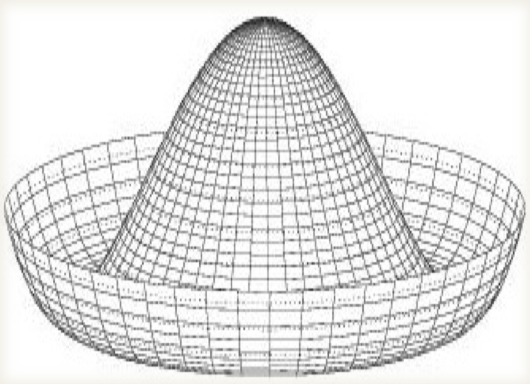
HIGGS PRECISION PHYSICS



LHCP, 2020
S. Dawson, BNL
May, 2020

Is there physics beyond the SM?

- To the best of our knowledge…. The Higgs has no structure, no charge, no spin
- We know that the Higgs couples to fermions and gauge bosons at the 10-20% accuracy level
- We postulate that the Higgs interactions come from a scalar potential:

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

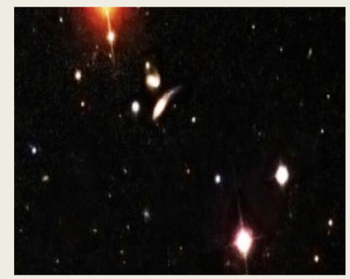
- The potential could just as easily be an effective theory:

$$V \to -\frac{M_H^2}{2} H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

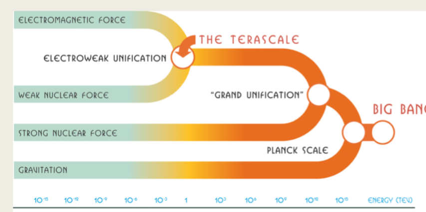
Must measure $\lambda_3 = \frac{M_H^2}{2v} = .13v$

Why might new physics hide in Higgs sector?

- Many *unanswered questions*: dark matter, the pattern of fermion masses (including neutrinos), baryogenesis, strong CP violation, EW hierarchy….
- Why does the SM only have one Higgs doublet?
  - *No good answer to this question*



- Higgs can be portal to dark matter
  - *Motivates models with extra Higgs gauge singlet*
- Higgs models can be constructed to have flavor violation such as $H \rightarrow \mu e$
  - *Motivates 2HDM type models*



All of these can change Higgs properties and be a window to high scale physics

Higgs physics is a tool for exploration

- Precision measurements
  - *Requires precise SM calculations*
  - *Requires precise effective field theory calculations*
  - *Precision constraints on Higgs properties*
  - *Precision constraints on new interactions*
- Searches for new Higgs particles
  - *Model specific*
  - *Arbitrary, but can yield stringent bounds*

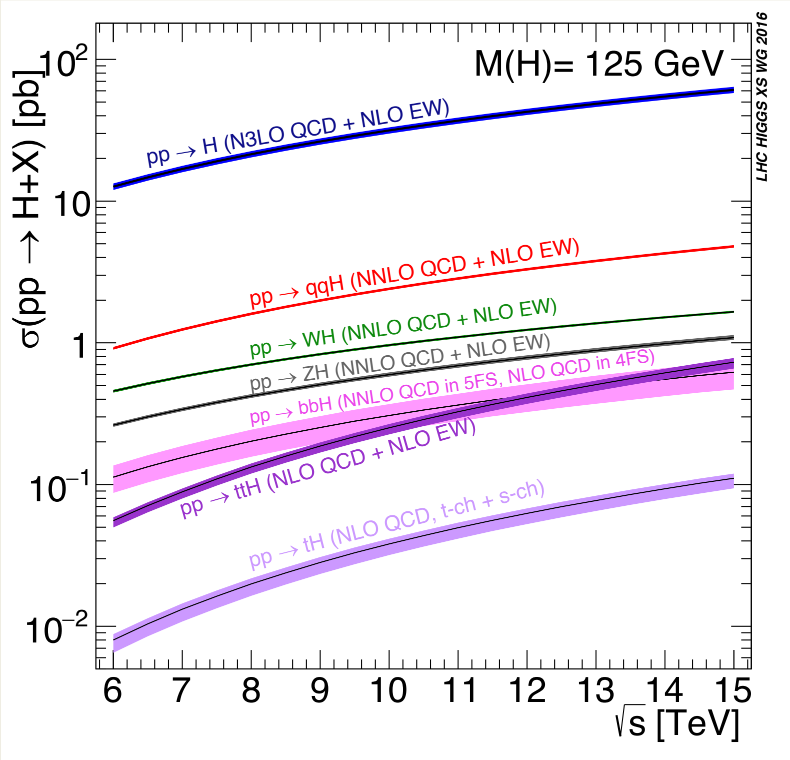
Both approaches are necessary: Today's talk will focus on progress in theoretical calculations of differential Higgs rates

Precision calculations for Higgs physics

- We know SM Higgs rates at NNLO QCD or further in perturbation theory (except ttH)
- We know SM Higgs rates at NLO+EW in perturbation theory
- High statistics from future LHC runs allows for precision measurement of distributions
  - *Need NLO (and higher) for both signal and background*
  - *Need to understand (and reduce) theoretical uncertainties*
- Much recent progress in precision calculations of Higgs properties
  - *Progress: differential rates at NNLO and top mass effects*
  - *Progress: connecting SM differential rates with EFT predictions*

SM Higgs

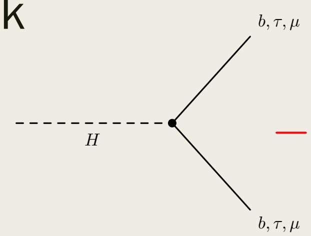
- Total cross sections well known
- Most cross sections to NNLO, with NLO EW
- Goal is to use these measurements to extract couplings, particularly couplings to b and t
- Many models have anomalous couplings to only 3[rd] generation



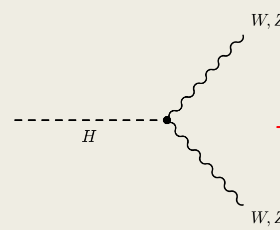
Total cross sections don't tell the whole story

Extracting Information from Higgs Measurements

- First approach is arbitrary modification of Higgs couplings
- Scaling factors κ multiply SM contributions by a constant
- In general, cannot consistently include higher order corrections in κ framework



$$-i\frac{m_f}{v}\kappa_f$$



$$-2i\frac{M_V^2}{v}g^{\mu\nu}\kappa_V$$

In the SM, gauge invariance requires κ=1

Need a comparison framework for SM

- Effective field theory extends SM Lagrangian
  - *Assume 1 Higgs doublet, SU(3) x SU(2) x U(1) symmetry, dimension 6 operators only, only SM particles*
- Expansion in (Energy)$^2/\Lambda^2$

$$L \rightarrow L_{SM} + \Sigma_i \frac{C_{6i}}{\Lambda^2} O_{6i} + \Sigma_i \frac{C_{8i}}{\Lambda^4} O_{8i} + \ldots$$

  - *Expect enhanced effects in tails of distributions*
- Global fits include LEP precision data, VV production, Higgs data, top data
  - *Effective field theory connects different processes with large correlations*
  - *Precision requires a complete set of operators, not just one at a time*

Gluon fusion is largest Higgs rate

- Calculation of Higgs production to NNNLO required:
  - *New analytic techniques*
  - *New computational techniques*
  - *Surprisingly large corrections to gluon fusion production:*

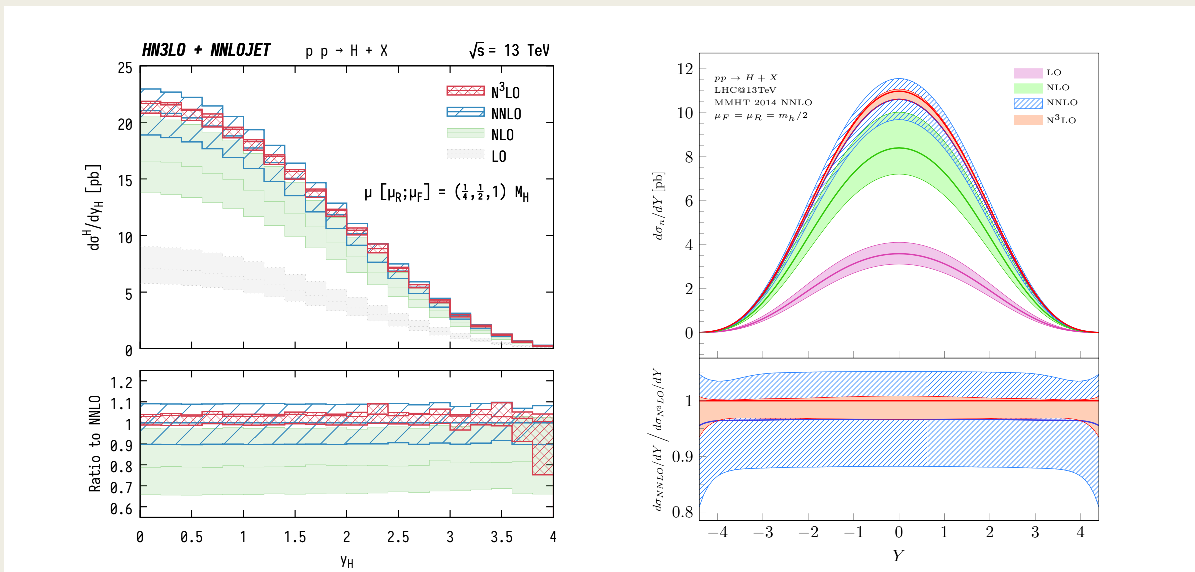
LO → NLO → NNLO → NNNLO

100% increase | 20% increase | 3% increase

1977 → 1991 → 2002 → 2015

Progress in distributions

- Gluon fusion rapidity distribution to N^{3}LO
- Rapidity distribution to N^{3}LO is perturbatively stable

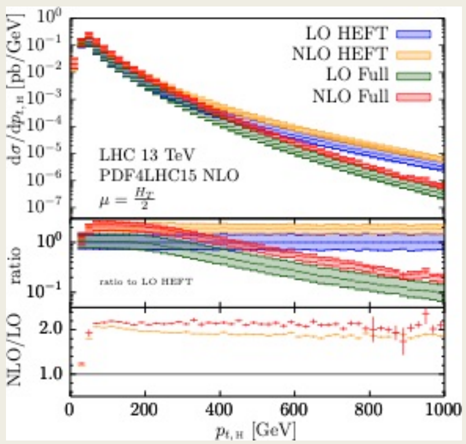


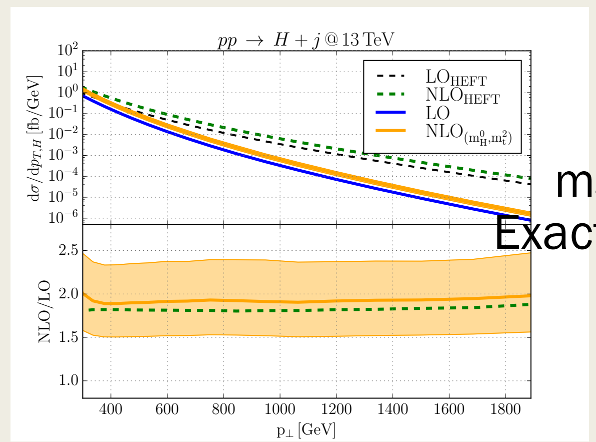
Distribution looks relatively flat with respect to NNLO

Cieri, Chen, Gehrmann, Glover, Huss: arXiv1807.11501
Dulat, Mistlberger, Pelloni: arXiv1810.09462

Higgs plus jet

- NLO Higgs p_T spectrum including all top mass effects





$m_t \to \infty$

Exact m_t dependence

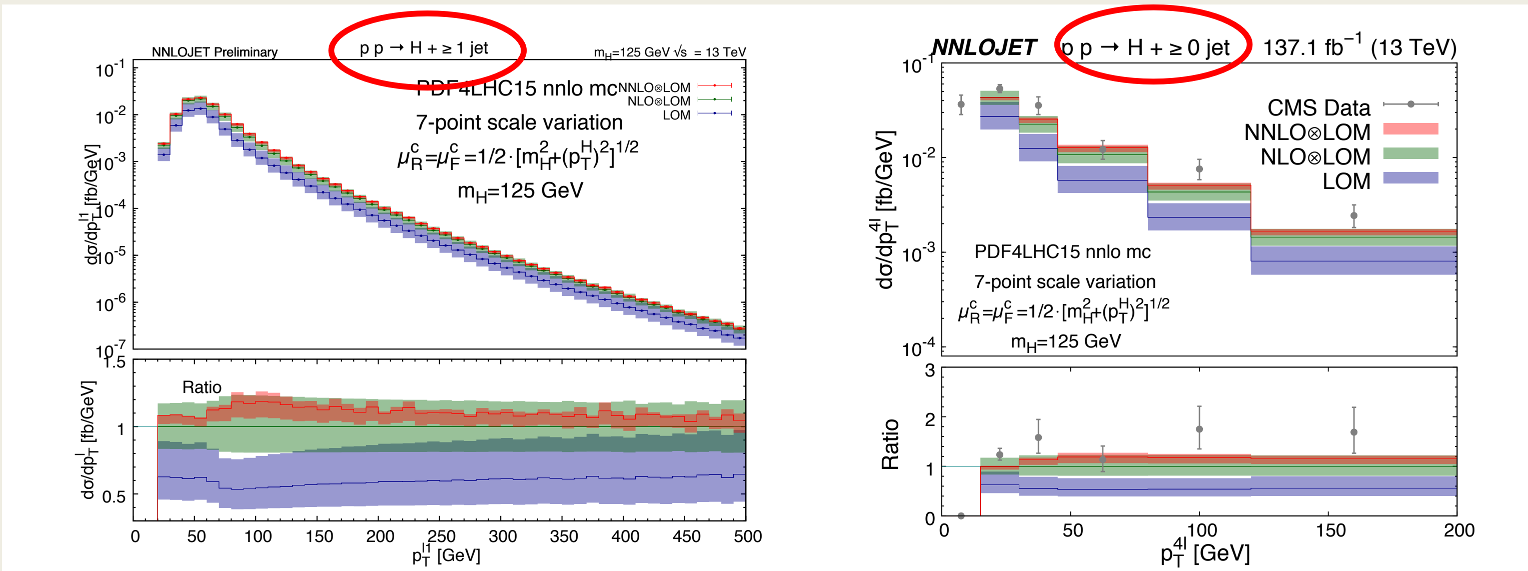
Understanding top mass effects

Kudashkin, Lindert, Melnikov, Wever: arXiv:1801.08226

Jones, Kerner, Luisoni: arXiv:1802.00349

Differential predictions for pp→H+jet →4l +jet

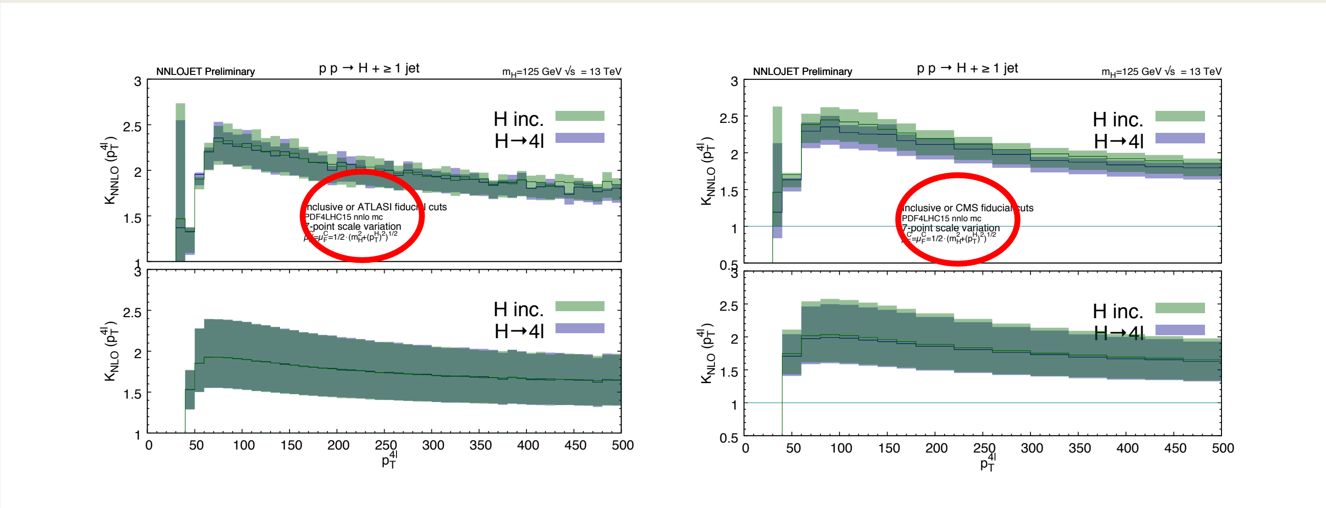
- NNLO QCD for 2 to 2 process: At theory forefront for distributions



Chen, Gehrmann, Glover, Huss: arXiv:1905.13738 *See Chen parallel talk

Differential predictions for pp→H+jet →4l +jet at NNLO

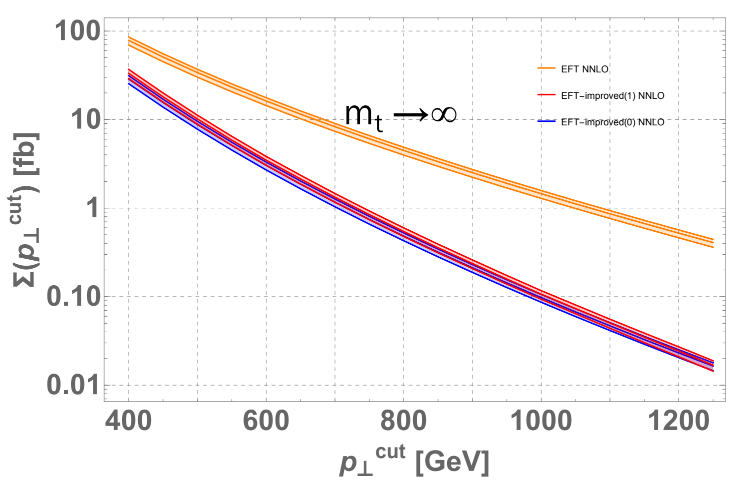
- CMS: ~9% difference between fiducial and inclusive K factors
- (Attributed to different lepton isolation algorithm than ATLAS)

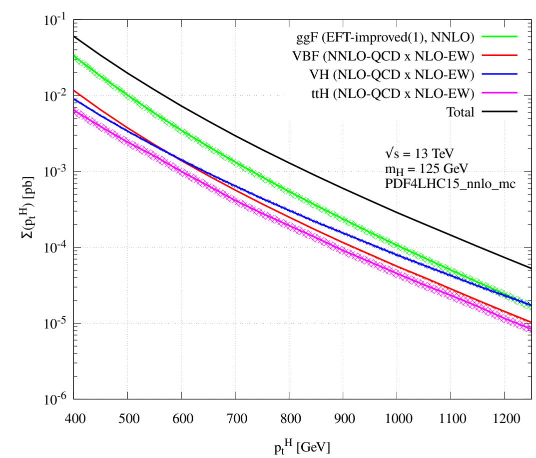


Chen, Gehrmann, Glover, Huss: arXiv:1905.13738

Gluon fusion in boosted regime: H+ ≧ 1 jet

- Combine full NLO calculation with NNLO in $m_t \to \infty$ for H+ ≧1 jet
- Cumulative cross sections for $p_{tH} > p_t^{cut}$





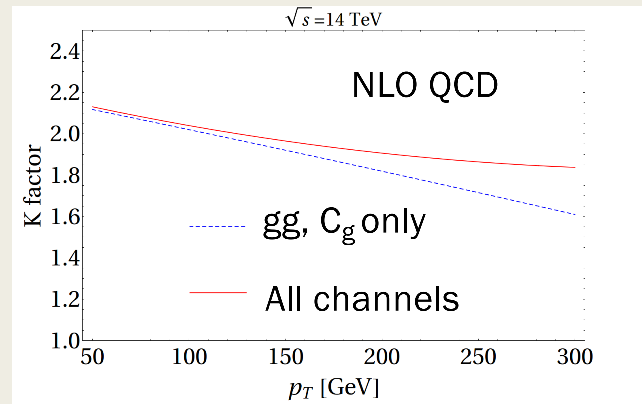
In tails, not only gg is important

Combination: Becker, Caola, Massironi, Massironi, Mistlberger, Monni: arXiv:2005.07762

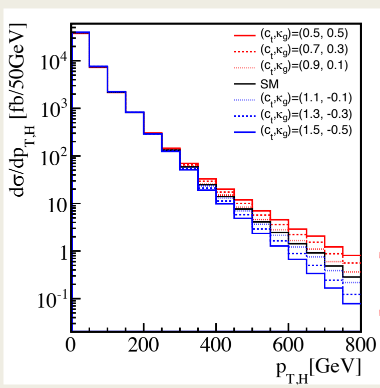
EFT operators change kinematic distributions

$$L_{eff} = L_{SM} + C_g \frac{\alpha_s}{12\pi} \frac{H}{v} G_{\mu\nu^A} G^{A,\mu\nu} - \delta Y_t m_t \frac{H}{v} \bar{t} t$$

- Small effects in tails of distributions
- Compare SM predictions with NLO rate in EFT



Higgs plus jet production at 14 TeV



New physics

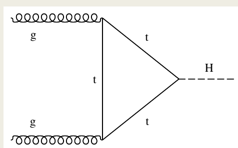
- Distributions can separate sources of new physics

Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant, arxiv:1405.4295
Dawson, Lewis, Zeng, arXiv:1409.6299

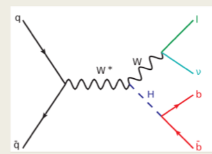
*details in Muhlleitner talk

Measuring the b quark Yukawa

- Higgs coupling to b's enhanced in many BSM models (e.g., 2HDM with large tan β)



Indirectly sensitive to t, b Yukawas



Directly sensitive to b Yukawa with H⟶bb

- Measurement of pp⟶ WH, H⟶ bb is at large p_{TW}

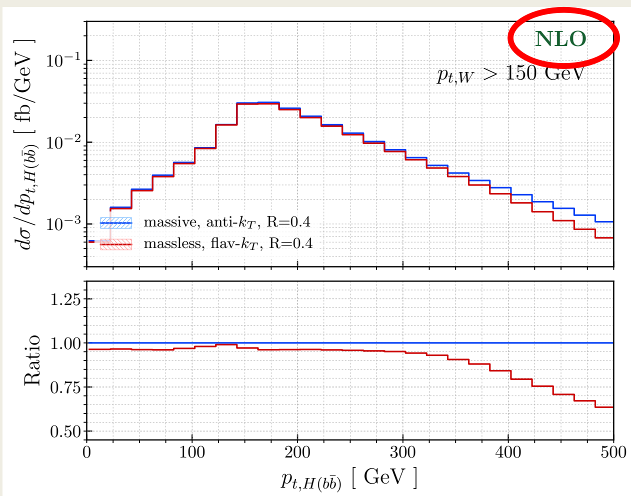
		σ_{fid} (fb)	σ_{fid} (p_{tW}>150 GeV) (fb)
LO	m_b=0	$22.623^{+.845}_{-1.047}$	$3.735\text{-}^{+.000}_{-.016}$
	m_b	$22.501^{+.796}_{-1.007}$	$3.638^{+.000}_{-.009}$
NLO	m_b=0	$25.364^{+.778}_{-.756}$	$4.586^{+.158}_{-.141}$
	m_b	$24.421^{+.853}_{-.879}$	$4.333^{+.165}_{--.154}$
NNLO	m_b=0	$24.225^{+.642}_{-.742}$	$4.530^{+.071}_{-.096}$
	m_b	$22.781^{+.791}_{-.898}$	$4.207^{+.097}_{-.116}$

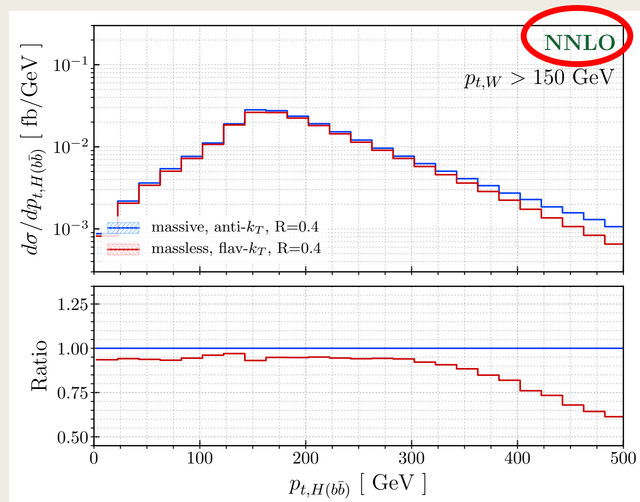
b mass effects important

Behring, Bizon, Caola, Melnikov, Rontsch, arXiv:2003.08321

Boosted Higgs in WH at NNLO

- pp⟶ WH, H⟶ bb at NNLO including b mass effects
- O(5%) effects from b mass in tails of distributions (just where you expect new physics)



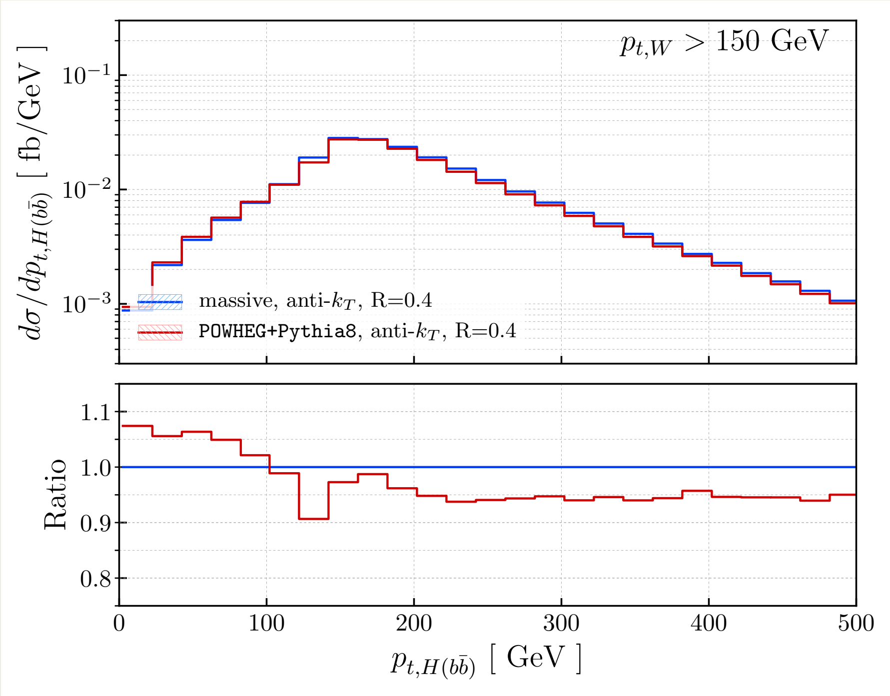


Ratio to massless case

Behring, Bizon, Caola, Melnikov, Rontsch: arXiv:2003.08321

Boosted Higgs in WH at NNLO

- Compare fixed order calculation with NLO POWHEG results for p_{tH} distribution:
  - O(5%) effects
  - At high p_T, POWHEG undershoots NNLO m_b result

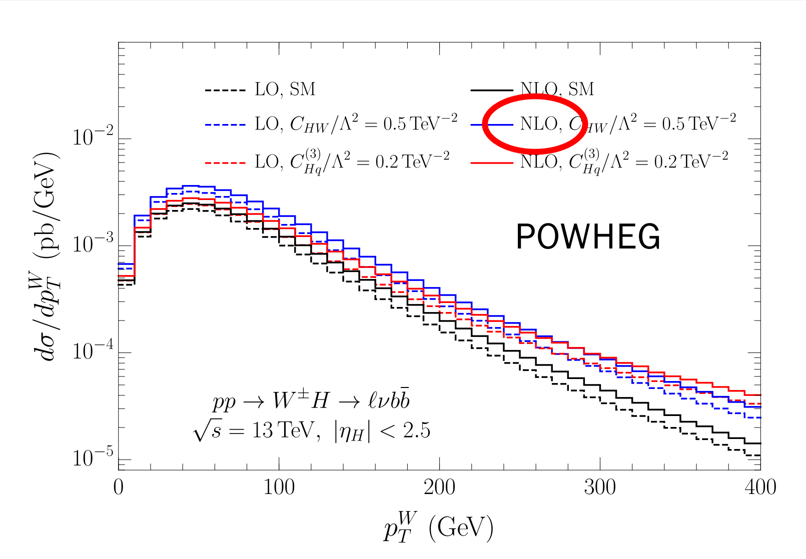


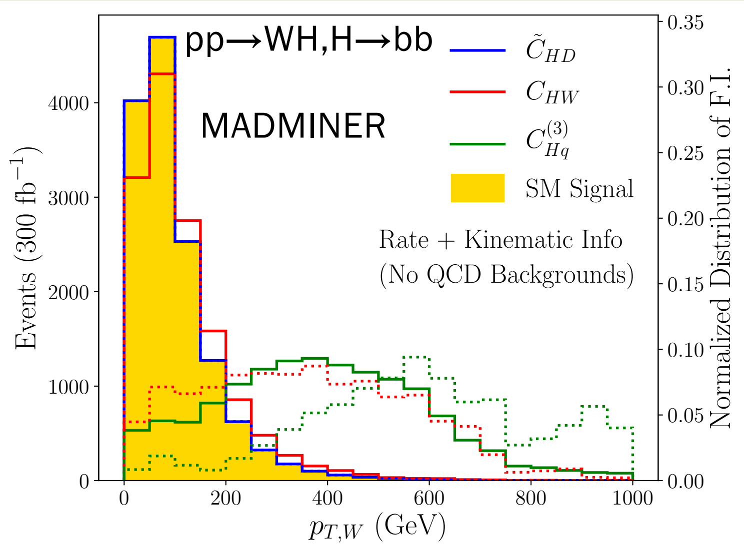
NNLO

Behring, Bizon, Caola, Melnikov, Rontsch: arXiv:2003.08321

Using differential information from WH

- Compare SM at high p_T with EFT predictions: Understanding SM at high p_T is crucial



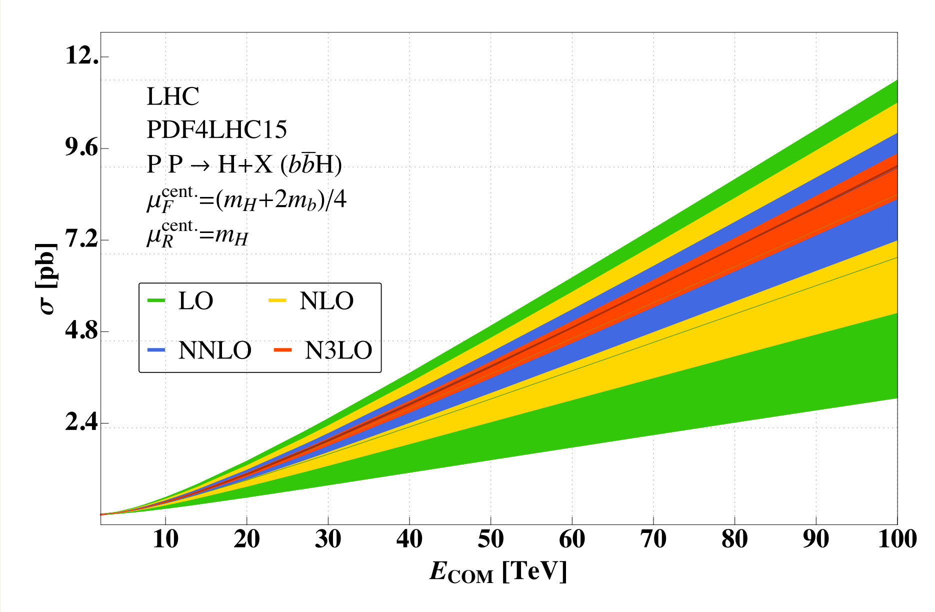


- Automated tools available for NLO EFT Madgraph5 aMC@NLO

Baglio, Dawson, Homiller, Lane, Lewis: arXiv:2003.07862;
Alioli, Dekens, Girad, Mereghetti: arXiv:1804.07407;
Brehmer, Dawson, Homiller, Kling, Plehn: arXiv:1908.06980

Looking for b Yukawa from bbH

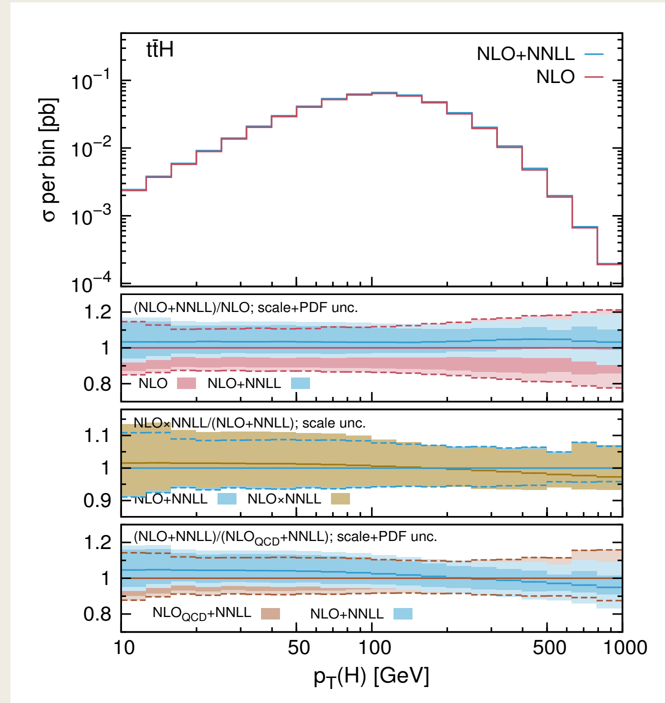
- Long history of calculations in both 4 and 5 flavor number scheme
- Total cross section for bb⟶H known at N^{3}LO QCD shows calculation well understood
- New NLO EW+QCD differential calculation in 4FNS for bbH (including ZH, and ggF +bb topology) has discouraging conclusion about measuring b Yukawa from bbH



Duhr, Dulat, Hirschi, Mistlberger: arXiv:2004.04752
Pagani, Shao, Zaro: arXiv:2005.10277

Looking for t Yukawa from ttH

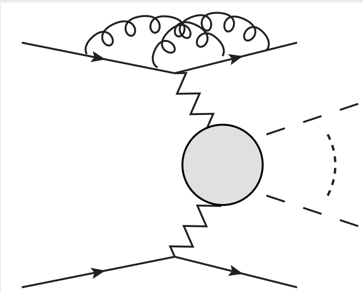
- Top Yukawa indirectly measured in gluon fusion, but ttH is cleaner determination
  - *Gluon fusion can have EFT contributions that are not top Yukawa modifications*
- ttH QCD and EW NLO results long known, inclusion of NNLL reduces scale uncertainty



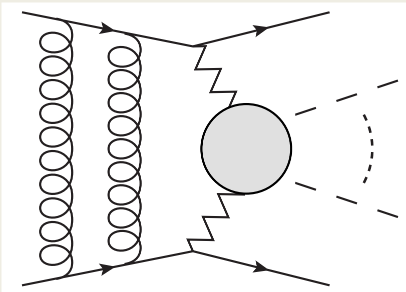
Broggio, Ferroglia, Frederix, Pagani, Pecjak,Tsinikos: arXiv:1907.04343

Progress on VBF

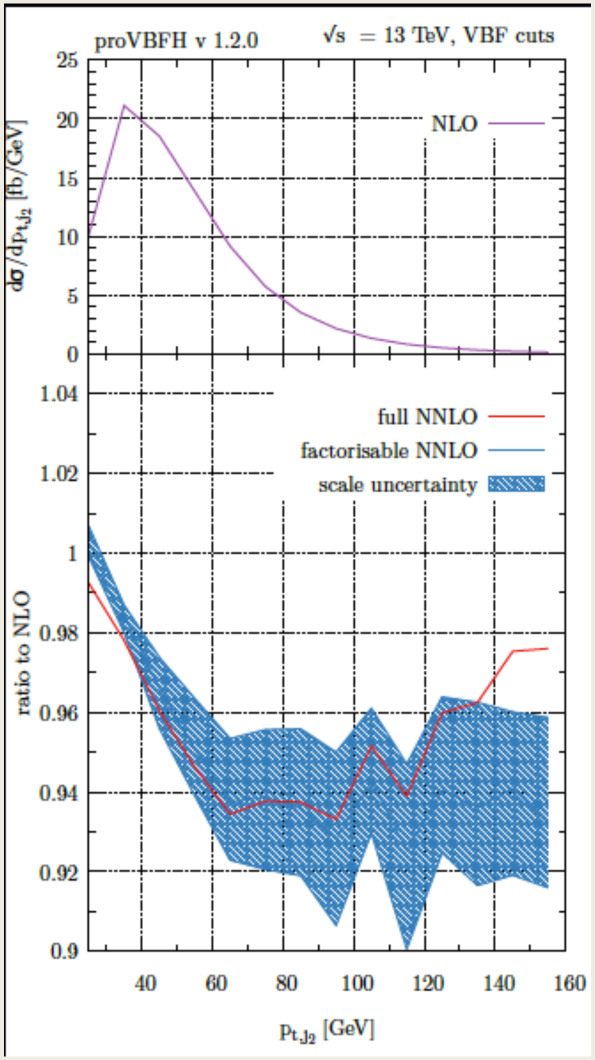
- Combining factorizable and non-factorizable contributions at NNLO
- Non-factorizable contributions may be relevant at high p_T, but more work needed on validity of Eikonal approximation in this region



Factorizable



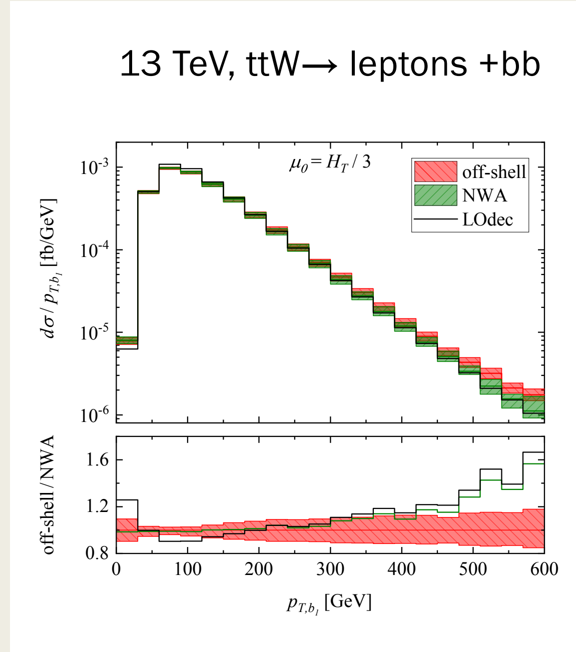
Non-Factorizable



Dreyer, Karlberg, Tancredi: arXiv:2005.11334

Progress in calculating backgrounds too

- New calculation of ttW at NLO QCD including off-shell top effects
  - *ttW+jets is a significant background for ttH production*
  - *Motivated by some theory/experimental discrepancies*
- Found significant effects from off-shell top in tails of distributions

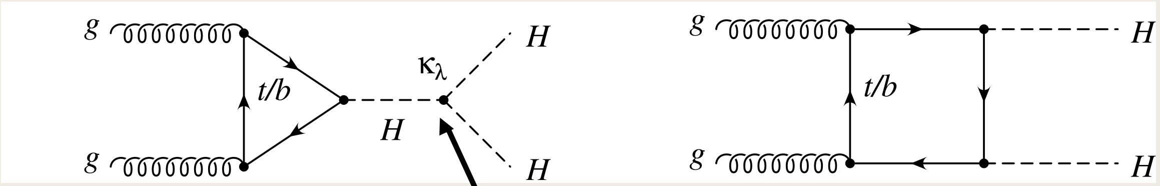


*See Bevilacqua parallel talk for details

Bevilacqua, Bi, Hartano, Kraus, Worek: arXiv:2005.09427

Higher order corrections to HH distributions

- HH first occurs at one-loop



Goal: Measure $\lambda/\lambda_{SM}=\kappa_\lambda$

- Large cancellation between diagrams
- Reduces sensitivity to HHH coupling
- Very small rate at LHC

NLO QCD is 2 loop with ~ scales: s, m_t, M_H

Measurement of Higgs tri-linear coupling necessary to confirm structure of Higgs potential

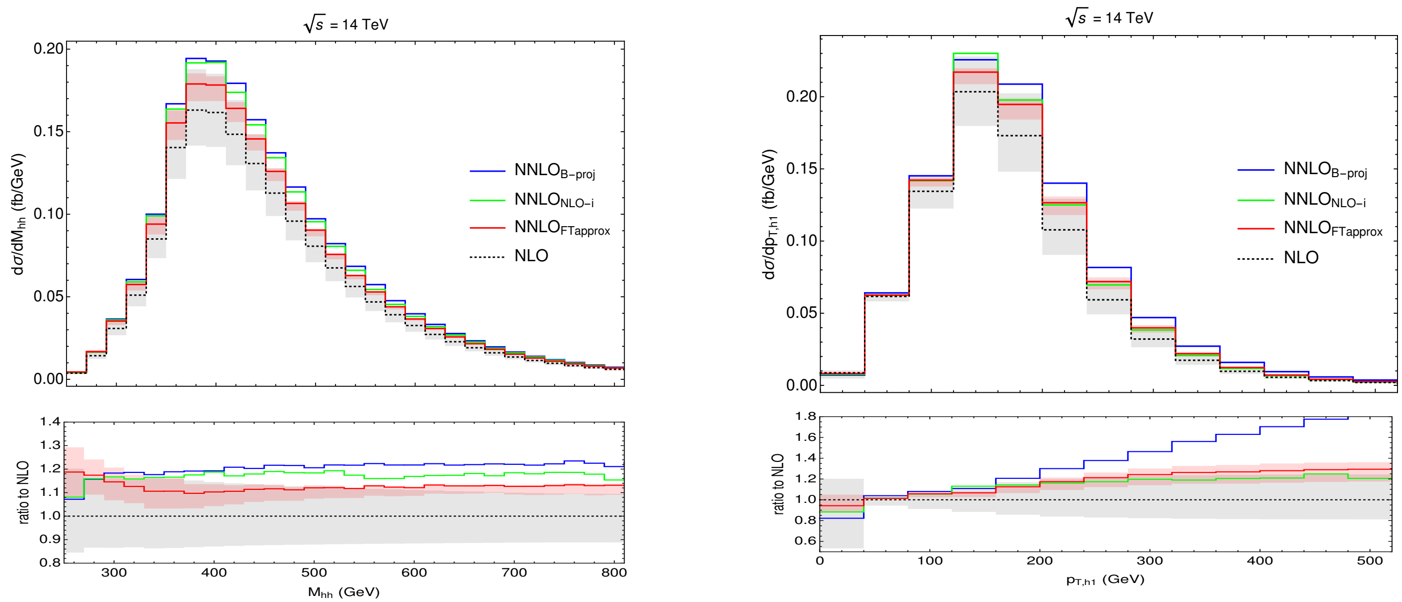
SM theory for gluon fusion production of HH

- NLO with full mass dependence (2-loop virtual)
  - *Reduces rate by -14%; changes distributions*
- NNLO+NNLL in large top mass limit
  - *Increases NLO by +5%*
- LHC HXSNWG: 13 TeV, σ=31.05 fb $^{+2.2\%}_{-5\%}$ ± 2.1% (Scale; α_s + PDF)
- N^3LO in large top mass limit increases rate by ~3% (NEW)
  - *M_{HH} shape unchanged with respect to NNLO*
  - *Scale uncertainties~3%, PDF uncertainties ~ 3.3%*

Grazzini, Heinrich, Jones,Kallweit,Kerner, Lindert, Mazzitelli,Heinrich, Jones: arXiv:1803.02463; Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk,Zirke: arXiv:1608.04798; Baglio, Campanario, Glaus,Muhlleitner, Spira, Streicher: arXiv:1811.05692; Chen, Li, Shao, Wan: , arXiv.1909.06808.pdf

SM theory for gluon fusion production of HH

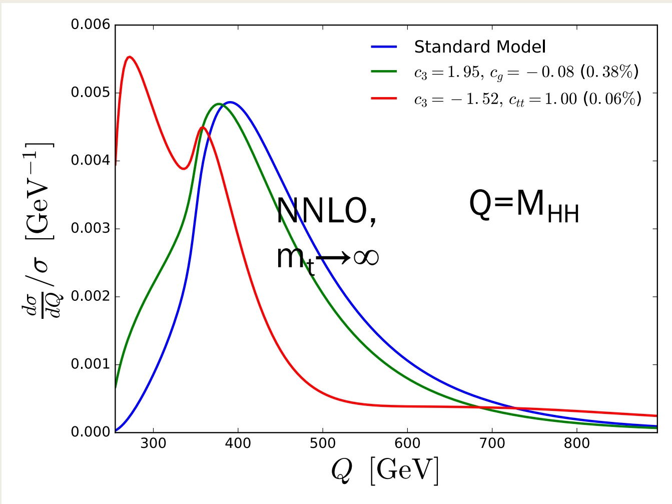
- NLO with exact top mass combined with NNLO in $m_t \to \infty$

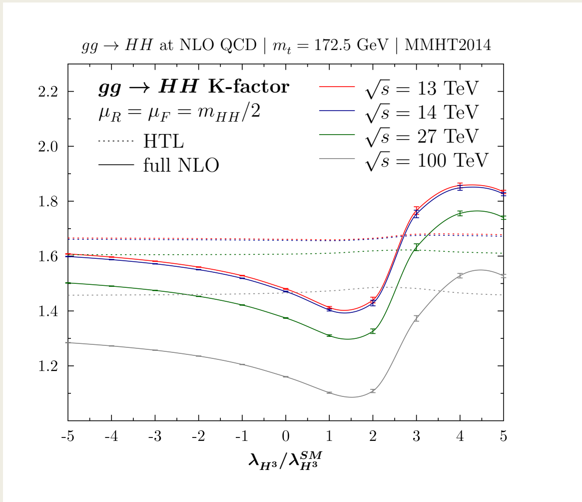


Grazzini, Heinrich, Jones,Kallweit,Kerner, Lindert, Mazzitelli,Heinrich, Jones: arXiv:1803.02463

QCD and EFT operators at NLO and NNLO

- K factors differ from SM and are not constant (QCD matters in EFT studies)
- Prediction for LHCP2021: Combination of SM HH to NLO with EFT HH to NLO distributions



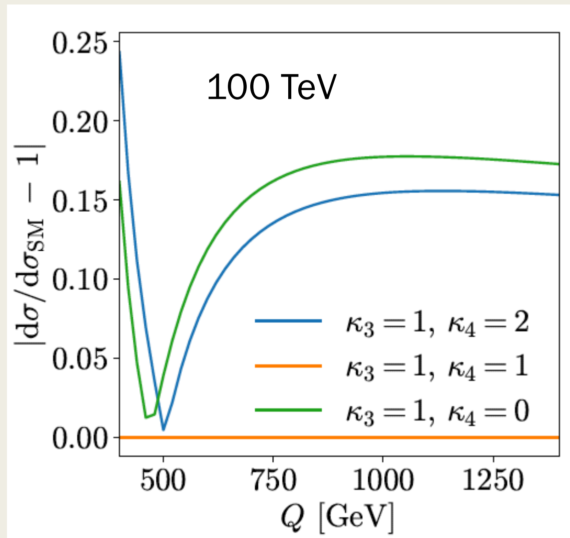


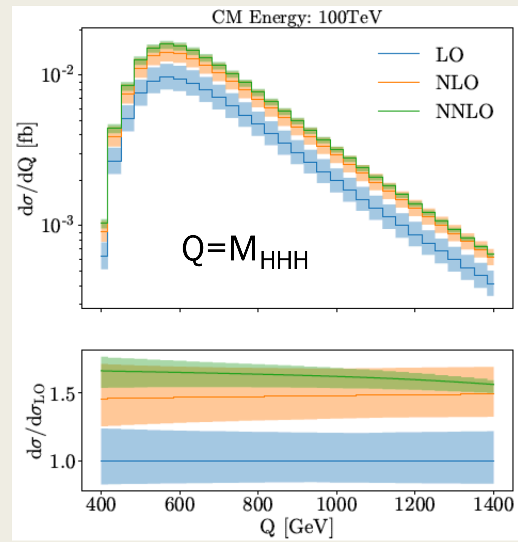
*See parallel talk by Glaus

de Florian, Fabre, Mazzitelli, arXiv:1704.05700;
Baglio, Campanario, Glaus, Muhlleitner, Ronca, Spira, Streicher, arXiv:2003.03227

Triple Higgs production at NNLO

- Very small rate, but sensitive to HHHH coupling
- Calculation in infinite top mass limit using dynamical reweighting to include top mass effects
- Cancellations between diagrams altered without SM coupling
- K factor relatively flat





14 TeV	σ=.103+5%-8% fb
100 TeV	σ=5.56+5%-6% fb

deFlorian, Fabre, Mazzitelli: arXiv:1912.02760

Conclusions

- The future is bright for Higgs physics
  - *Precision calculations of Higgs properties is a mature subject*
    - NNLO for distributions is becoming the gold standard for comparison

- ***Apologies for all the important and interesting calculations that I didn't mention. This is a dynamic and active area of theory***
- ***Part 2 of this talk should be a discussion of the many results matching fixed order to parton shower calculations at NNLO***
- ***Part 3 of this talk should be a discussion of higher order results for backgrounds***
- ***Part 4 of this talk should be a discussion of using SM calculations in an EFT framework beyond LO***