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

Elisabetta Furlan
ETH Zurich

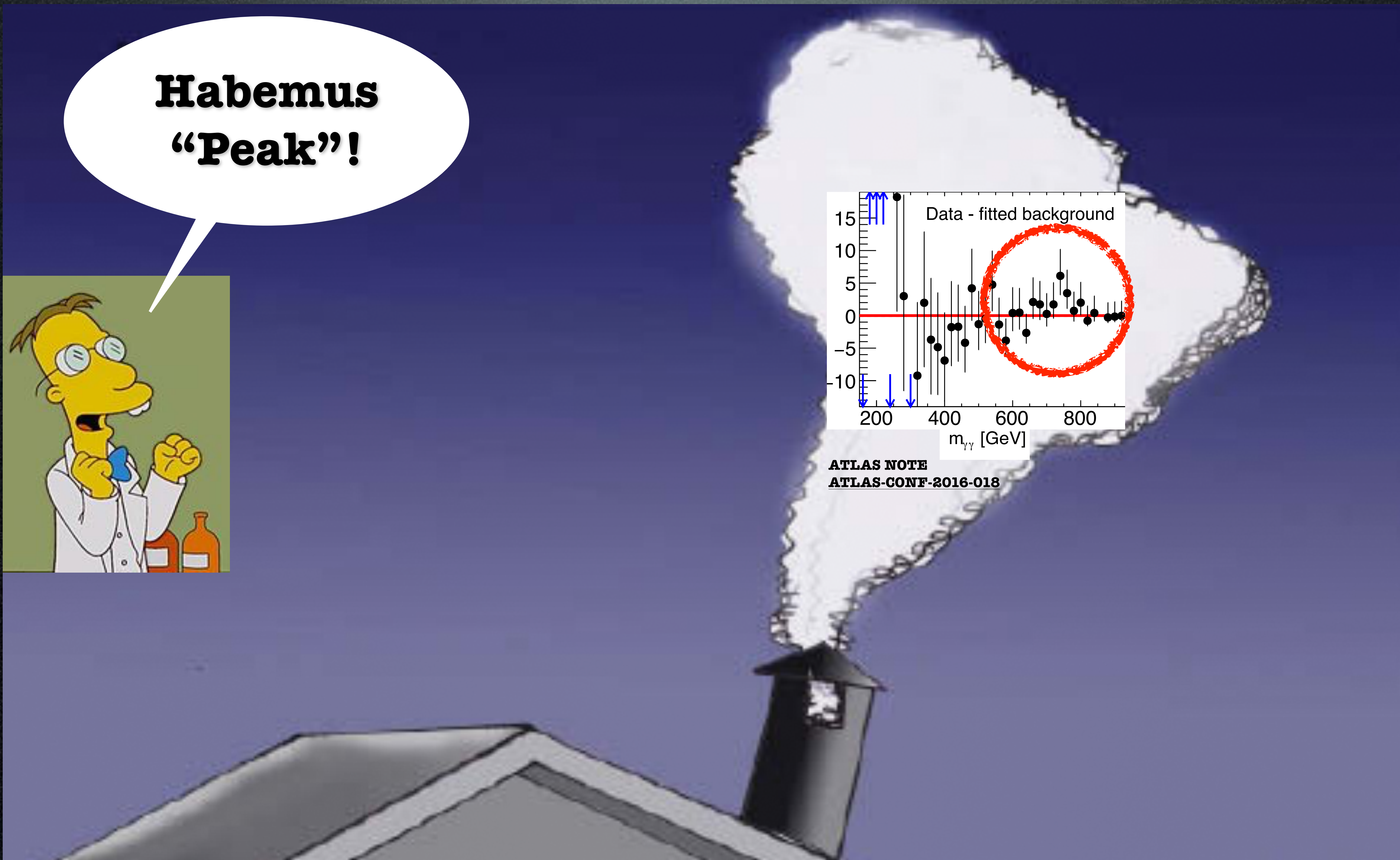
In collaboration with Babis Anastasiou, Claude Duhr, Falko Dulat, Thomas Gehrmann, Franz Herzog, Achilleas Lazopoulos, Bernhard Mistlberger

LHC Run II and the Precision Frontier, KITP Santa Barbara
5/19/2016

"Why such an unpopular topic?"

- After the discovery of the Higgs boson, many moved their hopes towards observing hints of new physics
- Many beyond-the Standard Model scenarios predict the existence of new particles that should be within the reach of the LHC...
- ... including additional scalar resonances (although maybe not one of the most expected, at least at low mass)

“Why such an unpopular topic?”

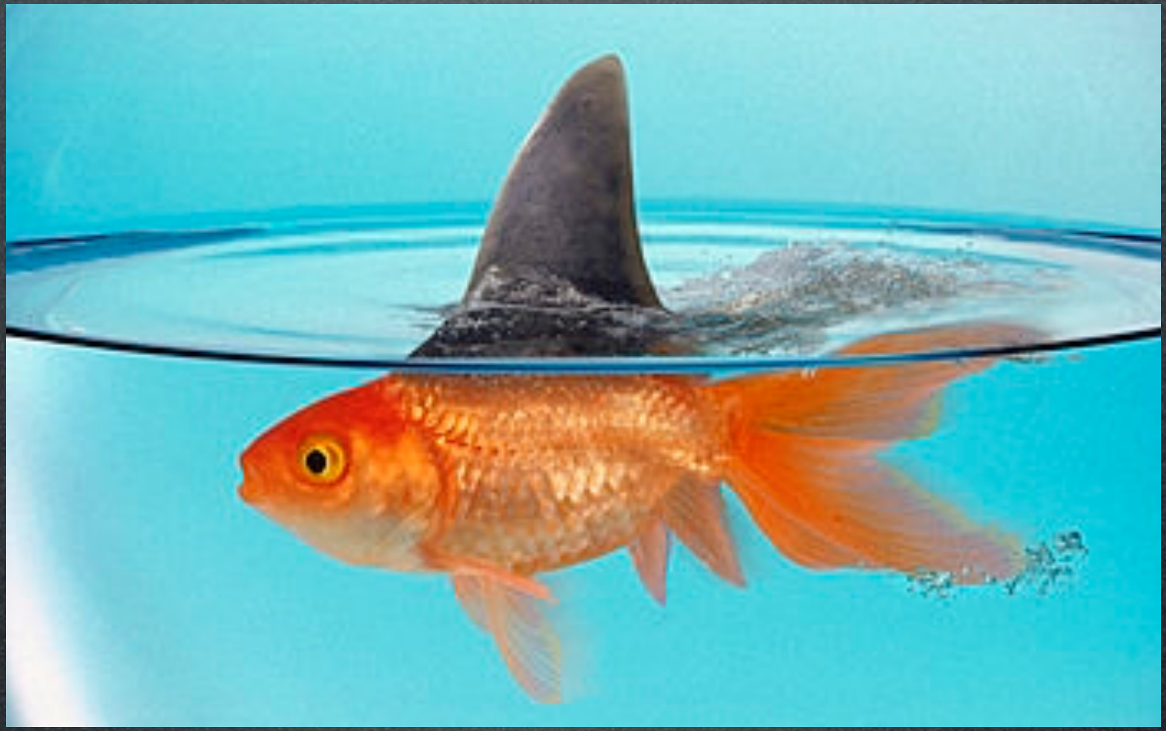


“Why such an unpopular topic?”

- It surely is too early for big celebrations - the local significance is about 3.9σ in ATLAS and 3.4σ in CMS...

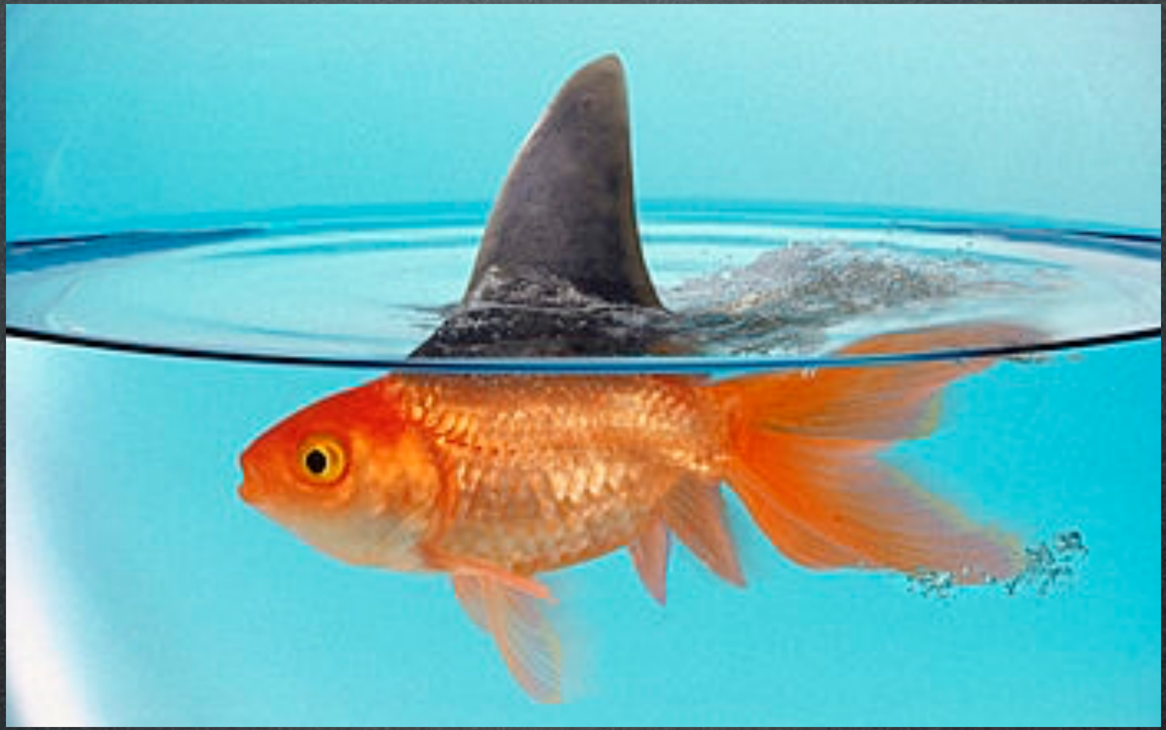
“Why such an unpopular topic?”

- It surely is too early for big celebrations - the local significance is about 3.9σ in ATLAS and 3.4σ in CMS...



“Why such an unpopular topic?”

- It surely is too early for big celebrations - the local significance is about 3.9σ in ATLAS and 3.4σ in CMS...



... yet, this excess is exemplary for the kind of signals that may arise from the production of an heavy scalar at the LHC

Higgs-like scalar production

- Due to the large gluon luminosity, gluon fusion is one of the most likely production channels for an Higgs-like scalar

$\sqrt{s}$	$C_{b\bar{b}}$	$C_{c\bar{c}}$	$C_{s\bar{s}}$	$C_{d\bar{d}}$	$C_{u\bar{u}}$	C_{gg}	$C_{\gamma\gamma}$
8 TeV	1.07	2.7	7.2	89	158	174	11
13 TeV	15.3	36	83	627	1054	2137	54

$$\sigma(pp \to S) = \frac{1}{sM_S} \sum_{\text{in}} C_{\text{in,in}} \Gamma_{\text{in}} \qquad , \text{in} = \{g, b, c, s, u, d, \gamma\}$$

Franceschini et al., JHEP 03:144, 2016

Higgs-like scalar production

Our approach: "agnostic"

- no 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

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

- 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

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

mass scale
from dim. reg.

Higgs-like scalar production

- can write the production cross section as

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

↓

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

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

  - 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

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

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

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

Higgs-like scalar production

- can write the production cross section as

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

  - the factorisation of the cross section introduces terms beyond N^3LO
  - they are captured by the scale variation theory error if one uses

$$\mu_{\rm central} = \frac{m_S}{2} \quad , \quad \mu \in \left[\frac{m_S}{4}, m_S\right]$$

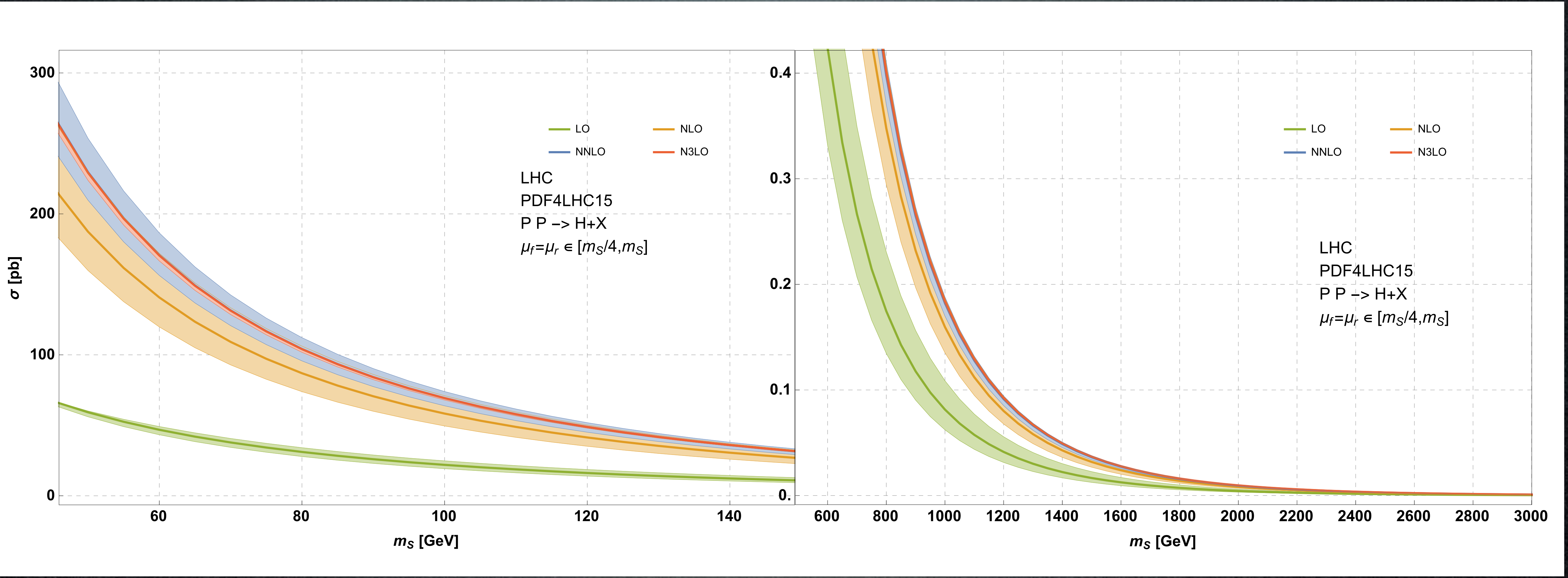
Higgs–like scalar production

- such choice of scales might introduces large logs
- for example, beyond NLO the SM Wilson coefficient contains terms in $\log(m_t/\mu)$

➡ can be more convenient to evaluate the SM Wilson coefficient with a top mass set to a larger values, for example the scale of new physics:

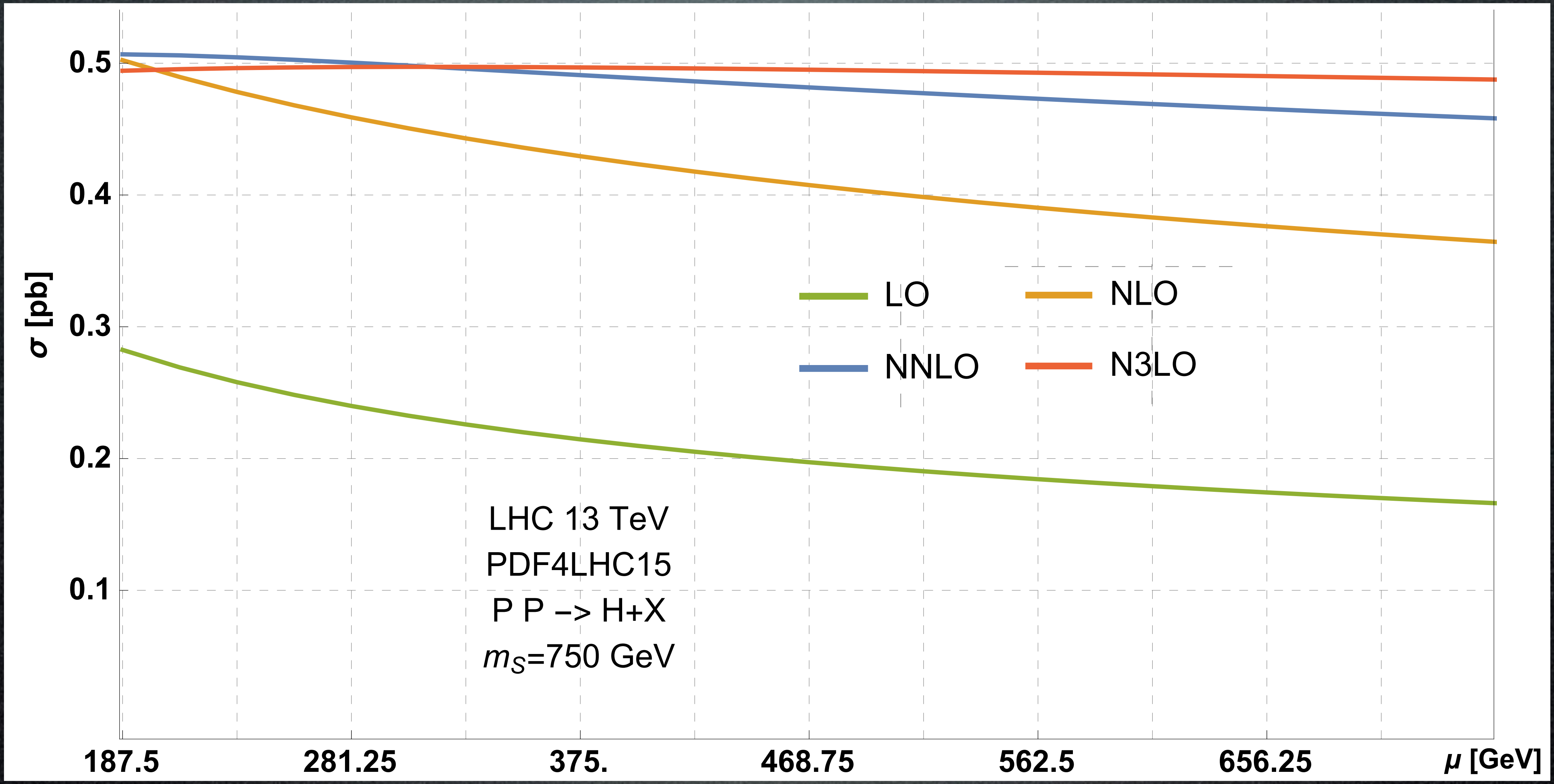
$$\sigma_H(m_S, \Lambda_{\rm UV}) = \left| \frac{C_H(\mu, \Lambda_{\rm UV})}{C_H(\mu, m_t)} \right|^2 \sigma_H(m_S, m_t)$$

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

Scale dependence



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

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

  - missing N^{3}LO parton distributions

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

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

Finite-width effects

- Previous result only holds for a scalar with negligible width
- Can be generalised to a narrow-width resonance as

$$\sigma_S(m_S, \Gamma_S, \Lambda_{\rm UV}) = \int dQ^2 \frac{Q\Gamma_S(Q)}{\pi} \frac{\sigma_S(Q, \Gamma_S = 0, \Lambda_{\rm UV})}{(Q^2 - m_S^2)^2 + m_S^2 \Gamma^2(m_S)}$$

➡ introduces an additional error of

$$\mathcal{O}\left(\frac{\Gamma_S(m_S)}{m_S}\right) \sim 6\%$$

for a 750 GeV scalar with a width of 45 GeV

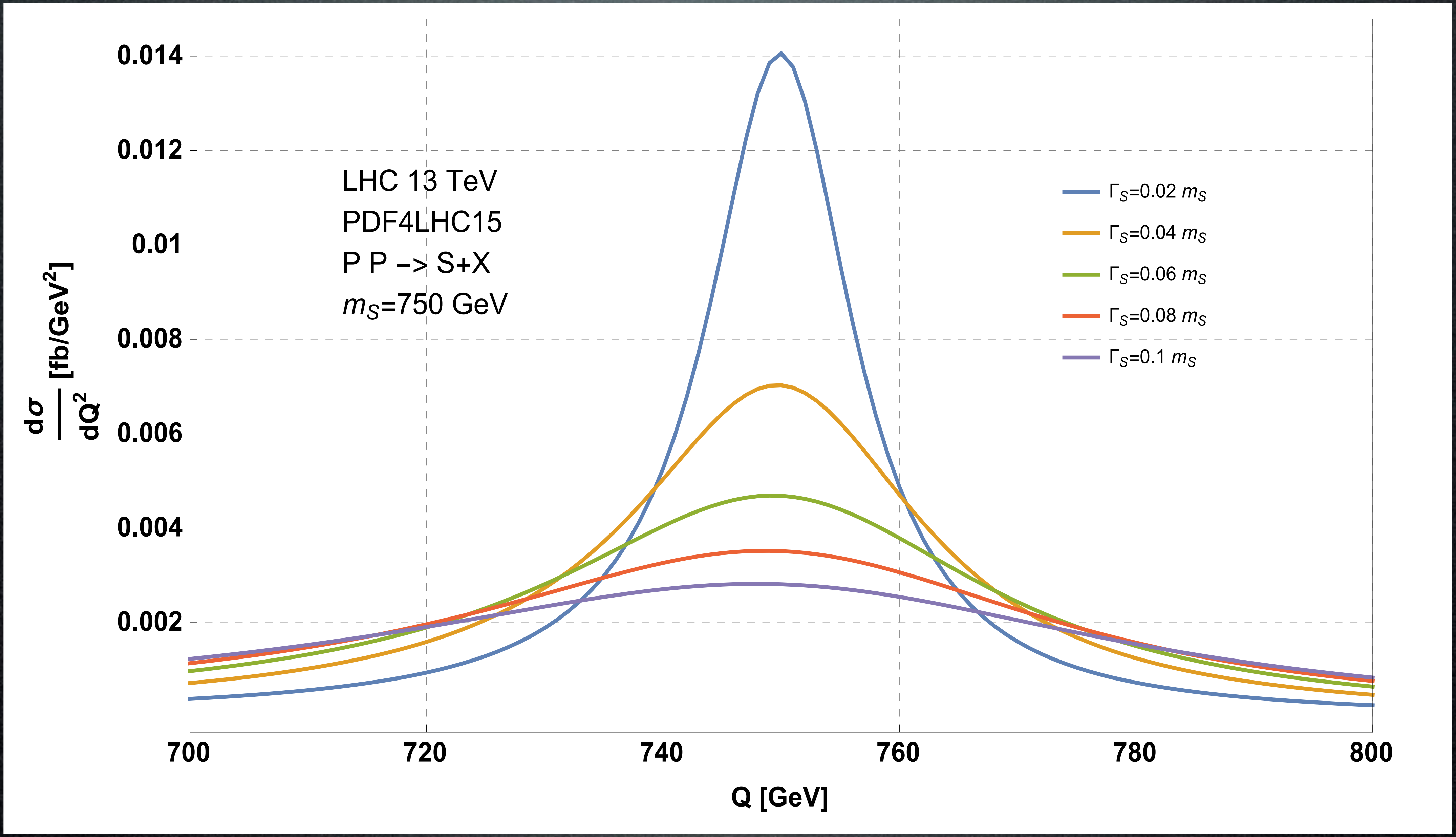
Finite-width effects

- In many beyond-the Standard Model scenarios the width around the peak does not depend on the virtuality

$$\Gamma_S(Q \approx m_S) = \Gamma_S$$

➡ obtain the invariant mass distribution from an interpolation of the zero-width cross sections

Finite-width effects



Finite-width effects

- Can perform a parametric fit for the line-shape; for example, for a 13 TeV collider and a scalar between 0.5 and 3 TeV,

$$\sigma_S(x) \approx \left(1 - \sqrt[3]{x}\right)^{9.71562} \; x^{-0.0040194\,\log^3 x} \; x^{-0.0474683\,\log^2 x - 0.240878\,\log x - 1.81243} \;\mathrm{pb}$$

$$x = \frac{Q(\mathrm{GeV})}{13\ \mathrm{TeV}}$$

Validity of the EFT approach

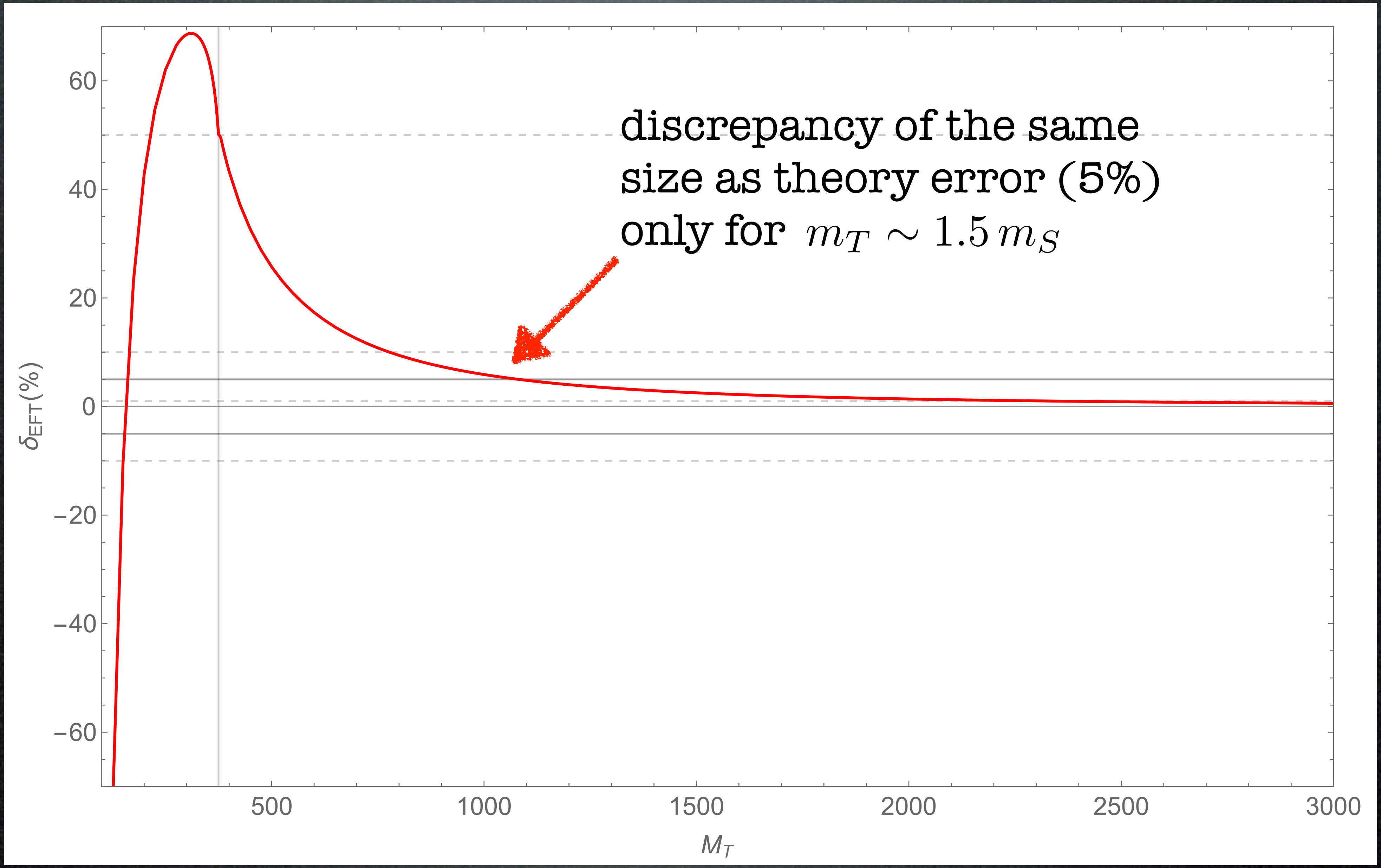
- How good is the EFT if the scalar couples to "light" particles?

- Example: 750 GeV scalar coupling to a top-like quark of mass m_T

- Can compute the cross section exactly through NLO and compare it with the prediction from the effective theory,

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

Validity of the EFT approach



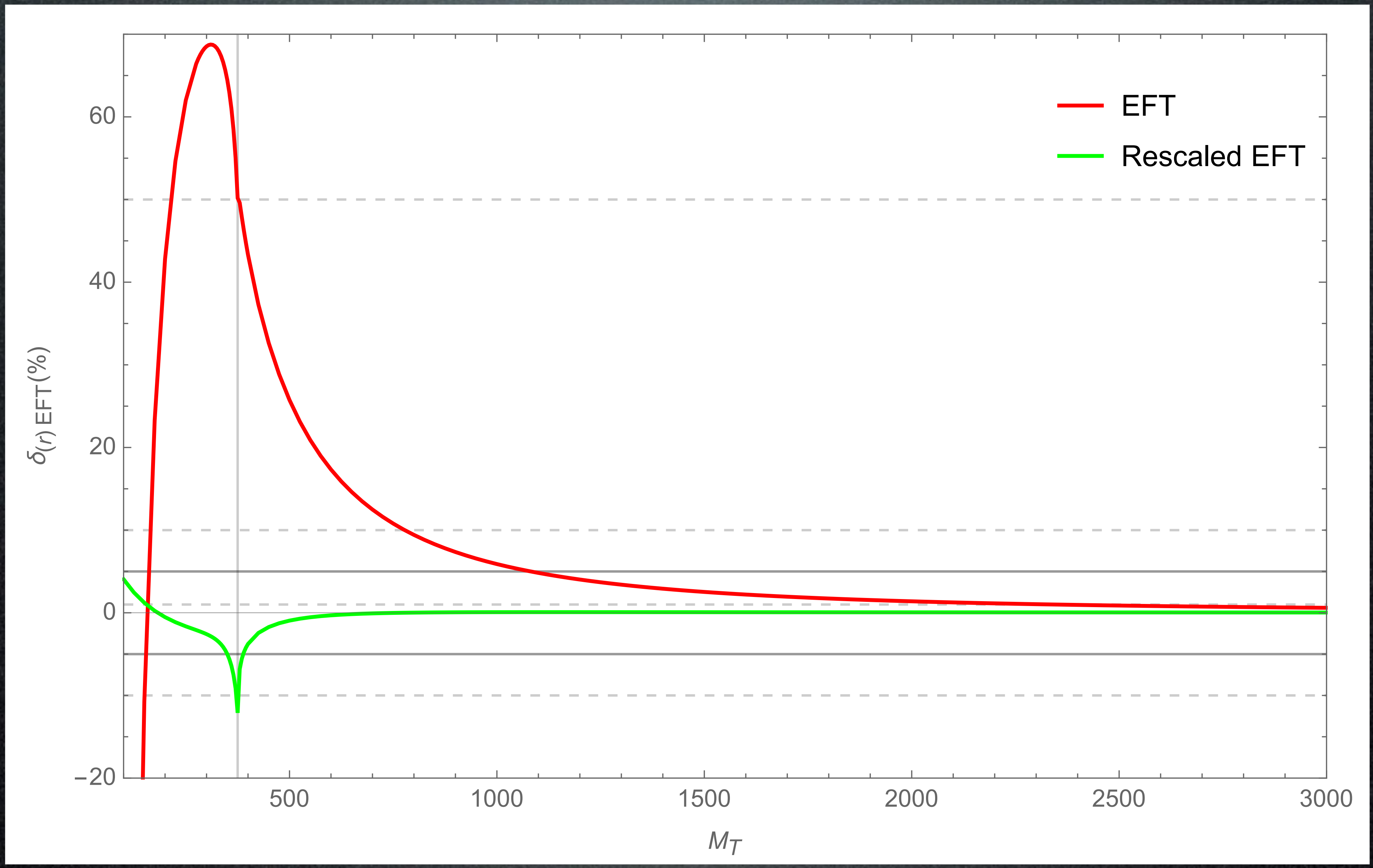
Validity of the EFT approach

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

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

- 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,

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

- 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

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

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

Top-quark contributions

- The NLO cross section becomes

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

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

➡ can use the N^3LO one

Top-quark contributions

- The NLO cross section becomes

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

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

$\sigma_S^{\rm NLO}[0,1]=|\mathcal{A}_{\rm t}|^2$ → full top-mass dependance → NLO

$\sigma_S^{\rm NLO}[1,1]=|\mathcal{A}_{\rm t}+\mathcal{A}_{\rm wc}|^2$ → full top-mass dependance

Theory error

- Lead by the NLO terms → evaluate it as

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

with

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

↘

estimate of missing contributions beyond NLO in the effective theory

Theory error

- Lead by the NLO terms → evaluate it as

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

with

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

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

→ scheme-dependence of top-quark contributions at NLO

Cross section components

- provide the $\sigma_S^{\mathrm{N^XLO}}[n_1, n_2]$ 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) [%]	δ(pdf+α_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

Cross section components

- can also perform parametric fits
- example: at 13 TeV, for the PDF4LHC15 set and a scalar between 500 GeV and 1 TeV,

$$\begin{aligned}\sigma_S^{\rm NLO}[1,1]/{\rm pb} = &\ 1.0459\times 10^8 x^2 + \frac{478.474}{x^2} - 7.72699\times 10^7 x^2 \log x \\ &- 8.14486\times 10^7 x - \frac{2.50557\times 10^6}{x} - 95661.5 \log^2 x \\ &- \frac{71863.4 \log^2 x}{x} - 7.67177\times 10^7 x \log x \\ &- 1.27372\times 10^7 \log x - \frac{802665 \log x}{x} - 3.08306\times 10^7\,,\end{aligned}$$

$$\sigma_S^{\rm NLO}[1,0]/{\rm pb} = \ \ldots$$

$$\sigma_S^{\rm NLO}[0,1]/{\rm pb} = \ \ldots$$

$$x = \frac{m_S/{\rm GeV}}{13{\rm TeV}}$$

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
- for example, for a scalar of 750 GeV the theory error is about (+2%,-4%) for all relevant LHC energies

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 in an EFT, can compute the cross section through N^3LO from the analogous result for Higgs production, choosing as central scale

Conclusions

Top-quark contributions:

- for an heavy scalar, 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 → N^3LO 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