Higgs production at N3LO in QCD

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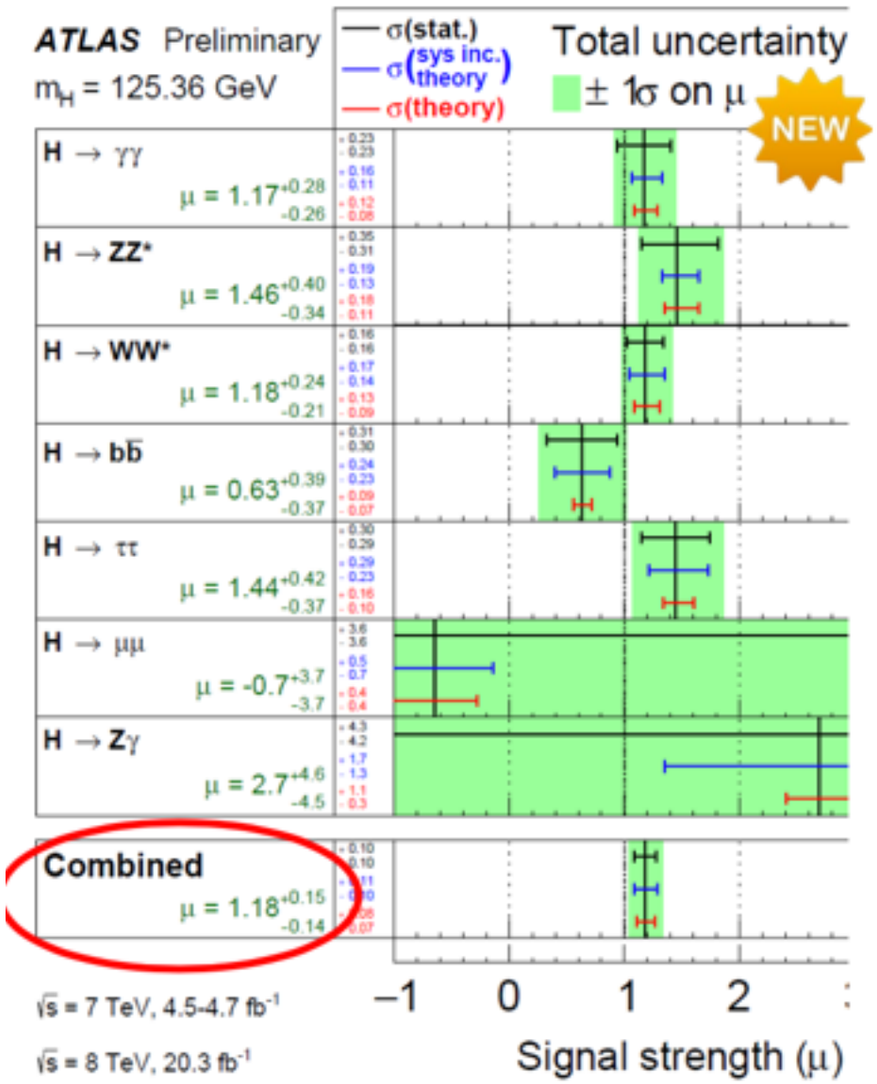
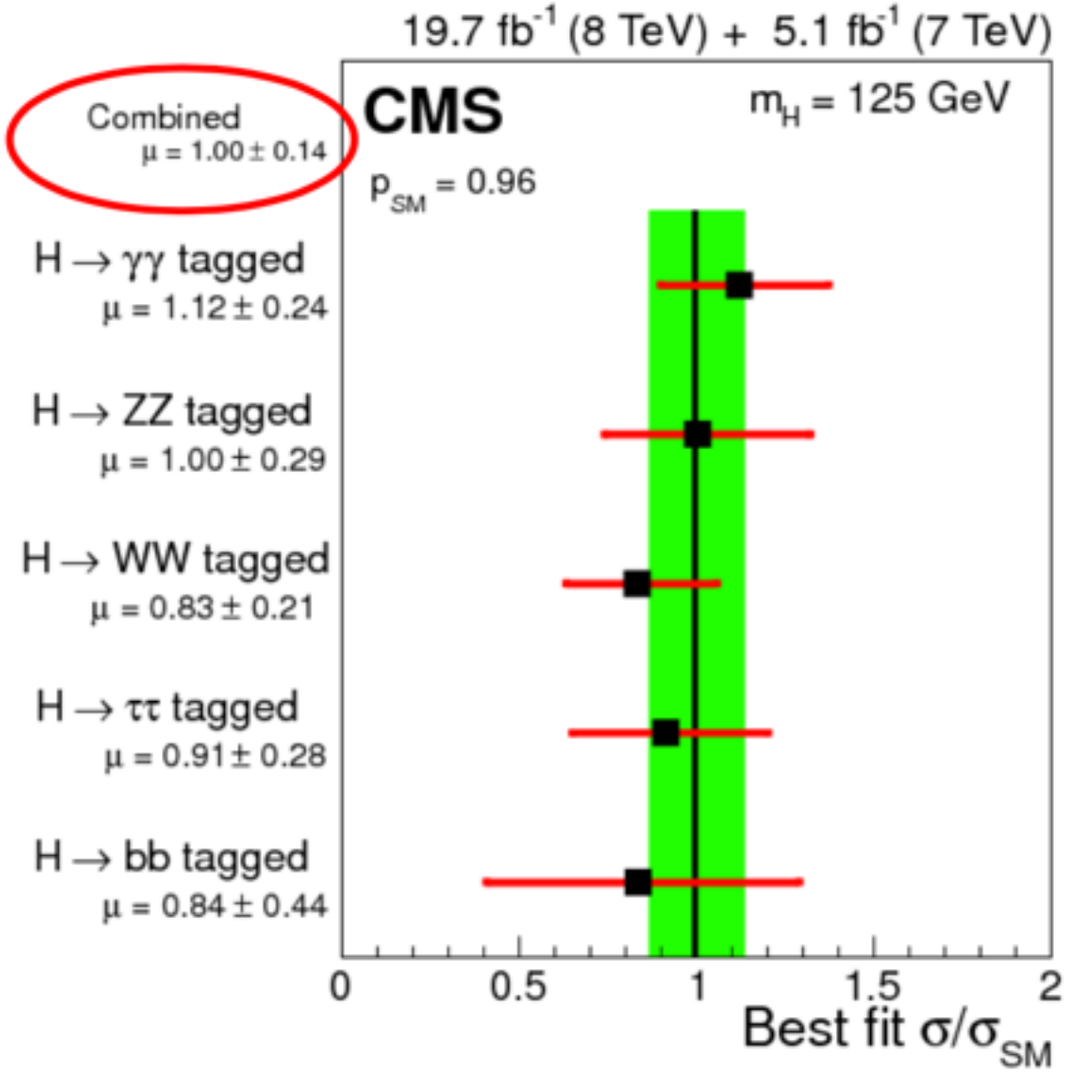
Higgs physics at the LHC



$$\mu_{ATLAS} = 1.18^{+0.15}_{-0.14}$$

$$\text{stat.} = {}^{+0.10}_{-0.10}$$

$$\text{sys. (inc. theo.)} = {}^{+0.11}_{-0.10}$$



$$\mu_{CMS} = 1.00 \pm 0.14$$

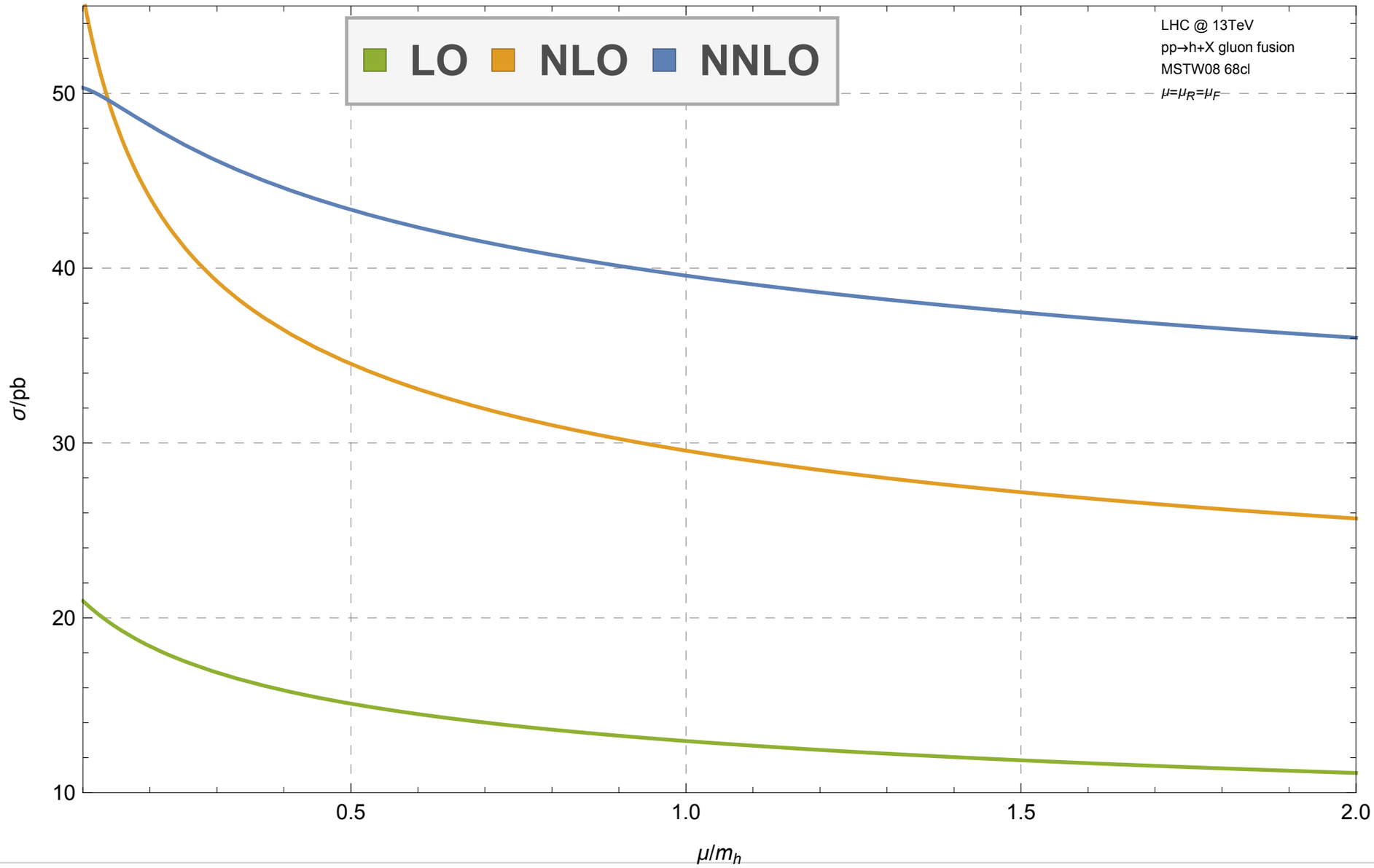
$$\text{theory} = {}^{+0.08}_{-0.07}$$

[M. Dührssen @ Moriond EW 2015]

The gluon fusion cross section

- Known at NLO and NNLO, but plagued by large perturbative uncertainties.

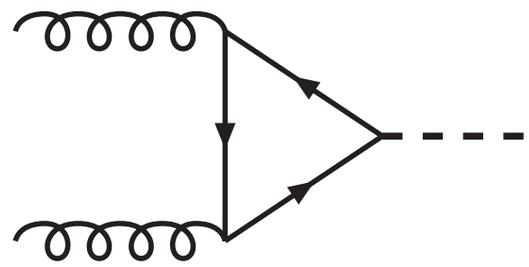
[Dawson; Djouadi, Spira, Zerwas; Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven]



The gluon fusion cross section

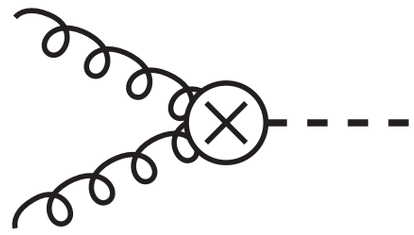
- The dominant Higgs production mechanism at the LHC is gluon fusion.

  ➡ Loop-induced process.



- For a light Higgs boson, the dimension five operator describing a tree-level coupling of the gluons to the Higgs boson

$$\mathcal{L} = \mathcal{L}_{QCD,5} - \frac{1}{4v} C_1 \, H \, G^a_{\mu\nu} \, G^{\mu\nu}_a$$



- Top-mass corrections known at NNLO.

  [Harlander, Ozeren; Pak, Rogal, Steinhauser; Ball, Del Duca, Marzani, Forte, Vicini; Harlander, Mantler, Marzani, Ozeren]

- In the rest of the talk, I will only concentrate on the effective theory.

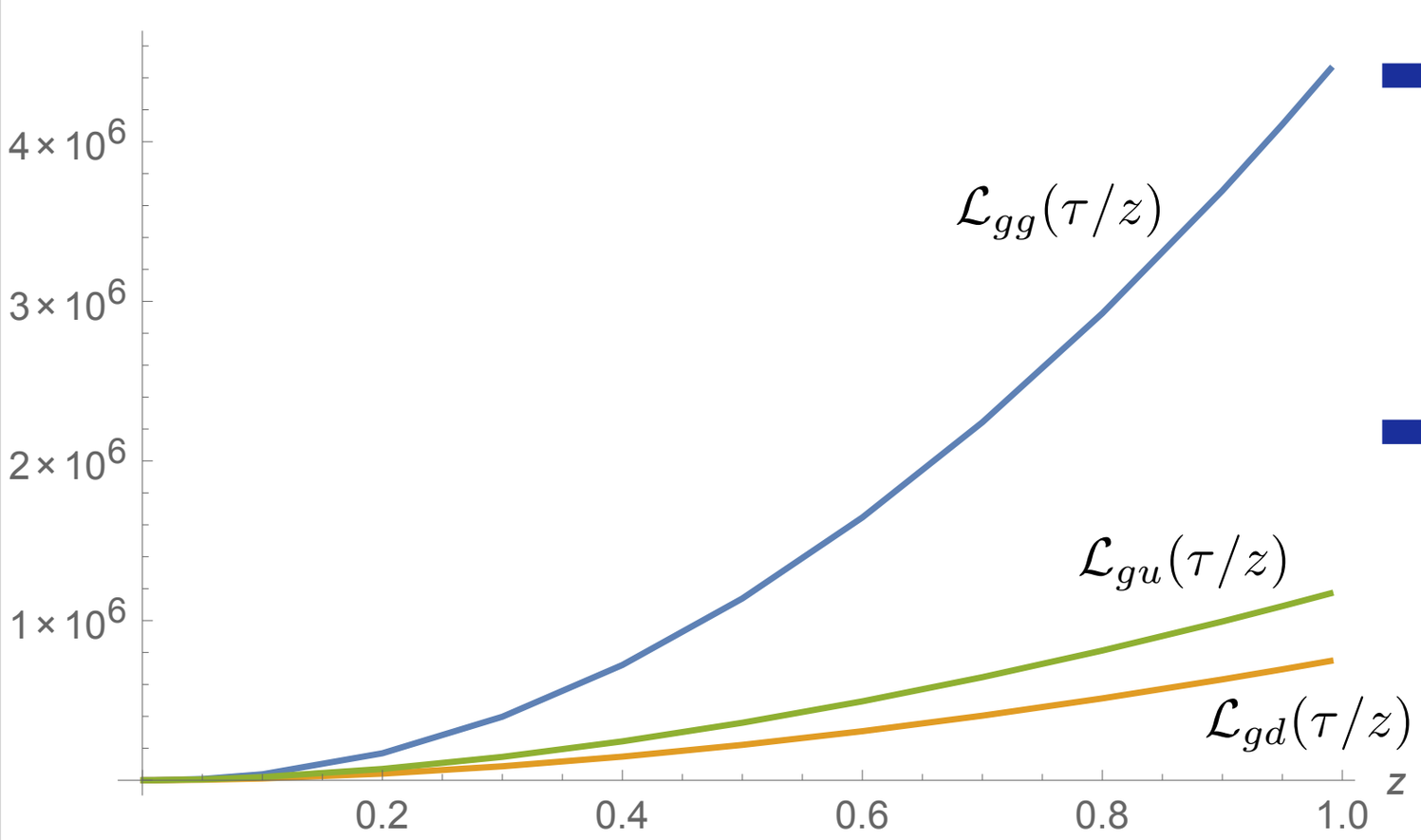
The gluon fusion cross section

- The gluon fusion cross section is given in perturbation theory by

$$\sigma = \tau \sum_{ij} \int_\tau^1 \frac{dz}{z}\, \mathcal{L}_{ij}(\tau/z)\, \frac{\hat{\sigma}_{ij}(z)}{z}$$

$$z = \frac{m_H^2}{\hat{s}}$$

$$\tau = \frac{m_H^2}{S} \simeq 10^{-4}$$



➡ Main contribution from region where $z \simeq 1$.

➡ Physically: production at threshold + emission of soft partons.

The threshold expansion

- Steep fall of the gluon luminosity!
  - ➡ Approximate partonic cross sections by threshold expansion:

$$\hat{\sigma}(z) = \sigma_{-1} + \sigma_0 + (1-z)\,\sigma_1 + \mathcal{O}(1-z)^2$$

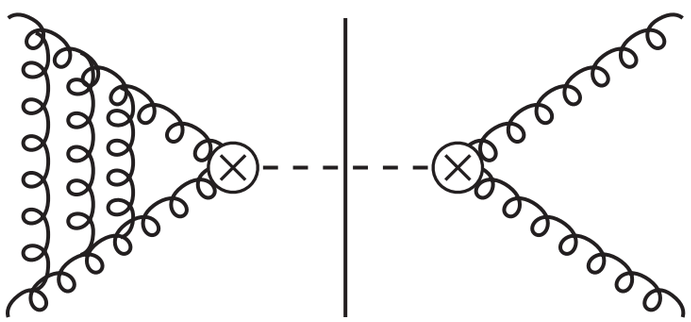
  - ➡ NNLO result was obtained in this way.

- Goal: Compute cross section as a series around threshold!

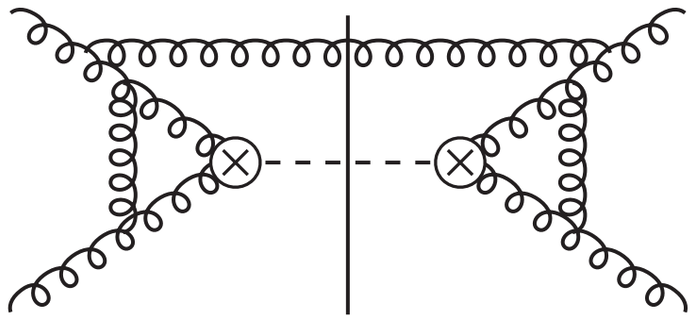
- Challenge: Never has an N3LO computation been performed so far...
  - ➡ Uncharted territory!
  - ➡ New conceptual challenges.

The gluon fusion cross section

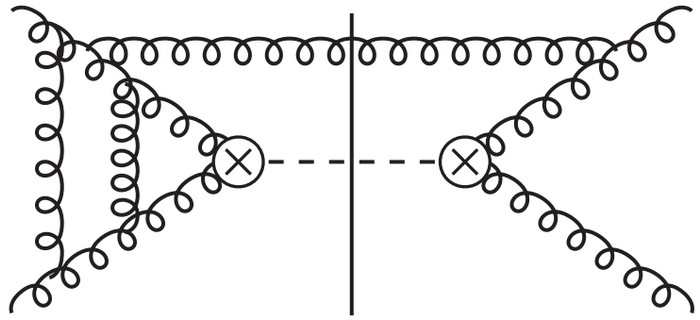
- At N3LO, there are five contributions:



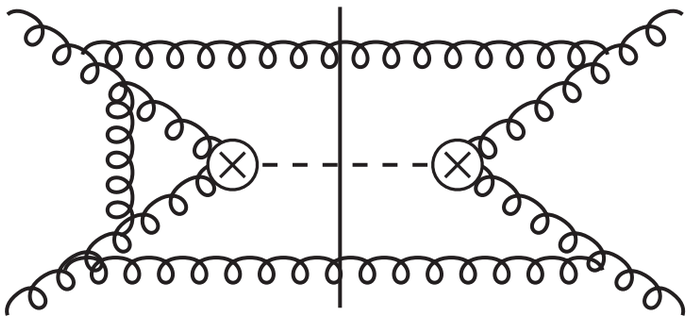
Triple virtual



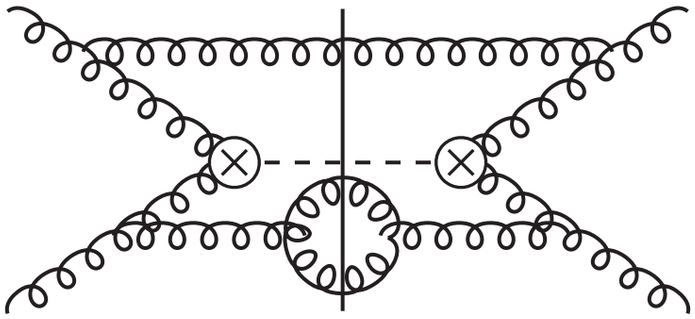
Real-virtual squared



Double virtual real



Double real virtual



Triple real

The gluon fusion cross section

- The 3-loop form factor. [Baikov, Chetyrkin, Smirnov, Smirnov, Steinhauser; Gehrmann, Glover, Huber, Ikizlerli, Studerus]
- Single-emission.
  - ➡ One-loop squared [Anastasiou, CD, Dulat, Herzog, Mistlberger; Kilgore]
  - ➡ Two-loop. [Gehrmann, Glover, Jaquier, Koukoutsakis; CD, Gehrmann, Jaquier; Dulat, Mistlberger]
- Double-emission at one-loop. [Anastasiou, CD, Dulat, Herzog, Mistlberger]
- Triple-real emission at one-loop.
- 3-loop splitting functions. [Moch, Vermaseren, Vogt]
- 3-loop beta function. [Tarasov, Vladimirov, Zharkov; Larin, van Ritbergen, Vermaseren; Czakon]
- UV and IR counterterms. [Anastasiou, Bühler, CD, Herzog; Höschele, Hoff, Pak, Steinhauser; Bühler, Lazopoulos]

An Unseen Complexity

	NNLO	N3LO
# diagrams	~ 1.000	
# integrals	~50.000	
# masters	27	
# boundary conditions	5	

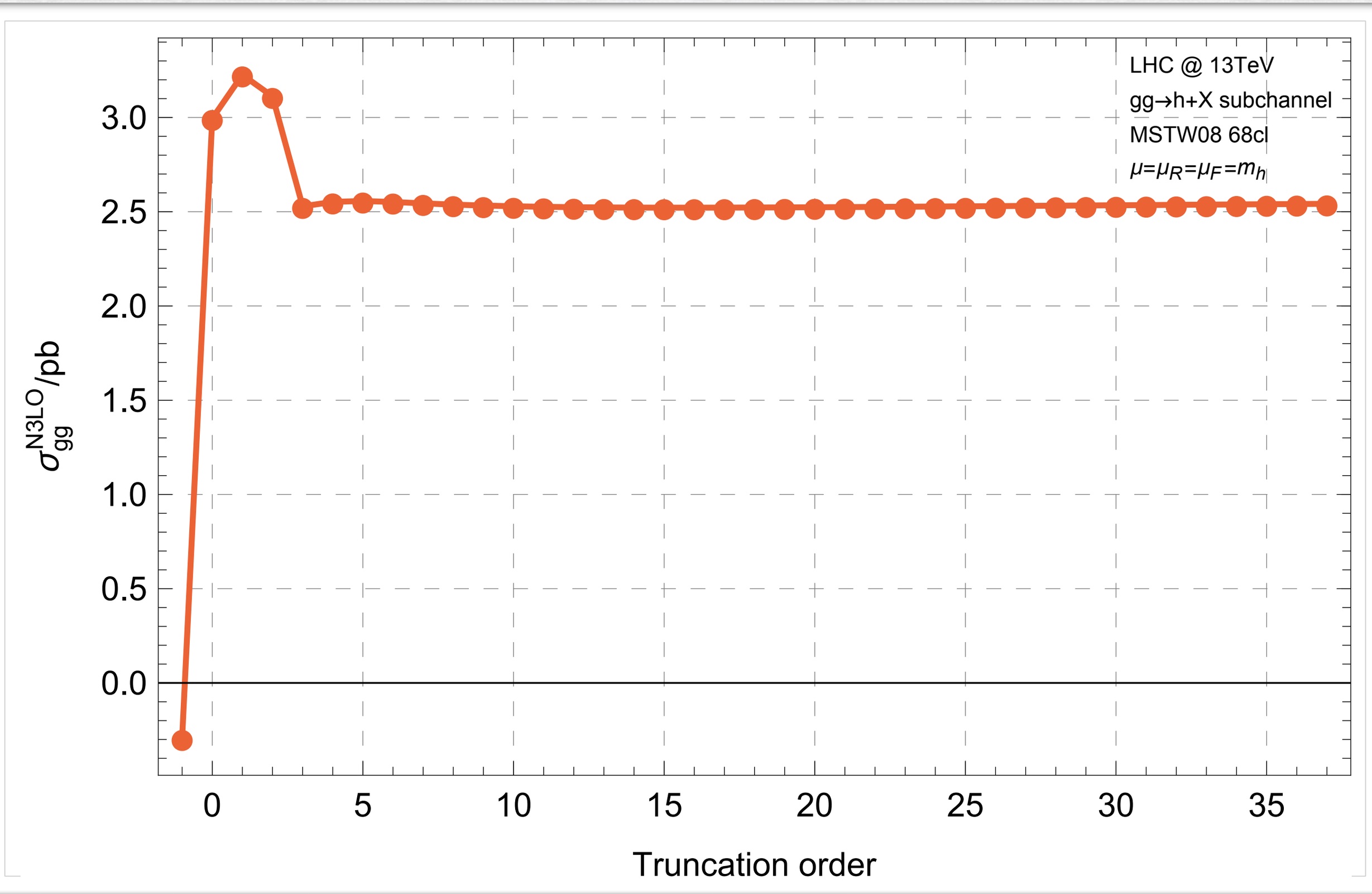
- On top of all this:
  - ➡ Form factor integral.
  - ➡ UV counterterms.
  - ➡ Convolution with PDF counterterms.
  - ➡ Wilson coefficient.

An Unseen Complexity

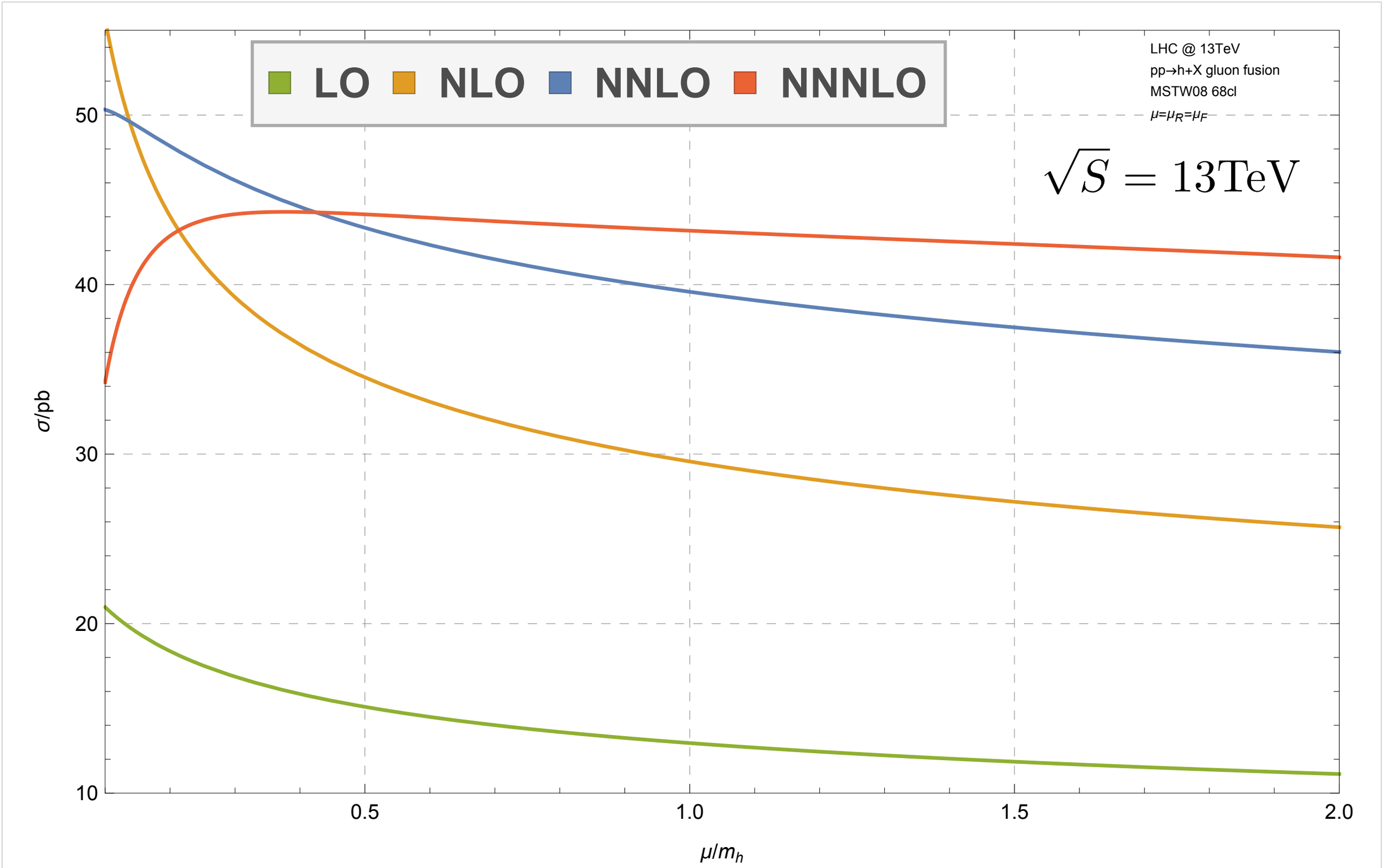
	NNLO	N3LO
# diagrams	~ 1.000	~100.000
# integrals	~50.000	517.531.178
# masters	27	1.028
# boundary conditions	5	78

- On top of all this:
  - ➡ Form factor integral.
  - ➡ UV counterterms.
  - ➡ Convolution with PDF counterterms.
  - ➡ Wilson coefficient.

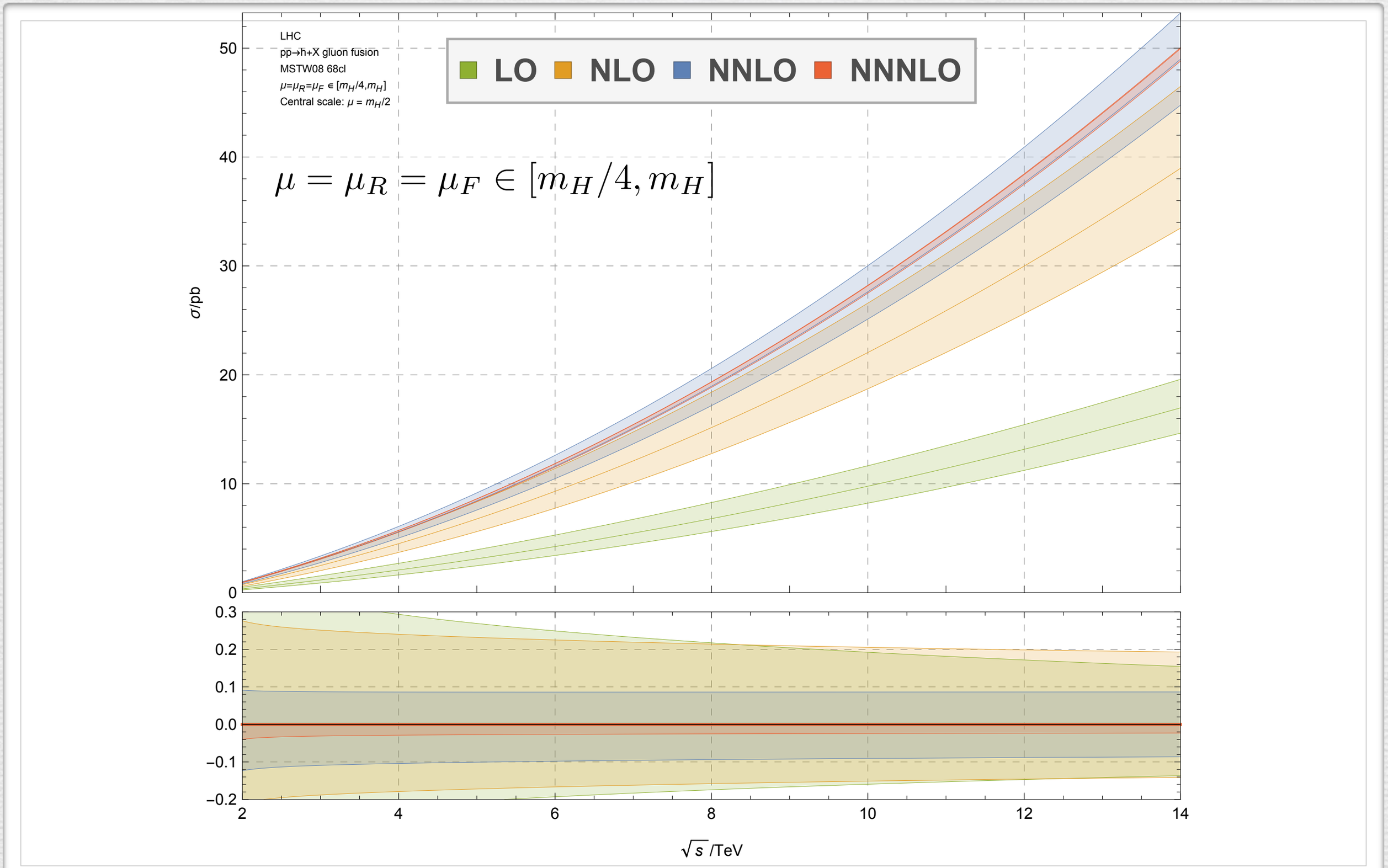
Threshold expansion



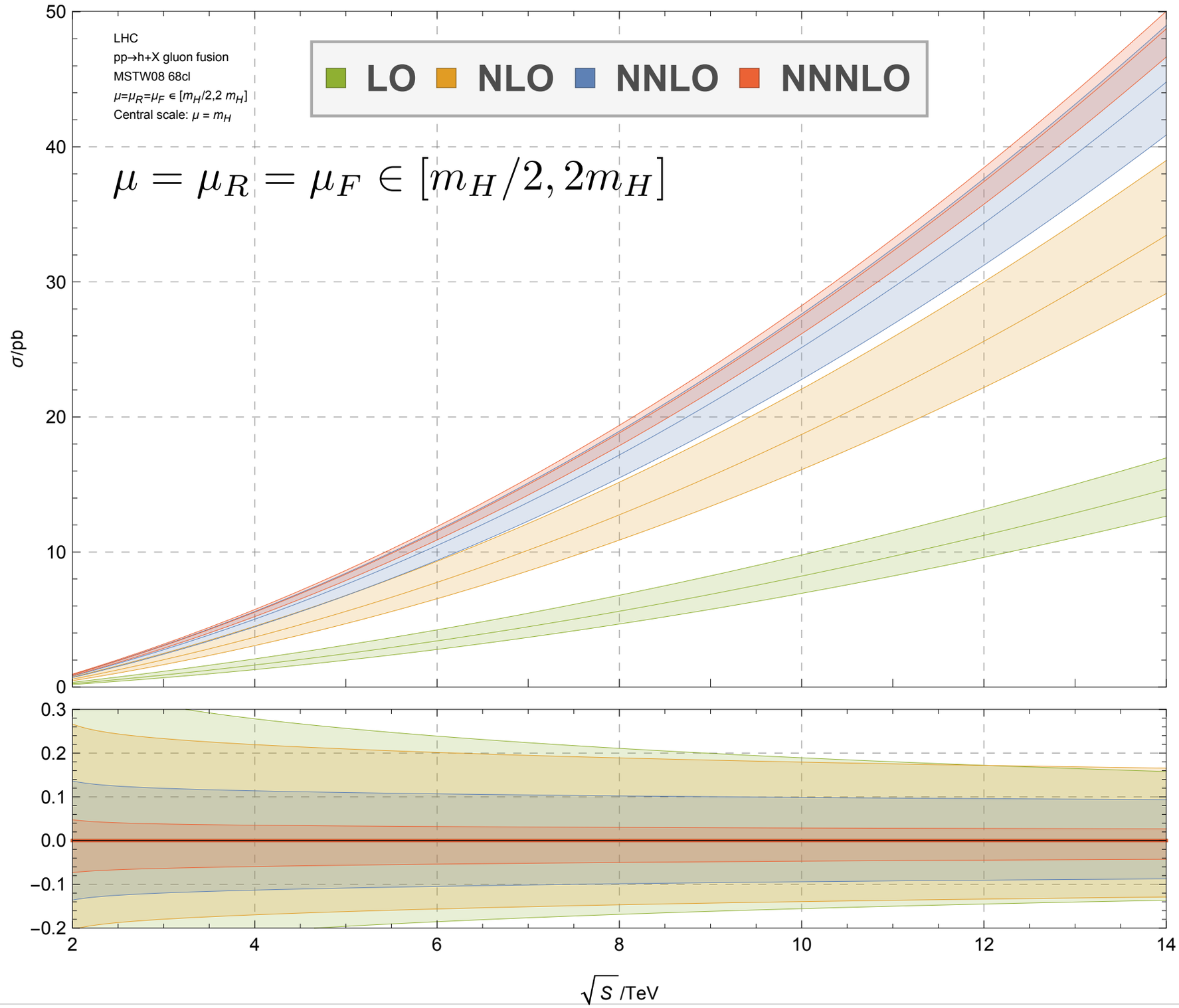
Scale variation



Energy variation



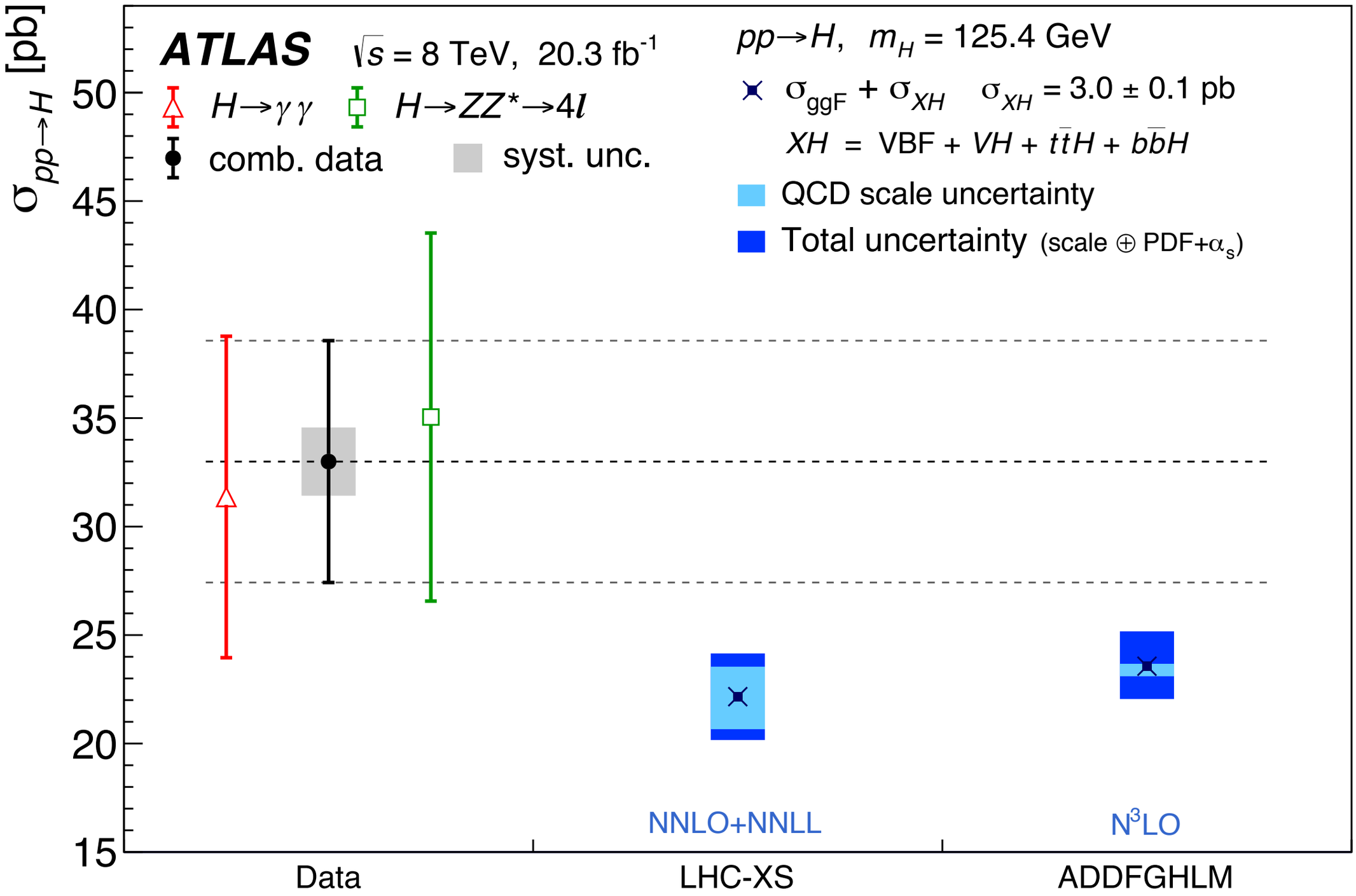
Energy variation



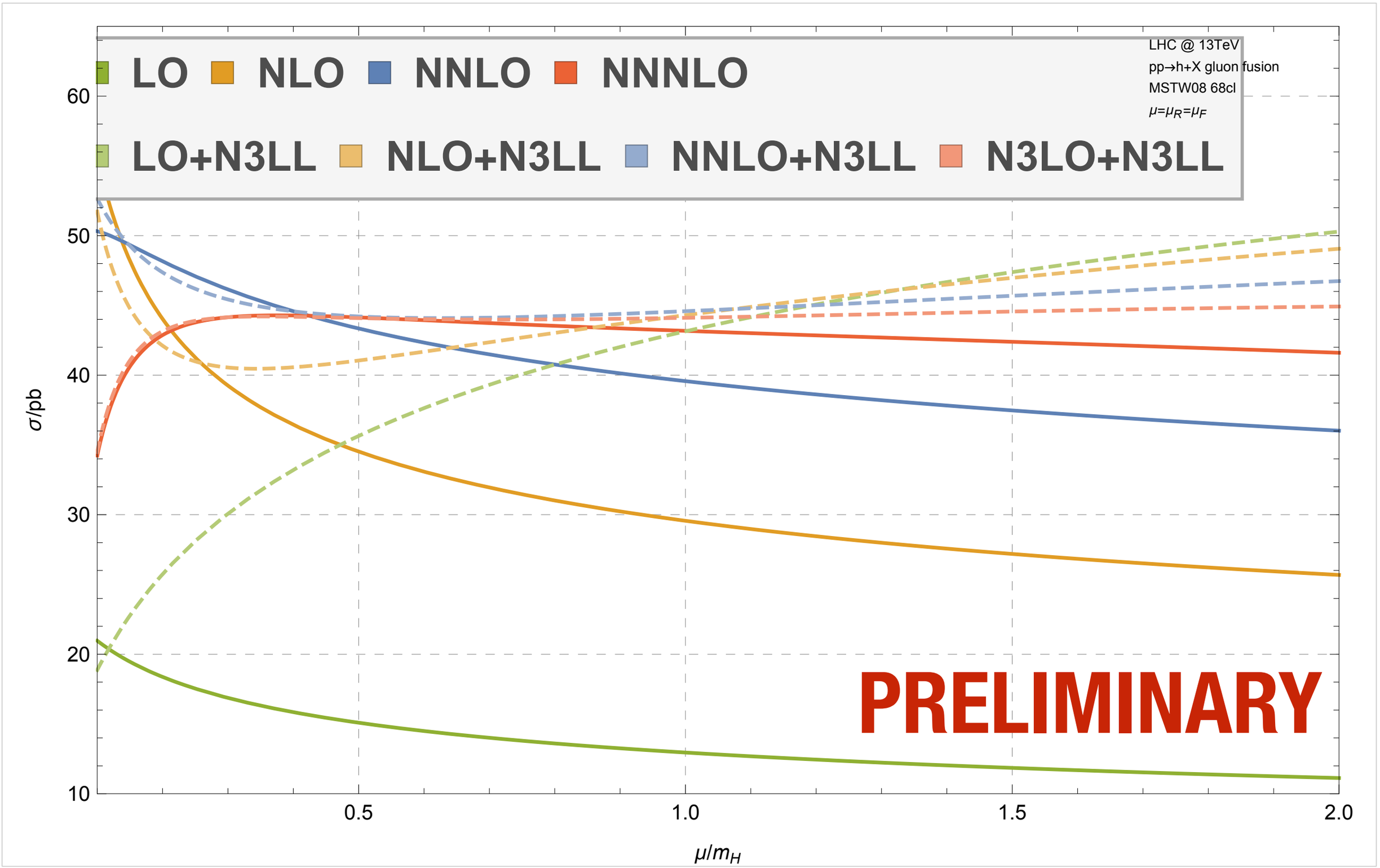
From QCD to LHC

- Perturbative QCD uncertainties are drastically reduced at N3LO!
- Other sources of uncertainty could now be of the same size.
  - ➡ N4LO QCD corrections.
  - ➡ Electroweak corrections.
  - ➡ Top-mass corrections.
  - ➡ Top-bottom interference.
  - ➡ PDF + α_S uncertainties.
- We are currently assessing these effects to produce a final result for the cross section!

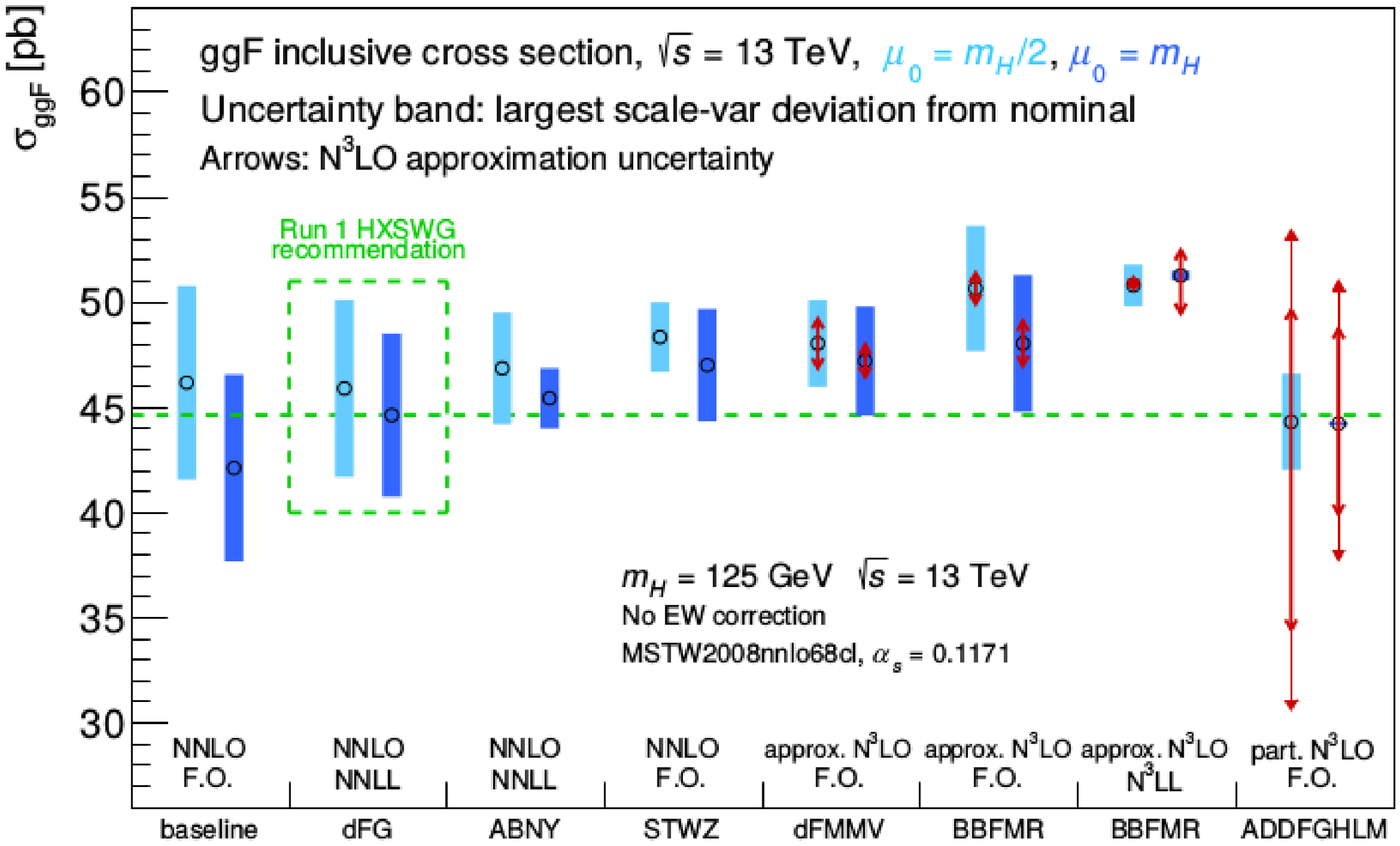
From QCD to LHC



N3LL threshold resummation

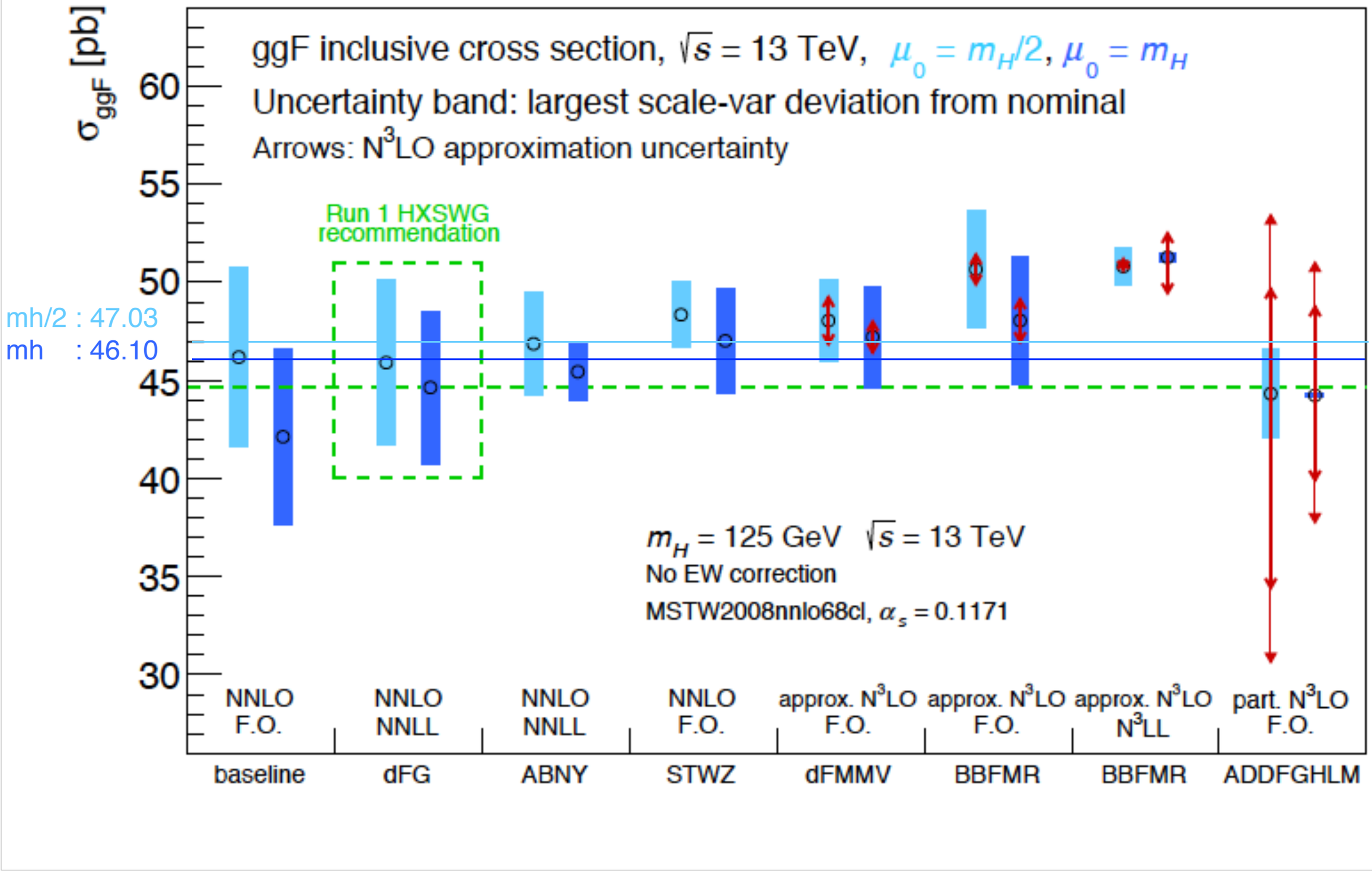


Comparison to Approximate N3LO

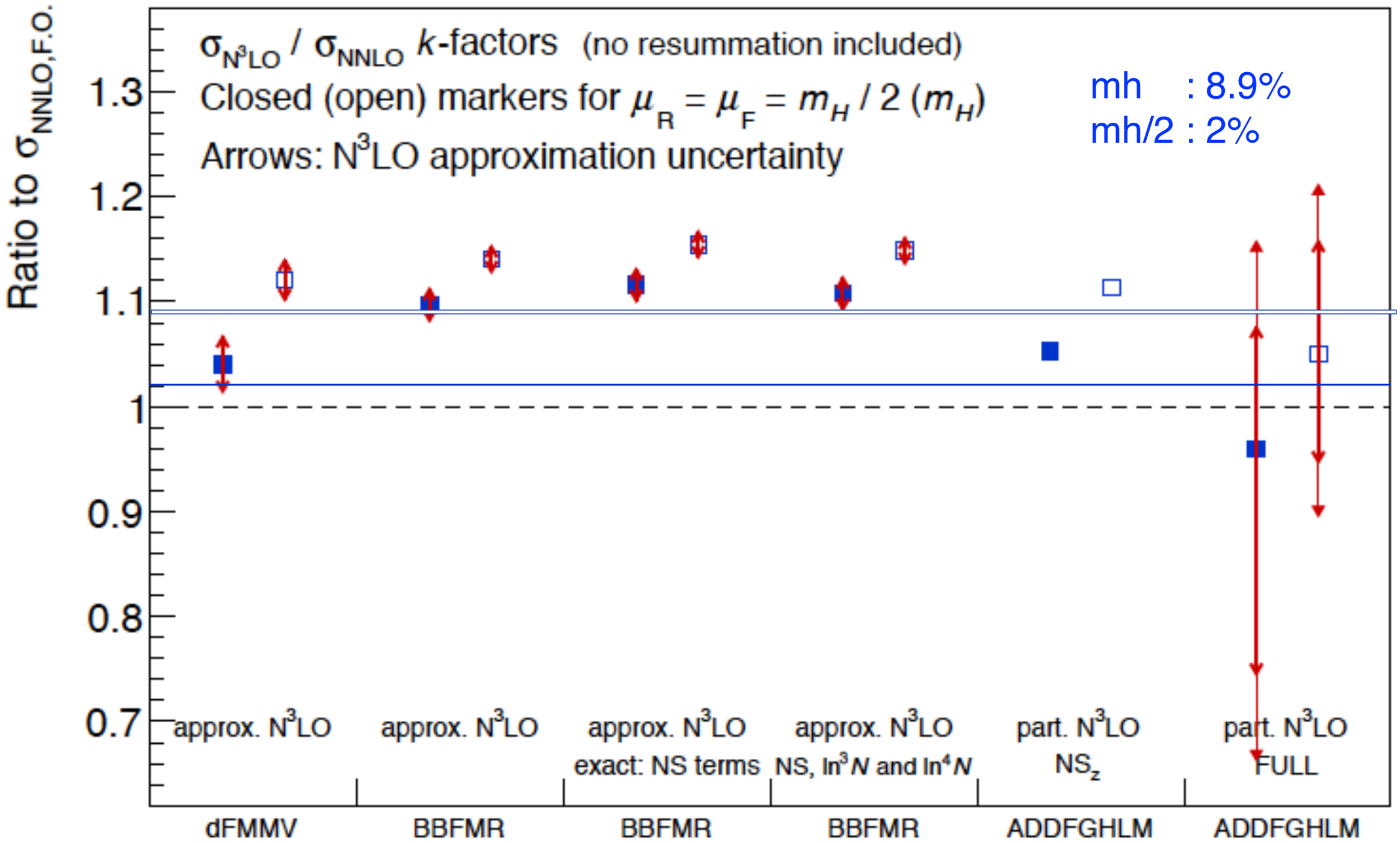


[Plot from HXSWG]

Comparison to Approximate N3LO



Comparison to Approximate N3LO

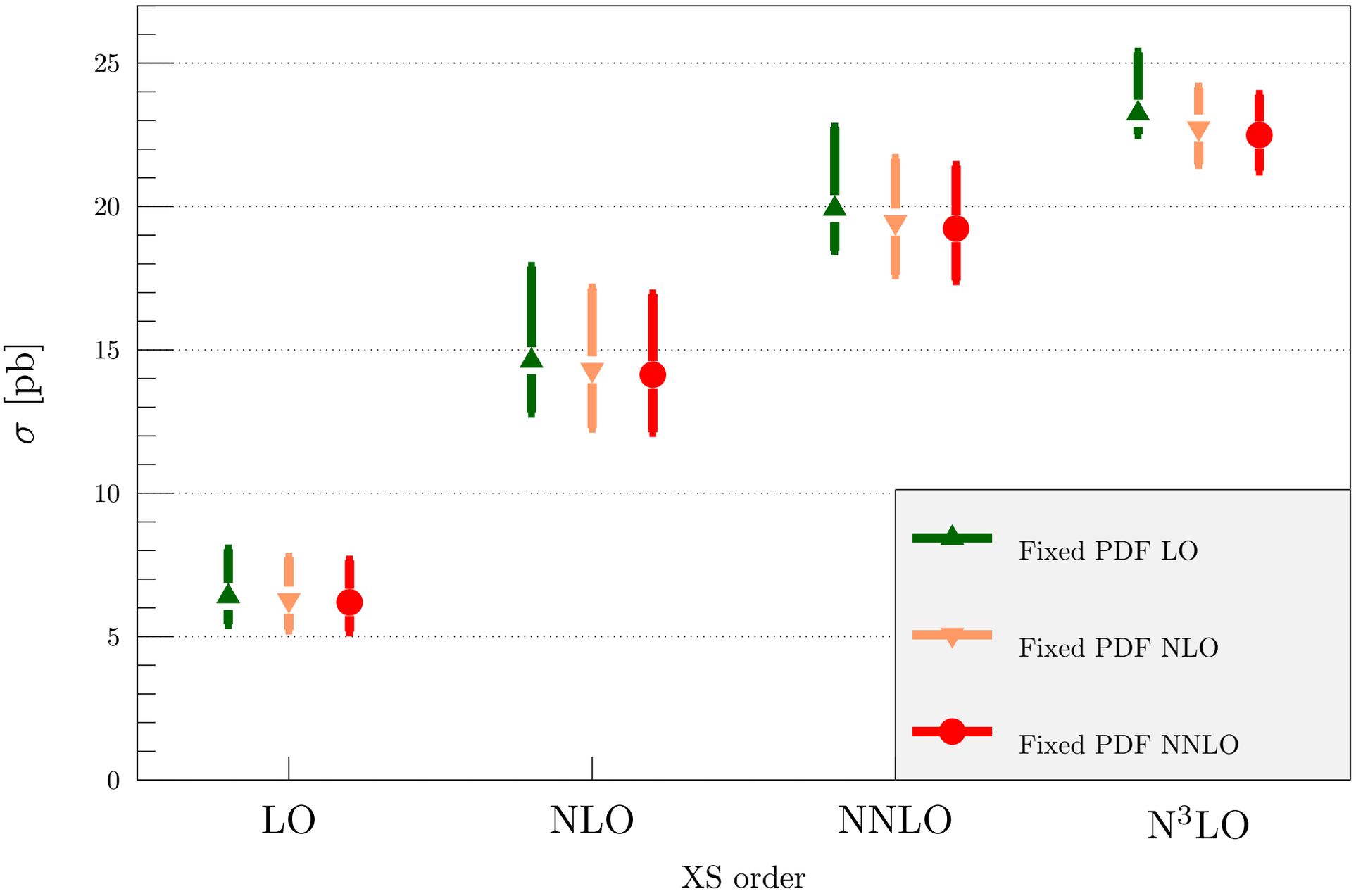


Conclusion

- The era of QCD Higgs phenomenology at N3LO has started!
  - ➡ QCD scale uncertainty immensely reduced!
- It is time to think about other effects that give rise to similar uncertainties:
  - ➡ N4LO QCD corrections.
  - ➡ Electroweak corrections.
  - ➡ Top-mass corrections.
  - ➡ Top-bottom interference.
  - ➡ PDF + α_S uncertainties.

Backup slides

NNLO vs. N3LO PDFs?



[Plot from Forte, Isgrò, Vita; N3LO is approximate]

Leading logarithms

- UV and IR counterterms are known exactly.
  - ➡ Three-loop beta function.

    [Tarasov, Vladimirov, Zharkov; Larin, Vermaseren; Czakon]
  - ➡ Three-loop splitting functions. [Moch, Vermaseren, Vogt]
  - ➡ Lower order cross sections to higher orders in epsilon + convolution with splitting functions.

    [Höschele, Hoff, Pak, Steinhauser, Uedal; Anastasiou, Bühler, CD, Herzog; Bühler, Lazopoulos]

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    [Höschele, Hoff, Pak, Steinhauser, Uedal; Anastasiou, Bühler, CD, Herzog; Bühler, Lazopoulos]
- Knowledge of counterterms and single-emission contribution, fixes the first three leading logarithms in the cross section.
  - ➡ Require pole cancellation in inclusive cross section.

    [Anastasiou, CD, Dulat, Furlan, Gehrmann, Herzog, Mistlberger]

$$\frac{\hat{\sigma}_{ij}(z)}{z} \sim A_{ij}(z)\,\log^5(1-z) + B_{ij}(z)\,\log^4(1-z) + C_{ij}(z)\,\log^3(1-z) + \dots$$