# NLO+PS study of $b\bar{b}H$ background to HH production

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# Introduction

- Lots of recent progress on the theoretical predictions for HH production ...
- ... but we need a good description of the backgrounds as well!

Due to the smallness of the HH signal, having the backgrounds under control becomes especially relevant

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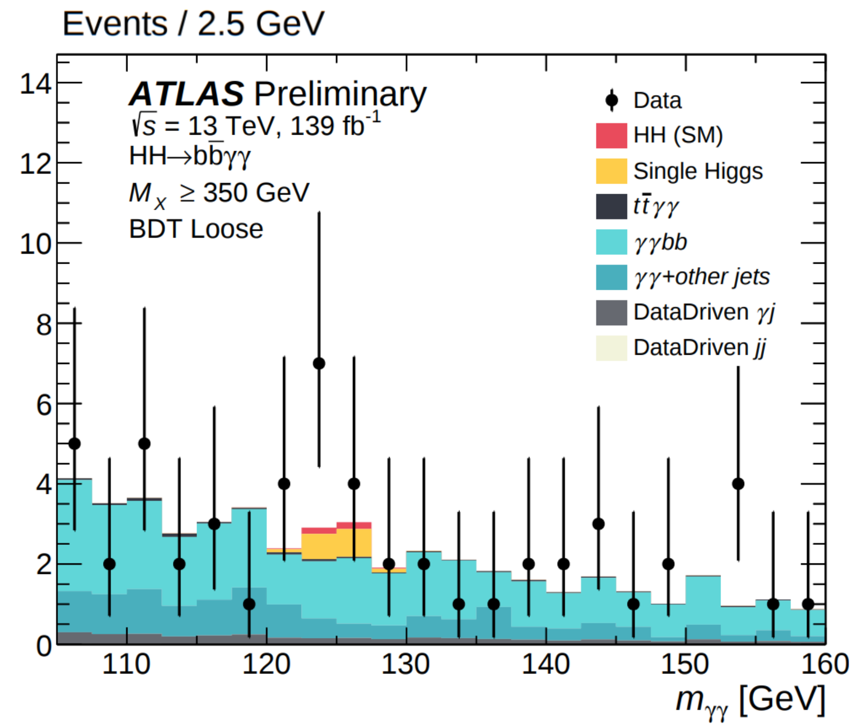
Uncertainties in the background estimation can lead to large reductions of the significance




- In addition, we are typically interested in corners of the background PS

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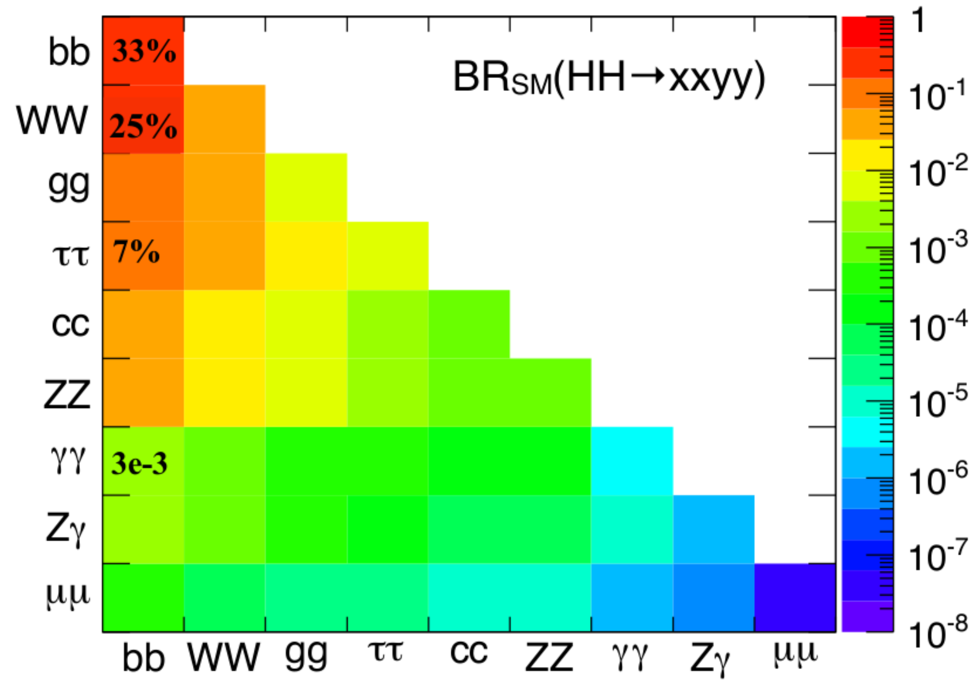
Fully differential higher-order corrections are crucial

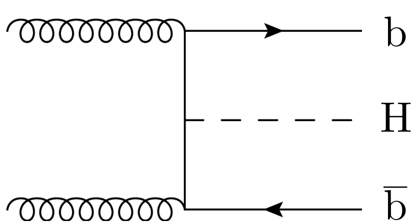
# The $b\bar{b}H$ background

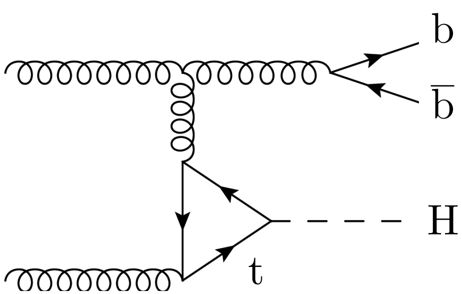
- Typically interested in this column to have a decent number of signal events




- Single Higgs production in association with a bottom pair is an irreducible background to all H(→bb)H(→xx) searches

- Working in the 4FS (massive b's) we have two different types of contributions:




(Also VBF and VH type of contributions exist, but they are suppressed)

$\mathcal{O}(\alpha_s^2 y_b^2)$ $\mathcal{O}(\alpha_s^4 y_t^2)$ → Strong coupling suppression but top-Yukawa enhancement

- Top-Yukawa contribution currently simulated using ggF NNLOPS → Only LO accurate in 2 jets configuration

- A 'conservative' 100% uncertainty is assigned to this background

# The $b\bar{b}H$ background

- This is not a small contribution when compared to the signal!

$b\bar{b}\gamma\gamma$ search [from ATLAS-CONF-2021-016] [Note: only MC uncertainties are quoted]

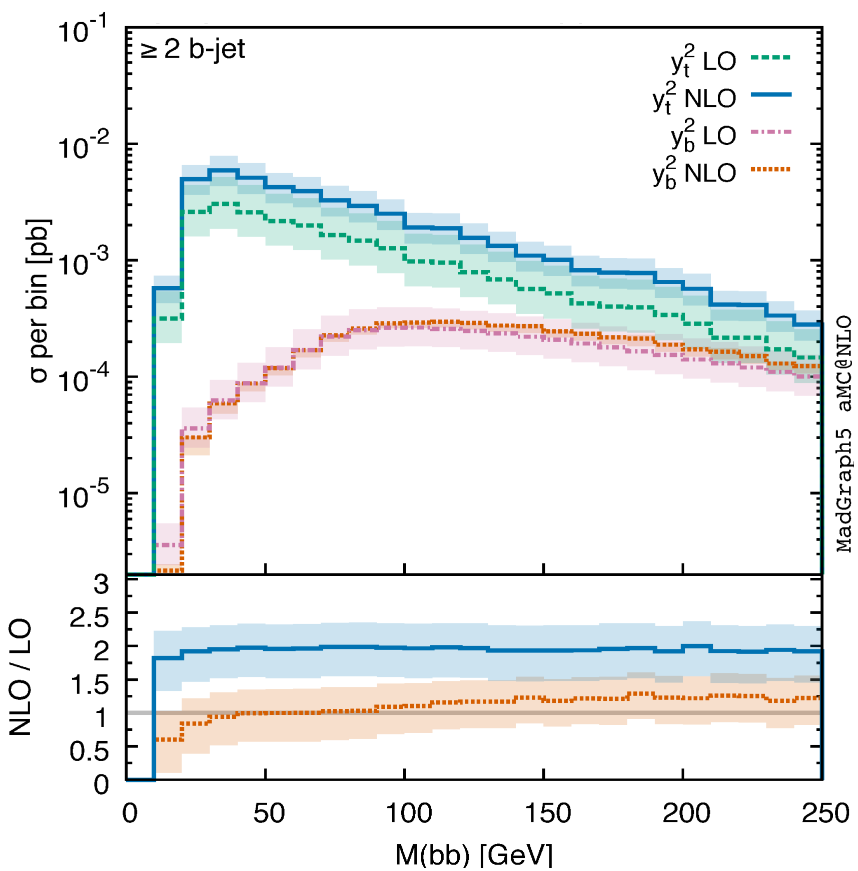
| | High mass BDT tight | High mass BDT loose | Low mass BDT tight | Low mass BDT loose |
|---|---|---|---|---|
| Continuum background | 4.9 ± 1.1 | 9.5 ± 1.5 | 3.7 ± 1.0 | 24.9 ± 2.5 |
| Single Higgs boson background | 0.670 ± 0.032 | 1.57 ± 0.04 | 0.220 ± 0.016 | 1.39 ± 0.04 |
| ggF | 0.261 ± 0.028 | 0.44 ± 0.04 | 0.063 ± 0.014 | 0.274 ± 0.030 |
| $t\bar{t}H$ | 0.1929 ± 0.0045 | 0.491 ± 0.007 | 0.1074 ± 0.0033 | 0.742 ± 0.009 |
| $ZH$ | 0.142 ± 0.005 | 0.486 ± 0.010 | 0.04019 ± 0.0027 | 0.269 ± 0.007 |
| Rest | 0.074 ± 0.012 | 0.155 ± 0.020 | 0.008 ± 0.006 | 0.109 ± 0.016 |
| SM $HH$ signal | 0.8753 ± 0.0032 | 0.3680 ± 0.0020 | $(49.4 \pm 0.7) \cdot 10^{-3}$ | $(78.7 \pm 0.9) \cdot 10^{-3}$ |
| ggF | 0.8626 ± 0.0032 | 0.3518 ± 0.0020 | $(46.1 \pm 0.7) \cdot 10^{-3}$ | $(71.8 \pm 0.9) \cdot 10^{-3}$ |
| VBF | 0.01266 ± 0.00016 | 0.01618 ± 0.00018 | $(3.22 \pm 0.08) \cdot 10^{-3}$ | $(6.923 \pm 0.011) \cdot 10^{-3}$ |
| Alternative $HH(\kappa_\lambda = 10)$ signal | 6.36 ± 0.05 | 3.691 ± 0.038 | 4.65 ± 0.04 | 8.64 ± 0.06 |
| Data | 2 | 17 | 5 | 14 |

- A better description will be necessary for future experimental measurements
- This motivates the use of NLO predictions for the $b\bar{b}H$ background

Note on conventions: when I talk about $b\bar{b}H$ background, I mean both $y_b$ and $y_t$ contributions. In the experiment these backgrounds are usually dubbed $b\bar{b}H$ and ggF, respectively. Also note that I talk about NLO predictions, since the LO is already $b\bar{b}H$. Not to be confused with the 'NNLO' results used to estimate the $b\bar{b}H(y_t)$ background, for which the LO is inclusive H

# $b\bar{b}H$ at NLO

- NLO corrections to bbH have been computed within MadGraph5_aMC@NLO
  [Deutschmann, Maltoni, Wiesemann, Zaro, 1808.01660]
- Both bottom and top Yukawa contributions, and their interference, have been included
- Top Yukawa contributions computed in the heavy top limit (HTL)




- Top Yukawa contribution dominant, while $y_t$-$y_b$ interference subleading
- Large K-factors (~2-3), with strong dependence on the fiducial cuts
- Still sizeable scale uncertainties, especially for the $y_t$ contribution
- From a LO comparison, the HTL seems to be a reliable approximation

No specific analysis targeting the HH signal region
No study on the matching to parton showers
→ Topic of this talk

[Carminati, Manzoni, Mazzeo, JM, Turra, Wiesemann, Zaro, in preparation]

# Setup

- We follow the approach of 1808.01660
  - $b\bar{b}H$ at NLO in QCD
  - Massive bottoms (4FS)
  - HTL for $y_t$ contributions

- We set $m_b$=4.92GeV, $m_t$=172.5GeV, $m_H$=125GeV, use NNPDF31_nlo_as_0118_nf_4
- Central scale (renorm/fact/shower): $H_T/4 = 1/4 \sum m_T(i)$
- We consider Higgs decays to two photons
- For simplicity, we generate the $y_b^2$ and $y_t^2$ distributions (interference subleading)
- We consider the following set of cuts, inspired in $HH \to b\bar{b}\gamma\gamma$ analysis:

Fiducial cuts

Anti-kT jets with R=0.4, $p_T(j)>25$GeV, $|\eta(j)|<2.5$

b-tagged if at least one B hadron among constituents

Exactly 2 b jets and 2 photons required

The b-jets must satisfy: 80GeV$<m(b_1,b_2)<$140GeV

The photons must satisfy: 105GeV$<m(\gamma_1,\gamma_2)<$160GeV, $|\eta(\gamma_i)|<2.37$

$p_T(\gamma_1)/m(\gamma_1,\gamma_2)>0.35$, $p_T(\gamma_2)/m(\gamma_1,\gamma_2)>0.25$

We consider $m^*_{2b2\gamma} = m_{2b2\gamma} - m(b_1,b_2) - m(\gamma_1,\gamma_2) + 2\, m_H$ and the three possibilities: $m^*_{2b2\gamma}<$350GeV, $m^*_{2b2\gamma}<$500GeV and no-$m^*_{2b2\gamma}$ cut

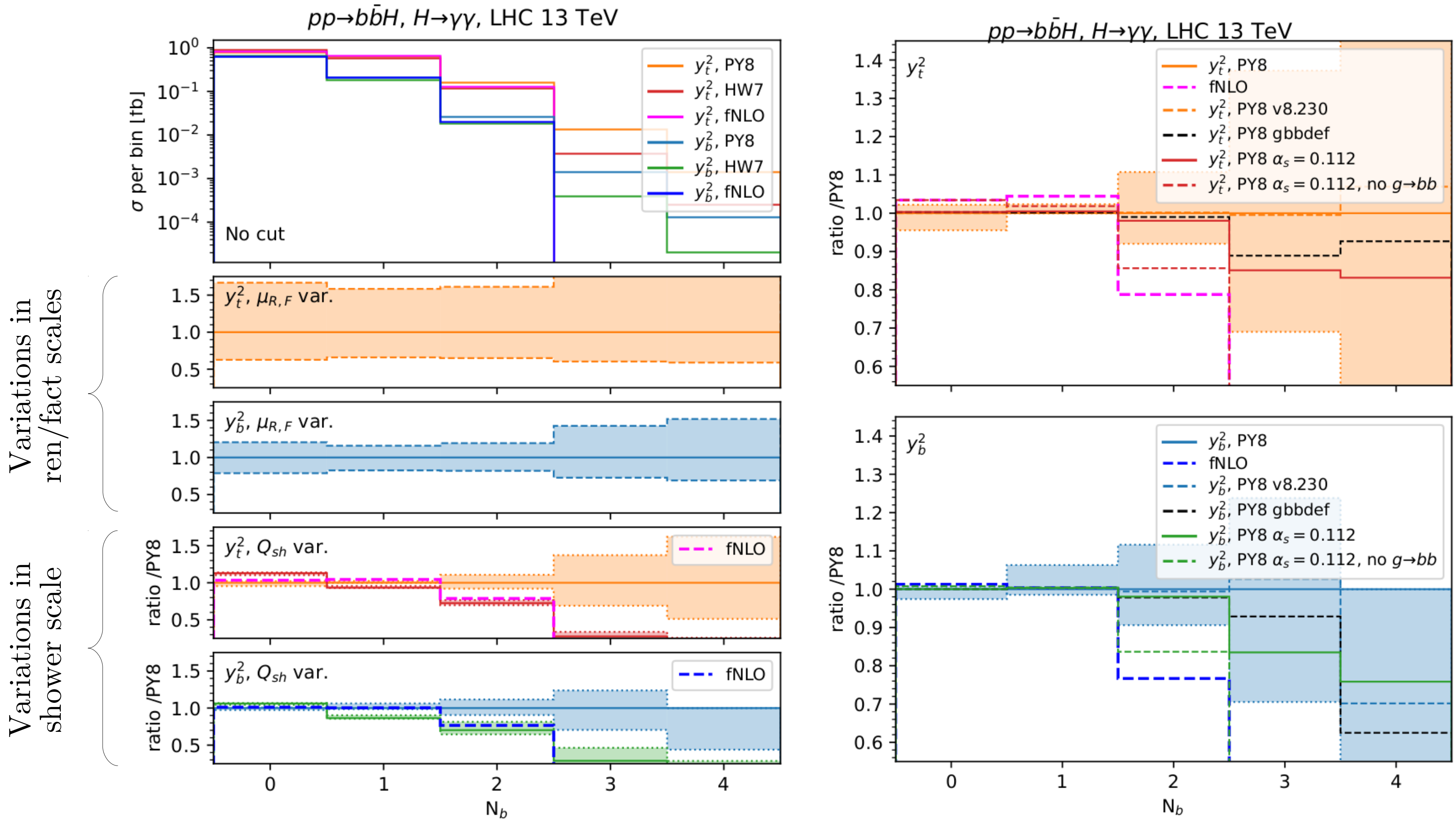
# Total cross sections

| Cut | Contr. | Run | $\sigma$ [fb] | $\delta\mu_{r,f}$ | Signal [fb] $gg \to HH \to b\bar{b}\gamma\gamma$ |
|---|---|---|---|---|---|
| No cut | $y_b^2$ | PY8 | $8.49\ 10^{-1}$ | $^{+18\%}_{-20\%}$ | $8.21\ 10^{-2}$ |
| | | HW7 | $8.50\ 10^{-1}$ | | |
| | $y_t^2$ | PY8 | $1.57\ 10^{0}$ | $^{+61\%}_{-35\%}$ | |
| | | HW7 | $1.57\ 10^{0}$ | | |
| Fid. cuts | $y_b^2$ | PY8 | $5.42\ 10^{-3}$ | $^{+20\%}_{-18\%}$ | $2.40\ 10^{-2}$ |
| | | HW7 | $3.84\ 10^{-3}$ | | |
| | $y_t^2$ | PY8 | $2.29\ 10^{-2}$ | $^{+62\%}_{-35\%}$ | |
| | | HW7 | $1.67\ 10^{-2}$ | | |
| Fid. cuts + $m^{\star}_{2b2\gamma} < 500\,\mathrm{GeV}$ | $y_b^2$ | PY8 | $5.26\ 10^{-3}$ | $^{+20\%}_{-17\%}$ | $1.67\ 10^{-2}$ |
| | | HW7 | $3.77\ 10^{-3}$ | | |
| | $y_t^2$ | PY8 | $1.62\ 10^{-2}$ | $^{+65\%}_{-36\%}$ | |
| | | HW7 | $1.15\ 10^{-2}$ | | |
| Fid. cuts + $m^{\star}_{2b2\gamma} < 350\,\mathrm{GeV}$ | $y_b^2$ | PY8 | $4.44\ 10^{-3}$ | $^{+19\%}_{-17\%}$ | $0.30\ 10^{-2}$ |
| | | HW7 | $3.26\ 10^{-3}$ | | |
| | $y_t^2$ | PY8 | $8.06\ 10^{-3}$ | $^{+67\%}_{-36\%}$ | |
| | | HW7 | $5.64\ 10^{-3}$ | | |

(Currently working on ggF at NNLOPS sample, to compare our $y_t$ results to what is currently used in analysis)

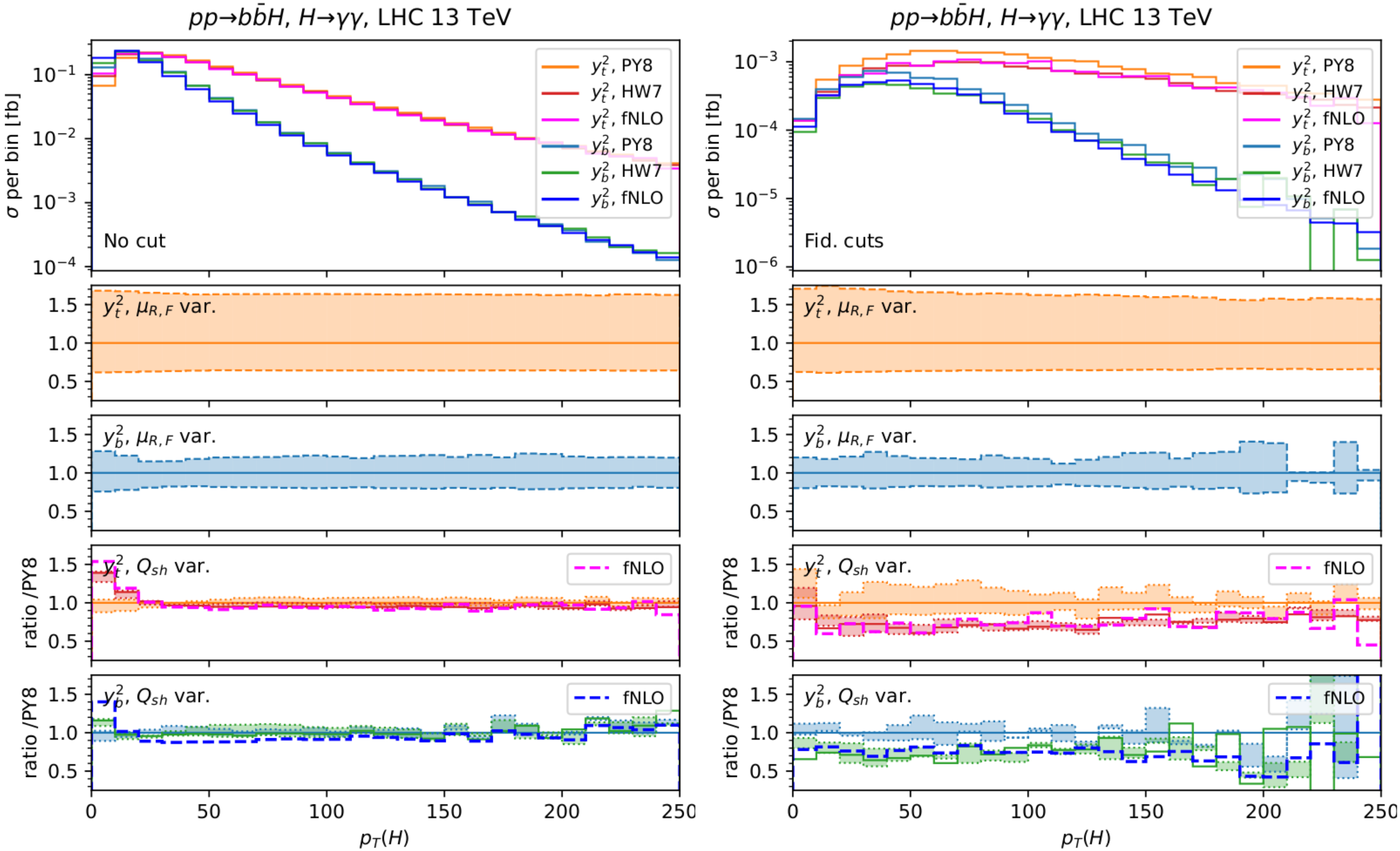
- Di-Higgs signal and $b\bar{b}H$ background are of similar size
- Relative $y_t/y_b$ contributions change with cuts, but top-Yukawa piece always dominant
- Still sizeable scale uncertainties, especially for the $y_t$ piece
- Large differences in fiducial cross sections between PY8 and HW7

# Differential distributions



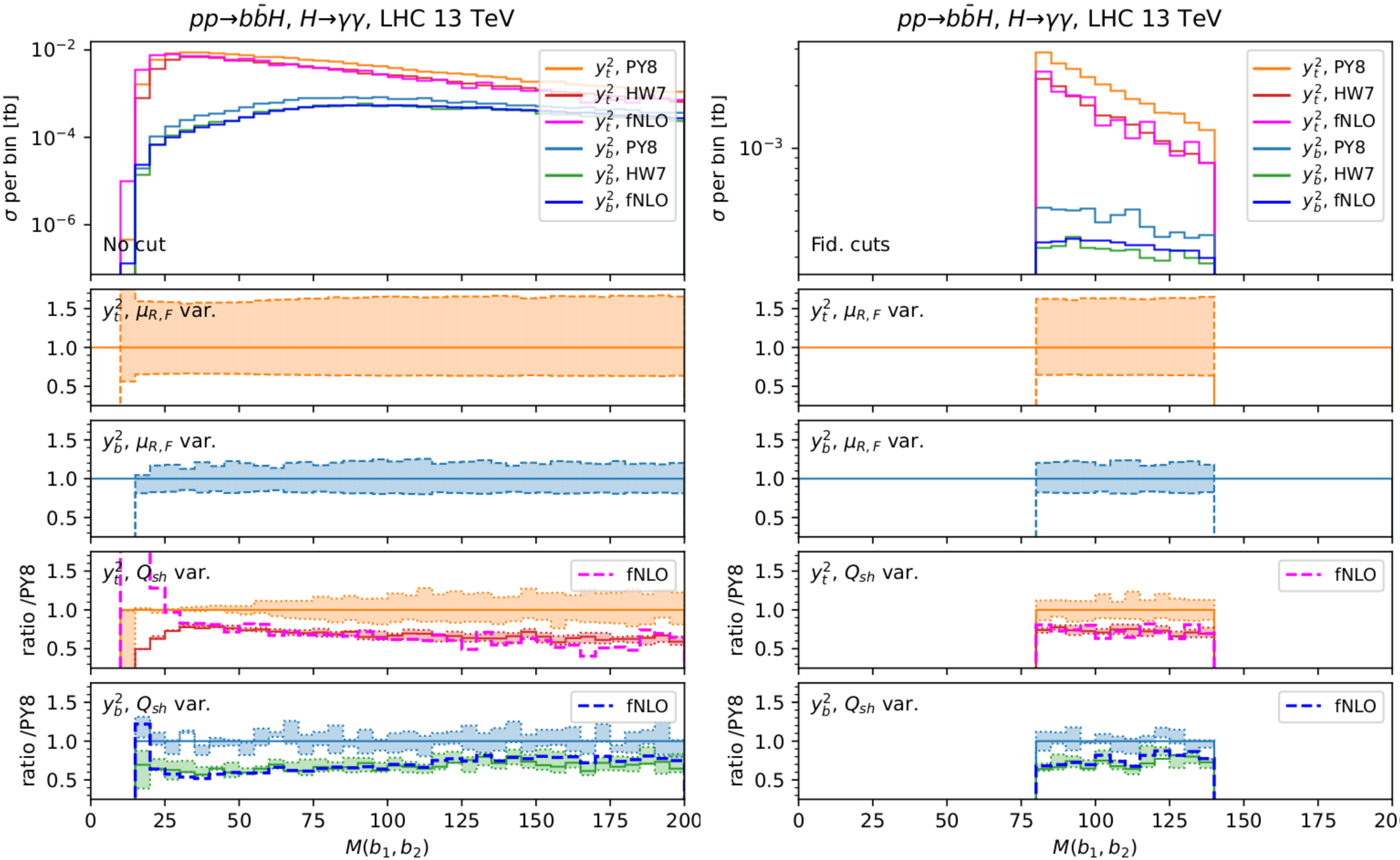

- Sizeable differences in shape between HW7 and PY8, HW7 closer to fixed order for $N_b=2$
- Difference originated from contributions with $g\to b\bar{b}$ splittings generated by the shower
- Further studies underway

# Differential distributions



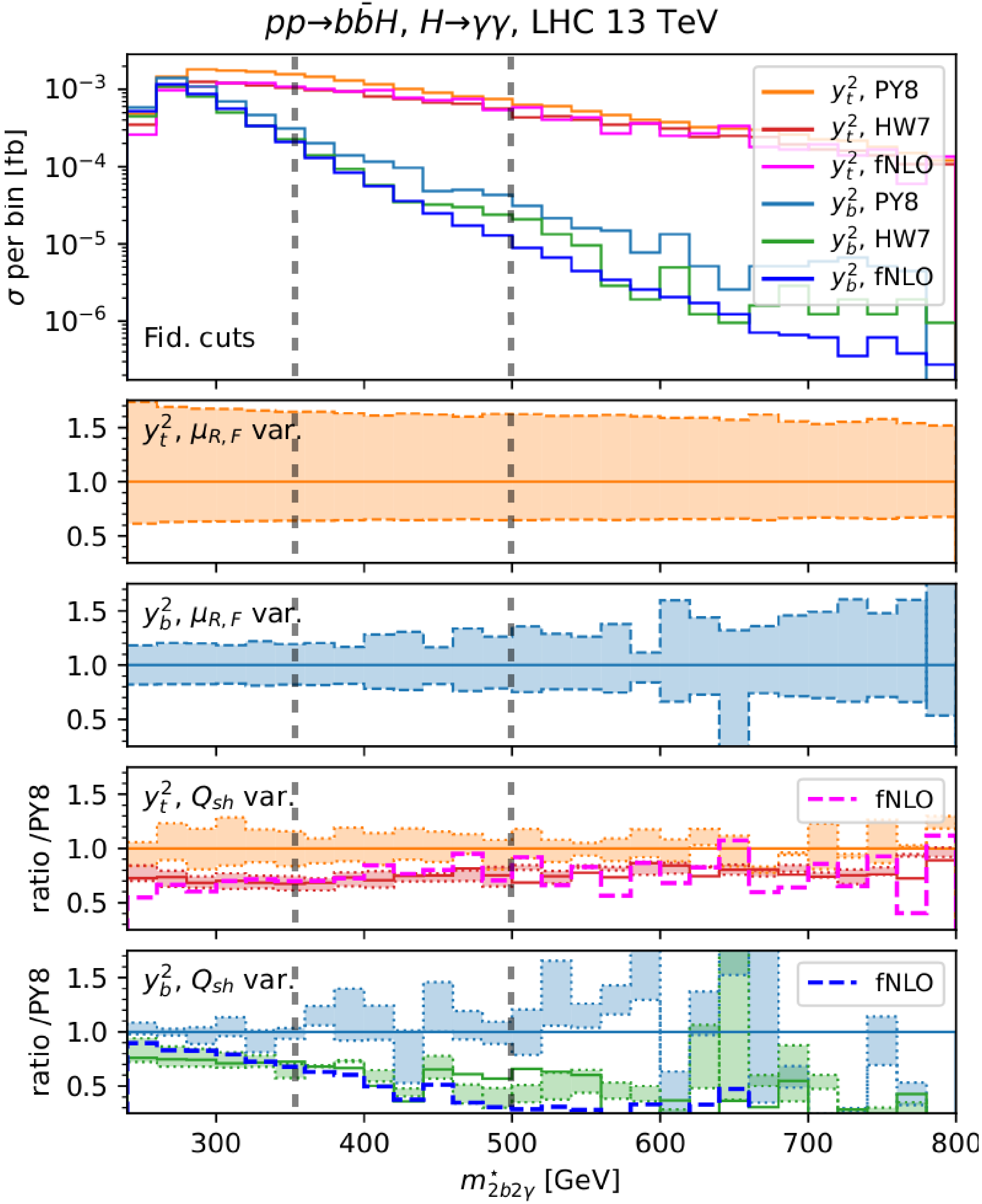

- Good agreement between PY8 and HW7 in inclusive case, only differences at low $p_T(H)$
- Discrepancies when applying the fiducial cuts, mostly on normalization

# Differential distributions




- Top-Yukawa piece prefers lower $M(b_1,b_2)$, since it is dominated by $g \to b\bar{b}$ splitting
- It also presents a larger relative variation in the $M(b_1,b_2)$ window relevant for HH

# Differential distributions




- Top and bottom Yukawa contributions prefer different values of $m^*_{2b2\gamma}$

- The $y_t$ piece prefers larger invariant masses, associated with configuration with hard gluon recoiling against H

- Shape difference explains different relative $y_t/y_b$ contributions when invariant mass cut is applied

- Difference between PY8 and HW7 again connected to secondary $g \to b\bar{b}$

# Summary and Outlook

- A good theoretical description of the backgrounds to HH is crucial to extract the signal
- $b\bar{b}H$ production is an irreducible background to searches with at least one $H \rightarrow b\bar{b}$
- Current simulation of $y_t$ contribution (ggF) only LO, O(100%) uncertainty
- An NLO study, including both $y_t$ and $y_b$ contributions, is underway
- Presented results for $b\bar{b}\gamma\gamma$ final state, in fiducial region typically used in HH searches
- $b\bar{b}H$ of same order of magnitude as HH signal
- Still sizeable uncertainties, especially for $y_t$ piece (about +60%-35%)
- Sizeable differences between PY8 and HW7 in fiducial region
- Further studies underway, stay tuned!

**Thanks!**