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

Javier Mazzitelli

In collaboration with S. Manzoni, E. Mazzeo, M. Wiesemann and M. Zaro

PAUL SCHERRER INSTITUT PSI

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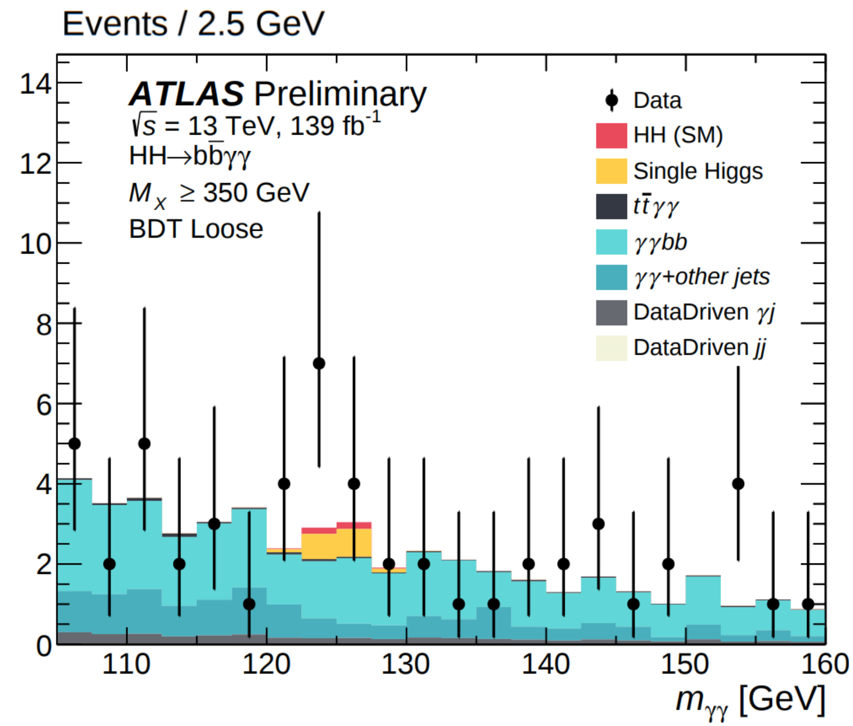
Uncertainties in the background estimation can lead to large reductions of the significance



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

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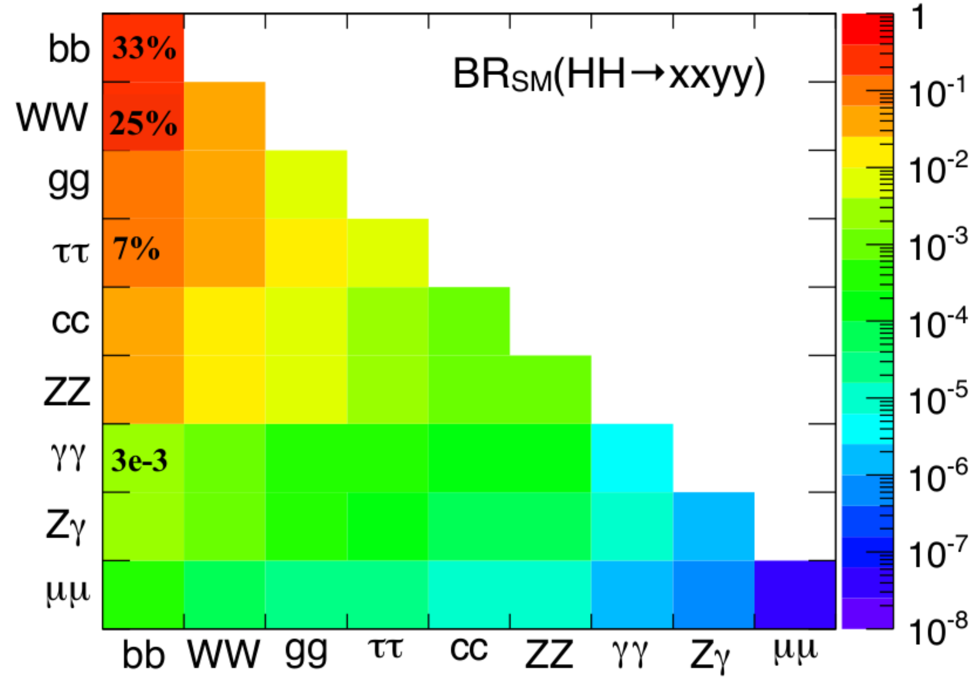
Fully differential higher-order corrections are crucial

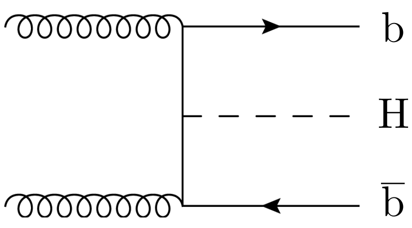
The $b\bar{b}H$ background

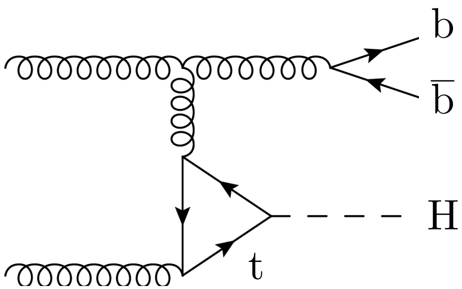
- Typically interested in this column to have a decent number of signal events



- 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:





$\mathcal{O}(\alpha_s^2 y_b^2)$

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

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

- 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

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]

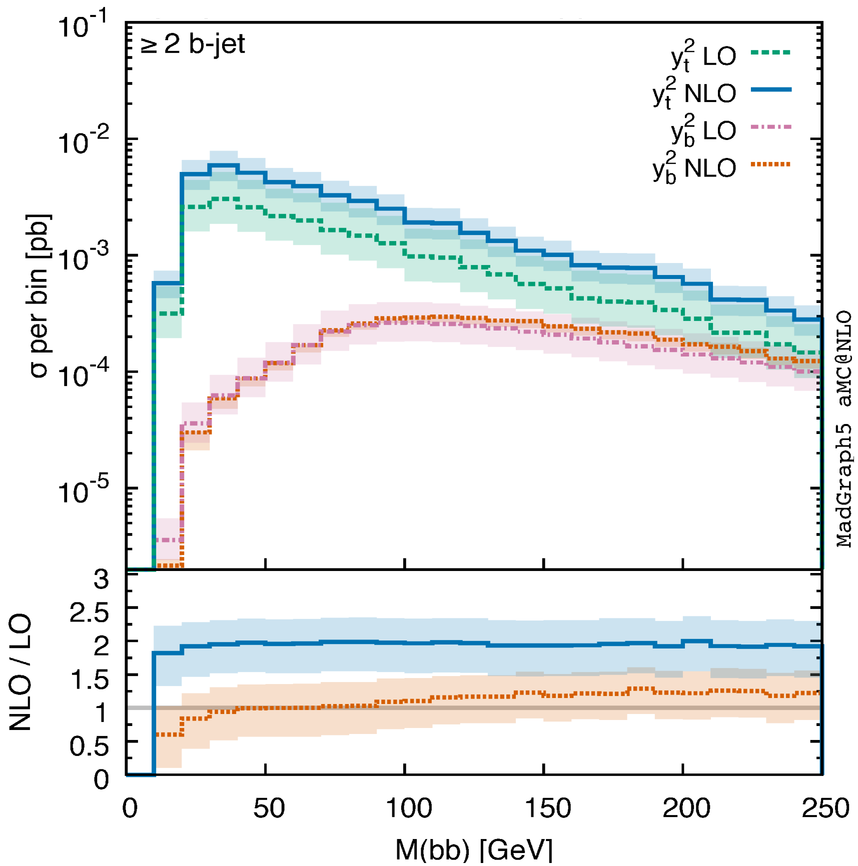
	High mass BDT tight	High mass BDT loose	Low mass BDT tight	Low mass BDT loose
Continuum background	4.9 ± 1.1	9.5 ± 1.5	3.7 ± 1.0	24.9 ± 2.5
Single Higgs boson background	0.670 ± 0.032	1.57 ± 0.04	0.220 ± 0.016	1.39 ± 0.04
ggF	0.261 ± 0.028	0.44 ± 0.04	0.063 ± 0.014	0.274 ± 0.030
$t\bar{t}H$	0.1929 ± 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

$b\bar{b}H$ 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

[Manzoni, Mazzeo, JM, 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, $p_T(j)$>25GeV, $|\eta(j)|$<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 5FS)	HH signal
No cut	y_b^2	PY8	561	849	$^{+18\%}_{-20\%}$	$^{+0\%}_{+0\%}$	–	82.1
		HW7	561	851		$^{+0\%}_{+0\%}$		
	y_t^2	PY8	655	1565	$^{+61\%}_{-35\%}$	$^{+0\%}_{+0\%}$		
		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	$^{+15\%}_{-15\%}$	$^{+10\%}_{-4\%}$	34.6	24.0
		HW7	2.59	4.08		$^{+8\%}_{-12\%}$		
	y_t^2	PY8	8.24	18.1	$^{+58\%}_{-34\%}$	$^{+10\%}_{-7\%}$		
		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 + $m^{\star}_{2b2\gamma} < 500\,\text{GeV}$	y_b^2	PY8	3.11	4.15	$^{+15\%}_{-15\%}$	$^{+11\%}_{-4\%}$	26.2	16.6
		HW7	2.56	4.02		$^{+8\%}_{-13\%}$		
	y_t^2	PY8	5.33	12.3	$^{+60\%}_{-34\%}$	$^{+12\%}_{-8\%}$		
		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 + $m^{\star}_{2b2\gamma} < 350\,\text{GeV}$	y_b^2	PY8	2.71	3.65	$^{+15\%}_{-16\%}$	$^{+9\%}_{-4\%}$	15.5	3.00
		HW7	2.22	3.54		$^{+8\%}_{-15\%}$		
	y_t^2	PY8	2.32	5.78	$^{+61\%}_{-34\%}$	$^{+13\%}_{-9\%}$		
		HW7	1.88	5.43		$^{+5\%}_{-3\%}$		
	sum	PY8	5.03	9.43	$^{+44\%}_{-27\%}$	$^{+12\%}_{-7\%}$		
		HW7	4.10	8.97		$^{+6\%}_{-8\%}$		

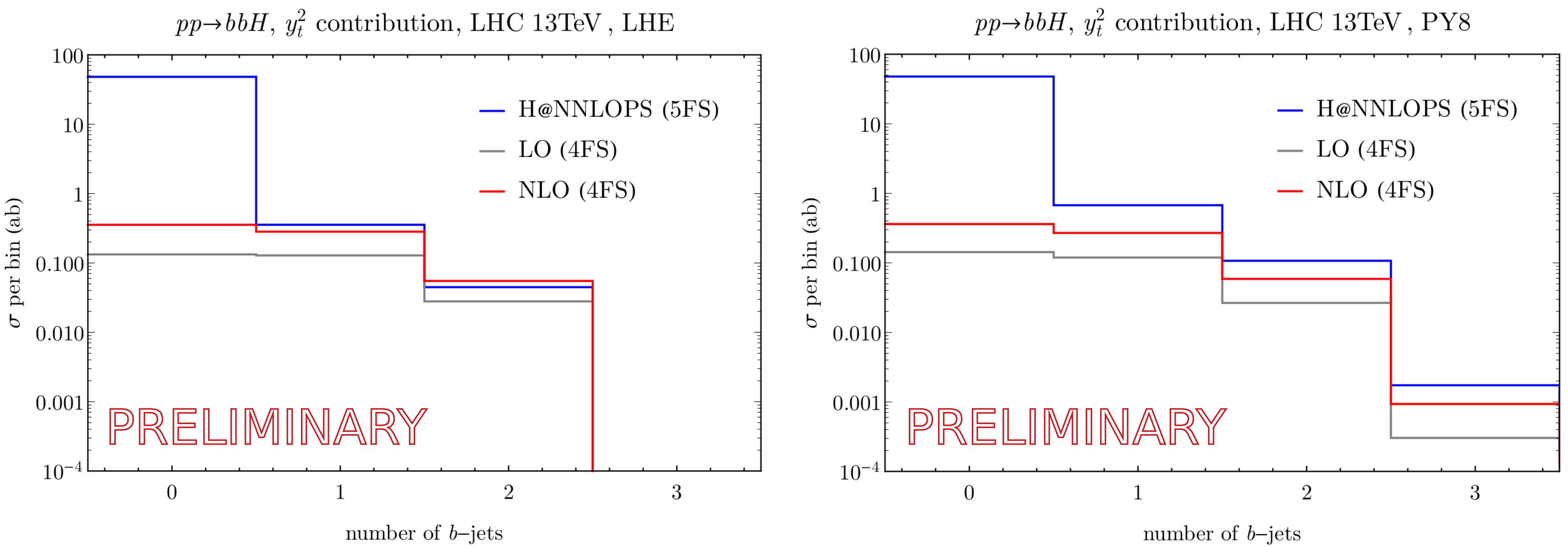
[all cross section numbers in ab]

PRELIMINARY

- 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 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 is about 2 times smaller than prediction obtained with ggF NNLOPS

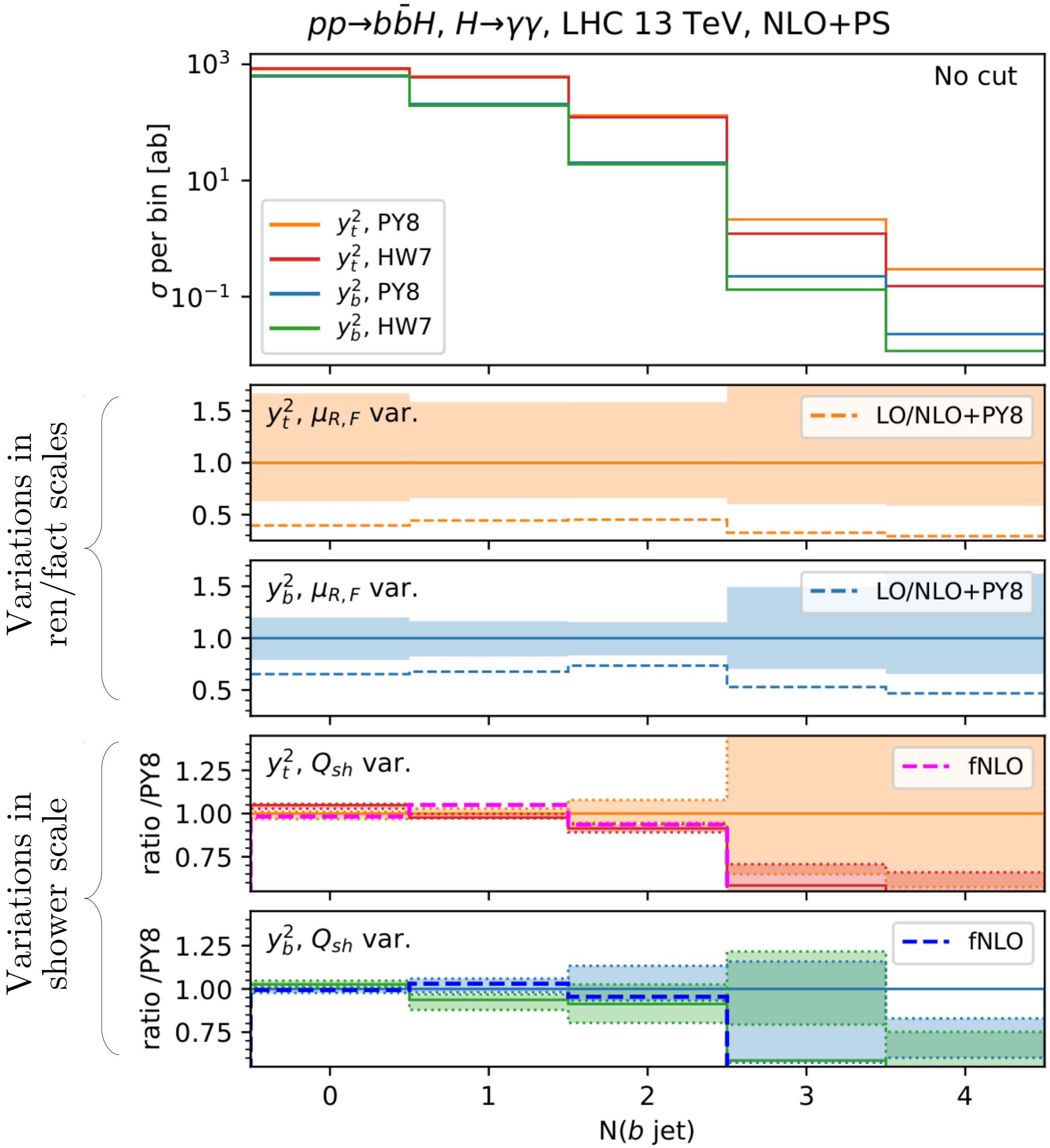
Impact of the shower

- Fiducial region in ggF NNLOPS is dominated by secondary bottom emissions



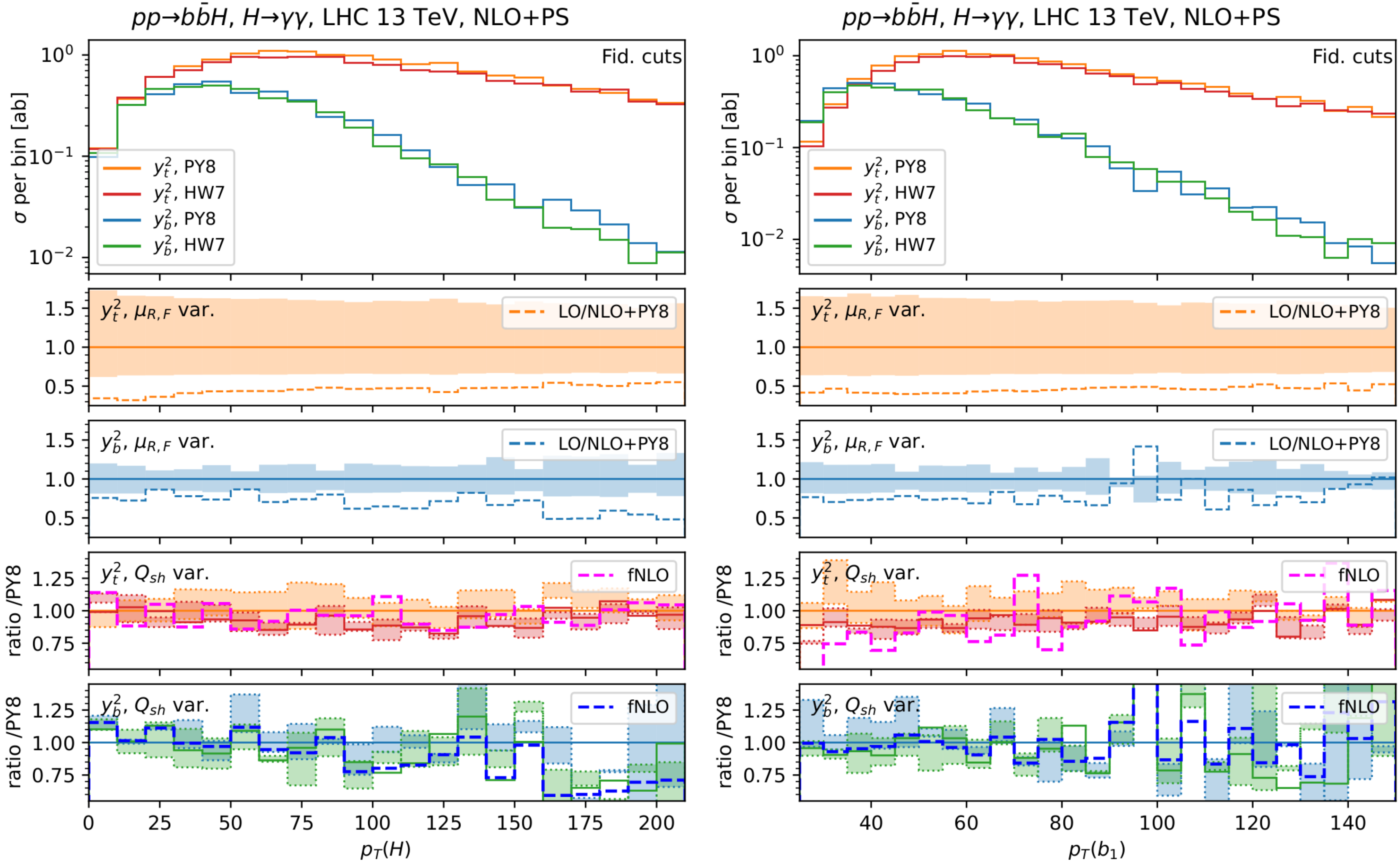
- Large migration from N(b jets)=0 to higher multiplicities due to the shower
- Effect entirely due to g→bb splitting
- Presumably, the results based on ggF NNLOPS will have a very large shower uncertainty
- Further studies underway

Differential distributions



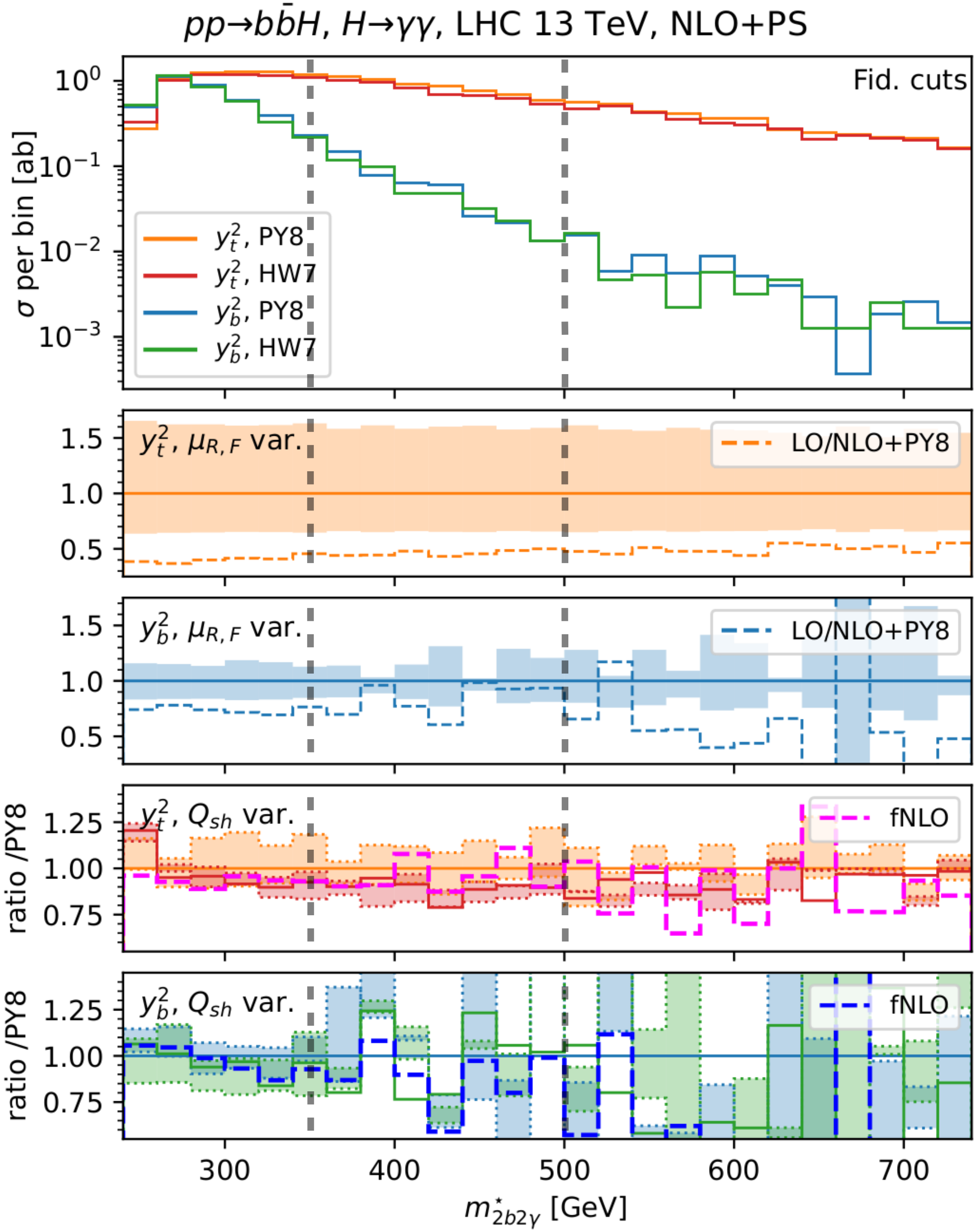
- Similarly large for N(b jet)=0, while y_t is dominant for larger multiplicities
- Top Yukawa contribution presents larger NLO corrections and uncertainties
- Difference between PY8 and HW7 increases with N(b jet), HW7 closer to FO
- Shower uncertainties are subleading for N(b jet)=2

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

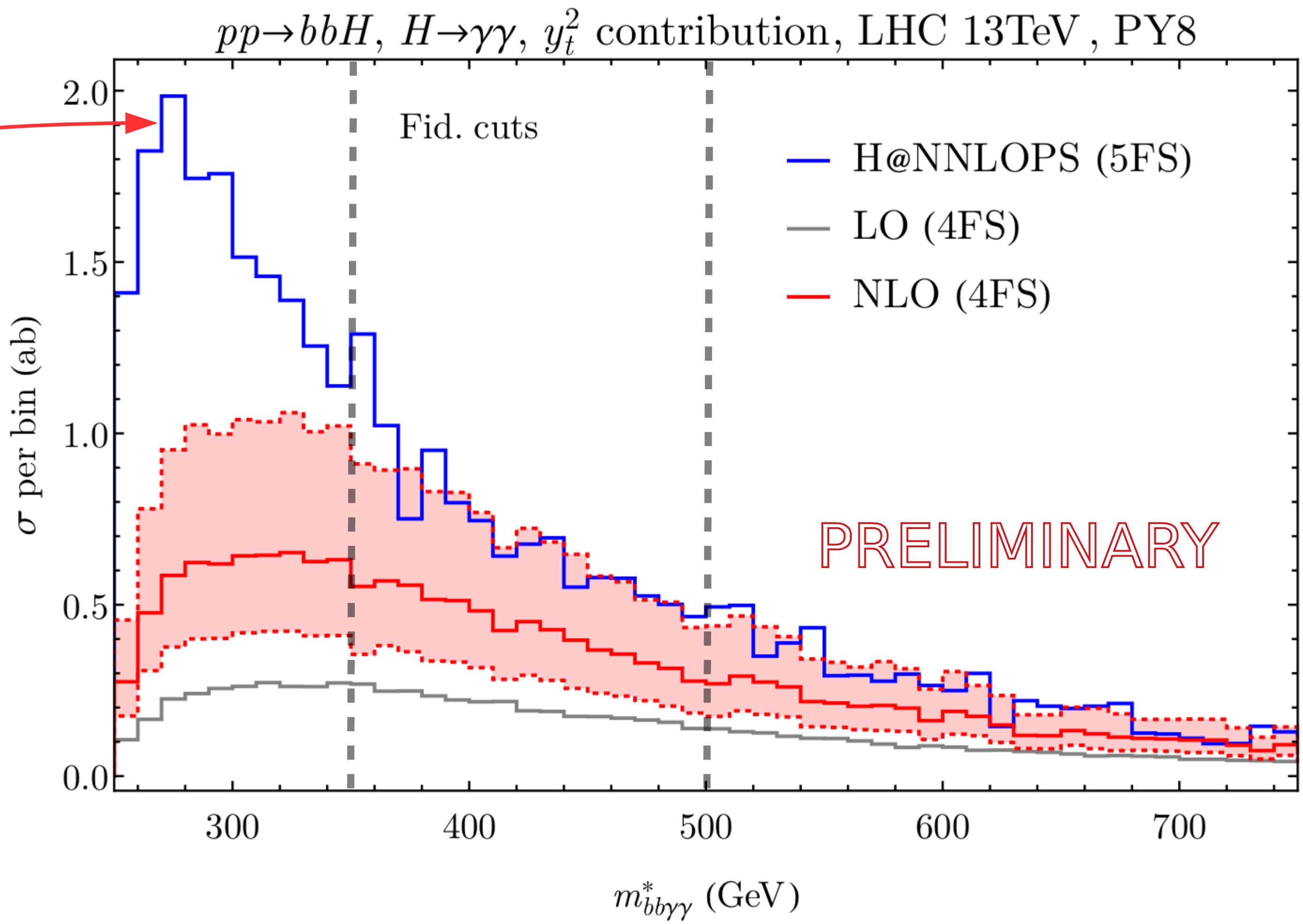
Differential distributions



- 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

Differential distributions

100% uncertainty
is currently
assigned to this result



- Result from ggF NNLOPS is close to upper uncertainty band of NLO 4FS result
- Larger differences in low invariant mass region
- Both the size and the uncertainties of this background are largely reduced in our NLO 4FS calculation

E.g.: fiducial cuts + $m^*_{2b2\gamma}$<350GeV
Upper limit of y_t background
is reduced by a factor of 3

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 $H \to b\bar{b}$
- Current simulation of y_t contribution (ggF 5FS) 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%)
- Results in the 4FS are smaller than the ones obtained in current simulations using ggF NNLOPS, the latter largely influenced by $g \to bb$ splittings in the shower
- Further studies underway, stay tuned!

Thanks!