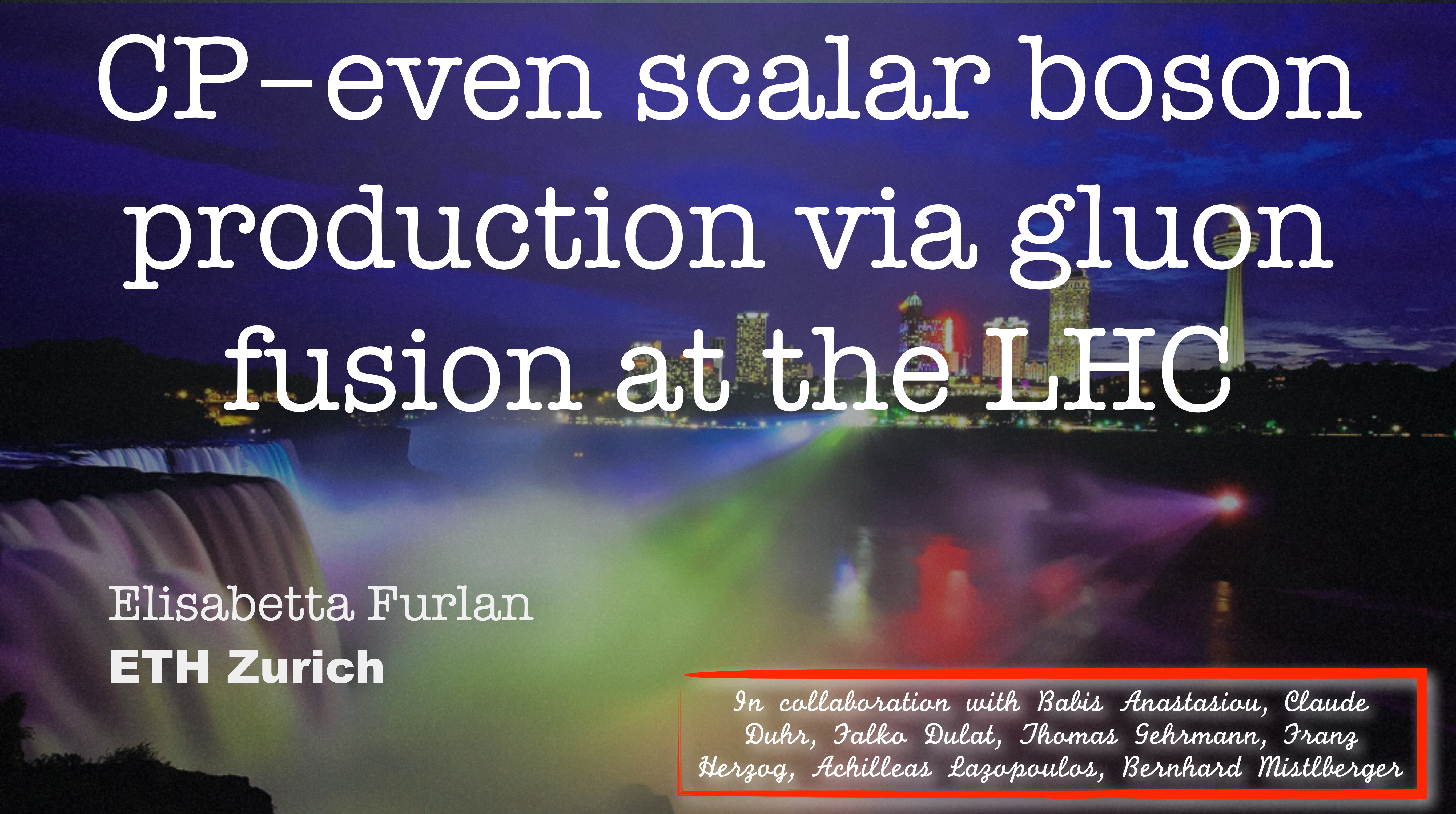

CP-even scalar boson production via gluon fusion at the LHC

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Higgs-like scalar production

- Many BSM scenarios introduce an extended Higgs sector with new scalars
- Undeniably, it has recently been a field of great attention
- Interesting playground to study effects from new high-energy physics (in an effective theory approach) and possibly their interplay with those of “light” Standard Model particles
- Great expertise from our previous, very precise studies of Higgs boson production

Higgs–like scalar production

- We focus on the gluon fusion channel
- No further assumption on the UV theory beyond the production of the new scalar S
- Effective theory: S couples to the gluons through a dimension 5 effective operator

$$\mathcal{L}_{\mathrm{eff}} = -\frac{1}{4v} C_S \, S \, G^a_{\mu\nu} G_a^{\mu\nu}$$

➡ same low–energy theory as the one describing the Higgs dimension–five couplings after decoupling the top quark

Higgs-like scalar production

- Can write the production cross section as

$$\sigma_S(m_S, \Lambda_{\rm UV}) = \left|C_S(\mu, \Lambda_{\rm UV})\right|^2 \eta(\mu, m_S)$$

Wilson coefficient

matrix element
in the effective theory

Higgs–like scalar production

- Can write the production cross section as

$$\sigma_S(m_S, \Lambda_{\mathrm{UV}}) = |C_S(\mu, \Lambda_{\mathrm{UV}})|^2 \, \eta(\mu, m_S)$$

mass scale
from dim. reg.

Higgs-like scalar production

- Can write the production cross section as

$$\sigma_S(m_S, \Lambda_{\mathrm{UV}}) = |C_S(\mu, \Lambda_{\mathrm{UV}})|^2 \, \eta(\mu, m_S)$$

scale of new physics / cutoff scale of
the effective theory description

typical mass scale of the heavy
particles that have been integrated out

example: for gluon-fusion Higgs production
in the light-flavour SM, $\Lambda_{UV} \sim m_t$

Higgs-like scalar production

- Can write the production cross section as

$$\sigma_S(m_S, \Lambda_{\rm UV}) = |C_S(\mu, \Lambda_{\rm UV})|^2\, \eta(\mu, m_S)$$

  - matrix element in the effective theory
  - for a CP-even, colourless scalar produced in gluon fusion, it is the same matrix element as the one for $gg \to H$
  - known through N^{3}LO, with the N^{3}LO term computed as an expansion around the Higgs threshold

Higgs-like scalar production

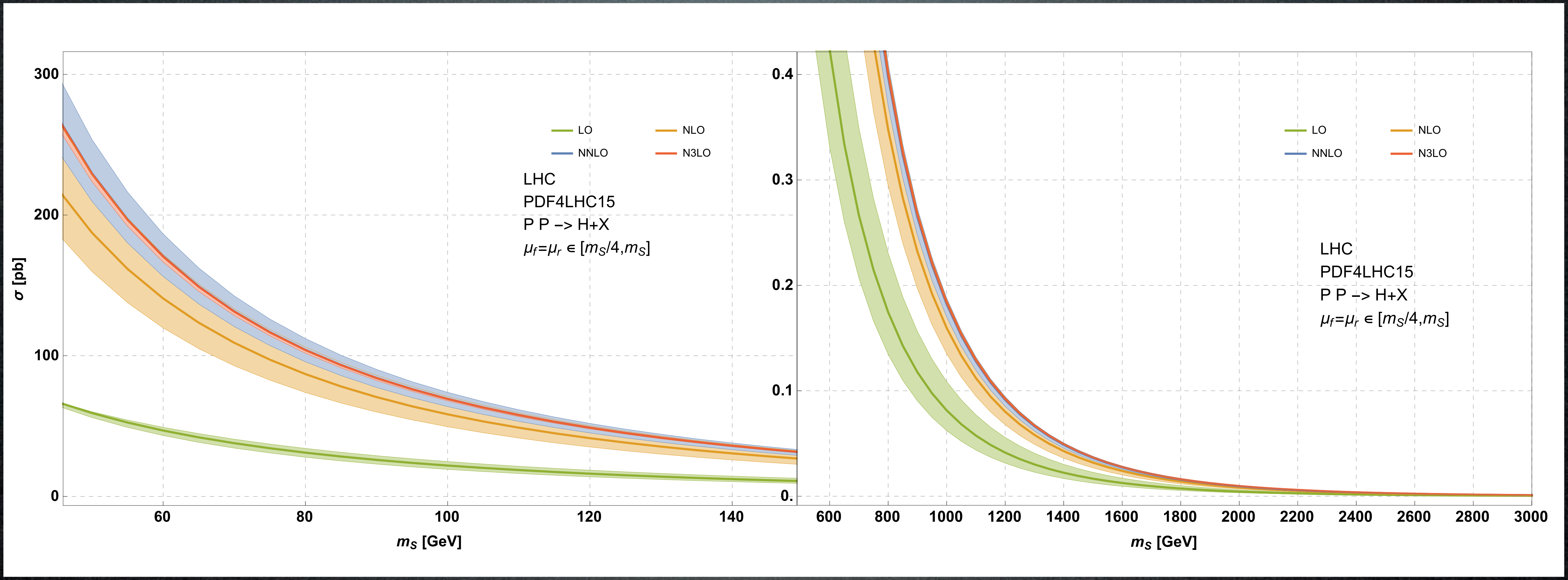
- Can write the production cross section as

$$\sigma_S(m_S, \Lambda_{\rm UV}) = |C_S(\mu, \Lambda_{\rm UV})|^2\, \eta(\mu, m_S)$$

  - derive the production cross section of S from the one for H as

$$\sigma_S(m_S, \Lambda_{\rm UV}) = \left|\frac{C_S(\mu, \Lambda_{\rm UV})}{C_H(\mu, m_t)}\right|^2 \sigma_H(m_S, m_t)$$

Higgs-like scalar production



- for all the range of scalar masses from 10 GeV to 3 TeV (HXSWG recommendations), good convergence of the perturbative expansion at N^{3}LO

The theory error

- As in the SM calculation, the theory error includes
  - scale variation $\mu \in \left[\frac{m_S}{4}, m_S\right]$
  - truncation error from the threshold expansion

$$\delta(\mathrm{trunc}) = 10 \times \frac{\sigma^{(3)}_{EFT}(37) - \sigma^{(3)}_{EFT}(27)}{\sigma^{\mathrm{N^3LO}}_{EFT}}$$

  - missing N^{3}LO parton distributions

$$\delta(\mathrm{PDF-TH}) = \frac{1}{2}\left|\frac{\sigma^{(2),NNLO}_{EFT} - \sigma^{(2),NLO}_{EFT}}{\sigma^{(2),NNLO}_{EFT}}\right|$$

The theory error

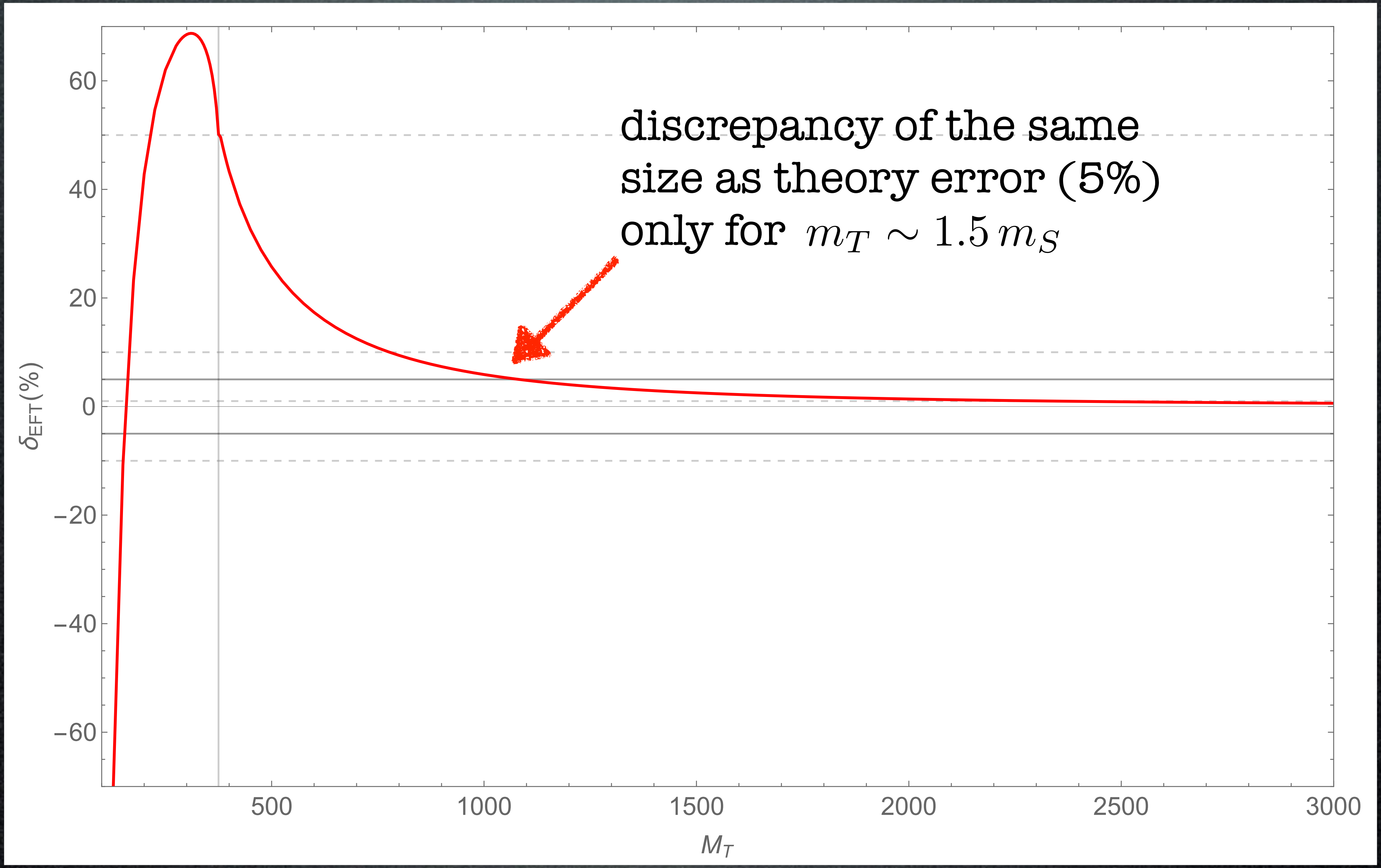
- caveat: we use the PDF set PDF4LHC15 in all the calculations but in the estimate of the PDF-TH error
  - ➡ accidental cancellation for scalar masses around 770 GeV!
  - ➡ for the PDF-TH error, take the envelope of the PDF-TH error given by CT14, NNPDF3.0 and PDF4LHC15
  - ➡ error typically of a few % (cfr. SM, 1.1%), but rapid increase to $\mathcal{O}(10\%)$ for scalar masses below 20 GeV

Validity of the EFT approach

- How good is the EFT if the scalar couples to some new “light” particle?
- Example: 750 GeV scalar coupling to a new quark of mass m_T
- Can compute the cross section exactly through NLO and compare it with the prediction from the effective theory,

$$\delta_{\rm EFT} = \frac{\sigma^{\rm NLO}_{\rm exact}(m_T) - \sigma^{\rm NLO}_{\rm EFT}}{\sigma^{\rm NLO}_{\rm exact}} \times 100$$

Validity of the EFT approach



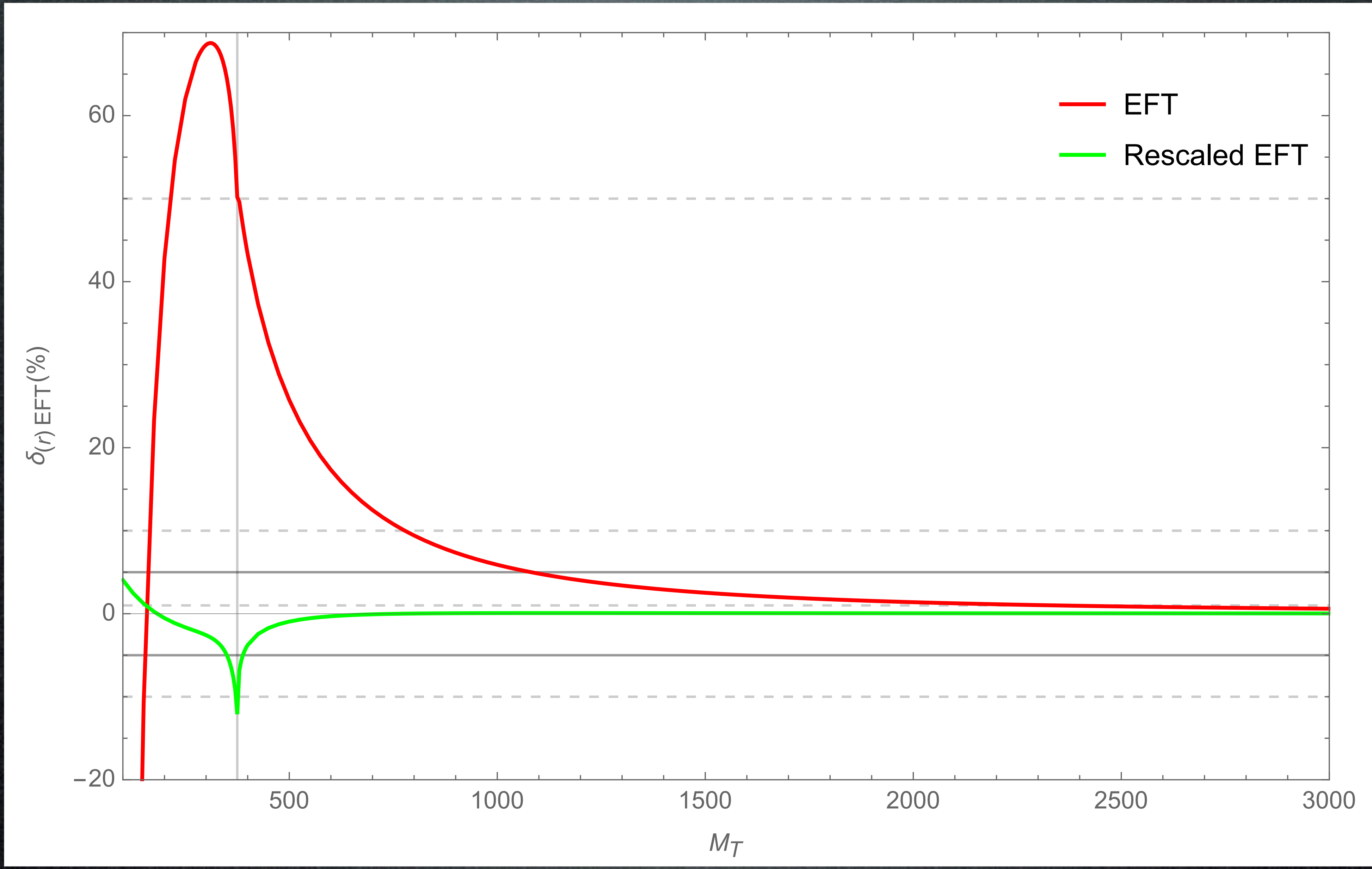
Validity of the EFT approach

- The EFT is typically “improved” by rescaling with the exact LO cross section,

$$\sigma_{\mathrm{rEFT}}^{\mathrm{NLO}} = \frac{\sigma_{\mathrm{exact}}^{\mathrm{LO}}}{\sigma_{\mathrm{EFT}}^{\mathrm{LO}}} \, \sigma_{\mathrm{EFT}}^{\mathrm{NLO}}$$

- Much better agreement with the exact NLO result!

Validity of the EFT approach



Validity of the EFT approach

- The EFT is typically “improved” by rescaling with the exact LO cross section,

$$\sigma_{\rm rEFT}^{\rm NLO} = \frac{\sigma_{\rm exact}^{\rm LO}}{\sigma_{\rm EFT}^{\rm LO}}\, \sigma_{\rm EFT}^{\rm NLO}$$

- Much better agreement with the exact NLO result!

➡ even in the presence of light new particles, can use the effective theory to compute the K-factors w.r.t. the exact LO cross section

Top-quark contributions

- In many extensions of the SM, new scalars can couple to the heavier SM particles, as the top quark (for example, to explain its large mass)
- For a light new scalar, can use an effective ggS vertex analogous to the SM one also for the top...
- ... but if the scalar is heavy, we cannot integrate the top out → model the top-scalar interaction as

$$\mathcal{L}_{\text{eff}} = -\frac{\lambda_{\text{wc}}}{4v} C_H \, S \, G^a_{\mu\nu} G_a^{\mu\nu} - \lambda_t \frac{m_t}{v} \, S \, \bar{t}t$$

$$\lambda_{\text{wc}} = \frac{C_S}{C_H} \qquad \lambda_t = \frac{Y_{ttS}}{Y_{ttH}}$$

Top-quark contributions

- The NLO cross section becomes

$$\begin{aligned}\sigma_S^{\mathrm{NLO}}[\lambda_{\mathrm{wc}},\lambda_t] &= |\lambda_{\mathrm{wc}}\mathcal{A}_{\mathrm{wc}}+\lambda_{\mathrm{t}}\mathcal{A}_{\mathrm{t}}|^2\\ &= \lambda_{\mathrm{wc}}(\lambda_{\mathrm{wc}}-\lambda_t)\sigma_S^{\mathrm{NLO}}[1,0]\\ &\quad +\lambda_t(\lambda_t-\lambda_{\mathrm{wc}})\sigma_S^{\mathrm{NLO}}[0,1]\\ &\quad +\lambda_{\mathrm{wc}}\lambda_t\,\sigma_S^{\mathrm{NLO}}[1,1]\end{aligned}$$

$\lambda_{\mathrm{wc}}^2\sigma_S^{\mathrm{NLO}}[1,0]=\lambda_{\mathrm{wc}}^2|\mathcal{A}_{\mathrm{wc}}|^2 \longrightarrow$ cross section in the EFT

➡ can use the N^3LO one

Top-quark contributions

- The NLO cross section becomes

$$
\begin{aligned}
\sigma_S^{\mathrm{NLO}}[\lambda_{\mathrm{wc}}, \lambda_t] &= |\lambda_{\mathrm{wc}} \mathcal{A}_{\mathrm{wc}} + \lambda_{\mathrm{t}} \mathcal{A}_{\mathrm{t}}|^2 \\
&= \lambda_{\mathrm{wc}}(\lambda_{\mathrm{wc}} - \lambda_t) \sigma_S^{\mathrm{NLO}}[1,0] \\
&\quad + \lambda_t(\lambda_t - \lambda_{\mathrm{wc}}) \sigma_S^{\mathrm{NLO}}[0,1] \\
&\quad + \lambda_{\mathrm{wc}} \lambda_t \, \sigma_S^{\mathrm{NLO}}[1,1]
\end{aligned}
$$

$\lambda_{\mathrm{wc}}^2 \sigma_S^{\mathrm{NLO}}[1,0] = \lambda_{\mathrm{wc}}^2 |\mathcal{A}_{\mathrm{wc}}|^2$ $\longrightarrow$ cross section in the EFT

$\sigma_S^{\mathrm{NLO}}[0,1] = |\mathcal{A}_{\mathrm{t}}|^2$

$\sigma_S^{\mathrm{NLO}}[1,1] = |\mathcal{A}_{\mathrm{t}} + \mathcal{A}_{\mathrm{wc}}|^2$

$\longrightarrow$ full top-mass dependance $\longrightarrow$ NLO

Theory error

- Lead by the NLO terms → evaluate it as

$$\frac{\delta\sigma^{\rm NLO}[n_1,n_2]}{\sigma^{\rm NLO}[n_1,n_2]} = \pm\delta_{>\rm NLO}\left(1+\delta_{\rm scheme}[n_1,n_2]\right), \quad n_i \in \{0,1\}$$

with

$$\delta_{>\rm NLO} = \left(\frac{\sigma^{\rm N^3LO}[1,0]-\sigma^{\rm NLO}[1,0]}{\sigma^{\rm NLO}[1,0]}\right)_{\rm EFT}$$

↘

estimate of missing contributions
beyond NLO in the effective theory

Theory error

- Lead by the NLO terms → evaluate it as

$$\frac{\delta\sigma^{\rm NLO}[n_1,n_2]}{\sigma^{\rm NLO}[n_1,n_2]} = \pm\delta_{>\rm NLO}\left(1+\delta_{\rm scheme}[n_1,n_2]\right), \quad n_i \in \{0,1\}$$

with

$$\delta_{>\rm NLO} = \left(\frac{\sigma^{\rm N^3LO}[1,0]-\sigma^{\rm NLO}[1,0]}{\sigma^{\rm NLO}[1,0]}\right)_{\rm EFT}$$

$$\delta_{\rm scheme}[n_1,n_2] = \frac{\left|\sigma_{\rm exact}^{\rm NLO,\overline{MS}}[n_1,n_2]-\sigma_{\rm exact}^{\rm NLO,OS}[n_1,n_2]\right|}{\sigma_{\rm exact}^{\rm NLO,\overline{MS}}[n_1,n_2]}$$

→ scheme-dependence of top-quark contributions at NLO

Cross section components

- provide the $\sigma_S^{\mathrm{N^X LO}}[n_1, n_2]$ for S production with SM-like Yukawa couplings at various collider energies and scalar masses
- they can be adapted to specific models by just rescaling the interactions

$\sqrt{s}$	Component	value[fb]	δ(theory) [%]	$\delta(\text{pdf}+\alpha_S)$ [%]
8 TeV	$\sigma_S^{\mathrm{N^3LO}}[1,0]$	111.4	${}^{+1.9}_{-4.0}$	6.1
	$\sigma_S^{\mathrm{NLO}}[1,0]$	89.37	19.18	6.23
	$\sigma_S^{\mathrm{NLO}}[0,1]$	98.92	22.3	6.22
	$\sigma_S^{\mathrm{NLO}}[1,1]$	245.3	21.71	6.2
13 TeV	$\sigma_S^{\mathrm{N^3LO}}[1,0]$	496.9	${}^{+2.0}_{-3.7}$	4.0
	$\sigma_S^{\mathrm{NLO}}[1,0]$	404.6	18.3	4.5
	$\sigma_S^{\mathrm{NLO}}[0,1]$	442.7	21.3	4.4
	$\sigma_S^{\mathrm{NLO}}[1,1]$	1108	20.7	4.4

$m_S = 750$ GeV

Cross section components

- good convergence of the top component to the EFT for low values of the scalar mass

m_S [GeV]	$\sigma_S^{NLO}[1,1]$[pb]	$\sigma_S^{NLO}[1,0]$[pb]	$\sigma_S^{NLO}[0,1]$[pb]
50	687.1	171.4	172.3
55	593.9	148.1	149.0
60	518.3	129.0	130.2
65	455.9	113.4	114.6
70	404.0	100.4	101.7

$\times 4$

➡ can use the N^{3}LO EFT cross section

Conclusions

Production of a CP-even scalar S:

- gluon-fusion is one of the most favourable channels
- in an EFT, can compute the cross section through N^3LO from the analogous result for Higgs production, choosing as central scale $\mu = m_S/2$
- in the theory error, account for scale variation, threshold truncation and missing N^3LO PDFs

Conclusions

Validity of the EFT:

- × for a relatively light particle mediating the production of S (expect errors around 60% in the threshold region for the pair production of the mediator)
- ✓ can still be used to estimate the K-factors

Conclusions

Top-quark contributions:

- for an heavy scalar, need to retain the full top mass dependence
  → can be computed only through NLO
  → large theory uncertainty ($\mathcal{O}(20\%)$)

- for a light scalar, can use an EFT Wilson coefficient also for the top → $\mathrm{N}^3\mathrm{LO}$ accuracy

Conclusions

- We provided the ingredients to compute the cross section for the production of a CP-even scalar via gluon fusion using the most precise higher order QCD corrections available, once its Wilson coefficient and the top-Yukawa coupling are known