High precision determination of the gluon-fusion Higgs cross section at the LHC

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Why the Higgs?

- The Higgs boson is a fundamental ingredient of the Standard Model - without it, this theory is not self-consistent!

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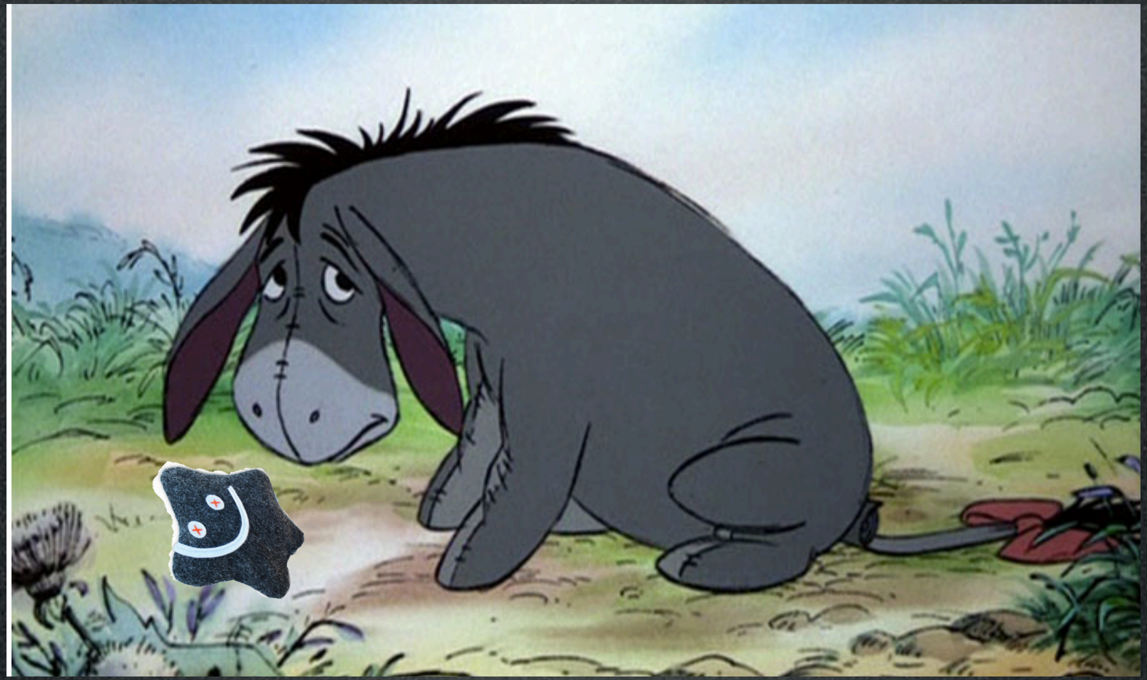
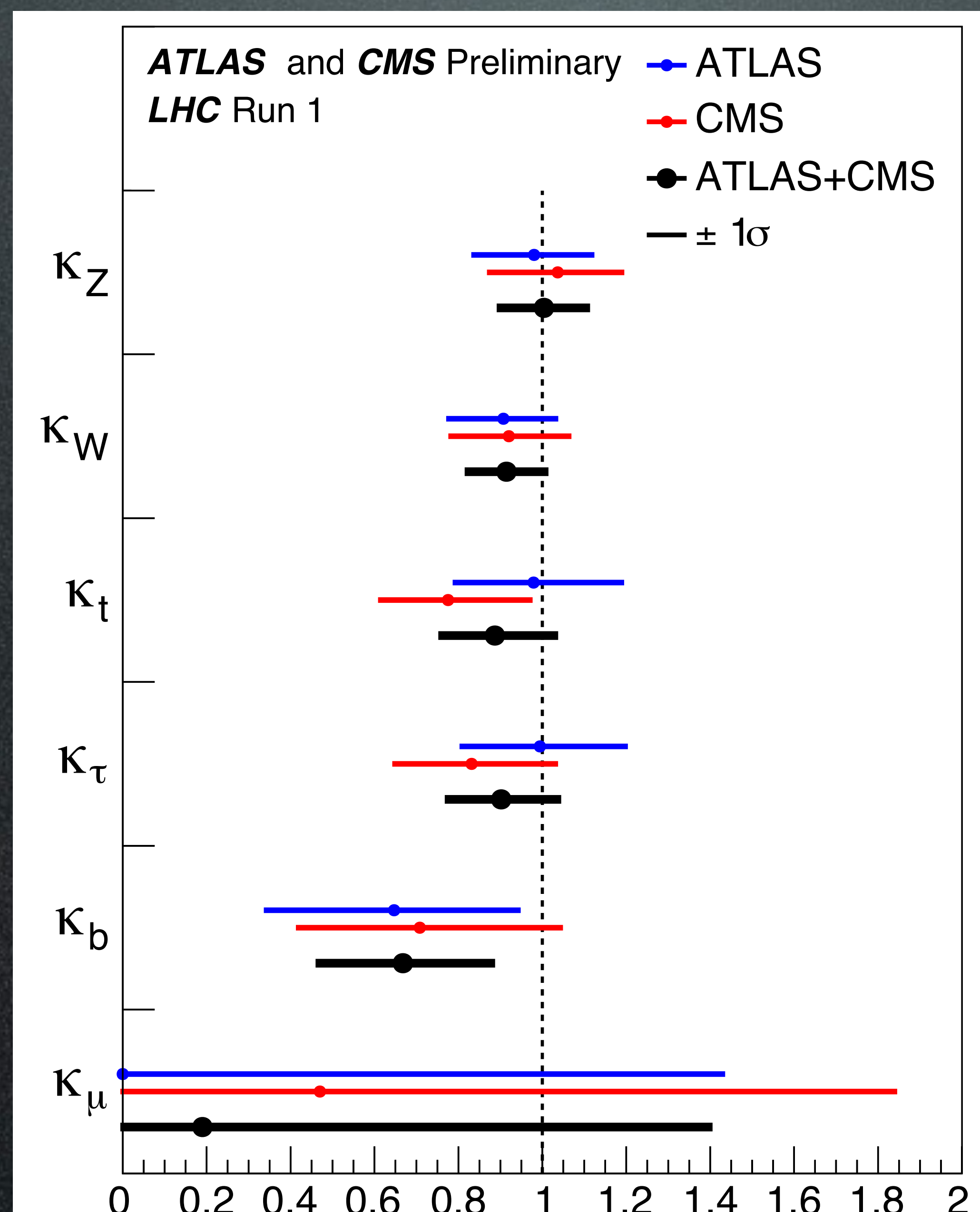
  ... and then a bit of depression..



Why the Higgs?

… this Higgs boson looks “too Standard-Model like”!



Parameter	ATLAS+CMS
$\kappa_j \geq 0$	Measured
κ_Z	$1.00^{+0.10}_{-0.11}$
κ_W	$0.91^{+0.09}_{-0.09}$
κ_t	$0.89^{+0.15}_{-0.13}$
κ_τ	$0.90^{+0.14}_{-0.13}$
κ_b	$0.67^{+0.22}_{-0.20}$
κ_μ	$0.2^{+1.2}_{-0.2}$

ATLAS-CONF-2015-044

Why precision Higgs?

- Many observed phenomena (neutrino mass, dark matter, ..) are not described by the Standard Model
  - can they be related to the origin of electroweak symmetry breaking? Can they affect Higgs physics?
- The Higgs boson is “unnaturally” light
  - is the Higgs sector more complicated than in the Standard Model (new particles/interactions)?

Why precision Higgs?

- If “hints” of new physics persist
  - is this new physics related to the Higgs boson?
  - does it change its properties (decays, couplings, width)?

Why precision Higgs?

- Precise predictions are fundamental
  - deviations in the Higgs phenomenology can be of just some few %

  → the current precision in the extraction of the Higgs properties is limited by the theoretical error on the NNLO gluon-fusion production rate

  - we want to study in depth the properties of new particles

  → we already developed a great set of tools for precision Higgs studies, extend them!

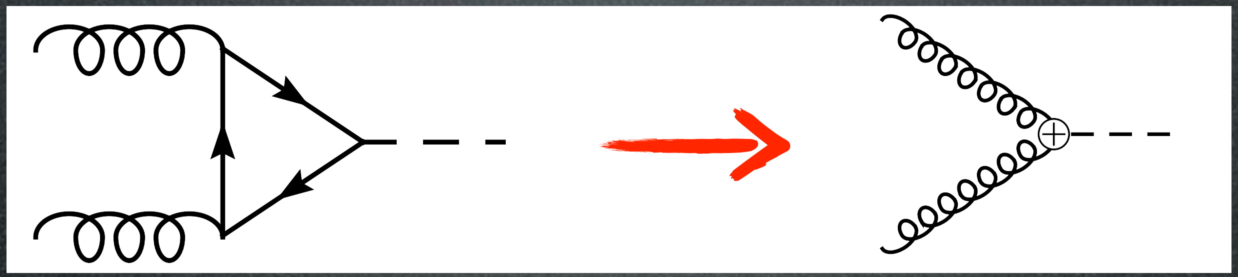
Higgs Production at N^{3}LO

"Ingredients"

- heavy-quark effective theory (HQET)
- full quark-mass effects (from top, bottom, charm) through NLO
- 2-loop EW, 3 loop QCD/EW corrections
- convolution with parton distribution functions (pdf)
- uncertainties (scale, pdf, α_s, missing contributions, approximations)

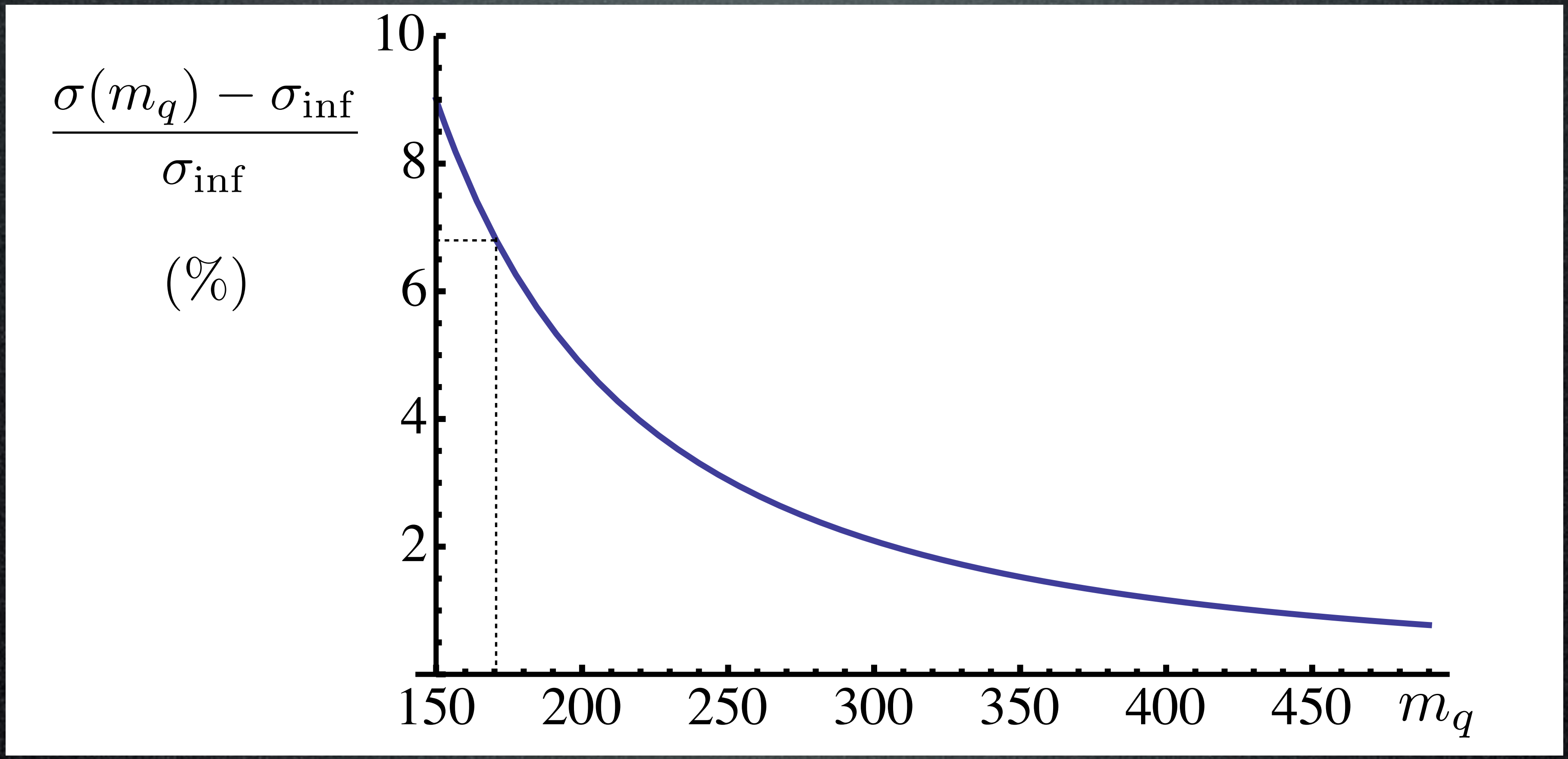
Heavy quark effective theory

- Integrate out the (heavy) top quark
  - the quark loop is replaced by an effective gluon-Higgs vertex



Heavy quark effective theory

- Is this a good approximation?
    - at LO



Heavy quark effective theory

- Is this a good approximation?
  - at NLO, "improve" the result from the EFT by rescaling it with the exact LO cross section:

$$\begin{aligned} \sigma^{NLO}_{EFT} &= 34.66 \text{ pb} \\ \sigma^{NLO}_{ex} &= 36.60 \text{ pb} \\ \sigma^{NLO}_{EFT,r} &= K \times \sigma^{NLO}_{EFT} = 36.83 \text{ pb} \end{aligned}$$

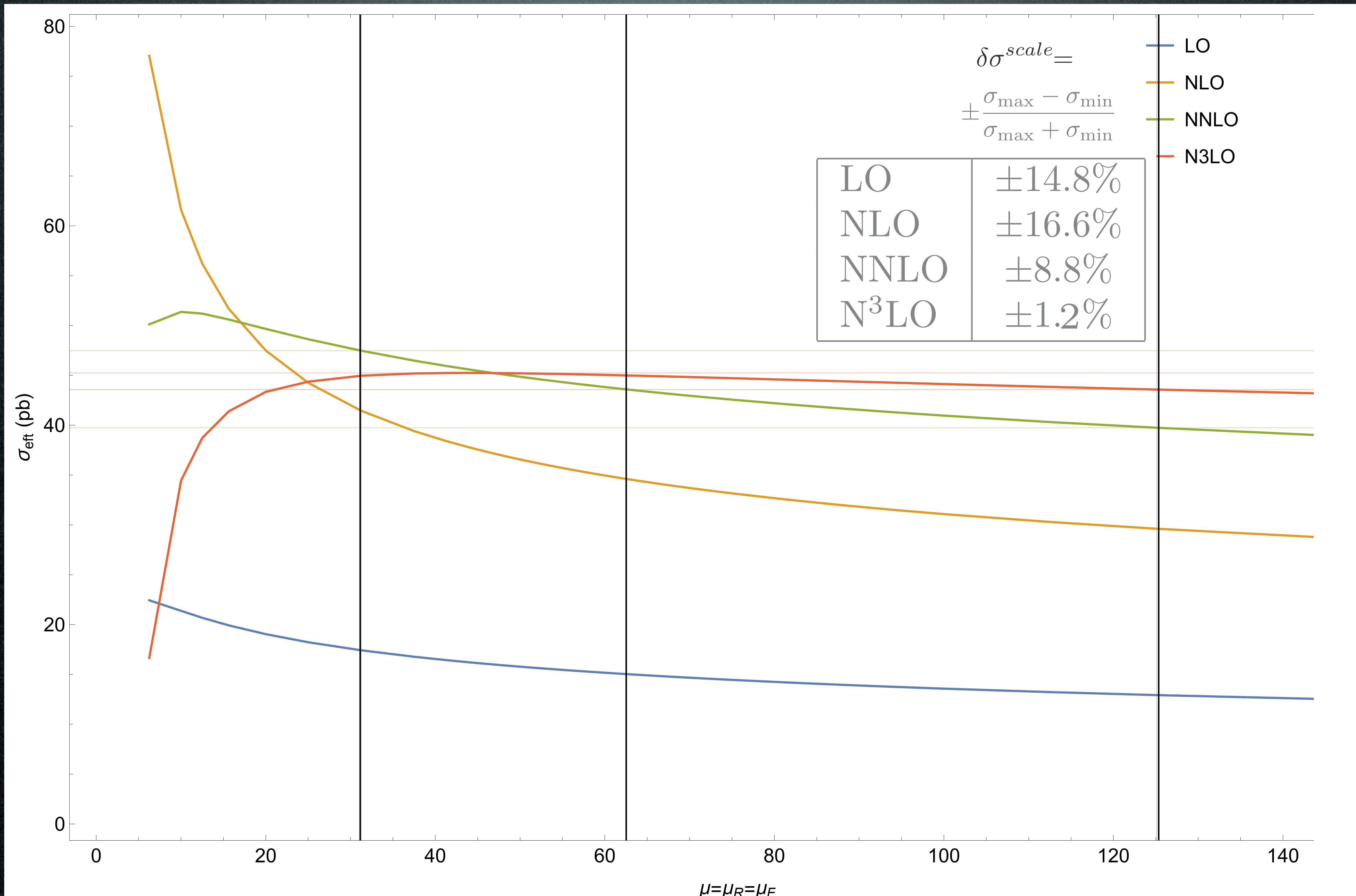
} 0.6%

$$K_{LO} = \frac{\sigma^{LO}_{exact}}{\sigma^{LO}_{EFT}} \simeq 1.06$$

$\sqrt{S}$	13TeV
m_h	125GeV
PDF	PDF4LHC15_nnlo_100
$a_s(m_Z)$	0.118
$m_t(m_t)$	162.7 ($\overline{MS}$)
$m_b(4.18GeV)$	4.18 ($\overline{MS}$)
$m_c(3GeV)$	0.986 ($\overline{MS}$)
$\mu = \mu_R = \mu_F$	62.5 ($= m_h/2$)

  - perform same rescaling also for the higher orders

Scale variation



Full quark-mass effects

- The full dependance of the Higgs production cross section on the quark mass is known exactly through NLO

Spira, Djouadi, Graudenz, Zerwas ; Harlander, Kant; Aglietti, Bonciani, Degrassi, Vicini.

- include it for top, bottom and charm quarks

+ 3.9% (top) -5.1% (bottom) -0.5% (charm) on σ_{EFT}^{NLO}

- estimate the error from unknown top-bottom interference effects at NNLO as

$$\delta_{tb} = \frac{\sigma_{t,b}^{NLO} - \sigma_{t}^{NLO}}{\sigma_{t,b}^{NLO}} \times \sigma_{EFT,r}^{NNLO} \sim \pm 0.7\%$$

Full quark-mass effects

- Rescale NNLO and N^3LO cross sections by the exact LO K-factor K_{LO}

- include known $1/m_t$ NNLO corrections

Harlander, Ozeren; Pak, Rogal, Steinhauser; Mantler, Marzani

$$gg \quad \sim \quad +1.2\%$$
$$gg \quad \sim \quad -0.5\%$$

- the error due to the truncation in the inverse-mass expansion is estimated as

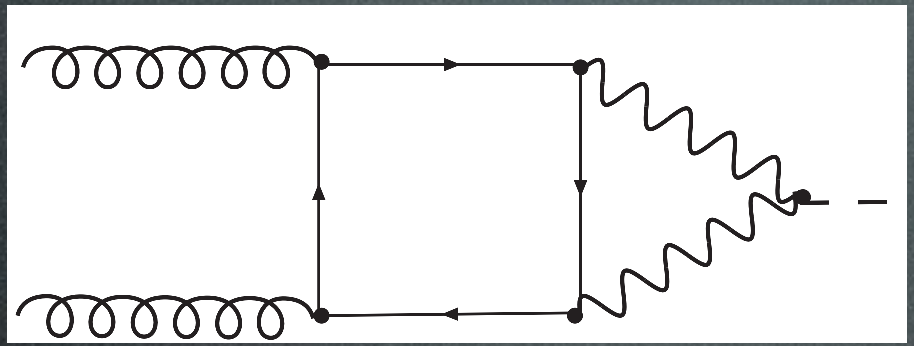
$$\delta_{1/m_t} \sim \pm 1\%$$

Harlander, Ozeren; Pak, Rogal, Steinhauser; Mantler, Marzani

Electroweak corrections

- Known exactly at LO in α_s $(\mathcal{O}(\alpha\alpha_s))$

Aglietti, Bonciani, Degrassi, Vicini;
Actis, Passarino, Sturm, Uccirati



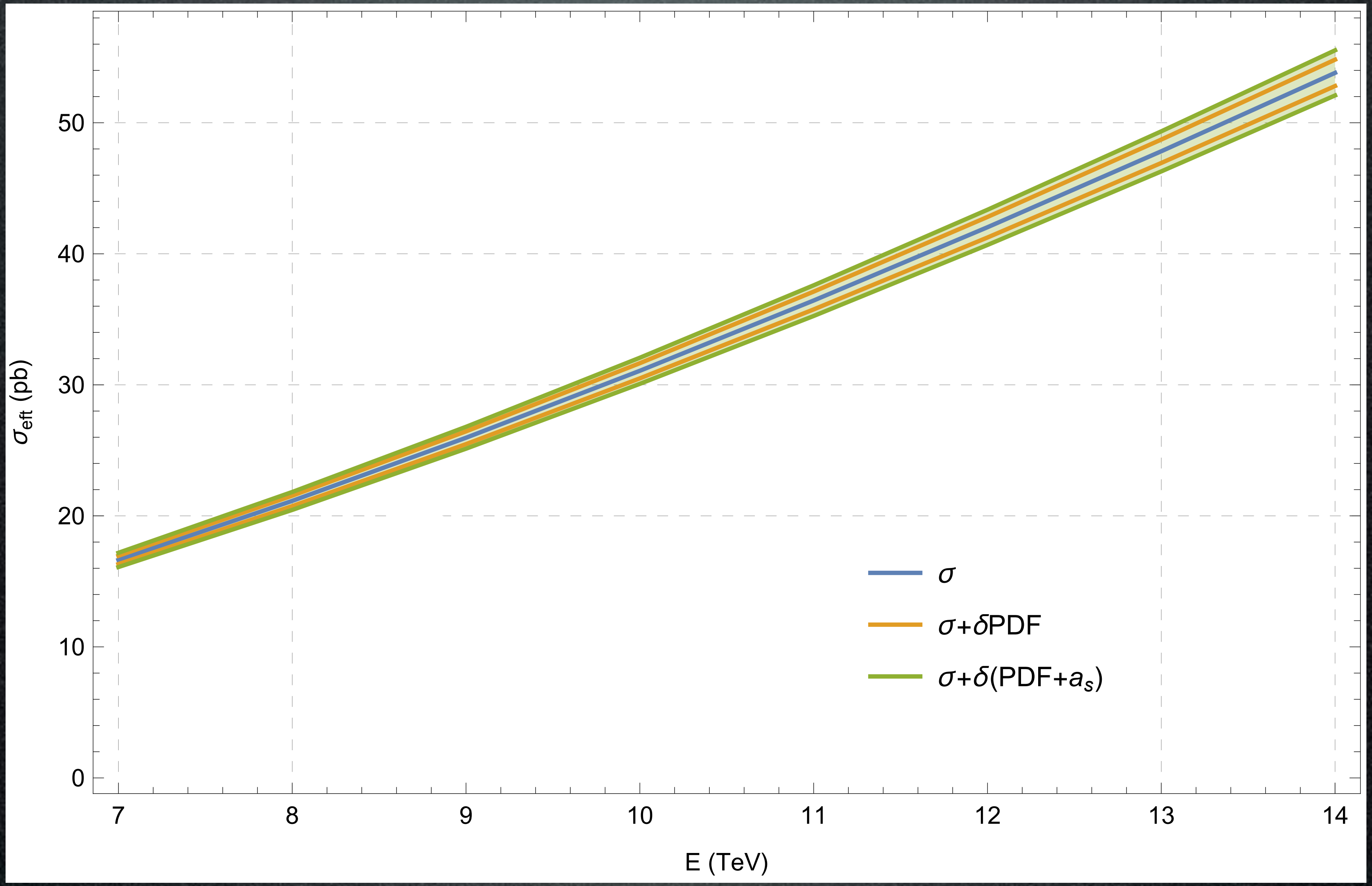
$\longrightarrow$ $+5.2\%$ on σ_{EFT}^{LO}

- At NLO, effects from light quarks are known in an effective theory $\longrightarrow$ $+5.1\%$ on σ_{EFT}^{NLO}

- Estimate the error from missing NLO contributions by varying the QCD/EW effective theory coefficient $\longrightarrow$ $\delta_{EW} \sim \pm 1\%$

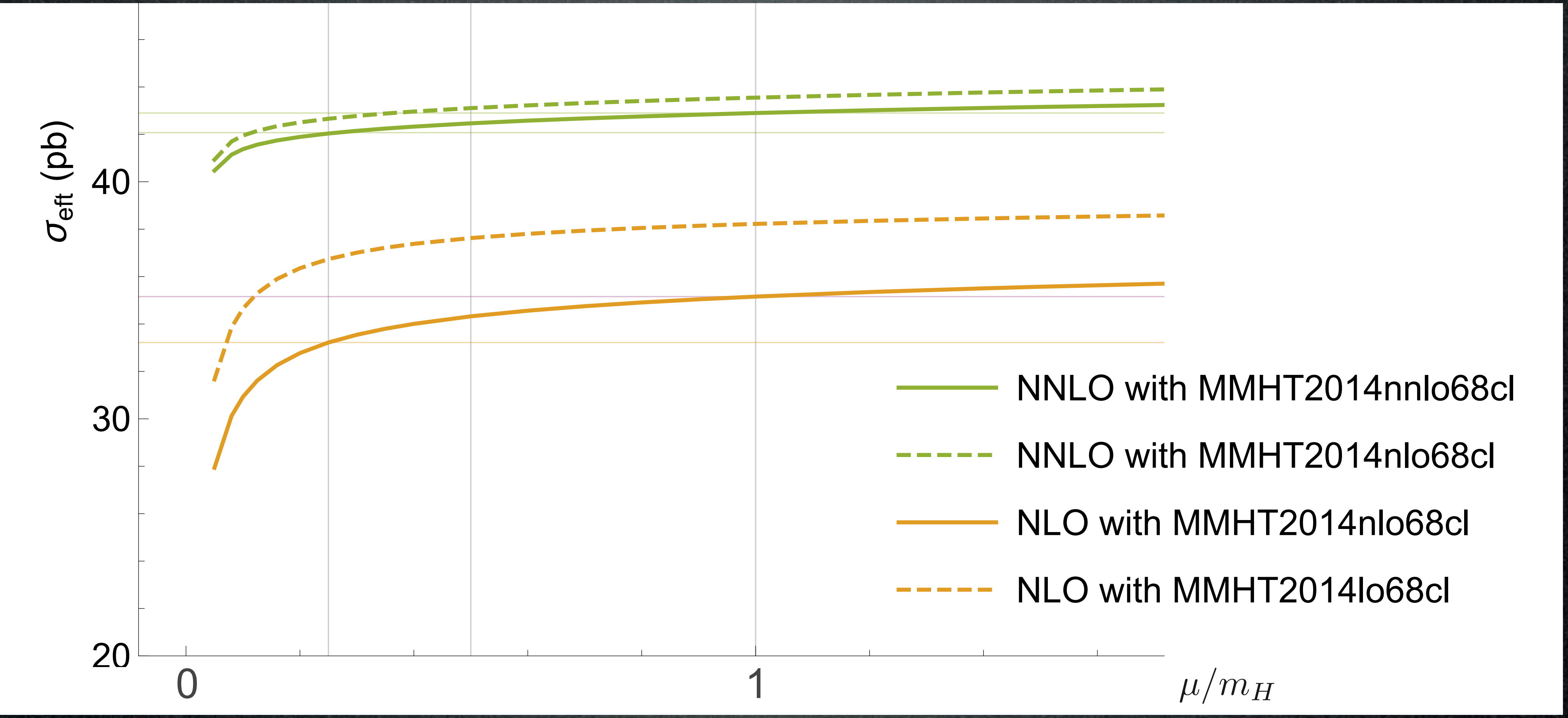
(pdf + α_s) uncertainty

- We follow the PDF4LHC recommendations for the separate calculation of PDF and α_s uncertainties, and combine them in quadrature



N^3LO pdf uncertainty

- N^3LO pdfs are not available; we use NNLO pdfs
  - how large is the error associated to this? To estimate it, we compare with the same situation all lower orders



N^3LO pdf uncertainty

- N^3LO pdfs are not available; we use NNLO pdfs
  - from the change of the NNLO result between NNLO and NLO pdfs, we estimate

$$\delta_{pdfTh} \sim \pm 1.2\%$$

Soft approximation

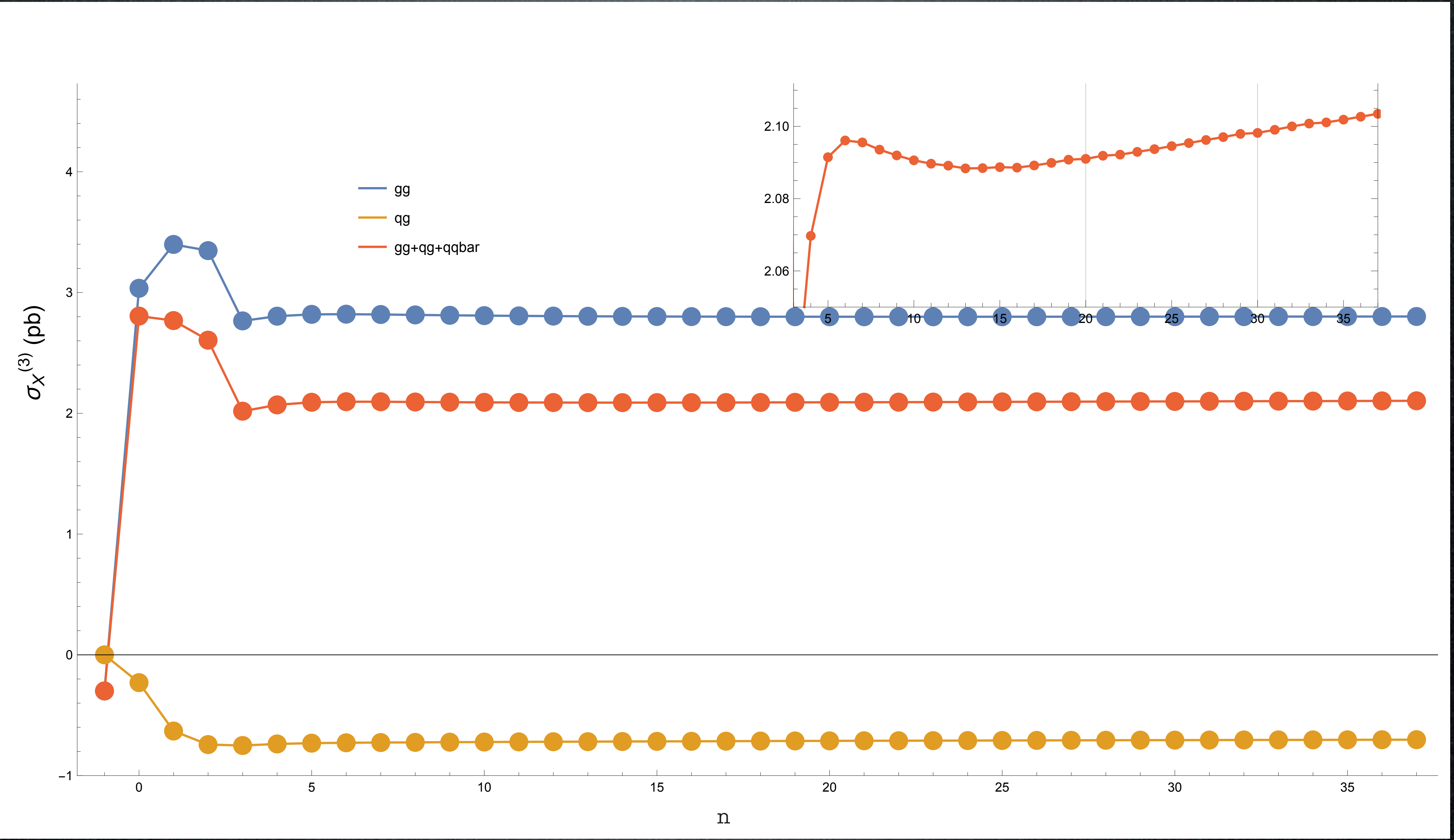
- The N^{3}LO cross section is computed as an expansion around the Higgs threshold $z = \frac{m_H^2}{s} = 1$

$$\hat{\sigma}(z) = \hat{\sigma}_{SV} + \sum_{n=0}^{N_{trunc}} \sigma^{(n)} (1-z)^n$$

  - what is the error associated to the truncation of this expansion?

Soft approximation

- Look at the convergence of the series:



Soft approximation

- As a conservative estimate we take

$$\delta_{trunc} = 10 \times (\sigma^{(3)}_{EFT}(30) - \sigma^{(3)}_{EFT}(20)$$
$$\Rightarrow 0.6\%$$

(consistent with other estimates of the truncation error)

Conclusion

The N^{3}LO Higgs boson production cross section and the associated errors are

σ	δ_{pdf}	δ_{α_s}	δ_{scale}	δ_{trunc}	δ_{pdfTh}	δ_{EW}	δ_{tb}	δ_{1/m_t}	
48.48	± 0.90	± 1.26	$^{+0.09}_{-1.11}$	± 0.29	± 0.58	± 0.48	± 0.34	± 0.48	pb
	± 1.86	± 2.60	$^{+0.19}_{-2.29}$	± 0.6	± 1.20	$\pm$ 1	± 0.7	$\pm$ 1	%

in quadrature

linearly

$$\sigma = (48.48 \pm 1.55^{+2.08}_{-3.10})\text{pb}$$
$$= 48.48\text{pb} \pm 3.19\%\,^{+4.29\%}_{-6.40\%}$$

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↔

"traditional" estimate $^{+0.96}_{-1.98}$ $^{+1.98\%}_{-4.08\%}$

Conclusion

- calculation of the N^{3}LO gluon-fusion production cross section in HQFT
- inclusion of all known effects beyond the HQET
- accurate estimate of the errors, including error from missing information and from approximations
- room for improvement
  - going beyond the threshold expansion
  - computing the missing effects