Status and future prospects for Higgs production computations

Claude Duhr

Rencontres du Vietnam 2014: Physics at LHC and beyond
Quy Nhon, 15 August 2014

BEH physics at LHC

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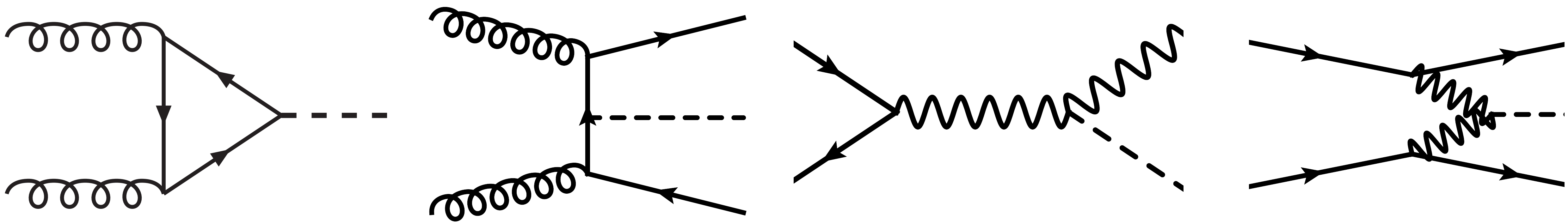

Gluon fusion TTH Higgs strahlung VBF

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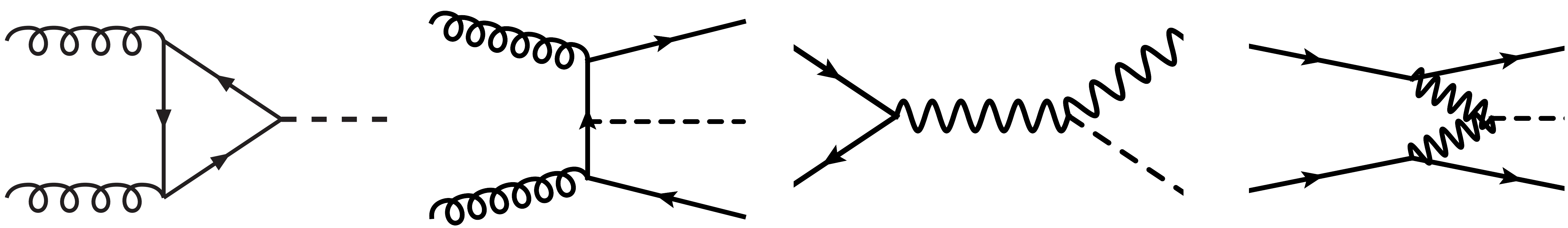

Gluon fusion TTH Higgs strahlung VBF

- Current status for the total cross section: [D. André @ ICHEP 2014]

$$\sigma/\sigma_{\rm SM} = 1.00 \pm 0.13\ \left[\pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.})\right]$$

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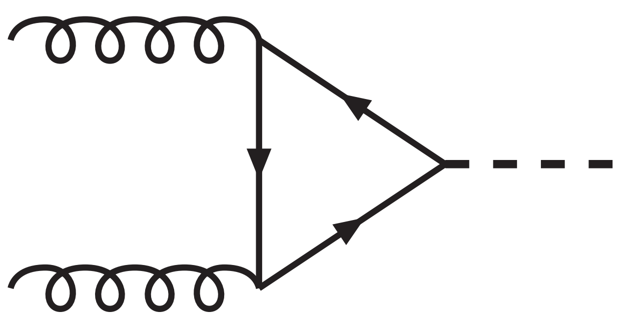
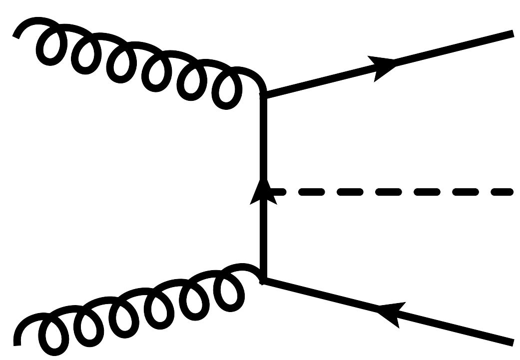
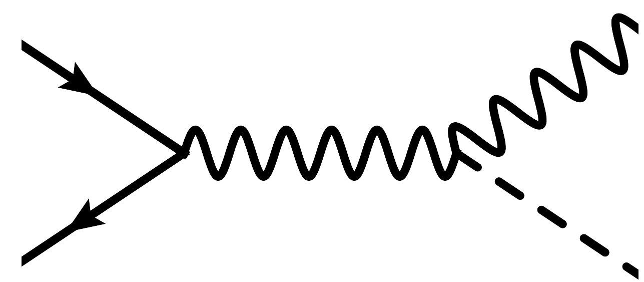


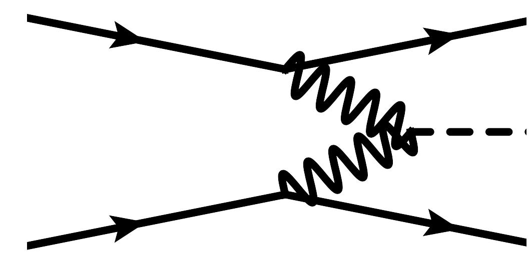
Gluon fusion



TTH



Higgs strahlung



VBF

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➡ Theo. and exp. uncertainties are of the same order.

➡ Need to improve our theory predictions!

Outline

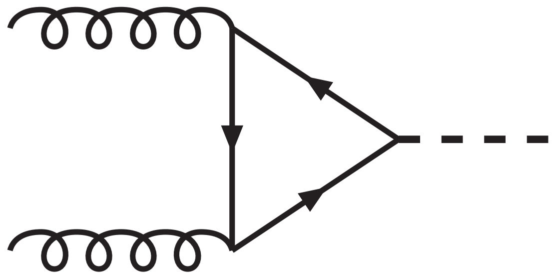
- There is a need to improve our theoretical predictions!
  - ➡ Requires higher order computations!

- Outline:
  - ➡ The gluon fusion cross section: Status
  - ➡ NNLO corrections to H + jet and Higgs pairs.
  - ➡ Towards N3LO corrections to inclusive Higgs production.

The gluon fusion cross section: Status

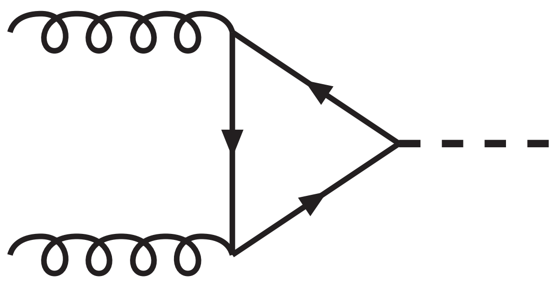
Gluon fusion

- The dominant Higgs production mechanism at the LHC is gluon fusion.



- Loop induced process!
  - ➡ Leads to technical complications!

Gluon fusion



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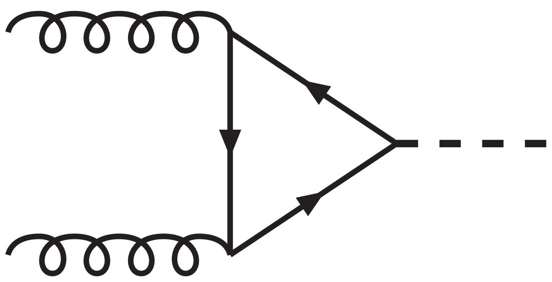
Gluon fusion



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- Loop induced process!
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- Complication 1:
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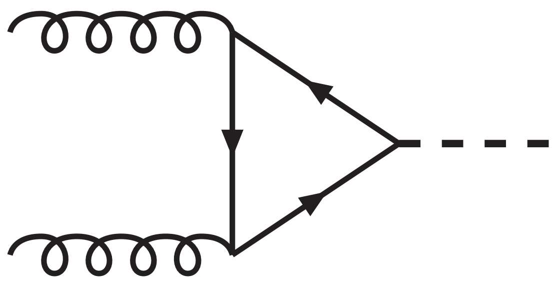
- Complication 2:
  Loops with massive virtual particles are generically beyond the state-of-the-art starting at two loops.

Gluon fusion



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- Loop induced process!

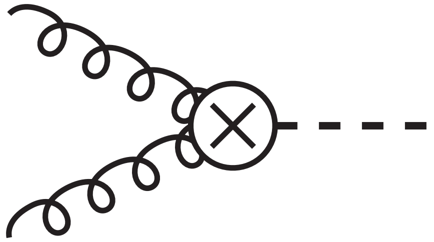
  ➡ Leads to technical complications!
- Complication 1:
  Everything is shifted by one loop order.
- Complication 2:
  Loops with massive virtual particles are generically beyond the state-of-the-art starting at two loops.
- Conclusion:

  Higher-order computations for gluon fusion are extremely difficult!

Gluon fusion

- For a light Higgs boson, the dimension five operator describing a tree-level coupling of the gluons to the Higgs boson

$$\mathcal{L} = \mathcal{L}_{QCD,5} - \frac{1}{4v} C_1 \, H \, G^a_{\mu\nu} \, G_a^{\mu\nu}$$



- Benefit: Removes both complications in one go!

Gluon fusion

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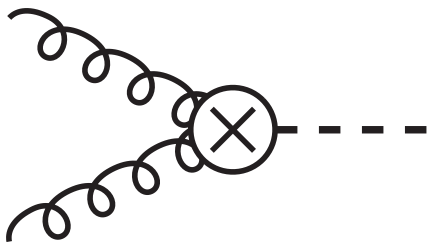


- Benefit: Removes both complications in one go!
- If we aim for precision, how good is this 'crude' approximation..?
  - ➡ Corrections in the top mass can be systematically computed.
  - ➡ Experience from NNLO shows that this approximation works amazingly well!
- Caveat! This is not true if other scales are involved that can be higher than the top threshold!

Gluon fusion: Status

- Status of the inclusive cross section:
  - ➡ NLO corrections including full top-mass effects.
  - ➡ NNLO corrections in effective theory.
  - ➡ Top mass corrections at NNLO.
  - ➡ Leading electroweak corrections.
  - ➡ Resummation up to NNLL.
- Fully differential cross sections are available up to NNLO!
- Next goal: Inclusive cross section at N3LO in the effective theory
  - ➡ More on this later!

NNLO corrections to H + jet and Higgs pairs

Higgs + jet

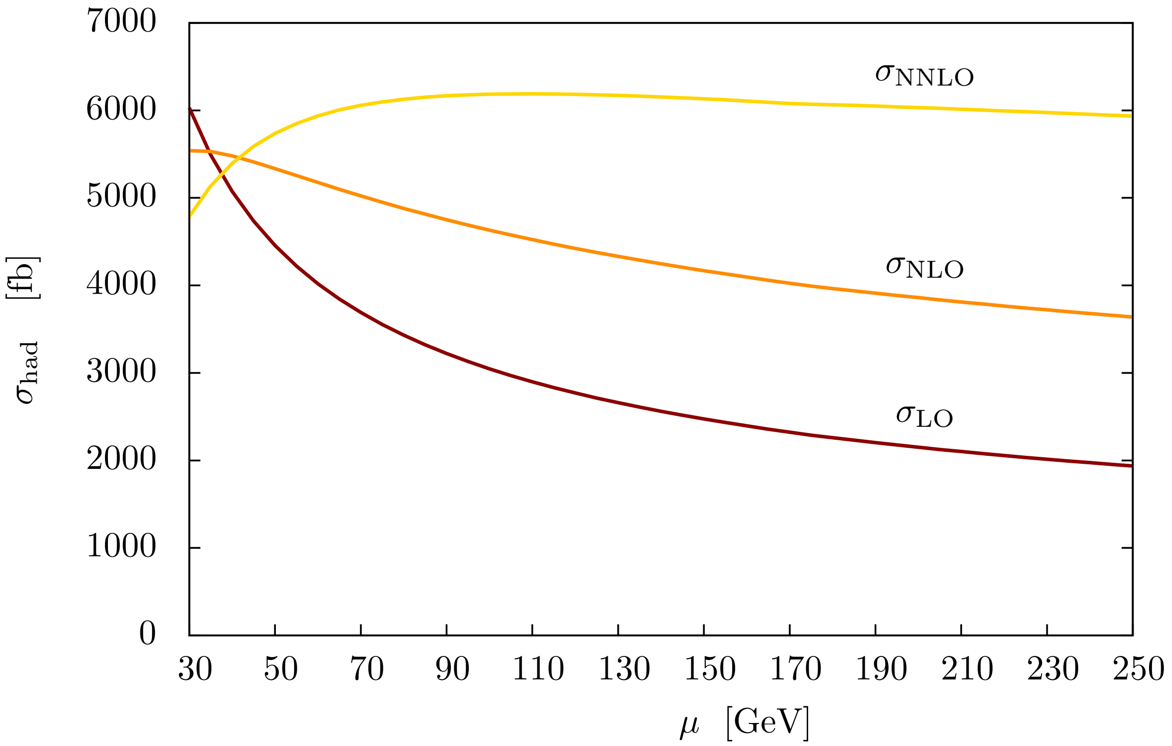
- The two-loop corrections to H+jet in the effective theory have been computed [Gehrmann, Glover, Jaquier, Koukoutsakis]
- Last year first steps were taken towards the computing the full NNLO corrections. [Boughezal, Caola, Melnikov, Petriello, Schulze]
- First process computed at NNLO where a jet function is required already at LO.
- Infrared singularities were subtracted using (a variant of) Stripper. [Czakon]

Higgs + jet

- Inclusive NNLO cross section computed last year (gluons only.)

$$\sigma_{\rm LO}(pp \to Hj) = 2713^{+1216}_{-776} \text{ fb},$$
$$\sigma_{\rm NLO}(pp \to Hj) = 4377^{+760}_{-738} \text{ fb},$$
$$\sigma_{\rm NNLO}(pp \to Hj) = 6177^{-204}_{+242} \text{ fb}.$$

[Boughezal, Caola, Melnikov, Petriello, Schulze]



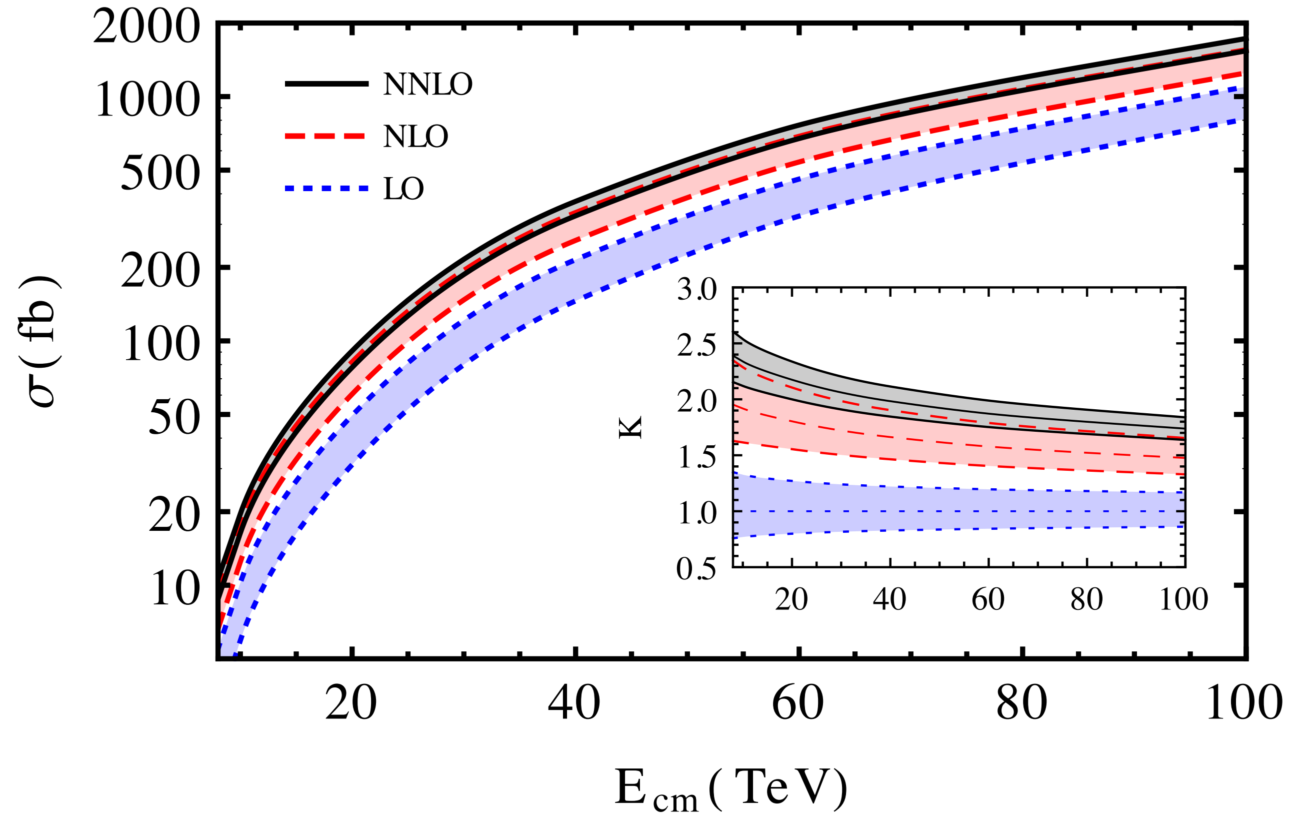
- At LoopFest preliminary differential distributions were announced.
  - ➡ Using (a variant of) Stripper. [Boughezal, Caola, Melnikov, Petriello, Schulze]
  - ➡ Using antenna subtraction. [Chen, Gehrmann, Glover, Jaquier]

Higgs pair production

- Last year NNLO correction to Higgs pair production in the large top-mass limit production became available.

$$\sigma_{\rm LO} = 17.8\,^{+5.3}_{-3.8}\,\text{fb}$$
$$\sigma_{\rm NLO} = 33.2\,^{+5.9}_{-4.9}\,\text{fb}$$
$$\sigma_{\rm NNLO} = 40.2\,^{+3.2}_{-3.5}\,\text{fb}$$

[de Florian, Mazzitelli]



- NNLO computations in EFT are normalised to exact LO matrix element
  - ➡ At NLO: ~10% agreement.

[Grigo, Hoff, Melnikov, Steinhauser]

Going beyond NNLO: towards N3LO

The need for N3LO

$$\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo.}) \pm 0.07(\mathrm{syst.})\right]$$

➡ We need to update our theory prediction!

- Next contribution is the N3LO contribution in the effective theory.

  ➡ Huge challenge!

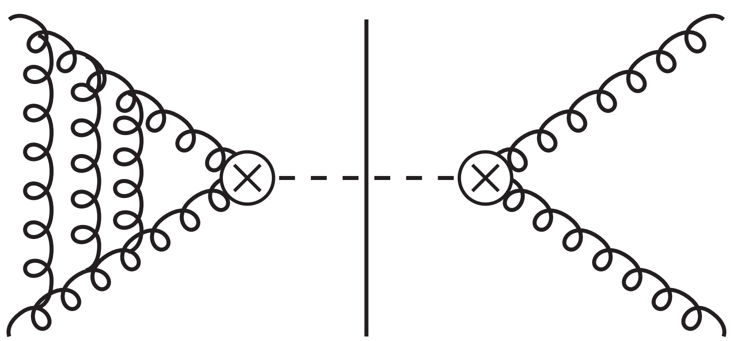
  ➡ Never has an N3LO computation been done for a hadron collider!

- Recently: Several approximate N3LO results have been presented.

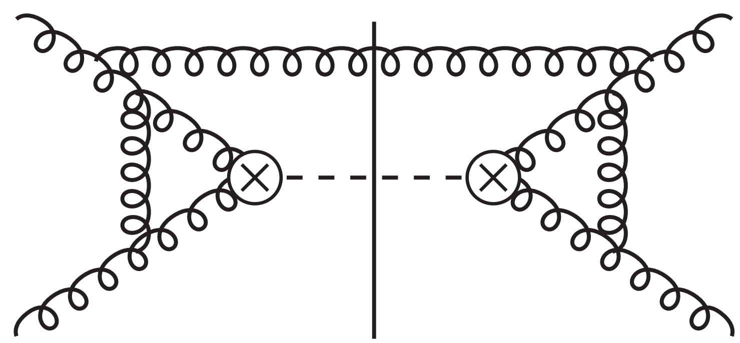
  ➡ Only full N3LO result will be final judge!

Contributions at N3LO

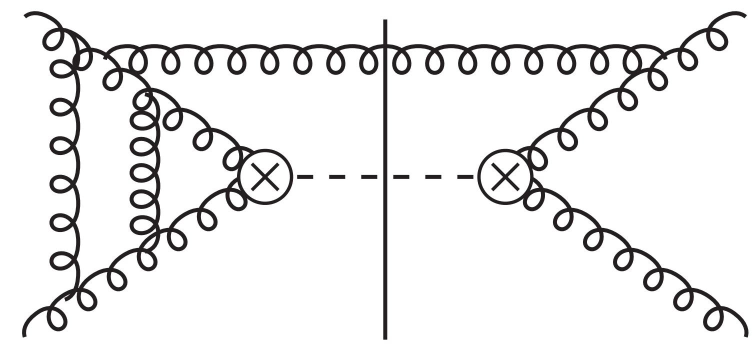
- At N3LO, there are 5 contributions:



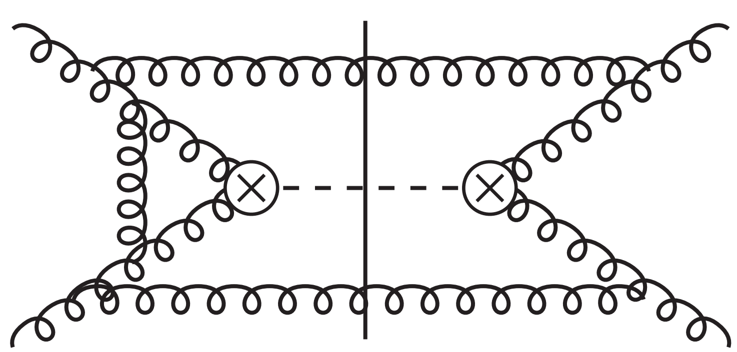
Triple virtual



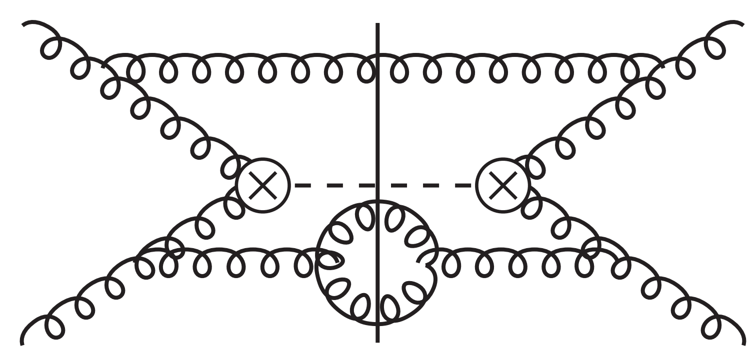
Real-virtual squared



Double virtual real



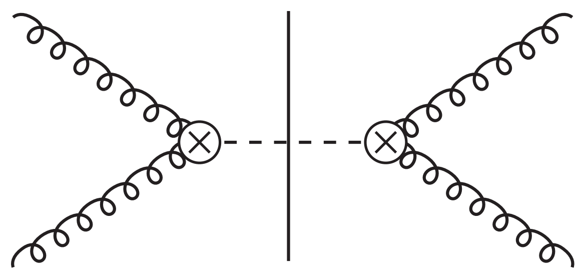
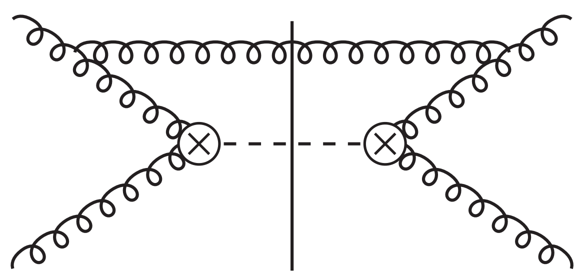
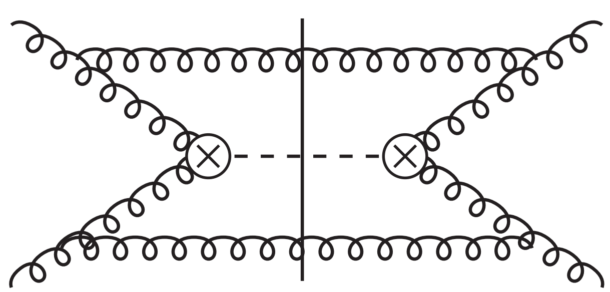
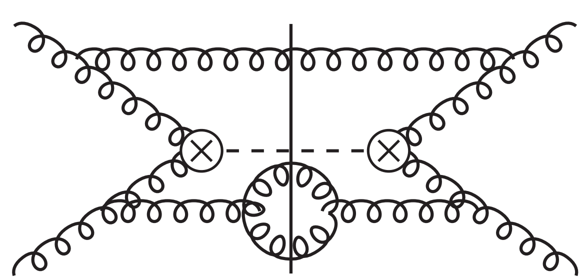
Double real virtual



Triple real

Reverse-unitarity @ N3LO

Growth in complexity for real emission

LO		1 diagram	1 integral
NLO			
NNLO			
N3LO			

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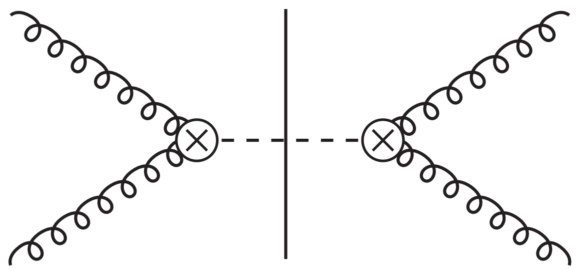
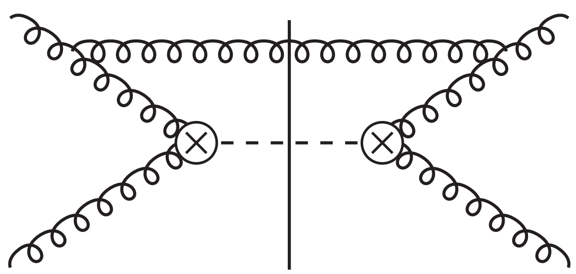
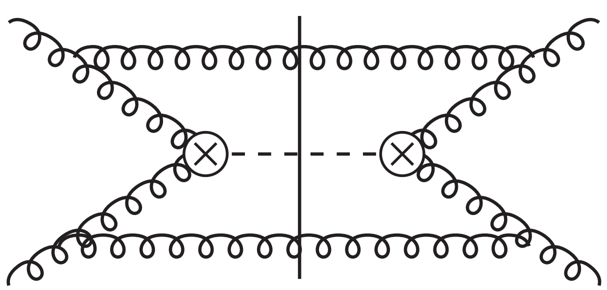
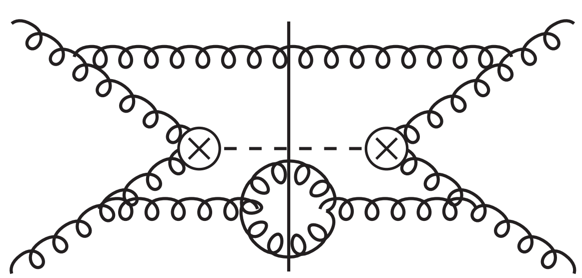
LO		1 diagram	1 integral
NLO		10 diagrams	1 integral
NNLO			
N3LO			

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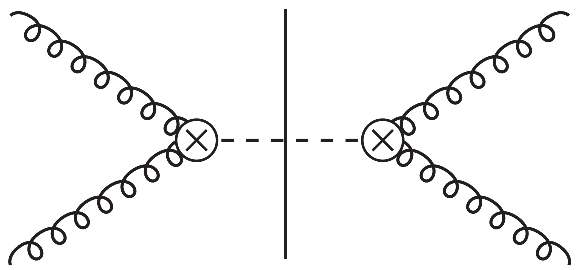
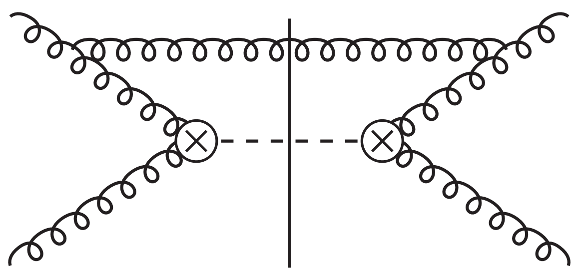
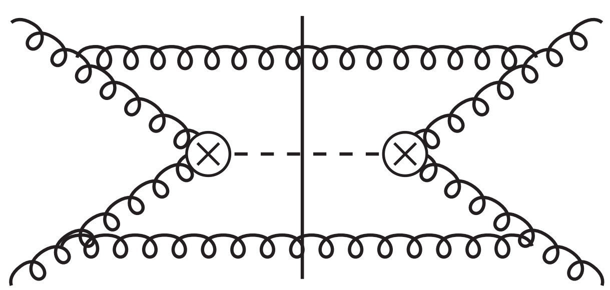
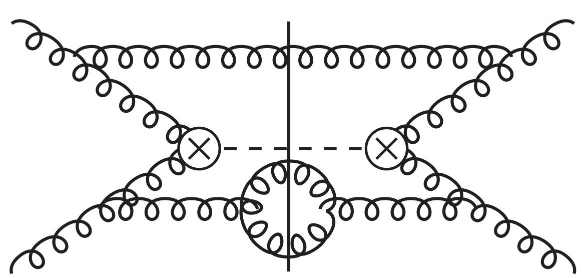
LO		1 diagram	1 integral
NLO		10 diagrams	1 integral
NNLO		381 diagrams	18 integrals
N3LO			

Reverse-unitarity @ N3LO

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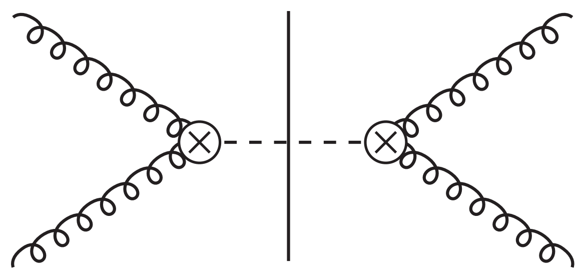
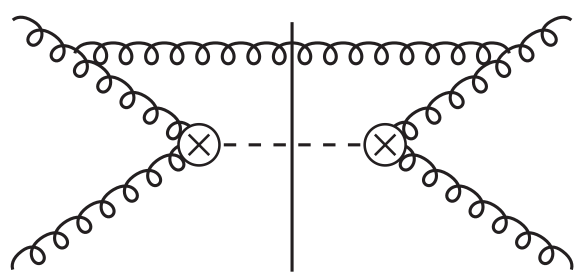
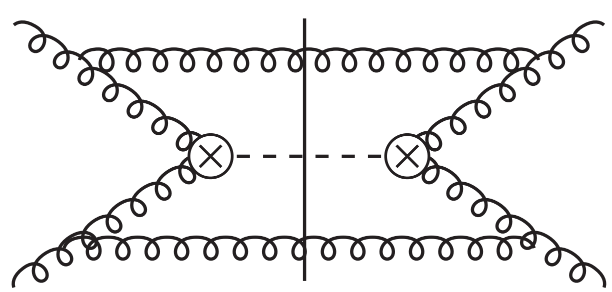
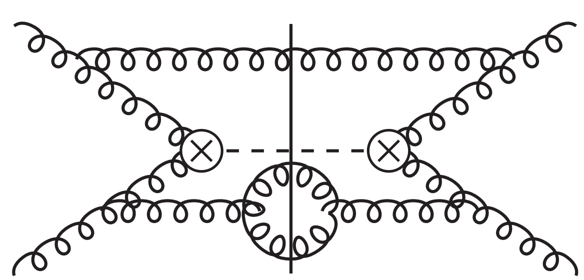
LO		1 diagram	1 integral
NLO		10 diagrams	1 integral
NNLO		381 diagrams	18 integrals
N3LO		26565 diagrams	~500 integrals

The threshold expansion

- There are 1000's of integrals to compute!
  - ➡ Tough nut to crack!
  - ➡ Concentrate on some approximation first.
- The gluon fusion cross section depends on one single parameter:

$$z = \frac{m^2}{s}$$

- Close to threshold ($z \sim 1$), we can approximate the triple real cross section by a power series:

$$\hat{\sigma}(z) = \sigma_{-1} + \sigma_0 + (1-z)\,\sigma_1 + \mathcal{O}(1-z)^2$$

- Goal:
  - ➡ First term captures complete 3-loop correction + emission of soft gluons.

The soft-virtual approximation

- The computation of the first term has been completed!

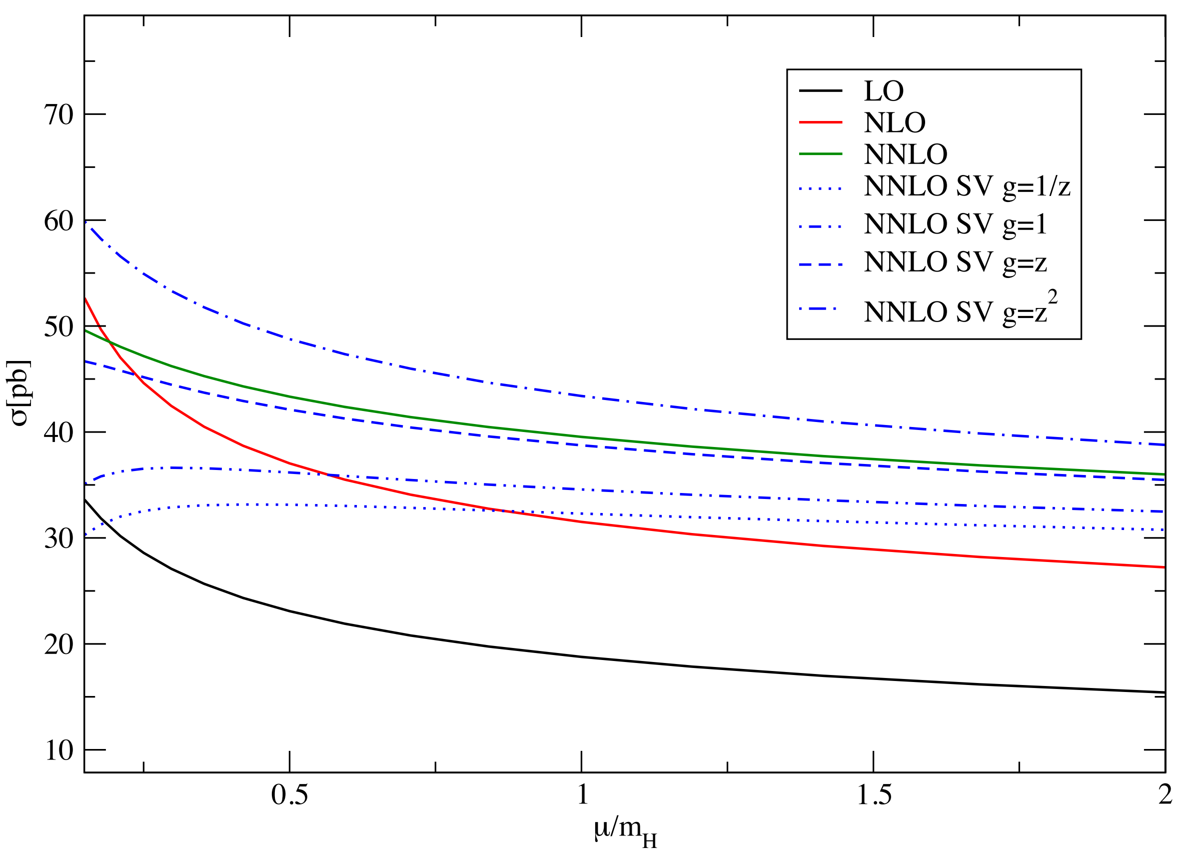
[Anastasiou, CD, Dulat, Furlan, Gehrmann, Herzog, Mistlberger]

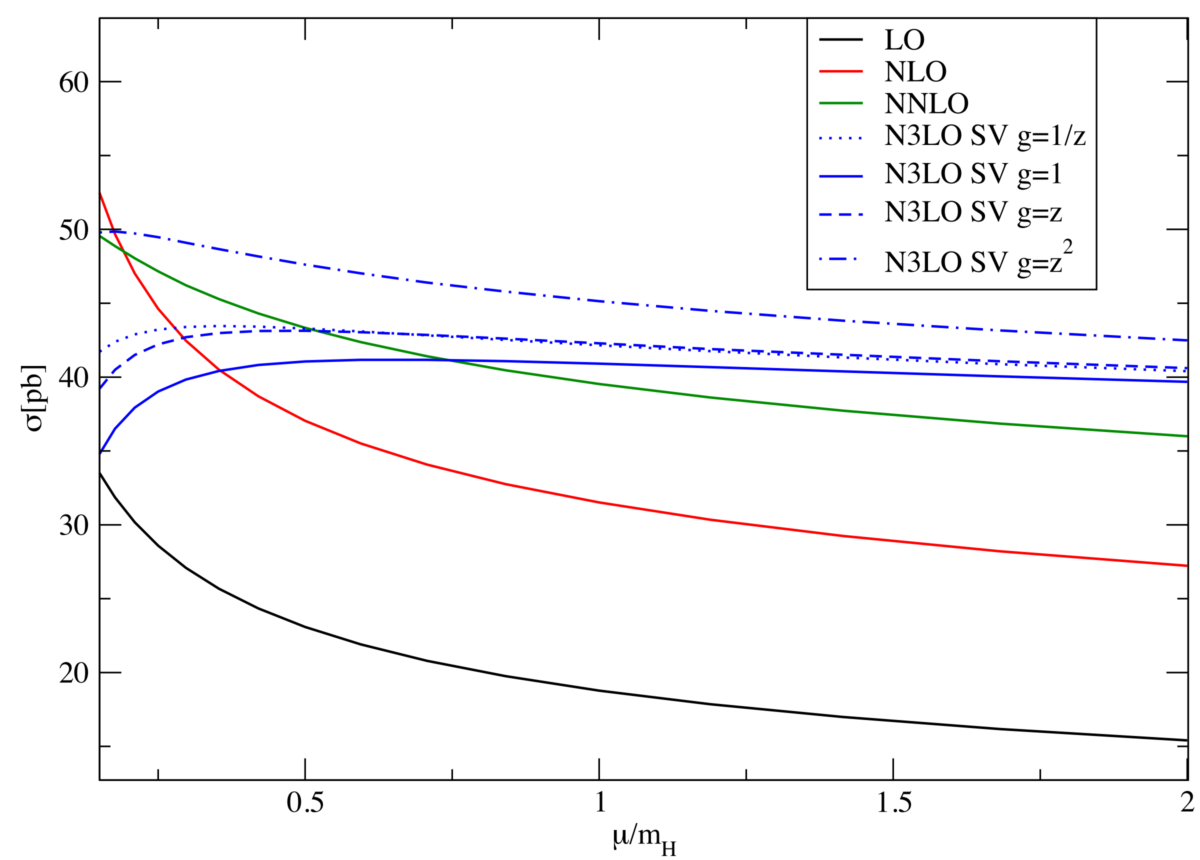
- Many different contributions are needed:
  - ➡ 22 three-loop. [Baikov, Chetyrkin, Smirnov, Smirnov, Steinhauser; Gehrmann, Glover, Huber, Ikizlerli, Studerus]
  - ➡ 3 double-virtual-real. [CD Gehrmann, Li, Zhu]
  - ➡ 7 real-virtual-squared. [Anastasiou, CD, Dulat, Herzog, Mistlberger; Kilgore]
  - ➡ 10 double-real-virtual. [Anastasiou, CD, Dulat, Furlan, Herzog, Mistlberger; Li, von Manteuffel, Schabinger, Zhu]
  - ➡ 8 triple real. [Anastasiou, CD, Dulat, Mistlberger]
  - ➡ three-loop splitting functions. [Moch, Vermaseren, Vogt]
  - ➡ three-loop beta function. [Tarasov, Vladimirov, Zharkov; Larin, Vermaseren]
  - ➡ three-loop Wilson coefficient. [Chetyrkin, Kniehl, Steinhauser; Schroeder, Steinhauser; Chetyrkin, Kuhn, Sturm]

Higgs soft-virtual @ N3LO

- Caveat!
- Source of ambiguity:

$$\int dx_1\, dx_2\, \left[f_i(x_1)\, f_j(x_2) z g(z)\right] \left[\frac{\hat{\sigma}_{ij}(s,z)}{z g(z)}\right]_{\text{threshold}} \qquad \lim_{z\to 1} g(z) = 1$$





[Herzog, Mistlberger]

Generalizations

- Soft-virtual corrections are universal, and the result can be extended to other processes.
- Can be used to predict the rapidity distribution of the Higgs boson at N3LO at threshold. [Ahmed, Mandal, Rana, Ravindran]
- Recently the 3-loop form factor for bb -> H was computed. [Gehrmann, Kara]
- The result was immediately extended to N3LO corrections to Higgs production in bottom fusion at threshold. [Ahmed, Rana, Ravindran]
  - ➡ N.B.: Bottom-fusion cross section available fully differentially at NNLO! [Buehler, Herzog, Lazopoulos, Mueller]
- Caveat for threshold approximation still applies!

Looking into the future...

- The soft-virtual term is only the beginning!
- Real-virtual-squared contribution already fully known.
  [Anastasiou, CD, Dulat, Herzog, Mistlberger; Kilgore]
- Next-to-soft term known for triple real contribution.
  [Anastasiou, CD, Dulat, Mistlberger]
- Two-loop matrix element for H+j known
  [Gehrmann, Glover, Jaquier, Koukoutsakis]
  - ➡ Phase space integration requires contribution from collinear regions!
- Once the N3LO result for the Higgs is available, more will follow!
  - ➡ Drell-Yan, bb -> H, ...

Conclusion

- LHC Run II will require very precise QCD computations for Higgs production.
  - ➡ Theory uncertainties are same size as experimental ones.
- A lot of progress was made regarding (differential) predictions at NNLO.
  - ➡ H + jet, Higgs pairs, bb -> H.
- N3LO result for inclusive cross section is in the making.
  - ➡ Threshold term already available!
  - ➡ More terms in threshold expansion and the full results are in the making.
  - ➡ Requires a lot of new and advanced technologies from the theory side!