# Status of precision calculations for Higgs production at the HL and HE LHC

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HL/HE-LHC meeting, 4-6 April, 2018, Fermilab

# LHC HXSWG 1

- Update from perspective as theory co-convener of LHC Higgs Cross-Section Working Group (HXSWG) 1
    - fellow conveners: F. Caola (theory), P. Francavilla (ATLAS), R. Covarelli (CMS).
- Divided into subgroups addressing precision branching ratios and each of the main production channels at 14 TeV:
    - BR
    - gluon fusion (ggF)
    - VBF
    - VH
    - ttH and tH
    - off-shell (interference)

★ Two further groups "at large":

- Higgs pair production (HH)
- bbH and bH

# Overview

- General meeting of the LHCHXSWG ten days ago:

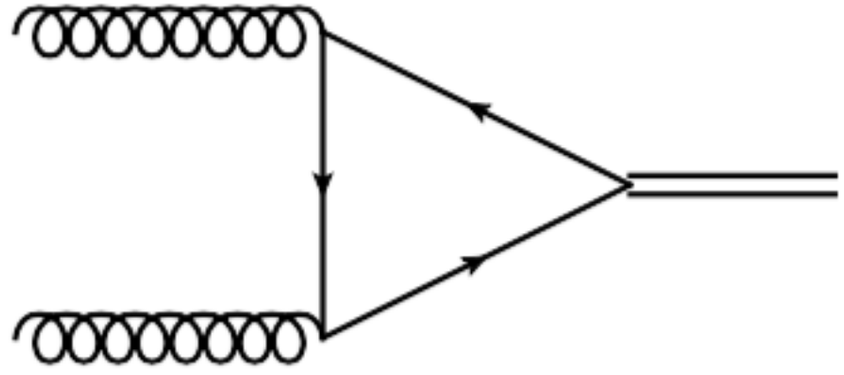
  https://indico.cern.ch/event/665524/timetable/?view=standard

- Subgroups provided updates on activities and initial progress towards HL/HE goals.

- Here — quick snapshot of theory highlights most relevant for this meeting.  Much more in the original slides.

# Gluon fusion

**[see talk of B. Mistlberger]**



- Cross-section now known exactly to N$^3$LO, lifting per-mille accuracy threshold approximation (Mistlberger, 1802.00833, et al.).

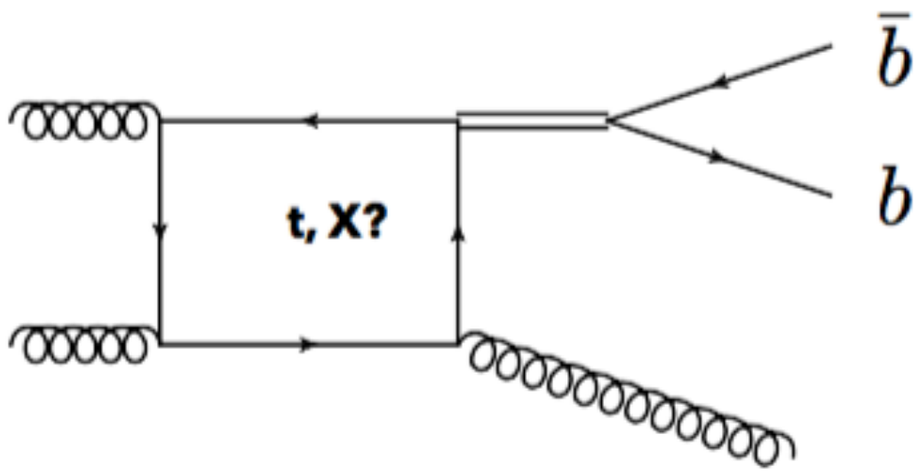
- Full analysis of 27 TeV production cross-section, including uncertainty estimates etc, a la YR4, already done.

## PREDICTIONS FOR A HADRON COLLIDER AT 27 TEV

| mH [GeV] | Cross Section [pb] | + Theory [%] | - Theory [%] | PDF+Alpha_S [%] | PDF [%] | Alpha_S [%] |
|---|---|---|---|---|---|---|
| 120.0 | 156.4 | 4.64 | -6.60 | 3.36 | 2.72 | 1.97 |
| 120.5 | 155.4 | 4.63 | -6.58 | 3.35 | 2.72 | 1.97 |
| 121.0 | 154.4 | 4.62 | -6.56 | 3.35 | 2.71 | 1.97 |
| 121.5 | 153.4 | 4.61 | -6.55 | 3.35 | 2.71 | 1.96 |
| 122.0 | 152.4 | 4.60 | -6.54 | 3.34 | 2.70 | 1.96 |
| 122.5 | 151.5 | 4.59 | -6.52 | 3.34 | 2.70 | 1.96 |
| 123.0 | 150.5 | 4.58 | -6.50 | 3.33 | 2.70 | 1.96 |
| 123.5 | 149.6 | 4.57 | -6.49 | 3.33 | 2.70 | 1.96 |
| 124.0 | 148.6 | 4.56 | -6.47 | 3.33 | 2.69 | 1.95 |

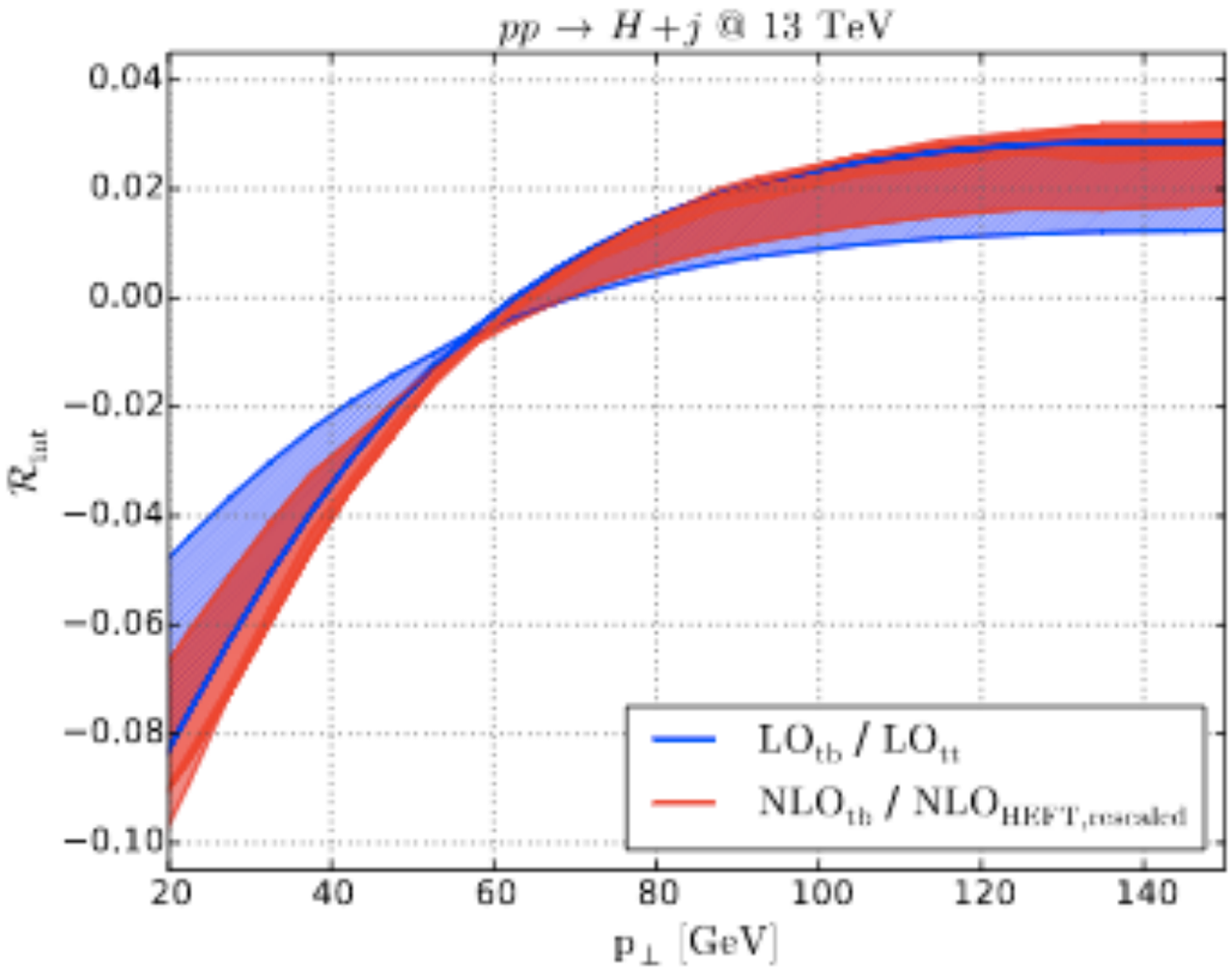
# ggF $p_T$ distribution

- At small $p_T$ fixed-order calculations have to be supplemented by resummation ($N^kLL$) in order to provide a sensible description.
  - current best is $N^3LL$+NNLO (Bizon et al, 1705.09127), other groups exploring variety of resummation and combination schemes.
- In general the $p_T$ distribution is very sensitive to the nature of loop coupling of gluons to H.
- This is true even for the particles we know about (t,b,c)!
  - In the last year some important SM effects have been pinned down more precisely.



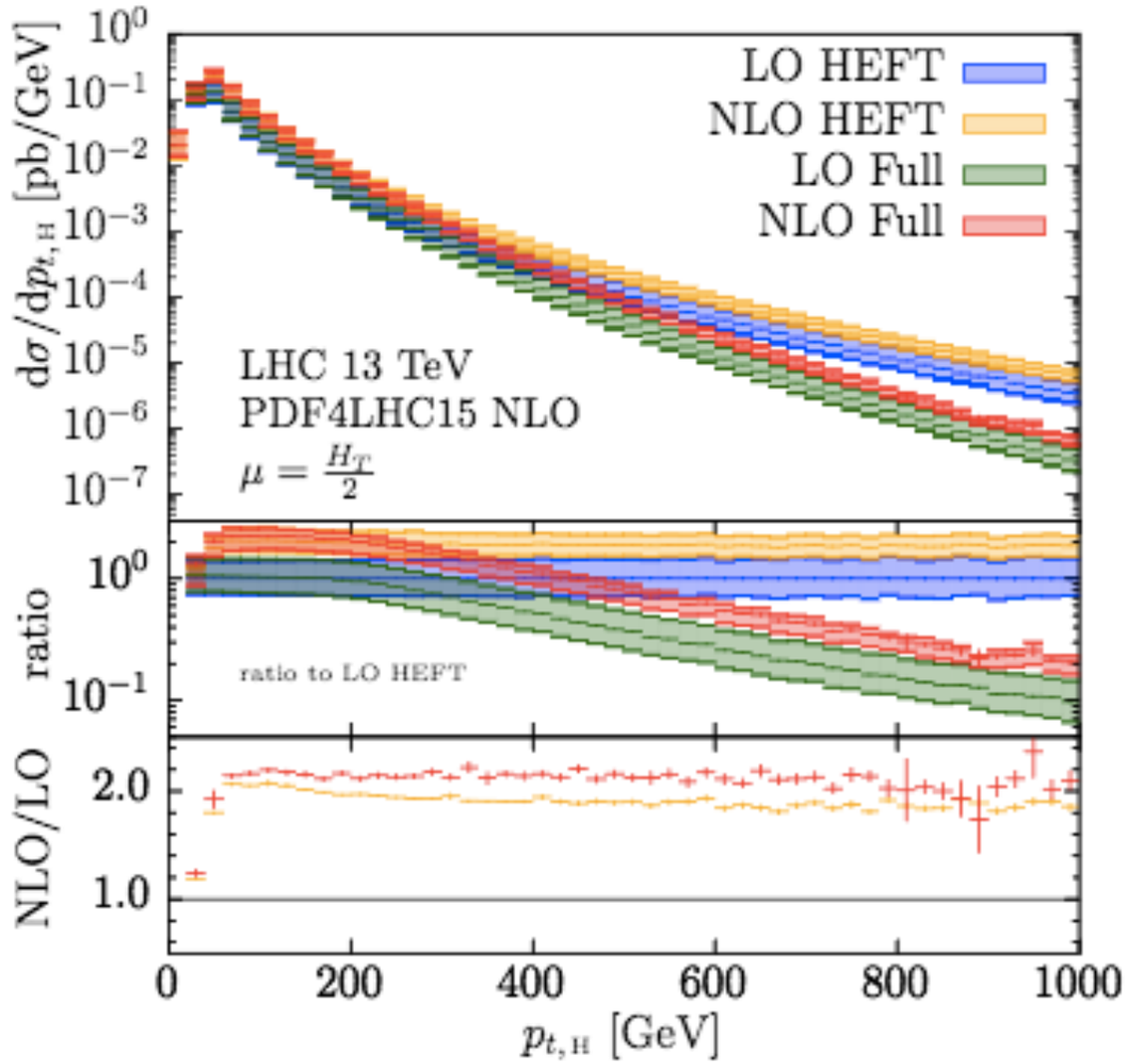
# Precision $p_T$ distribution

Lindert et al, 1703.03886




**bottom-quark interference contribution important at small pt**

**point-like coupling (HEFT) invalid for $p_T$~200 GeV, now known at NLO**




Jones et al, 1802.00349

# VBF

**[see talk of M. Rauch]**

- Inclusive cross-section also known to N$^3$LO (Dreyer, Karlberg, 1606.00840).

- Differential prediction especially important for identifying VBF region through tagging jets

  - known to NNLO since 2015 (Cacciari et al, 1506.02660), second independent calculation this year (Cruz-Martinez et al,1802.02445).

  - initial disagreement led to identification of bug in underlying (VBF-like) H+3 jets calculation used in VBFNLO and POWHEG-BOX.

- The two calculations are now in perfect agreement.

| | $\sigma^{\text{(VBF cuts)}}_{1506.02660}$ [pb] | $\sigma^{\text{(VBF cuts)}}_{1802.02445}$ [pb] | $\sigma/\sigma^{\text{NLO}}$ |
|---|---|---|---|
| LO | $0.957\,^{+0.066}_{-0.059}$ | $0.957\,^{+0.066}_{-0.059}$ | 1.092 |
| NLO | $0.876\,^{+0.008}_{-0.018}$ | $0.877\,^{+0.007}_{-0.017}$ | 1 |
| NNLO | $0.844\,^{+0.008}_{-0.008}$ | $0.844\,^{+0.009}_{-0.009}$ | 0.962 |

# VBF/ggF overlap

**Need continued interaction between groups, especially as we begin to explore the high-$p_T$ region where new features emerge.**

## Roadmap

short term

- parton-shower accuracy
  - comparisons between different matched samples and different showering options
  - dedicated focus on central-jet veto
  - possibly new recommendations on central value and uncertainties to be adopted
- high-$p_T$ Higgs boson
- cross sections for HE-LHC (27 TeV)
- Simplified Template Cross Sections uncertainty
  → preliminary results in experimental talk

medium & long term

- multi-jet merging of VBF-H+2jets and VBF-H+3jets
- QCD-induced *Hjj* background uncertainties
  - large contamination of theory uncertainties from *ggHjj* signal
  - *ggHjj* signal overestimated by current generators

  ↔ ggF sub-group
- higher-order corrections plus parton shower (NNLOPS)

## HIGGS BOSON PRODUCTION AT LARGE PT

**Best possible fixed order prediction for cumulative xs:**

| $p_T^{\text{cut}}$ | $\Sigma_{\text{ggF}}(p_T^{\text{cut}}) \times \text{BR}$ [fb] | $\Sigma_{\text{VBF}}(p_T^{\text{cut}}) \times \text{BR}$ [fb] | $\Sigma_{\text{ggF+VBF}}(p_T^{\text{cut}}) \times \text{BR}$ [fb] |
|---|---|---|---|
| 450 GeV | $11.1^{+4\%}_{-8.9\%}$ | $4.71^{+1\%}_{-1\%}$ | $15.3^{+2.8\%}_{-6.3\%}$ |

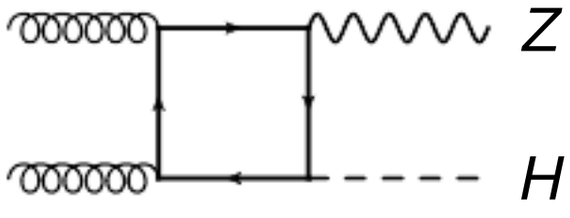
# VH

**[see talk of E. Re]**

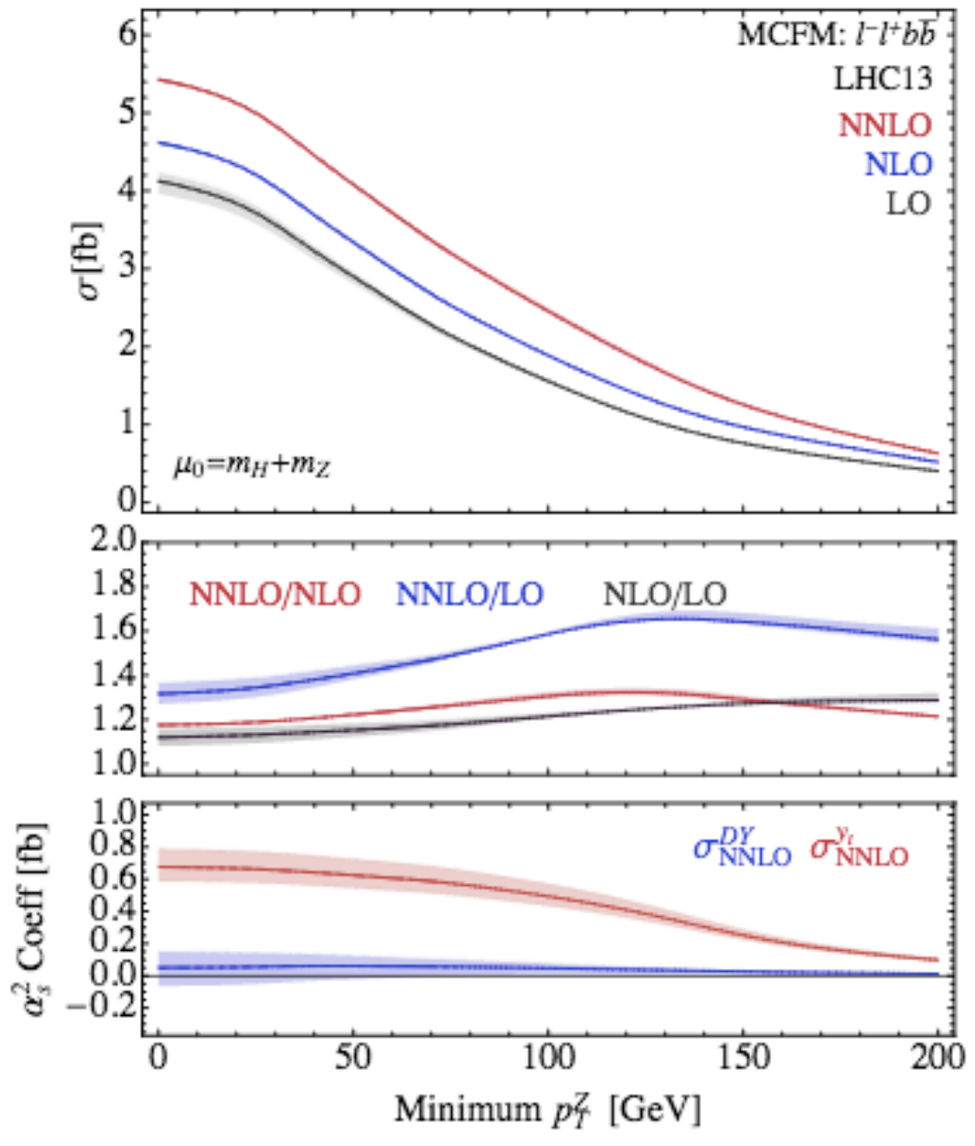
- Known to NNLO in differential form, with much recent work focussed on NNLO accuracy in H→bb decay.

- Expect NNLO+PS, with NLO decay, to be available soon.

- Ongoing study of current treatment of (large) gluon-fusion ZH contribution, fixed order vs. matching.




  - hope to precipitate full NLO calculation of this contribution.



# ttH

**[see talk of S. Pozzorini]**

- High-multiplicity, multiple mass scales → only NLO+PS.
- Focussed on estimating dominant ttbb background and uncertainties.

## Idea and goals

**Main goal is theory uncertainty estimate**

- comparing different NLOPS tools not sufficient
- comparing against data not sufficient: NLOPS needed for extrapolations
- we need intrinsic uncertainy of individual MC tools ⇒ should explain observed differences

**Roadmap** (until summer 2018)

- optimal choice of settings for coherent (apple-to-apple) comparison
- variations to isolate/rank uncertainties of fixed-order, matching and shower origin
- identify leading sources of MC differences/uncertainties
- technical/physical understanding of MC uncertainties/differences
- TH uncertainties recommendations (for $t\bar{t}H$ searches and $t\bar{t}b\bar{b}$ measurements)

**Status** `https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ProposalWwbbbb`

- preliminary results (also limited by MC statistics)
- no conclusion but good progress and interesting open questions/hypotheses

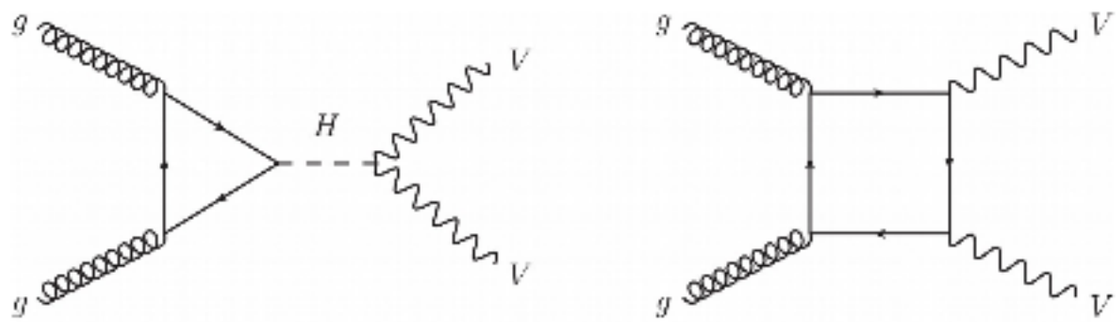
**Reminder: can be misleading to focus too much on signals without reassessing backgrounds!**

# Offshell/interference

**[see talk of J. Quevillon]**

- Group explores a range of effects that result from the interference of Higgs and continuum amplitudes

  - e.g. *O(10%)* of cross-section for H→ZZ at high invariant mass (offshell).




- Approximate NLO corrections to this effect known in a variety of approaches (Caola et al, 1605.04610,…; JC et al, 1605.01380)

  - better confidence in analyses based on interference (e.g. width constraints).

  - we know that NLO is insufficient for on-shell, but NNLO totally out of reach for now;  more study needed.

- Also ongoing studies of diphoton channel (mass-shift, rate change from interference) using resummation at NLL and in SHERPA.

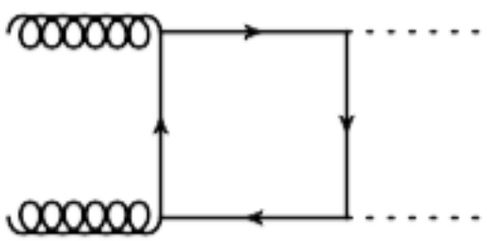
# Higgs pairs

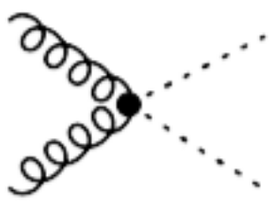
**[see talks of S. Jones, J. Mazzitelli]**

- Crucial goal for HL/HE program → better get theory right!

- Much better understanding of gg→HH in last year, resulting from new calculations that reduce reliance on HEFT approximation.

**finite $m_t$: accurate but hard (1-loop LO)**





**HEFT — poor approx. but can get to NLO+**

- Multiple approximations over the years using reweighting procedures that improve HEFT by including some $m_t$ effects.

- LO constraint lifted in 2016 by full NLO calculation (Borowka et al, 1604.06447), also with parton shower (Heinrich et al, 1703.09252).

  - difference wrt. some common approximations ~ 20%.

# Best prediction for HH

- Very recent calculation combining NLO finite-$m_t$ with NNLO HEFT, including some $m_t$ effects at NNLO (Grazzini et al, 1803.02463).

| $\sqrt{s}$ | 13 TeV | 14 TeV | 27 TeV | 100 TeV |
|---|---|---|---|---|
| NLO [fb] | $27.78\,^{+13.8\%}_{-12.8\%}$ | $32.88\,^{+13.5\%}_{-12.5\%}$ | $127.7\,^{+11.5\%}_{-10.4\%}$ | $1147\,^{+10.7\%}_{-9.9\%}$ |
| $\mathrm{NLO}_{\mathrm{FTapprox}}$ [fb] | $28.91\,^{+15.0\%}_{-13.4\%}$ | $34.25\,^{+14.7\%}_{-13.2\%}$ | $134.1\,^{+12.7\%}_{-11.1\%}$ | $1220\,^{+11.9\%}_{-10.6\%}$ |
| $\mathrm{NNLO}_{\mathrm{NLO-i}}$ [fb] | $32.69\,^{+5.3\%}_{-7.7\%}$ | $38.66\,^{+5.3\%}_{-7.7\%}$ | $149.3\,^{+4.8\%}_{-6.7\%}$ | $1337\,^{+4.1\%}_{-5.4\%}$ |
| $\mathrm{NNLO}_{\mathrm{B-proj}}$ [fb] | $33.42\,^{+1.5\%}_{-4.8\%}$ | $39.58\,^{+1.4\%}_{-4.7\%}$ | $154.2\,^{+0.7\%}_{-3.8\%}$ | $1406\,^{+0.5\%}_{-2.8\%}$ |
| $\mathrm{NNLO}_{\mathrm{FTapprox}}$ [fb] | $31.05\,^{+2.2\%}_{-5.0\%}$ | $36.69\,^{+2.1\%}_{-4.9\%}$ | $139.9\,^{+1.3\%}_{-3.9\%}$ | $1224\,^{+0.9\%}_{-3.2\%}$ |
| $M_t$ unc. $\mathrm{NNLO}_{\mathrm{FTapprox}}$ | $\pm 2.6\%$ | $\pm 2.7\%$ | $\pm 3.4\%$ | $\pm 4.6\%$ |
| $\mathrm{NNLO}_{\mathrm{FTapprox}}/\mathrm{NLO}$ | 1.118 | 1.116 | 1.096 | 1.067 |

**Best prediction smaller than current YR4 recommendation (~ -8%); remaining uncertainties (scale+$m_t$) ~ 5%.**

# Outlook: subgroup charge

- Produce reference numbers for production cross-sections and differential distributions.
  - HL:  3/ab with $m_H$=125.09 +/- 0.5 GeV
  - HE:  15/ab at 27 TeV, possibly broader range of energy/ luminosity if illuminating
- Estimate of the kind of precision expected for Higgs theory predictions at the HL/HE-LHC.
- Document in a timely manner (TWiki) to stream-line communication with HL/HE-LHC effort.

# HL-LHC

- A lot of work has already been performed,
  e.g. Snowmass 2013, WG reports, Les Houches studies, …

  - exercise to collate existing relevant studies in a coherent fashion

  - some updates required, e.g. unrealistic (over- or under-) estimated uncertainties

- Good to have a sense of what could be improved and which (primarily theory) systematics are expected to remain the same and/or be limiting factors.

# HE-LHC

- Precise and detailed results (e.g. differential distributions at NNLO) not an immediate priority.

- Better to follow 100 TeV path by collecting precision total cross-sections and studying interesting distributions.

  - in particular, try to identify proper fiducial regions and new paradigms.

- Identify problems due to, e.g. limited detector coverage, exposure to new limiting theory systematics, e.g. PDF uncertainties, EW corrections, ….

# Summary

- LHCXSWG very active across all subgroups
  - assimilating wealth of new theory calculations and continuously updating predictions for 14 TeV.
  - groups already producing predictions for 27 TeV at the same time.
- All subgroups committed to providing YR4-level HE-LHC predictions for cross-sections and important observables over the coming months.
  - reassessing theory systematics for both HL and HE scenarios, exploring new features that could emerge for HE-LHC.