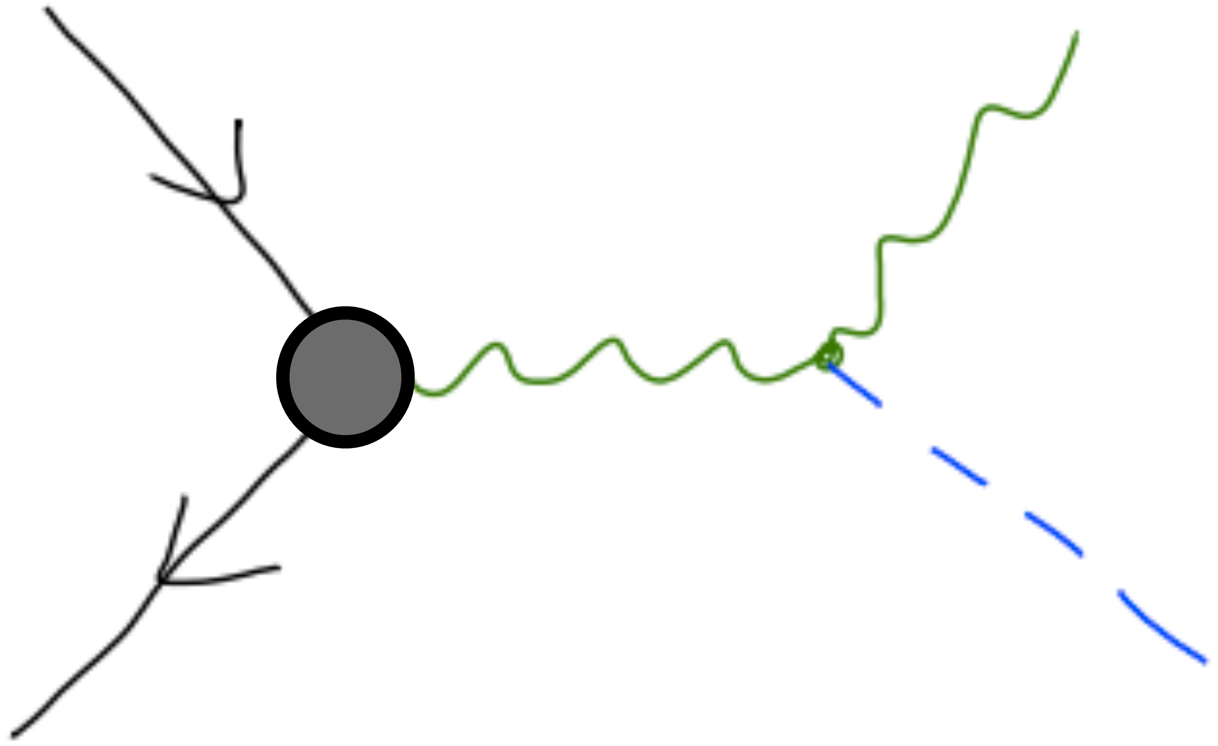


$$Q_{H\psi} \sim (H^\dagger \overleftrightarrow{D}_\mu H)\,\bar{\psi}\gamma^\mu\psi$$

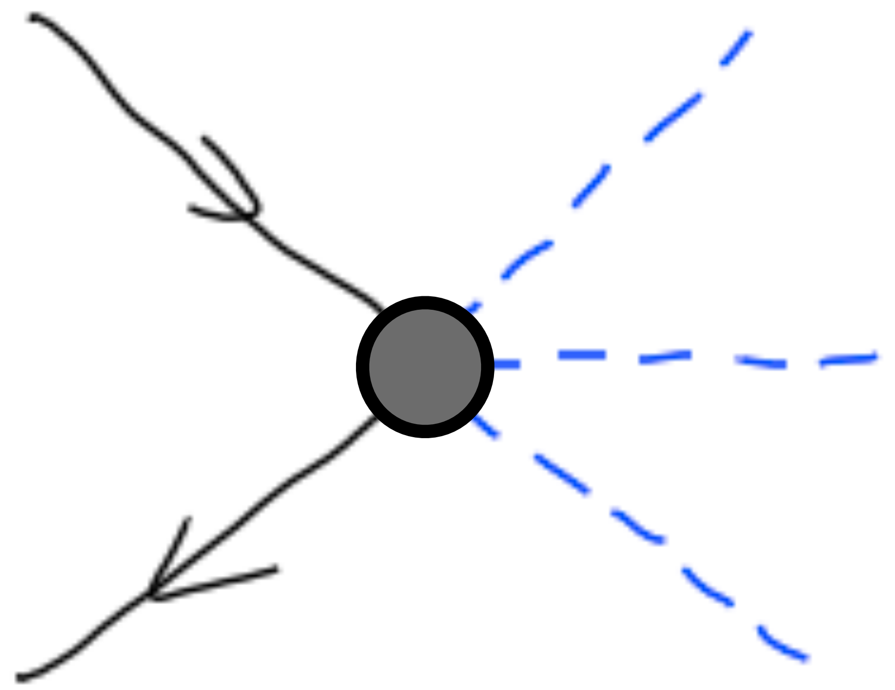


$$Q_{\psi W} \sim \bar{\psi}\sigma_{\mu\nu}\tau^i\psi\, H\, W^{i,\mu\nu}$$

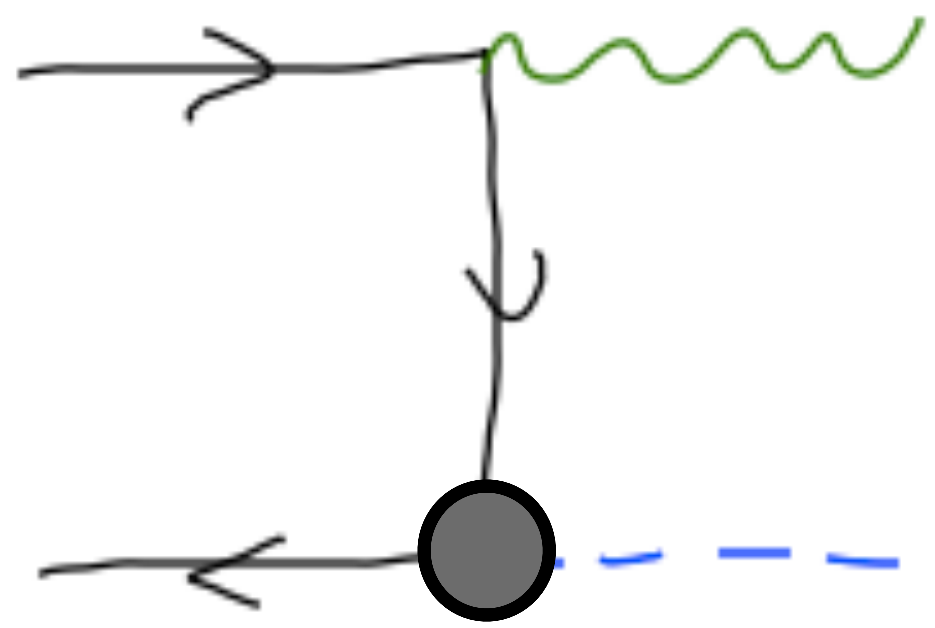




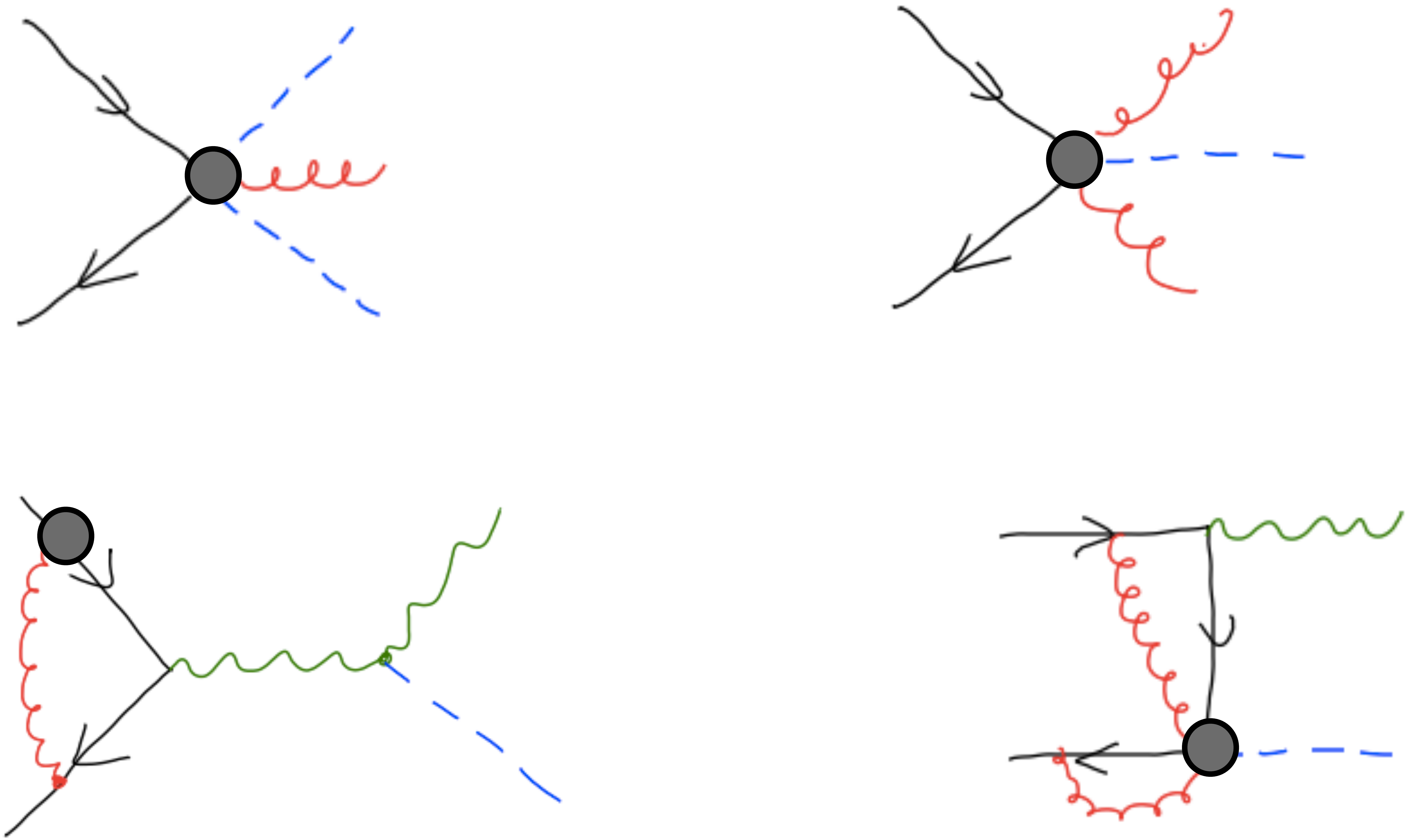
Contribute at LO,
require NNLO ren. → known!



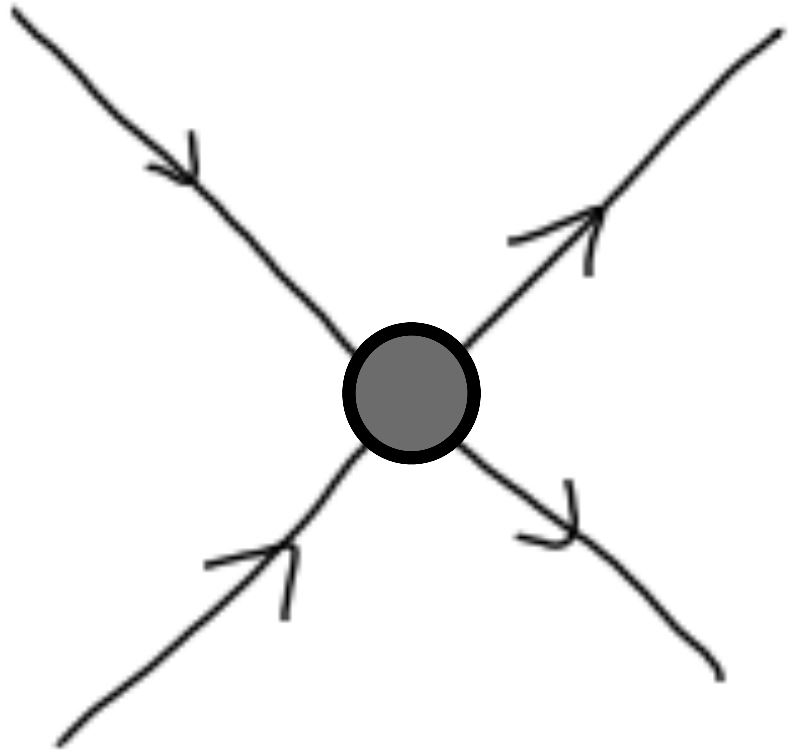
$$Q_{\psi H} \sim (H^\dagger H)(\bar{L}\psi_R H)$$



Contributes at LO,
requires NNLO ren. → known!

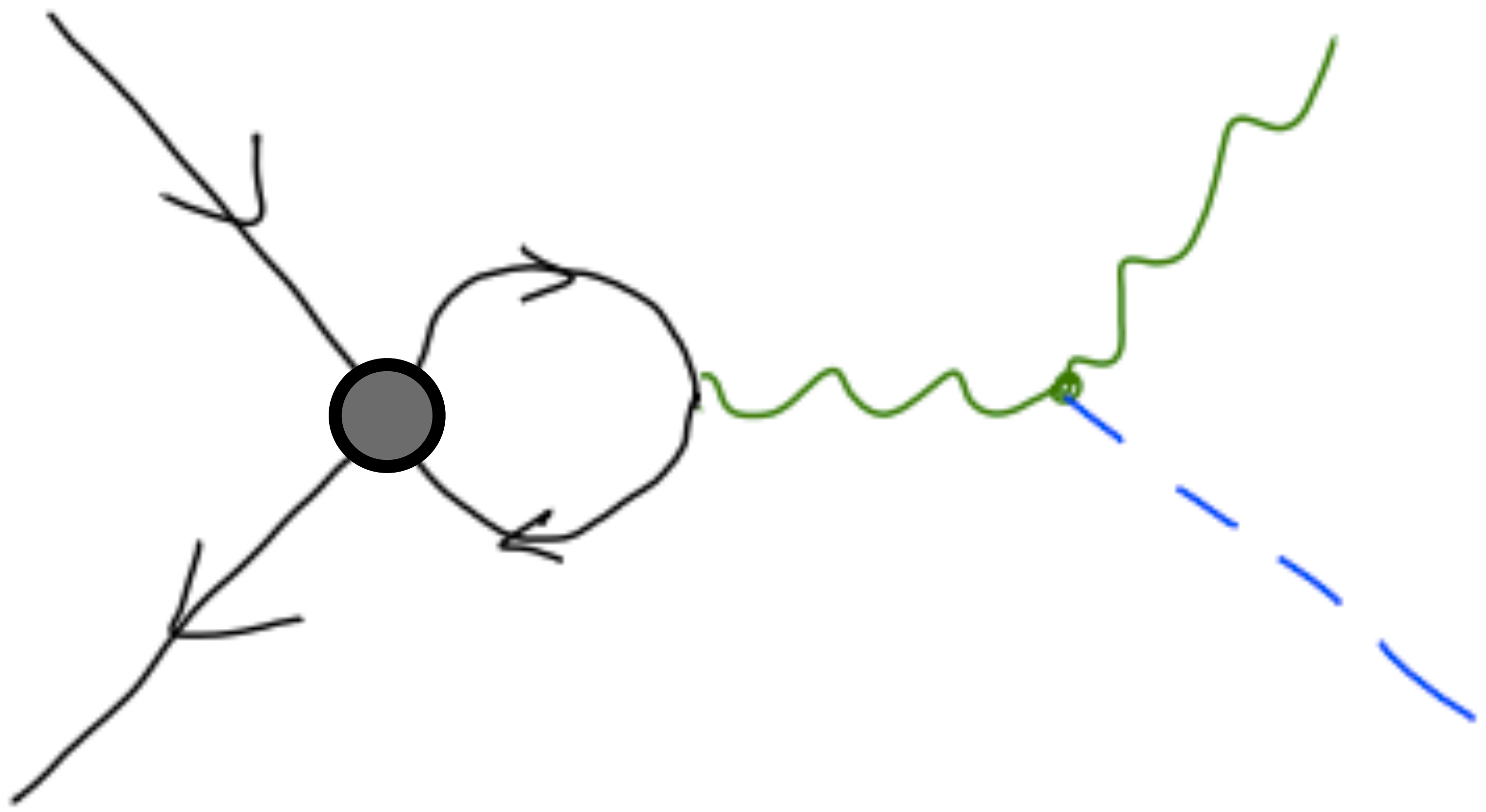


Contributes at NLO… … at NNLO

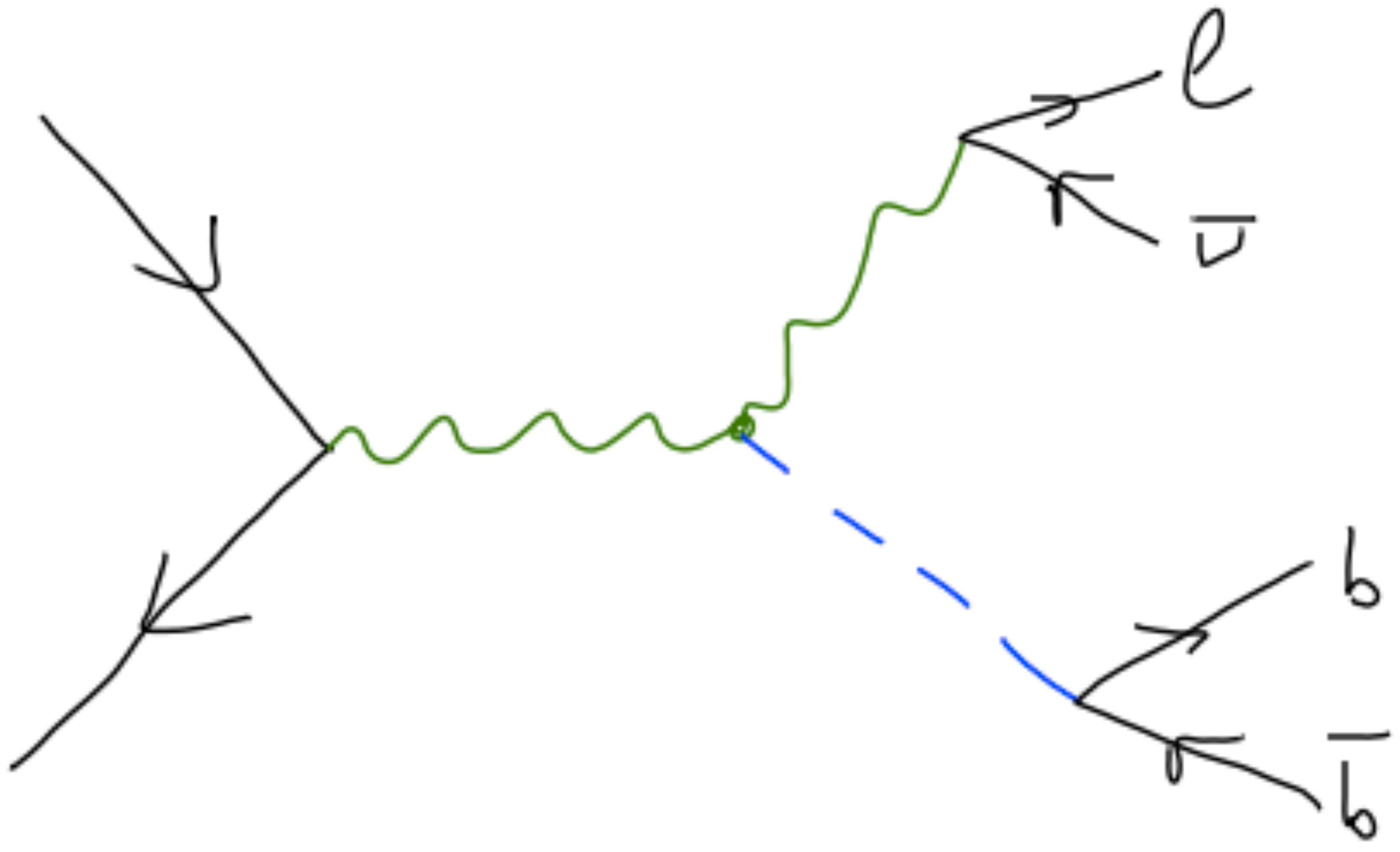


$$(\bar{\psi}\psi)(\bar{\psi}\psi)$$

$$(\bar{\psi}\sigma^{\mu\nu}\psi)(\bar{\psi}\sigma_{\mu\nu}\psi)$$

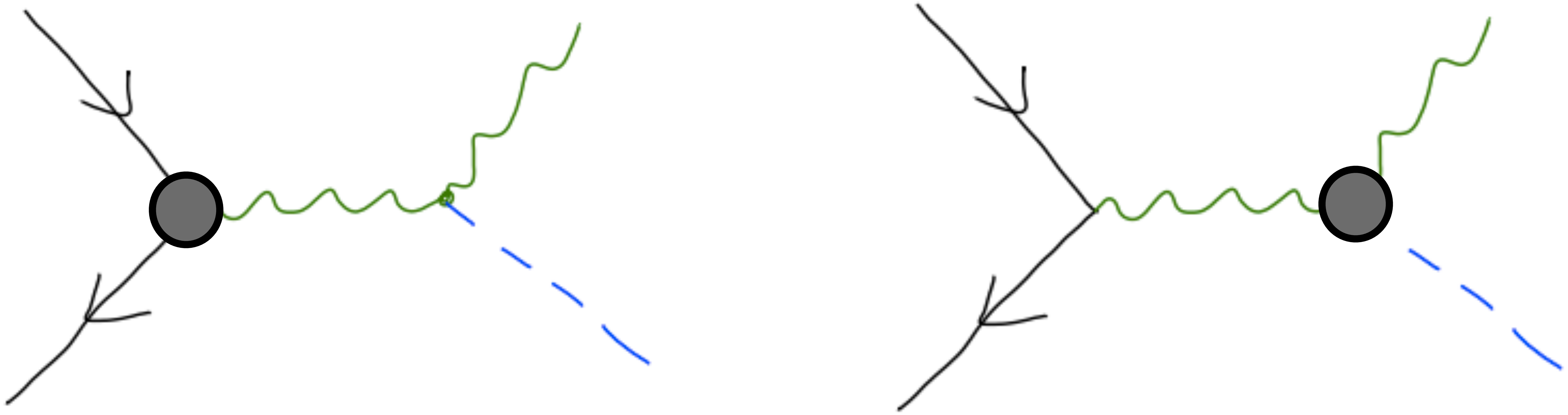


contributes at NLO…



…or when decay is taken into account.

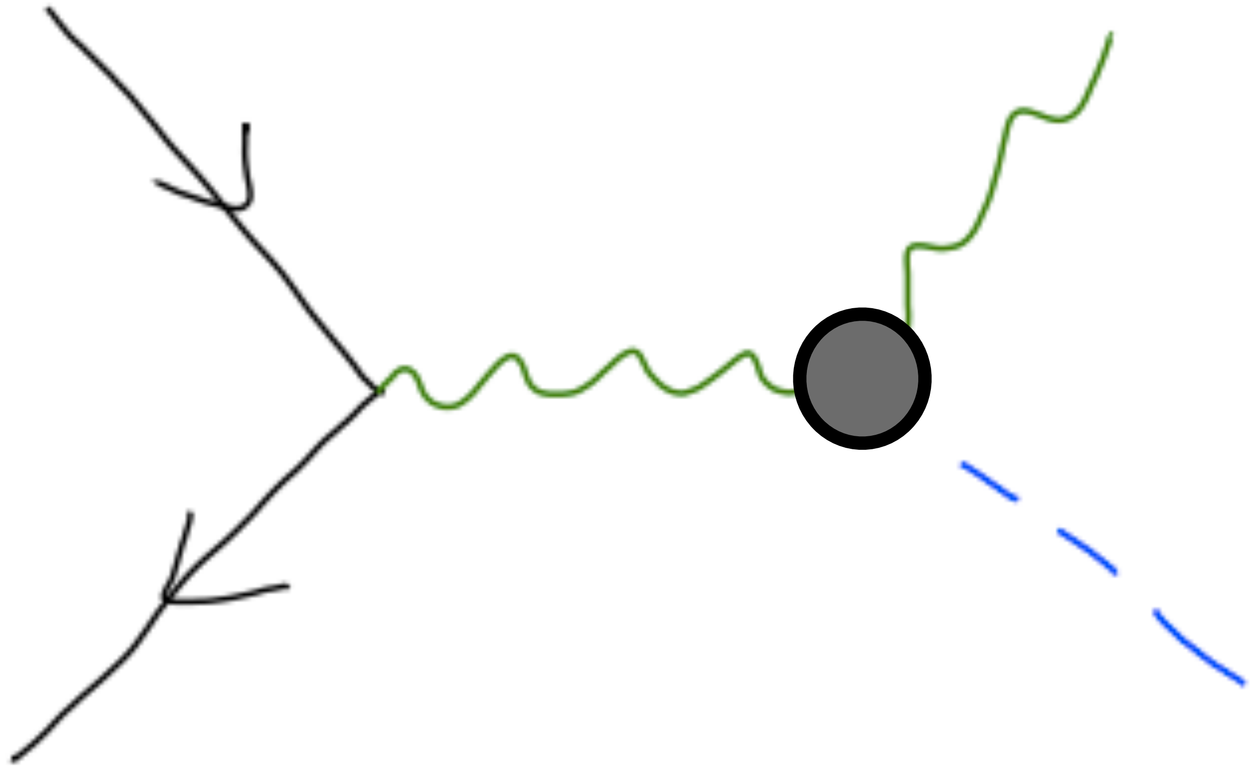
In summary, dim6 operators induce the following terms:



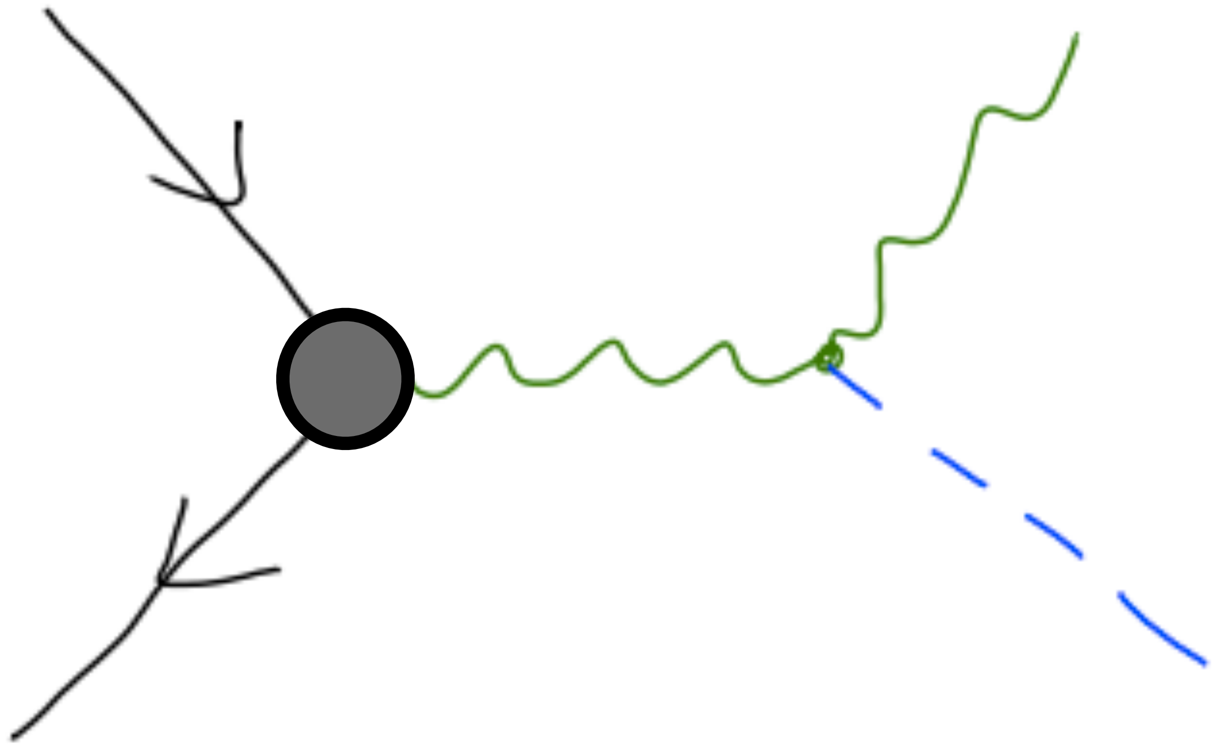
SM-like

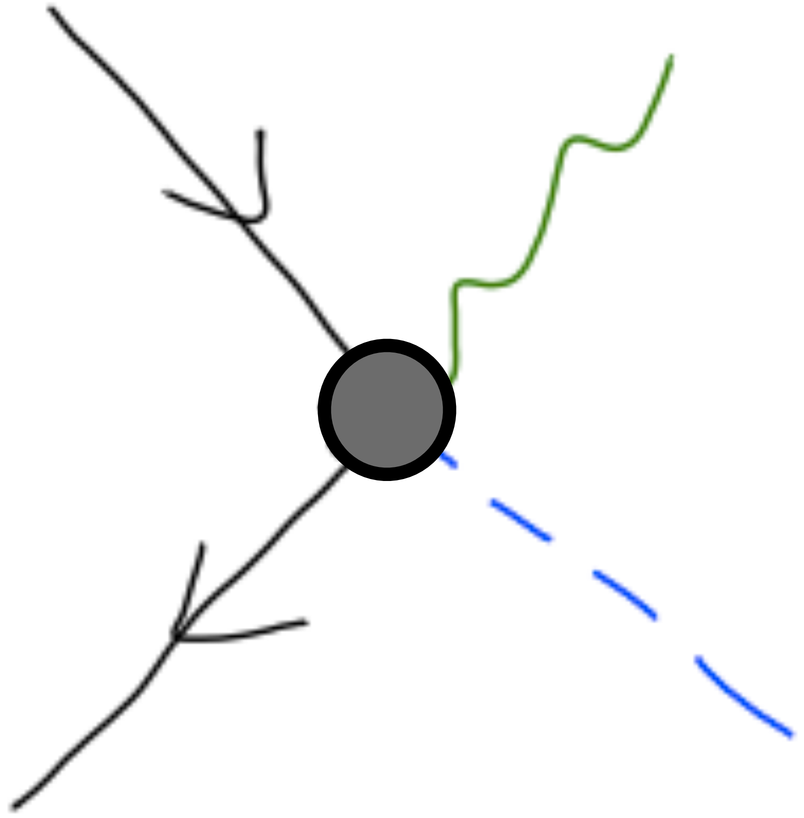
new

So far, only NLO analyses:



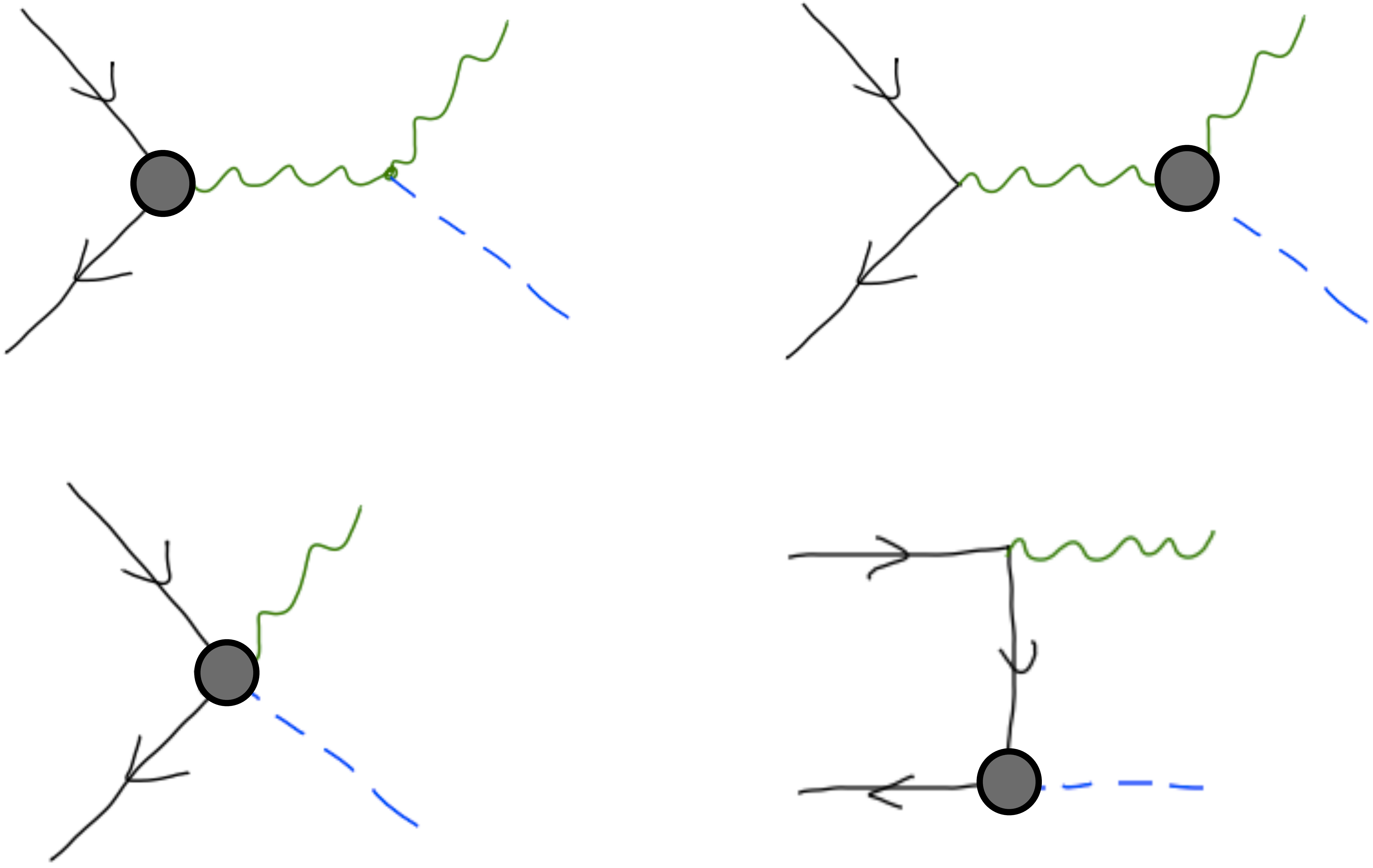
Maltoni, Mawatari, Zaro ’13
…



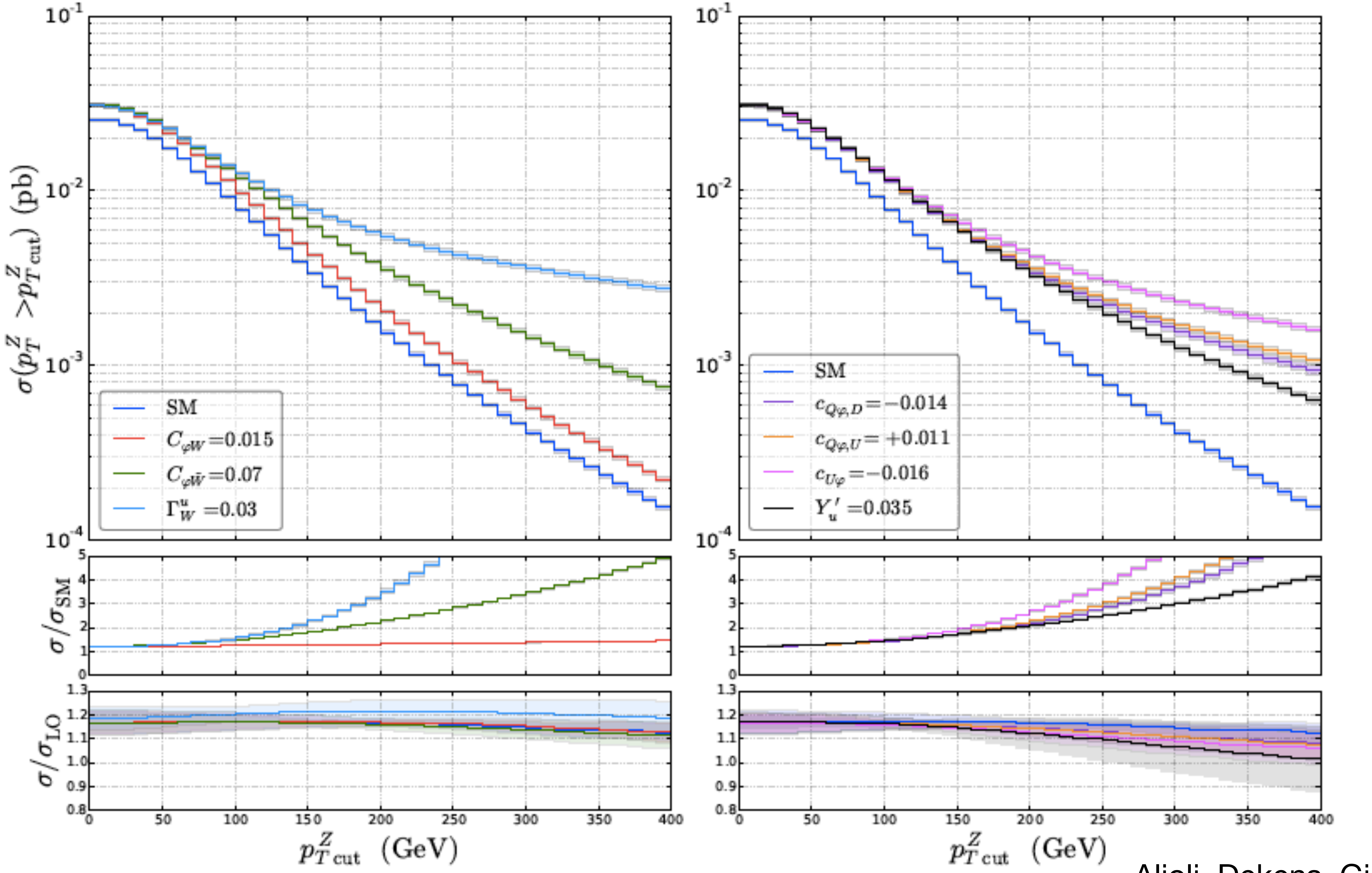


Greljo, Isidori, Lindert, Marzocca, Zhang ’17

Full NLO+PS:

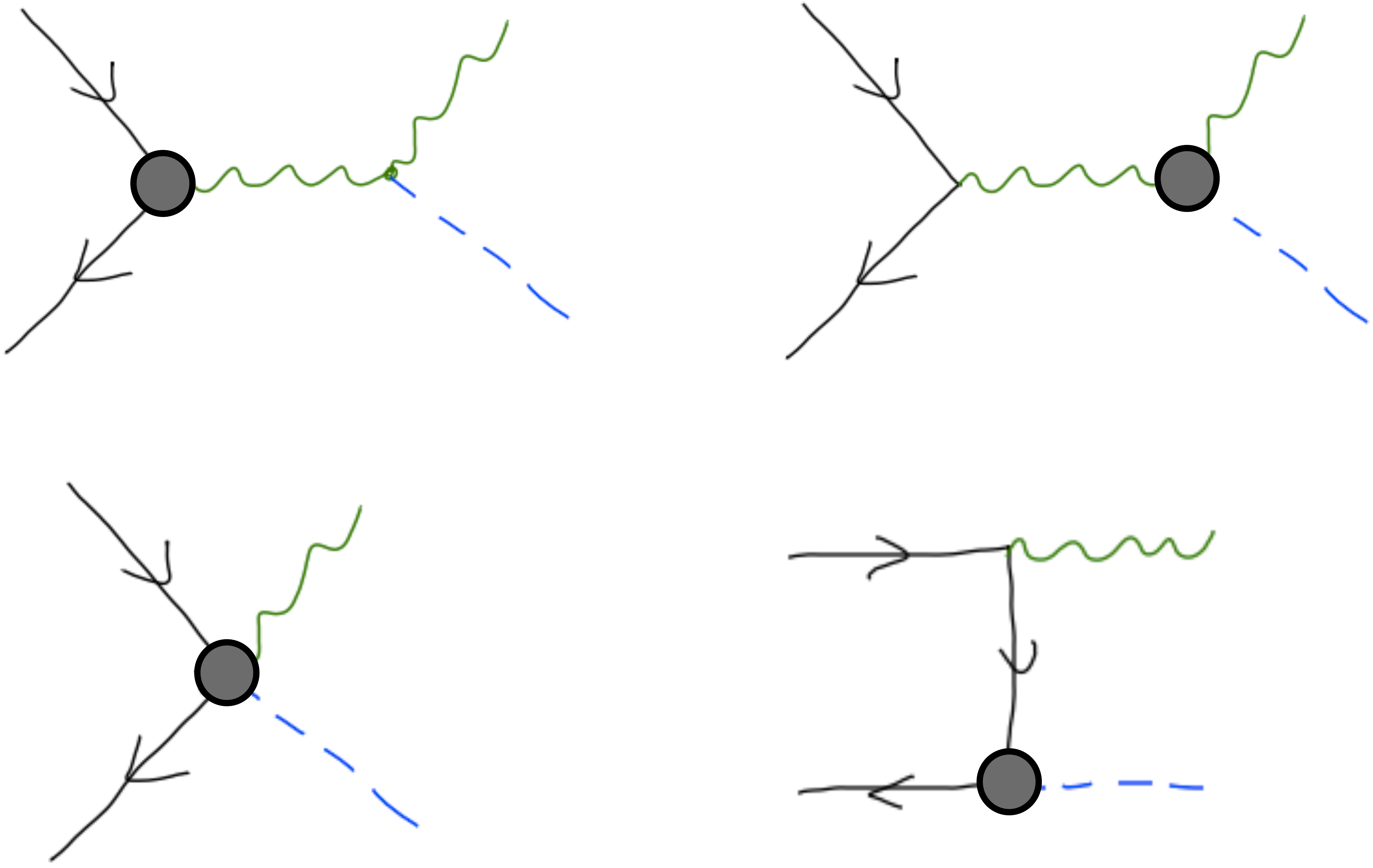


Alioli, Dekens, Girard, Mereghetti ‘18



Alioli, Dekens, Girard, Mereghetti '18

Moving to NNLO:



Subtraction terms same as in SM.

Caola, Luisoni, Melnikov, Röntsch ‘18

Renormalization

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{f_i}{\Lambda^2} \mathscr{O}_i^{(6)} + \ldots$$

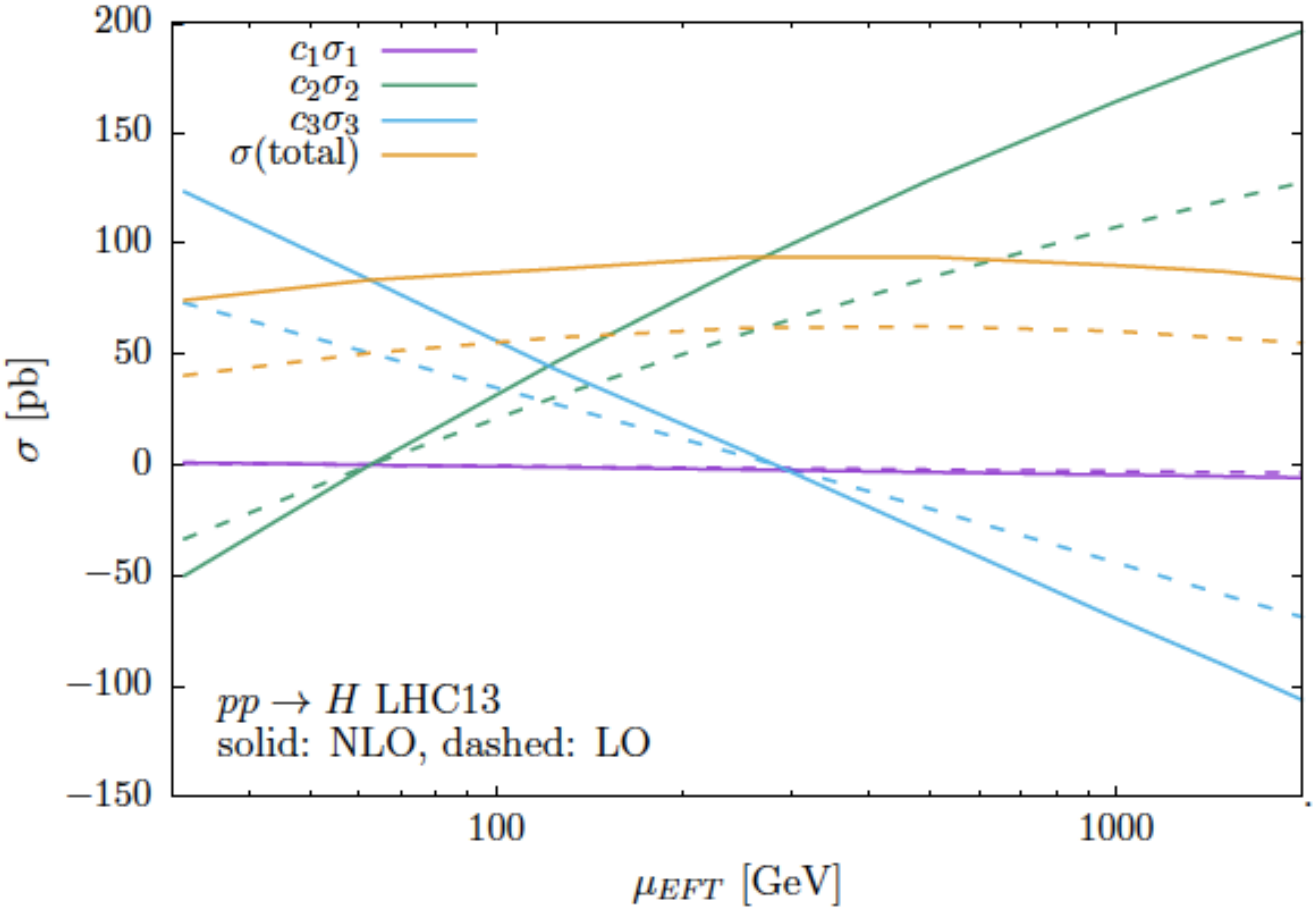
in general: $$f_i^B = \sum_j Z_{ij} f_j$$

Calculate appropriate Green's functions.

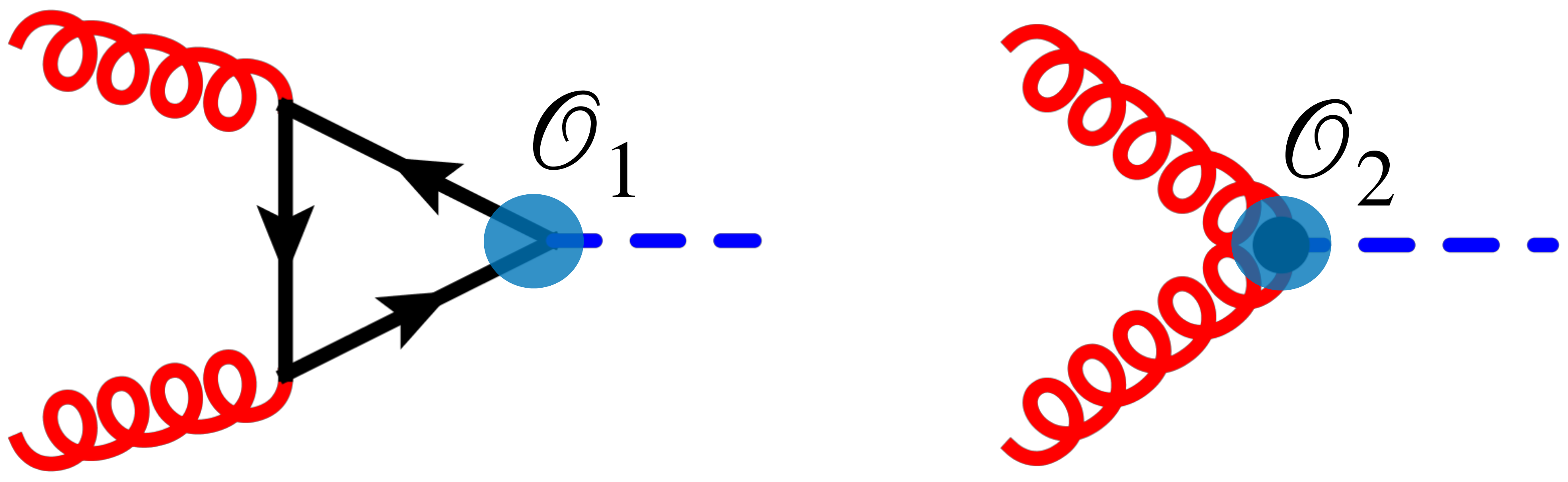
Mixing only occurs when operators contribute to the same Green's functions.

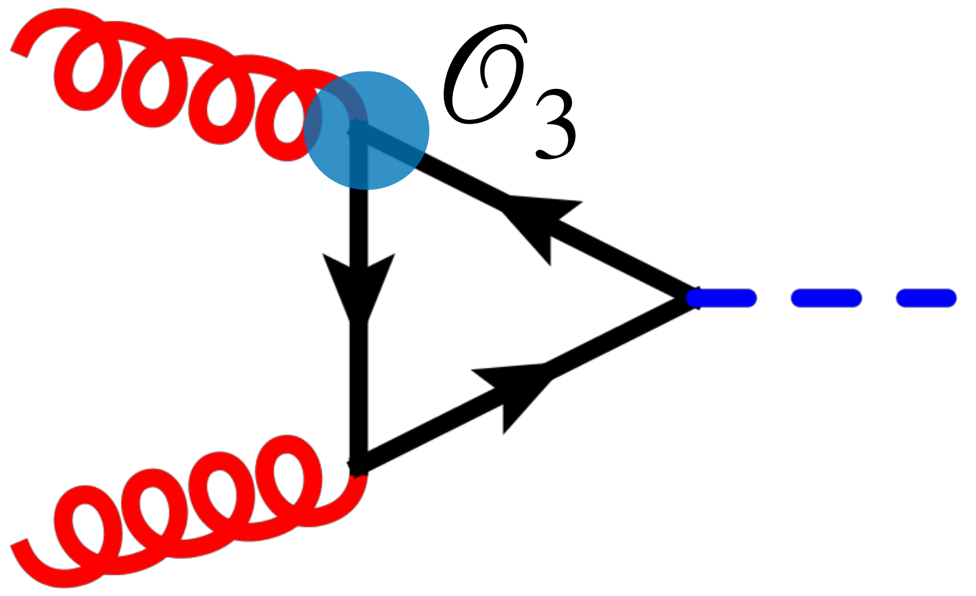
No mixing through NLO.

Example with mixing:



$$\mathscr{L} = \mathscr{L}_{SM} + \sum_x \frac{f_x}{\Lambda^2}\mathscr{O}_x^{(6)} + \ldots$$





Deutschmann, Duhr, Maltoni, Vryonidou '17

Plan:

- Calculate WH amplitudes in SMEFT through NNLO.
- Implement them into existing SM code for NNLO WH.
- Include SMEFT also for decays.
- Study effect of various operators on kinematic quantities.
- Make the code accessible to experimentalists.
- Move on to other Higgs production process.