Precise prediction for Higgs production via gluon fusion in BSM scenarios

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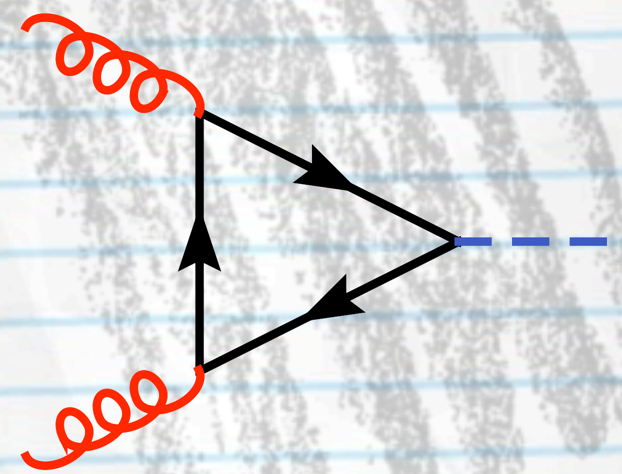
Motivation

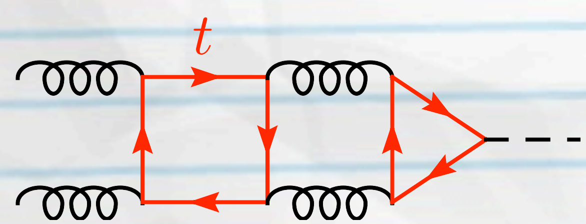
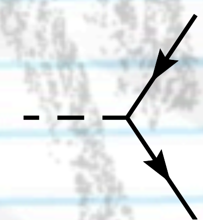
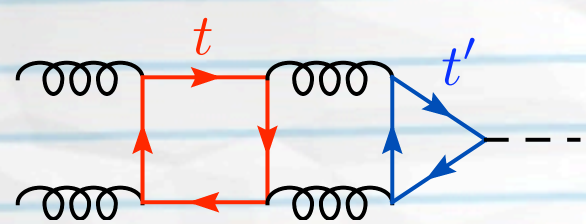
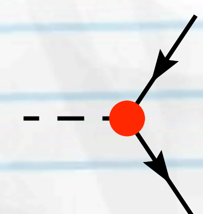
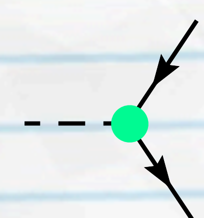


* gluon fusion is the main mechanism for Higgs production at hadron colliders
* it is sensitive to any coloured particle that couples to the Higgs, e.g. the top
* the Higgs sector is untested

} this channel is very sensitive to new physics effects

* the description of electroweak symmetry breaking provided by the Standard Model needs to be extended
* extensions of the SM require new particles which may contribute to gluon fusion

Motivation

particles in different representations of the Lorentz group	particles of different mass in the loops	particles in different colour representations	different structure of the Higgs coupling
quarks		singlets, triplets, octets	 $\sim \bar{\psi}\psi$
squarks		fundamental, adjoint	 $\sim \bar{\psi}\gamma_5\psi$
Majorana fermions	⋮	⋮	 $\neq \frac{m}{v}\bar{\psi}\psi$
⋮			⋮

Motivation

* Assume that we find...
  * a relatively light Higgs with a cross section much different than σ_{SM} ($\sigma \sim 0.35\,\sigma_{SM}, \sigma \sim 0.80\,\sigma_{SM}$?)
  * and/or some new heavy particles
  * ➡ lot of model-building activity ...
  * ➡ ... and of perturbative QCD calculations of the gluon fusion cross section for these models

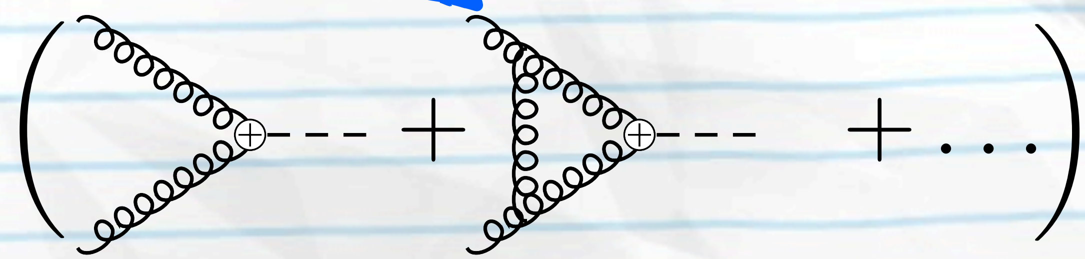
Effective-theory approach

* experiments (LEP, Tevatron, ..) indicate that new particles must be heavy, while the Higgs is light

* this allows for an effective-theory approach:

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

$$\left(C_0 + \left(\frac{\alpha_s}{\pi}\right) C_1 + \left(\frac{\alpha_s}{\pi}\right)^2 C_2 + \ldots \right)$$

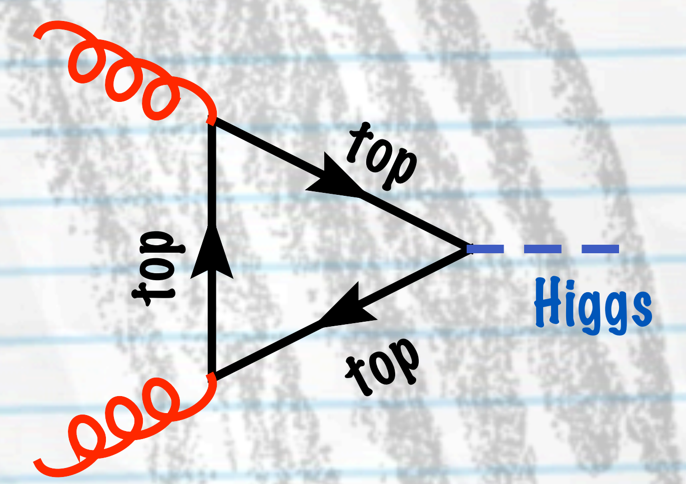


depends on the specific model

QCD only!

→ factorization of QCD and NP effects

Gluon fusion in the SM



* it is known very precisely...
* ... but it required tough calculations

$$\sigma^{(SM)}_{NNLO} = \sigma^{(SM)}_{LO}\,(1 + \underbrace{0.7}_{\text{NLO}} + \underbrace{0.3}_{\text{NNLO}})$$

Harlander, Kilgore;
Anastasiou, Melnikov;
Ravindran, Smith, van Neerven;
Graudenz, Spira, Zerwas

$$\left(\frac{\Delta\sigma}{\sigma}\right)^{\exp} \sim \pm 10\% \quad , \quad \left(\frac{\Delta\sigma}{\sigma}\right)^{NNLO}_{SM} \sim \pm 10\%$$

Gluon fusion in BSM

- Only very recent NNLO calculations in some BSM scenarios
  - ➡ scalar octects (Boughezal, Petriello)
  - ➡ fourth generation (Anastasoiu, Boughezal, Furlan)
- Why?

  The low-energy theory is the same as in the Standard Model, but the matching calculation at NNLO is much more complicated:

  - number of diagrams
  - renormalization
  - dependence on multiple mass scales

Technical challenges

- Large number of Feynman diagrams

  $\sim$500 in the SM, $\sim$2000 in four-generation SM, $\sim$6000 in composite Higgs, ...

- Apply costly differentiations for Taylor expansion

- Reduce a large number ($\sim 10^5$) of integrals to master integrals

  ➡ we wrote our own routines in
  - ✦ QGRAF (Nogueira)
  - ✦ Mathematica
  - ✦ FORM (Vermaseren)
  - ✦ AIR (Anastasiou, Lazopoulos)

  ➡ same methods for SM and BSM Wilson coefficients

Technical challenges

* Evaluate the master integrals

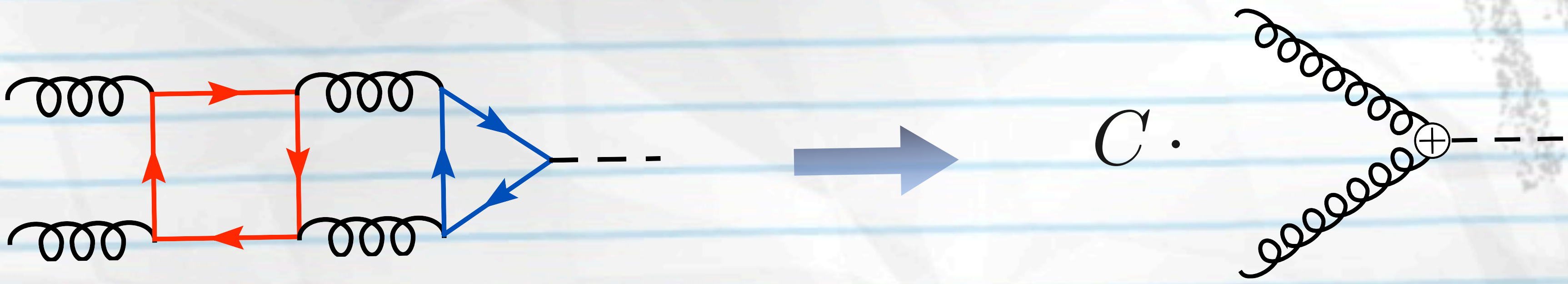
➡ much more difficult than in the SM (many mass scales)

➡ in many cases, impossible with traditional analytic methods -> sector decomposition

Hepp; Denner, Roth; Binoth, Heinrich; Anastasiou, Melnikov, Petriello; Anastasiou, Beerli, Daleo; Lazopoulos, Melnikov, Petriello

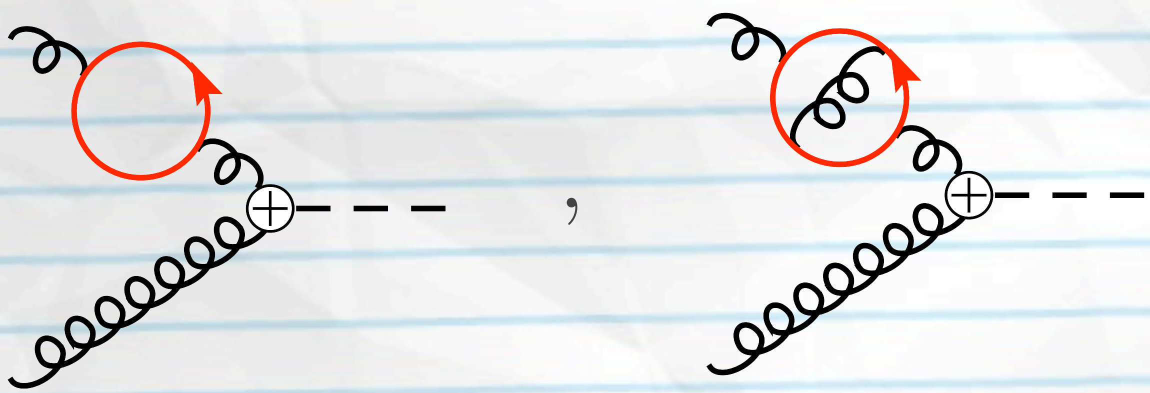
Decoupling

* We want to construct an effective theory that only contains light particles
* So far



Decoupling

* heavy particles give loop contributions to the self-energies and vertices of light particles



* contributions from heavy-particle loops are missing in the effective theory

➡ account for them by rescaling the fields and the couplings in the effective theory (Chetyrkin, Kniehl, Steinhauser)

Four-generation SM

in collaboration with C. Anastasiou and R. Boughezal

* Simple extension of the Standard Model

	I	II	III	IV ?	
quarks	u	c	b	B	γ
quarks	d	s	t	T	g
leptons	ν_e	ν_μ	ν_τ	ν'_τ	Z
leptons	e	μ	τ	τ'	W

gauge bosons

Four-generation SM

* Tevatron collaborations can put accurate experimental bounds on the mass of the Higgs boson in this model
* previous analyses are based on (Arik et al.)
  - NLO cross section
  - infinite-mass approximation

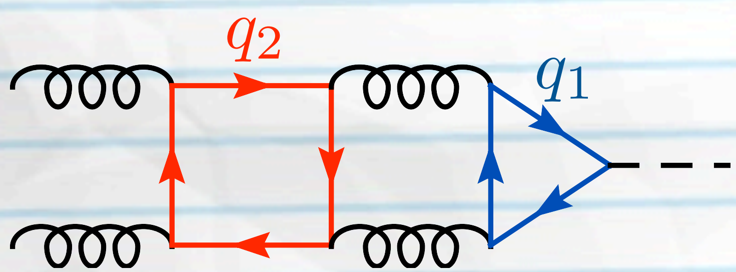
$$\left.\begin{matrix}\text{NLO cross section}\\ \text{infinite-mass approximation}\end{matrix}\right\} \quad \sigma^{(4,NLO)} = 9\sigma^{(3,NLO)}$$

Four-generation SM

* already at LO finite-mass effects can change the enhancement factor by 20%
* the theory uncertainty on the NLO cross section is much higher than the experimental uncertainty
* we have all the tools to compute the Higgs production cross section through gluon fusion at NNLO accuracy

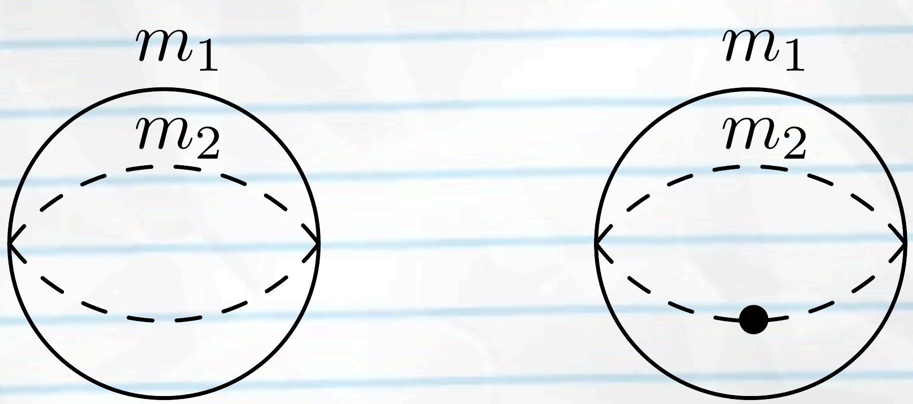
Four-generation SM

* at NNLO we have diagrams containing two different heavy-mass scales :



+ other 115

- master integrals can contain up to two, different, massive propagators

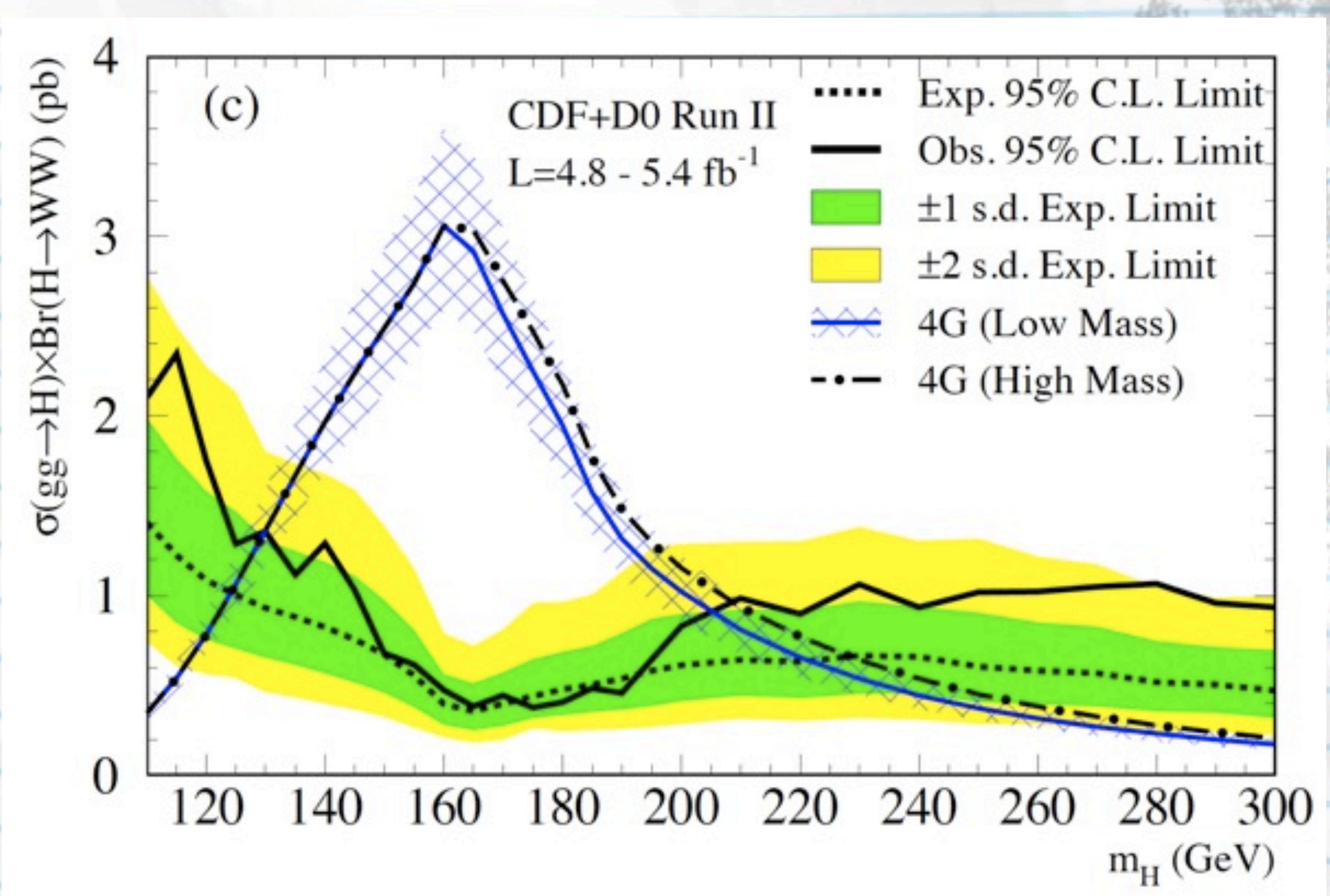


→ Bekavac, Grozin, Seidel, Smirnov

Higgs production cross-section

* the NNLO cross section is 10-15% higher than the NLO cross section
* the theoretical error decreases from 20-30% at NLO to 10% at NNLO
* our result has been used by the Tevatron collaborations to put accurate constraints on the mass of the Higgs boson in a four-generation Standard Model

Exclusion limits on m_H



(CDF & D0)

➡ exclude 131 GeV $\lesssim m_H \lesssim$ 204 GeV

Composite Higgs models

Georgi, Kaplan

* class of models that address the hierarchy problem
* the couplings of the Higgs boson are reduced with respect to the Standard Model
* new heavy quarks are typically introduced

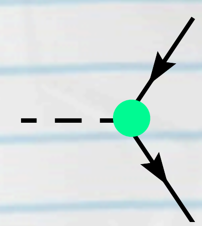
} how is the Higgs production cross section modified?

➡ example: multiplets of heavy quarks that transform under the fundamental representation of SO(5)

Composite Higgs models

Georgi, Kaplan

* difference to the SM: the couplings of the quarks to the Higgs boson are not proportional to the mass of the quarks



$$\frac{m_1}{v} \longrightarrow Y_1$$

⇨ need to understand renormalization

⇨ Y_1 renormalizes as the mass,

$$Y_1 = Z_m Y_1^R$$

(Chetyrkin, Kuhn, Kwiatkowski)

Wilson coefficient

* The three-loops term in the renormalized Wilson coefficient is

$$\left(\frac{\alpha_s'(\mu)}{\pi}\right)^2\left\{L_0\left[\frac{1877}{192}-\frac{77}{576}n_h+\sum_{i=1}^{n_h}\left(\frac{113}{96}\log\left(\frac{m_i}{\mu}\right)+\frac{3}{8}\log^2\left(\frac{m_i}{\mu}\right)\right)\right]\right.$$

$$-L_1\left[\frac{19}{8}+\frac{113}{96}n_h+\frac{3}{4}\sum_{i=1}^{n_h}\log\left(\frac{m_i}{\mu}\right)\right]+\frac{3}{8}n_hL_2-n_l\left(\frac{67}{96}L_0+\frac{2}{3}L_1\right)$$

$$+\sum_{\substack{1\le i<n_h\\ i<j\le n_h}}\left[(y_i-y_j)\left(\frac{57}{128}\left(\frac{m_i^2}{m_j^2}-\frac{m_j^2}{m_i^2}\right)+\left(\frac{57}{128}\frac{m_i^2}{m_j^2}+\frac{57}{128}\frac{m_j^2}{m_i^2}+\frac{43}{32}\right)\log\left(\frac{m_i}{m_j}\right)\right.\right.$$

$$\left.+\frac{57}{256}\frac{m_i^6+m_j^6}{m_i^2m_j^2\left(m_i^2-m_j^2\right)}\log^2\left(\frac{m_i}{m_j}\right)\right)-\log^2\left(\frac{m_i}{m_j}\right)\left(\frac{73}{256}(y_i+y_j)+\frac{23}{128}\frac{y_im_i^2-y_jm_j^2}{m_i^2-m_j^2}\right.$$

$$+3\left(m_i^2-m_j^2\right)\frac{19m_i^4+24m_i^2m_j^2+19m_j^4}{512m_i^3m_j^3}\left(y_j\log\left(\frac{m_j-m_i}{m_j+m_i}\right)-y_i\log\left(\frac{m_i-m_j}{m_i+m_j}\right)\right)\Bigg)$$

$$-3\frac{19m_i^6+5m_i^4m_j^2-5m_i^2m_j^4-19m_j^6}{1024m_i^3m_j^3}\left(8y_i\mathrm{Li}_3\left(\frac{m_j}{m_i}\right)-8y_j\mathrm{Li}_3\left(\frac{m_i}{m_j}\right)-y_i\mathrm{Li}_3\left(\frac{m_j^2}{m_i^2}\right)\right.$$

$$\left.\left.\left.+y_j\mathrm{Li}_3\left(\frac{m_i^2}{m_j^2}\right)-2\log\left(\frac{m_i}{m_j}\right)\left(y_i\mathrm{Li}_2\left(\frac{m_j^2}{m_i^2}\right)+y_j\mathrm{Li}_2\left(\frac{m_i^2}{m_j^2}\right)-4y_i\mathrm{Li}_2\left(\frac{m_j}{m_i}\right)-4y_j\mathrm{Li}_2\left(\frac{m_i}{m_j}\right)\right)\right)\right]\right\}$$

$$y_i=\frac{Y_i}{m_i}\;,\;L_0=\sum_i y_i\;,\;L_1=\sum_i\left(y_i\log(m_i)\right)\;,\;L_2=\sum_i\left(y_i\log^2(m_i)\right)\;.$$

Higgs production cross-section

* include
  - ➡ exact LO cross-section
  - ➡ NLO and NNLO Wilson coefficient in the infinite-mass approximation

	$\frac{\sigma_{CH}^{NNLO}}{\sigma_{SM}^{NNLO}}$
one multiplet	33 - 34%
two multiplets	1 - 360%

✓ Falkowski

Higgs production cross-section

* why do we obtain so large deviations from the SM?
  - ➡ the leading contribution to the Higgs production cross section depends on

$$\left(\sum_q \frac{Y_q}{m_q}\right)^2$$

  - ➡ top quark with a relatively large Yukawa coupling Y_t + other relatively light new quarks with a coupling of the same sign as Y_t ⇨ enhancement
  - ➡ light fermions with small Yukawa couplings, or with Yukawa couplings of about the same size, but with opposite signs ⇨ suppression

Higgs production cross-section

* higher-order terms affect the LO result differently than in the SM for small values of the cross section ($\sigma^{NNLO} \simeq \sigma^{LO}$, $\sigma^{NNLO} \simeq 4\sigma^{LO}$)

* the couplings of the Higgs to the gauge bosons are less suppressed than the couplings to the fermions

➡ electroweak corrections can be more relevant than in the SM

Conclusions

* the Higgs boson is likely to come with some new physics
* many viable BSM theories exist, and many introduce new coloured particles
* new particles can significantly affect the gluon-fusion cross section
* we adopt an effective-theory approach to disentangle new physics from QCD
* we have automatised the matching procedure for BSM models through NNLO
* examples: four-generation SM, composite Higgs models
  - ➡ can have large deviations from the Standard Model!