Precision Higgs physics at hadron colliders

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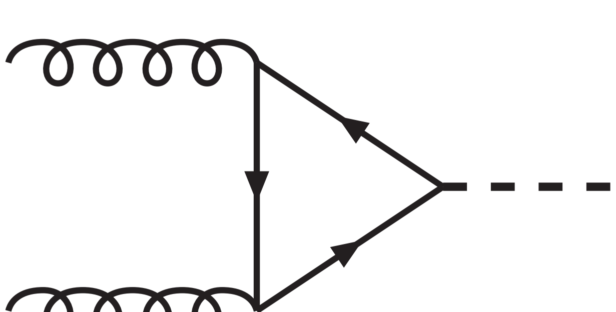
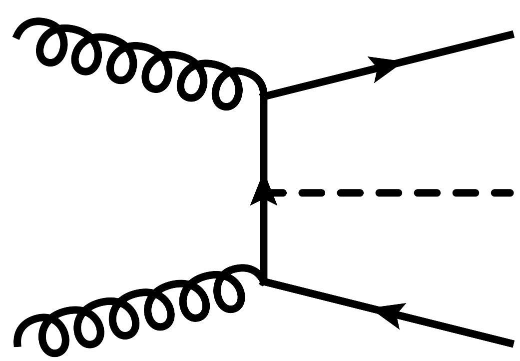
UCLA, 16/06/2015

Higgs physics at the LHC

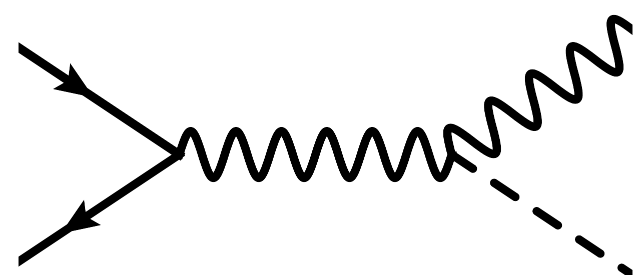
- Establishing whether the BEH mechanism and its boson is SM-like will be of outmost importance for the run of the LHC.
- Higgs-boson production modes at the LHC:



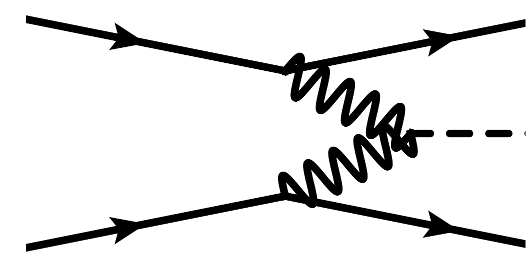
Gluon fusion



TTH



Higgs strahlung



VBF

Higgs physics at the LHC

- Establishing whether the BEH mechanism and its boson is SM-like will be of outmost importance for the run of the LHC.

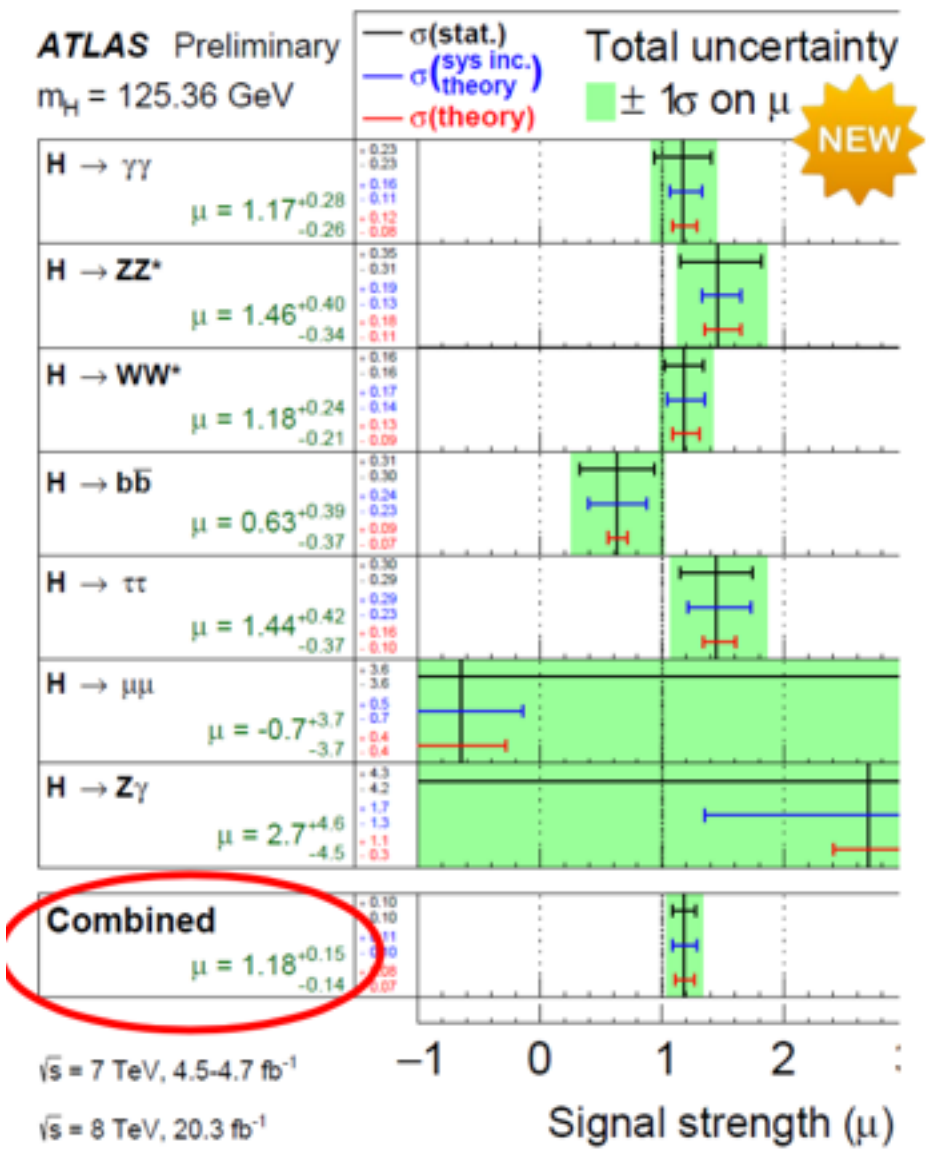
- Higgs-boson production modes at the LHC:

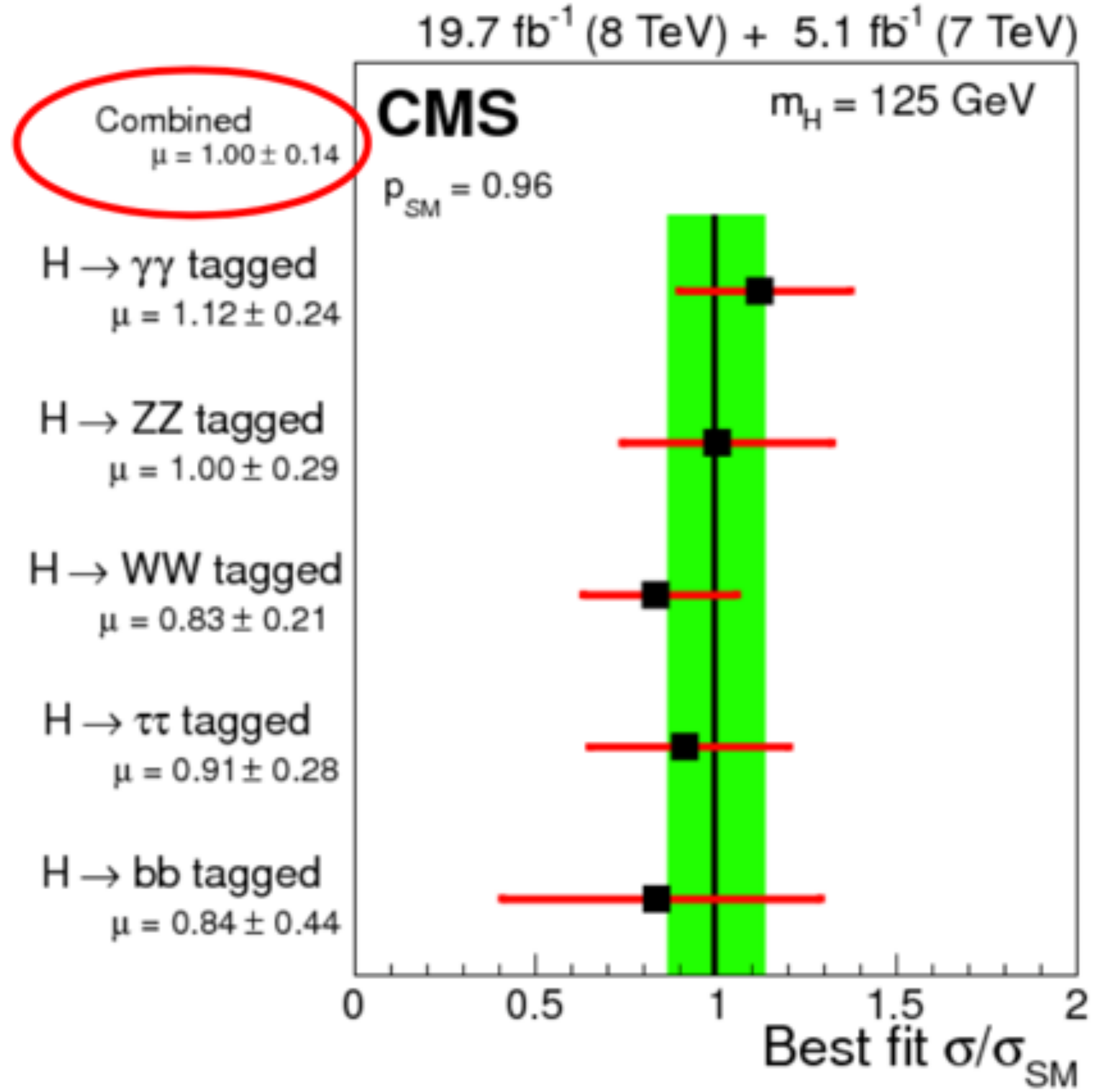
Dominant production mode at the LHC

Gluon fusion TTH Higgs strahlung VBF

- We want to know the gluon-fusion cross section precisely!

Higgs physics at the LHC





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

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

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

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

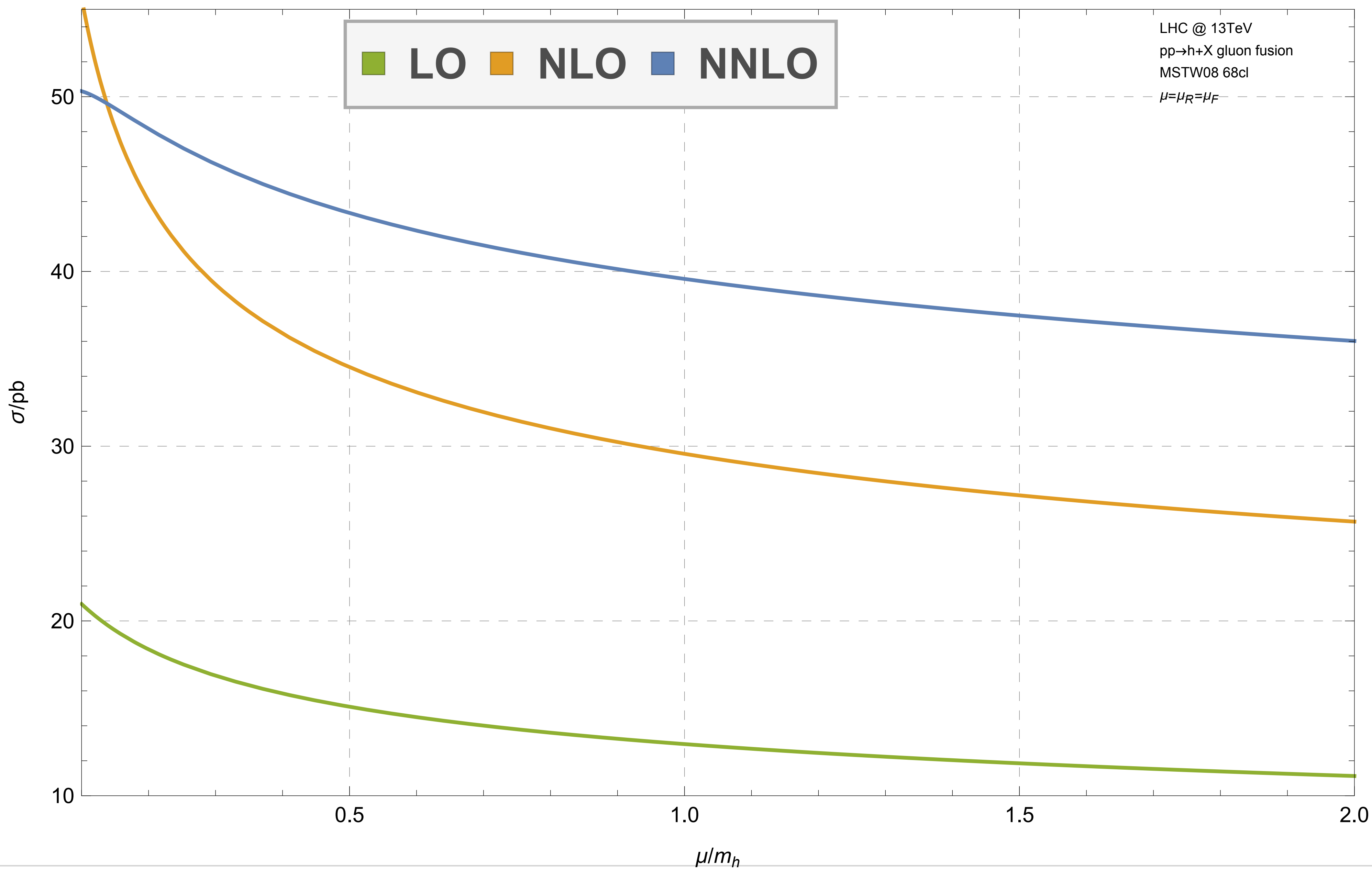
$$\text{theory} = {}^{+0.08}_{-0.07}$$

[M. Dührssen @ Moriond EW 2015]

The gluon fusion cross section

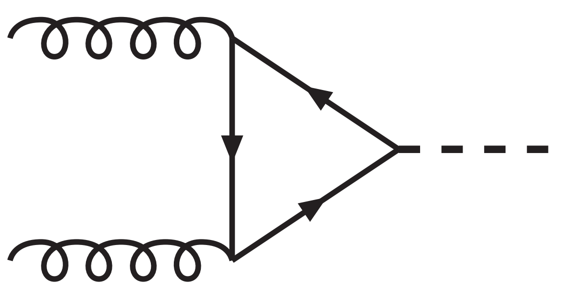
- Known at NLO and NNLO, but plagued by large perturbative uncertainties.

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



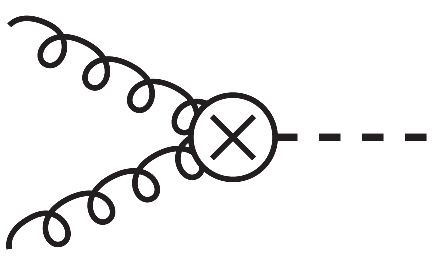
The gluon fusion cross section

- 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

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



- 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.

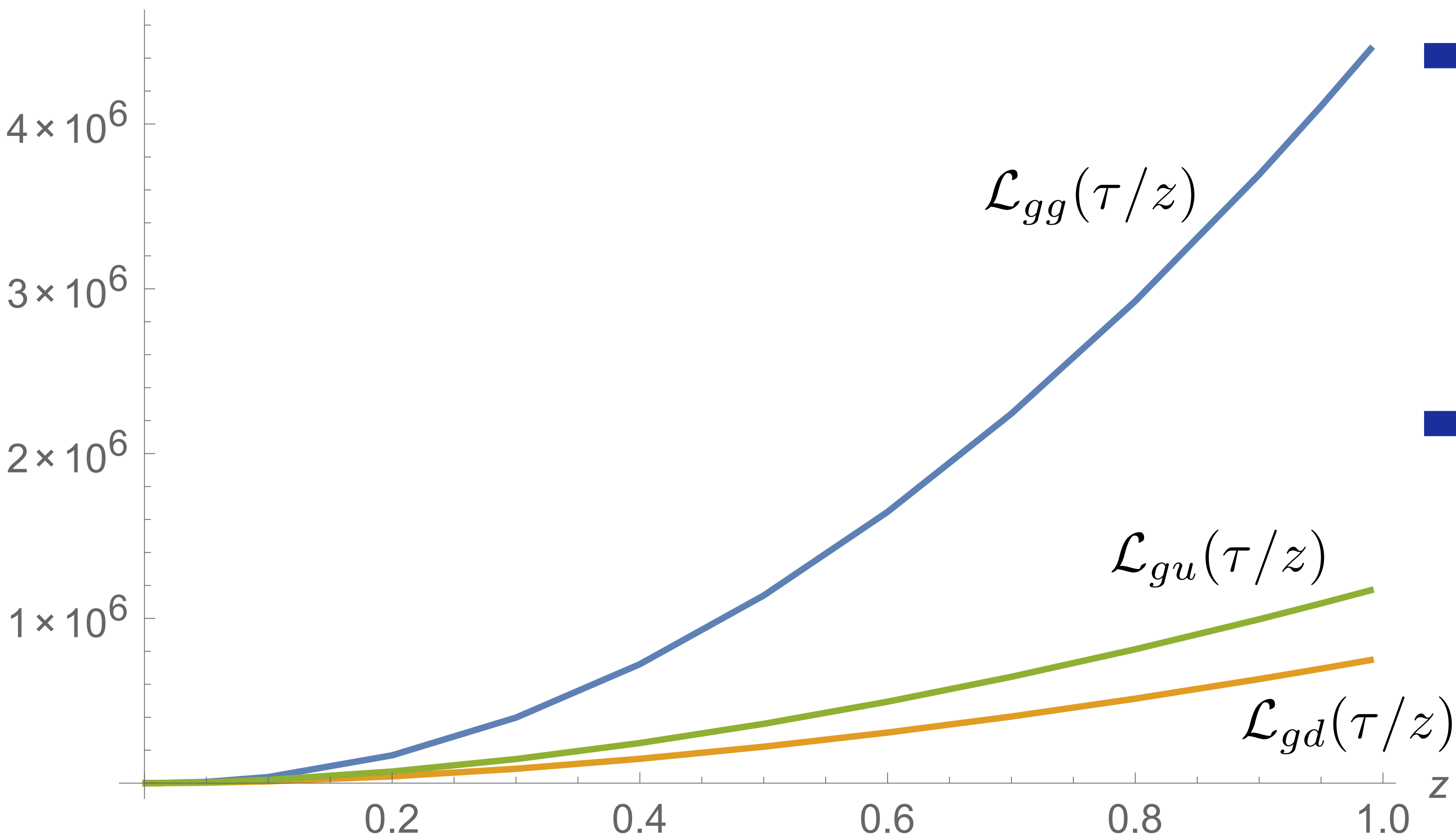
The gluon fusion cross section

- 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.

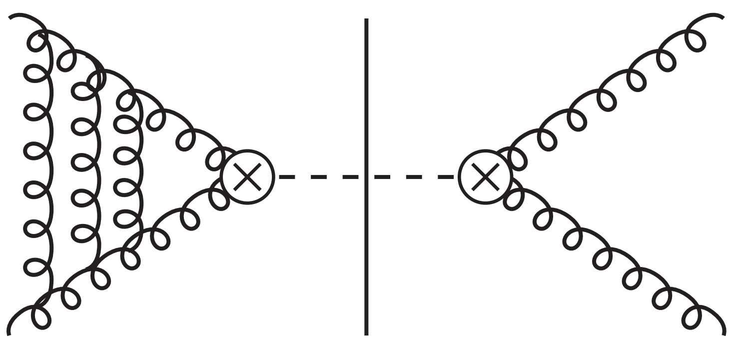
Outline

- Goal: Compute cross section as a series around threshold!
- Outline:
    - ➡ The threshold expansion at N3LO.
    - ➡ A first glimpse at Higgs phenomenology at N3LO.
- Details about the computational methods:
    - ➡ Mistlberger (Wed).
    - ➡ Furlan (Thu).

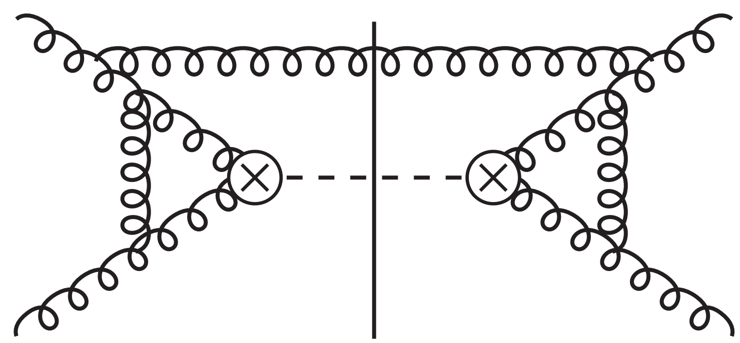
The threshold expansion at N3LO

The gluon fusion cross section

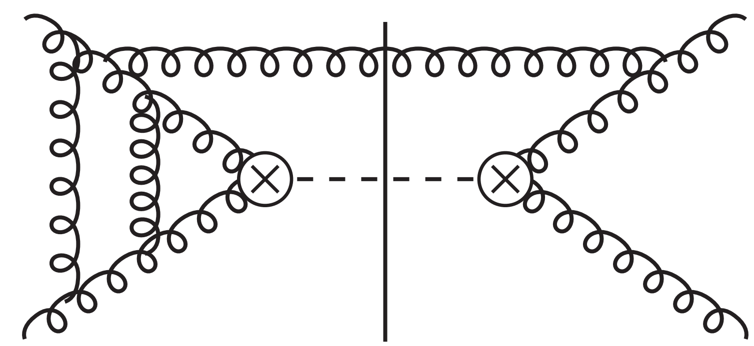
- At N3LO, there are five contributions:



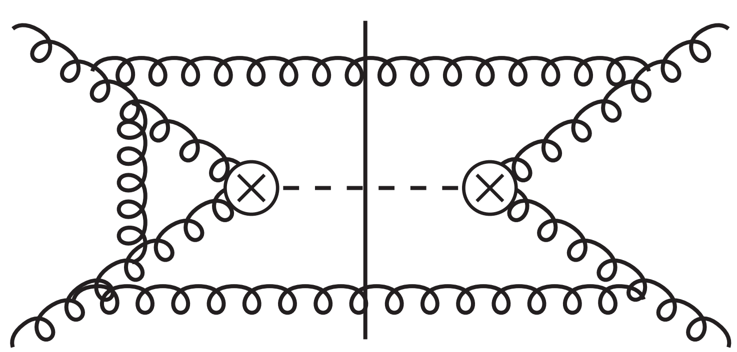
Triple virtual



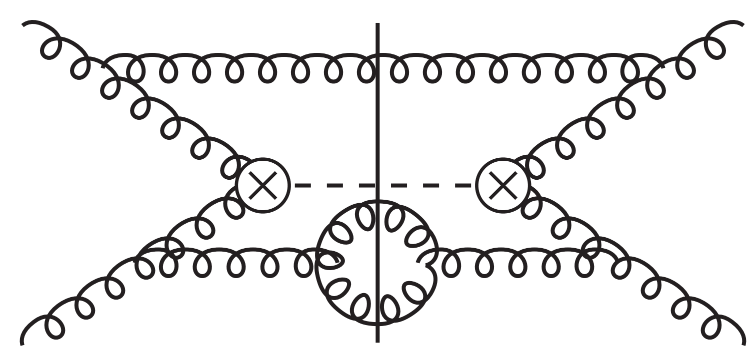
Real-virtual squared



Double virtual real



Double real virtual



Triple real

Systematics of the expansion

$$\frac{\hat{\sigma}_{ij}(z)}{z} = \hat{\sigma}^{SV}\,\delta_{ig}\,\delta_{jg} + \sum_{N=0}^{\infty} \hat{\sigma}_{ij}^{(N)}\,(1-z)^N$$

- Goal: Compute enough terms to establish convergence.

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- Goal: Compute enough terms to establish convergence.
- The coefficients in the expansion are not constants, but they are polynomials in $\log(1-z)$.
  - ➡ At N3LO: $\hat{\sigma}_{ij}^{(N)} = \sum_{k=0}^{5} c_{ijk}^{(N)}\,\log^k(1-z)$
  - ➡ Coefficients in this polynomial are zeta values.

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- The first term is called the soft-virtual term and is distribution-valued:

  ➡ At N3LO: $\hat{\sigma}^{SV} = a\,\delta(1-z) + \sum_{k=0}^{5} b_k\,\left[\frac{\log^k(1-z)}{1-z}\right]_+$

The soft-virtual contribution

$$\frac{\hat{\sigma}_{ij}(z)}{z} = \hat{\sigma}^{SV}\,\delta_{ig}\,\delta_{jg} + \sum_{N=0}^{\infty} \hat{\sigma}_{ij}^{(N)}\,(1-z)^N$$

$$\boxed{a\,\delta(1-z) + \sum_{k=0}^{5} b_k \left[\frac{\log^k(1-z)}{1-z}\right]_+}$$

- Contributes to the gluon-channel only.
- Plus-distributions already known a decade ago.
  - ➡ Soft gluon emissions. [Moch, Vogt; Laenen, Magnea]
- delta-function contribution computed last year.
  [Anastasiou, CD, Dulat, Furlan, Gehrmann, Herzog, Mistlberger]
  - ➡ Later confirmed independently by [Li, von Manteuffel, Schabinger, Zhu]
  - ➡ Contains the complete three-loop corrections.
    [Baikov, Chetyrkin, Smirnov², Steinhauser; Gehrmann, Glover, Huber, Ikizlerli, Studerus]
  - ➡ See talk by Ravindran on thursday!

The regular contributions

$$\frac{\hat{\sigma}_{ij}(z)}{z} = \hat{\sigma}^{SV}\,\delta_{ig}\,\delta_{jg} + \sum_{N=0}^{\infty} \hat{\sigma}_{ij}^{(N)}\,(1-z)^N$$

$$\hat{\sigma}_{ij}^{(N)} = \sum_{k=0}^{5} c_{ijk}^{(N)}\,\log^k(1-z)$$

- Describes subleading soft emissions.
- Single-emission contributions known exactly.

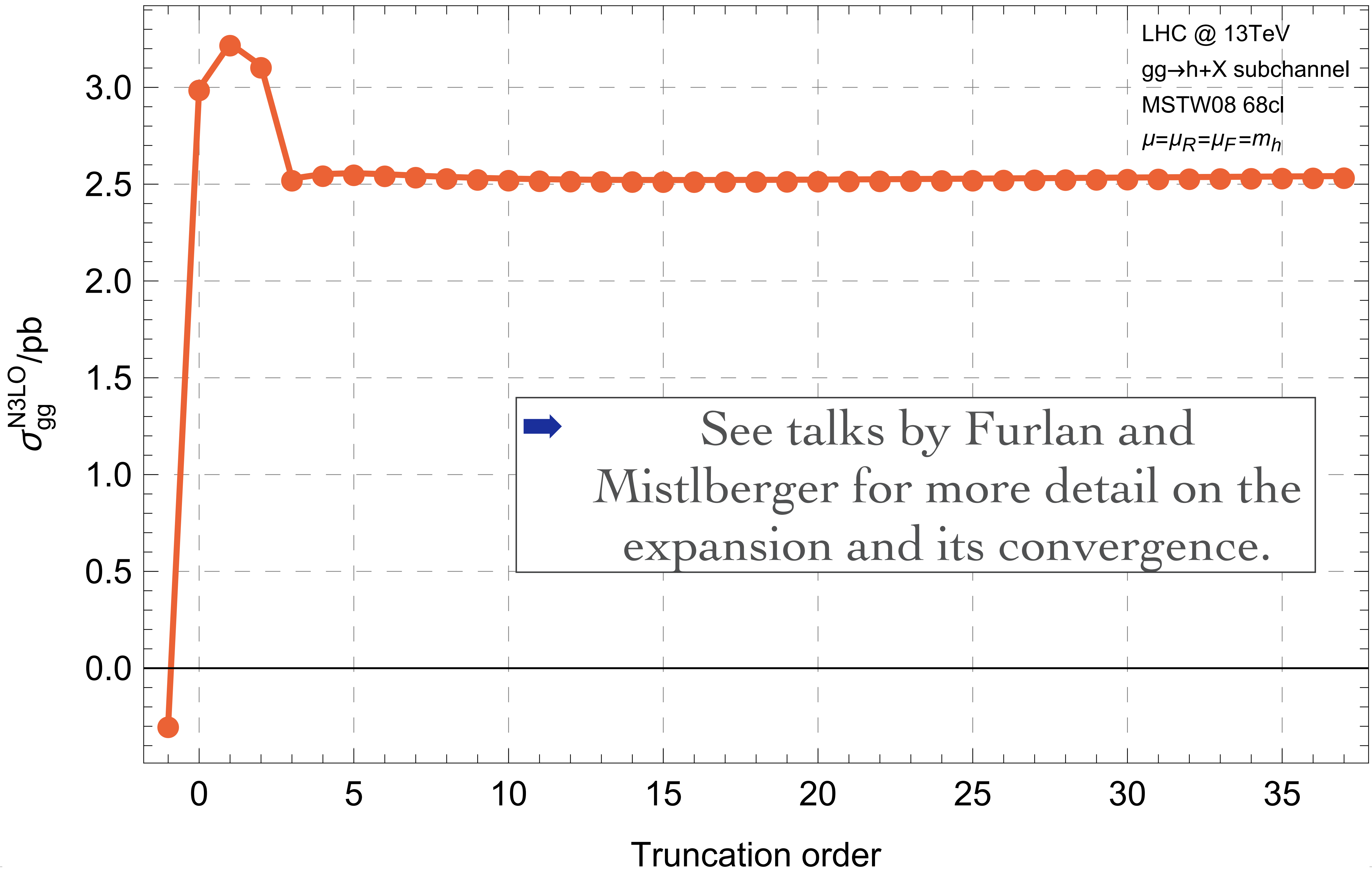
  [Anastasiou, CD, Dulat, Herzog, Mistlberger; Kilgore; Gehrmann, Glover, Jaquier, Koukoutsakis, CD, Gehrmann, Jaquier; Dulat, Mistlberger]

- Double- and triple-emissions only known as an expansion around threshold. [Anastasiou, CD, Dulat, Herzog, Mistlberger]

  ➡ Exact result for qq' channel was recently published.

  [Anzai, Hasselhuhn, Hoff, Höschele, Kilgore, Steinhauser, Ueda]

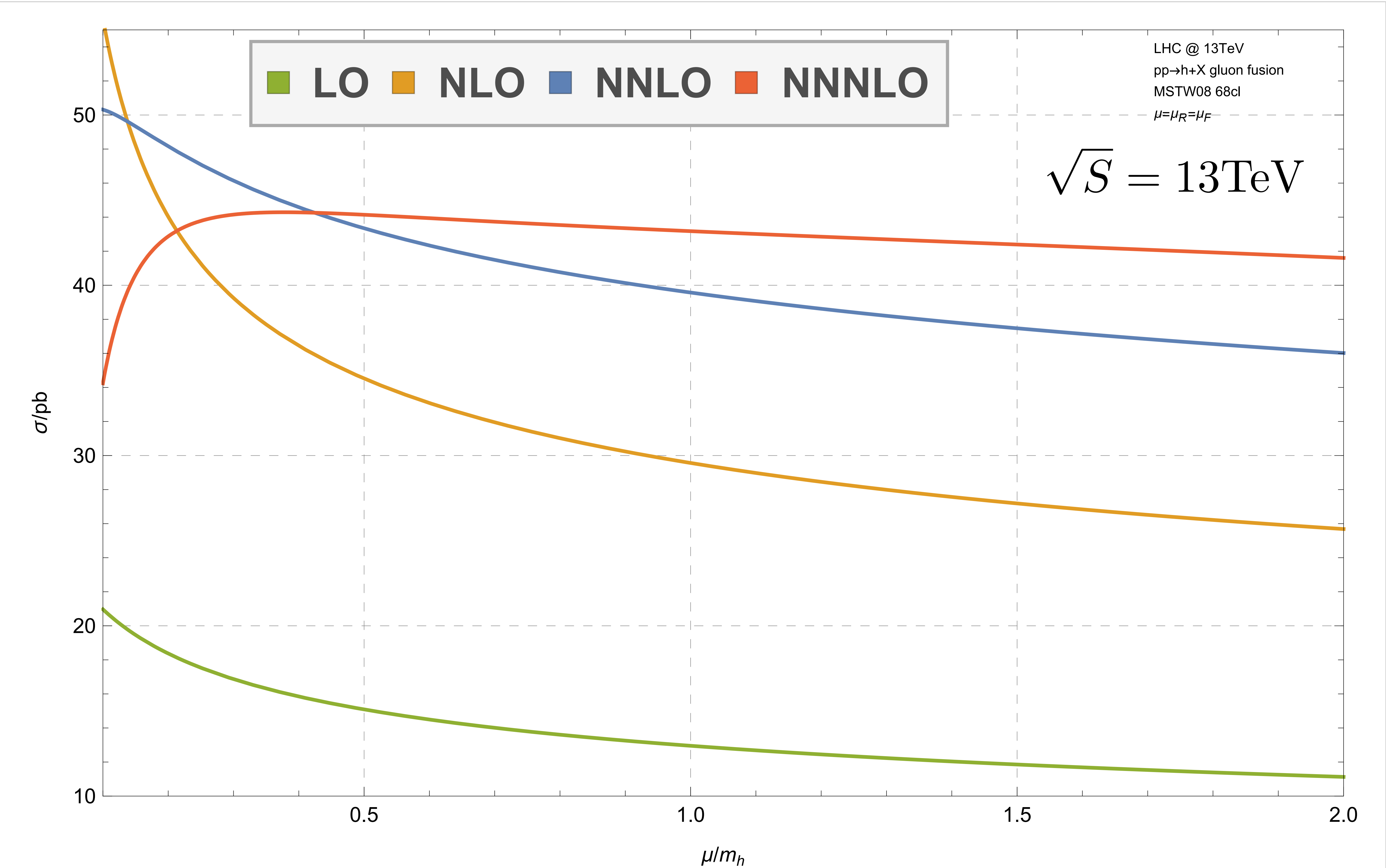
Threshold expansion



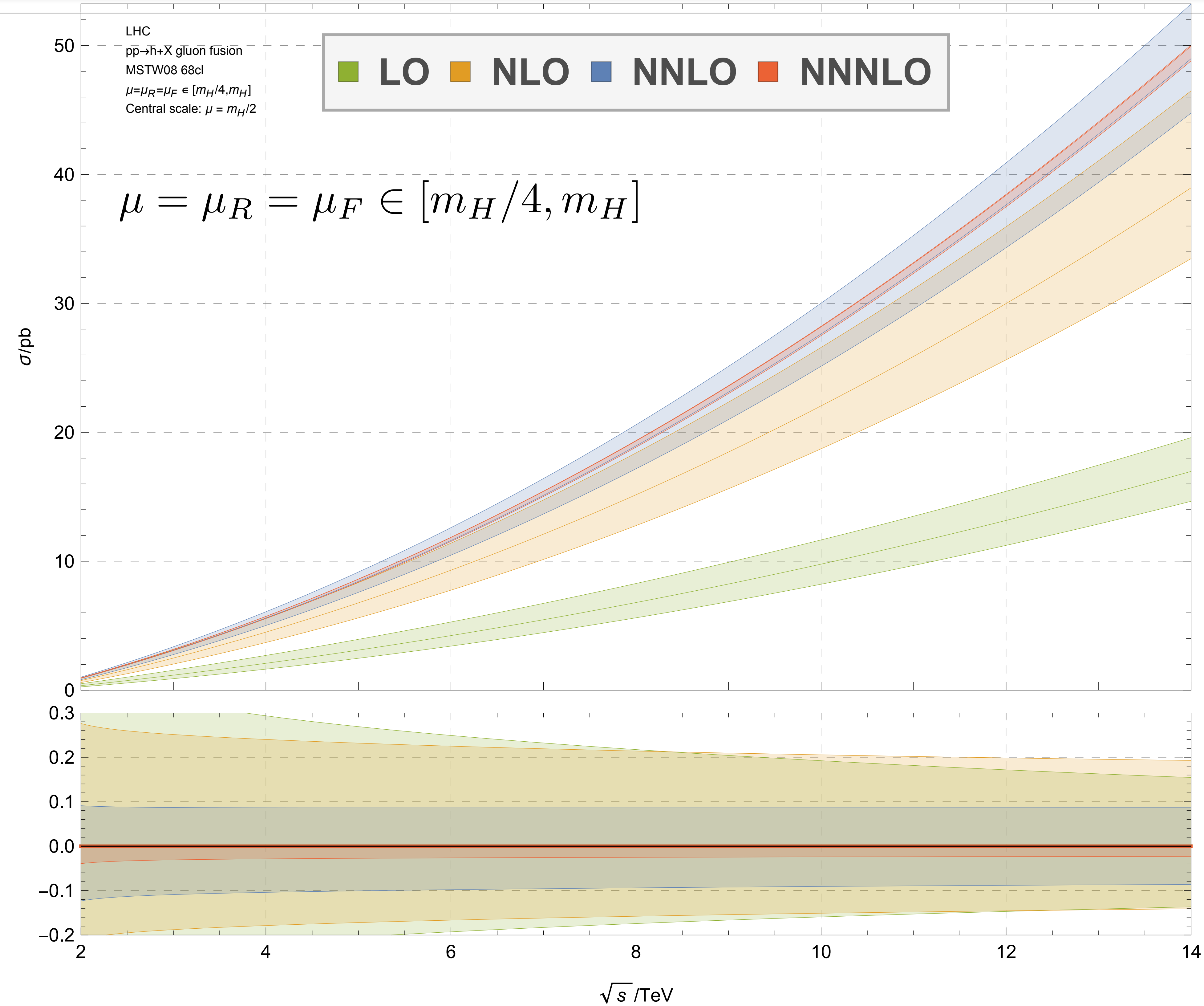
➡ See talks by Furlan and Mistlberger for more detail on the expansion and its convergence.

A first glimpse at Higgs phenomenology at N3LO

Scale variation



Energy variation



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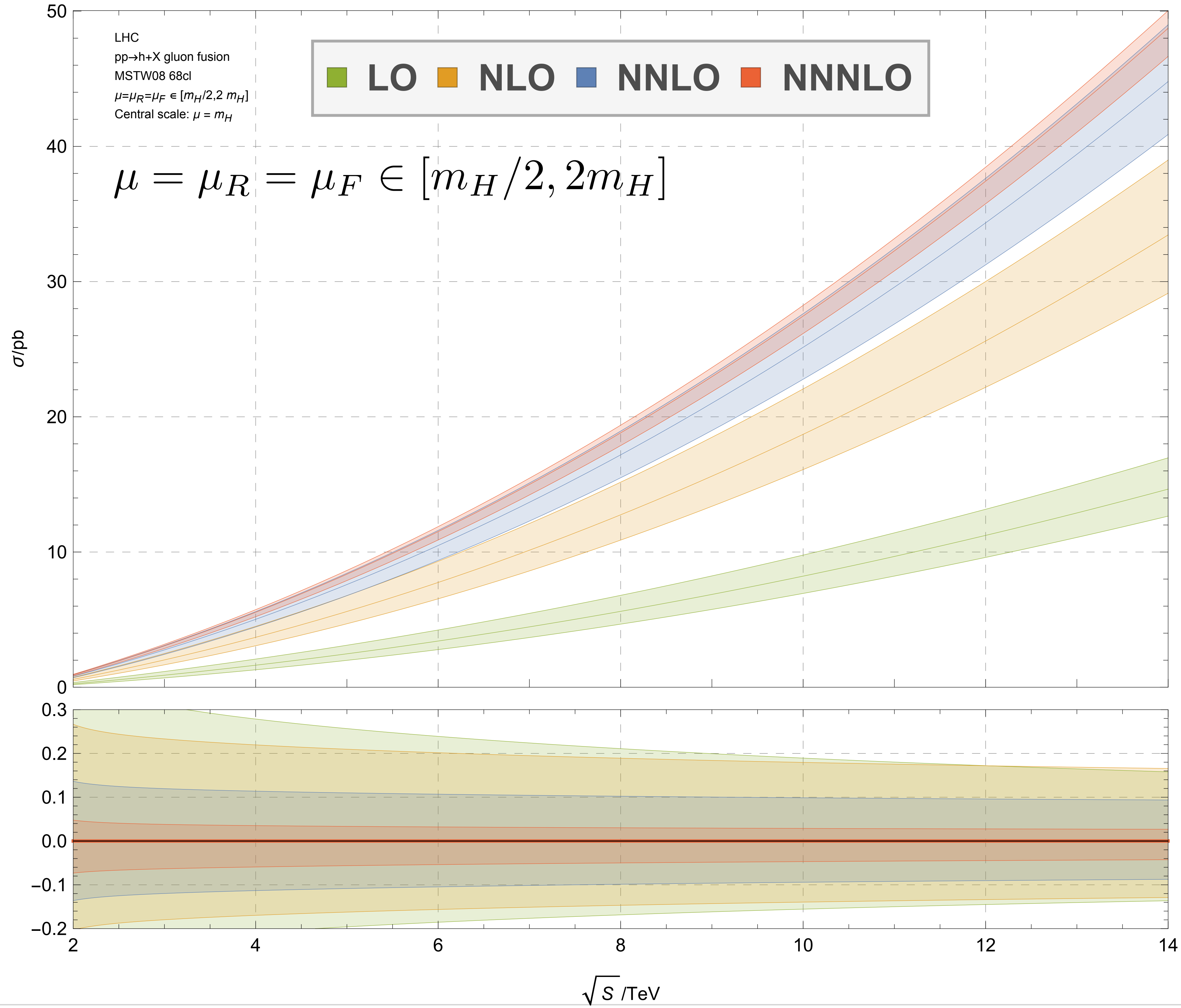
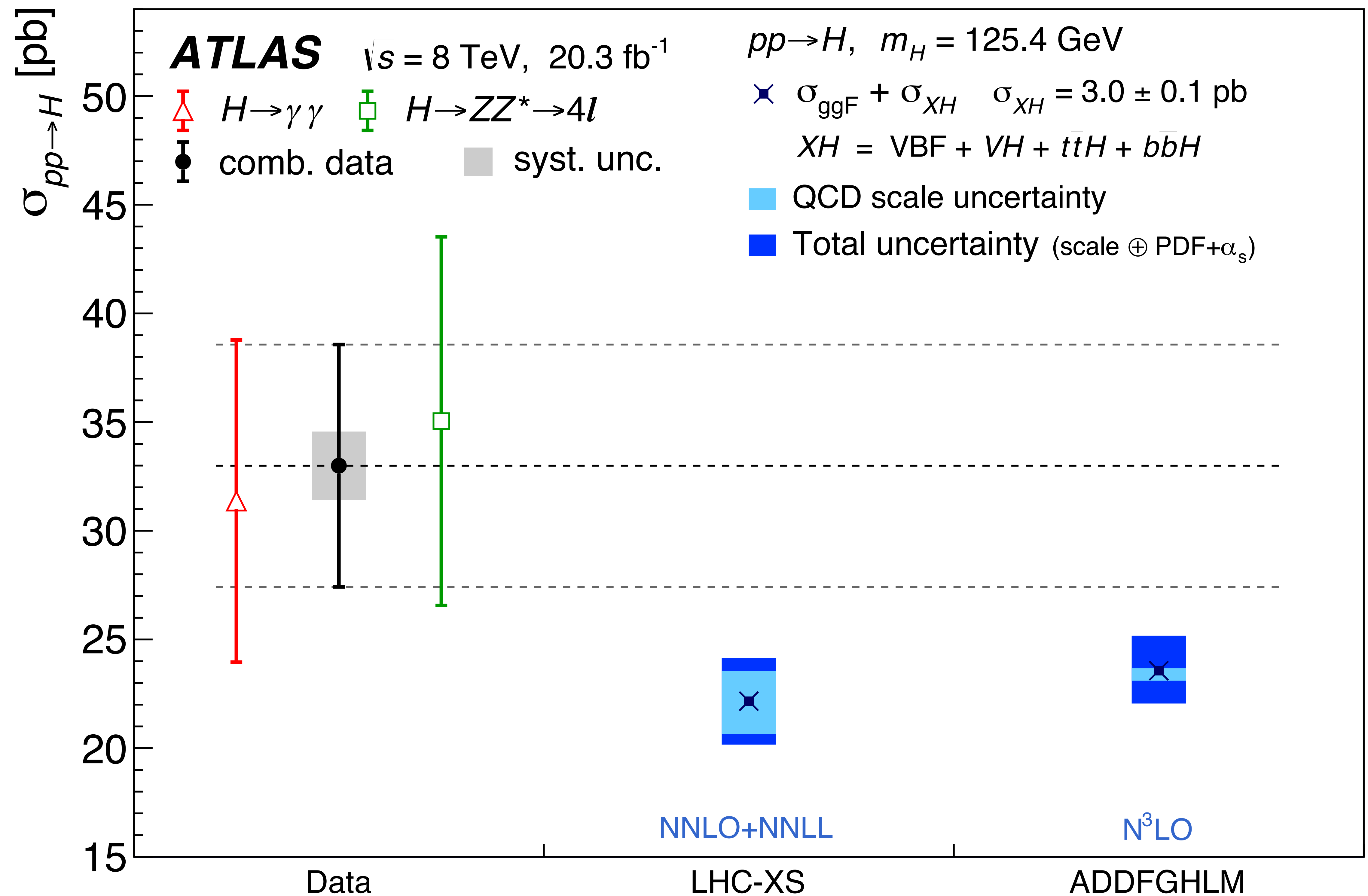


Scale vs. PDF uncertainty



Uncertainties

- Perturbative QCD uncertainties are drastically reduced at N3LO!
- Scale uncertainty negligible compared to PDF + α_S uncertainties at N3LO.
- Other sources of uncertainty could now be of the same size.
    - ➡ Threshold resummation / missing higher orders.
    - ➡ Top-mass corrections.
    - ➡ Electroweak corrections.
    - ➡ Top-bottom interference.

Threshold resummation

- Soft gluon emissions exponentiate in Mellin space!

$$a\,\delta(1-z) + \sum_{k=0}^{5} b_k \left[\frac{\log^k(1-z)}{1-z}\right]_+ \longrightarrow \tilde{a} + \sum_{k=1}^{6} \tilde{b}_k \,\log^k N$$

$$\hat{\sigma}_{gg}^{resum} = g_0(\alpha_s)\,\exp\left[\frac{1}{\alpha_s^2}\sum_{k=1}^{\infty}\alpha_s^k\, g_k(\alpha_s \log N)\right]$$

[Catani, Trentadue; Sterman]

- Resummation functions g_i known up to N3LL (k=4).

[Moch, Vermaseren, Vogt; Bonvini, Marzani; Catani, Cieri, de Florian, Ferrara, Grazzini]

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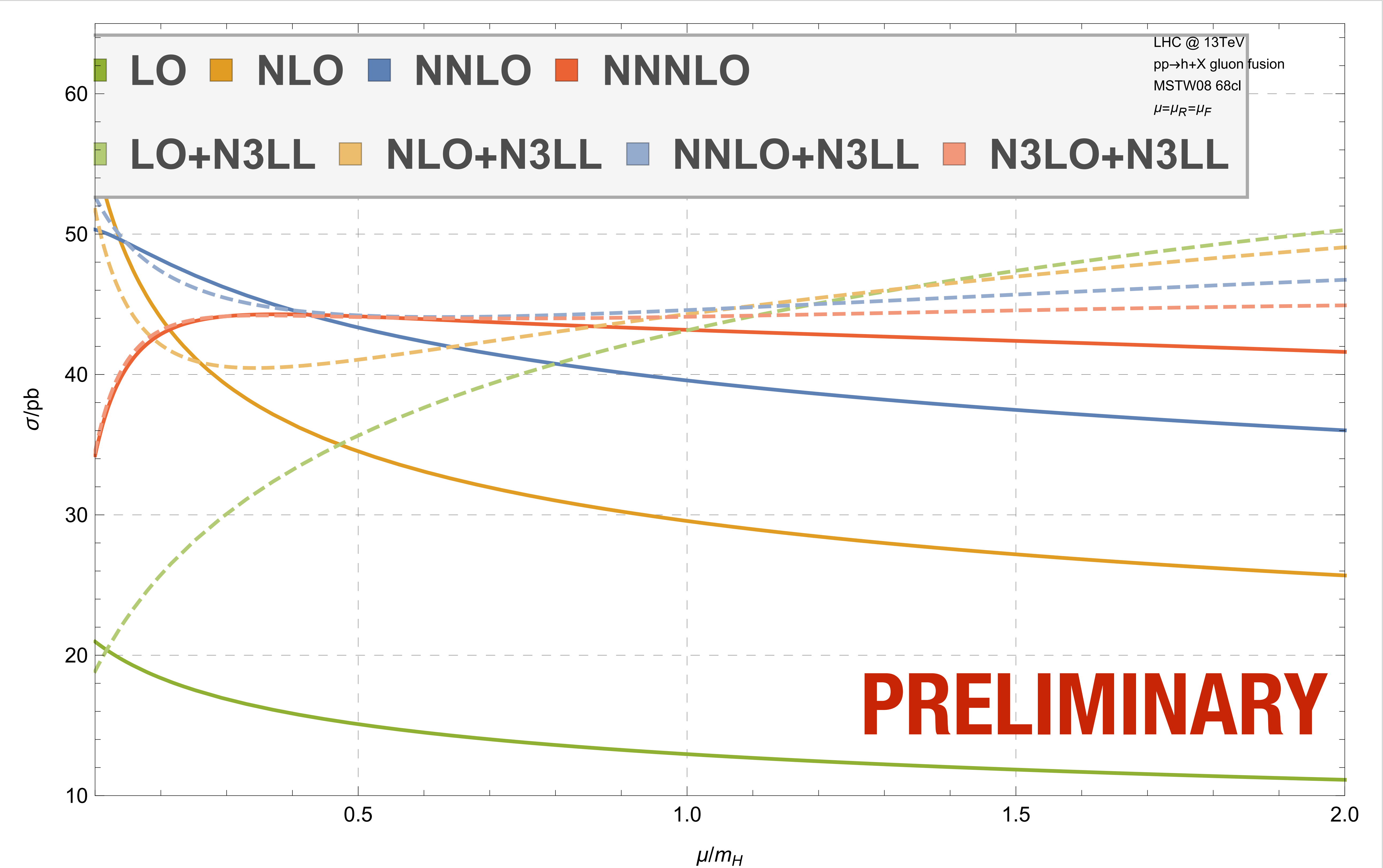
- N3LL resummation needs 4-loop cusp anomalous dimension.
  - ➡ Only known via Pade approximation, assuming Casimir scaling. [Moch, Vermaseren, Vogt]
  - ➡ Casimiar scaling assumption likely to fail at four loops.
  - ➡ Numerical impact small!

N3LL threshold resummation



Scale uncertainty

- $\mu = m_H/2$ seems to be a good scale choice.
  - ➡ Reduced scale uncertainty compared to $\mu = m_H$.
  - ➡ Series seems to converge.
  - ➡ Negligible impact of soft-gluon resummation.
  - ➡ Current recommendation of HXSWG: $\mu = m_H$.
- Scale uncertainty negligible compared to PDF + α_S uncertainties at N3LO.
- We are reaching the point where we should critically assess our method of estimating the uncertainty by scale variation!

Other sources of uncertainties

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

- Finite top-mass effects:
  - ➡ Gives tiny contributions at NNLO.

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- Electroweak corrections:

  ➡ Two-loop corrections partially known.

  [Djouadi, Gambino, Kniehl; Aglietti, Bonciani, Degrassi; Degrassi, Maltoni; Anastasiou, Boughezal, Petriello; Actis, Passarino, Sturm, Uccirati]

  ➡ Leads to a shift in the cross section by a few percent.

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  ➡ Leads to a shift in the cross section by a few percent.

- Top-bottom interference:

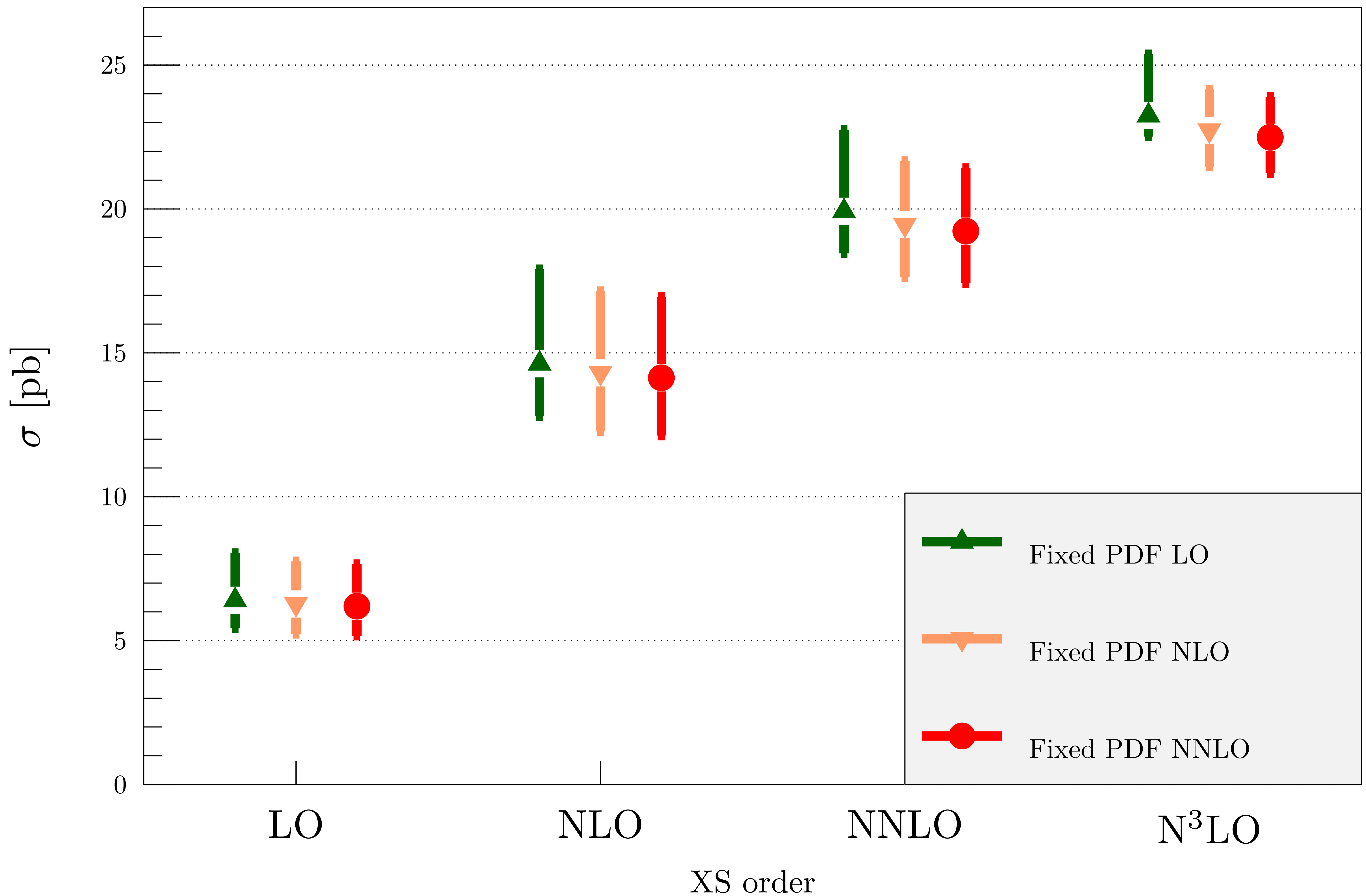
  ➡ Currently unknown beyond NLO, but could give rise to a few percent.

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:
  - ➡ Threshold resummation / missing higher orders.
  - ➡ Electroweak corrections.
  - ➡ Top-mass corrections.
  - ➡ Top-bottom interference.
  - ➡ PDF + α_S uncertainties.

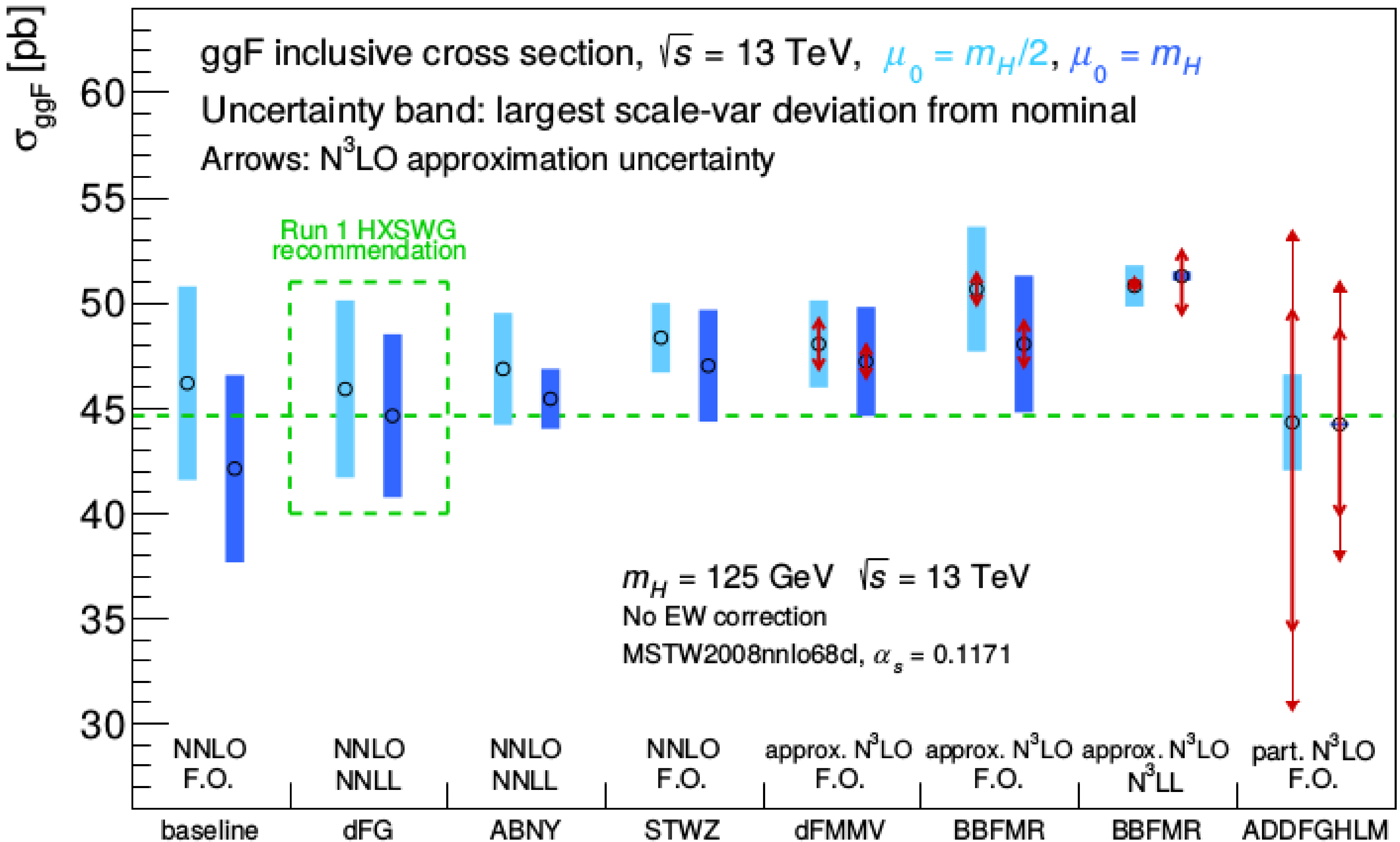
Backup slides

NNLO vs. N3LO PDFs?



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

Comparison to Approximate N3LO



[Plot from HXSWG]

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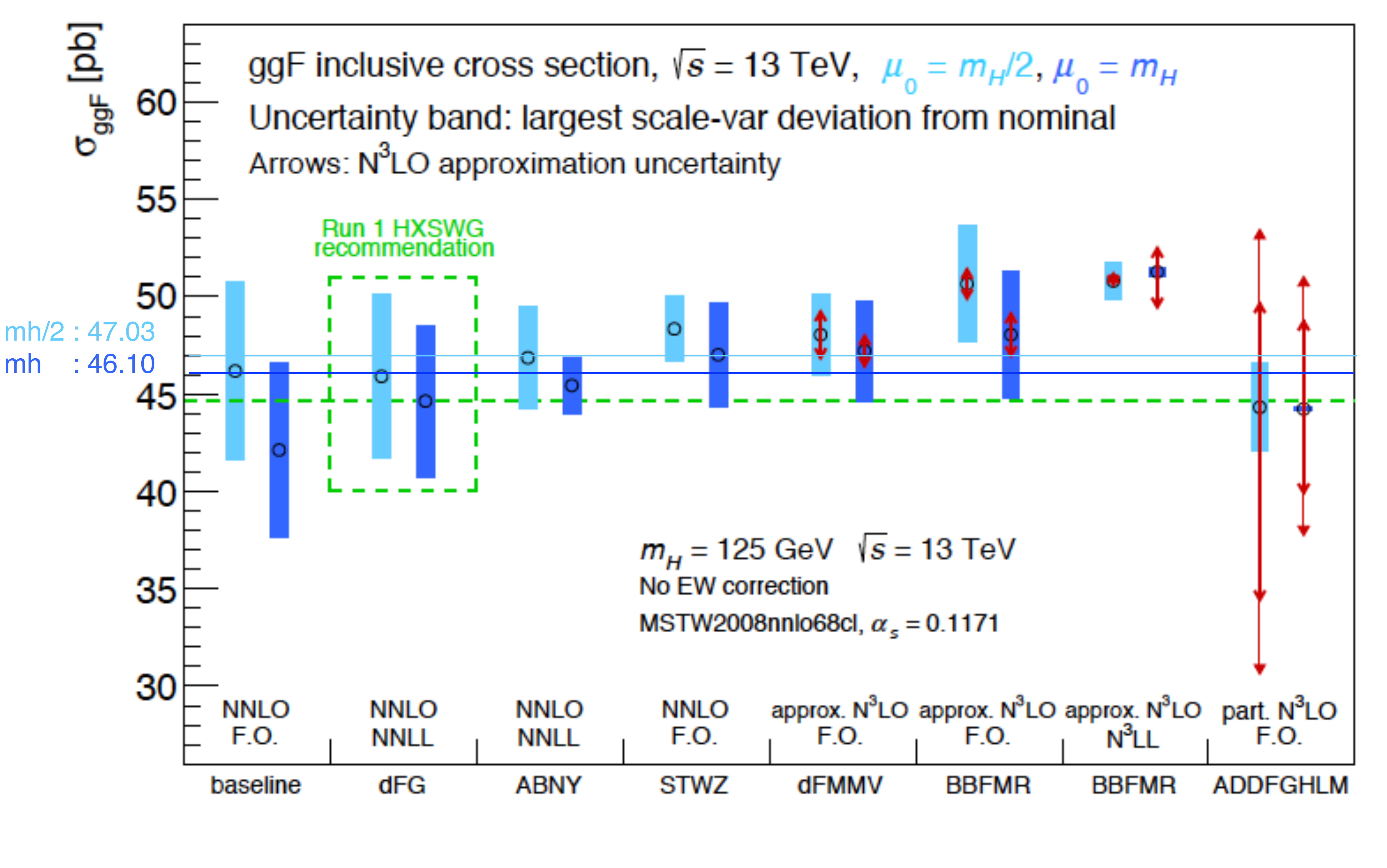

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