Karlsruhe Institute of Technology

Institute for Theoretical Particle Physics

Advances in Higgs Boson Theory

Higgs Hunting 2026, Paris, September 16, 2026

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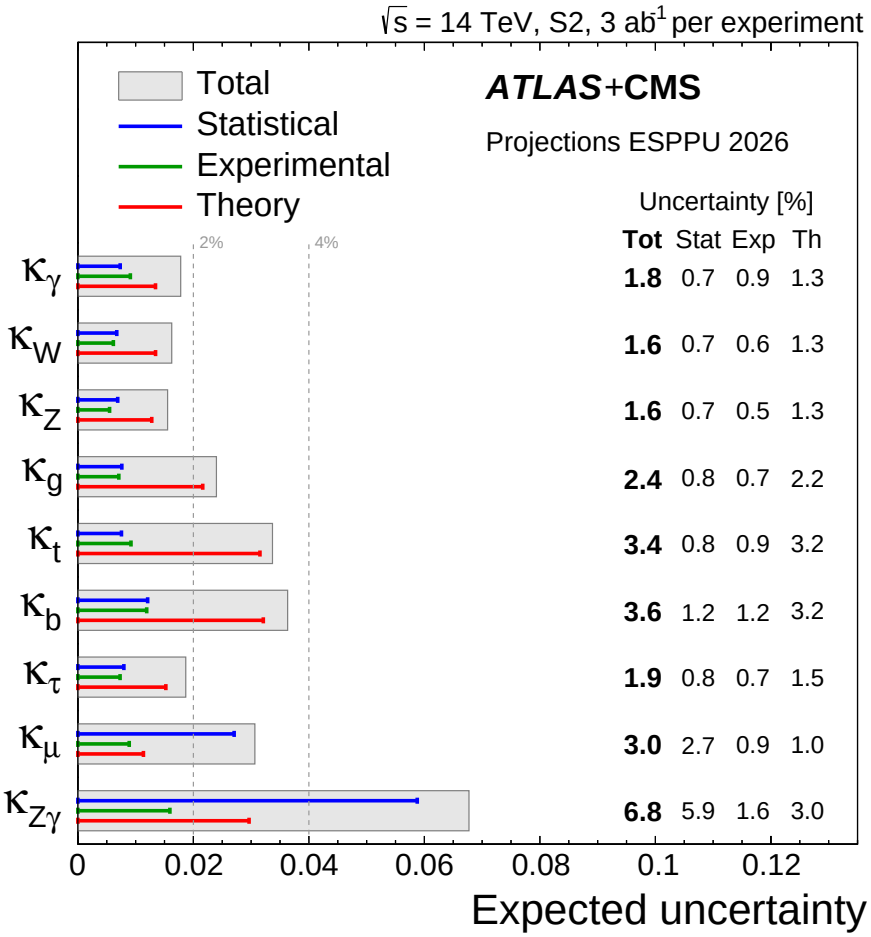
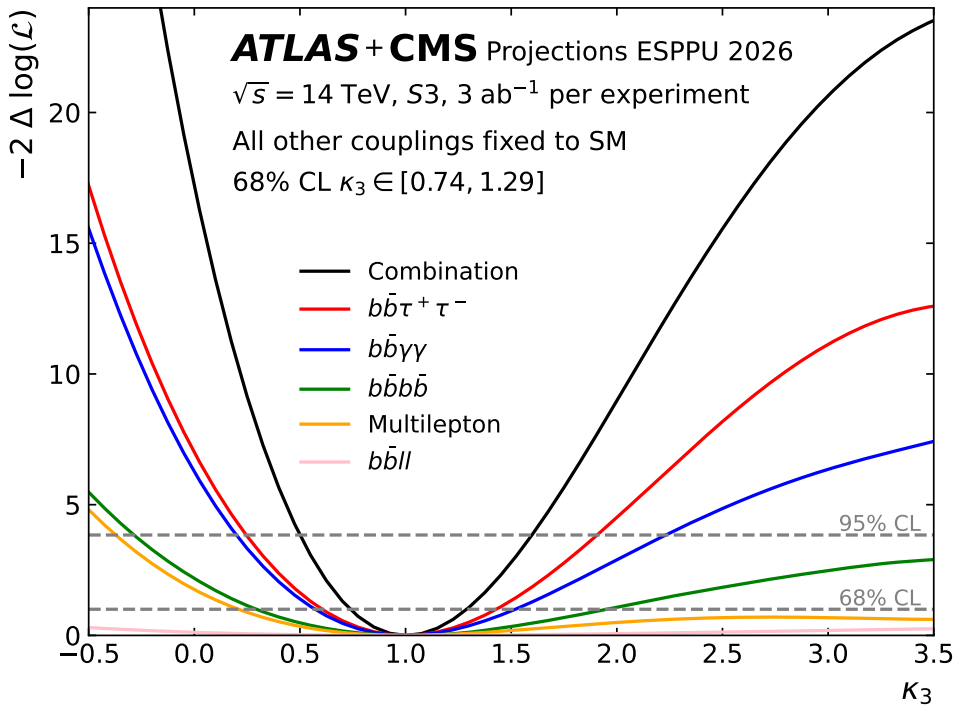
Purpose of this talk

- Progress in Higgs theory calculations
- New results from $\approx$ last year
- "Theoretical amplitudes" and "Phenomenological results"
- Disclaimer:
  personal selection of topics

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO_{QCD}^{(t,t\times b)}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}^{(HTL)}}$ $\mathrm{NLO_{QCD}}$	$\mathrm{N^4LO_{HTL}}$ (incl.)
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO_{QCD}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL}} \otimes \mathrm{LO_{QCD}}$ $\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ (incl.) $\mathrm{NNLO_{QCD}^{(VBF^*)}}$ $\mathrm{NLO_{EW}^{(VBF)}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ $\mathrm{NNLO_{QCD}^{(VBF)}}$ $\mathrm{NLO_{QCD}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO_{QCD}^{(VBF)}}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NNLO_{QCD}^{(VBF^*)}}$
$pp \to VH$	$\mathrm{N^3LO_{QCD}}$ (incl.) $+ \mathrm{NLO_{EW}}$ $\mathrm{NLO_{gg\to HZ}^{(t,b)}}$	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to VH + j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to HH$	$\mathrm{N^3LO_{HTL}} \otimes \mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to HH + 2j$	$\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ (incl.) $\mathrm{NNLO_{QCD}^{(VBF^*)}}$ $\mathrm{NLO_{EW}^{(VBF)}}$	$\mathrm{NLO_{QCD}}$
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	$\mathrm{NLO_{QCD}}$
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NNLO_{QCD}}$ (approx.)	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$

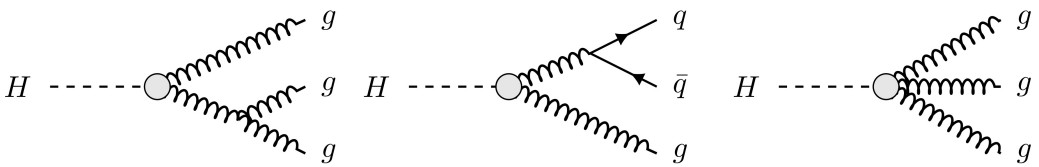
Higgs couplings: $\kappa = \frac{c_{\text{measure}}}{c_{\text{SM}}}$





H → 3 partons to 3 loops

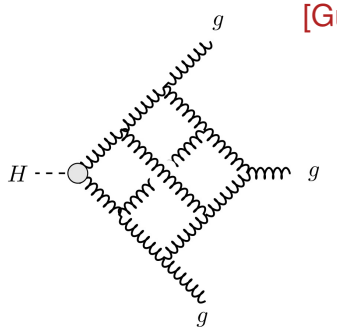
- 3-loop scattering amplitude, heavy-top-limit (HTL): *Hggg*, *Hqq̄g*



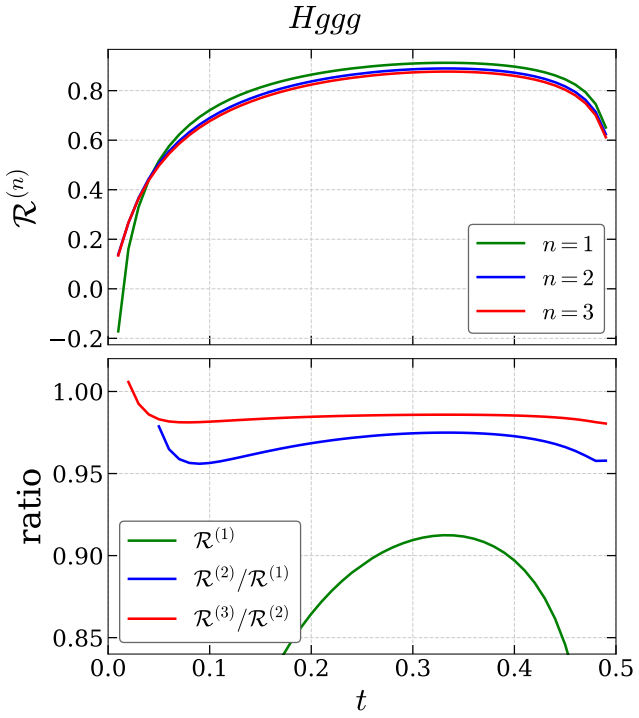
- virtual corrections for N^{3}LO H+jet
- contrib. to inclusive N^{4}LO H production
- *H* decay to jets

- 46 integral families, 250.000 integrals,
- Main bottleneck: integration-by-parts (IBP) reduction, `FINITEFLOW` [Peraro'19] and `Blade` [Guan,Liu,Ma,Wu'24]
- Analytic results; generalized polylogarithms
- Sub-leading colour contributions numerically important

[Guan,Mistlberger,Ruf'26]

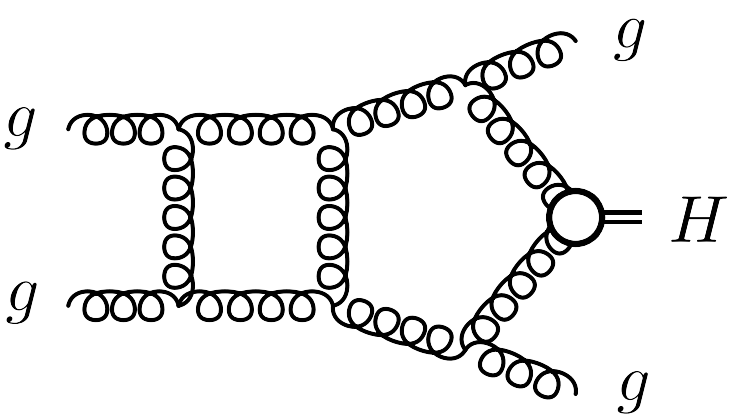


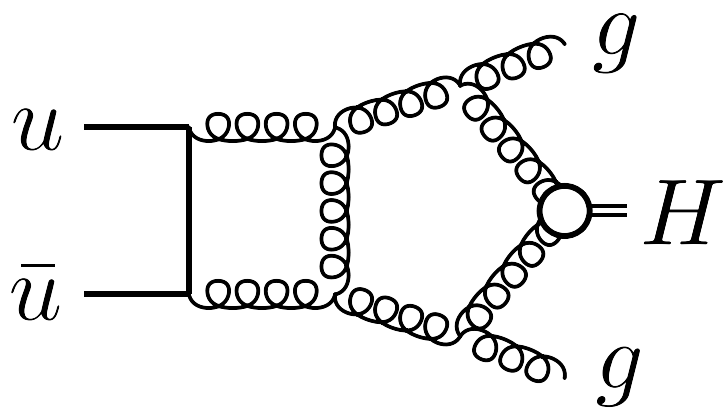
$$\mathcal{R}^{(n)} = \sum_k \left(\frac{\alpha_s}{\pi}\right)^k \mathrm{Re}\frac{\mathcal{M}^{(k)}}{\mathcal{M}^{(0)}}$$



Higgs + 2 jets

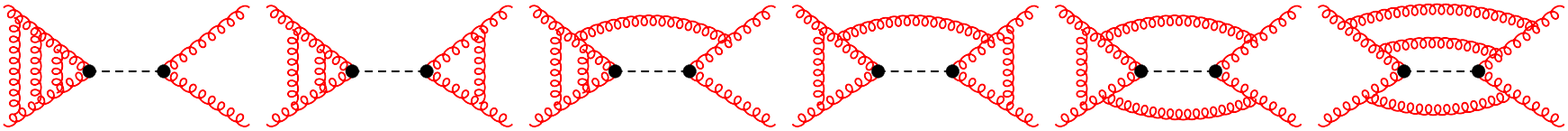
- $q\bar{q}/gg \to H + 2$ jets, HTL, leading colour [De Laurentis,Ita,Kuschke,Ruf,Sotnikov'26]
- Irreducible background to VBF H production
- NNLO virtual-virtual (VV) for $gg \to Hgg$ or $H \to 4$ jets
- 2-loop $2 \to 3$ with massive particle in final state
- Functional reconstruction in finite fields:
  perform numerical evaluation to obtain analytic result
- Analytic results for helicity amplitudes expressed in terms of "one-mass pentagon functions"
- Numerical evaluation: 1 to 10 seconds per phase-space point



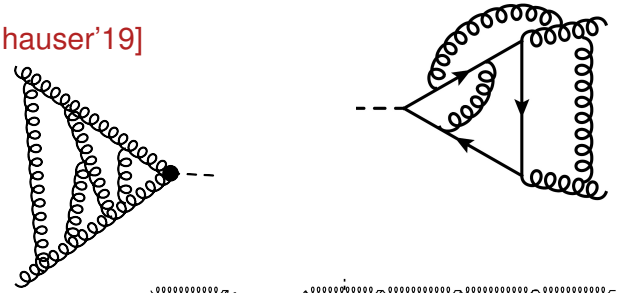


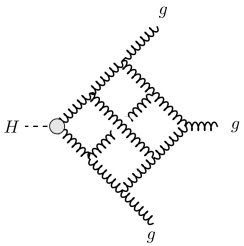
Inclusive H production: status

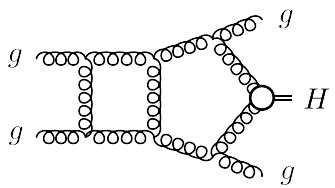
- m_t, m_b dependence at NNLO [Czakon,Harlander,Klappert,Niggetiedt'21; Czakon,Eschment,Niggetiedt,Poncelet,Schellenberger'24]
  - ➪ small for $\overline{\rm MS}$ bottom quark mass
- HTL up to N^{3}LO: [Anastasiou,Duhr,Dulat,Furlan,Gehrmann,Herzog,Lazopoulos,Mistlberger'16; Mistlberger'18]



  - ➪ $\delta_{\rm scale} \approx 3\%$
- finite-m_t terms for virtual N^{3}LO: [Davies,Herren,Steinhauser'19]
- N^{4}LO:
  - 4-loop Hgg form factor [Lee,von Manteuffel,Schabinger,Smirnov,Smirnov,Steinhauser'22]
  - "RVV x V" [Mistlberger,Suresh'25]
  - $Hggg$ and $Hq\bar{q}g$ amplitudes [Guan,Mistlberger,Ruf'26]
  - $gg \to Hgg$ at 2 loops [De Laurentis,Ita,Kuschke,Ruf,Sotnikov'26]
  - Soft-virtual approximation [Das,Moch,Vogt'20; Das,Moch'25]







Boosted Higgs-strahlung at N^{3}LO

- $pp \to W^+(\to e^+\nu_e)H$
- Boosted $H + W$ boson
- Large p_T of the H
  ➪ sensitivity to H couplings
- inclusive N^{3}LO: [Baglio,Duhr,Mistlberger,Szafron'22]
- Fully differential to N^{3}LO
- Method: q_T slicing [Catani,Grazzini'07]

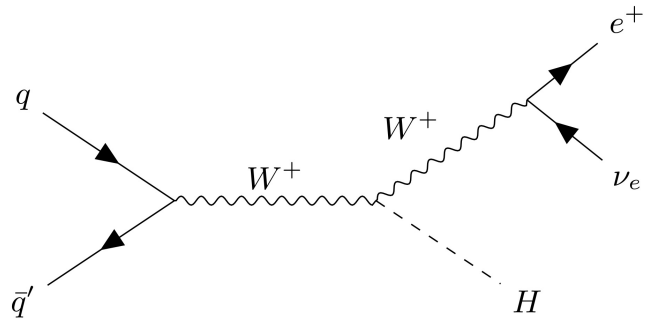
$$\sigma = \int_{q_T < q_T^{\rm cut}} \mathrm{d}\sigma^{\rm singular} + \int_{q_T > q_T^{\rm cut}} \mathrm{d}\sigma^{\rm regular}$$

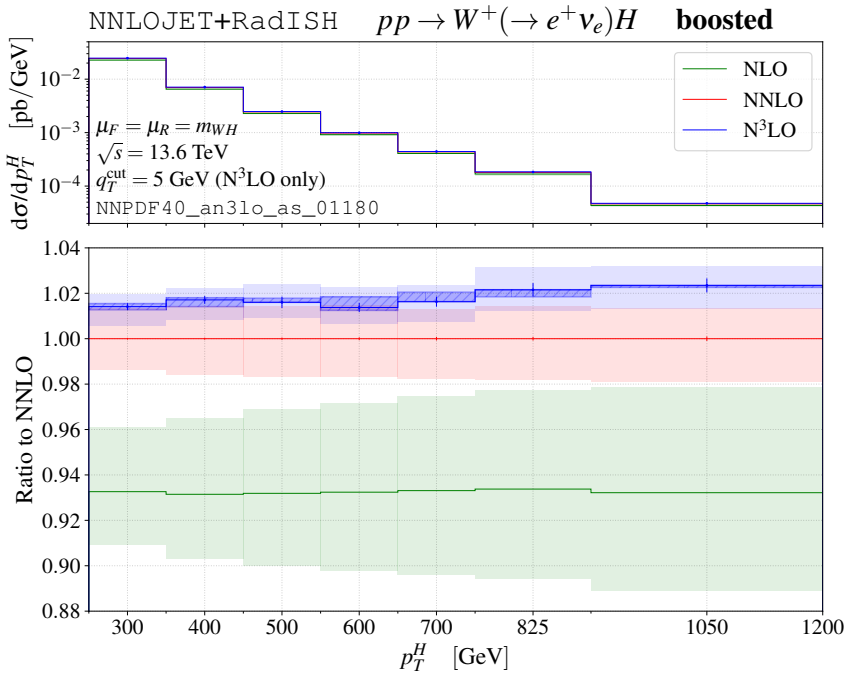
N^{3}LO, q_T resum.
RadISH [Monni et al.'16; Bizon et al.'17; Re et al'21]

NNLO $pp \to W^+H$+jet
NNLOJET [Huss et al.'25]

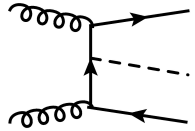
- N^{3}LO:
  - +2% in boosted regime
  - residual scale dependence below percent level

[Gehrmann-De Ridder,Huss,Marcoli,Monni,Re,Rottoli,Silvetti,Torrielli'26]

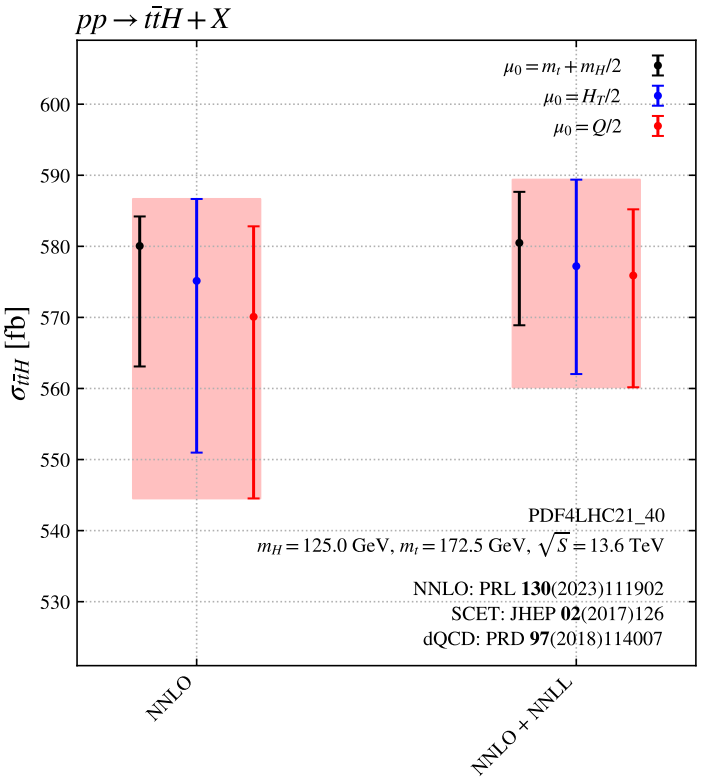


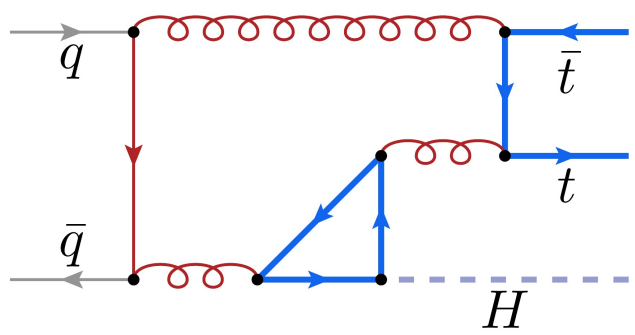


$pp \to t\bar{t}H$ at NNLO



- direct model-indep. determination of y_t
- NLO $>$ 20 years ago:
  [Beenakker,Dittmaier,Krämer,Plumper,Spira,Zerwas'02'03]
  [Dawson,(Orr),Reina,Wackeroth'02'03]
- NNLO bottleneck: 2-loop $2 \to 3$ with massive internal and external particles
- [Devoto,Grazzini,Kallweit,Mazzitelli,Savoini'24]: soft Higgs boson approximation $\otimes$ high-energy expansion in the small top-mass limit
- [Balsach et al.'25]: supplemented by NNLL soft-gluon resummation
- Full 2-loop calculation on the way
  [Cordero,Figueiredo,Kraus,Page,Reina'23]
  [Agarwal,Heinrich,Jones,Kerner,Klein,Lang,Magerya,Olsson'24]
  [Wang,Xia,Yang,Ye'24]
- NNLO event generation for $t\bar{t}H$: NNLO+PS, MiNNLO$_{\rm PS}$
  [Biello,Savoini,Signorile-Signorile,Wiesemann'26]

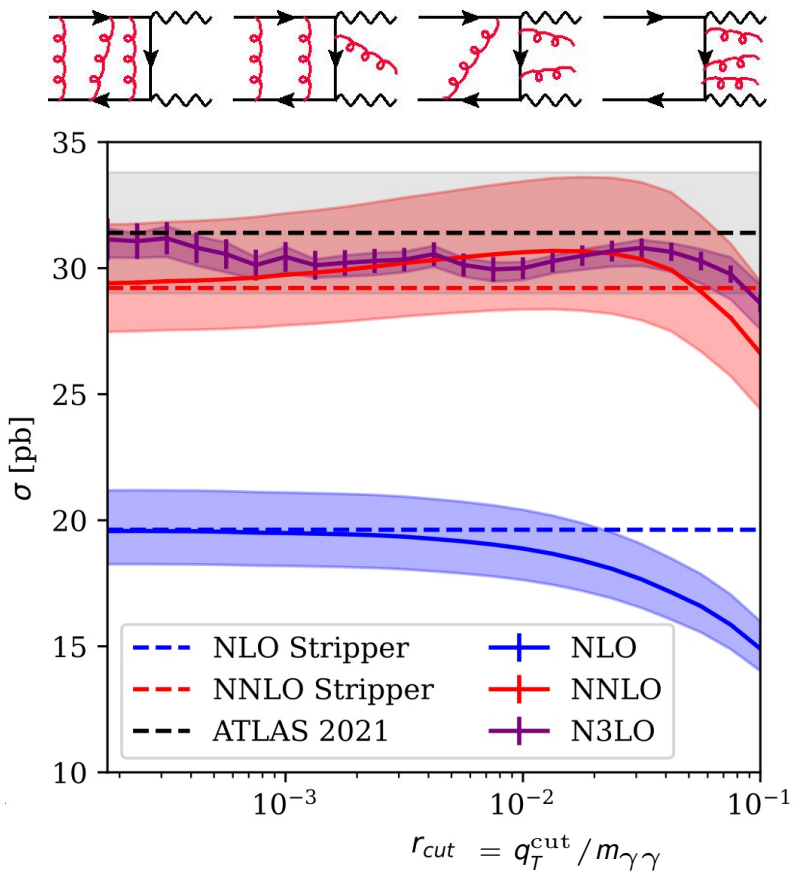




$pp \to \gamma\gamma$ to N^{3}LO

[Czakon,Eschment,Generet,Poncelet'26]

- Important background for $H \to \gamma\gamma$
- Large NLO and NNLO corrections
- Convergent behaviour after including N^{3}LO
- q_T slicing [Catani,Grazzini'07]:
  - $q_T = 0$ ➪ virtual N^{3}LO corrections [Caola,von Manteuffel,Tancredi'21]
  - $q_T \neq 0$ ➪ NNO $pp \to \gamma\gamma$+jet, STRIPPER [Czakon'10]
- Monte Carlo integration uncertainty $\approx$ renormalization scale uncertainty $\approx 2\%$
- First N^{3}LO QCD calculation with $2 \to 2$ kinematics
- Fiducial cuts:

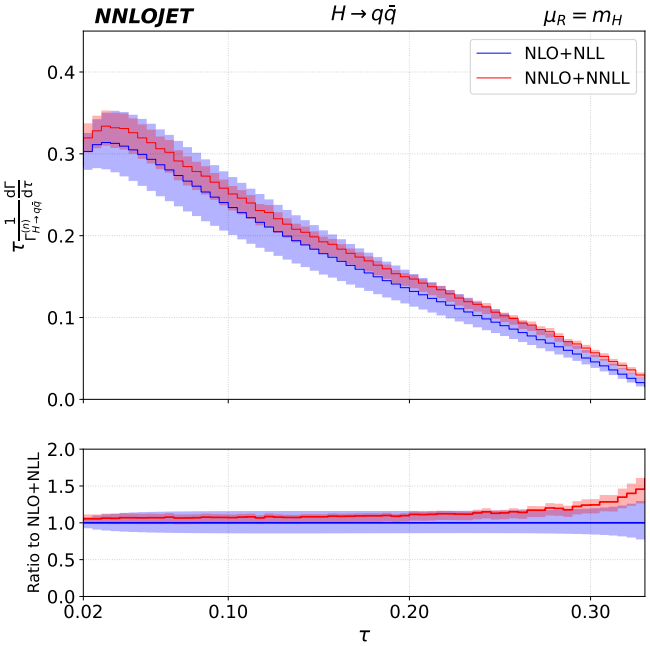


$$\sigma^{pp\to\gamma\gamma}_{\text{N}^3\text{LO}} = 31.2(6)^{+0.5}_{-0.7}\ \text{pb}$$
$$\sigma^{pp\to\gamma\gamma}_{\text{ATLAS}} = 31.4 \pm 0.1\ (\text{stat.}) \pm 2.4\ (\text{syst.})\ \text{pb}$$

H decay: event shapes to NNLO + NNLL

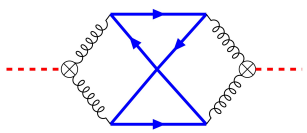
- Higgs factories: event shapes for hadronic Higgs decays: $H \to b\bar{b}$, $H \to gg$
- Thrust distribution τ
  $\tau = 0$: 2 back-to-back jets
  $\tau = 1/2$: isotropic event
- $\tau \to 0$: resummation of $\log(\tau)$ term needed
- NNLOJet [Huss et al.'25] for NNLO, ARES [Banfi et al.'14'18] framework for NNLL resummation
- (Essentially) positive corrections; reduced scale uncertainty as compared to NLO+NLL [Gehrmann-De Ridder,Preuss,Reichelt,Schumann'25]

[Fox,Gehrmann–De Ridder,Gehrmann,Glover,Marcoli,Preuss'25]



Further new results on Higgs boson decay:

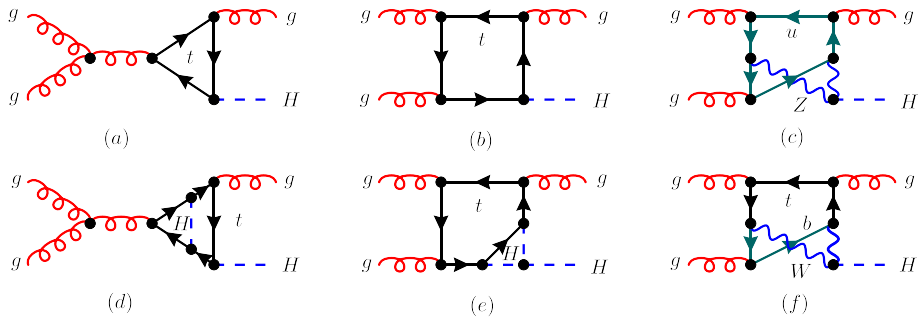
- [Wang,Wang,Wang'26] $\Gamma(H \to b\bar{b})$ to $\mathcal{O}(\alpha_s^4)$
  (no pure gg cuts)

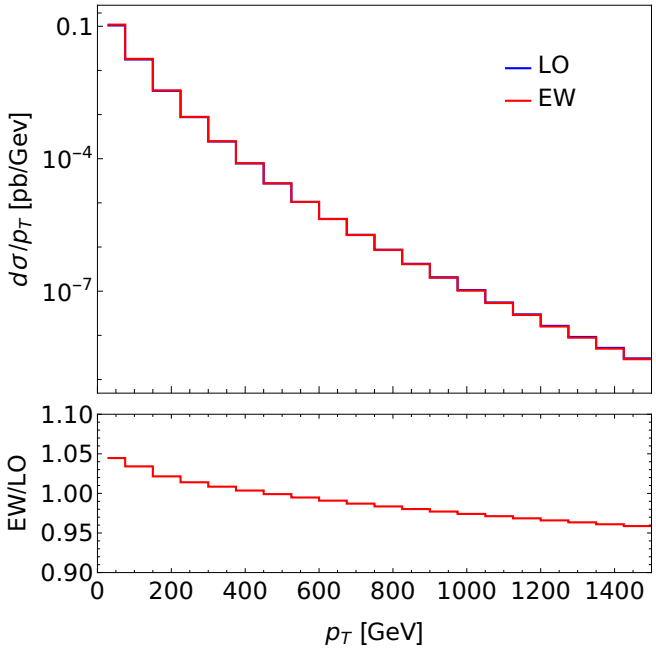


NLO EW corrections to H+jet

- $gg \to H+$ jet, NLO EW corrections
- [Chen,Li,Sang'25]
  - IBP reduction to 3.600 MIs
  - Numerical calculation of MIs
    DE + `AMFlow` [Liu,Ma'23]
- [Bi,Ma,Mu'25]
  - IBP reduction: Dimensional parameter $D = 4 - 2\epsilon$: $\epsilon = \pm 1/1000$
  - Cover phase-space with asymptotic expansions and interpolations
- MIs for fixed $\{m_W, m_Z, m_t, m_H\}$
- $+4\%$ for total cross section

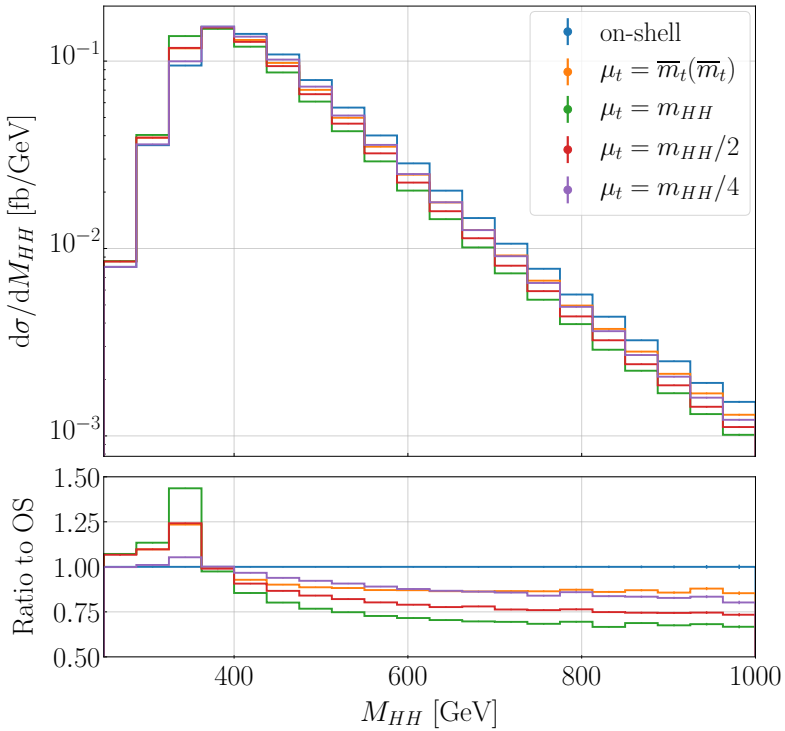
[Chen,Li,Sang'25],[Bi,Ma,Mu'25]



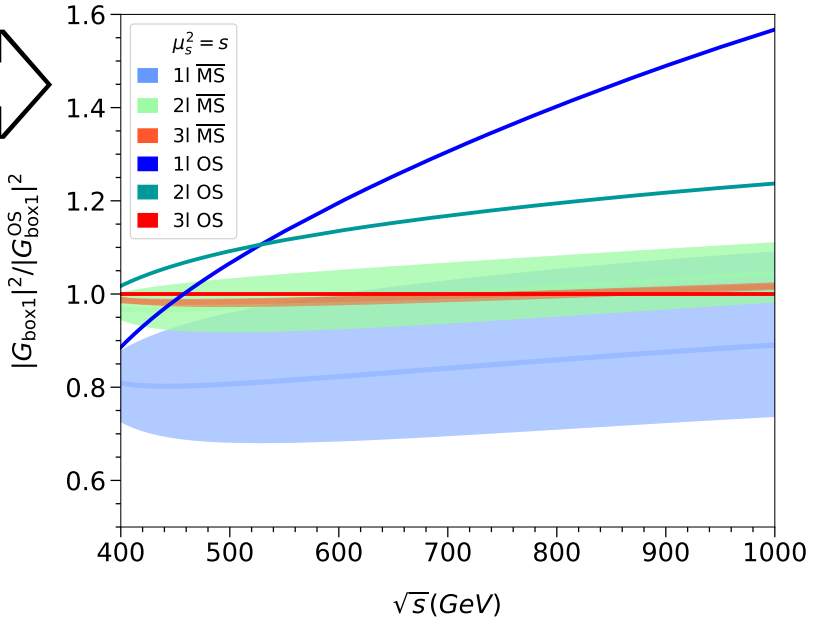


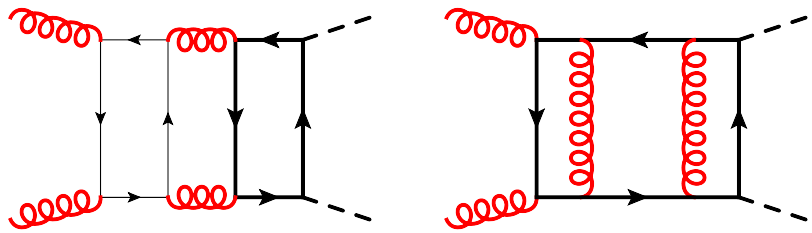
$gg \to HH$: Towards NNLO QCD

NLO



NNLO





[Davies,Schönwald,Steinhauser'23'25]

10-20% uncertainty

from m_t renormalization scheme

[Baglio,Campanario,Glaus,Mühlleitner,Ronca,Spira'20]

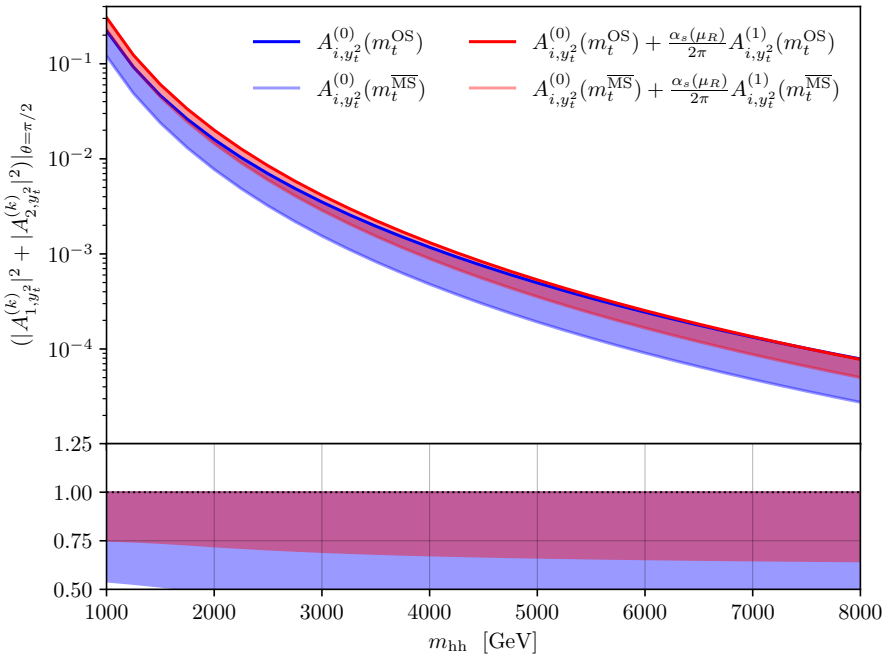
[Bagnaschi,Degrassi,Gröber'23]

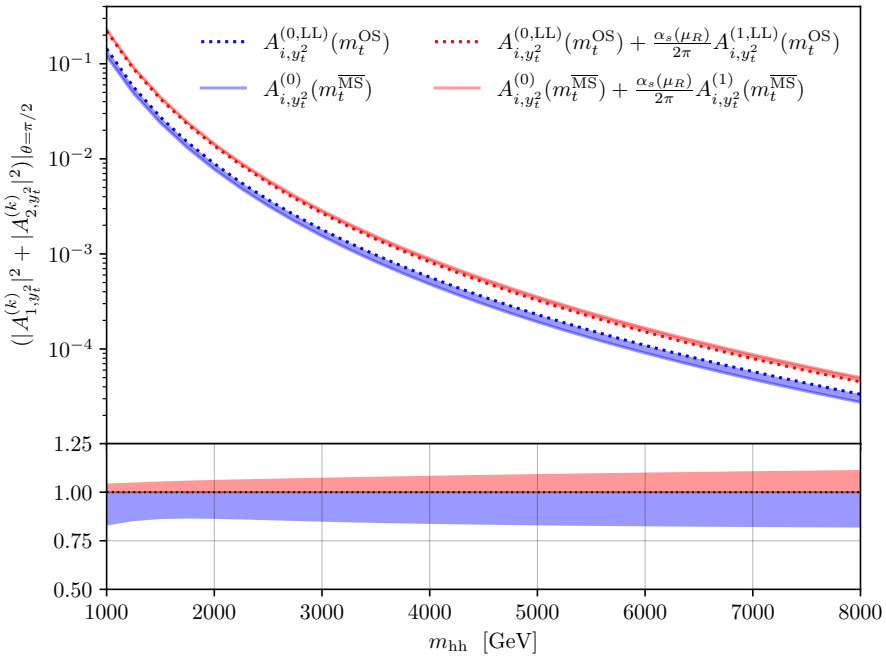
[Davies,Schönwald,Steinhauser,Stremmer'25]

Resummation at high energies

[Jaskiewicz,Jones,Szafron,Ulrich'24]

- Origin of large logarithms $\log(m_t^2/s)$ in leading $y_t^2 \sim m_t^2$ term: running of m_t
- Incorporate in OS result



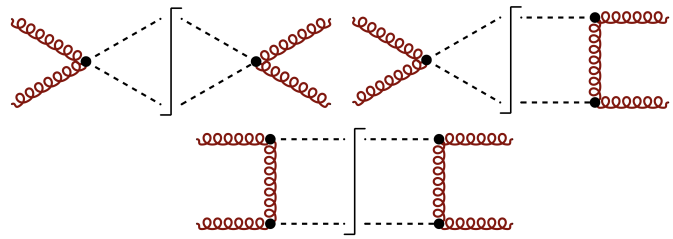


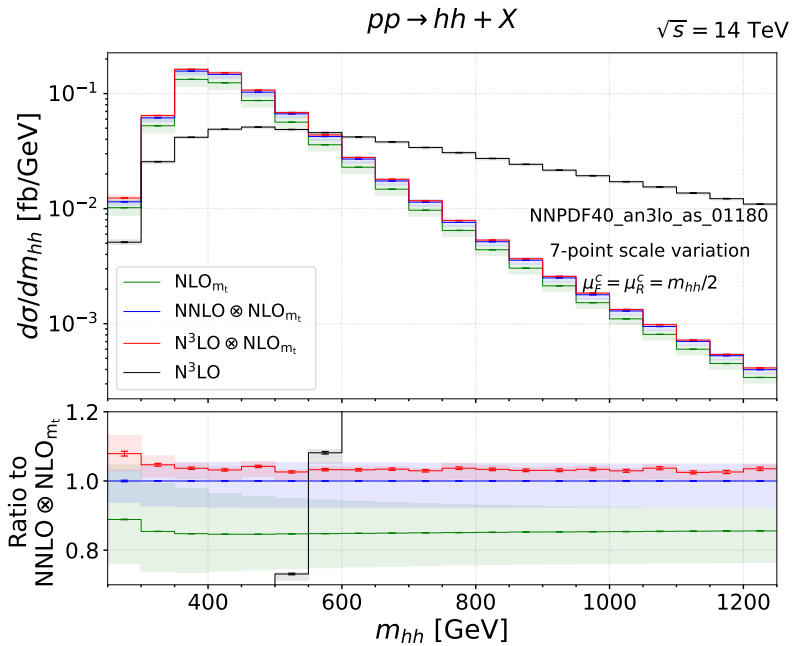
- Note: very high energies!
- Situation for physical relevant region ($m_{hh} \sim 300 - 800$ GeV) ?
- Real contributions neglected

$gg \to HH$: differential at N^{3}LO

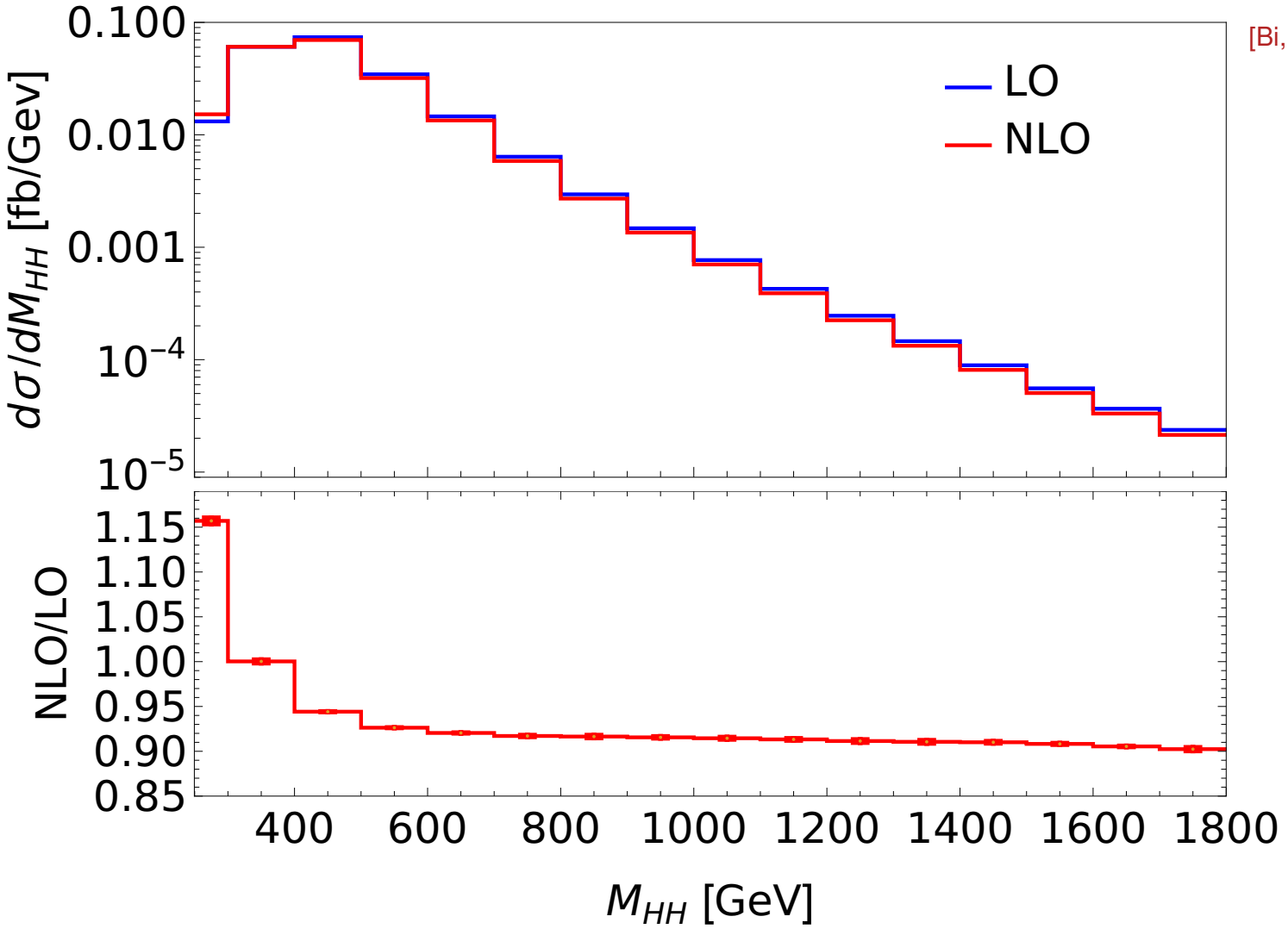
[Chen,Dai,Li,Li,Shao,Wang'26]

- Fully differential $gg \to HH$ at N^{3}LO
- HTL (at NNLO and N^{3}LO)
- Exact top quark mass effects up to NLO important
- Fiducial cross sections
- Factor-3 reduction of scale uncertainty





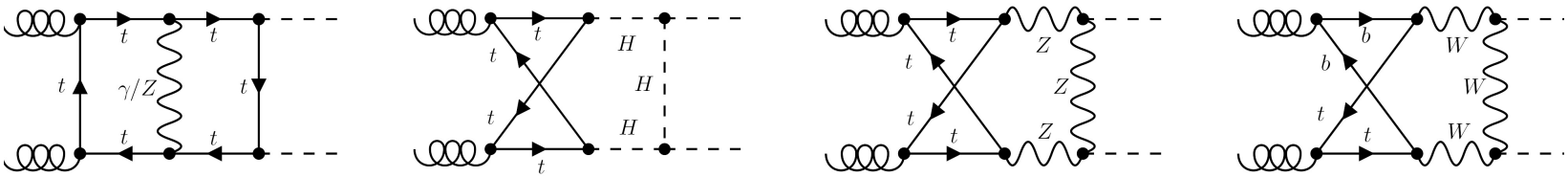
NLO EW corrections: $gg \to HH$



[Bi,Huang,Huang,Ma,Yu'24]

NLO EW corrections: $gg \to HH$

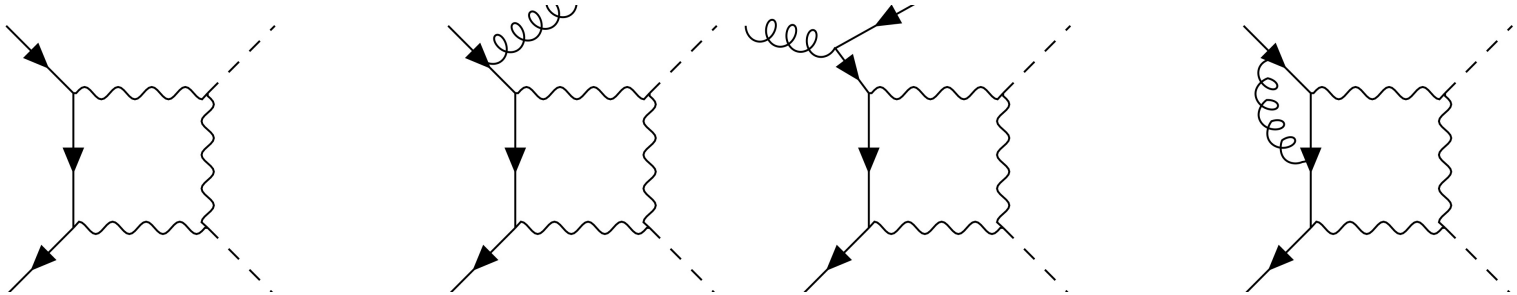
- [Bi,Huang,Huang,Ma,Yu'24]: Complete SM,
  But: numerical (fixed input parameters) ➪ not flexible
  Also: cross check needed
- (Different) numerical approach(es):
  [Heinrich,Jones,Kerner,Stone,Vestner'24;Bhattacharya,Campanario,Carlotti,Chang,Mazzitelli,Mühlleitner,Ronca,Spira'25]
  ➪ Partial results: (y_t, λ)
- Asymptotic (analytic) expansions [Davies,Mishima,Schönwald,Steinhauser,Zhang'22'23'25'26]
  ➪ Complete SM, in high-energy limit: $s, t \gg m_t^2, m_H^2$
  explicit dependence on all parameters, fast and flexible



- Light quarks [Bonetti,Rendler,Bobadilla'25; Bonetti,Heinrich,Rendler,Bobadilla'26; Bhattacharya et al.'25]

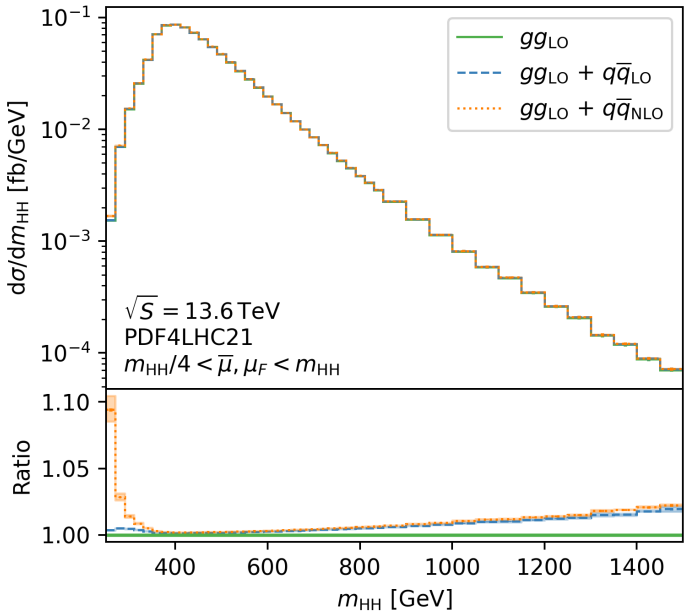
NLO EW corrections: $q\bar{q} \to HH$

[Bonetti,Heinrich,Rendler,Bobadilla'26]



- Light-quark channel
- analytic NLO virtual corrections

  [Bonetti,Rendler,Bobadilla'25; Bonetti,Heinrich,Rendler,Bobadilla'26]
- σ_{tot}: $\mathcal{O}(1\%)$
- larger impact on differential observables



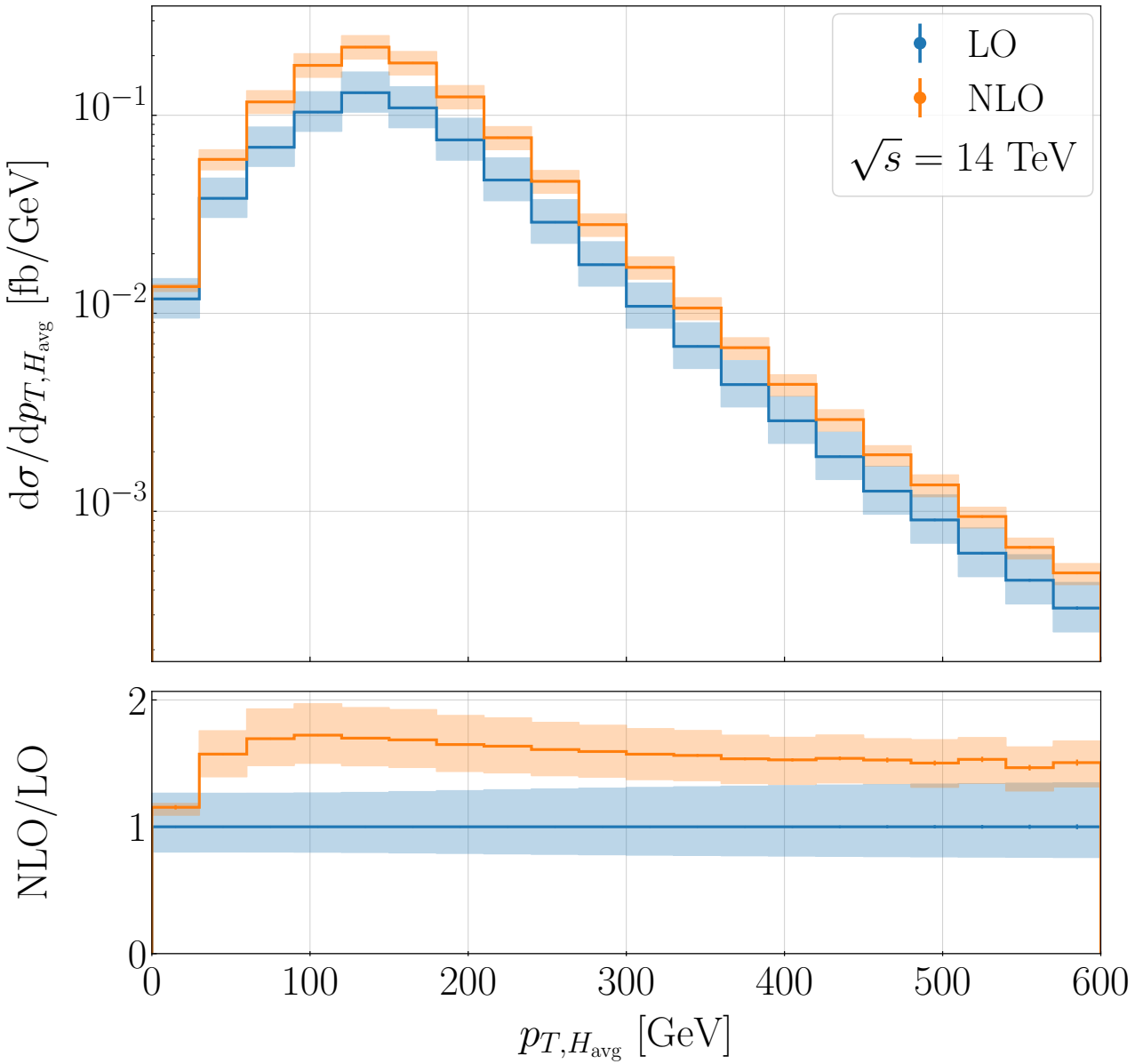
ggxy

[Davies,Schönwald,Steinhauser,Stremmer'25]

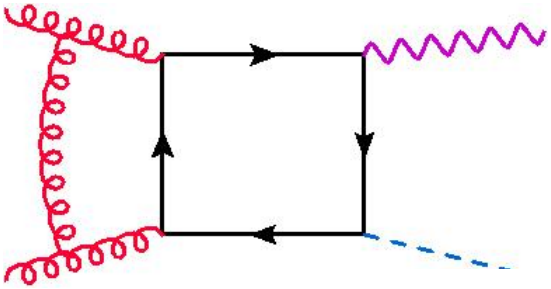
- C++ library
- $gg \to HH$, $gg \to ZH$, (soon: $gg \to ZZ$, $gg \to WW$, $gg \to Hg$)
- POWHEG interface ➪ parton showers with Pythia
- Features: total and differential cross sections,
  parameter variation (e.g. $m_t, m_H, \lambda, \ldots$),
  OS and $\overline{\rm MS}$ scheme for m_t, ...
- Typical runtime: $\approx$ 30 minutes (single core) to obtain a statistical uncertainty of 0.2% (including 7-point scale variation)
- Virtual corrections: analytic expansions in various regions in phase space
- Real corrections: Recola [Actis,Denner,(Lang,)Hofer,Scharf,Uccirati'12'16]

https://gitlab.com/ggxy/ggxy-release

ggxy: p_T distribution for $gg \to HH$



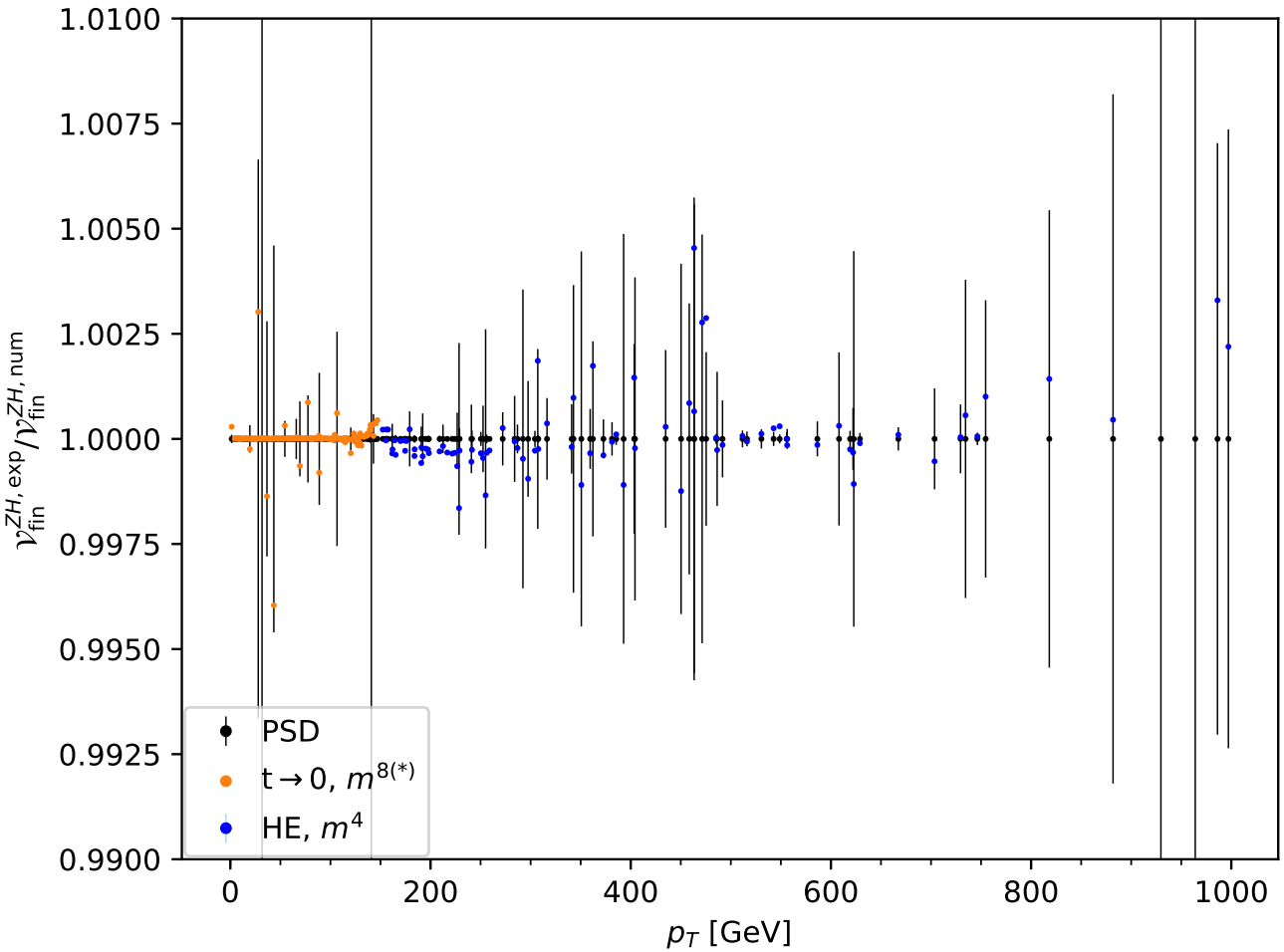
NLO virtual corrections for $gg \to ZH$



Compare: numerical vs. analytic approach (ggxy)

numerical results from: [Chen,Heinrich,Jones,Kerner,Klappert,Schlenk'20]

Analytic expansions: [Davies,Grau,Schönwald,Steinhauser,Stremmer,Vitti'25]



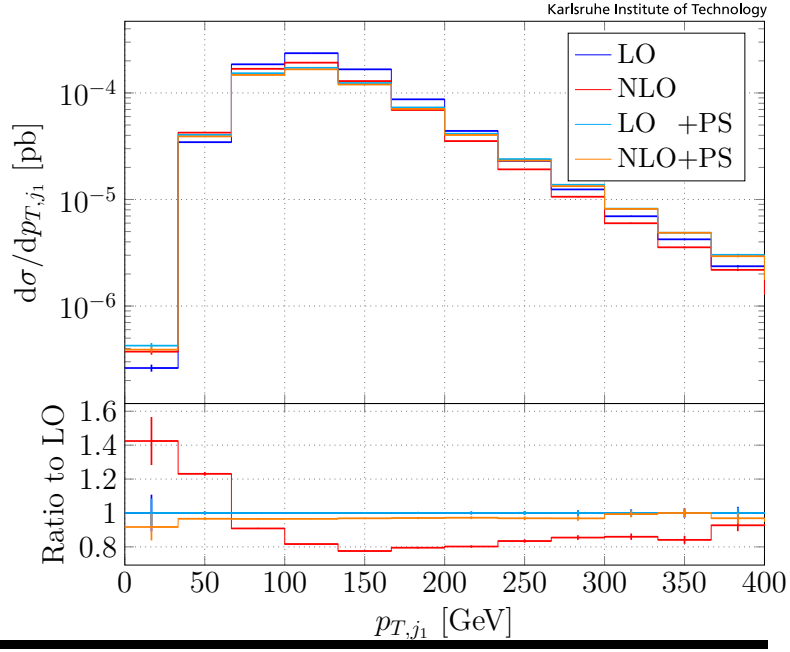
Importance of parton showers

- $gg \to HH \to b\bar{b}\gamma\gamma$
- FO: Large QCD corrections ($\mathcal{O}(20\%)$) for fiducial cross section

  [Li,Si,Wang,Zhang,Zhao'24]
- Washed out by parton showers

  [Braun,Fontes,Heinrich'25]

  (POWHEG, Herwig, Rivet)



- VBF $\to H \to b\bar{b}$, high p_T cut
- NNLO, fidutial cross section: -40%

  [Asteriadis,Behring,Melnikov,Novikov,Röntsch'24]
- Use parton showers

  ($\hat{=}$ resummation of large QCD effects)

  [Behring,Melnikov,Novikov,Zanderighi'25]

  (POWHEG, Pythia, MiNNLO)

σ/fb	fixed order	LO+PS	MiNNLO+PS
LO	75.6	46.6	45.2
NLO	52.4	43.6(1)	42.3
NNLO	44.6(1)	43.1(1)	41.4(1)

Conclusions

- Impressive new recent results
- Many technical developments
- New tools
- Multi-loop-multi-leg amplitudes
- Fiducial cross sections

Les Houches Wishlist ➪

[Huss,Huston,Jones,Pellen,Röntsch'25]

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO_{QCD}^{(t,t\times b)}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}^{(HTL)}}$ $\mathrm{NLO_{QCD}}$	$\mathrm{N^4LO_{HTL}}$ (incl.)
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO_{QCD}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL}} \otimes \mathrm{LO_{QCD}}$ $\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ (incl.) $\mathrm{NNLO_{QCD}^{(VBF^*)}}$ $\mathrm{NLO_{EW}^{(VBF)}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ $\mathrm{NNLO_{QCD}^{(VBF)}}$ $\mathrm{NLO_{QCD}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO_{QCD}^{(VBF)}}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NNLO_{QCD}^{(VBF^*)}}$
$pp \to VH$	$\mathrm{N^3LO_{QCD}}$ (incl.) $+ \mathrm{NLO_{EW}}$ $\mathrm{NLO_{gg\to HZ}^{(t,b)}}$	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to VH + j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to HH$	$\mathrm{N^3LO_{HTL}} \otimes \mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to HH + 2j$	$\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ (incl.) $\mathrm{NNLO_{QCD}^{(VBF^*)}}$ $\mathrm{NLO_{EW}^{(VBF)}}$	$\mathrm{NLO_{QCD}}$
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	$\mathrm{NLO_{QCD}}$
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NNLO_{QCD}}$ (approx.)	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$