Next-to-Next-to-Leading Order QCD Corrections to Higgs Boson Pair Production

Javier Mazzitelli - *DESY (Hamburg) and Universidad de Buenos Aires*

in collaboration with **Daniel de Florian**

LHCPhenoNet Workshop on Particle Physics – June 2014, Paris

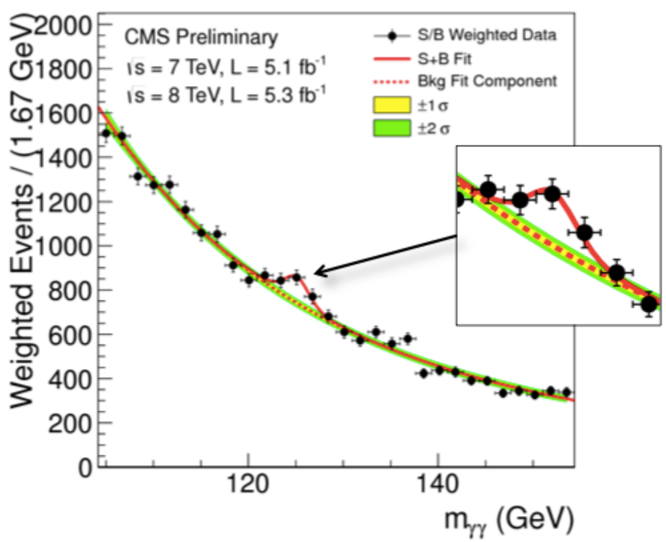
Outline

- **Measuring Higgs self-coupling**
- **NNLO inclusive XS**
- **Numerical results for the LHC**
- **Conclusions**

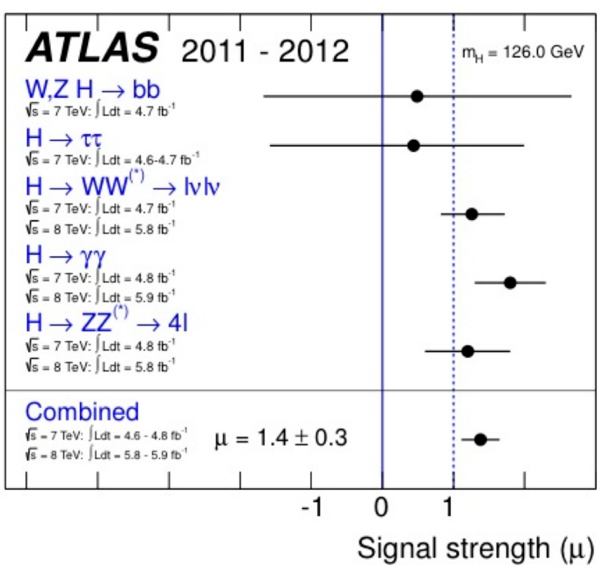
D. de Florian and JM, “Two-loop virtual corrections to Higgs pair production”, Phys. Lett. B 724 (2013) 306 [arXiv:1305.5206 [hep-ph]].

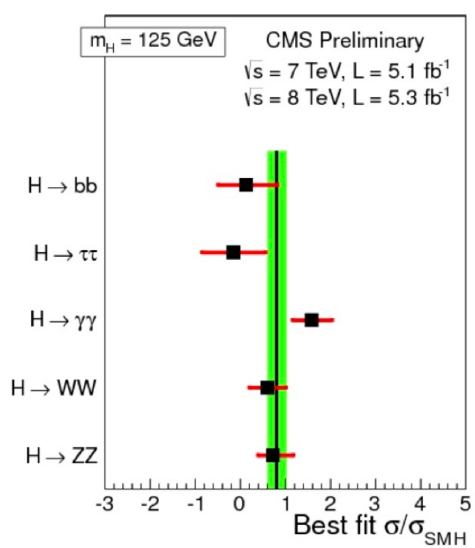
D. de Florian and JM, “Higgs Boson Pair Production at Next-to-Next-to-Leading Order in QCD”, Phys. Rev. Lett. 111 (2013) 201801 [arXiv:1309.6594 [hep-ph]].

Measuring the Higgs self-couplings



- Scalar particle of mass ~126 GeV discovered at the LHC
- Its couplings to fermions and gauge bosons so far compatible with SM Higgs
- No experimental result for the Higgs self-coupling yet





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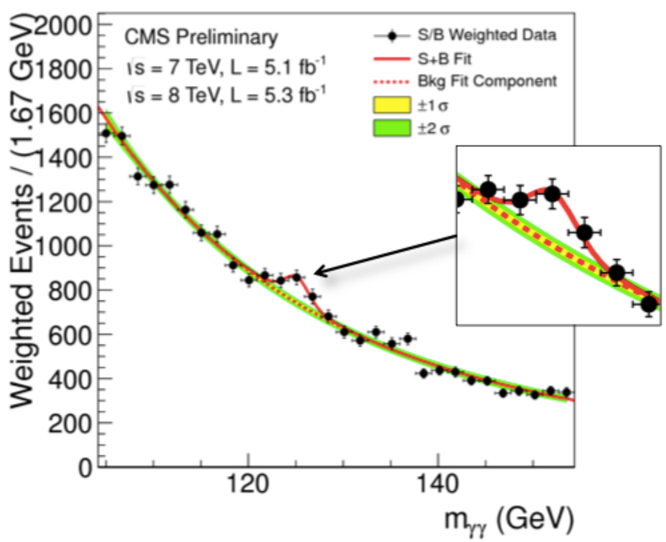
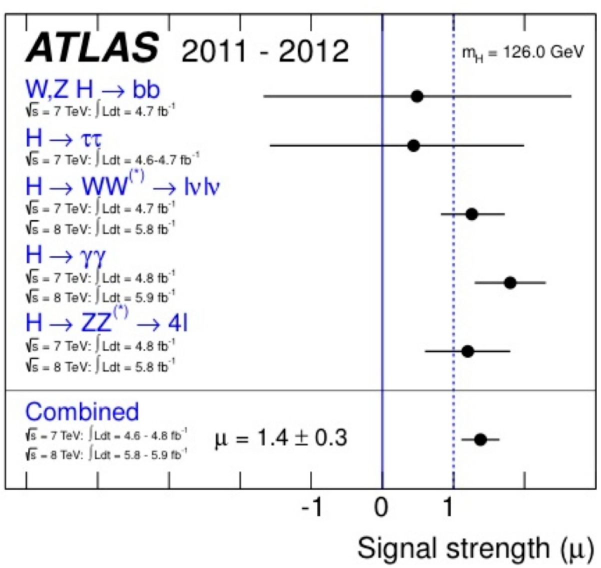
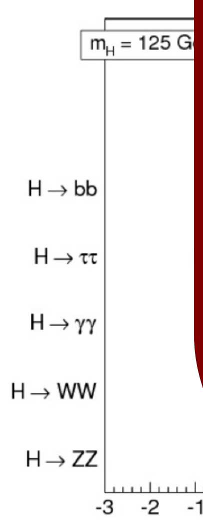
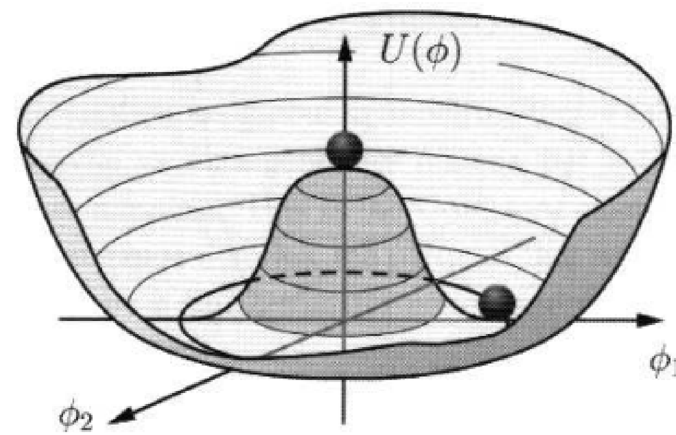






Determined by the Higgs potential



$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda' H^4$$

In the standard model

$$\lambda = \lambda' = M_H^2/(2v^2)$$

Important in order to understand the EWSB

Measuring the Higgs self-couplings

Produce an off-shell Higgs boson that decays into:

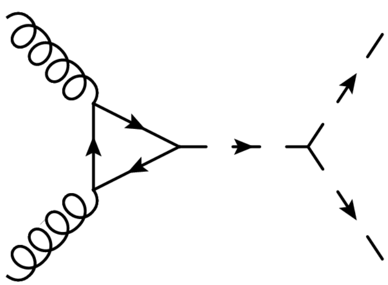
Trilinear coupling

$$H^* \to HH$$

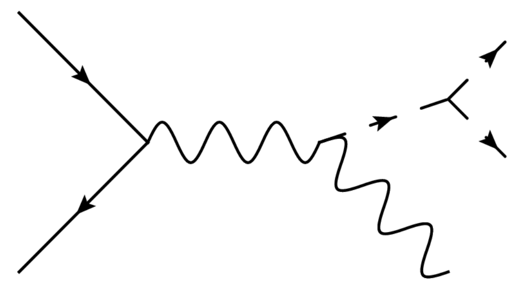
Quartic coupling

$$H^* \to HHH$$

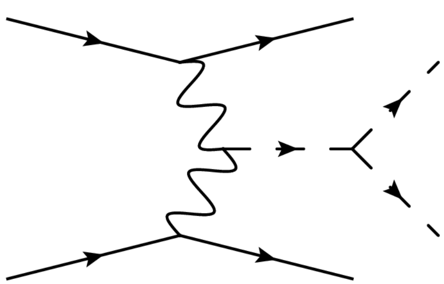
At hadron colliders: same production mechanisms than in the single Higgs case



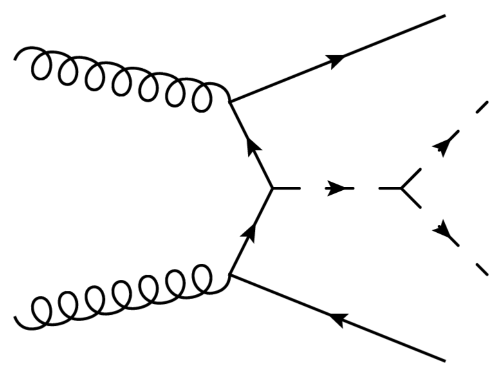
Gluon fusion



Higgs–strahlung



Vector boson fusion

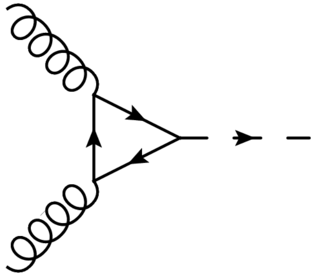


Top pair associated production

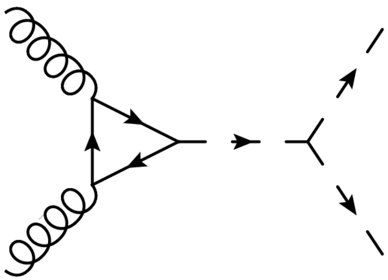
Measuring the Higgs self-couplings

Experimentally very challenging!

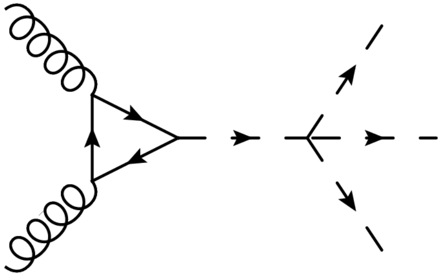
Main problem: small size of the XS



$$\mathcal{O}(\mathrm{pb})$$



$$\mathcal{O}(\mathrm{fb})$$



$$\mathcal{O}(\mathrm{ab})$$

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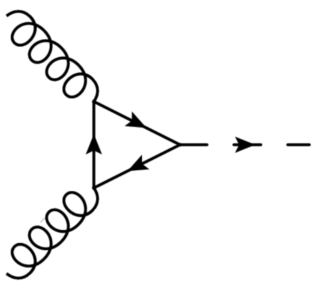
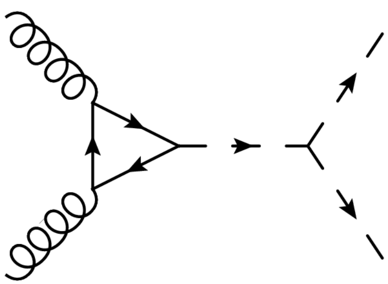


$\mathcal{O}(\text{pb})$



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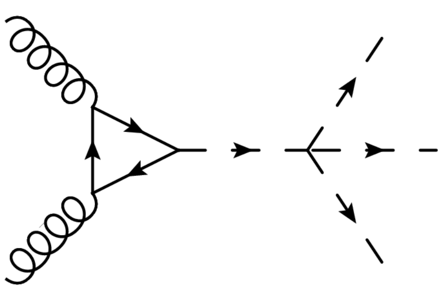

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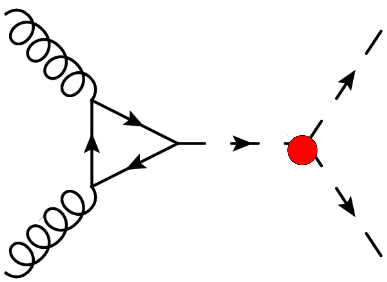
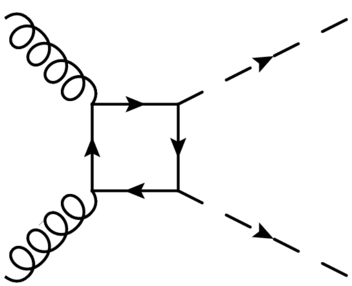
Not all the diagrams are sensitive to the value of the self-coupling



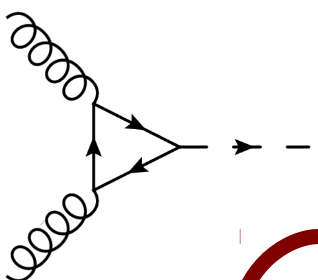


Extracting the self-coupling is even more difficult

Measuring the Higgs self-couplings

Experimentally very challenging!

Main problem: small size of the XS



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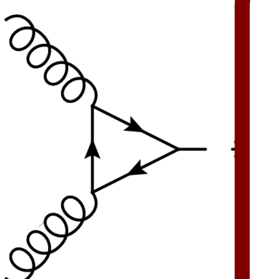

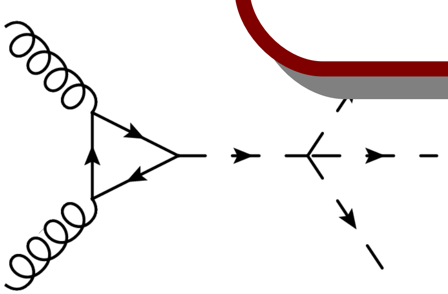

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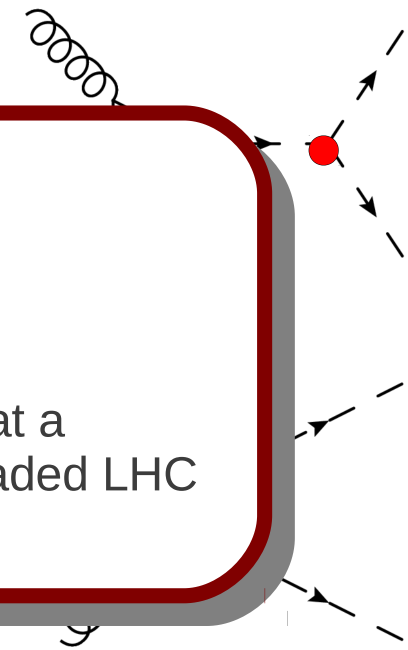

Quartic coupling → Hopeless

Trilinear coupling → Possible at a luminosity-upgraded LHC

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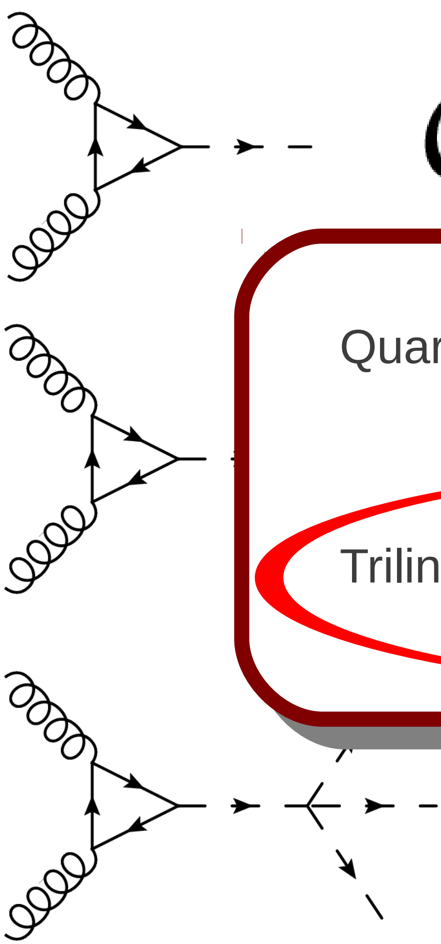

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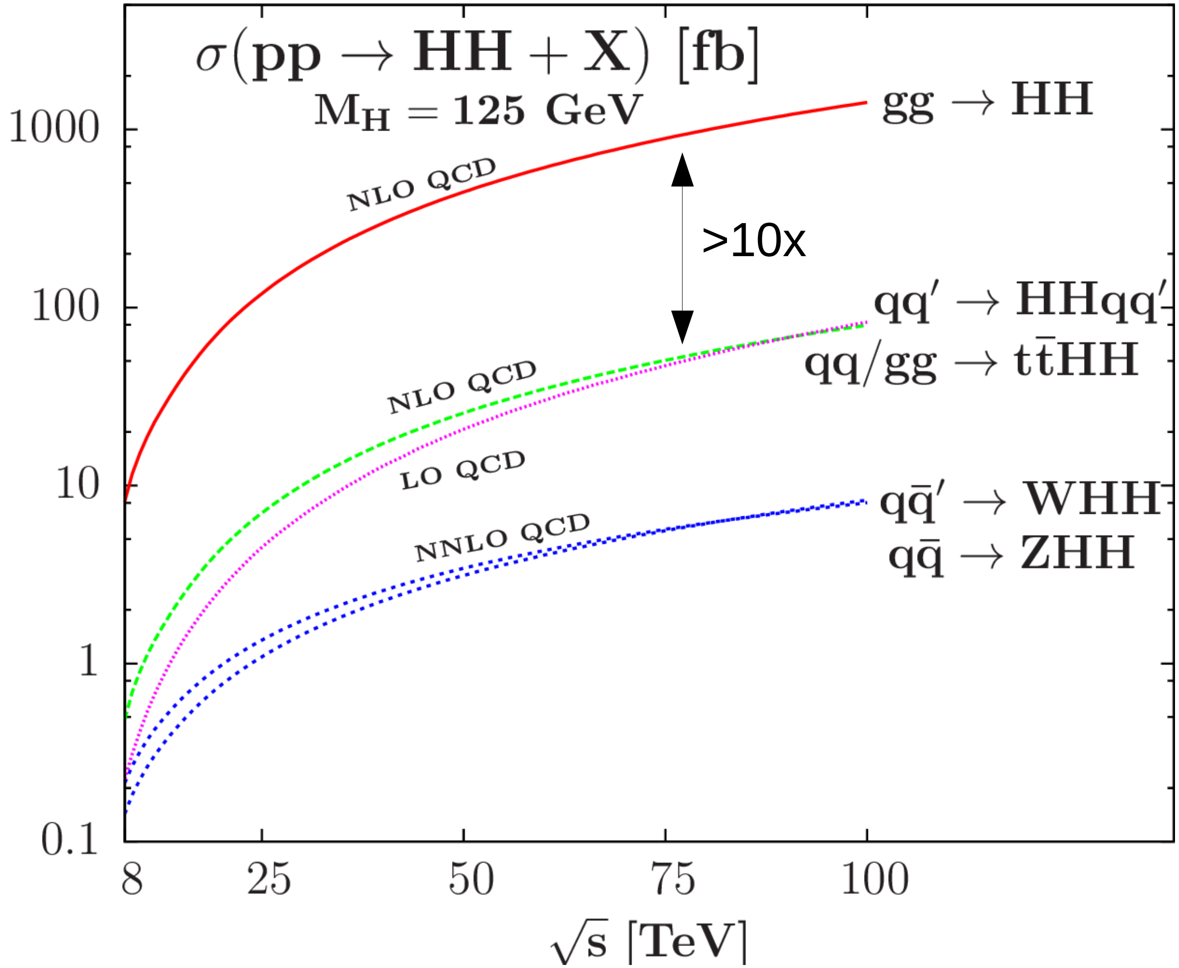
Measuring the Higgs self-couplings

Higgs pair production mechanisms:



Gluon fusion

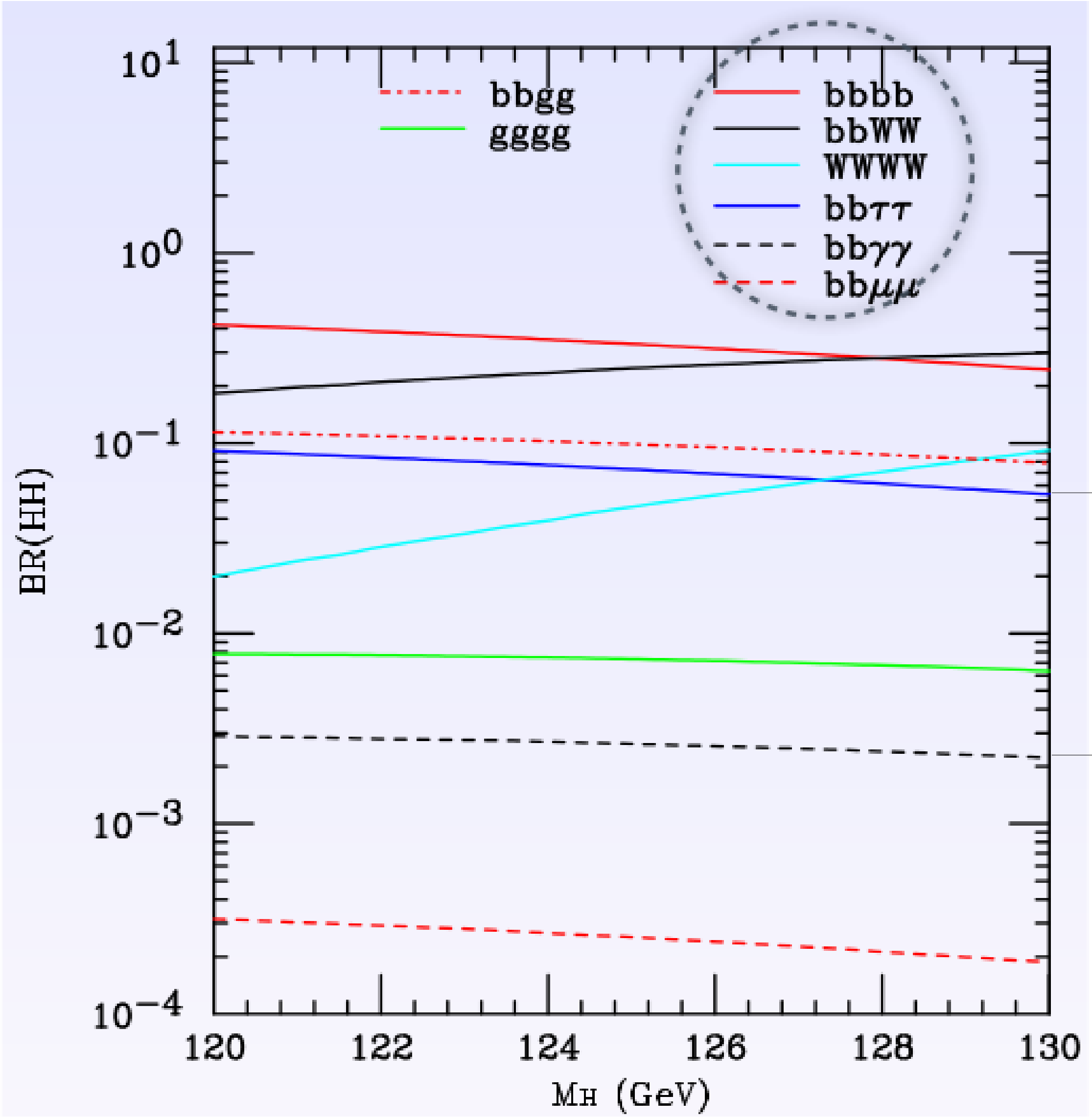
Main production channel

~1000 times smaller than single Higgs XS

J. Baglio, A. Djouadi, R. Gröber, M.M. Mühlleitner, J. Quevillon and M. Spira, "The measurement of the Higgs self-coupling at the LHC: theoretical status," JHEP 1304 (2013) 151 [arXiv:1212.5581 [hep-ph]].

Measuring the Higgs self-couplings

Decay channels:



- Main decay channels: bbbb, bbWW, bbgg
- Huge backgrounds

Most promising channels:

► $HH \to b\bar{b}\tau\bar{\tau}$

► $HH \to b\bar{b}\gamma\gamma$

Measuring the Higgs self-couplings

$\sqrt{S} = 14$ TeV and $\int \mathcal{L} = 3000$ fb^{-1}

Decay channel	Main backgrounds	Significance
$HH \to b\bar{b}\gamma\gamma$ $BR[b\bar{b}\gamma\gamma] = 0.263\%$	$b\bar{b}\gamma\gamma$ $t\bar{t}(\to W^+W^- b\bar{b})H(\to \gamma\gamma)$ $Z(\to b\bar{b})H(\to \gamma\gamma)$	~ 16 (~50 signal events)
$HH \to b\bar{b}\tau\bar{\tau}$ $BR[b\bar{b}\tau\bar{\tau}] = 7.29\%$	$b\bar{b}\tau\bar{\tau}$ $b\bar{b}\tau\bar{\tau}\nu_\tau\bar{\nu}_\tau$ $ZH(\to b\bar{b}\tau\bar{\tau})$	~ 9 (~300 signal events)

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HH ... | | ~ 9

$BR[b\bar{b}\tau\bar{\tau}]$ | $ZH(\to b\bar{b}\tau\bar{\tau})$ | (~300 signal events)

Using these channels

λ_{SM} → $30 - 50\%$ uncertainty

V. Barger et.al., Phys. Lett. B 728 (2014) 433 [arXiv:1311.2931 [hep-ph]].
F. Goertz et.al, JHEP 1306 (2013) 016 [arXiv:1301.3492 [hep-ph]].

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Theoretical predictions (SM Higgs pair production **via gluon fusion**)

- Leading order XS

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- Next-to-leading order XS (large top-mass limit)

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K factor close to 2

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- Finite top-mass effects at NLO

J. Grigo, J. Hoff, K. Melnikov and M. Steinhauser, Nucl. Phys. B 875 (2013) 1 [arXiv:1305.7340 [hep-ph]].

- Matching to parton showers

Q. Li et.al., Phys. Rev. D 89 (2014) 033015 [arXiv:1312.3830 [hep-ph]].

P. Maierhöfer et.al., JHEP 1403 (2014) 126 [arXiv:1401.0007 [hep-ph]].

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D.Y. Shao et.al., JHEP 1307 (2013) 169

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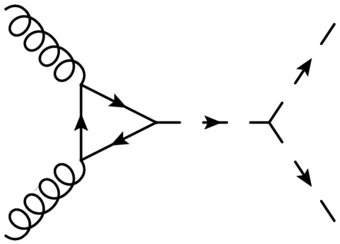
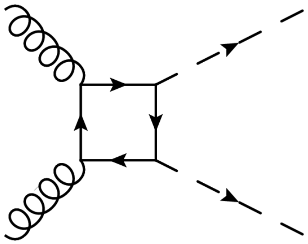
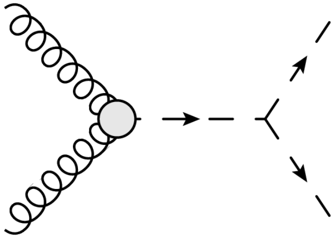
Virtual corrections

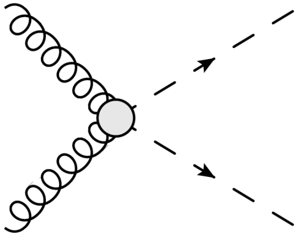
Leading Order (1-loop)





Full theory

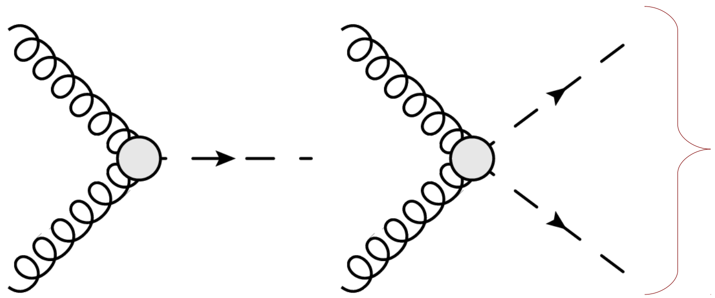




Eff. theory

Virtual corrections

Le

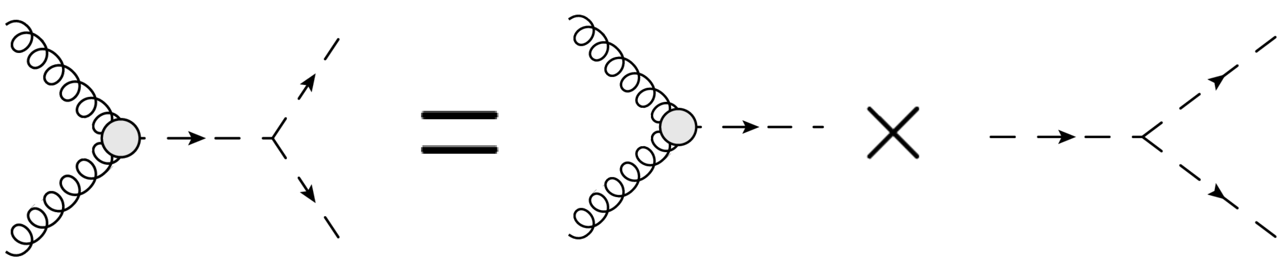


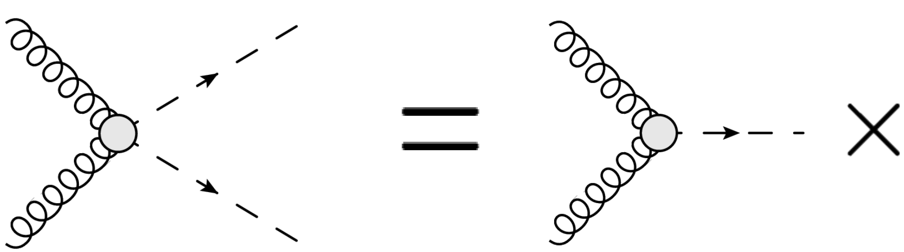
Same structure

$$\mathcal{L}_{ggH} \propto G_{\mu\nu}G^{\mu\nu}H/v$$

$$\mathcal{L}_{ggHH} \propto G_{\mu\nu}G^{\mu\nu}(H/v)^2$$

- We don't need to calculate these diagrams again if we know the single Higgs one:





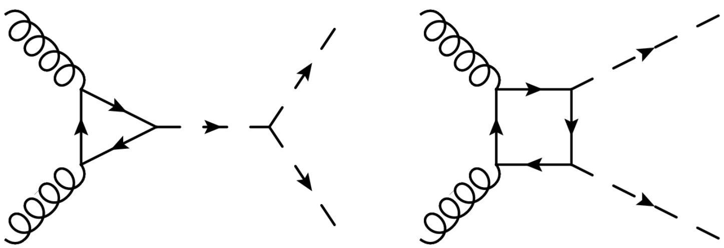
$$\left(-\frac{1}{v}\right)$$

Full theory

Eff. theory

Virtual corrections

Leading Order (1-loop)



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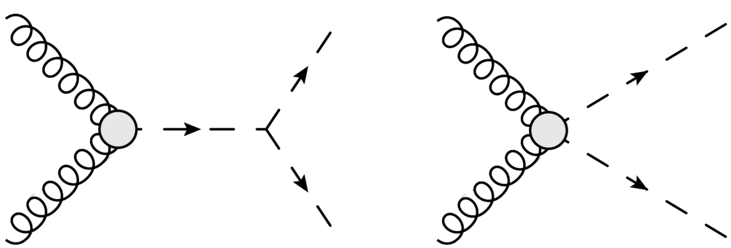
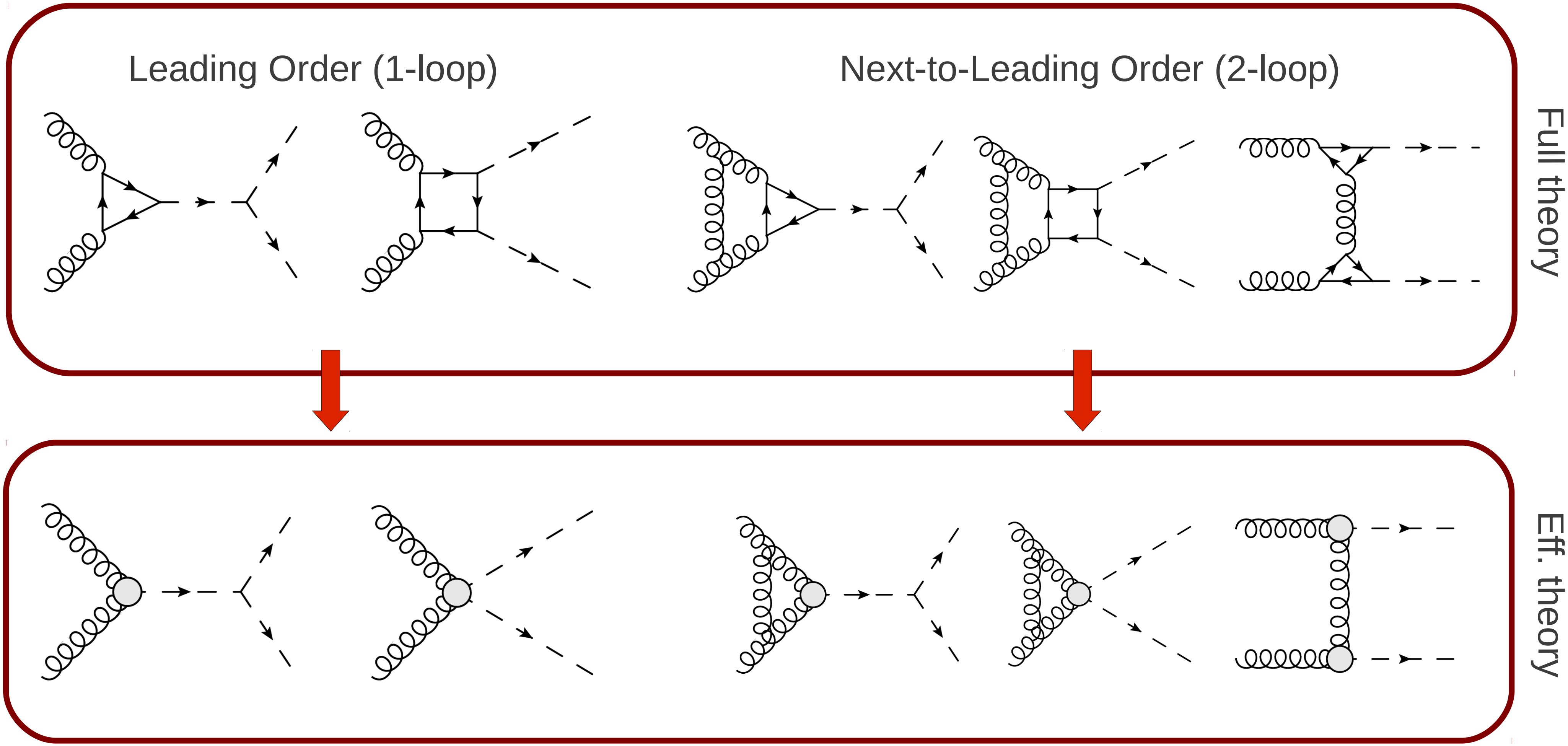


Eff. theory

Virtual corrections



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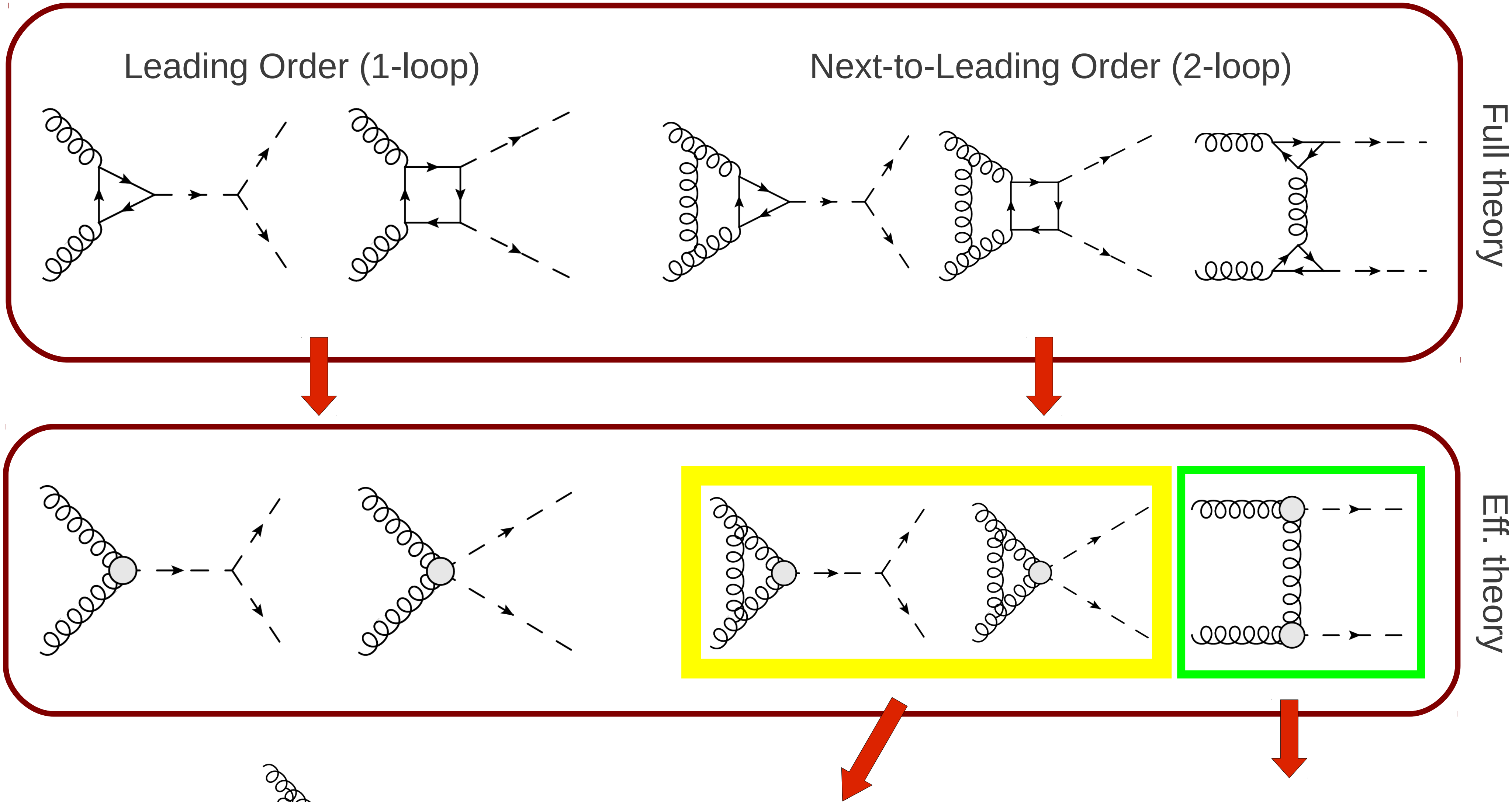
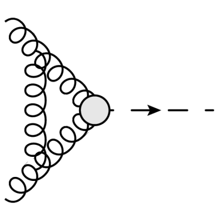


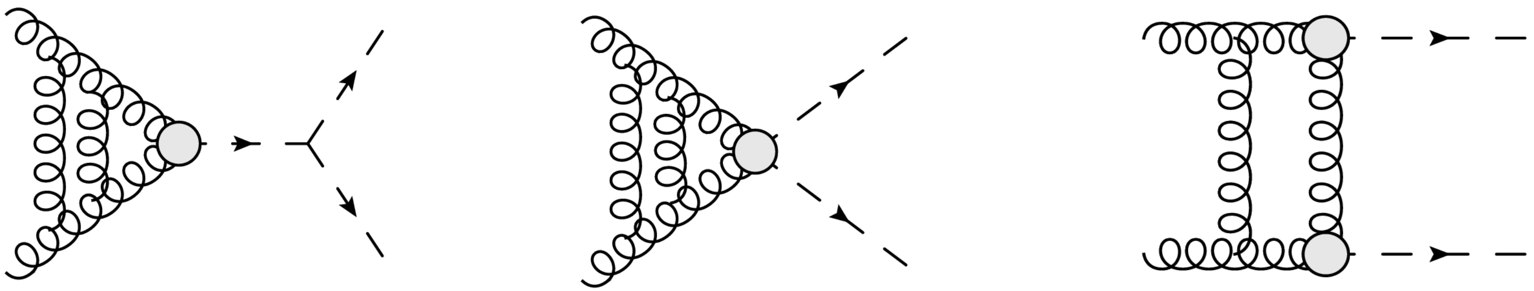


Single Higgs one-loop corrections
(One-loop QCD form factor)

Two-vertices new contribution
Tree level at NLO

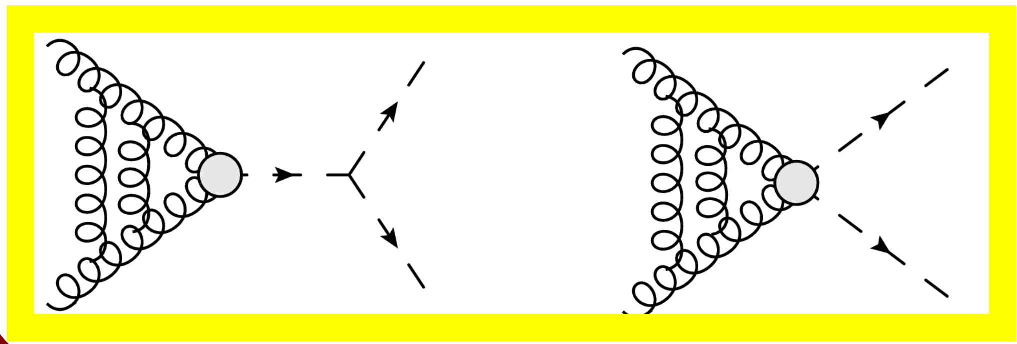
Virtual corrections

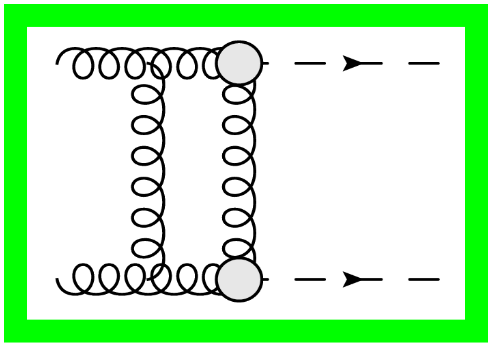
Next-to-Next-to-Leading Order

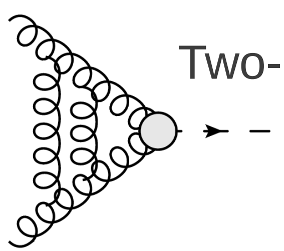


Virtual corrections

Next-to-Next-to-Leading Order





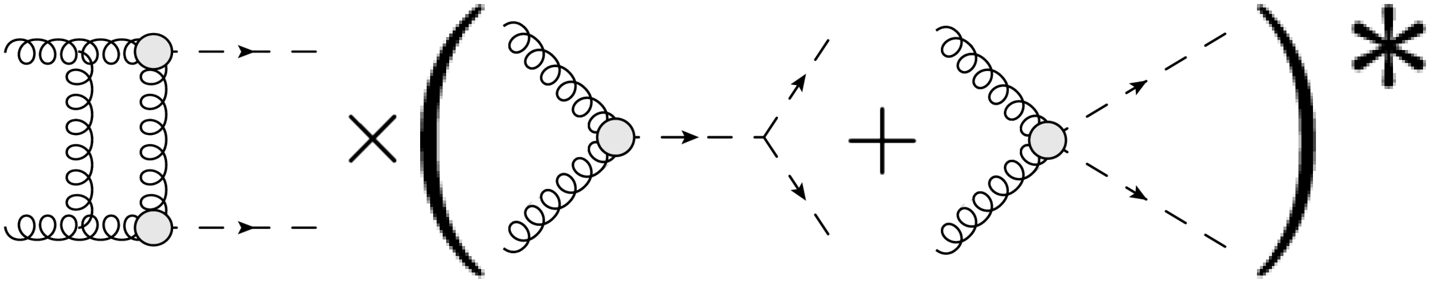


Two-loop form factor

One-loop NNLO contribution

Complexity similar to 2 → 2 process at NLO

Virtual corrections



- FeynArts and FeynCalc → Generate and manipulate the amplitudes $D = 4 - 2\epsilon$

T. Hahn, Comput. Phys. Commun. 140 (2001) 418
R. Mertig et.al., Comput. Phys. Commun. 64 (1991) 345.

- Feynman Integral Reduction (FIRE) → Reduce to Master Integrals

A.V. Smirnov, JHEP 0810 (2008) 107.

Ellis and Zanderighi, JHEP 0802 (2008) 002.

Virtual corrections → IR divergent (double poles)

IR regulated result: $\mathrm{Re}(C_{\mathrm{LO}})\,\mathcal{R}^{(2)} + \mathrm{Im}(C_{\mathrm{LO}})\,\mathcal{I}^{(2)} + \mathcal{V}^{(2)}$ with $C_{LO} = \frac{6\,\lambda\,v^2}{s - M_H^2 + i M_H \Gamma_H} - 1$

$$
\begin{aligned}
\mathcal{V}^{(2)} &= \frac{1}{(3stu)^2}\left[M_H^8(t+u)^2 - 2M_H^4 tu(t+u)^2 + t^2u^2\left(4s^2+(t+u)^2\right)\right] \\
\mathcal{I}^{(2)} &= 4\pi\left(1+\frac{2M_H^4}{s^2}\right)\log\left(\frac{(M_H^2-t)(M_H^2-u)}{t\,u}\right) \\
\mathcal{R}^{(2)} &= -\left(1+\frac{2M_H^4}{s^2}\right)\left\{-\frac{24}{3}\zeta_2 + 2\mathrm{Li}_2\left(1-\frac{M_H^4}{t\,u}\right) + 4\mathrm{Li}_2\left(\frac{M_H^2}{t}\right) + 4\mathrm{Li}_2\left(\frac{M_H^2}{u}\right)\right. \\
&+ \left. 4\log\left(1-\frac{M_H^2}{t}\right)\log\left(-\frac{M_H^2}{t}\right) + 4\log\left(1-\frac{M_H^2}{u}\right)\log\left(-\frac{M_H^2}{u}\right) - \log^2\left(\frac{t}{u}\right)\right\} \\
&+ \frac{4M_H^2}{s} + \frac{314}{9} - \frac{20}{27}N_f - \frac{33-2N_f}{9}\log\left(\frac{t\,u}{s^2}\right)
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$$+\ 4\log\left(1-\frac{M_H^2}{t}\right)\log\left(-\frac{M_H^2}{t}\right) + 4\log\left(1-\frac{M_H^2}{u}\right)\log\left(-\frac{M_H^2}{u}\right) - \log^2\left(\frac{t}{u}\right)\Big\}$$

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$$\mathcal{L}_{\mathrm{eff}} = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu}\left(C_H\frac{H}{v} - C_{HH}\frac{H^2}{v^2}\right)$$

$$C_{HH} = -\frac{1}{3}\frac{\alpha_{\mathrm{S}}}{\pi}\left\{1 + \frac{11}{4}\frac{\alpha_{\mathrm{S}}}{\pi} + \left(\frac{\alpha_{\mathrm{S}}}{\pi}\right)^2 C_{HH}^{(2)} + \mathcal{O}(\alpha_{\mathrm{S}}^3)\right\}$$

- Up to $\mathcal{O}(\alpha_S^2)$ we have $C_H = C_{HH}$
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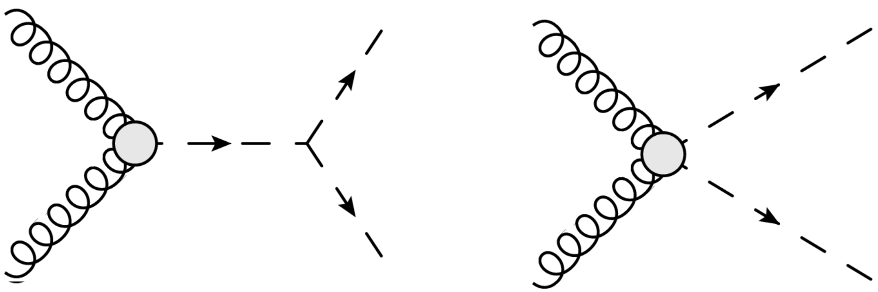
- Up to $\mathcal{O}(\alpha_S^2)$ we have $C_H = C_{HH}$
- $\mathcal{O}(\alpha_S^3)$ corrections to ggHH vertex are still unknown
- Varied in the region $0 \le C_{HH}^{(2)} \le 2C_H^{(2)}$ → ~2% effect

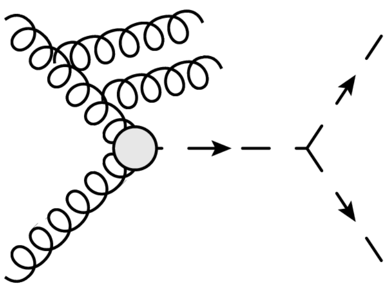
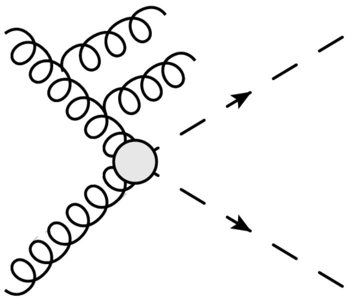
Real corrections

Double real emission



Real corrections

Double real emission

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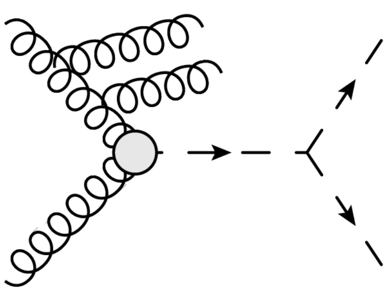

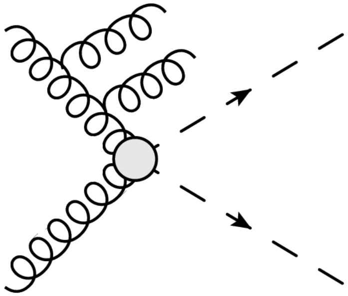

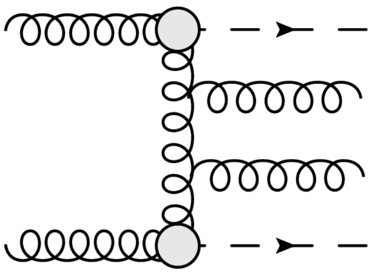

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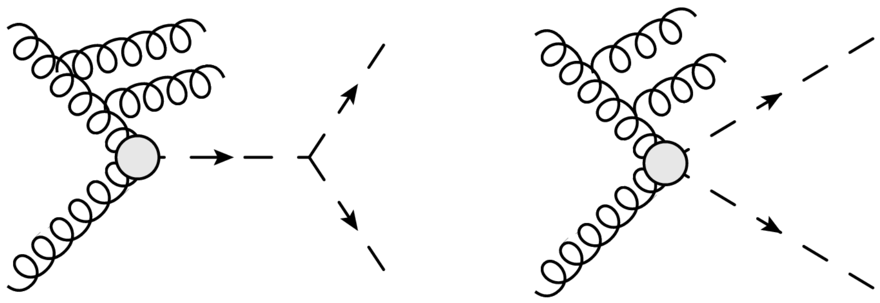
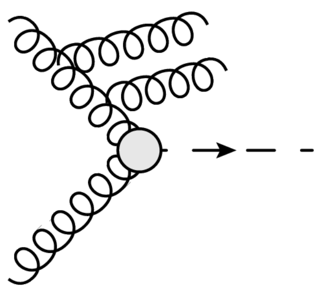
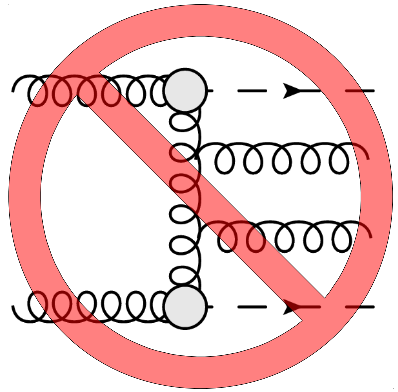


NNLO single Higgs inclusive XS

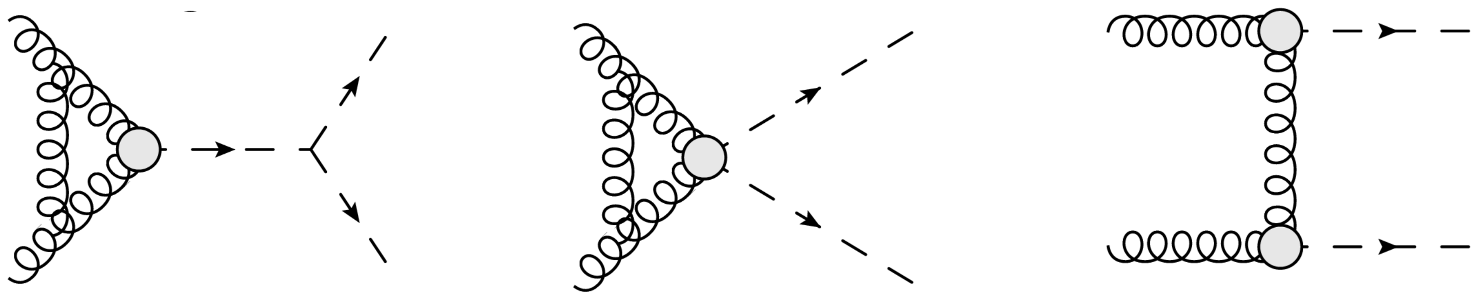




N3LO contribution

Real corrections

"One-loop" corrections to single real emission



Real corrections

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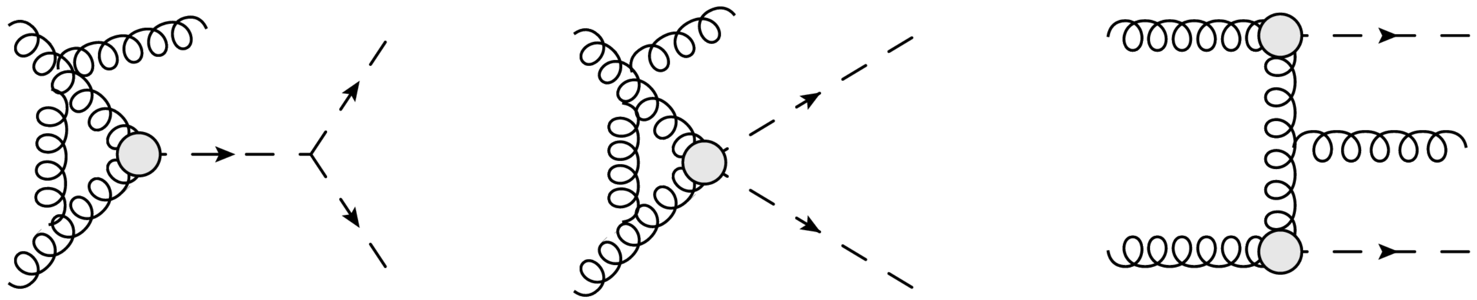

Real corrections

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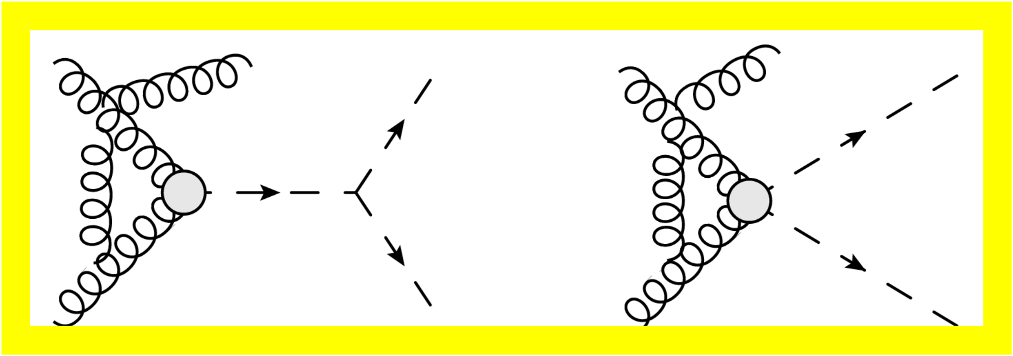

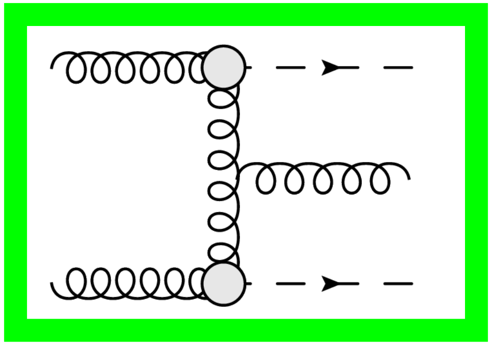

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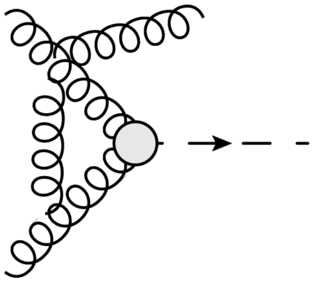
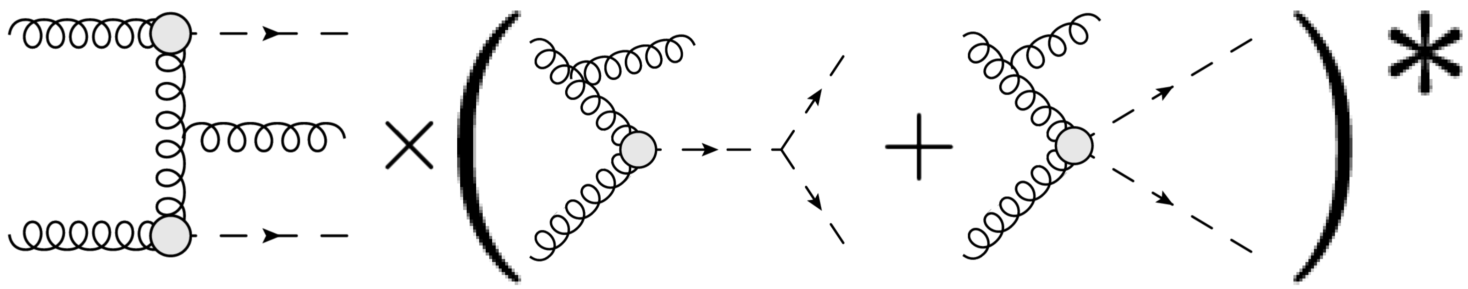


Tree-level
Single soft and collinear sing.

Complexity similar to 2 → 2 process at NLO

Real corrections



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R. Mertig et.al., Comput. Phys. Commun. 64 (1991) 345.

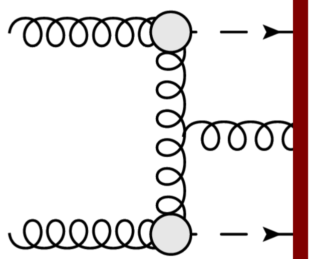
- Frixione, Kunszt and Signer subtraction → Analytical expressions for the poles

Integrate the rest in 4 dimensions

S. Frixione et.al., Nucl. Phys. B 467 (1996) 399.

The same for qg and $q\bar{q}$ (and ghosts) initiated processes

Real correcti



Soft and colinear bahaviour of the ME

$$(1-x)^{-1-2\epsilon}(1-y^2)^{-1-\epsilon} = -\frac{1}{2\epsilon}\,\delta(1-x)\,(1-y^2)^{-1-\epsilon}$$
$$-\frac{2^{-2\epsilon}}{2\epsilon}\left[\delta(1-y)+\delta(1+y)\right]$$
$$\times\left[\left(\frac{1}{1-x}\right)_+ - 2\epsilon\left(\frac{\log(1-x)}{1-x}\right)_+\right]$$
$$+\frac{1}{2}\left(\frac{1}{1-x}\right)_+\left[\left(\frac{1}{1-y}\right)_+ + \left(\frac{1}{1+y}\right)_+\right]$$

Easy to integrate

- FeynArts and Feyn

T. Hahn, Comput. Phys. Commu
R. Mertig et.al., Comput. Phys. Co

- Frixione, Kunszt and Signer subtraction → Analytical expressions for the poles

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The same for qg and $q\bar{q}$ (and ghosts) initiated processes

In short...

Split the calculation: $$Q^2\frac{d\hat{\sigma}}{dQ^2} = \hat{\sigma}^a + \hat{\sigma}^b$$

Single-Higgs like ($\hat{\sigma}^a$)

New topologies with two effective vertices ($\hat{\sigma}^b$)

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$$\hat{\sigma}^a_{ij} = \hat{\sigma}_{LO}\left\{\eta^{(0)}_{ij} + \left(\frac{\alpha_S}{\pi}\right)\eta^{(1)}_{ij} + \left(\frac{\alpha_S}{\pi}\right)^2\left[\eta^{(2)}_{ij} + \delta_{ig}\delta_{jg}\delta(1-z)\frac{2\mathrm{Re}(C_{LO})}{|C_{LO}|^2}(C^{(2)}_H - C^{(2)}_{HH})\right]\right\}$$

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Known coefficients from single Higgs XS

Possible differences in the second order corrections to the effective vertex

$$C_{HH} = -\frac{1}{3}\frac{\alpha_S}{\pi}\left\{1 + \frac{11}{4}\frac{\alpha_S}{\pi} + \left(\frac{\alpha_S}{\pi}\right)^2 C^{(2)}_{HH} + \mathcal{O}(\alpha_S^3)\right\}$$

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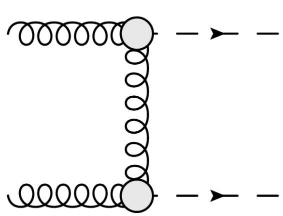
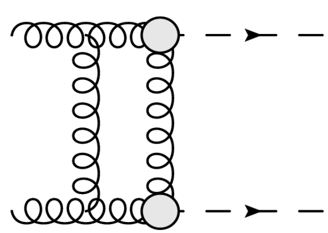
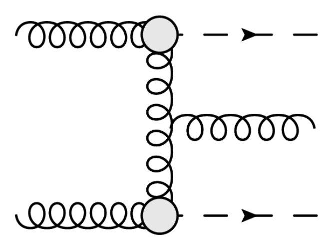
$\hat{\sigma}^b =$  $+$  and 

Starting at NLO

Reduced to MIs

FKS subtraction

Outline

- Measuring Higgs self-coupling
- NNLO inclusive XS
- **Numerical results for the LHC**
- **Conclusions**

D. de Florian and JM, “Two-loop virtual corrections to Higgs pair production”, Phys. Lett. B 724 (2013) 306 [arXiv:1305.5206 [hep-ph]].

D. de Florian and JM, “Higgs Boson Pair Production at Next-to-Next-to-Leading Order in QCD”, Phys. Rev. Lett. 111 (2013) 201801 [arXiv:1309.6594 [hep-ph]].

Numerical results for the LHC

- Central value $\mu_F = \mu_R = Q$ (Higgs pair inv. Mass), and $M_H = 126\ \mathrm{GeV}$
- Scale variation: $0.5Q \leq \mu_F, \mu_R \leq 2Q$ with the constraint $0.5 \leq \mu_F/\mu_R \leq 2$
- MSTW08 parton distributions and QCD coupling
- Exact LO top and bottom-mass dependence normalization

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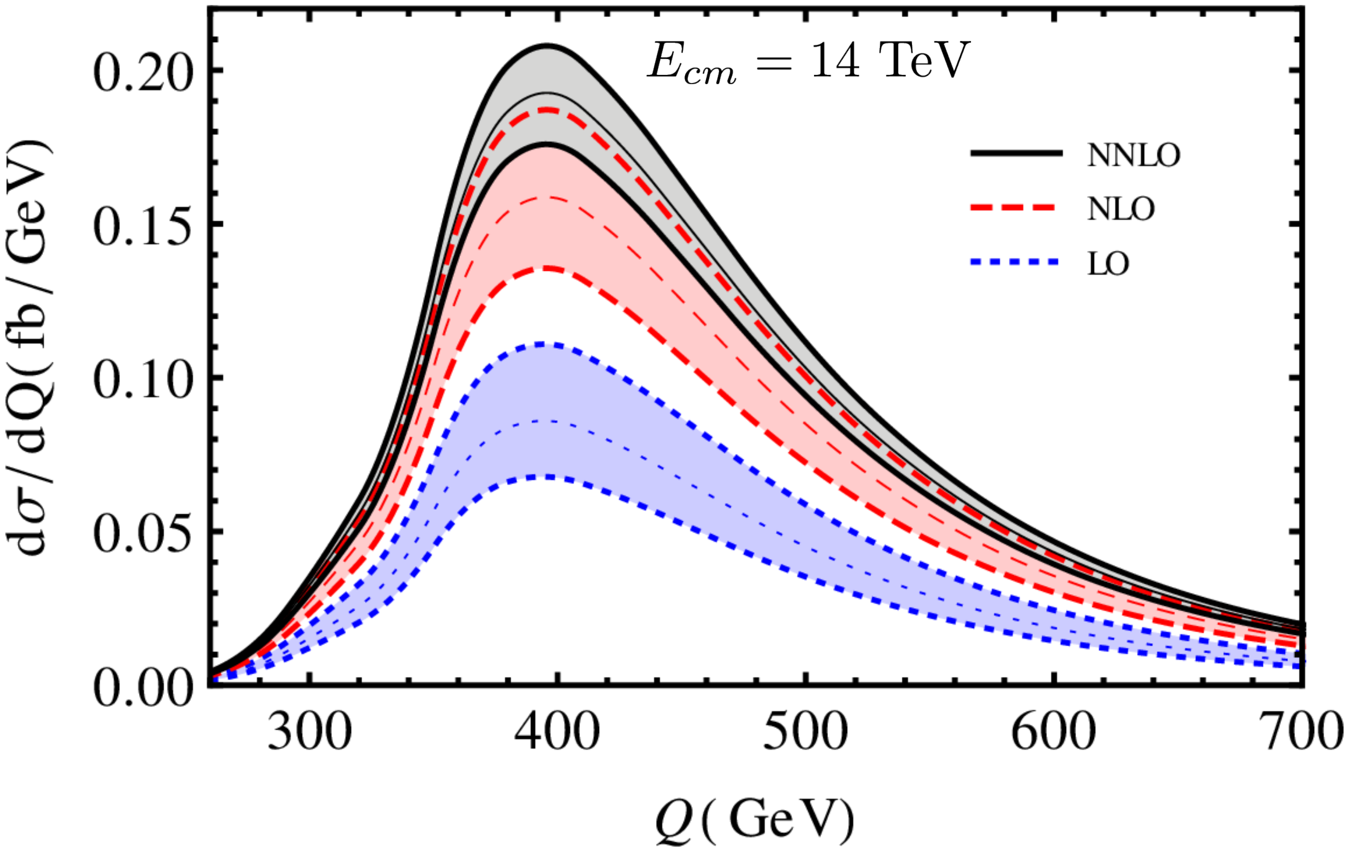

- Overlap between NLO and NNLO bands
- K factor approx. constant

  $K_{\text{NNLO}} = 2.3$

  $\sim 20\%$ increase w.r.t. NLO
- $\pm 8\%$ scale uncertainty

  (2 times smaller than NLO)

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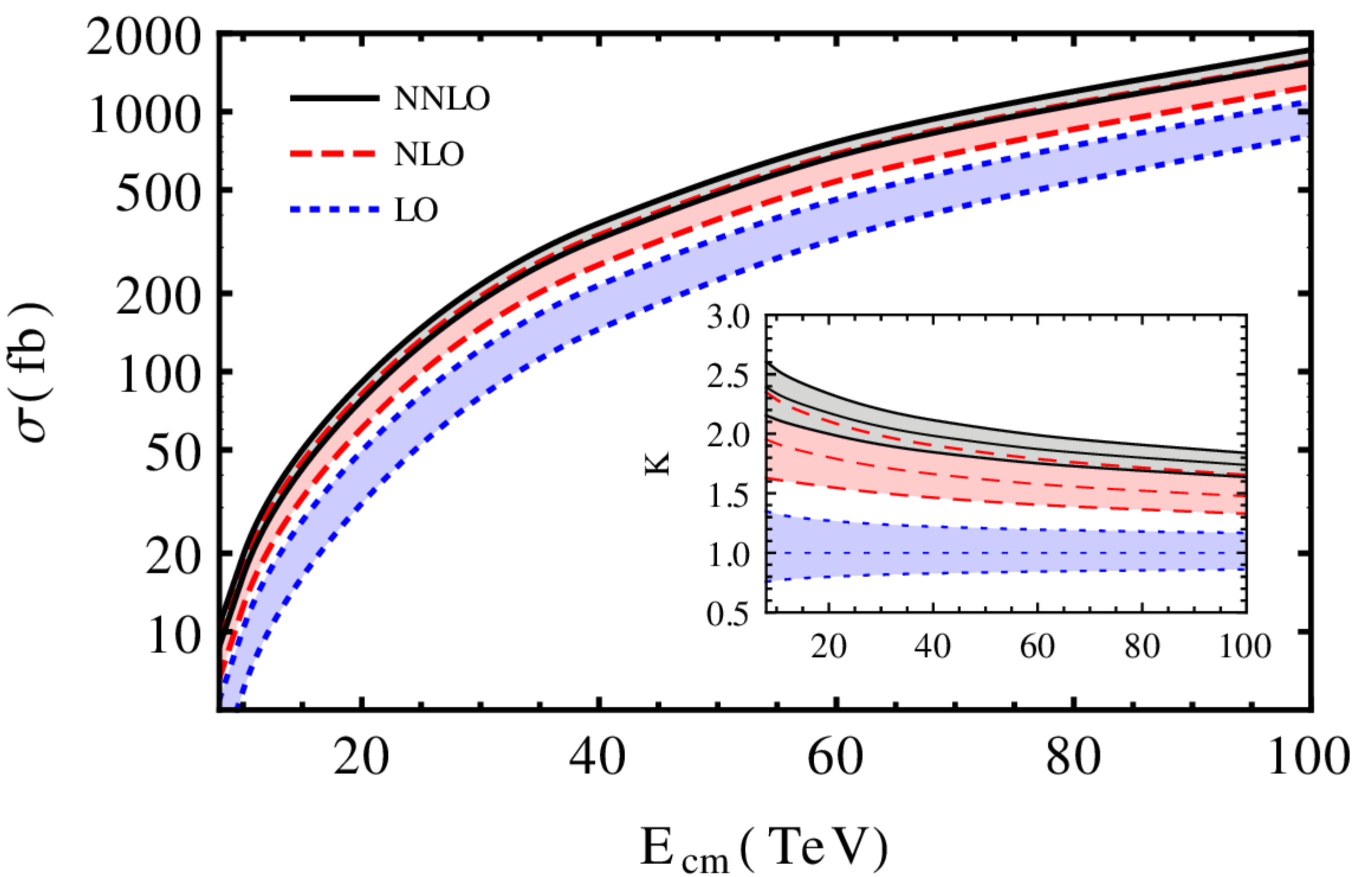

- Overlap between NLO and NNLO bands
- K factor smaller as the center of mass energy increases
- Substantial reduction of the scale uncertainty

Numerical results for the LHC

- Missing higher orders → Scale variation
- Uncertainties in the PDFs and QCD coupling determination → 90% C.L. MSTW08 sets

E_{cm}	8 TeV	14 TeV	33 TeV	100 TeV
$\sigma_{\rm NNLO}$	9.76 fb	40.2 fb	243 fb	1638 fb
Scale [%]	$+9.0 - 9.8$	$+8.0 - 8.7$	$+7.0 - 7.4$	$+5.9 - 5.8$
PDF [%]	$+6.0 - 6.1$	$+4.0 - 4.0$	$+2.5 - 2.6$	$+2.3 - 2.6$
PDF+$\alpha_{\rm S}$ [%]	$+9.3 - 8.8$	$+7.2 - 7.1$	$+6.0 - 6.0$	$+5.8 - 6.0$

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- Total scale unc. drops from 19% (8TeV) to 12% (100TeV)

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- Large difference between PDF and PDF+α_S unc.

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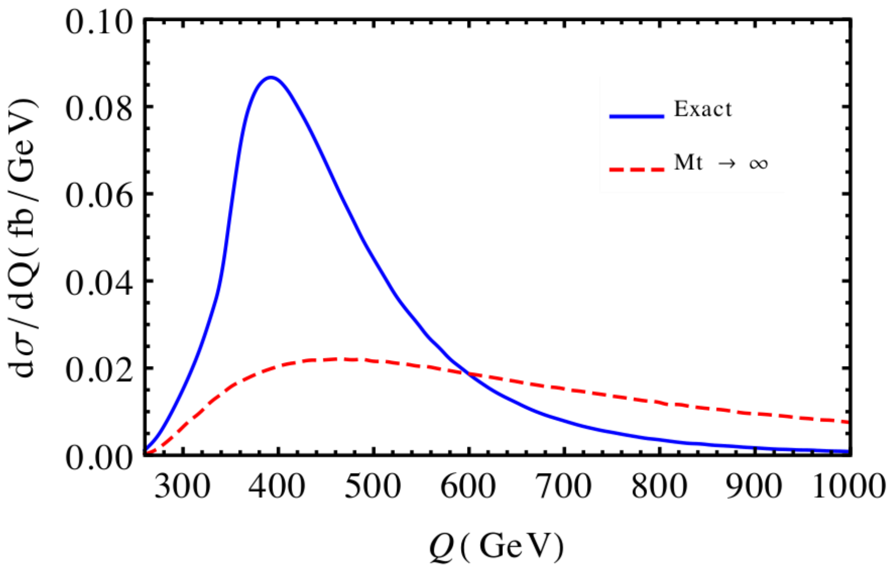
PDF [%]	$+6.0-6.1$	$+4.0-4.0$	$+2.5-2.6$	$+2.3-2.6$
PDF+α_S [%]	$+9.3-8.8$	$+7.2-7.1$	$+6.0-6.0$	$+5.8-6.0$

- Total scale unc. drops from 19% (8TeV) to 12% (100TeV)
- Also non-perturbative unc. drop as E_{cm} increases
- Large difference between PDF and PDF+α_S unc.
- Pert. and non pert. unc. are of the same order

Numerical results for the LHC

- Large top-mass limit works worse than in the single Higgs case (larger inv. Mass)
- Underestimates the LO by a ~20%
- But QCD corrections are dominated by initial state soft radiation, not sensitive to the vertex structure
- Should be reliable to compute the corrections (normalizing with the exact LO)



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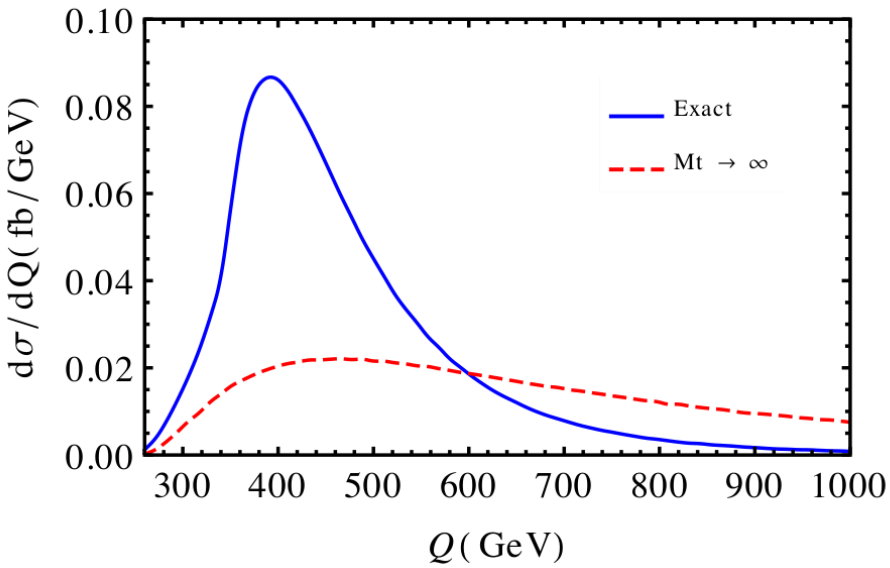


NLO XS (14TeV) → ~10% increase → ~20% in the NLO contribution

If the finite top-mass provides a ~20% effect in the NNLO contribution → O(5%) effect in the NNLO XS

J. Grigo et.al., Nucl. Phys. B 875 (2013) 1 [arXiv:1305.7340 [hep-ph]].

Outline

- Measuring Higgs self-coupling
- NNLO inclusive XS
- Numerical results for the LHC
- **Conclusions**

D. de Florian and JM, “Two-loop virtual corrections to Higgs pair production”, Phys. Lett. B 724 (2013) 306 [arXiv:1305.5206 [hep-ph]].

D. de Florian and JM, “Higgs Boson Pair Production at Next-to-Next-to-Leading Order in QCD”, Phys. Rev. Lett. 111 (2013) 201801 [arXiv:1309.6594 [hep-ph]].

Conclusions

- We computed the NNLO corrections to the inclusive Higgs pair production XS for the gluon fusion production channel.
- We worked within the large top-mass approximation (normalizing our results with the exact LO).
- We found an increase of ~20% w.r.t. the NLO prediction (E_{cm}=14TeV).
- The scale uncertainty is substantially reduced (~17%), and we found an overlap with the previous order result.
- PDFs and α_S uncertainties are of the same order.
- Finite top-mass effects are estimated to be O(5%) at 14 TeV.

Conclusions

Future:

- Compute the two-loop corrections to the effective vertex ggHH.
- Exclusive NNLO calculation.
- Study the accuracy of the large top-mass limit for distributions.

Thanks!

Backup

- Impact on the self-coupling determination studies:

λ_{SM} → $\sim 40\%$ uncertainty with NLO XS

$\sim 30\%$ uncertainty with NNLO XS

V. Barger et.al., Phys. Lett. B 728 (2014) 433 [arXiv:1311.2931 [hep-ph]].

- Soft-virtual approximation at NNLO
(delta and plus distributions in Mellin space)

  - Overestimates the total NNLO result by less than a 2%
  - Better than in the single Higgs case (larger inv. Mass, closer to the threshold)

Backup

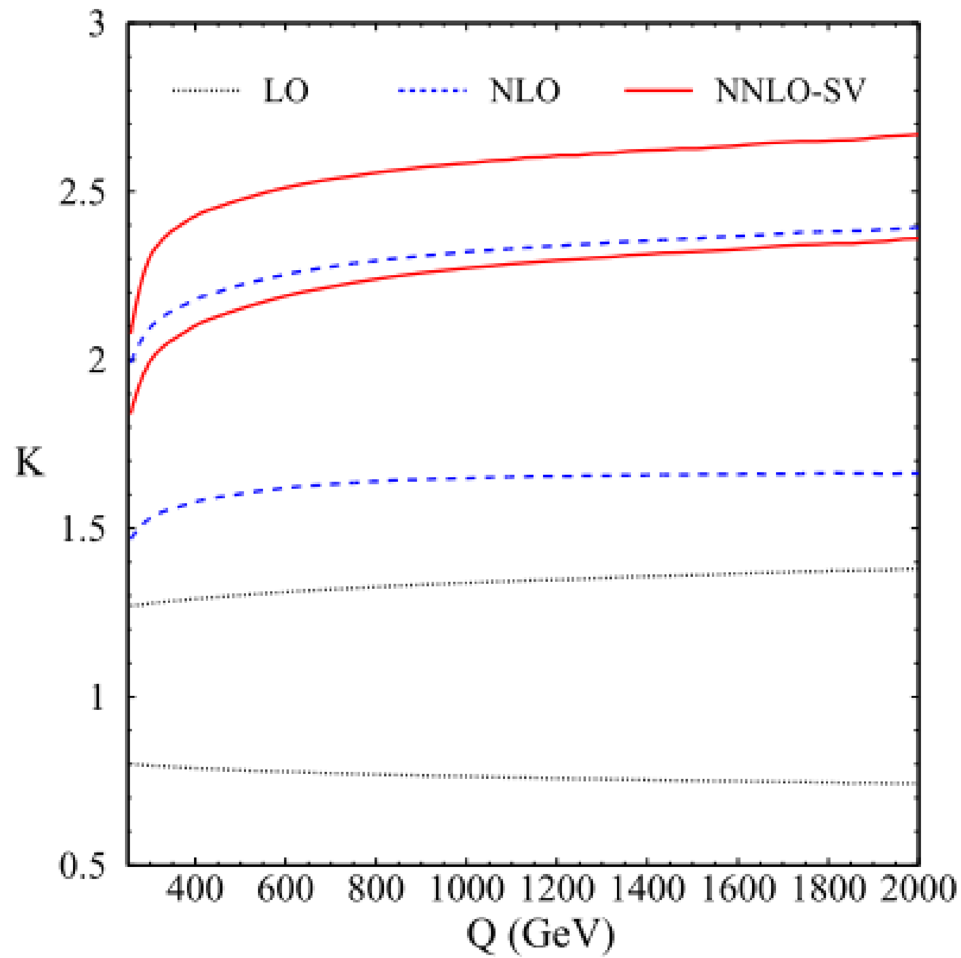
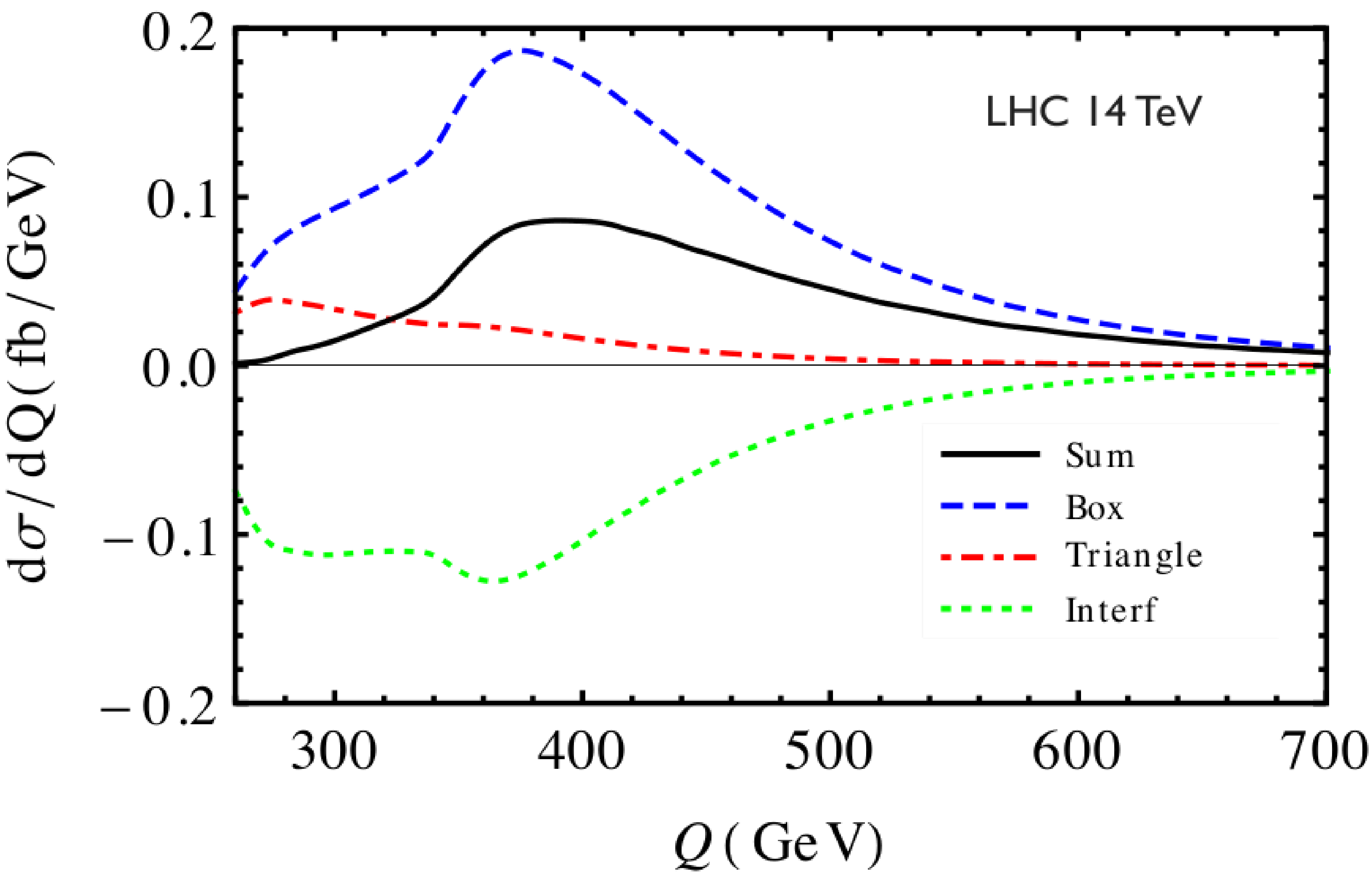
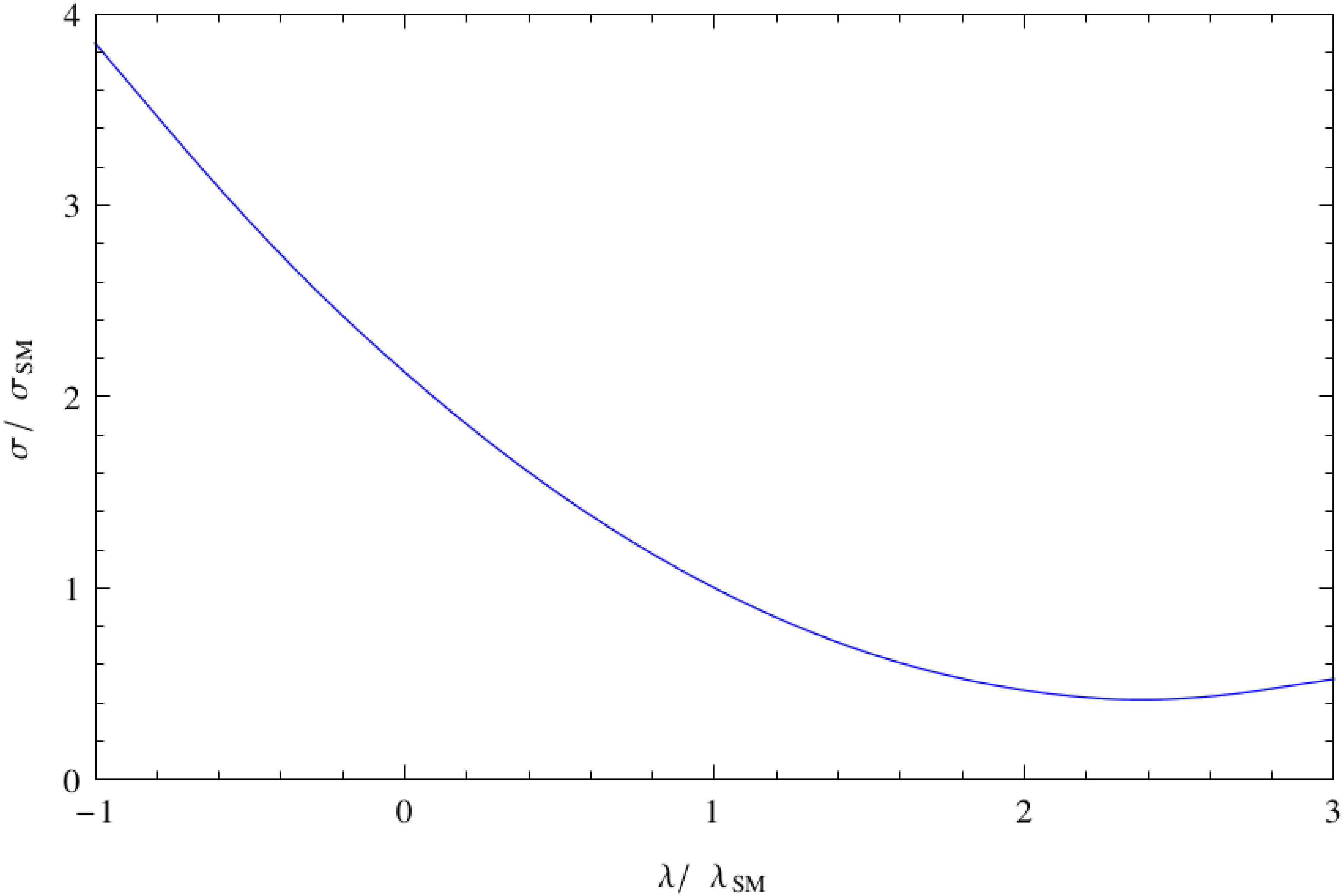


Figure 2: K-factors for Higgs pair production at the LHC as a function of the Higgs pair invariant mass Q. The bands are obtained by varying the renormalization and factorization scales as described in the main text.

Backup


LHC 14 TeV
Sum
Box
Triangle
Interf
0.2
0.1
0.0
– 0.1
– 0.2
300
400
500
600
700
dσ / dQ(fb / GeV)
Q (GeV)

Backup



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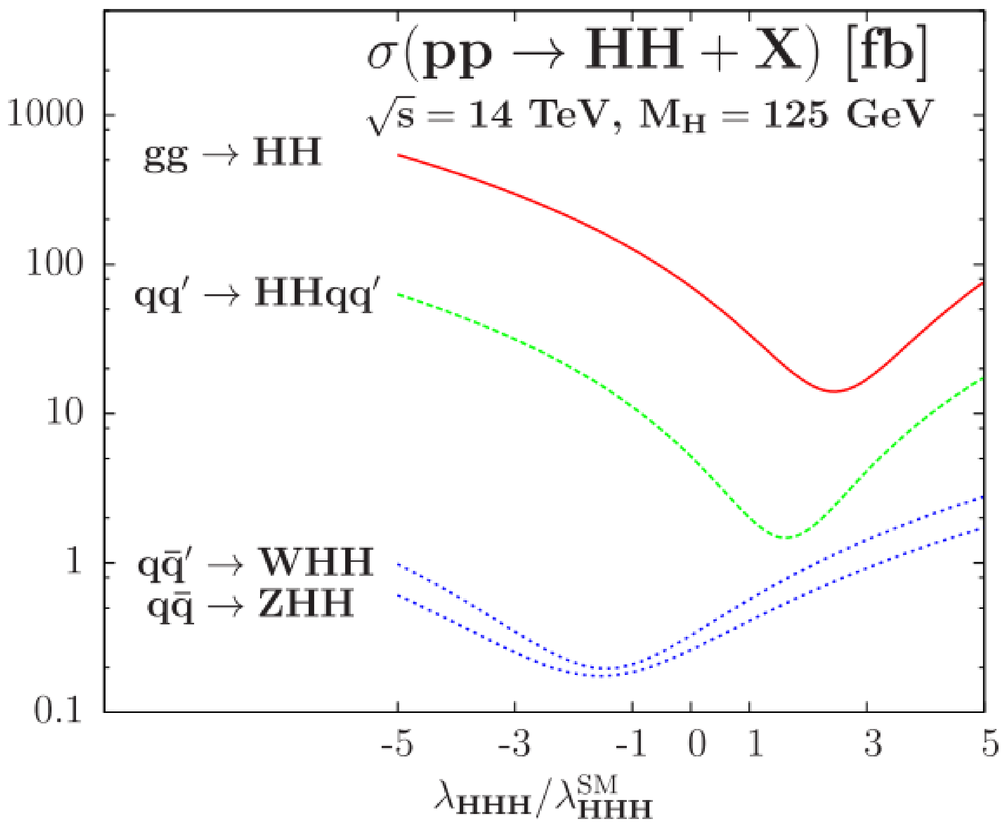
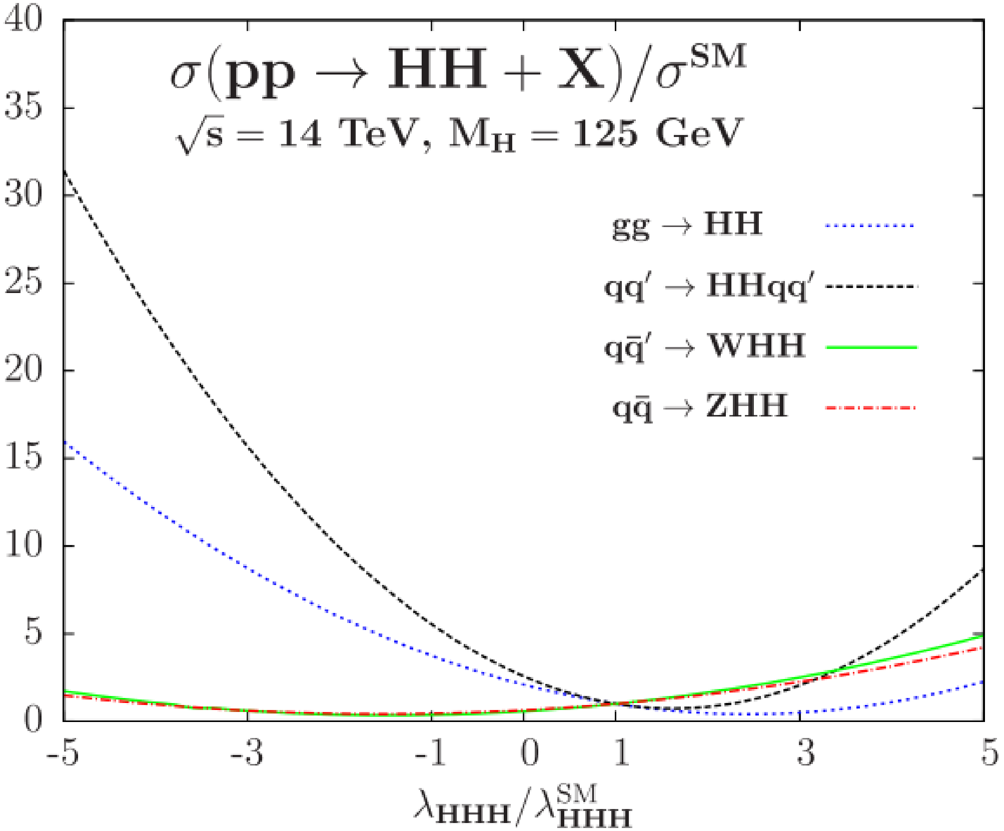


σ(pp → HH + X) [fb]
√s = 14 TeV, M_H = 125 GeV
gg → HH
qq′ → HHqq′
qq̄′ → WHH
qq̄ → ZHH
1000
100
10
1
0.1
-5
-3
-1
0
1
3
5
λ_HHH/λ_HHH^SM



σ(pp → HH + X)/σ^SM
√s = 14 TeV, M_H = 125 GeV
gg → HH
qq′ → HHqq′
qq̄′ → WHH
qq̄ → ZHH
40
35
30
25
20
15
10
5
0
-5
-3
-1
0
1
3
5
λ_HHH/λ_HHH^SM

Backup

	HH	$b\bar{b}\gamma\gamma$	$t\bar{t}\gamma\gamma$	ZH	S/B	$S/\sqrt{B}$
Cross-section NLO [fb]	8.92×10^{-2}	5.05×10^{3}	1.39	3.33×10^{-1}	1.77×10^{-5}	6.87×10^{-2}
Reconstructed Higgs from bs	4.37×10^{-2}	4.01×10^{2}	8.70×10^{-2}	1.24×10^{-3}	1.09×10^{-4}	1.20×10^{-1}
Reconstructed Higgs from γs	3.05×10^{-2}	1.78	2.48×10^{-2}	3.73×10^{-4}	1.69×10^{-2}	1.24
Cut on M_{HH}	2.73×10^{-2}	3.74×10^{-2}	7.45×10^{-3}	1.28×10^{-4}	6.07×10^{-1}	7.05
Cut on $P_{T,H}$	2.33×10^{-2}	3.74×10^{-2}	5.33×10^{-3}	1.18×10^{-4}	5.44×10^{-1}	6.17
Cut on η_H	2.04×10^{-2}	1.87×10^{-2}	3.72×10^{-3}	9.02×10^{-5}	9.06×10^{-1}	7.45
Cut on $\Delta R(b,b)$	1.71×10^{-2}	0.00	3.21×10^{-3}	7.44×10^{-5}	5.21	16.34

$$\begin{aligned} M_{HH} &> 350 \text{ GeV} \\ P_{T,H} &> 100 \text{ GeV} \\ |\eta_H| &< 2 \\ \Delta R(b,b) &< 2.5 \end{aligned}$$

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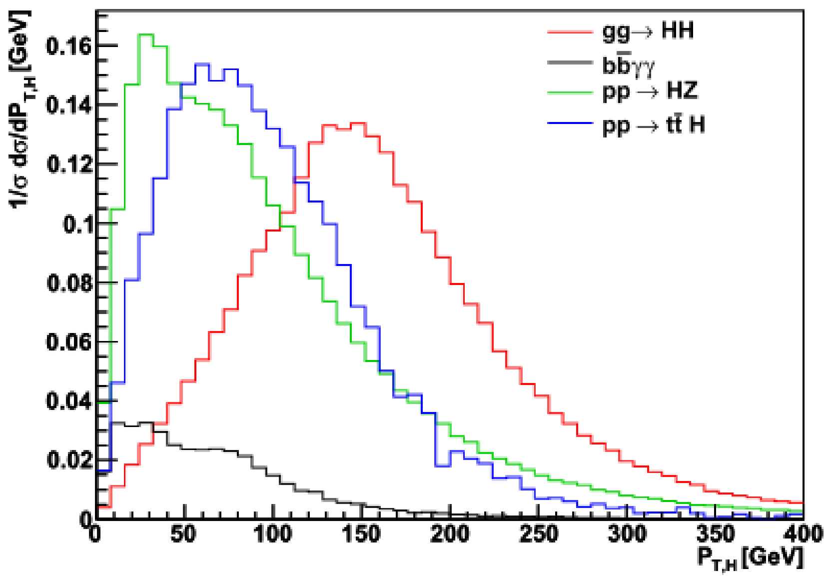

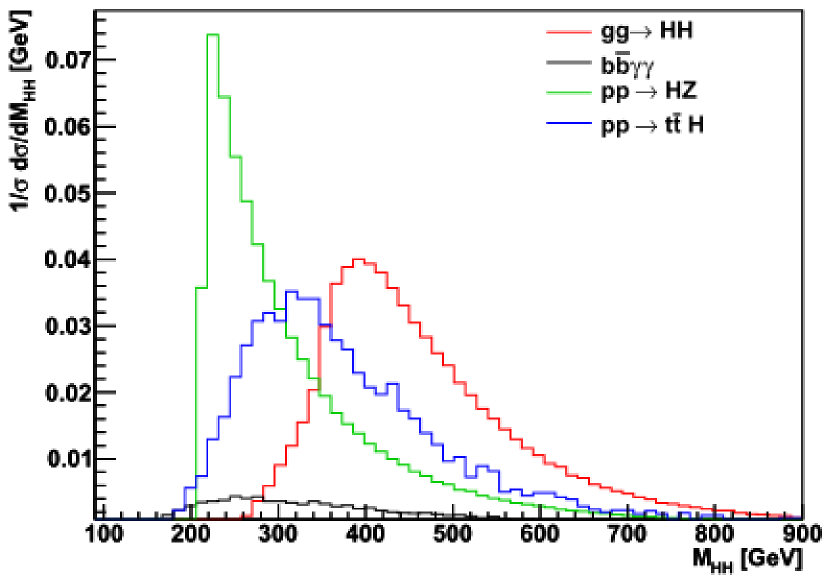

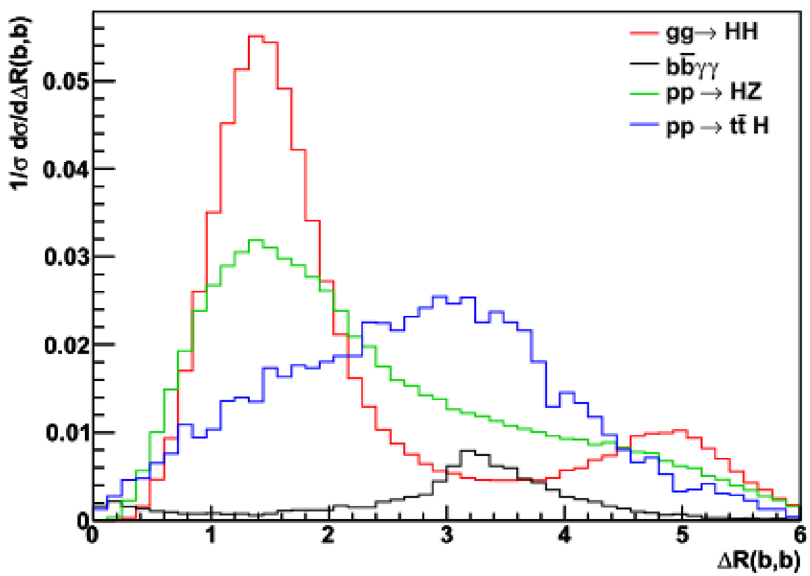

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\end{aligned}
$$

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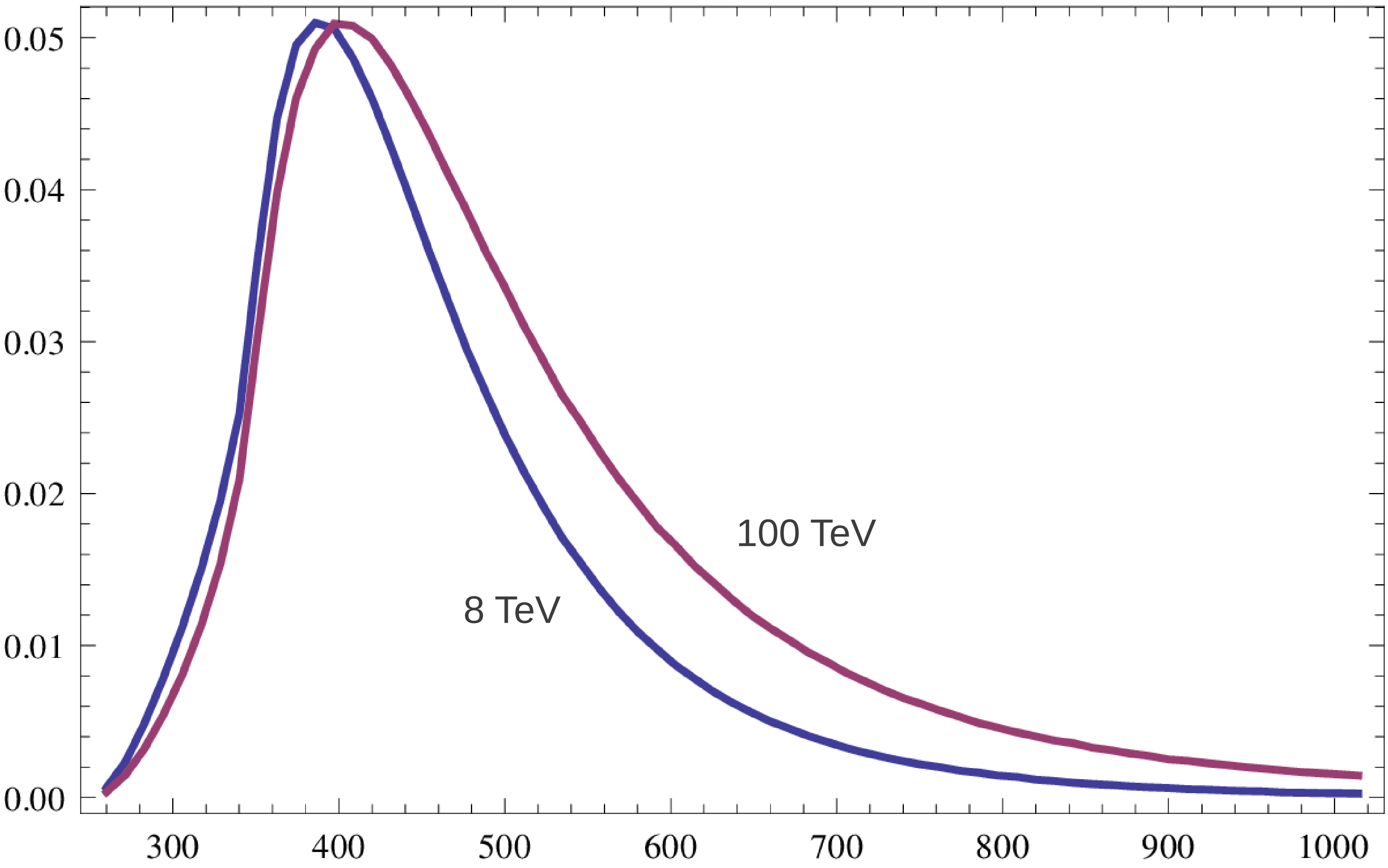
0.05
0.04
0.03
0.02
0.01
0.00
300
400
500
600
700
800
900
1000
100 TeV
8 TeV