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Higgs production: A theory overview

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Higgs Hunting 2023, September 11-13, Paris

11.09.2023

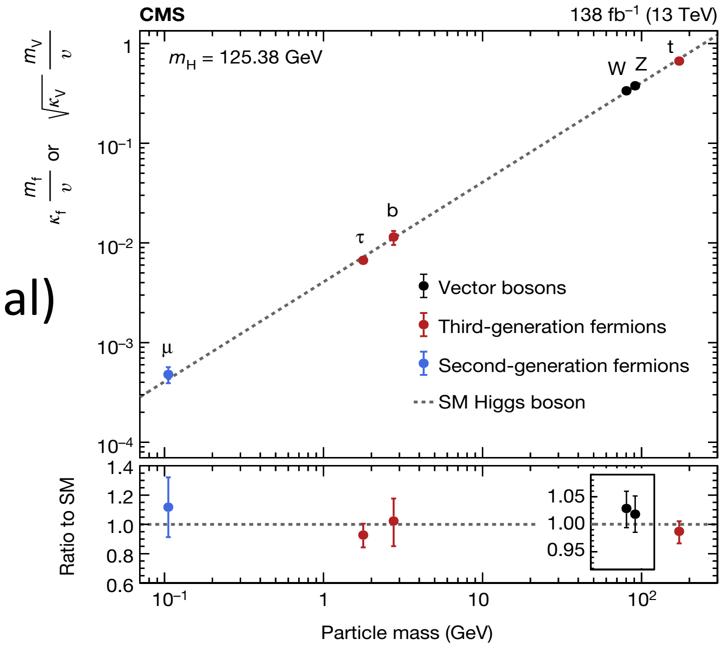
Swiss National Science Foundation

Outline

- Status of the Higgs boson after LHC run-II
- Selected recent theory developments for precision Higgs physics

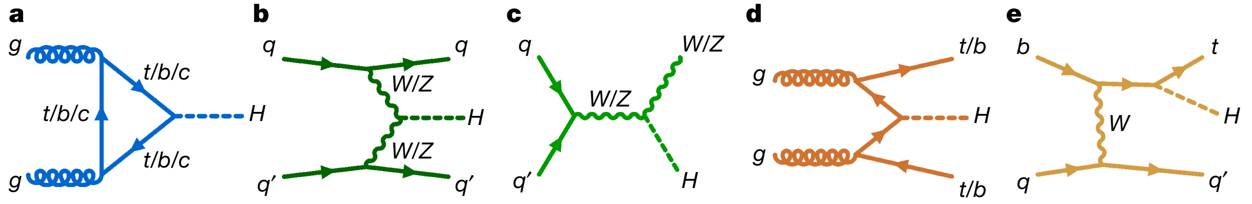
The Higgs boson in the Standard Model

- Higgs boson H: prediction of Brout-Englert-Higgs mechanism (1964, Nobel 2013) of electroweak symmetry breaking for mass generation of Standard Model (SM) particles
- Discovered in 2012 the $H \to \gamma\gamma$ channel [ATLAS: 1207.7214, CMS:1207.7235]
- Present data compatible with a scalar particle with spin 0 and even parity (as predicted by the SM) of mass $m_H \sim 125.2$ GeV
- Couplings
  - fermions (f): $g_{Hff} \sim m_f/v$ (largest for top-quarks)
  - EW gauge bosons (V): $g_{HVV} \sim m_V^2/v^2$ (no direct γ-coupling)
  - Higgs (H): $g_{HHH} \sim m_H^2/v$, $g_{HHHH} \sim m_H^2/v$ (Ultimate test of Higgs potential)
- No deviations from SM observed so far
- Couplings probed in Higgs production or decay channels



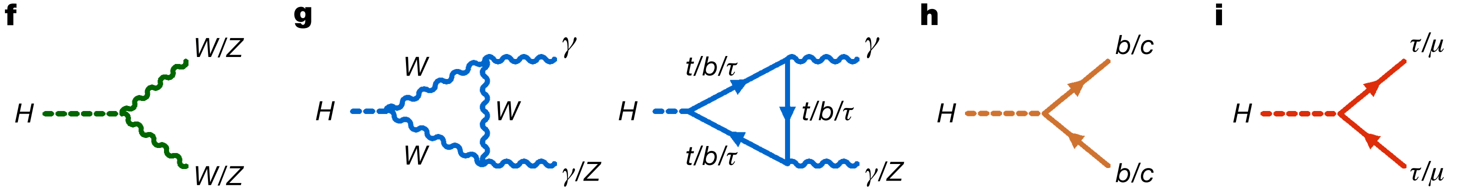
Higgs production and decay

- Higgs production:



  - gluon-gluon fusion dominant: thoroughly studied in theory, precise predictions, mostly in heavy-top EFT

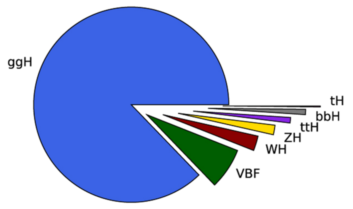
- Higgs Decay:

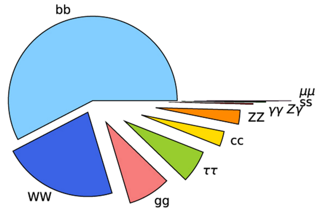


  - Rare loop-induced channels (like $\gamma\gamma$) prefered over dominant modes (e.g. bottom quarks) due to large and irreducible QCD background

Production mode	Cross section (pb)	Decay channel	Branching fraction (%)
ggH	48.31 ± 2.44	bb	57.63 ± 0.70
VBF	3.771 ± 0.807	WW	22.00 ± 0.33
WH	1.359 ± 0.028	gg	8.15 ± 0.42
ZH	0.877 ± 0.036	ττ	6.21 ± 0.09
ttH	0.503 ± 0.035	cc	2.86 ± 0.09
bbH	0.482 ± 0.097	ZZ	2.71 ± 0.04
tH	0.092 ± 0.008	γγ	0.227 ± 0.005
		Zγ	0.157 ± 0.009
		ss	0.025 ± 0.001
		μμ	0.0216 ± 0.0004

- Higgs signal: need to combine production and decay, challenging for experiment and theory
  - Relative importance of production and decay modes at √s=13 TeV
    [Higgs Working group (2016): CMS Nature (2022) 2207.00043]

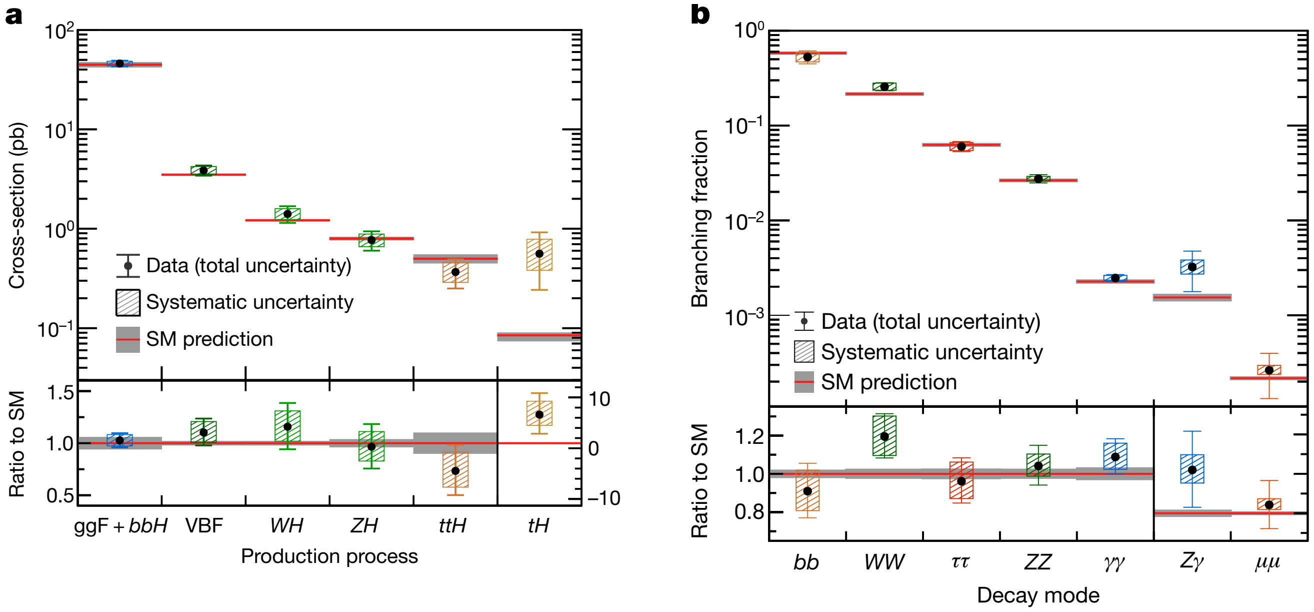


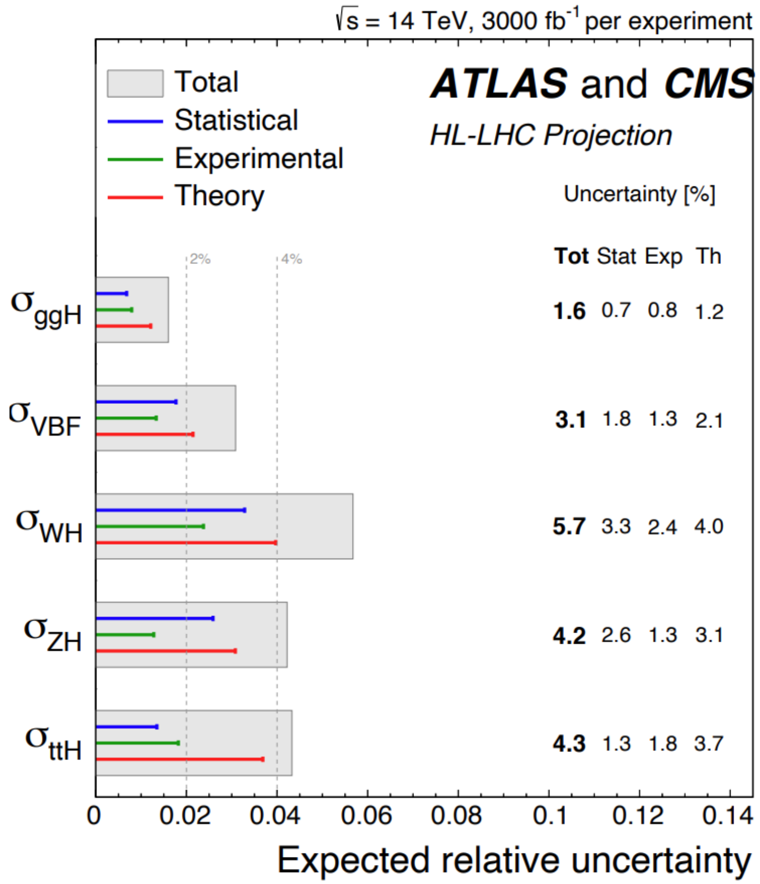


Higgs production and decay

- Present: Good agreement between theory and experiment

  [ATLAS (Nature (2022): 2207.0009; theory: Higgs Working Group 1610.07922]

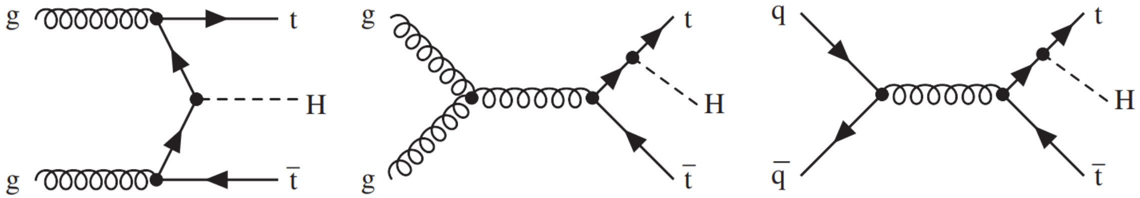




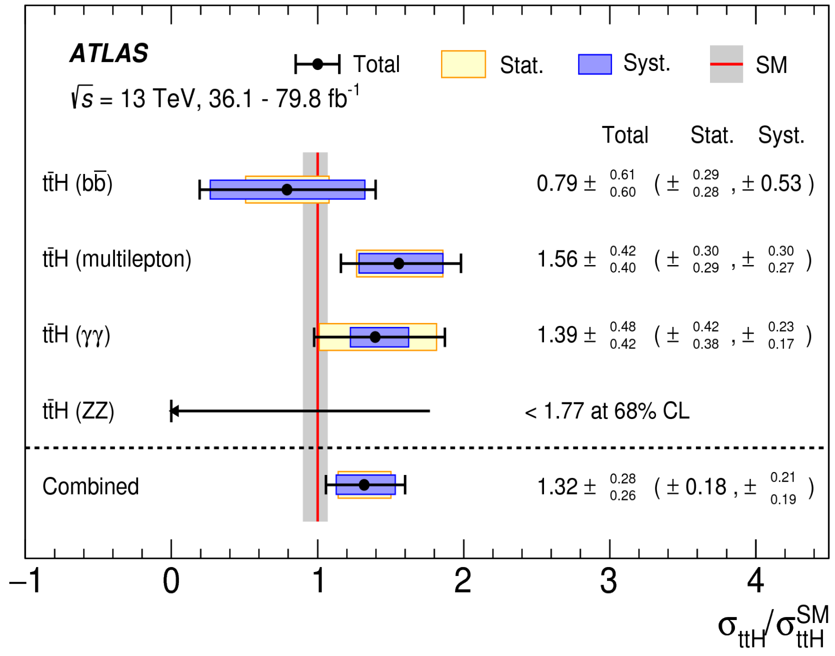
- Future: HL-LHC experimental precision on production channels expected to go down to O(2%) [HL-LHC report 1902.00134]
- Precise theoretical predictions required to match experimental results

Associated top-antitop-Higgs production

- ttH production gives direct access to top quark Yukawa coupling ($y_t \sim m_t/v$)



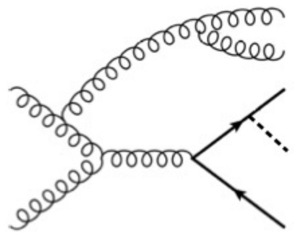
- Experimental status
  - Higgs boson observed in ttH channel in 2018 by LHC experiments in various decay channels
    [CMS 1804.02610; ATLAS 1806.00425]
    - Compatible with SM so far
    - But: Present experimental uncertainty of (20 %) expected to reach O(2%) at HL-LHC
  - Precise theoretical predictions needed
    [HL-LHC report 1902.00134]



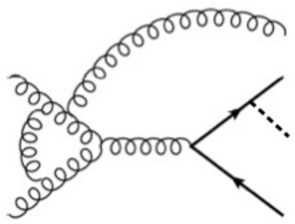
[ATLAS (2018)]

ttH production: Theoretical status

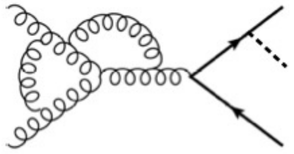
- Previous NLO results
  - NLO QCD + EW corrections (on-shell top quarks) including NNLL soft gluon resummation
    [Broggio et al. 1907:04343, Kulesza et al. 2001:03031]
  - Full off-shell calculations at NLO QCD and NLO QCD +EW corrections
    [Denner et al : 1612.07922]
  - NLO predictions are affected by an uncertainty of (10%) [Higgs WG (2016) 1610:07922]
- At NNLO level : Final states with up to two more partons contribute to the cross section:



RR: Real-Real



RV: Real-Virtual



VV: Virtual-Virtual

- Bottleneck: Genuinly 2-loop contribution unknown
- 2-loop Amplitude for $(2\rightarrow3)$ with 3 external masses: Beyond present calculational technology

ttH production @NNLO QCD

- ttH production computed up to NNLO QCD (with all partonic channels included)
  [Catani, Devoto, Grazzini,Kallweit, Mazzitelli, Savoini, 2210.07846]

- Using parton-level event generator MATRIX adapted to ttH final states
  [MATRIX: Grazzini, Kallweit, Wiesemann, 1711.006631]
  - extended NNLO q_T subtraction method originally formulated for colour-neutral final states
  - extended to heavy quark pair production, account for soft radiation off heavy quarks
    [Catani, Devoto, Mazzitelli, 2301.11786]

ttH production @NNLO QCD

- Unknown virtual 2-loop amplitude approximated using the soft Higgs limit
  - In the soft Higgs limit (momentum k → 0), the scattering amplitude can be rewritten

$$\mathcal{M}(\{p_i\},k) \simeq F(\alpha_S(\mu_R); \tfrac{m_t}{\mu_R}) \frac{m_t}{v} \sum_{i=3,4} \frac{m_t}{p_i \cdot k} \mathcal{M}(\{p_i\})$$

  - F: soft limit of scalar heavy quark form factor, $\mathcal{M}$: known tt-production amplitudes
- In q_T subtraction framework
  - contribution from 2-loop finite remainder function: computed using soft Higgs approximation
  - require momentum mapping to account for physical Higgs momentum
  - 2-loop contribution to cross section at NNLO numerically small compared to real radiation parts

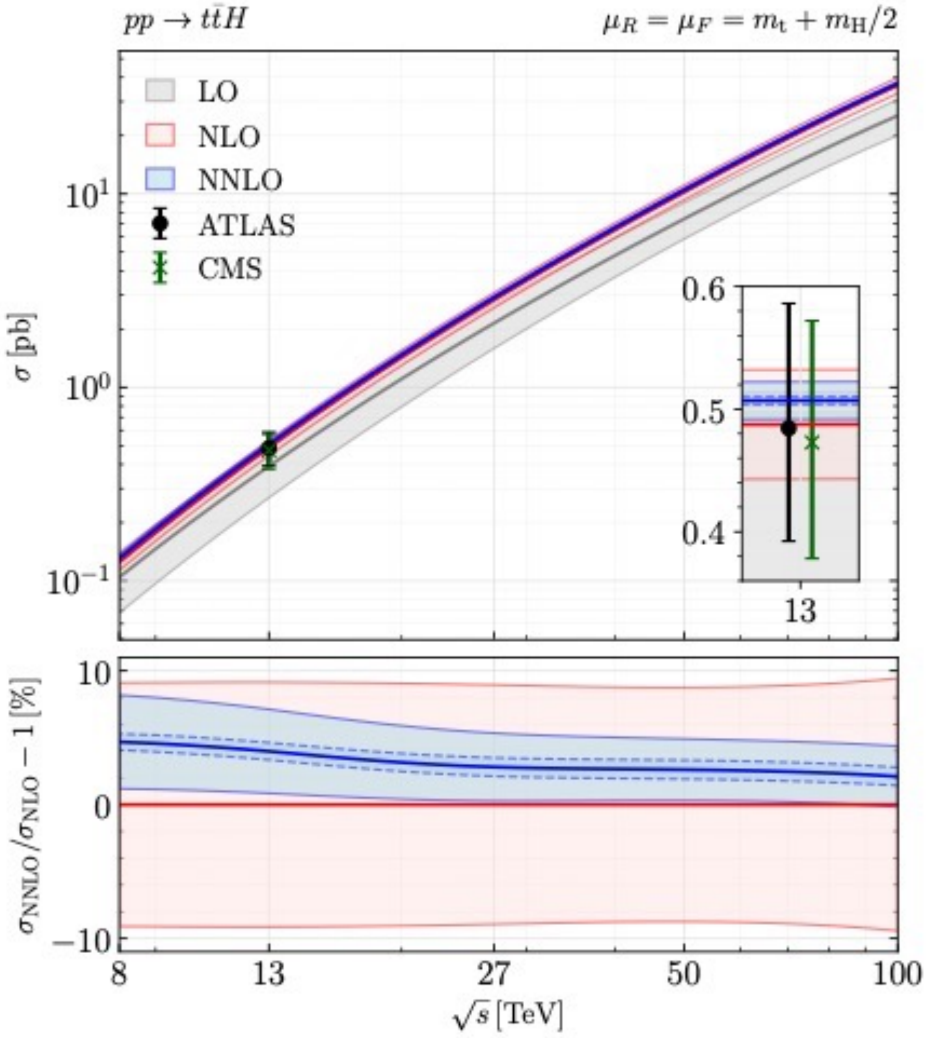
Total cross section for ttH@NNLO

- NNLO calculation versus data at 13 TeV
  [ATLAS: 2207.00092, CMS: 2207.00043]
  [Catani, Devoto, Grazzini,Kallweit, Mazzitelli, Savoini, 2210.07846]

σ [pb]	$\sqrt{s} = 13\,\text{TeV}$	$\sqrt{s} = 100\,\text{TeV}$
σ_{LO}	$0.3910\,^{+31.3\%}_{-22.2\%}$	$25.38\,^{+21.1\%}_{-16.0\%}$
σ_{NLO}	$0.4875\,^{+5.6\%}_{-9.1\%}$	$36.43\,^{+9.4\%}_{-8.7\%}$
σ_{NNLO}	$0.5070\,(31)^{+0.9\%}_{-3.0\%}$	$37.20(25)\,^{+0.1\%}_{-2.2\%}$

  - Error includes scale variation and uncertainty from soft Higgs approximation estimated on exact result at NLO level

- NNLO corrections moderate (2-4 %) with significant reduction of theoretical uncertainty to per-cent level



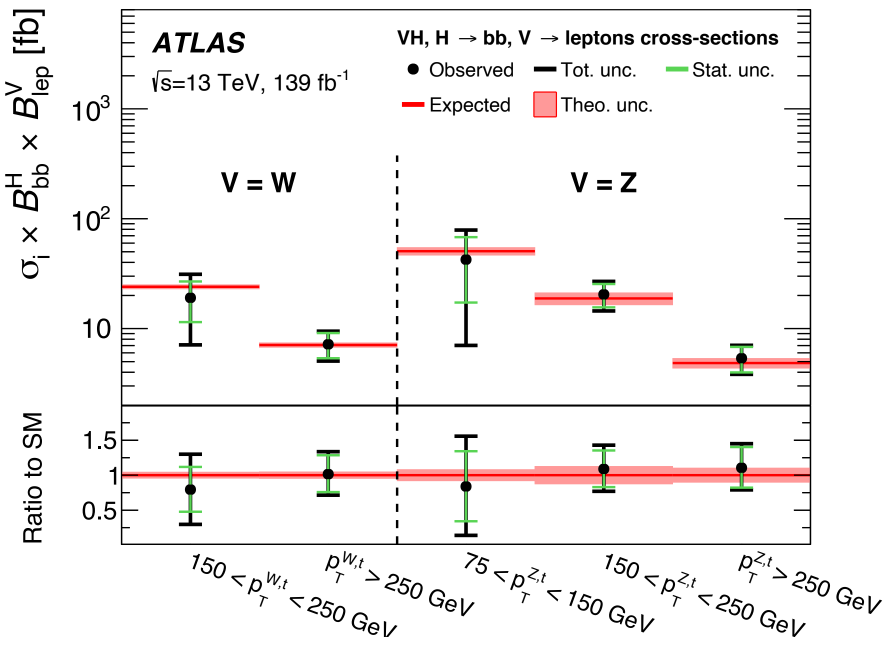
VH production

- VH+Jet observables computed to NNLO for $pp \to VH + \text{jet} \to H + l\bar{l} + \text{jet}$ with V=(Z,W^+,W^-) and stable Higgs [Gauld, Glover, Huss, Majer, AG, 2110.12992]
- Experimental status of VH (+jet)
  - Clear leptonic signature from V decay: H identification easier
  - VH channel: First evidence for H → bb decay

    [ATLAS: 1808.08238, CMS: 1808:08242]
- Measurement as function of p_T^V
  - Using a simplified cross section template
  - Factorization of Higgs boson production and decay

$$\sigma = \sigma_{VH} \times Br_{bb}^{H} \times Br_{ll}^{V}$$

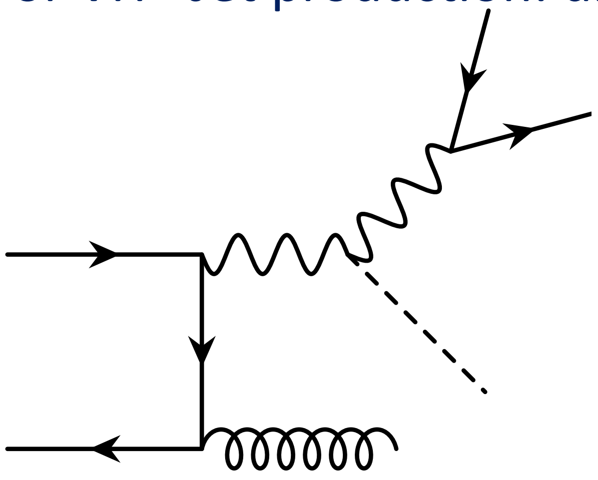
  - Higgs candidate: two b-jets (anti-k_T)
  - Need: exclusive and inclusive VH+J contributions in experimental VH signal extraction (multivariate methods)
  - first step towards more differential measurements



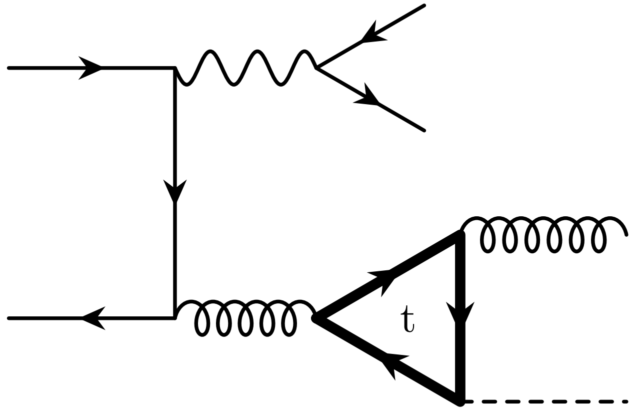
[ATLAS: 2008.02508]

VH+Jet production: ingredients up to O(α_s^3)

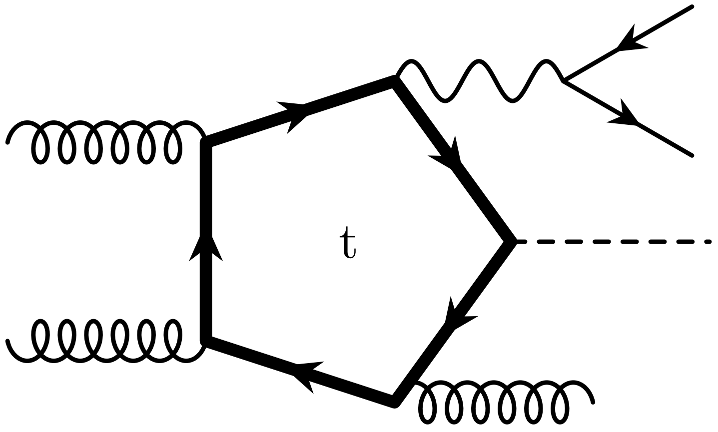
- Previous NLO results: NLO QCD(+PS) and NLO QCD+EW
  [Astill, Bizon, Re, Zanderighi, 1804.08141; Granata, Lindert, Oleari, Pozzorini, 1706.03522]
- For VH+ Jet production: different process categories contributing at higher orders



(a) Drell-Yan type: Born O(α_s)
Higgs couples to off-shell V



(b) O(y_t) top-loop qq-induced:
starts at O(α_s^2),
present for ZH and WH



(c) O(y_t) top-loop gluon-induced:
starts at O(α_s^3),
present for ZH only,
sizeable effects on observables

WH+Jet production: inclusive vs. exclusive

- W^+H+J: Fiducial cross sections in inclusive (≥ 1j) and exclusive (=1j) cases
  [Gauld, Glover, Huss, Majer, AG, 2110.12992]
  - Jets selected with anti-k_T algorithm with p_t> 20 GeV
  - Include Drell-Yan at $\alpha_s{}^3$ and top-loop (qq-induced) at $\alpha_s{}^2 y_t$
  - both contributions of comparable size

$$\delta\sigma_{\geq 1\mathrm{j}}(\alpha_\mathrm{s}^3) = 0.24\,\mathrm{fb},\ \delta\sigma(\alpha_\mathrm{s}^2 y_t) = 0.32\,^{+0.07}_{-0.06}\,\mathrm{fb},$$

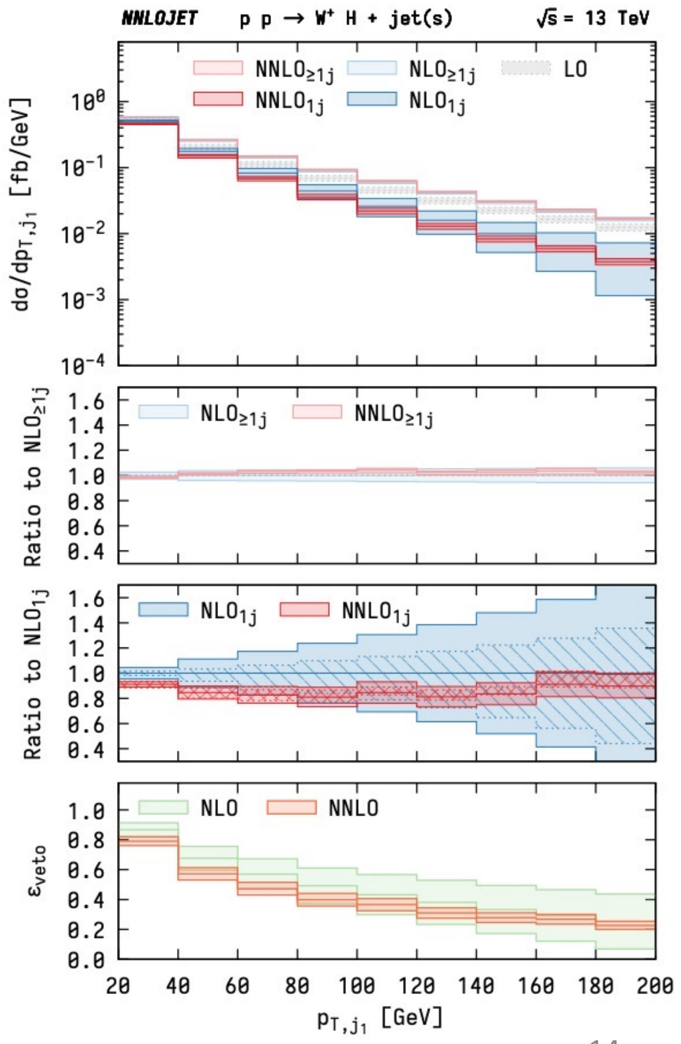
	$\mathrm{W}^+\mathrm{H}+\geq 1\mathrm{jet}$	$\mathrm{W}^+\mathrm{H}+1\mathrm{jet}$
σ^{LO} [fb]	$20.99\,^{+2.09}_{-1.83}$	$20.99 \pm 1.96\,(^{+2.09}_{-1.83})$
σ^{NLO} [fb]	$26.12\,^{+0.94}_{-0.99}$	$17.42 \pm 2.10\,(^{+0.73}_{-1.35})$
σ^{NNLO} [fb]	$26.36\,^{+0.04}_{-0.24}$	$15.59 \pm 0.59\,(^{+0.48}_{-0.44})$

- Exclusive (=1j) case computed as $\sigma_{1j} \equiv \sigma_{\geq 1j} - \sigma_{\geq 2j}$
- Theory uncertainty computed with central scale M_{HW}
  - corrections larger in exclusive case, reduction of error bands only @NNLO
  - overlapping uncertainty bands only for uncorrelated scale variation in exclusive cross section

WH+Jet production: inclusive vs. exclusive

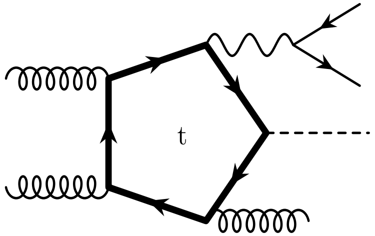
- Transverse momentum spectrum of the leading jet $p_{T,j1}$
- Sizeable differences in NNLO versus NLO
  - Inclusive (≥ 1j) case: Small (positive) NNLO corrections
    and uncertainties (at % level)
  - Exclusive (=1j) case: Large (negative) NNLO corrections
    and uncertainties, specially as $p_{T,j1}$ increases

- At large $p_{T,j1}$: dominated by WH+2-jet production
  - Exclusive process is strongly suppressed
    - Best seen for veto efficiency decreasing with increasing p_T
  - Consequence: NNLO prediction only NLO-accurate
    - Large NNLO scale uncertainties at 10% level



ZH + Jet production

- Two types of top-loop contributions
  - qq-induced: at order $\alpha_s^2 y_t$ from interference with Drell-Yan amplitudes (as for W^+, W^-)
  - gg-induced: at order $\alpha_s^3 y_t^2$ from (1-loop-amplitude)^2 (Z only)

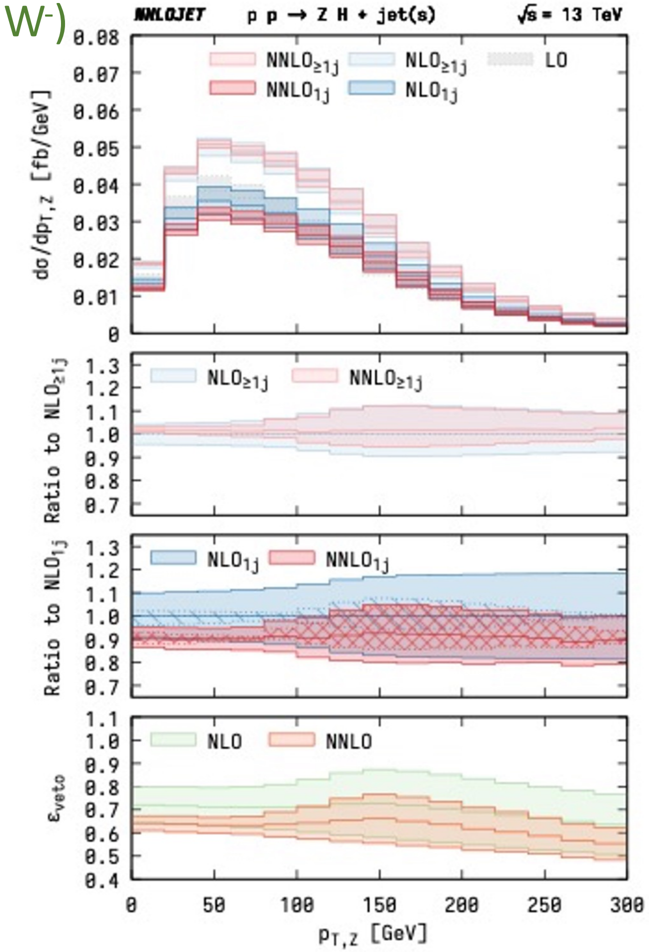


- Fiducial inclusive cross sections: effects of top-loop

$\sigma_{\rm NLO}$ [fb]	$6.81^{+0.22}_{-0.24}$	$6.89^{+0.24}_{-0.25}$
$\sigma_{\rm NNLO}$ [fb]	$6.92^{+0.02}_{-0.04}$	$8.04^{+0.42}_{-0.32}$
	(without top)	(with top)

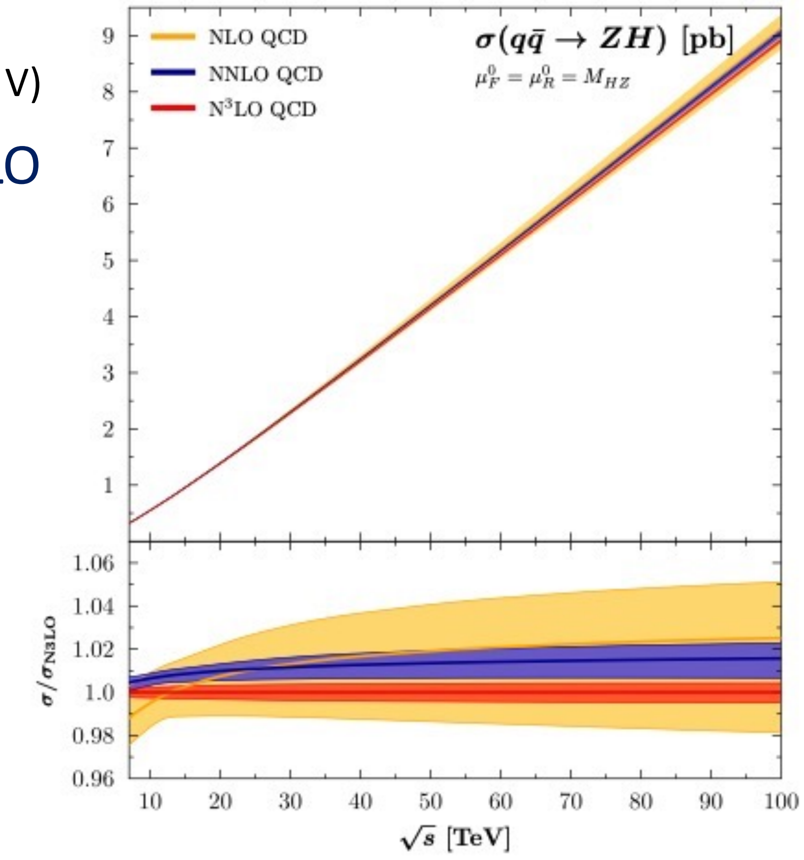
  - @ NLO: slight increase of cross section, but no sizeable effect on uncertainty
  - @ NNLO: size of corrections and uncertainties enlarged

- Transverse momentum spectrum of Z boson
  - @ NNLO: Sizeable impact of gg-loop induced contributions
    - 15% in inclusive case and even larger in exclusive mode
    - Large remaining uncertainty band

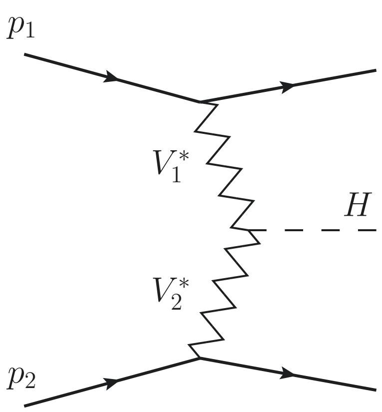


VH production at N^{3}LO

- VH inclusive cross section computed to N^{3}LO
  [Baglio, Duhr, Mistlberger, Szafron; 2209.06138]
    - Contributions up to N^{3}LO: Drell-Yan type (only) (H couples to off-shell V)
- Scale uncertainty not decreasing when going from NNLO to N^{3}LO
- N^{3}LO results outside NNLO uncertainty band
    - same pattern as for DY process at N^{3}LO [Duhr, Dulat, Mistlberger, 2001.07717]
- N^{3}LO residual theoretical uncertainty
    - dominated by PDF uncertainties (of various sources) (~1.5%)
    - scale uncertainties at 1 %
- Mismatch between perturbative orders
    - NNLO PDF and N^{3}LO coefficient functions combined
- Strong motivation for N^{3}LO PDF



Higgs production in weak boson fusion



- Weak vector boson fusion (WBF)
  - Higgs production mode with the second-largest cross section at the LHC
  - essential for precise determination of HVV coupling: g_{HVV}

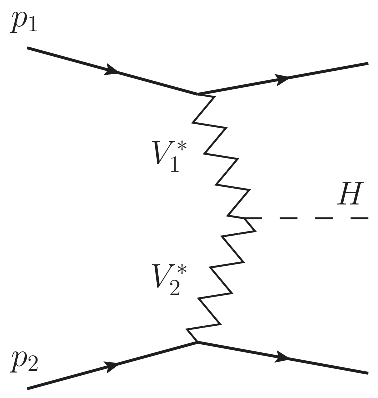
- Experimental status: Studied by ATLAS and CMS using a number of Higgs decay modes
  - observed event rate (µ-value) compatible with SM expectations

$\mu_{\rm VBF} = 1.21 \pm 0.18 \ (\text{stat.})$ [ATLAS: 1909.02845] $\mu_{\rm VBF} = 0.73 \pm 0.23 \ (\text{stat.})$ [CMS: 1809.10733]

Higgs production in WBF

- Double DIS Picture: space-like Z and W fusing into a Higgs boson
  - independent QCD corrections to upper and lower quark line
  - exact at LO and NLO, well-established
- Factorisable (double DIS) corrections well-known
  - Total cross section and Higgs distributions: known to N^3LO QCD [Dreyer, Karlberg, 1606.00840]
  - Differential results: known to NNLO QCD [Cacciari et al., 1506.02660; Cruz-Martinez et al., 1802.02445]
- From NNLO onwards: non-factorizable corrections (percent level)
  - a priori suppressed by colour and kinematics
  - approximated using soft eikonal approximation
- Numerical impact on kinematical distributions studied

  [Asteriadis et al., 2305.08016, Dreyer et al., 2005.11334]



WBF including decays at NNLO

- Differential NNLO results so-far: computed for a stable Higgs boson
  - Kinematical cuts on Higgs decay products can potentially impact the NNLO corrections
- Aim: directly compare predictions for fiducial cross sections and distributions
  - realistic final states
  - WBF including Higgs decays, with production and decay at NNLO
- First steps [Asteriadis et al., 2110.02818]
  - H production at NNLO in factorisable double-DIS
  - H decays : $H \to bb$ at LO and $H \to l\nu l\nu$, independent of H production part

WBF including decays at NNLO

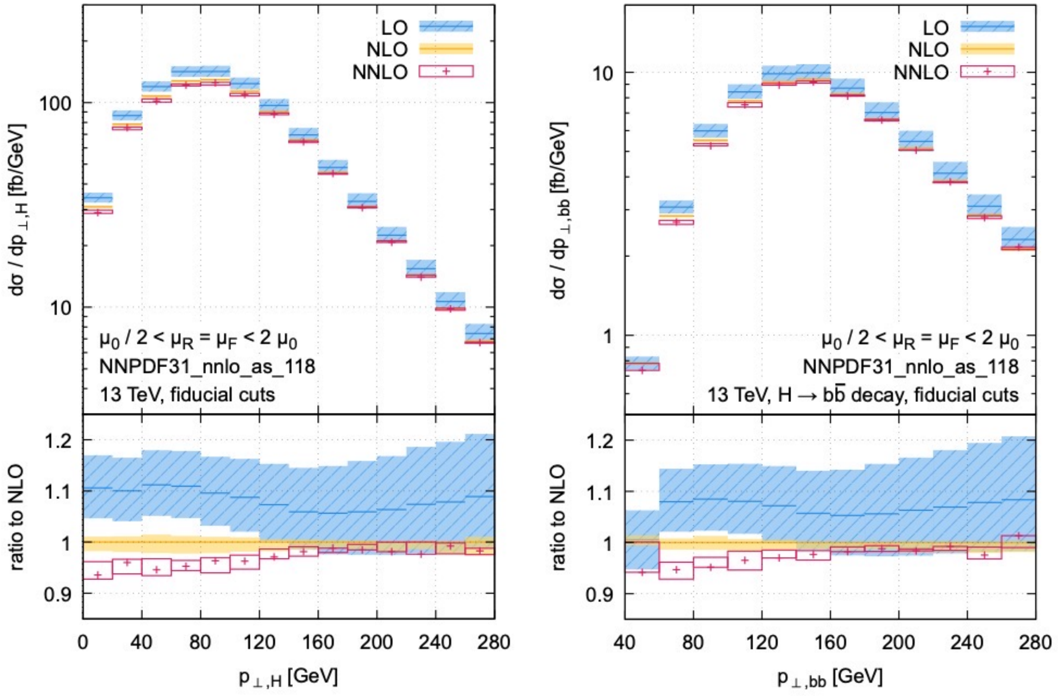
- Setup and Characteristics
  - For $H \to bb$:
    - standard anti-kt jet algorithm
    - WBF cuts for non-b-jets applied
    - restrictive cut p_T(b-jet) > 65 GeV
  - For $H \to l\nu l\nu$:
    - higher-multiplicity final state from Higgs decay
    - decay products not clustered with QCD partons
- Fiducial cross sections in $H \to bb$
  - K-factors at NLO and NNLO modified:
    -11% (stable Higgs) versus -8% (bb final state)
  - shift of +3% comparable to size of NNLO corrections

$$\frac{\sigma^{H}_{\mathrm{NLO}}}{\sigma^{H}_{\mathrm{LO}}} = 0.917(1)\,, \qquad \frac{\sigma^{b\bar{b}}_{\mathrm{NLO}}}{\sigma^{b\bar{b}}_{\mathrm{LO}}} = 0.934(1)\,,$$

$$\frac{\sigma^{H}_{\mathrm{NNLO}}}{\sigma^{H}_{\mathrm{LO}}} = 0.885(1)\,, \qquad \frac{\sigma^{b\bar{b}}_{\mathrm{NNLO}}}{\sigma^{b\bar{b}}_{\mathrm{LO}}} = 0.914(2)\,,$$

WBF @NNLO with H⟶ bb decay

- Transverse momentum distribution: H⟶ bb case
  - Significant shape distorsion at NLO, less at NNLO
  - NNLO result outside NLO scale uncertainty band
- Application of H⟶ bb fiducial cuts: crucial impact
  - about 90% reduction of cross section
- With H⟶ bb: p_T spectrum harder than for stable Higgs
  - mainly caused by cuts imposed on p_T(b-jet) > 65 GeV
  - Peak of p_T distribution shifted: 100 GeV (stable H) to 150 GeV (bb)
  - Perturbative convergence and scale uncertainty better than for stable Higgs

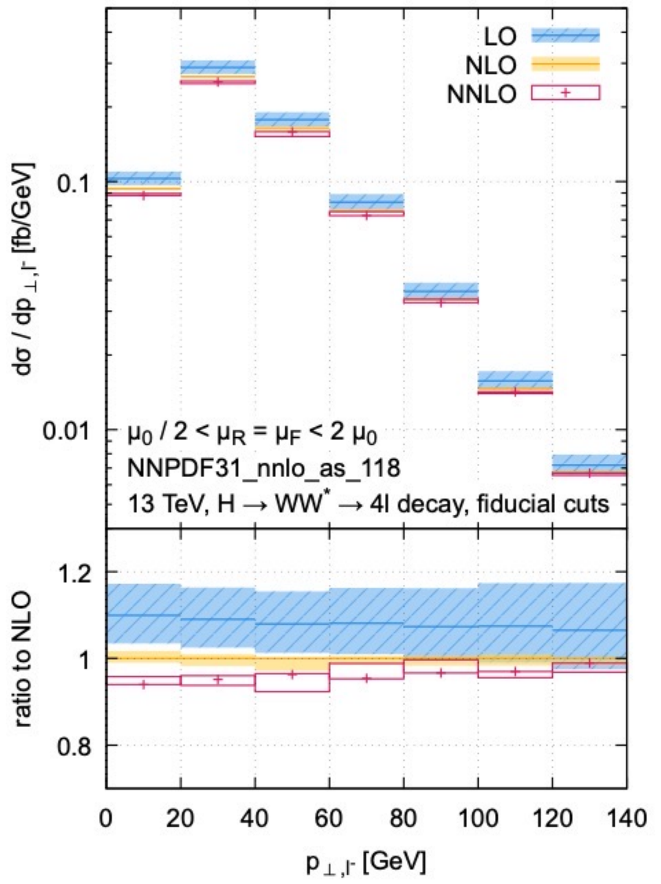


WBF @NNLO with H$\rightarrow$ lνlν decay

- Fiducial cross sections for H→ lνlν

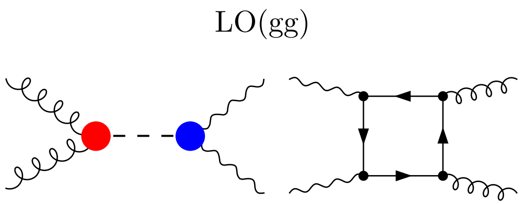
$$\sigma_{\mathrm{LO}}^{e\bar{\nu}_e\bar{\mu}\nu_\mu} = 0.719^{-0.045}_{+0.051}\,\mathrm{fb}, \qquad \sigma_{\mathrm{NLO}}^{e\bar{\nu}_e\bar{\mu}\nu_\mu} = 0.662^{+0.005}_{-0.012}\,\mathrm{fb}, \qquad \sigma_{\mathrm{NNLO}}^{e\bar{\nu}_e\bar{\mu}\nu_\mu} = 0.632^{+0.008}_{-0.008}\,\mathrm{fb}.$$

- Pattern of corrections similar to stable Higgs case
  - similar kinematics, interplay of fiducial cuts with QCD radiation minimal
- transverse momentum spectrum of charged lepton
  - flat K-factors at NLO and NNLO
  - could use inclusive K-factors for H→ lνlν decay channel



Signal–background interference

- Higgs width can not be directly measured, not even in clean $H\to\gamma\gamma$ or $H \to 4l$ modes
  - Higgs resonance too narrow for kinematical reconstruction of line-shape
  - Best constraints from indirect analyses (on-shell versus off-shell in $H \to 4l$)
    [CMS: 1706.09936,ATLAS:2207.00348]
- Alternative strategy for indirect determination of the Higgs decay width in $H\to\gamma\gamma$
  - Higgs production in gluon fusion and $H\to\gamma\gamma$ interferes with continuum background from loop-induced $gg\to\gamma\gamma$ (signal-background interference)
  - Di-photon invariant mass distribution is affected by this interference (shift of mass peak)
  - Mass shift is sensitive to Higgs width in the Higgs propagator



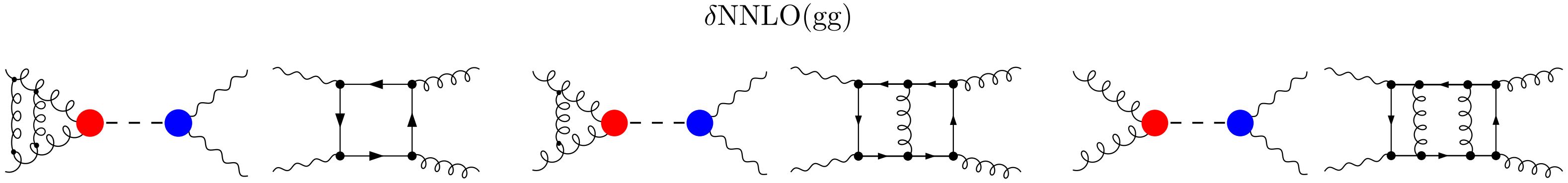
$$\mathcal{M}_{gg\to\gamma\gamma} = \frac{\mathcal{M}_{\rm sig}}{m_{\gamma\gamma}^2 - m_H^2 + i\Gamma_H m_H} + \mathcal{M}_{\rm bkg}$$

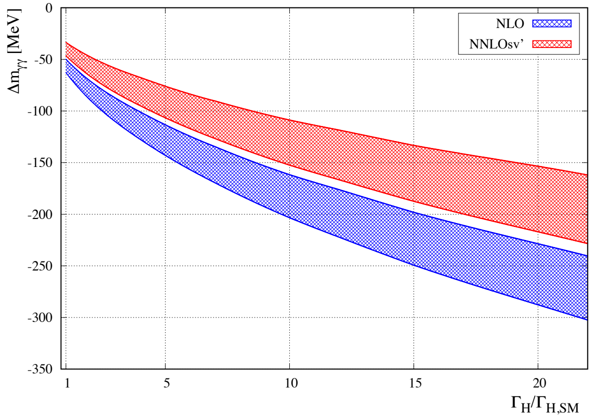
[Bargiela et al., 2212.06287]

Signal–background interference

- Require precise theory predictions for signal-background interference to extract the width from mass shift
  - for SM Higgs width, expect shift of up to 150 MeV at LO, with large uncertainty [Martin, 1208.1533]
  - previous NLO calculations found sizable effects O(40%) [Dixon, Li, 1305.3854, de Florian et al., 1303.1397]

- NNLO corrections to signal-background interference computed recently
  [Bargiela, Buccioni, Caola, Devoto, von Manteuffel, Tancredi, 2212.06287 and talk of F.Devoto]
  - contains three-loop gg→γγ amplitudes





mass shift as function of Higgs width

Conclusions and Outlook

- Important theory progress on precision predictions for various Higgs production modes and decay channels
- Higher order QCD corrections can have crucial impact on fiducial cross sections and distributions
  - predictions for realistic final states
  - case-by-case assessment needed
- Theory uncertainties approach per-cent level
  - keep in mind the full uncertainty budget from approximations made, PDFs, etc.
- Looking forward to an exciting Higgs Hunting 2023

THANK YOU !!