Precise predictions for Higgs production via gluon fusion in BSM scenarios

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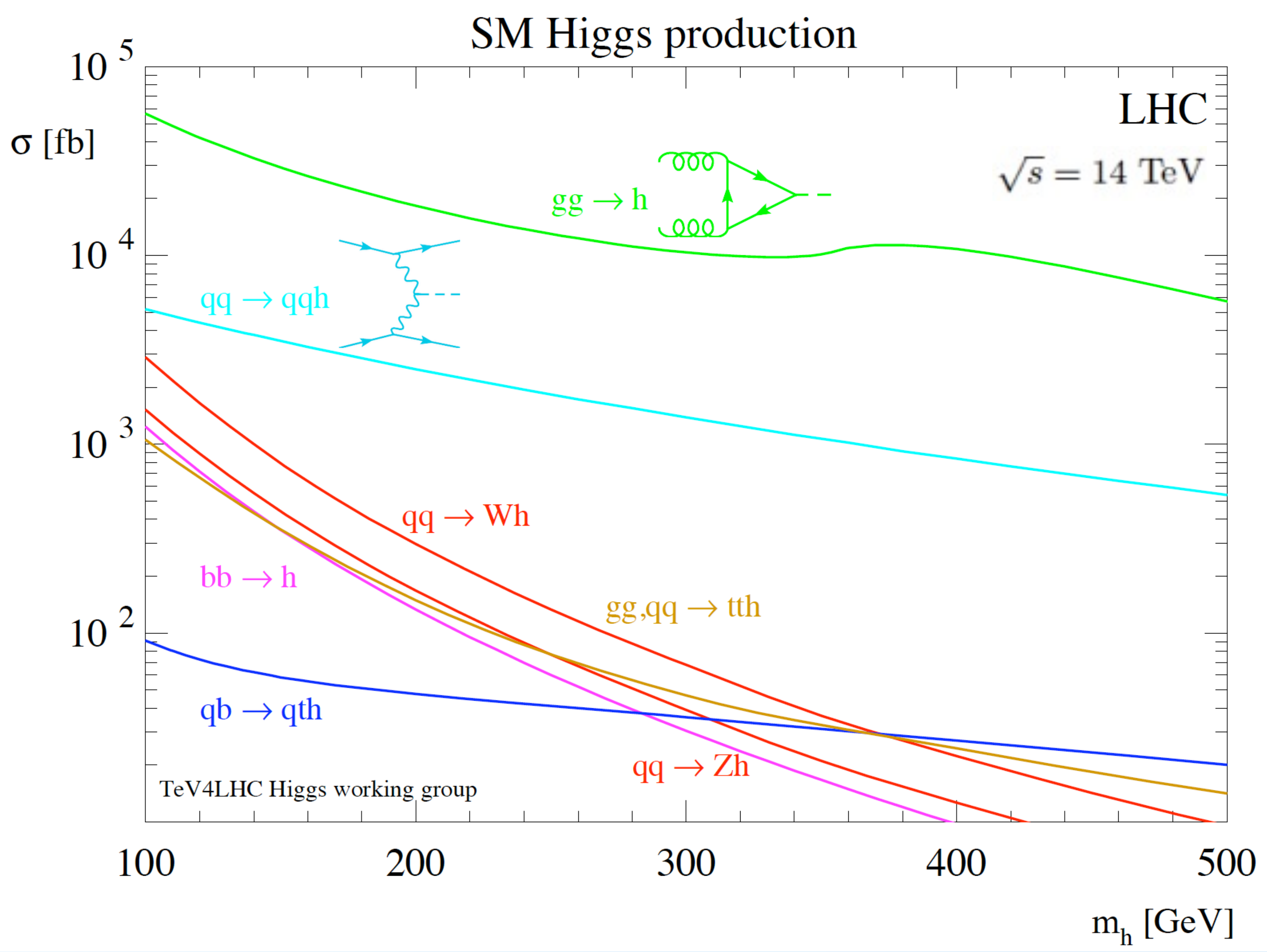
Motivation

* gluon fusion is the main mechanism for Higgs production at hadron colliders



Motivation

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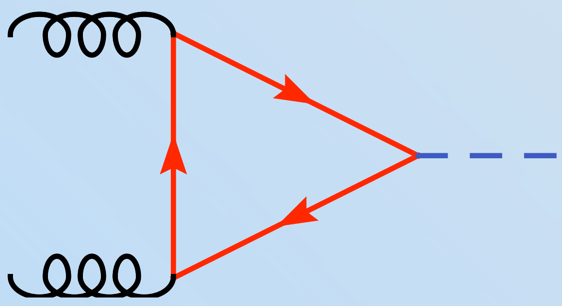
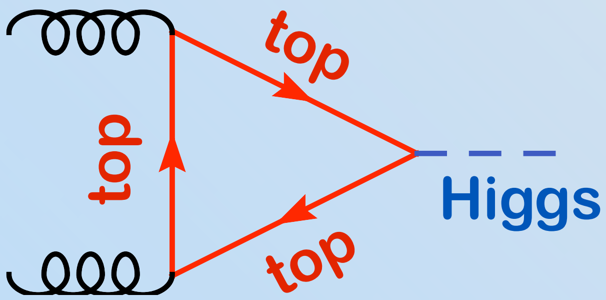


* it is sensitive to any coloured particle that couples to the Higgs, e.g. the top

* extensions of the SM require new particles which may contribute to gluon fusion

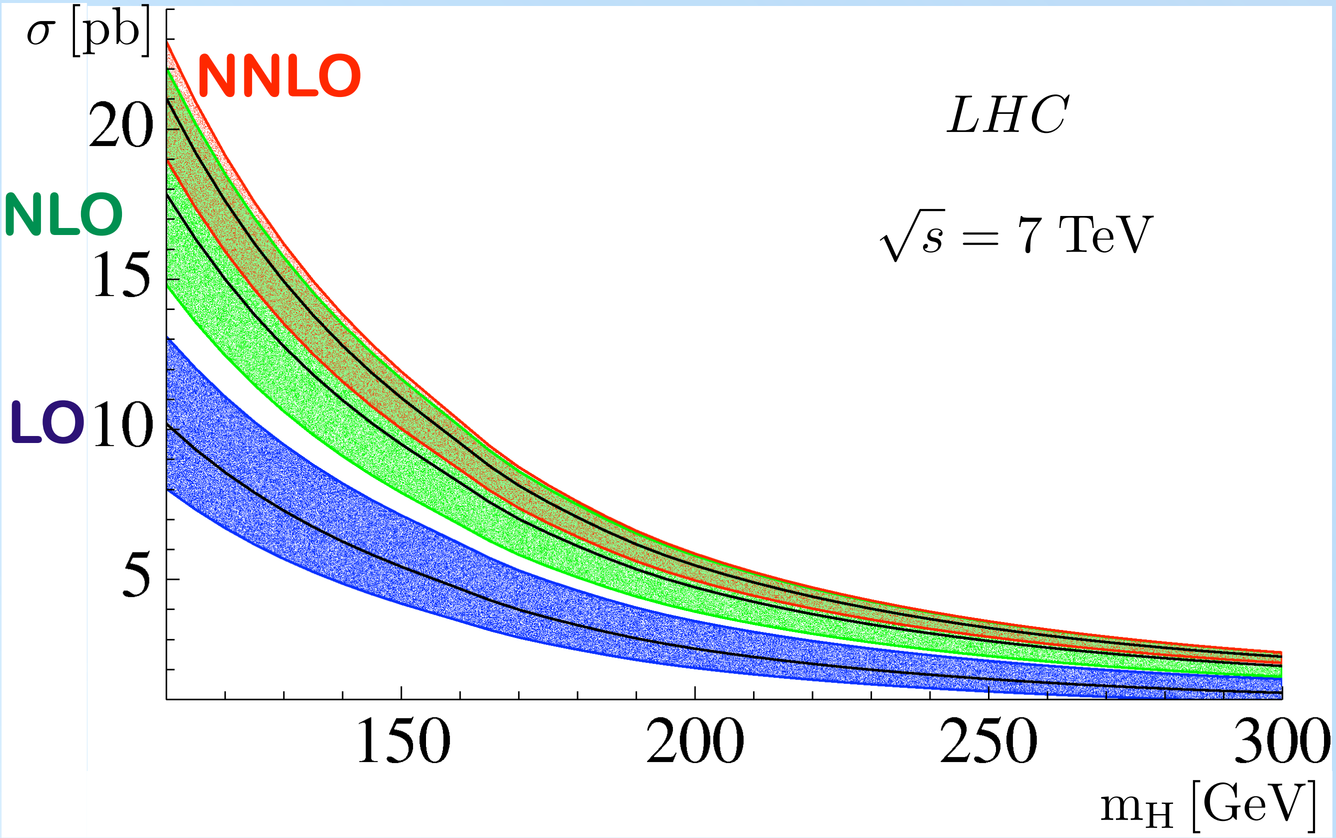
➡ this channel is very sensitive to new physics effects

Gluon fusion in the SM



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

Harlander, Kilgore; Anastasiou, Melnikov;
Ravindran, Smith, van Neerven



Gluon fusion in the SM

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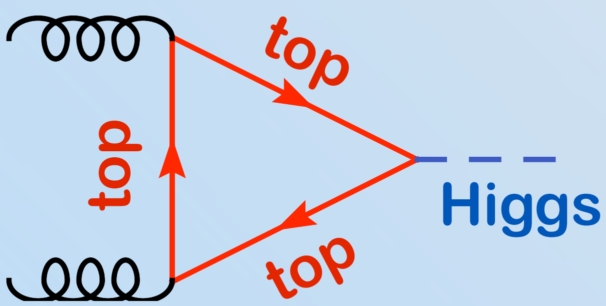
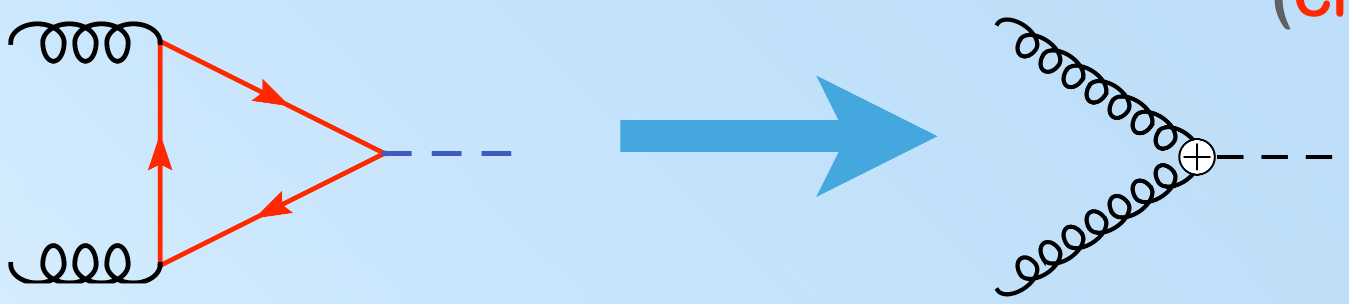


* ... and it required an heavy-quark effective theory (HQET) approach
  ⇨ integrating out the top quark

(Chetyrkin, Kniehl, Steinhauser)



Gluon fusion in BSM

* only very recent NNLO calculations in some BSM scenarios

  scalar octects (Boughezal, Petriello); 4th generation (Anastasoiu, Boughezal, EF; Anastasoiu, Buehler, EF, Herzog, Lazopoulos); MSSM (Pak, Steinhauser, Zerf); composite Higgs (EF)

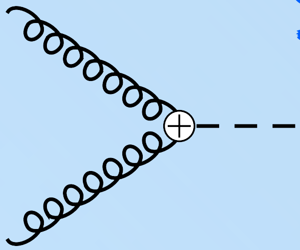
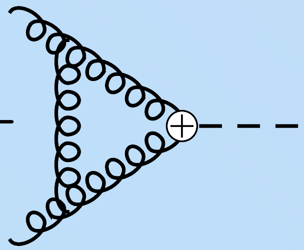
* the low-energy theory is the same as in SM HQET, but the matching calculation at NNLO is much more complicated:
  - number of diagrams (~10^3 - 10^4)
  - renormalization (e.g., new vertices)
  - dependence on multiple mass scales

Separating new physics

* we can construct an effective theory that contains only the light degrees of freedom of the Standard Model
  - ➡ particles that are heavier than half the Higgs mass are integrated out
  - ➡ obtain an effective gluon-gluon-Higgs vertex

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

$$\underbrace{\left(C_0 + \left(\frac{\alpha_s}{\pi}\right) C_1 + \left(\frac{\alpha_s}{\pi}\right)^2 C_2 + \dots\right)}_{\text{depends on the specific model}}$$

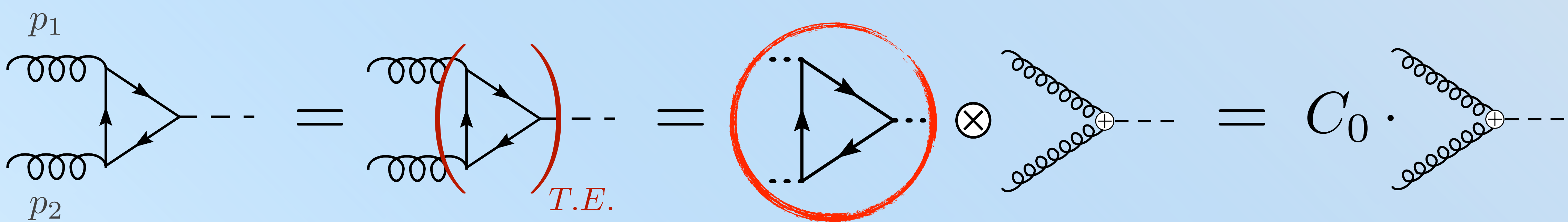
( +  + ...)

light-flavour QCD only!

Method

* **expansion by subgraphs** (Chetyrkin; Gorishny; V. A. Smirnov)

  + small momentum expansion (Fleischer, Tarasov):



$$\sum_{n=0}^{\infty} \mathcal{F}_n (p_1 \cdot p_2)^n \ ,$$

$$\mathcal{F}_n = \mathcal{D}_n \mathcal{F}\Big|_{p_1=p_2=0}$$

we are computing vacuum bubbles!

$$\left(\mathcal{D}_0 = 1\,, \mathcal{D}_1 = \frac{1}{d}\Box_{12}\,, \ldots\right)$$

Method

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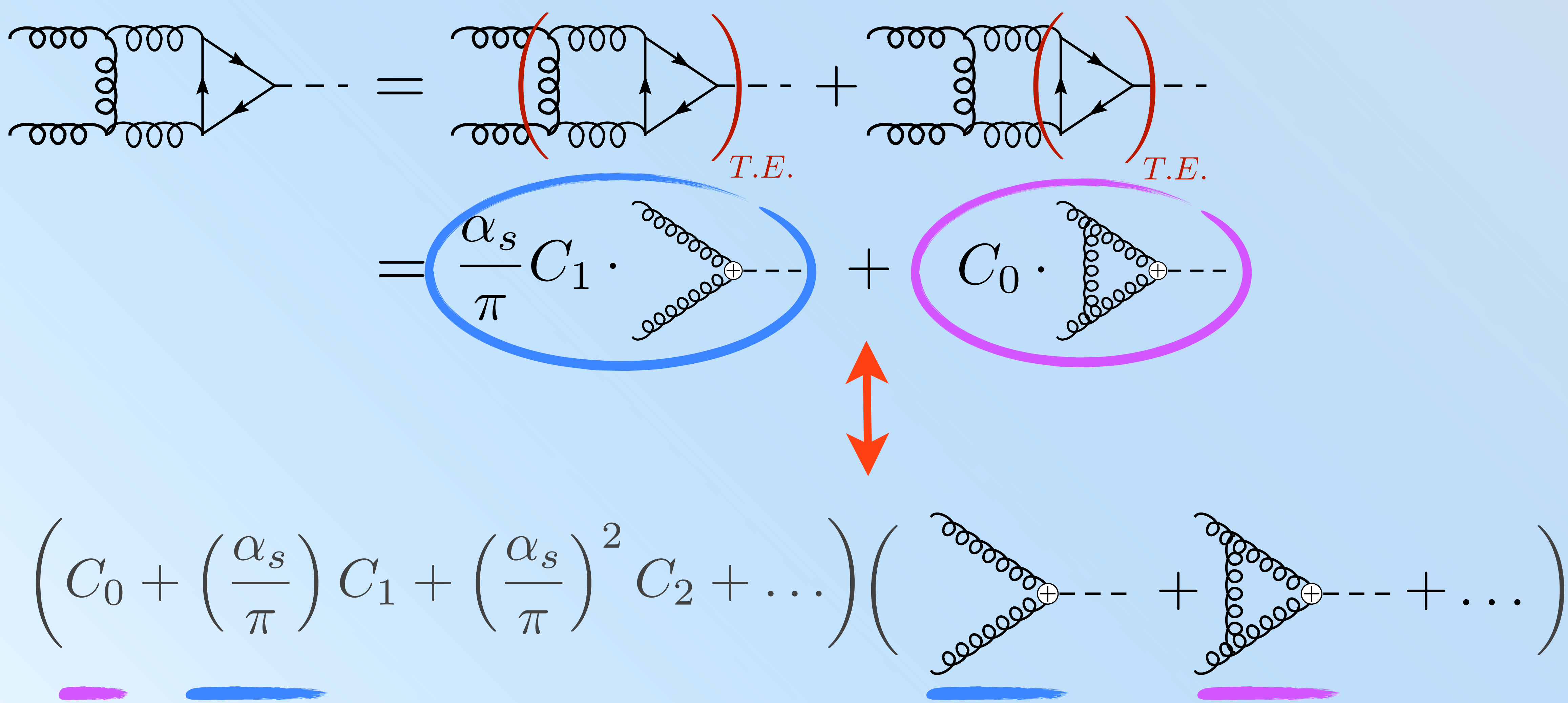
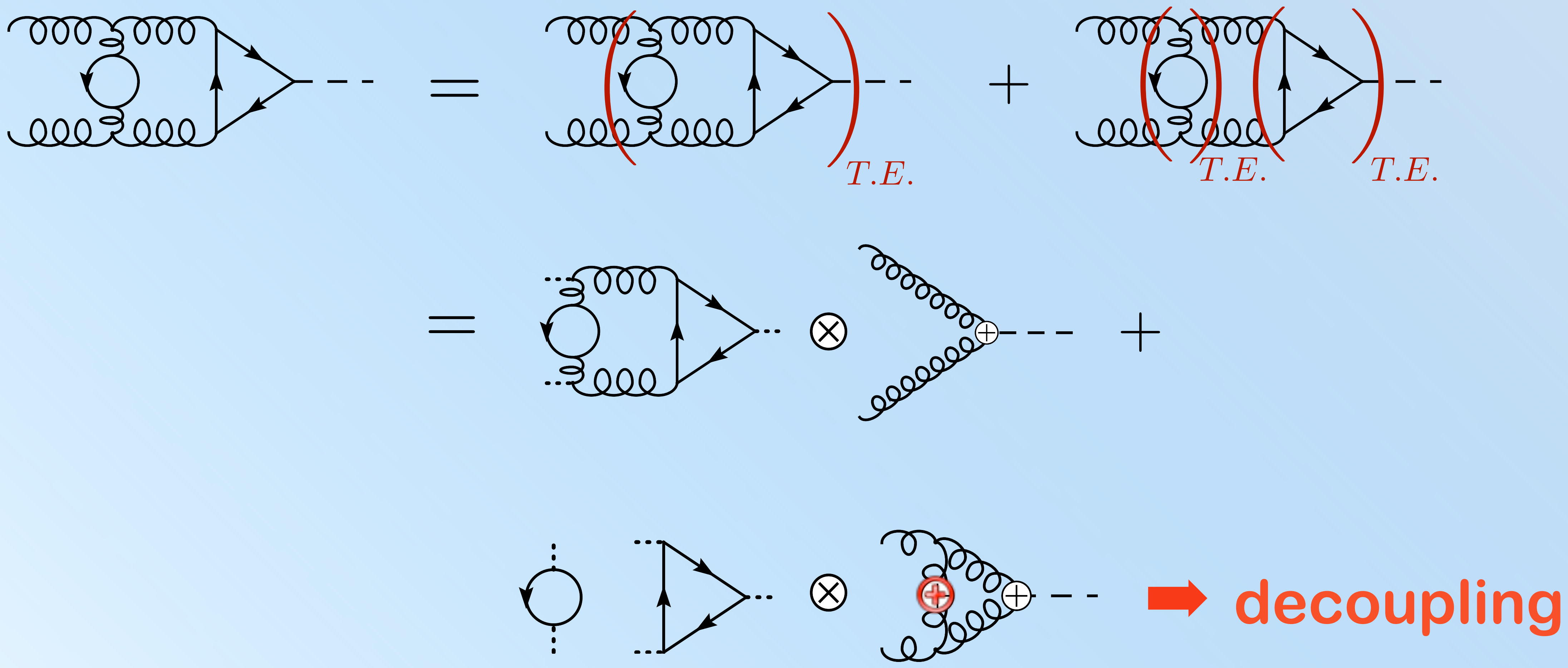


Method

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

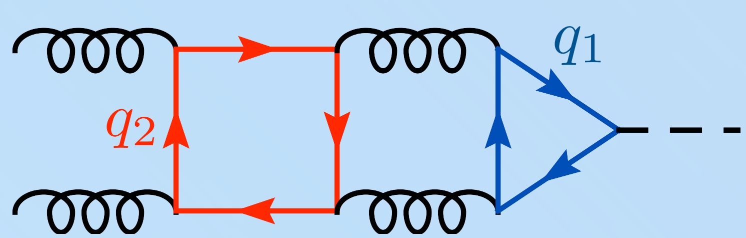


Extra quarks

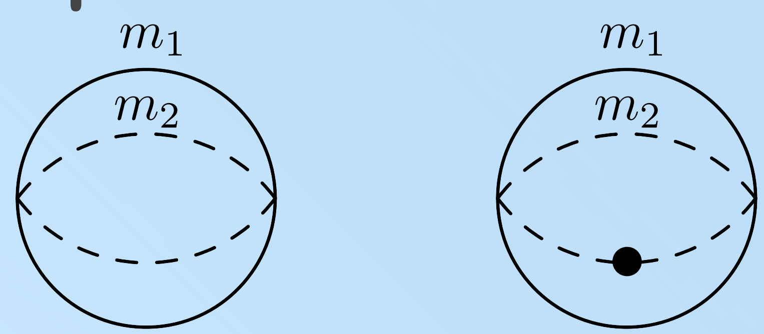
* consider extensions of the SM with additional heavy quarks / non-standard Yukawa interactions:
  - ➡ four-generation SM
  - ➡ fermions in composite Higgs models

Extra quarks

* “complications”:
  - at NNLO we have diagrams containing two different heavy quarks

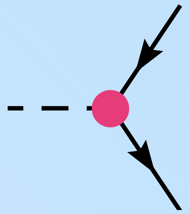


  - integrals with up to two different massive propagators



Bekavac, Grozin, Seidel, Smirnov

  - new kind of vertex to renormalize



$$\cancel{\frac{m_q}{v}} \longrightarrow Y_q$$

Extra quarks

$$
\begin{aligned}
C_1 = & -\frac{1}{3}\Upsilon_0 - \frac{11}{12}\frac{\alpha_s'(\mu)}{\pi}\Upsilon_0 - \frac{1}{3}\left(\frac{\alpha_s'(\mu)}{\pi}\right)^2 \Bigg\{ -n_l\left(\frac{67}{96}\Upsilon_0 + \frac{2}{3}\Upsilon_1\right) + \Upsilon_0\left(\frac{1877}{192} - \frac{77}{576}n_h + \frac{113}{96}L_1 + \frac{3}{8}L_2\right) \\
& - \Upsilon_1\left(\frac{19}{8} + \frac{113}{96}n_h + \frac{3}{4}L_1\right) + \frac{3}{8}n_h\Upsilon_2 + \sum_{\substack{1\leq i<n_h \\ i<j\leq n_h}} \Bigg[(y_i - y_j)\Bigg(\left(\frac{57}{128}\frac{m_i^2}{m_j^2} + \frac{57}{128}\frac{m_j^2}{m_i^2} + \frac{43}{32}\right)\log\left(\frac{m_i}{m_j}\right) \\
& + \frac{57}{256}\frac{m_i^6 + m_j^6}{m_i^2 m_j^2\left(m_i^2 - m_j^2\right)}\log^2\left(\frac{m_i}{m_j}\right) + \frac{57}{128}\left(\frac{m_i^2}{m_j^2} - \frac{m_j^2}{m_i^2}\right)\Bigg) - \log^2\left(\frac{m_i}{m_j}\right)\Bigg(\frac{73}{256}(y_i + y_j) + \frac{23}{128}\frac{y_i m_i^2 - y_j m_j^2}{m_i^2 - m_j^2} \\
& + \frac{3}{512}(m_i^2 - m_j^2)\frac{19m_i^4 + 24m_i^2 m_j^2 + 19m_j^4}{m_i^3 m_j^3}\left(y_j\log\left(\frac{m_j - m_i}{m_j + m_i}\right) - y_i\log\left(\frac{m_i - m_j}{m_i + m_j}\right)\right)\Bigg) \\
& - \frac{3}{1024}\frac{19m_i^6 + 5m_i^4 m_j^2 - 5m_i^2 m_j^4 - 19m_j^6}{m_i^3 m_j^3}\cdot\Bigg(8y_i\mathrm{Li}_3\left(\frac{m_j}{m_i}\right) - 8y_j\mathrm{Li}_3\left(\frac{m_i}{m_j}\right) - y_i\mathrm{Li}_3\left(\frac{m_j^2}{m_i^2}\right) + y_j\mathrm{Li}_3\left(\frac{m_i^2}{m_j^2}\right) \\
& - 2\log\left(\frac{m_i}{m_j}\right)\left(y_i\mathrm{Li}_2\left(\frac{m_j^2}{m_i^2}\right) + y_j\mathrm{Li}_2\left(\frac{m_i^2}{m_j^2}\right) - 4y_i\mathrm{Li}_2\left(\frac{m_j}{m_i}\right) - 4y_j\mathrm{Li}_2\left(\frac{m_i}{m_j}\right)\right)\Bigg)\Bigg]\Bigg\}
\end{aligned}
$$

SM-like Yukawa couplings

implemented in iHixs
(Anastasious, Buhler, Herzog, Lazopoulos)

$$
C_1 = -\frac{1}{3}\frac{\alpha_s'(\mu)}{\pi}\left\{n_h + \frac{11}{4}\frac{\alpha_s'(\mu)}{\pi}n_h - \left(\frac{\alpha_s'(\mu)}{\pi}\right)^2\left[-\frac{1877}{192}n_h + \frac{77}{576}n_h^2 + \frac{19L_m}{8} + n_l\left(\frac{67}{96}n_h + \frac{2L_m}{3}\right)\right]\right\}
$$

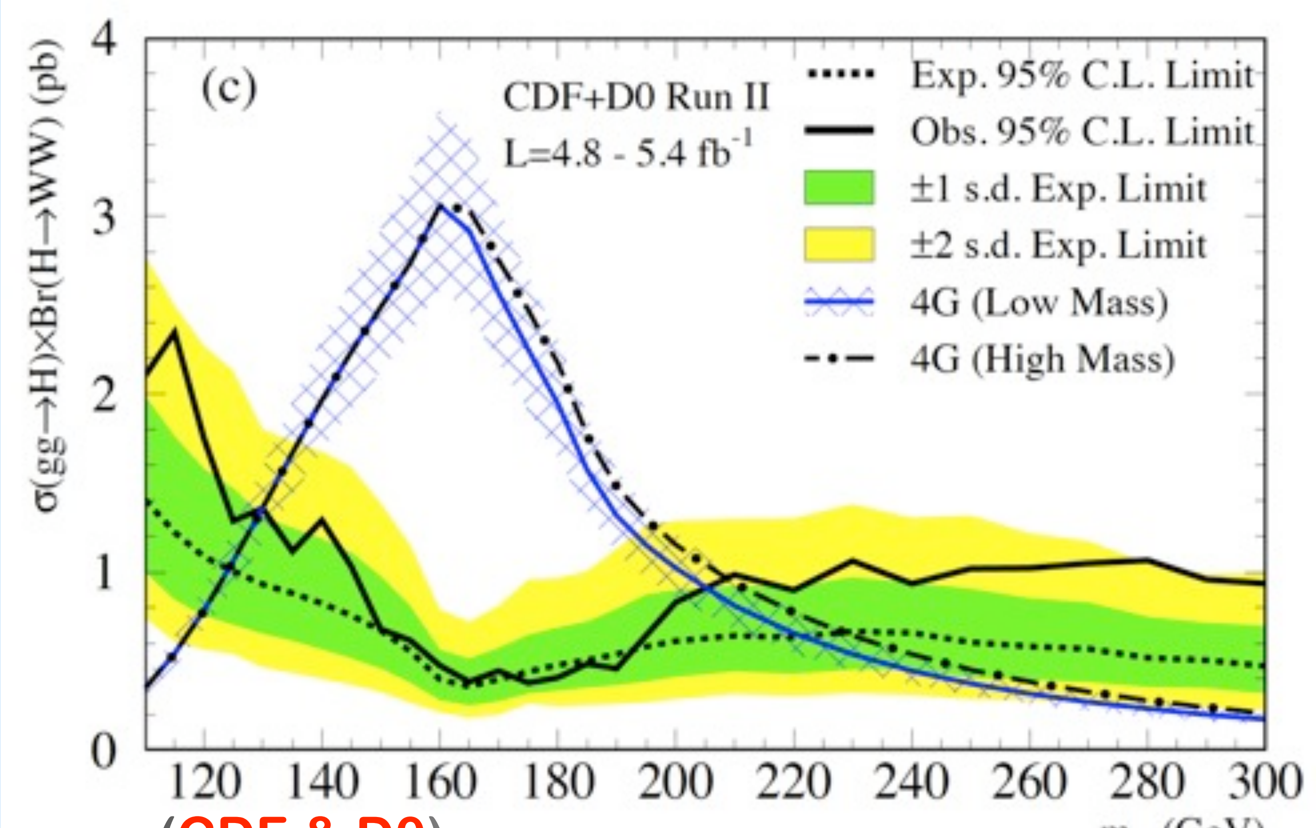
Four-generation SM

(Anastasoiu, Boughezal, EF; Anastasoiu, Buehler, EF, Herzog, Lazopoulos)

* 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

* these results have been used by the experimental collaborations to put accurate constraints on the mass of the Higgs boson in a four-generation SM



(CDF & D0)

Composite Higgs models

Gerogi, Kaplan; Contino, Nomura, Pomarol;
Agashe, Contino, Pomarol; Contino, Da Rold, Pomarol

* class of models that address the hierarchy problem
* introduce additional, heavy vector-like quarks
* the top-quark gets its mass partly through mixing with the new quarks, partly through the Higgs mechanism
  - ➡ non-standard Yukawa couplings
  - ➡ more than one heavy quark coupling to the Higgs boson

Higgs production

- 30-35% suppression with respect to the SM production cross section ✓ Falkowski
  - for $m_h = 120\,\mathrm{GeV}$,

    $$\sigma_{SM} = 17.6\,\mathrm{pb}$$

    while σ_{CH} is in the range $5.9 - 6.4\,\mathrm{pb}$
- as in the SM, the scale variation error reduces from ${}^{+(27\div 33)\%}_{-(19\div 23)\%}$ at LO to ${}^{+(6\div 12)\%}_{-(7\div 10)\%}$ at NNLO

Higgs production

* K-factors are similar to the Standard Model

LHC, 7 TeV	SM	CHM
$\frac{\sigma_{tbew}^{NLO}}{\sigma_{tbew}^{LO}}$	+ 75%	+ 77 - 78%
$\frac{\sigma_{tbew}^{NNLO}}{\sigma_{tbew}^{LO}}$	+ 106%	+ 108 - 110%

* bottom-quark and two-loop electroweak corrections are more important than in the Standard Model

	SM	CHM
$\frac{\sigma_{tb}^{LO} - \sigma_{t}^{LO}}{\sigma_{t}^{LO}}$	- 7%	- 10%
$\frac{\sigma_{tb}^{NLO} - \sigma_{t}^{NLO}}{\sigma_{t}^{NLO}}$	- 4%	- 6%
$\frac{\sigma_{tew} - \sigma_{t}}{\sigma_{t}}$	+ 5%	+ 7%

Conclusions

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

Composite Higgs models

Gerogi, Kaplan; Contino, Nomura, Pomarol;
Agashe, Contino, Pomarol; Contino, Da Rold, Pomarol

* there is a new, strongly interacting sector responsible for the breaking of the electroweak symmetry
* the new sector possesses a spontaneously broken global symmetry
* we choose the minimal (custodial) symmetry breaking pattern
  SO(5)/SO(4)
* the Higgs boson is the (pseudo) Goldstone boson associated to this symmetry breaking

Composite Higgs models

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- ➡ its mass is naturally light, as it is generated at loop level and is not sensitive to radiative corrections above the compositeness scale
- ➡ other composite bosons are much heavier than the Higgs a can adopt a “non-linear sigma model” description that allows to decouple them
- ➡ this description breaks down at a scale

$$\Lambda \sim 2\pi f$$

- ➡ we choose $f = 500\,\mathrm{GeV}$ not to have too large fine-tuning

Composite Higgs models

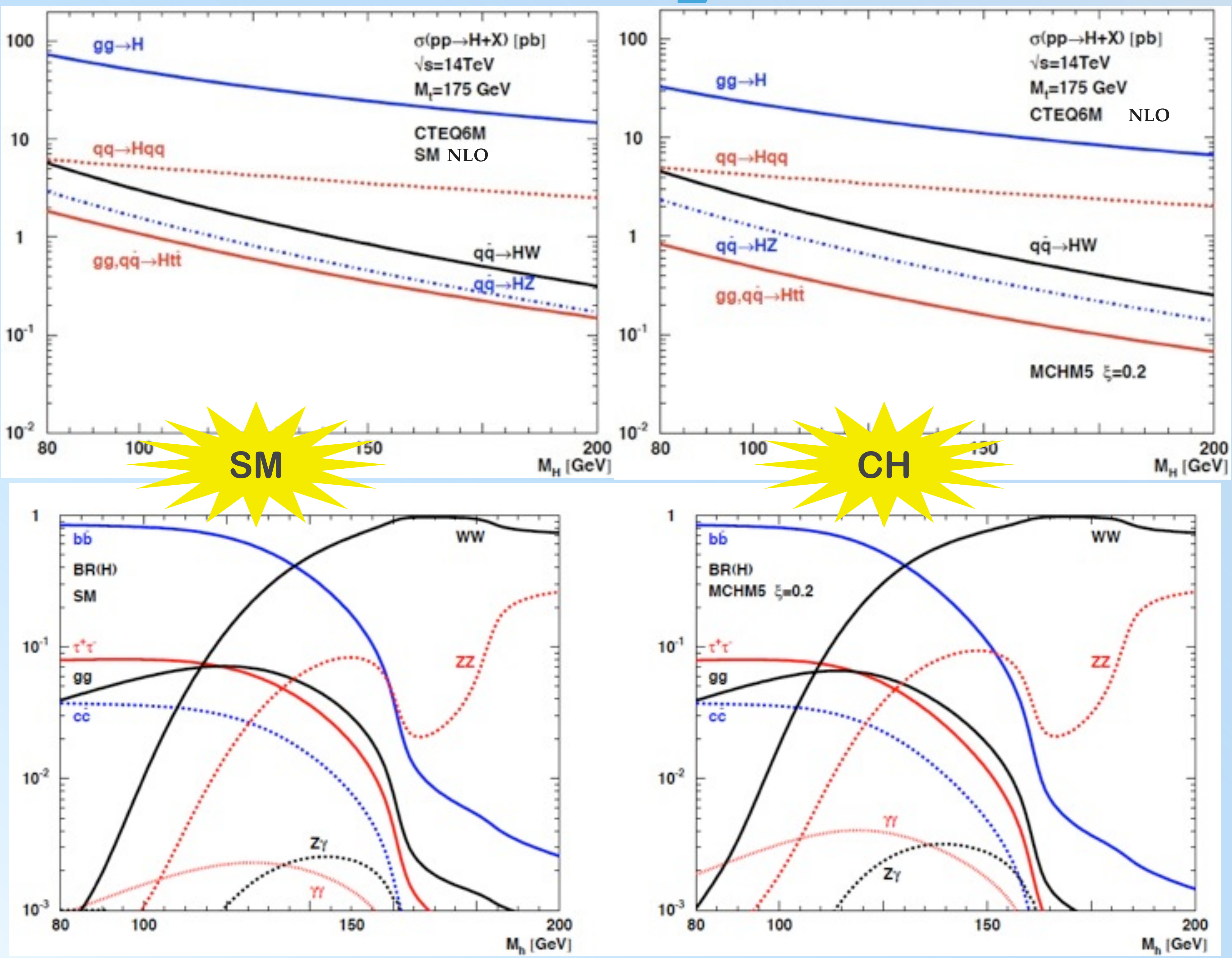
Gerogi, Kaplan; Contino, Nomura, Pomarol;
Agashe, Contino, Pomarol; Contino, Da Rold, Pomarol

* Standard Model particles get their masses through mixing with composite fermions of the new sector
  - ➡ heavy quarks are largely "composite", so they couple more with the Higgs boson
  - ➡ couplings to the Higgs boson are reduced with respect to the Standard Model

$$g_{VVh} = g^{SM}_{VVh}\sqrt{1 - v^2/f^2} \simeq 87\%\ g^{SM}_{VVh}$$

    - this reduction puts the model in contrast with current bounds from electroweak precision tests
  - ➡ the new quarks can help in restoring the agreement of the model with electroweak precision tests

Composite Higgs: production and decay channels



Espinosa, Grojean, Muehlleitner