VH: theory

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CERN & LAPTh Annecy

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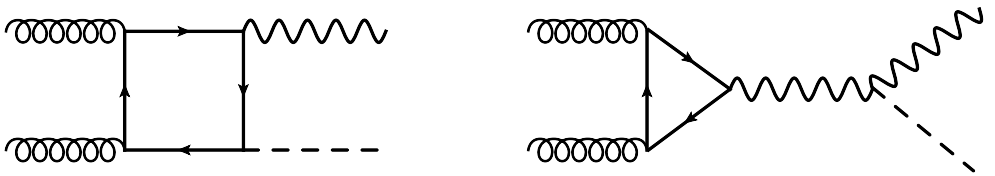
$pp \to VH$: production

- QCD NNLO correction to production
  - inclusive (+ NLO EW): `vh@nnlo` [Brein et al.]
  - differential: 3 groups [Ferrera et al. '11-'17 [HVNNLO], Campbell et al. '16 [MCFM], Caola et al. '17]
- in general, NNLO corrections moderate
- $gg \to HZ$ (NNLO) term sizeable above $t\bar{t}$ threshold



  - responsible for the dominant uncertainty

WH

$\sqrt{s}$[TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$[pb]	Δ_{scale}[%]	$\Delta_{\text{PDF}\oplus\alpha_s}$[%]
13	1.358	$^{+0.51}_{-0.51}$	1.35
14	1.498	$^{+0.51}_{-0.51}$	1.35
27	3.397	$^{+0.29}_{-0.72}$	1.37

ZH

$\sqrt{s}$[TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$[pb]	Δ_{scale}[%]	$\Delta_{\text{PDF}\oplus\alpha_s}$[%]
13	0.880	$^{+3.50}_{-2.68}$	1.65
14	0.981	$^{+3.61}_{-2.94}$	1.90
27	2.463	$^{+5.42}_{-4.00}$	2.24

[updated numbers by A. Mueck for HL/HE studies]

- $gg \to HZ$ at NLO with full mass dependence is one of the TH priorities

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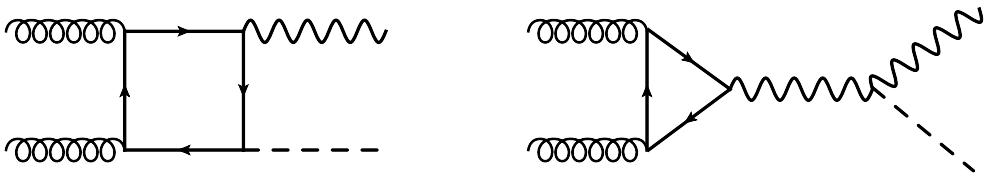


  - responsible for the dominant uncertainty especially in the boosted regime

Fiducial cross section	MCFM-8.0
no $gg \to$ HZ	$7.14^{+0.5\%}_{-0.9\%}$ fb
with $gg \to$ HZ	$7.92^{+2.0\%}_{-1.5\%}$ fb
no $gg \to$ HZ, high-$p_{t,Z}$	$1.21^{+0.1\%}_{-0.2\%}$ fb
with $gg \to$ HZ, high-$p_{t,Z}$	$1.49^{+5.3\%}_{-4.1\%}$ fb

- $gg \to HZ$ at NLO with full mass dependence is one of the TH priorities

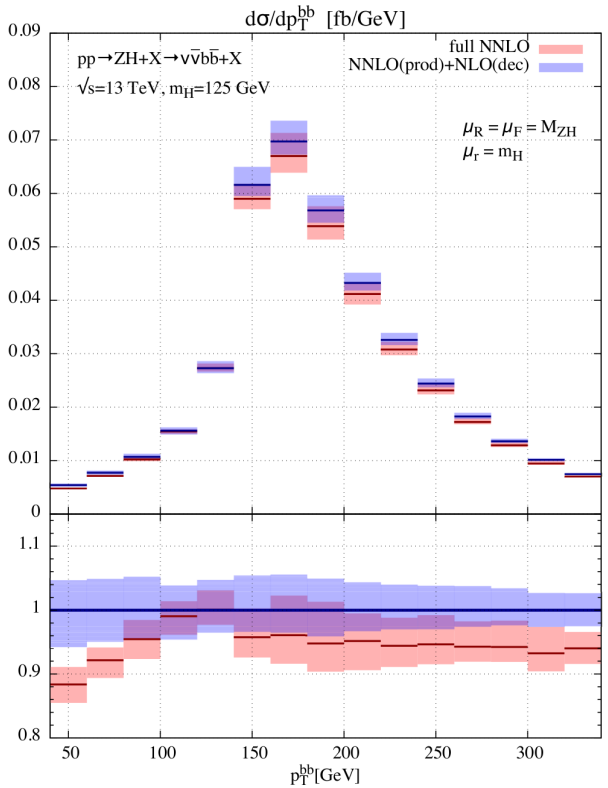
$pp \to VH$: the $H \to b\bar{b}$ decay

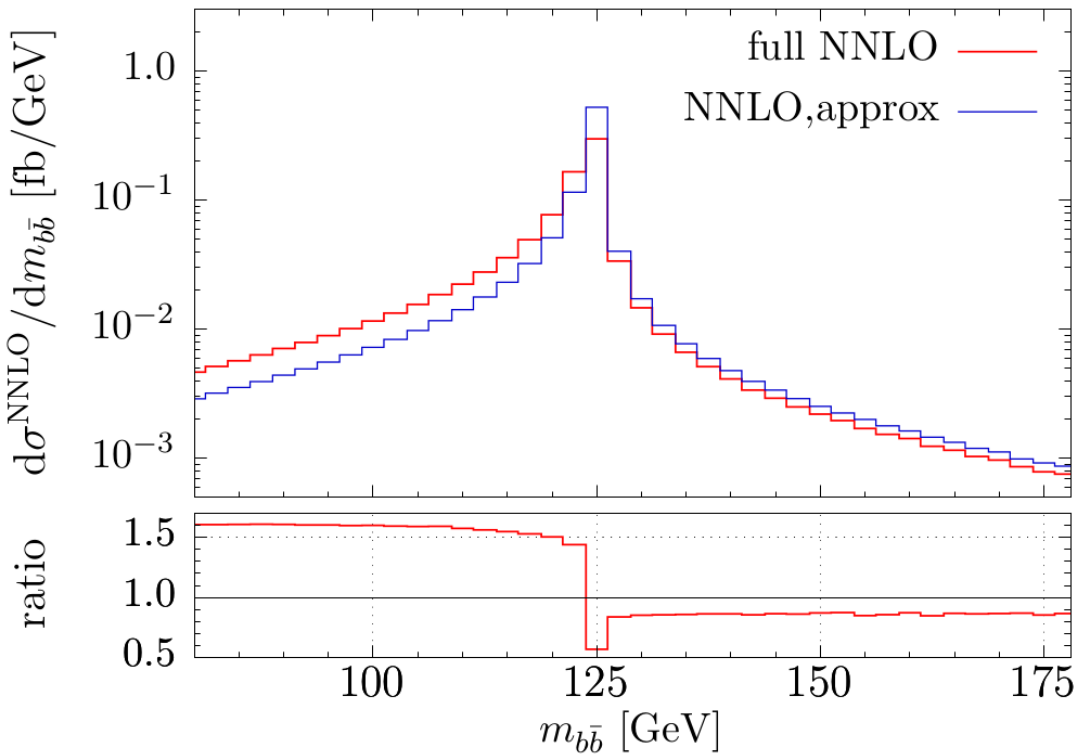
- NNLO QCD corrections to $H \to bb$: 2 groups, massless b-quarks

[Anastasiou et al. '12, Del Duca et al. '15]

- More recently, included in fully-differential NNLO computation (NNLO QCD for production and decay)

[Ferrera et al. '17. Caola et al. '17]



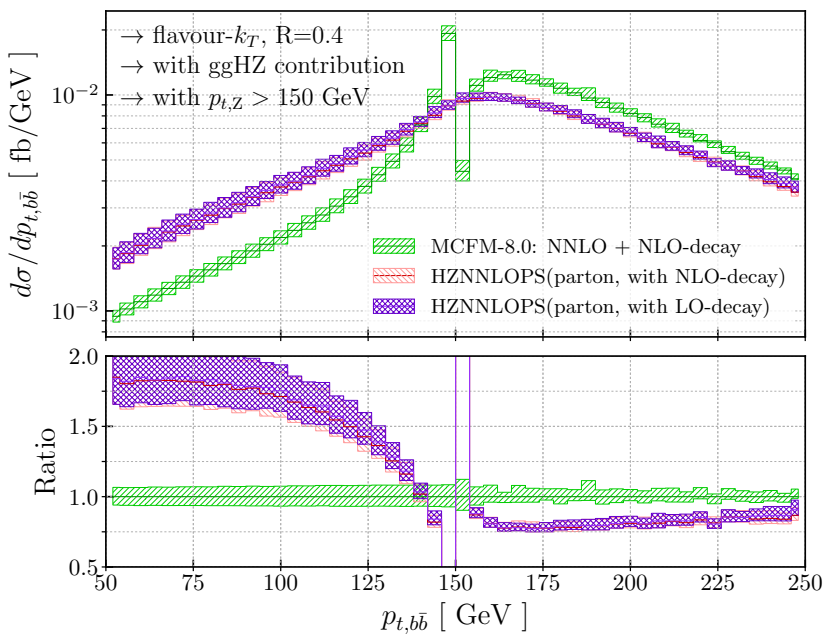


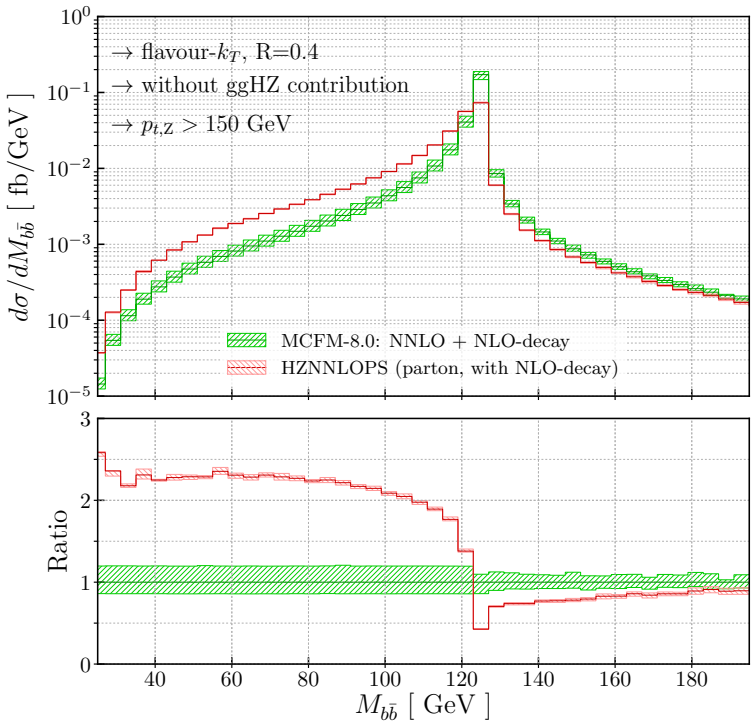
- large corrections mostly in regions not populated at LO
  ($\to$ K-factors depend on cuts. Dominated by extra emissions in decay.)
- there's ongoing work to compute NNLO corrections to the decay with massive b

[e.g. Bernreuther et al. '18]

$pp \to VH$: event generators

- NLO+PS (POWHEG or MC@NLO) available with many generators
- more recent developments:
  1. VH and VH+jet: NLO QCD + NLO EW + PS [Granata et al. '17]
  2. NNLOPS with NLO $H \to b\bar{b}$ decay [Astill et al. '16-'18]
     - MCFM (HVNNLO) as input for NNLO ; POWHEG-BOX-RES (with MiNLO) to deal with NLO corrections in production and decay.
     - $gg \to HZ$ included (with m_t-dependence, but just at LO, no extra partons in fixed-order part)

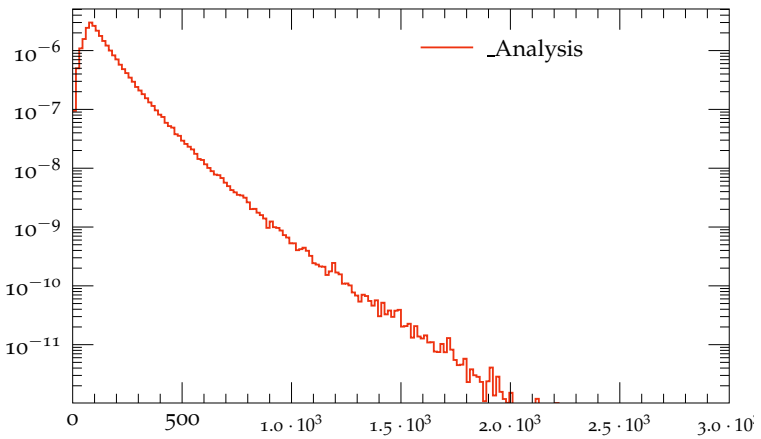


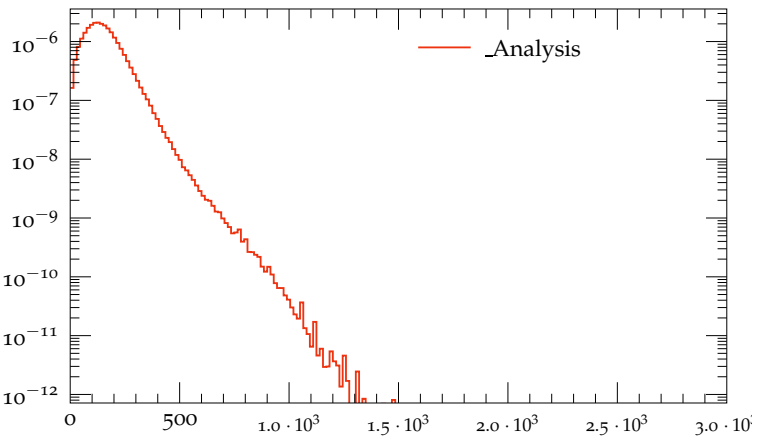


- in absence of a "(NNLO QCD+NLO EW)+PS tool", 1. could also be used to compute EW differential rescaling as: (MiNLO + NLO EW) / (MiNLO without EW)

$gg \to HZ$

- at NNLO, the $gg \to HZ$ contribution is effectively a "LO" term, but quite relevant, especially in boosted regime
  - currently this is included in EXP analysis at LO (with m_t dependence), and the total cross-section is rescaled to an approximate NLO+NLL results (fully inclusive, $m_t \to \infty$) [Altenkamp et al. '12, Harlander et al '14]
- more differential results exist, where 0 and 1 jet merging is performed at LO
- desirable to compare currently used results (LO+PS) against LO merging of the 0 and 1 jet (loop-induced) processes
- ongoing activity in VH group:





[PRELIMINARY results by S. Kuttimalai. More to come.]

- "final result" should come from an exact NLO computation...

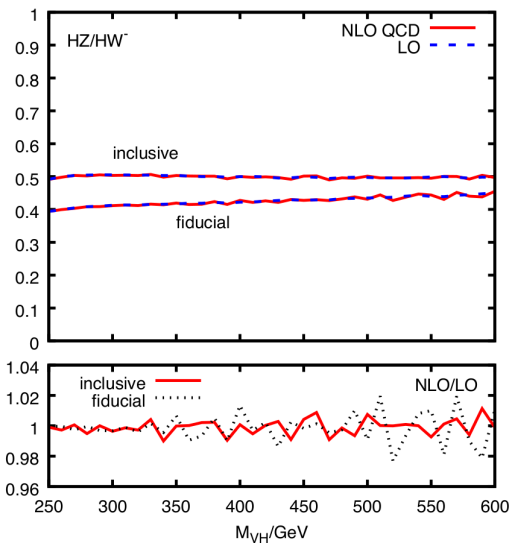
$gg \to HZ$: new TH/EXP ideas

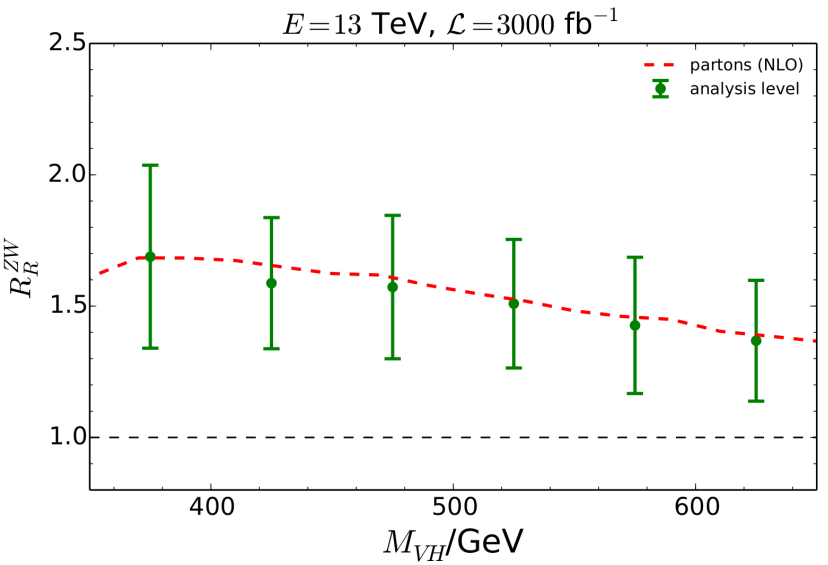
[Harlander,Klappert,Pandini,Papaefstathiou '18]

- data-driven strategy to isolate $gg \to HZ$ for associated HZ at NNLO
- based on comparison of the ZH to the WH cross section, as a function of M_{HV}
- define $R_{\rm DY}^{ZH} = \dfrac{\sigma^{ZH}}{\sigma_{\rm DY}^{ZH}}$ and use $R_R^{ZW} = \dfrac{\sigma^{ZH}/\sigma^{WH}}{\sigma_{\rm DY}^{ZH}/\sigma^{WH}}$

→ denominator from SM TH, very robust (left)

→ numerator measured from data ; pheno study, at hadron level, using 1- and 2-leptons channels with realistic cuts





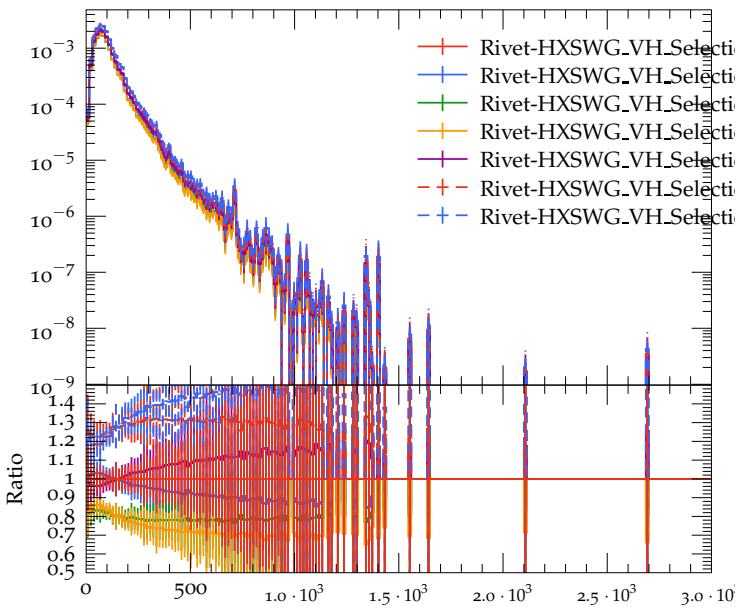
- $gg \to ZH$ in the SM: can be established at the $\sim 3.2\sigma$ level, at the HL-LHC

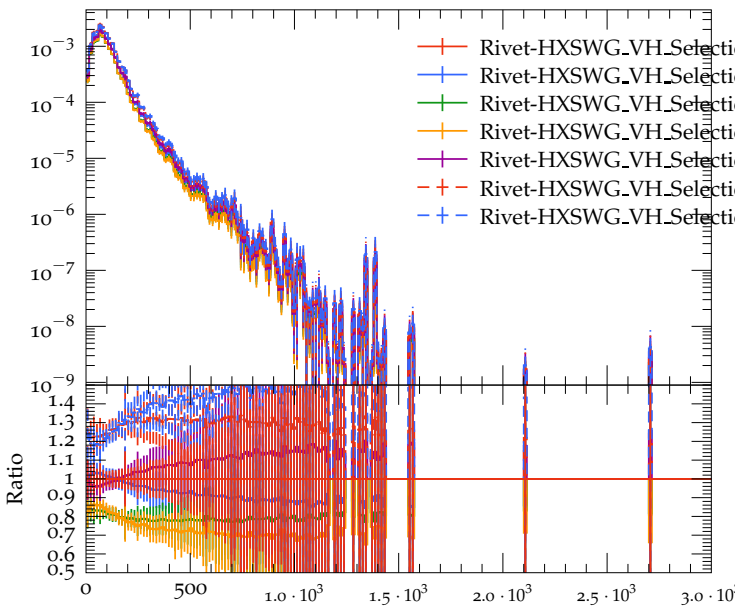
→ potentially better if using also 0-lepton channel

→ assessing BSM effects requires better control of $gg \to ZH$ (NLO).

$pp \to V + b\bar{b}$

- V + heavy flavour production is one of the main backgrounds to $pp \to VH(\to b\bar{b})$.
- study more precisely its impact (and uncertainties thereof) in the signal region
- ongoing activity in VH group: comparison between the currently-used tools, and several, more accurate, predictions.
  - for instance, currently in ATLAS: `Sherpa MEPS@NLO (5FS)` vs. `MG+PY8 (5FS, CKKW)`





[PRELIMINARY results for $W^+b\bar{b}$ at NLO+PS; thanks to L. Buonocore, C. Oleari, F. Tramontano. More to come.]

conclusions

- we have taken part in the activities for the HL/HE report
  [thanks to the HAWK team - A. Mueck in particular - for their help]
- we started 2 MC studies, with the pragmatic approach of addressing to which extent tools currently used in ATLAS and CMS are doing a good job, compared to more advanced ones; at least for the $gg \to HZ$ study, we hope to get results soon.
- TH improvements for the future:
  - probaly the priority is the computation of $gg \to HZ$ at NLO
  - there's work in progress on the computation of the $H \to b\bar{b}$ decay at NNLO with massive b-quarks
  - NNLOPS with NNLO decay should be feasible

Thanks for your attention

Extra slides

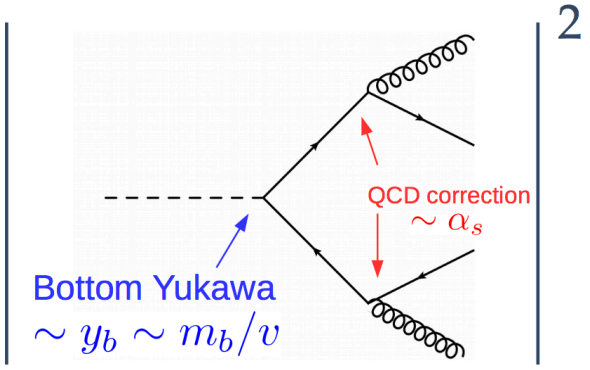
Caola et al 1712.06954

Decay in the massless approximation: extract Yukawa and then set $m_b = 0$

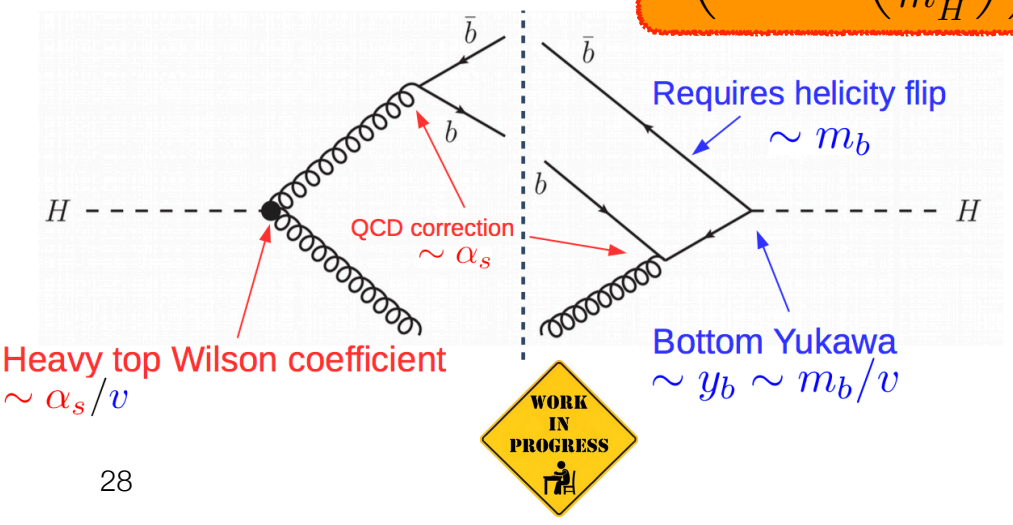
$$\Gamma_{H\to bb} = y_b^2 \left(\Gamma_{m_b=0} + \mathcal{O}\left(\frac{m_b^2}{m_H^2} \right) \right)$$

Above works at LO and NLO, but fails at NNLO as it neglects contributions that are of the same order, i.e. $y_b^2 \alpha_s^2$, that arise in diagrams with a helicity flip (and hence a mass insertion)

Standard NNLO correction: $\mathcal{O}(y_b^2 \alpha_s^2)$



New NNLO contribution: $\mathcal{O}\left(y_b^2 \alpha_s^2 \ln\left(\frac{m_b^2}{m_H^2} \right) \right)$



28

slide from G. Zanderighi talk at Higgs Couplings 2018