Recent QCD results in precision Higgs physics

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Why the Higgs?

- The Standard Model describes the properties and interactions of the fundamental constituents of all visible matter
- It is an highly predictive theory that has been validated by a huge number of collider experiments
- The Higgs boson is essential for the self-consistency of the Standard Model!

Why the Higgs?

- In the “Standard Model” description of electroweak symmetry breaking, all the couplings of the Higgs are strictly fixed
  - ➡ once its mass is known, all the properties of the Higgs boson (production cross sections, decay rates,..) can be predicted

- So, why do we keep taking data if “we know everything”?

Expecting surprises!

See also the talk of M. Spiropulu on Monday

- We have many hints that the Standard Model is not the “theory of everything”
  - why is the Higgs so light?
  - why is it there such a large hierarchy in the fermion masses?
  - what about dark matter, neutrino masses, dark energy? Does the Higgs play any role there? (e.g., can it decay into dark matter?)

Precision Higgs physics

- Many scenarios of "physics beyond the Standard Model" try to address these questions
- They typically predict modifications in the Higgs phenomenology
- These effects can be rather small ($\mathcal{O}(\text{few}\%)$)

Precision Higgs physics

- ➡ to validate the Standard Model (or see hints of new physics) we need
  - very accurate measurements of the properties of the Higgs boson ..
  - .. and equally accurate theoretical predictions of these properties!

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extremely active field of work

Recent progress

- Inclusive cross section for Higgs production in gluon fusion ➜ N^3LO

C. Anastasiou, C. Duhr, F. Dulat, EF, T. Gehrmann, F. Herzog, A. Lazopoulos, B. Mistlberger, JHEP 1605 (2016) 058

- Double Higgs production ➜ exact (full top-mass dependance) at NLO + differential distributions

S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk, U. Schubert, T. Zirke, PRL 117 (2016) no.1, 012001, Erratum: PRL 117 (2016) no.7, 079901; arXiv:1608.04798

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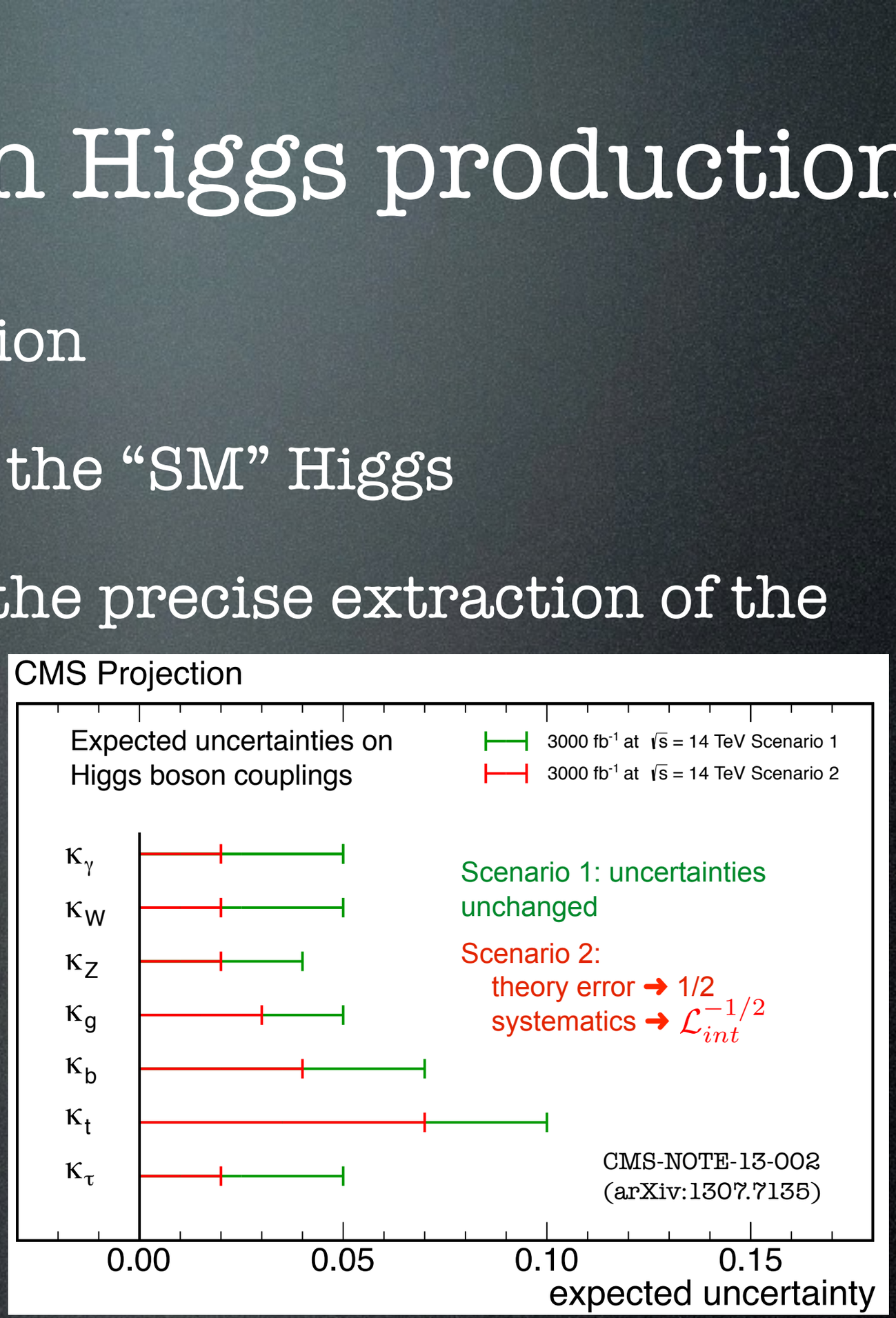
why are these quantities so important?

Gluon fusion Higgs production

Inclusive cross section

- important test of the “SM” Higgs
- fundamental for the precise extraction of the Higgs couplings



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1978 LO $\hat{\sigma}^{8TeV} = 9.6pb \pm 25\%$

Georgi et al, Higgs bosons from two gluon annihilation in proton proton collisions,

1991 NLO $\hat{\sigma}^{8TeV} = 16.7pb \pm 20\%$

Dawson; Djouadi, Spira, Zerwas; Graudenz, Spira, Zerwas; Spira, Djouadi, Graudenz, Zerwas

2002 NNLO $\hat{\sigma}^{8TeV} = 19.6pb \pm 9\%$

Harlander, Kilgore; Anastasiou, Melnikov

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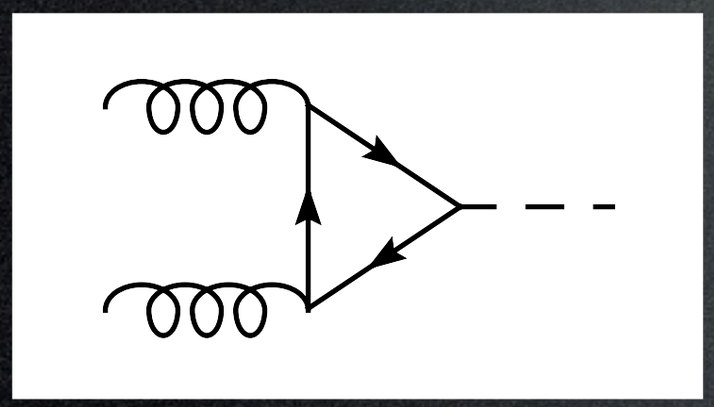

leading (lowest) order, “LO”
➜ already one loop
➜ largest contribution from top quark → massive particle
➜ two external momenta

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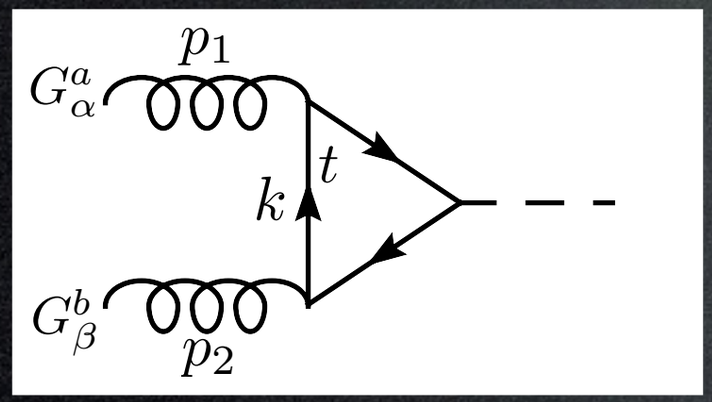
- .. but **very** hard to compute!



$$\sim\int_\infty^\infty \frac{d^dk}{(2\pi)^d}\frac{Tr\left[(\not{p}_1+\not{k}+m_t)\gamma^\alpha(\not{k}+m_t)\gamma^\beta(\not{k}-\not{p}_2+m_t)\right]}{[(p_1+k)^2-{m_t}^2][k^2-{m_t}^2][(k-p_2)^2-{m_t}^2]}$$

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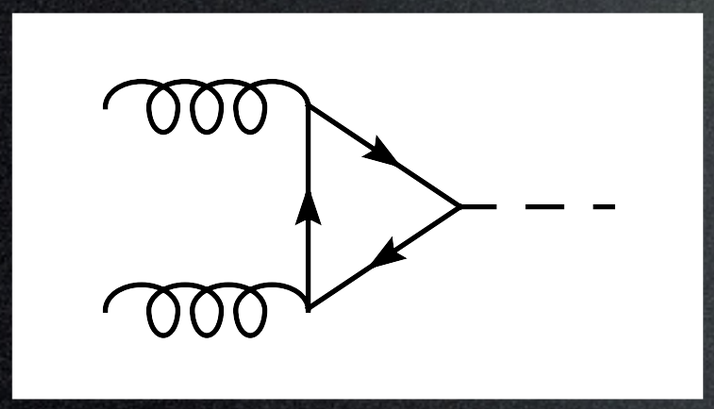
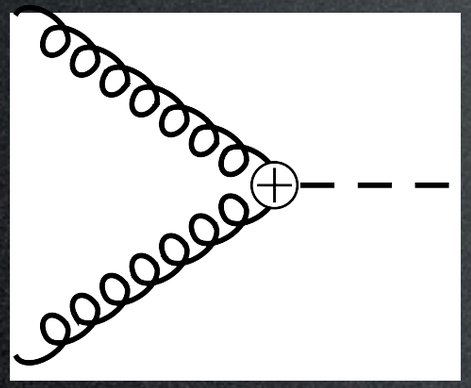


➡ so, N^3LO is four loops ($\sim$ 15.000 diagrams)?!?

Heavy quark effective theory

- The top quark is heavy compared to the Higgs boson $(m_t \gg m_H/2)$...
- ... so heavy that one can consider it *infinitely* heavy and integrate it out

➡ obtain an effective gluon-Higgs vertex



$$\mathcal{L}_{eff} = -\frac{\alpha_S}{4v} C H G^a_{\mu\nu} G^{a\mu\nu}$$

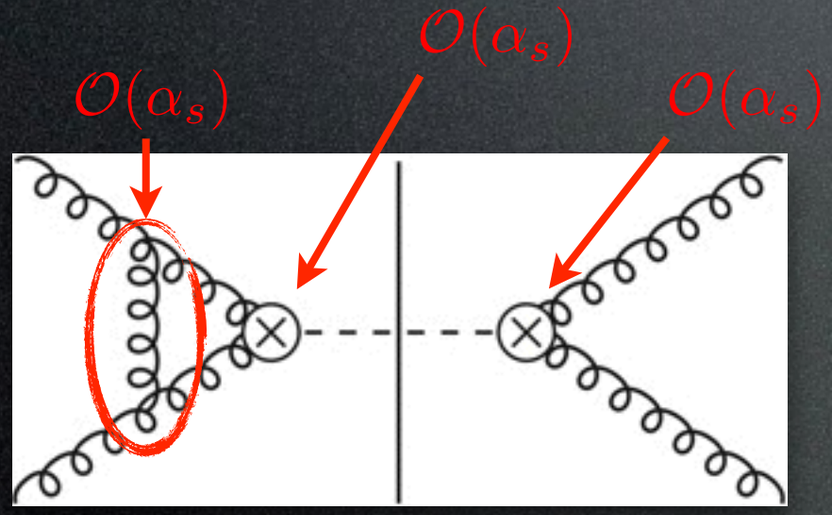
➡ the effects of the top quark are accounted for by a Wilson coefficient ➜ known at four loops

Y. Schroder and M. Steinhauser, JHEP 01 (2006) 051; K. G. Chetyrkin, J. H. Kuhn and C. Sturm, N. P. B744 (2006) 121–135

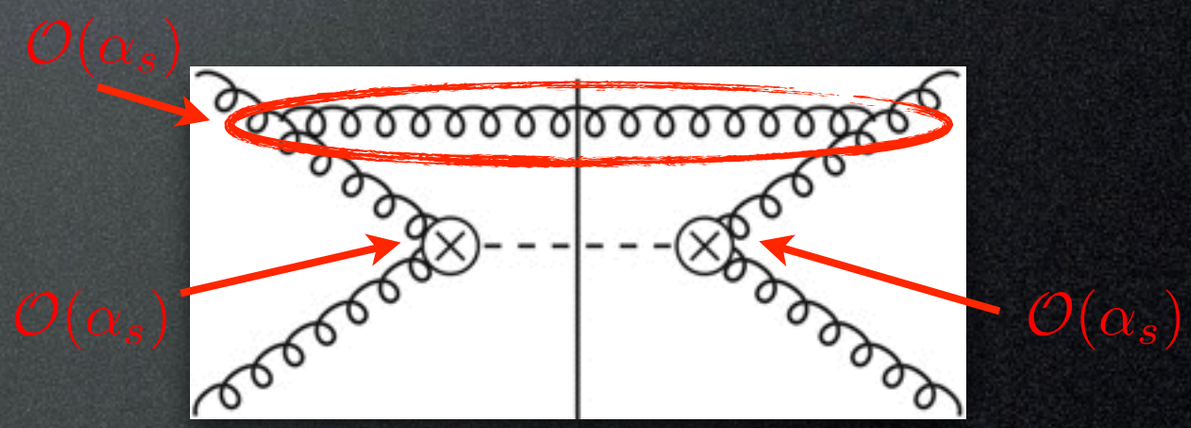
Beware: radiation!!

- The bottleneck of this calculation does not come from the virtual gluon-Higgs loops, but from other kind of diagrams
- at NLO ($\mathcal{O}(\alpha_s^3)$), there are two contributions in addition to the two loop gluon-Higgs vertex

Dawson, Nucl. Phys. B 359 (1991) 283;
Djouadi et al., Phys. Lett. B 264 (1991)



Virtual corrections

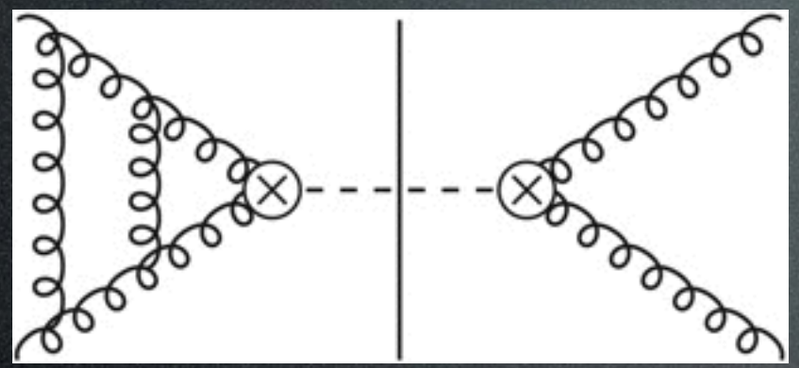


Real radiation

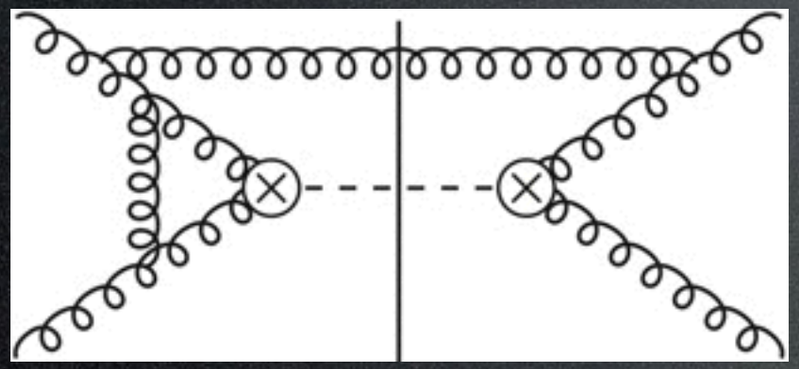
➡ ~ 10 diagrams

Beware: radiation!!

- at NNLO, one has

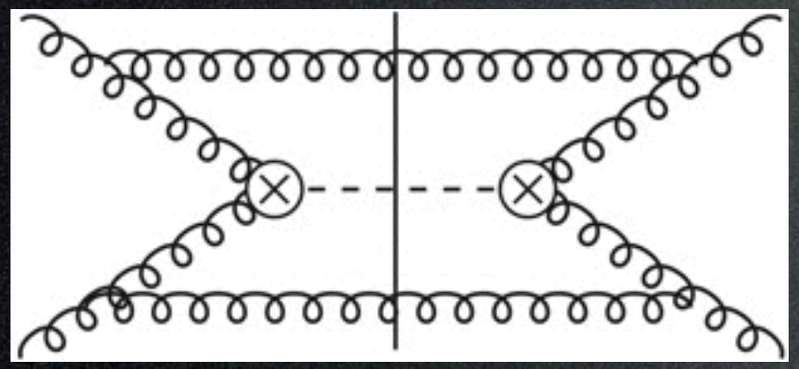


Double-virtual corrections



Real-virtual corrections

➡ ~ 1000 diagrams

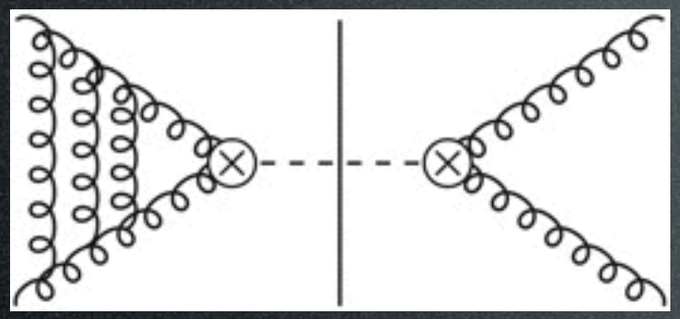


Double-real corrections

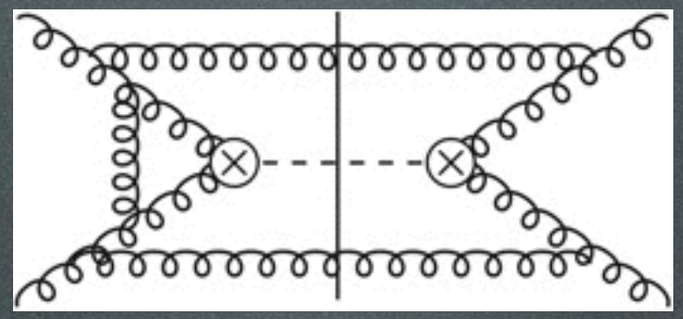
Harlander and Kilgore, PRL 88, 201801 (2002);
Anastasiou and Melnikov, NP B 646 (2002) 220;
Ravindran et al., NP B 665, 325 (2003)

Beware: radiation!!

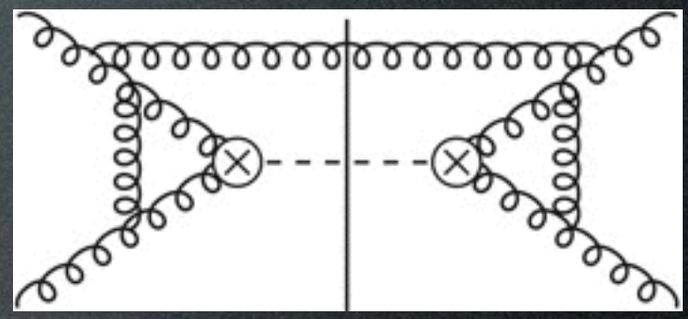
- at N^3LO,



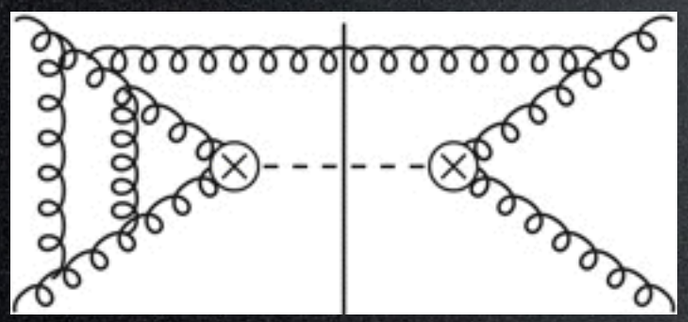
triple-virtual corrections



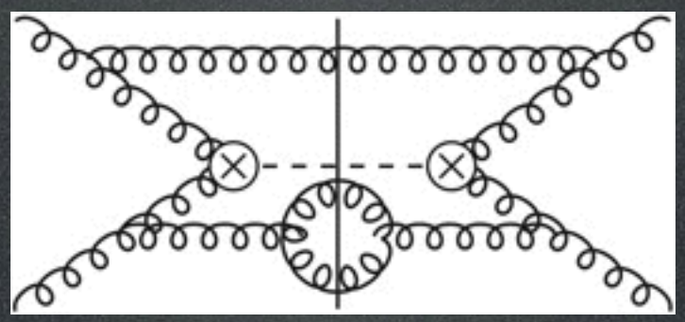
double-real virtual corrections



real-virtual squared corrections



double-virtual real corrections



triple-real corrections

➡ ~ 100000 diagrams

Gluon fusion Higgs production

➡ the number of interference diagrams increases by a factor of 100 from NNLO to N^3LO

➡ the number of integrals increases by 10.000!

NNLO	N^3LO
~ 50.000	~ 500.000.000

How can we tackle this problem?

Gluon fusion Higgs production

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How can we tackle this problem?

➡ automation

➡ simplifying assumptions

➡ new ideas/tools

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How can we tackle this problem?

➡ automation
write our own routines to generate the diagrams and perform the numerical manipulations

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How can we tackle this problem?

➡ simplifying assumptions (heavy quark effective theory, expansion around Higgs threshold production)

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NNLO	N^3LO
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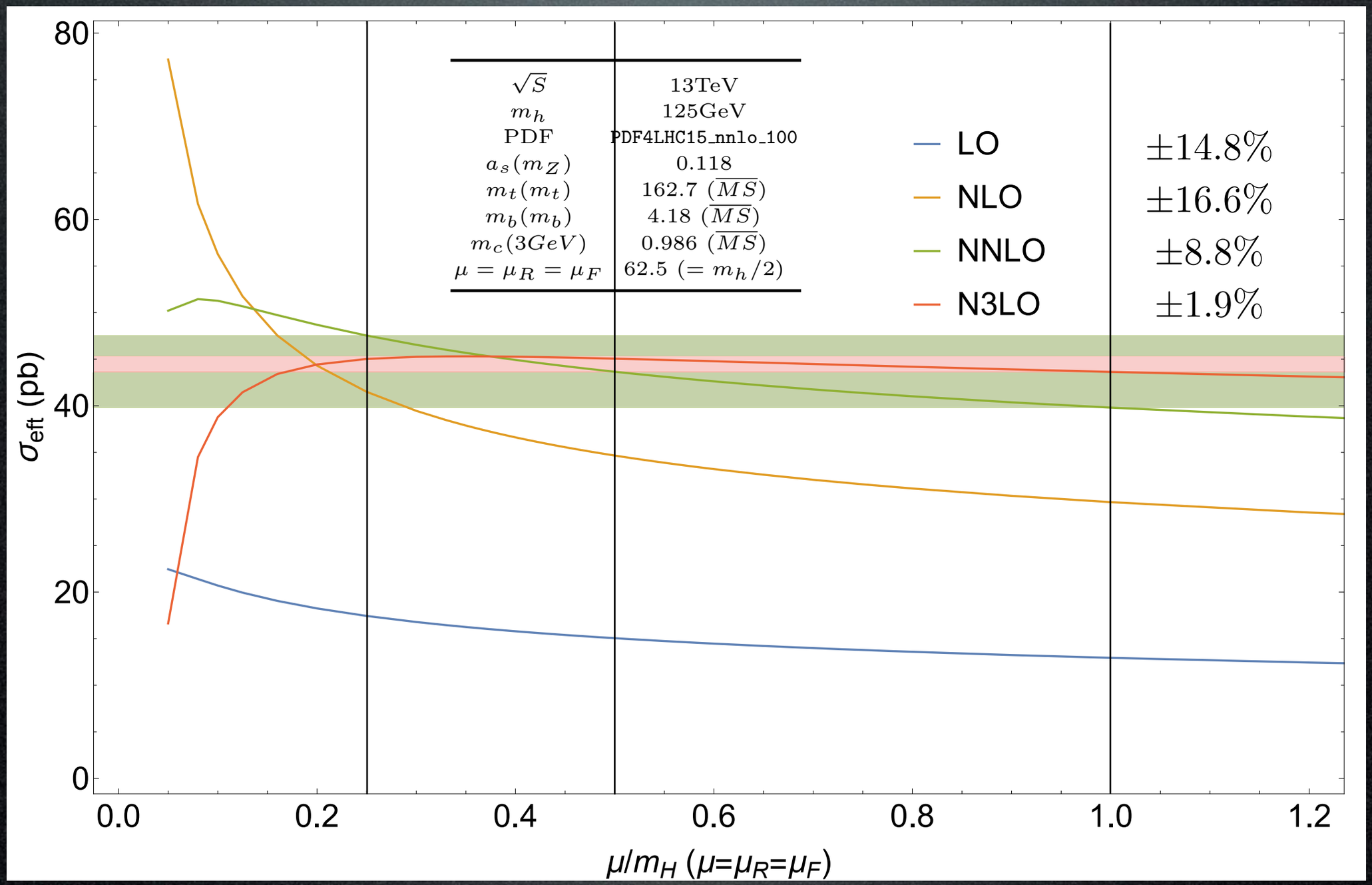
How can we tackle this problem?

➡ new ideas/tools (inverse unitarity, integration by part identities, strategy of regions, differential equations method, Henn canonical forms, Mellin space, symbol algrbra,...)

The N^{3}LO cross section



The N^{3}LO cross section

The N^{3}LO Higgs boson production cross section and the associated errors are

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)$$

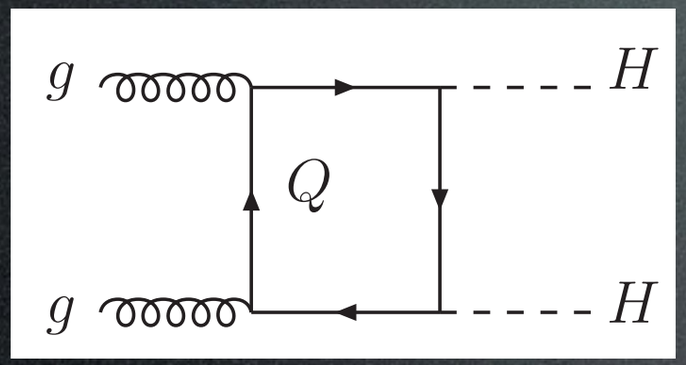
$$\sigma^{NNLO} = 47.02\ \text{pb}\ ^{+5.13\ \text{pb}\ (10.9\%)}_{-5.17\ \text{pb}\ (11.0\%)}\ (\text{theory})^{+1.48\ \text{pb}\ (3.14\%)}_{-1.46\ \text{pb}\ (3.11\%)}\ (\text{PDF}+\alpha_s)$$

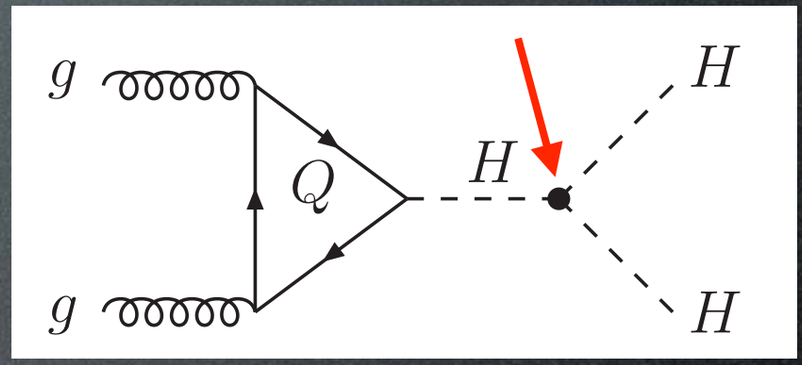
- ➡ Good convergence of the expansion in the strong coupling
- ➡ Theory error halved! (and can be further reduced)

Double Higgs production

S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk, U. Schubert, T. Zirke,
PRL 117 (2016) no.1, 012001, Erratum: PRL 117 (2016) no.7, 079901; arXiv:1608.04798

- Fundamental to probe the Higgs trilinear coupling in the Standard Model





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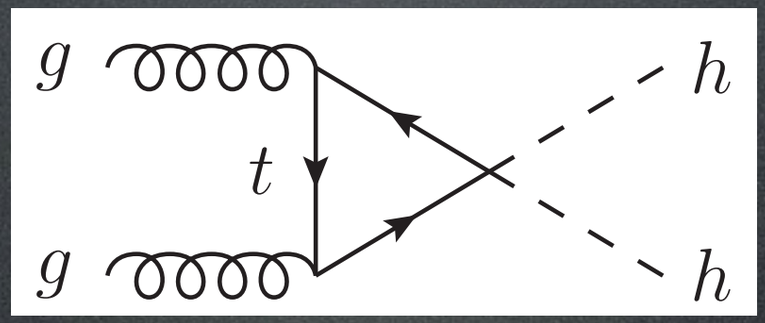
- Sensitive also to higher dimensional operators induces by (some) new physics



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- Sensitive also to higher dimensional operators induces by (some) new physics
- Known through NNLO in the heavy quark effective theory, where the NLO corrections double the LO result

S. Dawson, S. Dittmaier, M. Spira, Acta Phys. Polon. B29 (1998) 2875-2882; D. de Florian and J. Mazzitelli, PRL 111 (2013) 201801

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- Also known that the effective theory does not work well in this case!

E. W. N. Glover and J. J. van der Bij, N.P.B 309 (1988) 282;
F. Maltoni, E. Vryonidou, M. Zaro, JHEP 1411 (2014) 079;
J. Grigo, J.Hoff and M. Steinhauser, N.P. B900 (2015) 412-430

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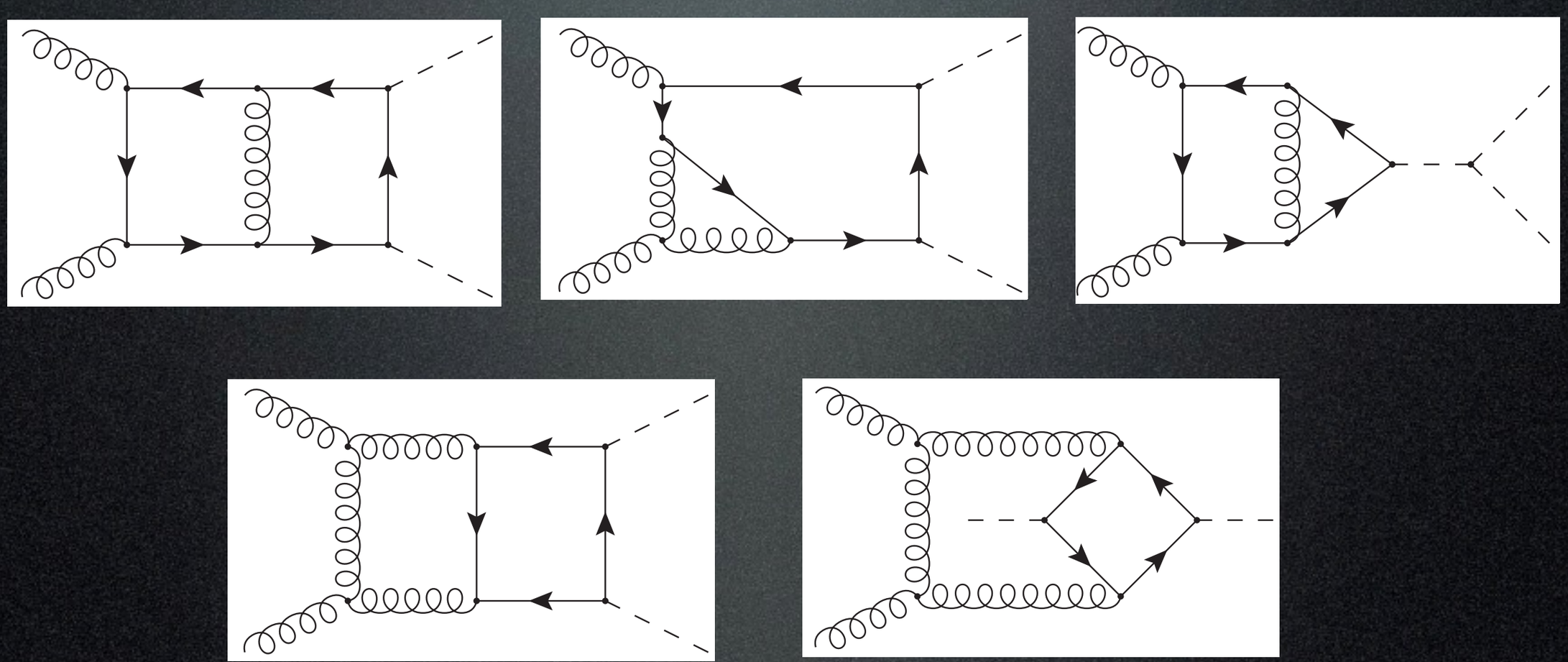
➡ Need to include the full top-mass dependance at NLO!

- Very difficult calculation



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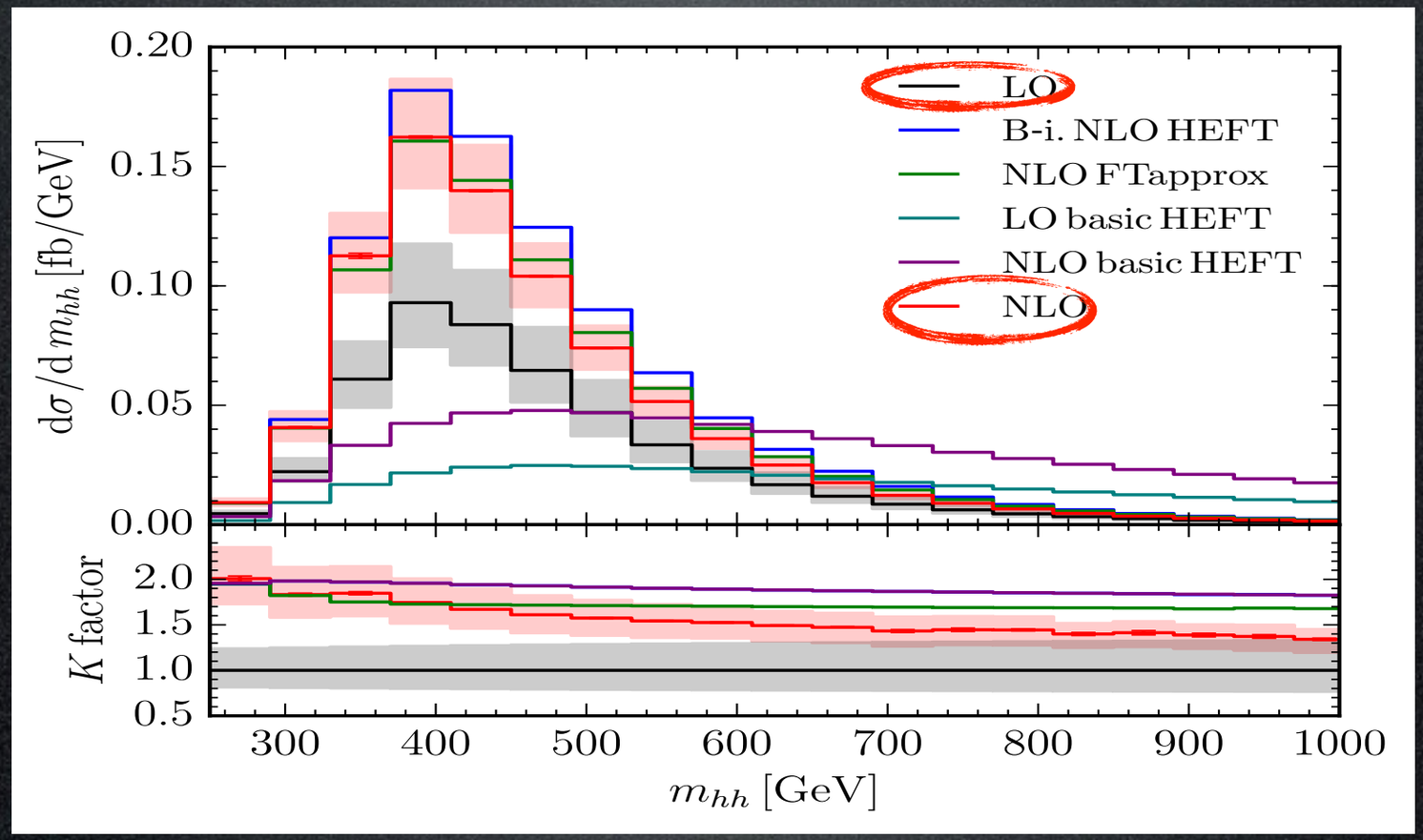
- Very difficult calculation
- Recently accomplished!



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- Very difficult calculation
- Recently accomplished!

$$\sigma^{NLO} = 32.91^{+14\%}_{-13\%}\ \text{fb}$$

$$\sigma^{NLO}_{HEFT} = 38.32^{+18\%}_{-15\%}\ \text{fb}$$

$$\sigma^{LO} = 19.85^{+28\%}_{-21\%}\ \text{fb}$$

(-14%)

theory error halved

Summary

- (More) Precise theoretical calculations of the Higgs properties are fundamental in order to probe/validate the Higgs sector (anomalous couplings, new particles, decays into dark matter, ..)

➡ very active field of investigation

➡ many results recently achieved or within reach

- inclusive Higgs cross section at N^3LO
- Higgs pair production at NLO, with full dependence on the top mass

Summary

- Higgs produced in association with a jet, with full dependence on the top mass (sensitive to new particles in the loops)
- Missing contributions in single Higgs production (reduce the theory error on the N^3LO result)
- Differential cross sections at N^3LO (allow to implement experimental cuts)
- Interference effects between gg ➜ H ➜ ZZ and gg ➜ ZZ (indirect determination of the Higgs width)