Precise predictions for Higgs production via gluon fusion in BSM scenarios

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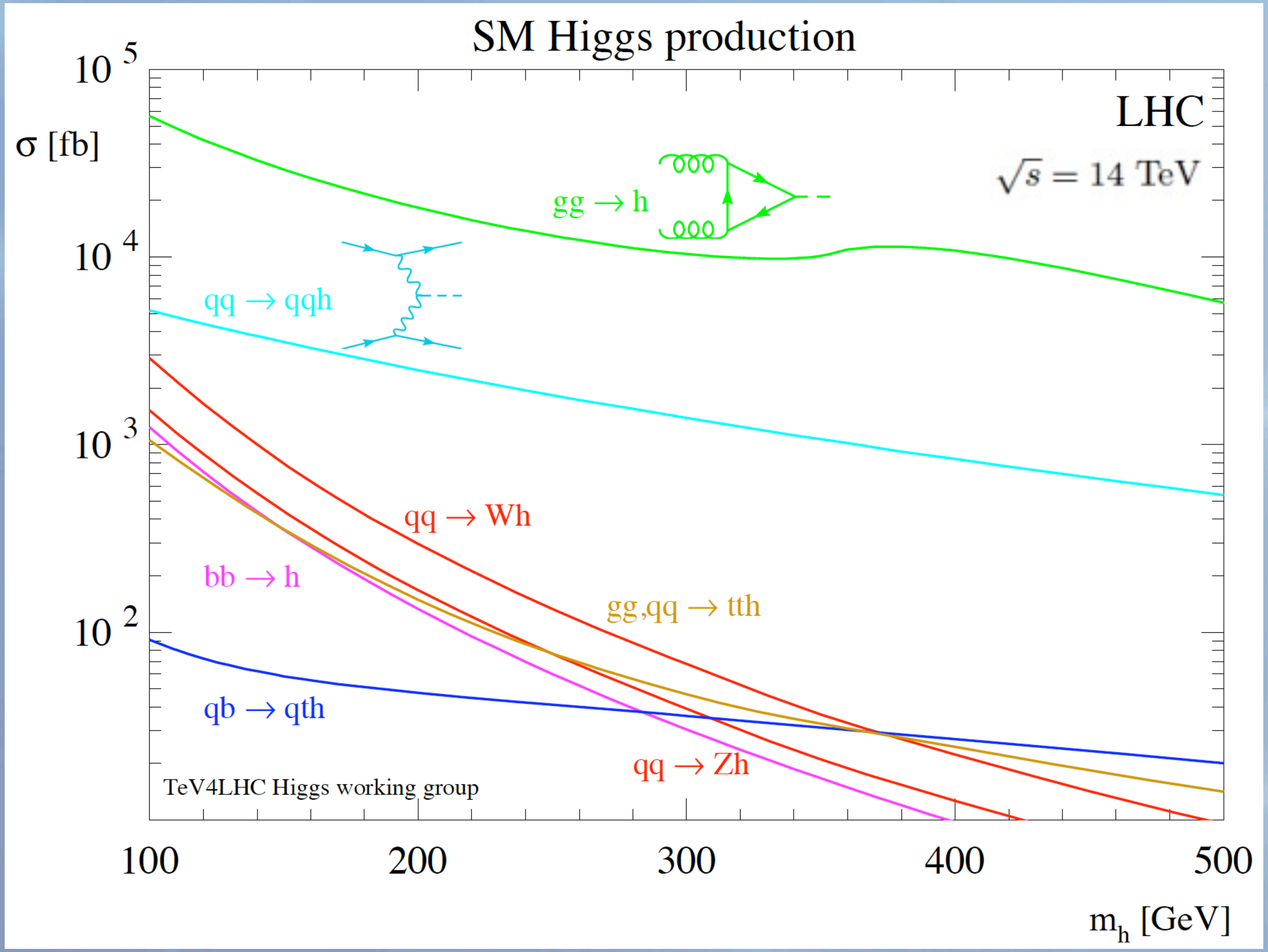
Motivation

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



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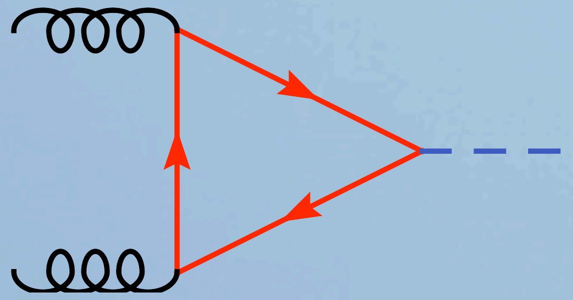
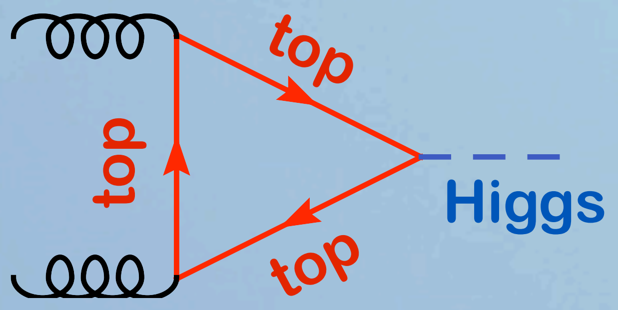


- it is sensitive to any coloured particle that couples to the Higgs, e.g. the top
- extensions of the SM require new particles which may contribute to gluon fusion

➡ this channel is very sensitive to new physics effects

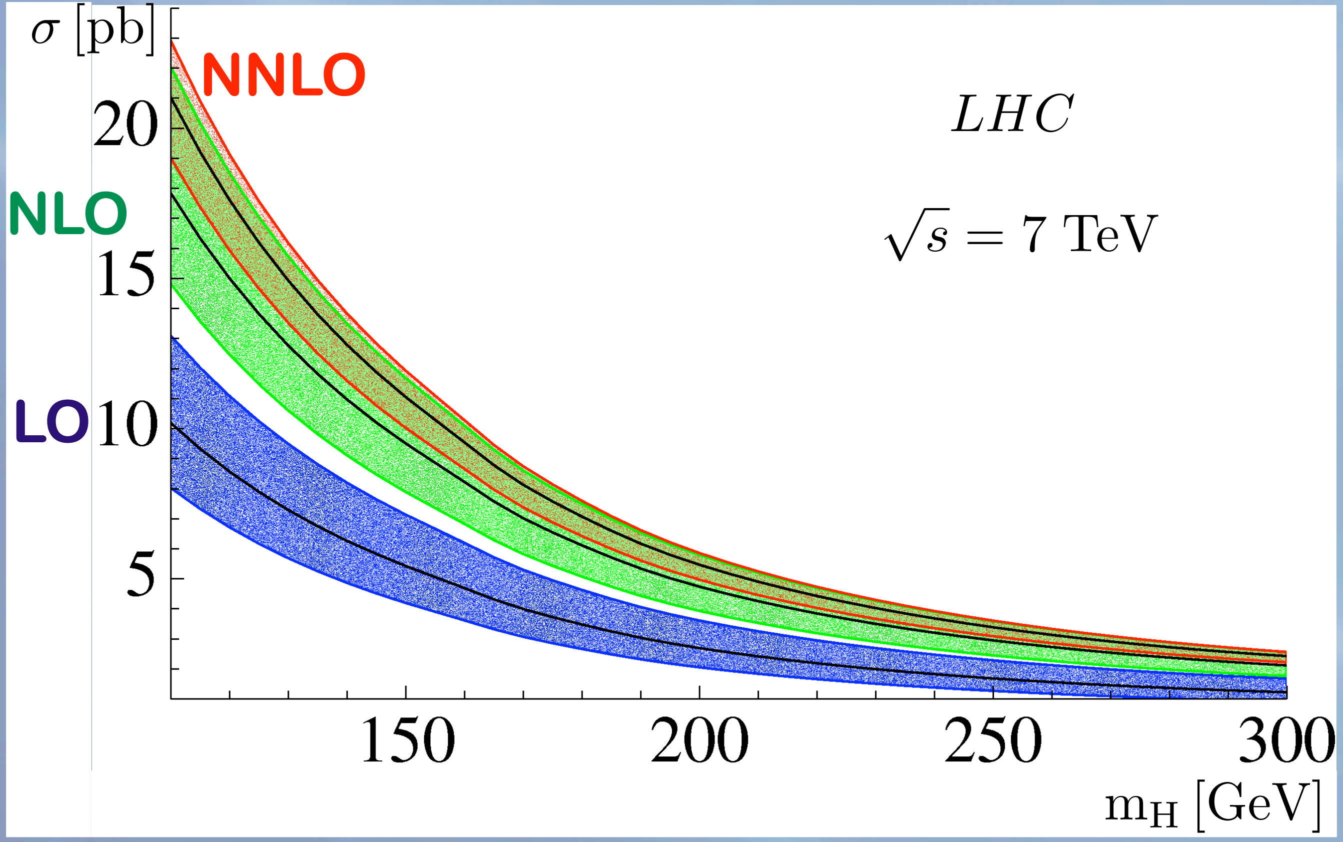
Gluon fusion in the SM

- **it is known very precisely...**



- **... but it required tough calculations**

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



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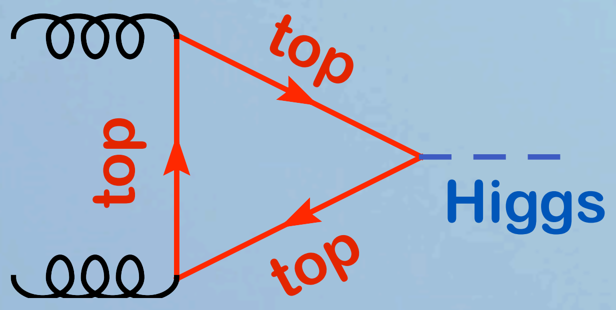


- ... and it required an heavy-quark effective theory (HQET) approach
  ⇨ integrating out the top quark

(**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)

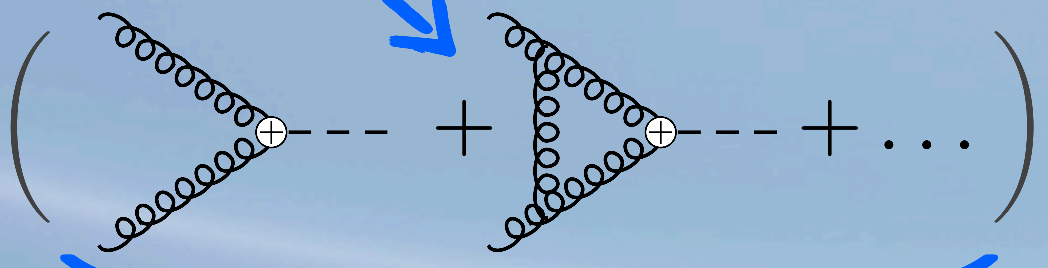
- **the low-energy theory is the same as in SM HQET, but the matching calculation at NNLO is much more complicated:**
  - number of diagrams (~10^3 - 10^4)
  - renormalization (e.g., new vertices)
  - dependence on multiple mass scales

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

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

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

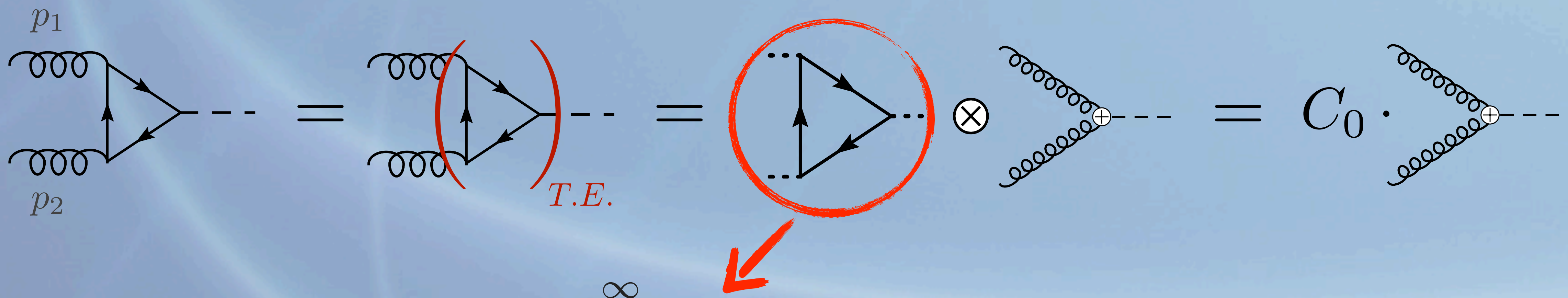


light-flavour QCD only!

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!

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

Method

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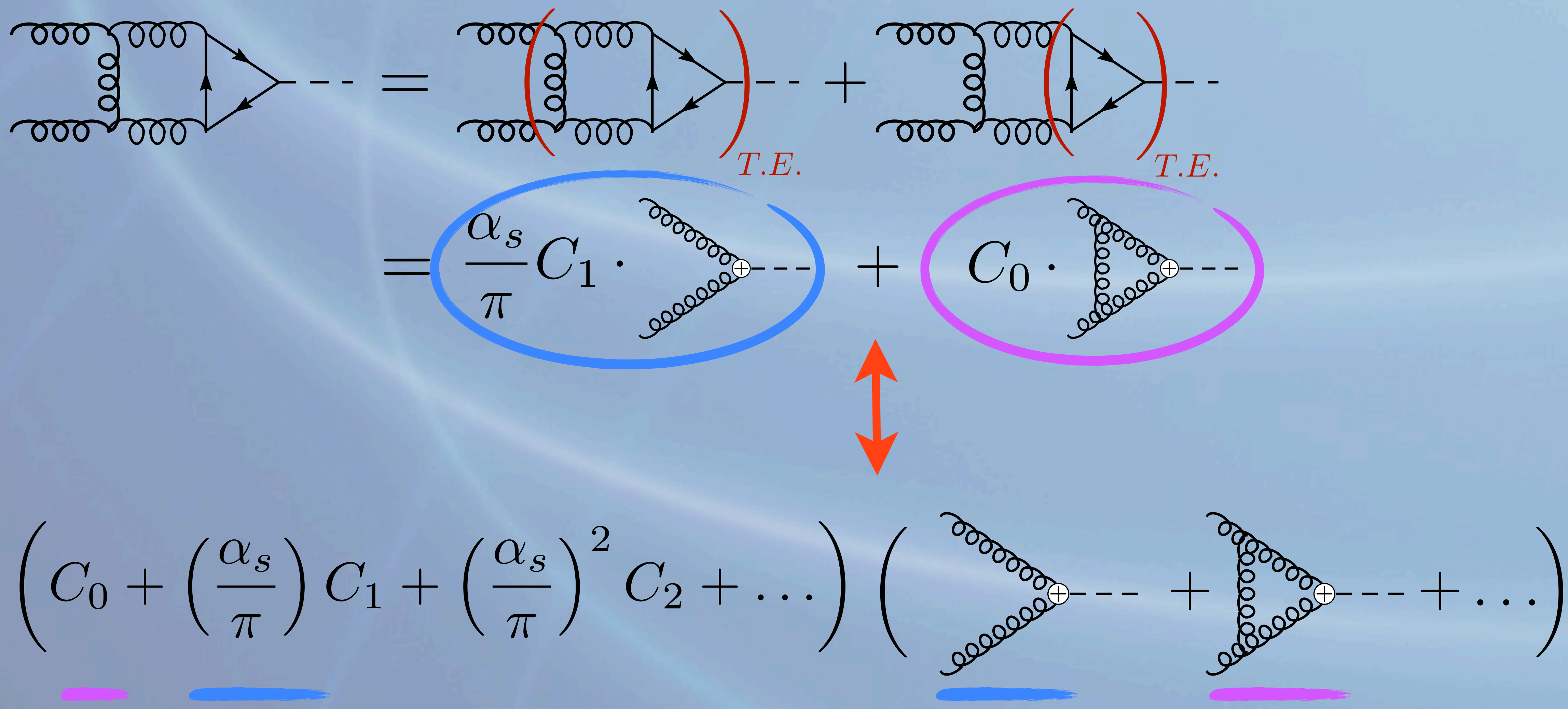
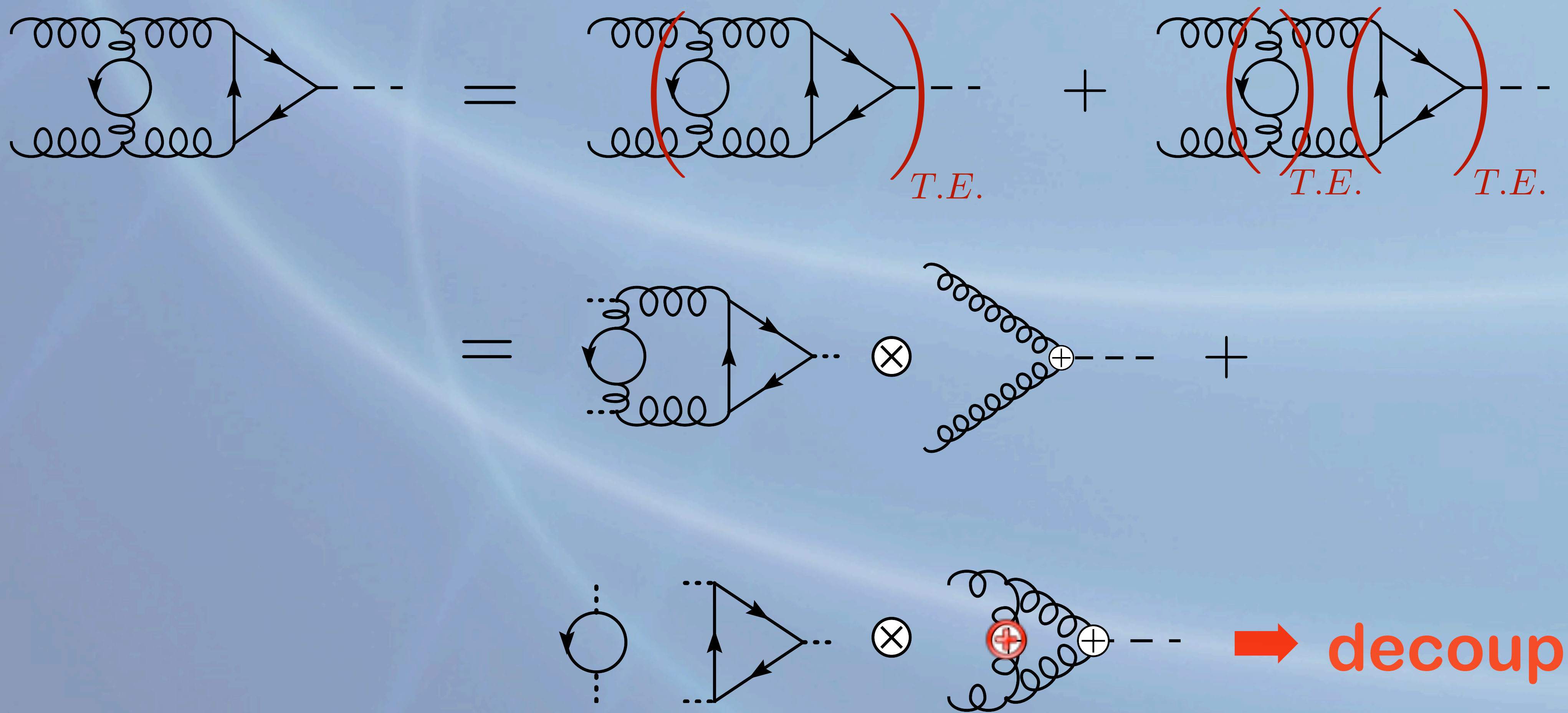


Method

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



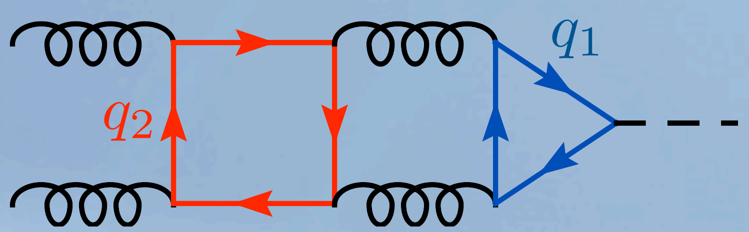
➡ decoupling

Extra quarks

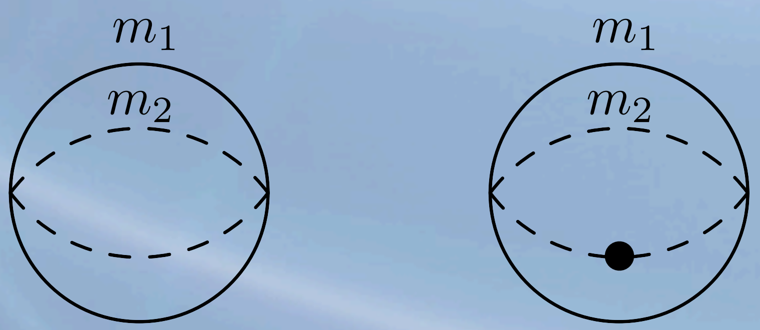
- consider extensions of the SM with additional heavy quarks / non-standard Yukawa interactions:
  - four-generation SM
  - fermions in composite Higgs models

Extra quarks

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

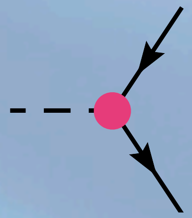


    - integrals with up to two different massive propagators



Bekavac, Grozin, Seidel, Smirnov

  - ➡ new kind of vertex to renormalize



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

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; EF
  - 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 ${}^{+(27\div33)\%}_{-(19\div23)\%}$ at LO to ${}^{+(6\div12)\%}_{-(7\div10)\%}$ 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;
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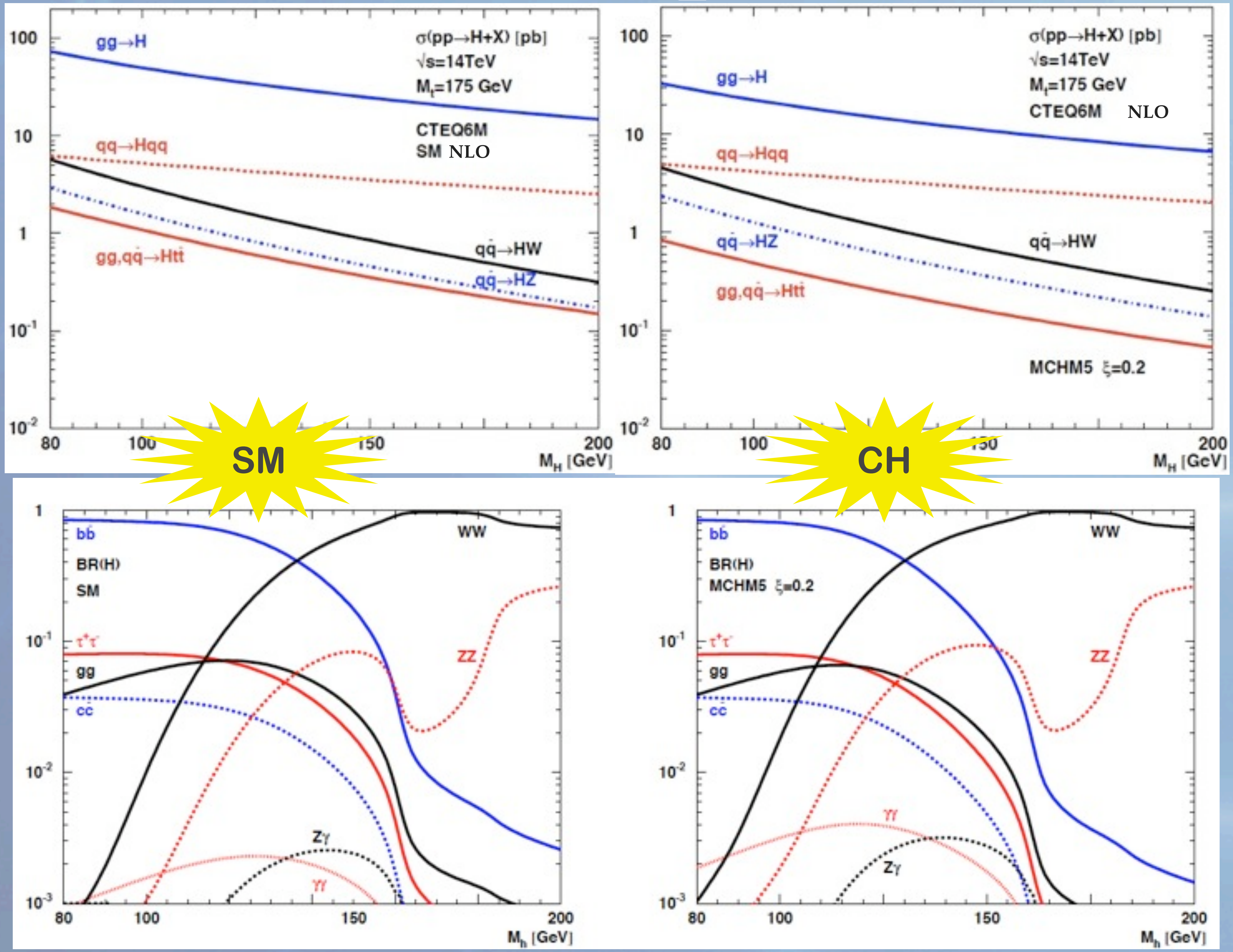
- Standard Model particles get their masses through mixing with composite fermions of the new sector
  - ➡ heavy quarks are largely “composite”, so they couple more with the Higgs boson
  - ➡ couplings to the Higgs boson are reduced with respect to the Standard Model

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

    - 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