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

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Based on: S. Manzoni, E. Mazzeo, JM, M. Wiesemann and M. Zaro,
JHEP 09 (2023), 179 [arXiv:2307.09992 [hep-ph]]

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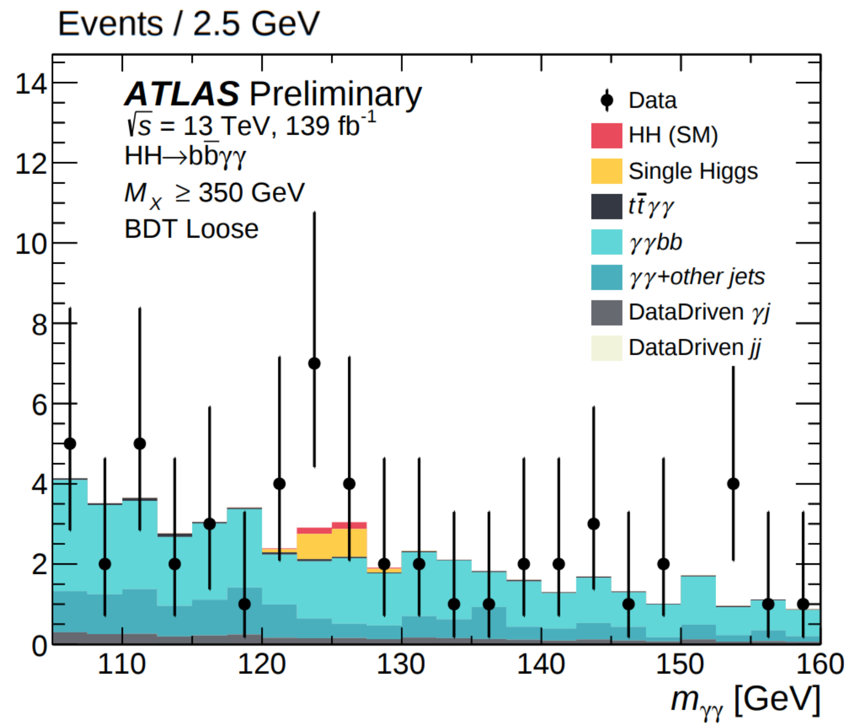
Uncertainties in the background estimation can lead to large reductions of the significance



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

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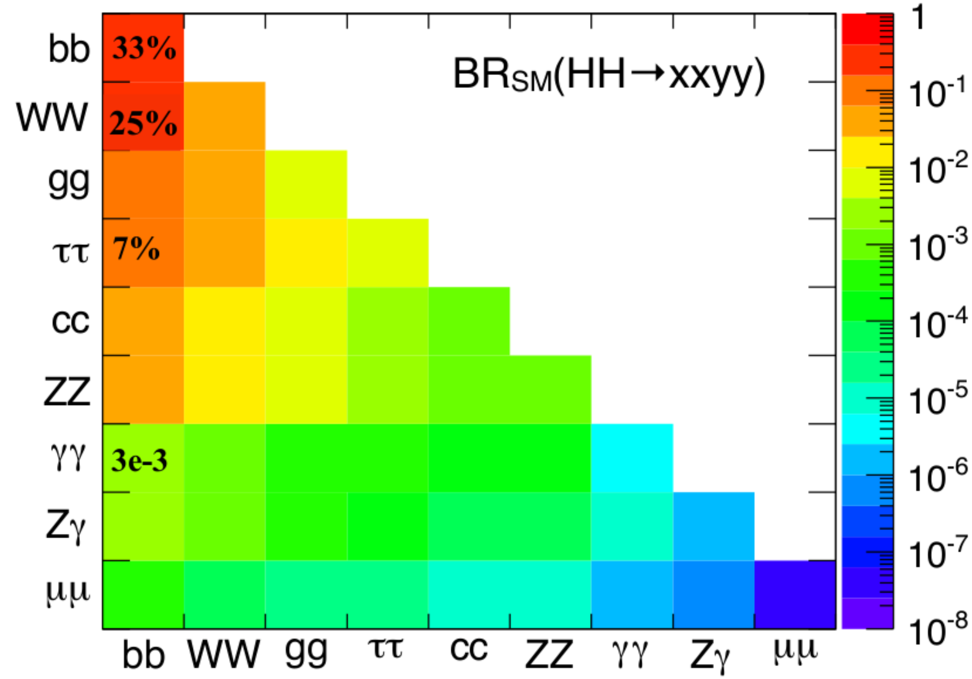
Fully differential higher-order corrections are crucial

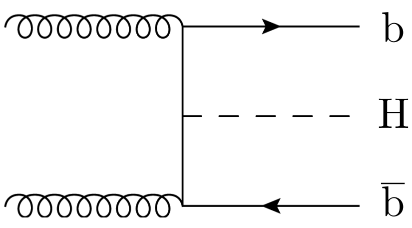
The $b\bar{b}H$ background

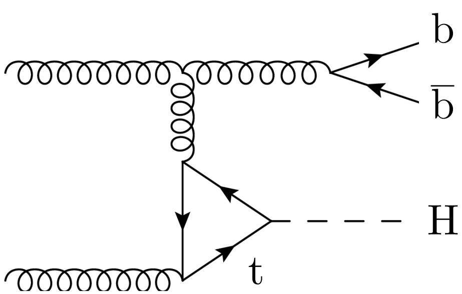
- Typically interested in this column to have a decent number of signal events



- Single Higgs production in association with a bottom pair is an irreducible background to all H(→$b\bar{b}$)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 → { Within 5FS; Only LO accurate in 2 jets configuration }

- A 'conservative' 100% uncertainty is assigned to this background, also motivated by disagreement with data in other analyses

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 analysis 2112.11876]

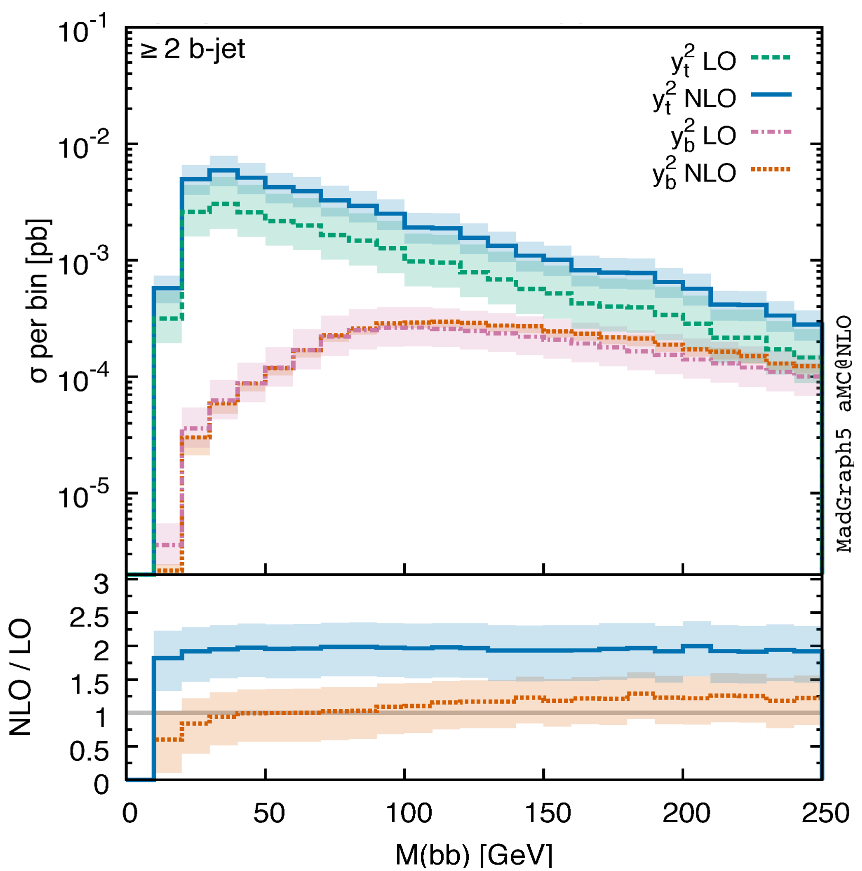
	High mass BDT tight	High mass BDT loose	Low mass BDT tight	Low mass BDT loose
Continuum background	$4.9^{+1.1}_{-1.3}$	$9.5^{+1.5}_{-1.7}$	$3.7^{+0.9}_{-1.1}$	$24.9^{+2.3}_{-2.5}$
Single Higgs boson background	$0.67^{+0.29}_{-0.13}$	$1.6^{+0.6}_{-0.2}$	$0.23^{+0.09}_{-0.03}$	$1.40^{+0.33}_{-0.16}$
ggF+bbH	$0.26^{+0.28}_{-0.16}$	$0.4^{+0.5}_{-0.2}$	$0.07^{+0.08}_{-0.04}$	$0.27^{+0.27}_{-0.16}$
$t\bar{t}H$	$0.19^{+0.03}_{-0.03}$	$0.49^{+0.09}_{-0.07}$	$0.107^{+0.022}_{-0.017}$	$0.75^{+0.13}_{-0.11}$
ZH	$0.142^{+0.035}_{-0.025}$	$0.48^{+0.09}_{-0.07}$	$0.040^{+0.020}_{-0.014}$	$0.27^{+0.06}_{-0.04}$
Rest	$0.074^{+0.032}_{-0.014}$	$0.16^{+0.07}_{-0.03}$	$0.012^{+0.008}_{-0.004}$	$0.111^{+0.030}_{-0.012}$
SM $HH(\kappa_\lambda = 1)$ signal	$0.87^{+0.10}_{-0.18}$	$0.37^{+0.04}_{-0.07}$	$0.049^{+0.006}_{-0.010}$	$0.078^{+0.008}_{-0.015}$
ggF	$0.86^{+0.10}_{-0.18}$	$0.35^{+0.04}_{-0.07}$	$0.046^{+0.006}_{-0.010}$	$0.072^{+0.008}_{-0.015}$
VBF	$(12.6^{+1.3}_{-1.2}) \cdot 10^{-3}$	$(16.1^{+1.4}_{-1.2}) \cdot 10^{-3}$	$(3.2^{+0.4}_{-0.4}) \cdot 10^{-3}$	$(6.9^{+0.5}_{-0.6}) \cdot 10^{-3}$
Alternative $HH(\kappa_\lambda = 10)$ signal	$6.5^{+1.0}_{-0.8}$	$3.6^{+0.6}_{-0.4}$	$4.5^{+0.7}_{-0.6}$	$8.5^{+1.3}_{-1.0}$
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

$b\bar{b}H$ at NLO

- NLO corrections to $b\bar{b}H$ 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

[Manzoni, Mazzeo, JM, Wiesemann, Zaro]

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

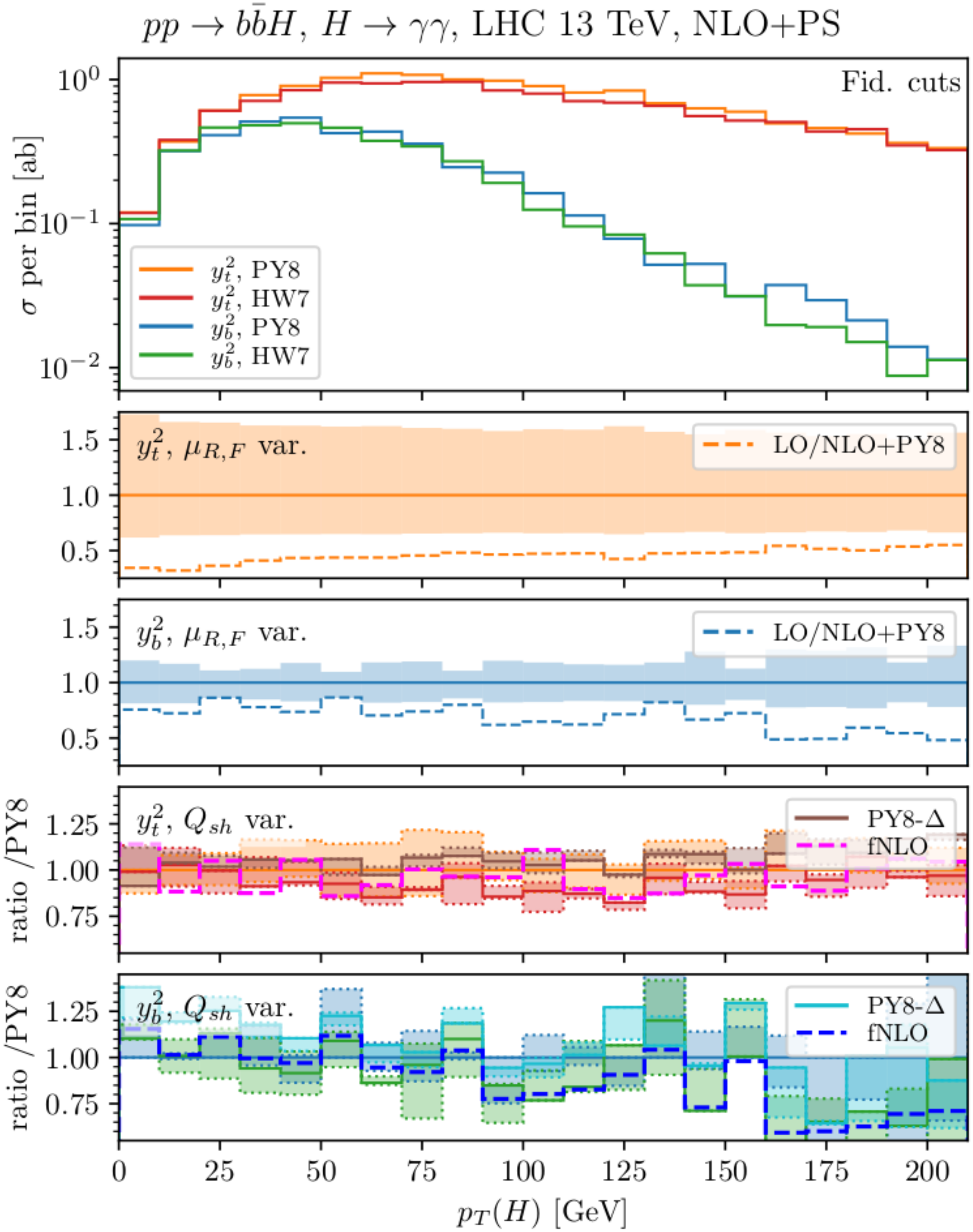
Simulation similar to what is currently used by ATLAS

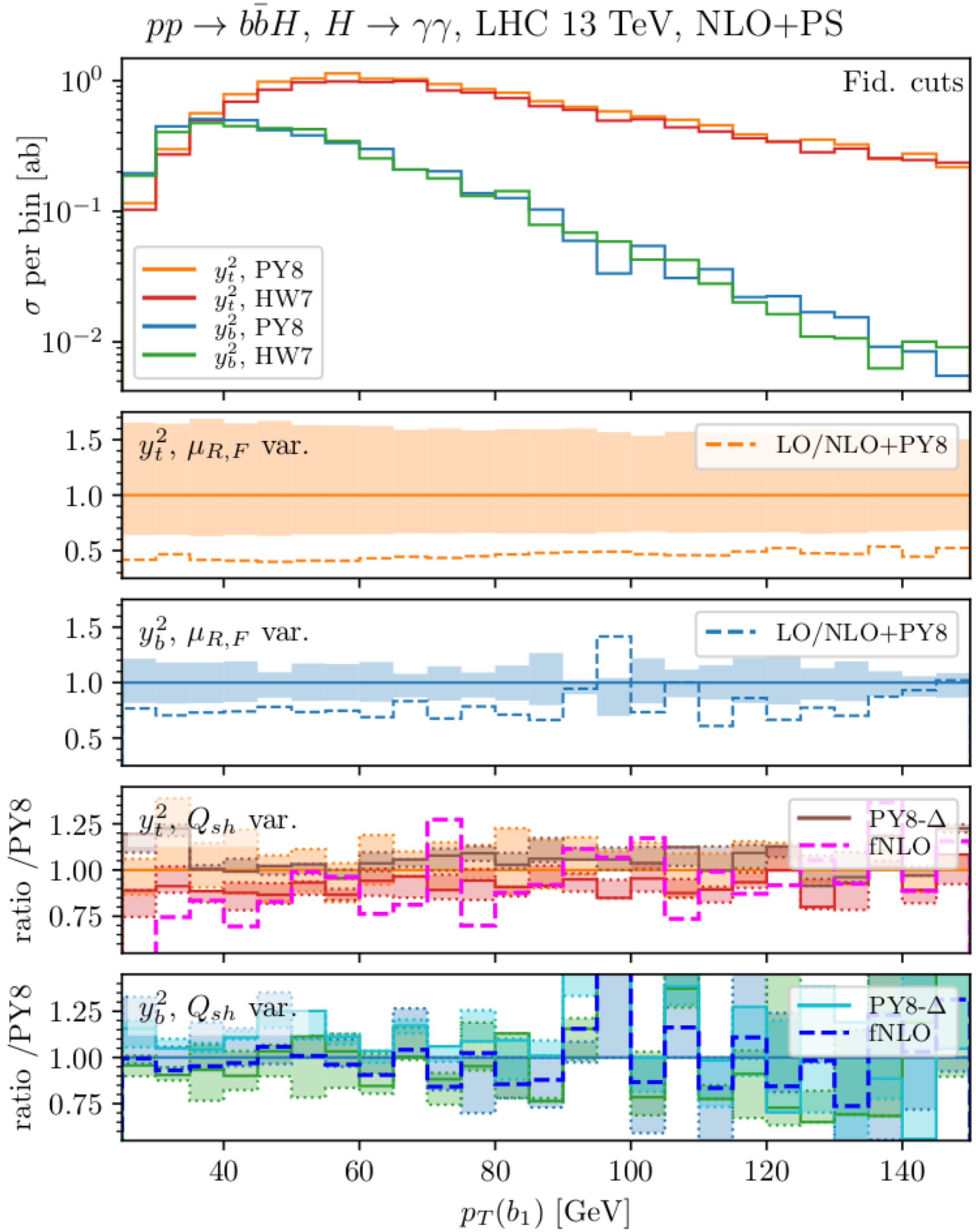
Cut	Contr.	Run	LO	NLO	$\delta\mu_{R,F}$	δQ_{sh}	NNLOPS (y_t^2 LO)	HH signal
No cut	y_b^2	PY8	561	849	$^{+18\%}_{-20\%}$	$^{+0\%}_{+0\%}$	4867	82.1
		HW7	561	851		$^{+0\%}_{+0\%}$		
	y_t^2	PY8	655	1565	$^{+61\%}_{-35\%}$	$^{+0\%}_{+0\%}$	$g \not\to b\bar{b}$: 2140	
		HW7	655	1578		$^{+0\%}_{+0\%}$		
	sum	PY8	1217	2414	$^{+46\%}_{-29\%}$	$^{+0\%}_{+0\%}$		
		HW7	1216	2429		$^{+0\%}_{+0\%}$		
Fid. cuts	y_b^2	PY8	3.15	4.22	$^{+15\%}_{-15\%}$	$^{+10\%}_{-4\%}$	29.9	22.7
		HW7	2.59	4.08		$^{+8\%}_{-12\%}$		
	y_t^2	PY8	8.24	18.1	$^{+58\%}_{-34\%}$	$^{+10\%}_{-7\%}$	$g \not\to b\bar{b}$: 17.2	
		HW7	6.83	16.6		$^{+4\%}_{-5\%}$		
	sum	PY8	11.4	22.3	$^{+50\%}_{-30\%}$	$^{+10\%}_{-6\%}$		
		HW7	9.42	20.7		$^{+4\%}_{-6\%}$		
Fid. cuts + $m^{\star}_{2b2\gamma} < 500$ GeV	y_b^2	PY8	3.11	4.15	$^{+15\%}_{-15\%}$	$^{+11\%}_{-4\%}$	22.3	15.7
		HW7	2.56	4.02		$^{+8\%}_{-13\%}$		
	y_t^2	PY8	5.33	12.3	$^{+60\%}_{-34\%}$	$^{+12\%}_{-8\%}$	$g \not\to b\bar{b}$: 13.3	
		HW7	4.31	11.3		$^{+5\%}_{-5\%}$		
	sum	PY8	8.44	16.5	$^{+49\%}_{-29\%}$	$^{+12\%}_{-7\%}$		
		HW7	6.86	15.3		$^{+6\%}_{-7\%}$		
Fid. cuts + $m^{\star}_{2b2\gamma} < 350$ GeV	y_b^2	PY8	2.71	3.65	$^{+15\%}_{-16\%}$	$^{+9\%}_{-4\%}$	11.5	2.84
		HW7	2.22	3.54		$^{+8\%}_{-15\%}$		
	y_t^2	PY8	2.32	5.78	$^{+61\%}_{-34\%}$	$^{+13\%}_{-9\%}$	$g \not\to b\bar{b}$: 6.82	
		HW7	1.88	5.43		$^{+5\%}_{-3\%}$		
	sum	PY8	5.03	9.43	$^{+44\%}_{-27\%}$	$^{+12\%}_{-7\%}$		
		HW7	4.10	8.97		$^{+6\%}_{-8\%}$		

[all cross section numbers in ab]

- Di-Higgs signal and $b\bar{b}H$ background are of similar size
- Relative y_t/y_b contributions change with cuts, top-Yukawa piece is always dominant
- Still sizeable scale uncertainties, especially for the y_t piece
- Differences in fiducial cross sections between PY8 and HW7 are smaller than scale uncertainties
- Top-Yukawa contribution in the 4FS about 2 times smaller than prediction obtained with ggF NNLOPS
- Rates in ggF NNLOPS sample are largely affected by secondary bottom emissions from shower

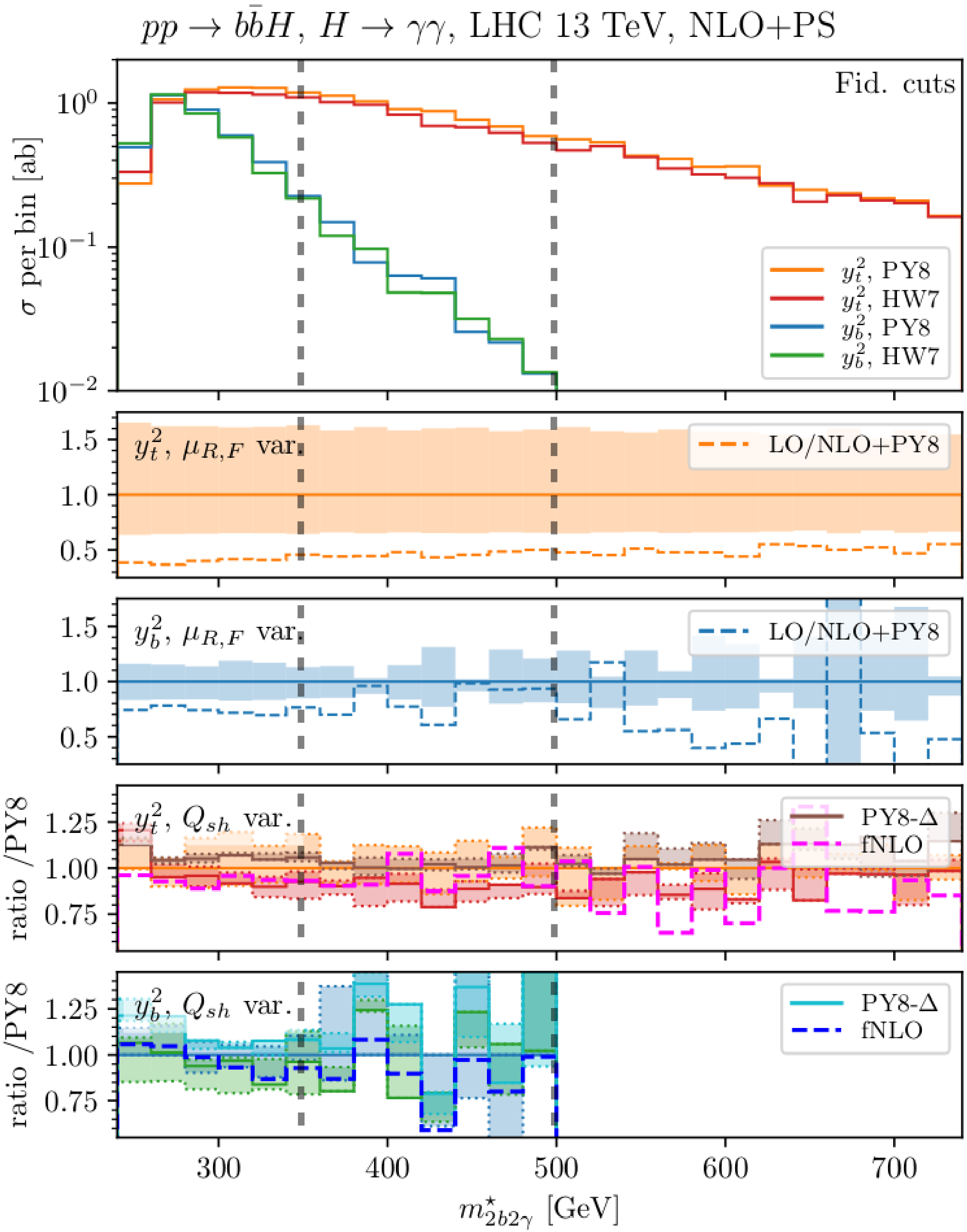
Differential distributions





- Top Yukawa contribution prefers harder H/b jet, due to contributions with hard gluon recoiling against H
- Nice agreement in the shapes obtained with PY8 and HW7

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

Effect of g→bb splittings in NNLOPS sample

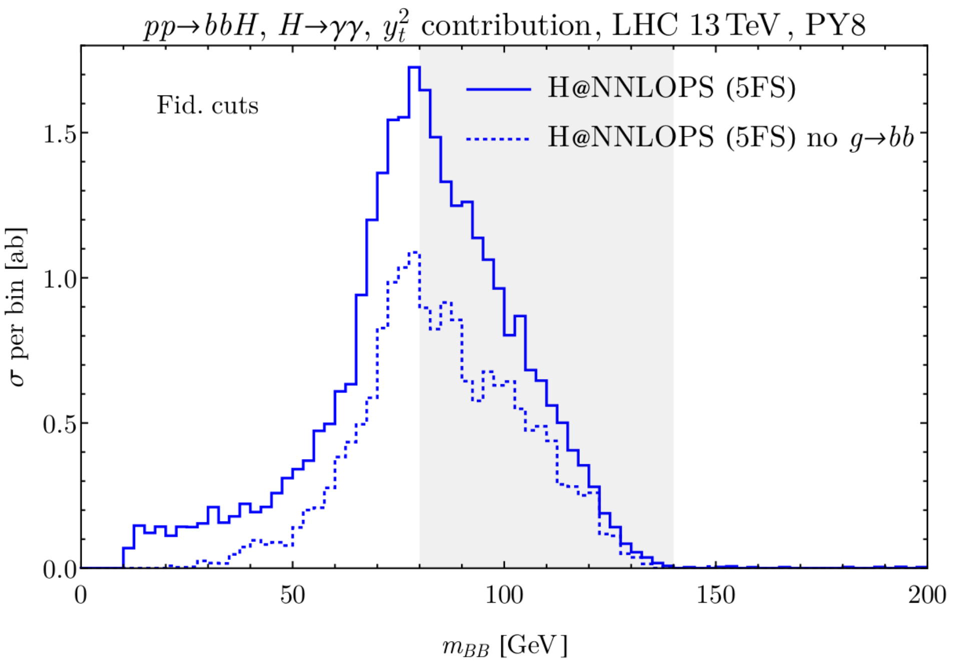
We studied the NNLOPS sample in the fiducial region after showering:

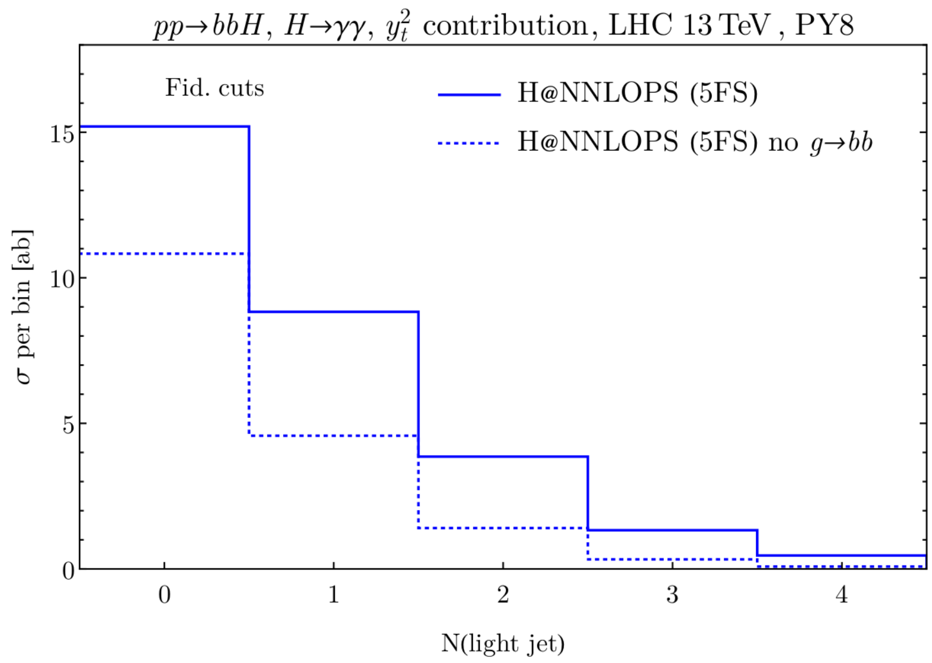
- Vast majority of events have exactly 2 bottom quarks ➡ single large-angle g→b$\bar{\text{b}}$ splitting

Are the emitted b's soft and falling inside additional hard light jets?

- Invariant mass of b$\bar{\text{b}}$ system quite close to the required window for the 2 b-jets invariant mass

- Most events don't have additional light jets

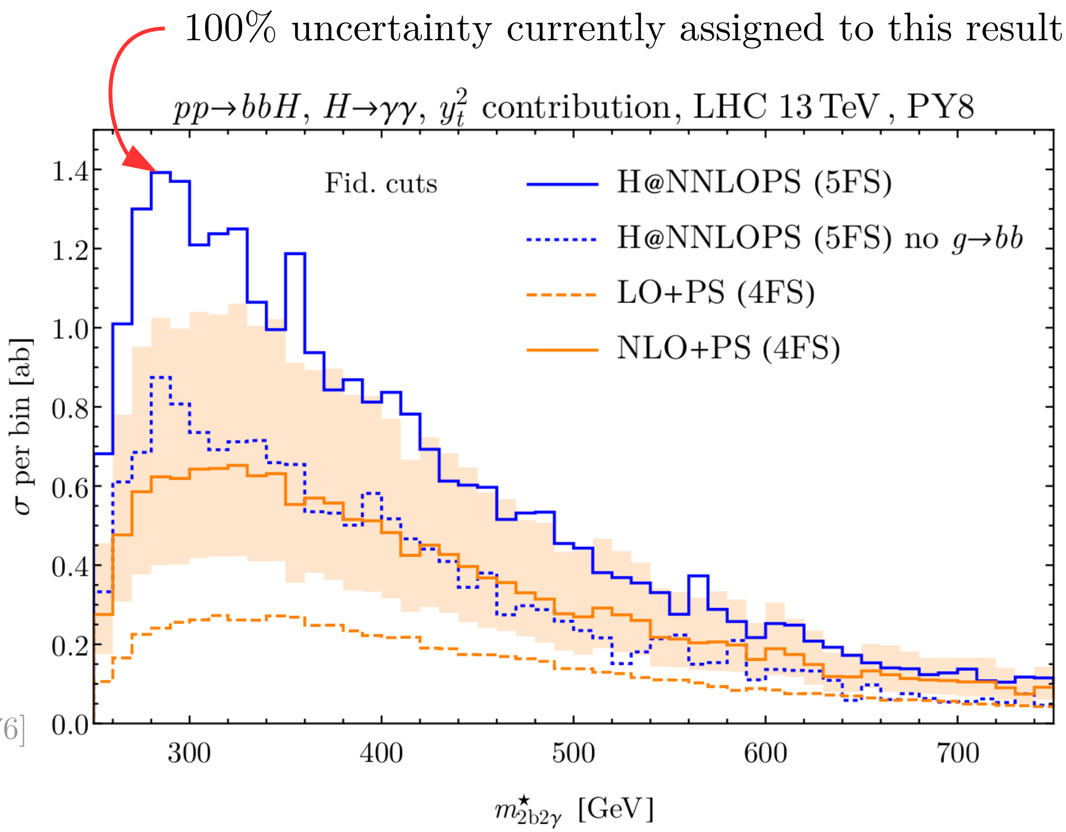




PS generates two hard b-jets at large angle from a single g→b$\bar{\text{b}}$ splitting

Poorly described in soft/collinear approximation of the PS
+ potentially double counting contributions present in hard ME

Impact on HH searches



- Result from ggF NNLOPS close to upper uncertainty band of NLO 4FS
- Larger differences for low invariant masses
- Size and uncertainties of this background are reduced in our NLO 4FS calculation

Positive impact on HH searches

- We have propagated the new NLO 4FS rates to an ATLAS search in the $2b2\gamma$ channel [2112.11876] as well as the $2b2\tau$ channel [2209.10910]

Rescaled NNLOPS sample to NLO 4FS rates

- Subtlety: NNLOPS sample also used for b-jet mistagging estimate! Only rescale the true b-jet contribution (80% of the full sample)
- We also replace the 100% uncertainty by the NLO 4FS scale uncertainties

Improvement in XS limits	Current	HL-LHC
$2b2\gamma$	~2%	~5%
$2b2\tau$	~10%	~20%

Larger improvement in $2b2\tau$ due to analysis being less stat. dominated, plus larger relative contribution from single Higgs background

Summary and Outlook

- $b\bar{b}H$ production is an irreducible background to searches with at least one $H \to b\bar{b}$
- Current simulation of y_t contribution (ggF 5FS) only LO, O(100%) uncertainty
- We presented an NLO+PS study for $b\bar{b}H$, including both y_t and y_b contributions, working in the 4FS, in a fiducial region typically used in HH searches
- Large corrections, sizeable uncertainties, especially for y_t piece (about +60%-35%)
- Results in the 4FS are smaller than the ones obtained in with ggF NNLOPS 5FS
- ggF NNLOPS largely influenced by $g \to b\bar{b}$ splittings in the shower potentially inducing a double counting
- We estimated the effect of using the new NLO 4FS sample in HH searches
- Significant improvement in XS limits, depending on channel and luminosity
- Looking forward to seeing this MC being used in LHC analyses!

Thanks!