Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Institut für Theoretische Teilchenphysik und Kosmologie | RWTH AACHEN UNIVERSITY

Research Training Group Physics of the Heaviest Particles at the LHC | RWTH AACHEN UNIVERSITY

Top-Bottom Interference Contribution to Fully-Inclusive Higgs Production

Based on: [Czakon et al., 2312.09896] and ongoing research

Tom Schellenberger

DIS, April 10, 2023

In collaboration with M. Czakon, F. Eschment, M. Niggetiedt and R. Poncelet

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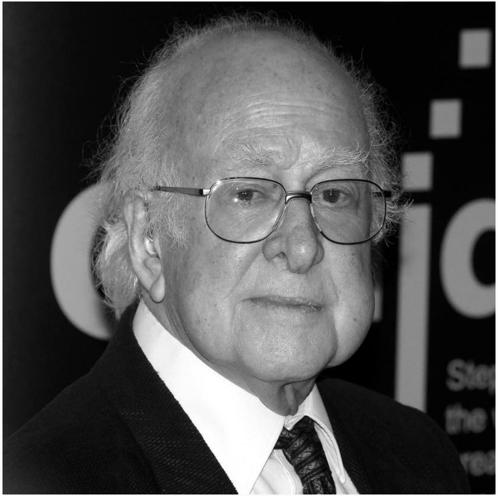
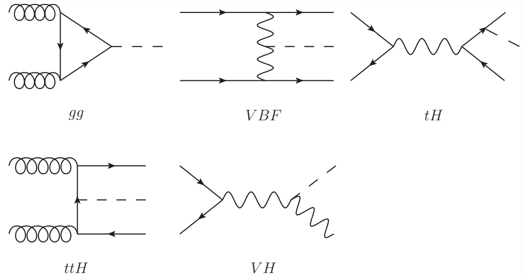


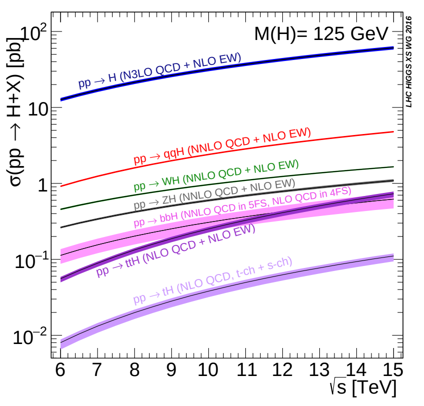
1929-2024

Higgs Production

Motivation

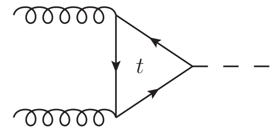
- With the discovery of the Higgs in 2012 we have entered a new era of precision physics.
- We need to know properties of the Higgs very accurately to be able to search for new Physics.
- An important observable here is the Higgs **production cross section**.
- The gluon fusion channel is the most dominant production channel. It is therefore the channel we must determine most precisely.



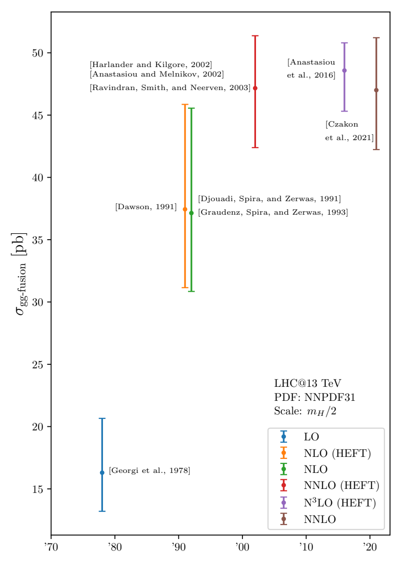


(Florian et al., 1610.07922)

The Gluon Fusion Channel



- gg-fusion receives large correction (∼100% at NLO)



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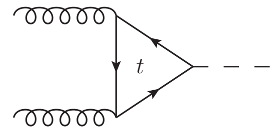
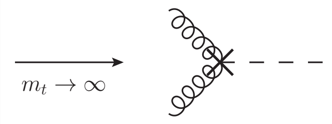
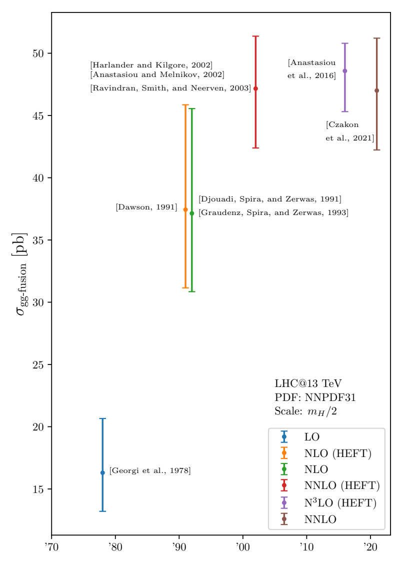




- gg-fusion receives large correction (∼100% at NLO)
- Calculations in full QCD are hard! Instead work in the **Heavy-Top-Limit** (HTL)
- The Heavy-Top-Limit can be improved by rescaling to match the LO predictions: **Higgs-Effective-Field-Theory** (HEFT)

$$\sigma_{\mathsf{HEFT}} = \sigma_{\mathsf{HTL}} \frac{\sigma^{\mathsf{LO}}}{\sigma^{\mathsf{LO}}_{\mathsf{HTL}}}$$

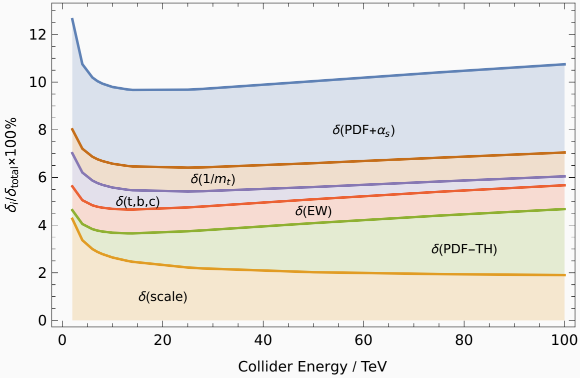
- Effective theory works surprisingly well given $\frac{m_H^2}{4m_t^2} = 0.13 \ll 1$ is rather poor approximation



The Gluon Fusion Channel

- Current state of the art for gluon fusion in HEFT is **N3LO** (Anastasiou et al., 1602.00695).

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}(+4.56\%)}_{-3.27\,\text{pb}(-6.72\%)}\,(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\,(\text{PDF} + \alpha_s)$$



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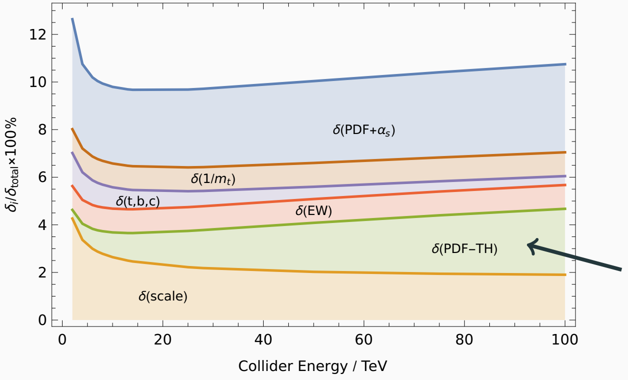

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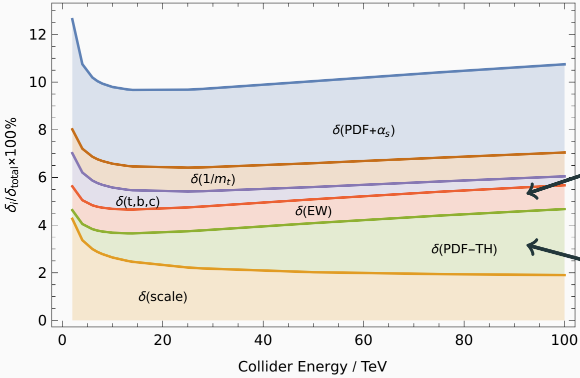

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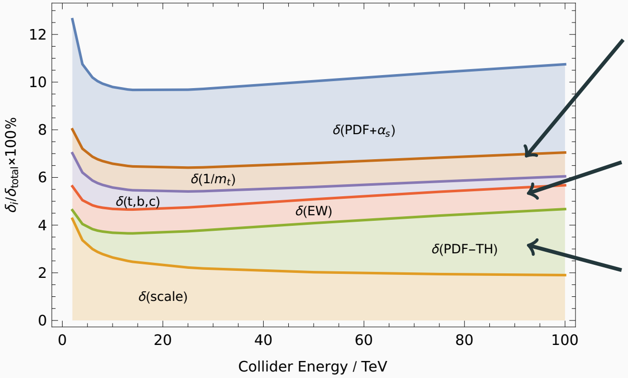

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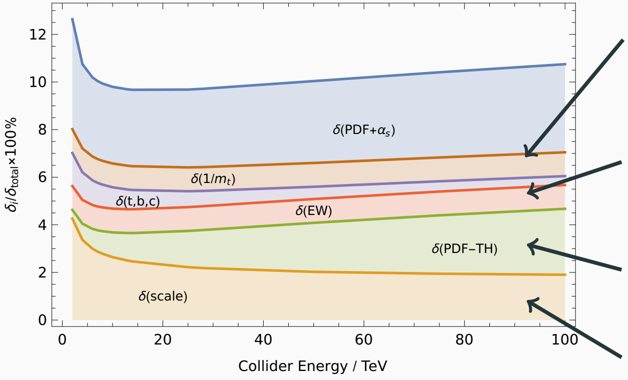

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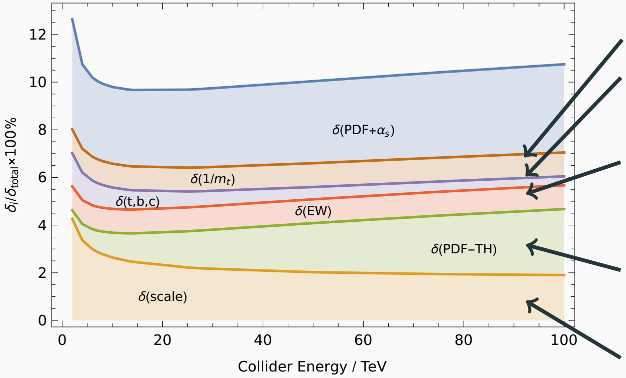

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Our Goal: Finite b- and c-mass effects

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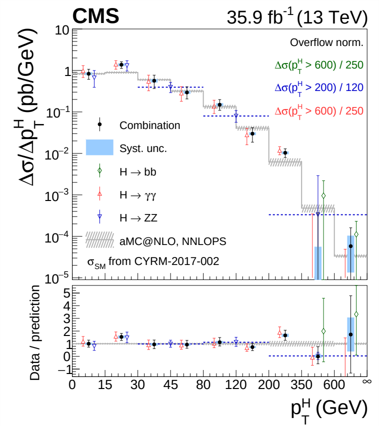
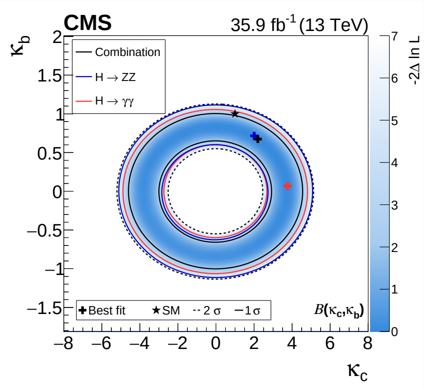
Yukawa-Couplings



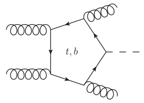


(Sirunyan et al., 1812.06504)

- Higgs-p_T and -rapidity distributions can be used to measure the couplings to the lighter quark flavors (b,c)
- Measuring the charm-quark Yukawa coupling could become possible with HL-LHC

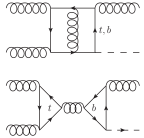
Computation

Real-Real



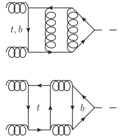
- Easy, since one-loop
- We use `MCFM` (Budge et al., 2002.04018)

Real-Virtual



- Mixed contributions factorize
- Use differential equations and solve the rest numerically

Virtual-Virtual



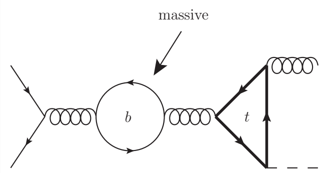
- Use deep expansion of the Higgs-gluon form factor (Czakon and Niggetiedt, 2001.03008) (Niggetiedt and Usovitsch, 2312.05297)

Phase-Space Integration

- Use MC-techniques to perform phase-space integration
- Infrared divergences are dealt with using `Stripper` – our in-house C++ implementation of the sector improved residue subtraction scheme (Czakon, 1005.0274)

Flavor-Schemes

- Care must me taken to have a consistent picture of heavy quarks!



$$\xrightarrow{m_b \to 0} \ln m_b^2$$

Mass divergence!

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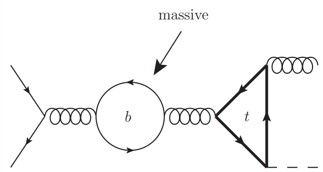
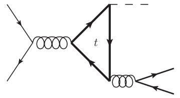


$\xrightarrow{m_b \to 0} \ln m_b^2$ **Mass divergence!**

4 Flavor-Scheme (4FS)

- Consistently treat bottom-quark as massive
- Exclude bottom-quark from initial state
- Also consider massive b-quark radiation



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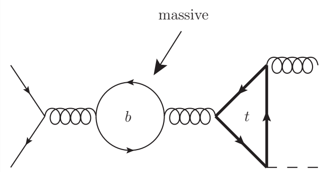

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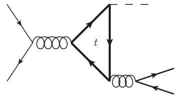


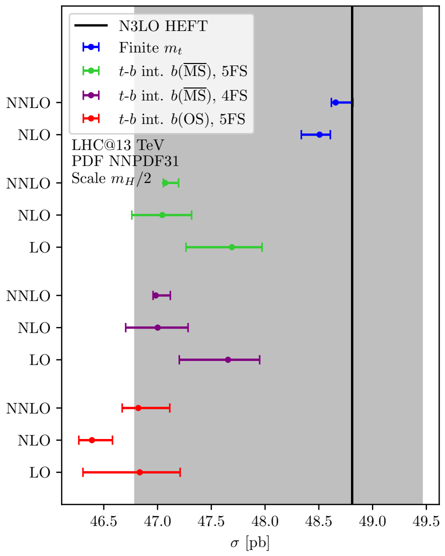
...

5 Flavor-Scheme (5FS)

- Treat bottom-quark as a massless particle
- Except for closed fermion loops that couple to the Higgs
- Equivalent to a theory with replica b-quark
  - → Gauge invariant
  - → Divergences cancel

Results

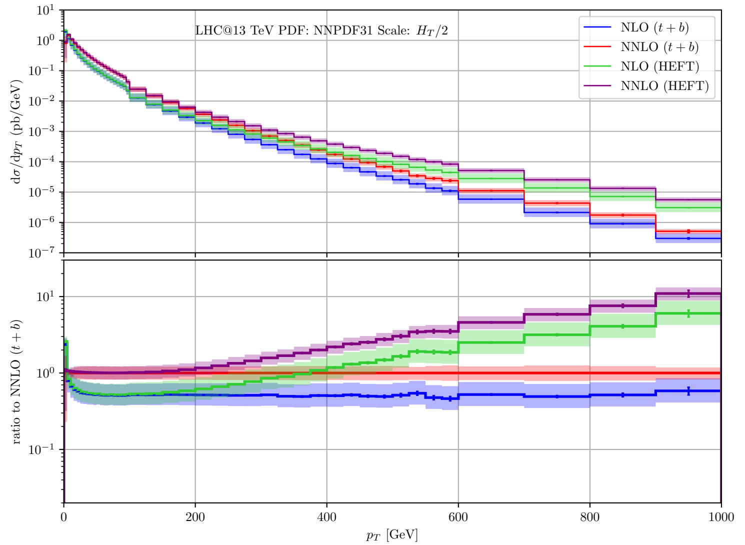
Fully-Inclusive Cross Sections



Preliminary

- On-Shell scheme result shows **increased** scale uncertainties
- $\overline{\text{MS}}$ scheme shows better convergence
- 4FS and 5FS show very good agreement, justifying the treatment of the bottom-quark mass in the 5FS.

p_T-distributions

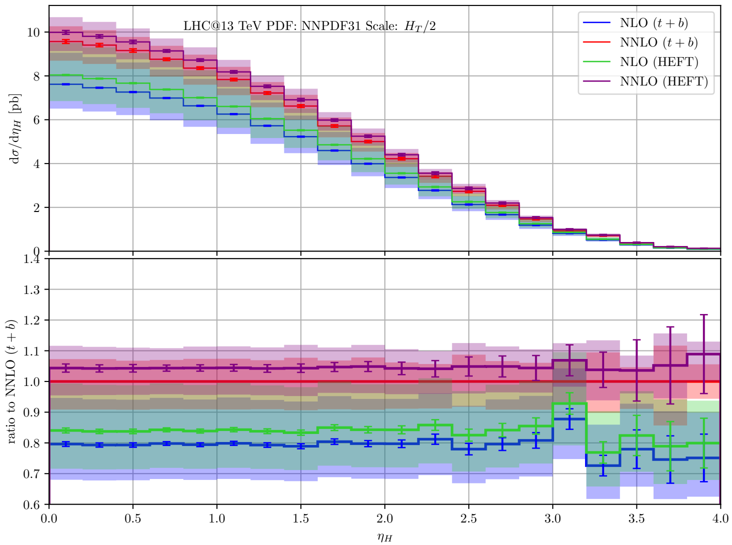


Preliminary

$b(\overline{\text{MS}})$, 5FS

- Notice the different scaling behavior of the HEFT $(p_{T,H}^{-2})$ and full QCD $(p_{T,H}^{-4})$ result (Greiner et al., 1608.01195).
- Good agreement with existing data (Lindert et al., 1703.03886), (Jones, Kerner, and Luisoni, 1802.00349)

Rapidity-distributions



Preliminary

$b(\overline{\text{MS}})$, 5FS

- Finite Quark mass effects are have less pronounced features for the rapidity distributions.
- Less sensitive for fitting to Yukawa couplings. This was already noticed at LO (Soreq, Zhu, and Zupan, 1606.09621)

Conclusions

Conclusions

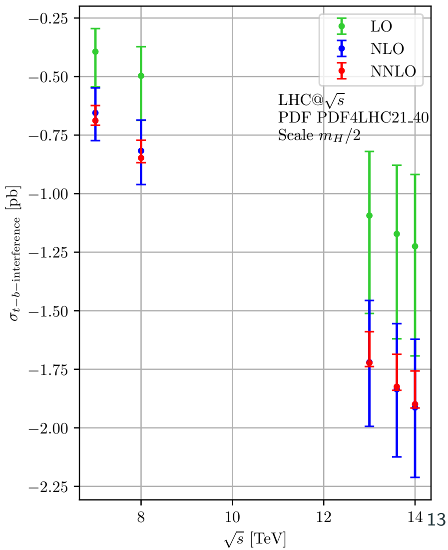
- Including finite quark mass effects for the Higgs-production cross section is crucial for precision physics at the LHC
- The $\overline{\text{MS}}$-scheme shows generally a better perturbative convergence
- The 4FS and 5FS showed very good agreement, i.e. the treatment of the bottom quark as a massless particle is justified

LHC@13 TeV, PDF NNPDF31, Scale $m_H/2$

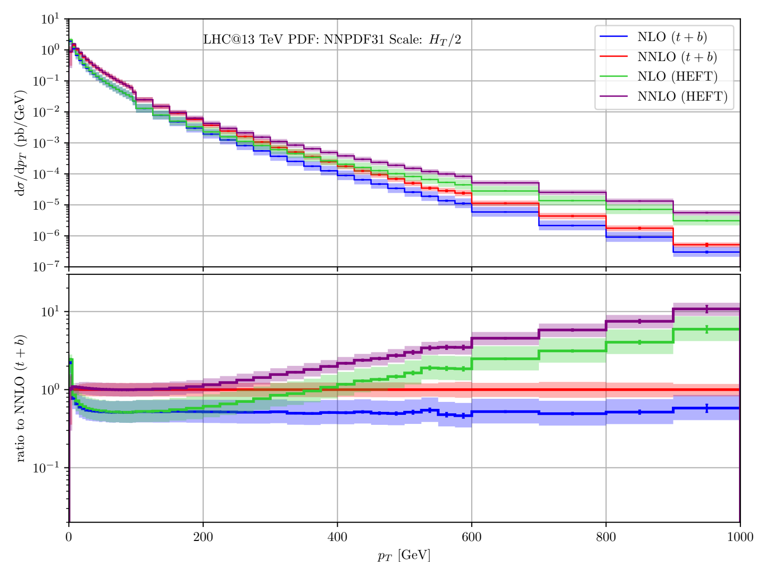
Preliminary

$$\sigma_{gg-\text{fusion}} = \underbrace{48.81^{+0.65}_{-2.02}}_{\text{HEFT}} \underbrace{-0.16^{+0.13}_{-0.03}}_{\text{finite } t} \underbrace{-1.74^{+0.13}_{-0.01}}_{t-b \text{ int.}} \text{ pb}$$

- $m_b(m_b) = 4.18$ GeV
- $m_t = 173.05$ GeV
- $m_H = 125$ GeV



p_T-distributions (OS, 5FS)



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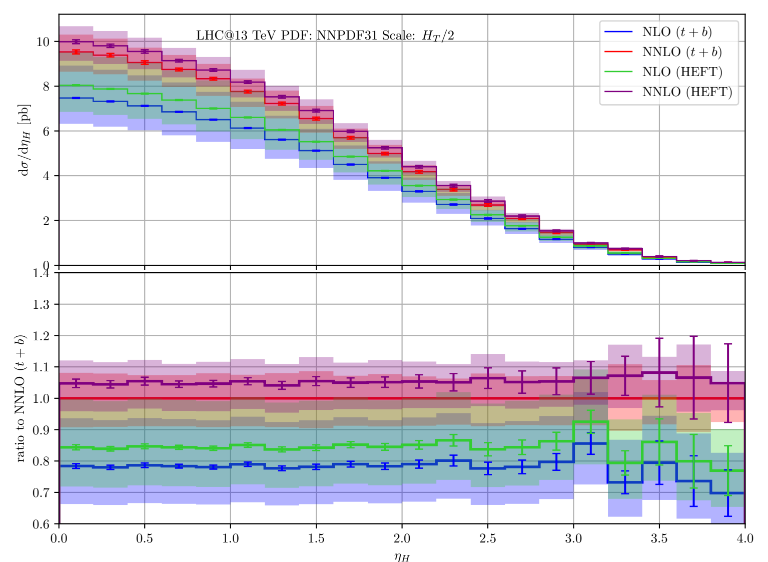
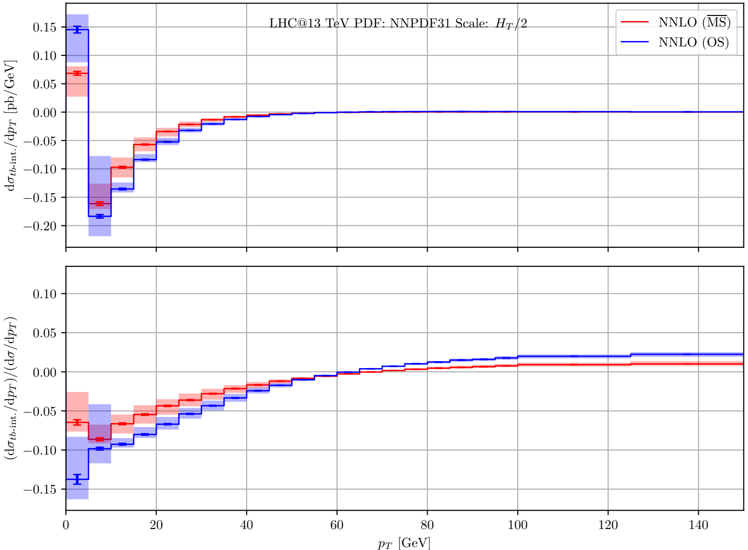


Top-Bottom Interference p_T-Distribution



Top-Bottom Interference Rapidity-Distribution