ICHEP, Prague, 17-24 Jul. 2024

bbH as a background for *HH*:

taming a leading theoretical uncertainty in *HH* measurements via accurate simulation of *bbH* production

JHEP 09 (2023) 179

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Outline

Observation of the Higgs boson by ATLAS and CMS ($H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ channels)

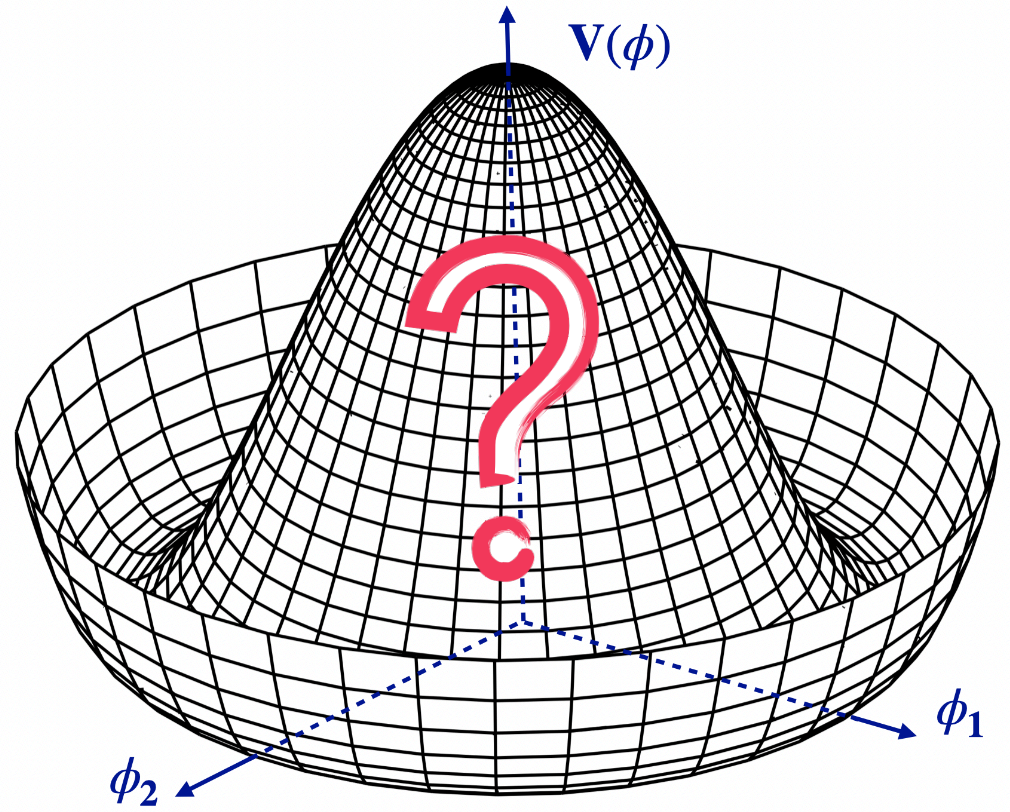
Ongoing campaign of **measurements** of the Higgs boson **properties**… → **Excellent agreement** with the **Standard Model (SM)**!

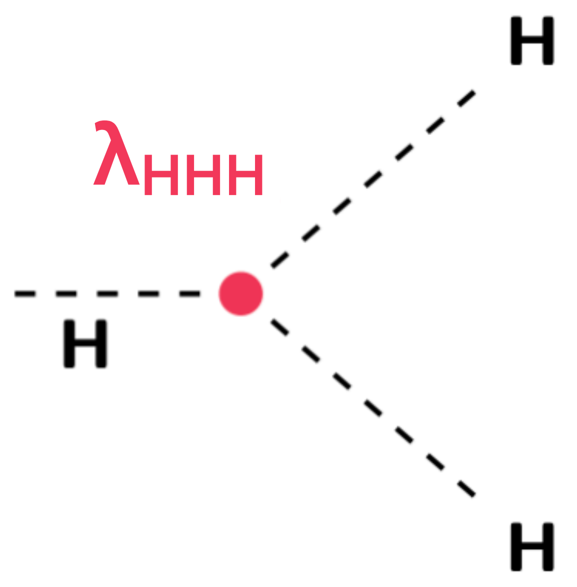
2012 — **2018** — **Now**

Observation of the $H \to b\bar{b}$ decay

More and more ***pp* collision data** delivered by the LHC during **Run 3**!

- Precision of measurements will increase.
- New couplings will become accessible! → The **Higgs boson trilinear self-coupling λ_{HHH}**!





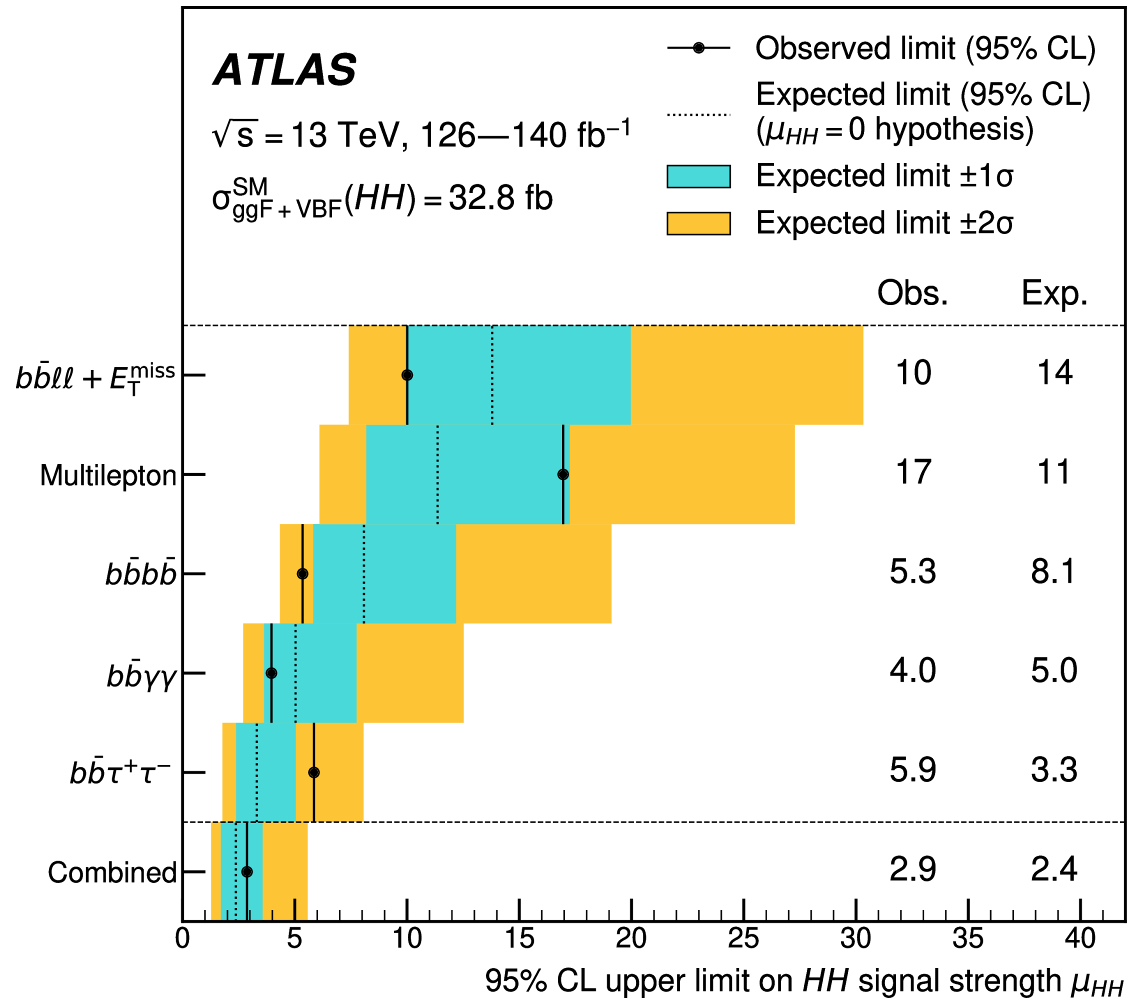
- Measuring λ_{HHH} allows to shed light on the **shape** of the **Higgs boson potential**.
- The **only direct way** to access λ_{HHH} is via **Higgs boson pair production (*HH*)!**

Extremely rare process! → In the SM, **σ(HH) ≈ 10^{-3} × σ(H)**!

- **No hint** of ***HH*** with **Run 2** data. → But we are getting **close** to **SM-like sensitivity**…

Current observed (expected) **constraints** on *HH* production:

- ATLAS = **σ(HH) < 2.9 (2.4) × σ^{SM}(HH);**
- CMS = **σ(HH) < 3.4 (2.5) × σ^{SM}(HH).**

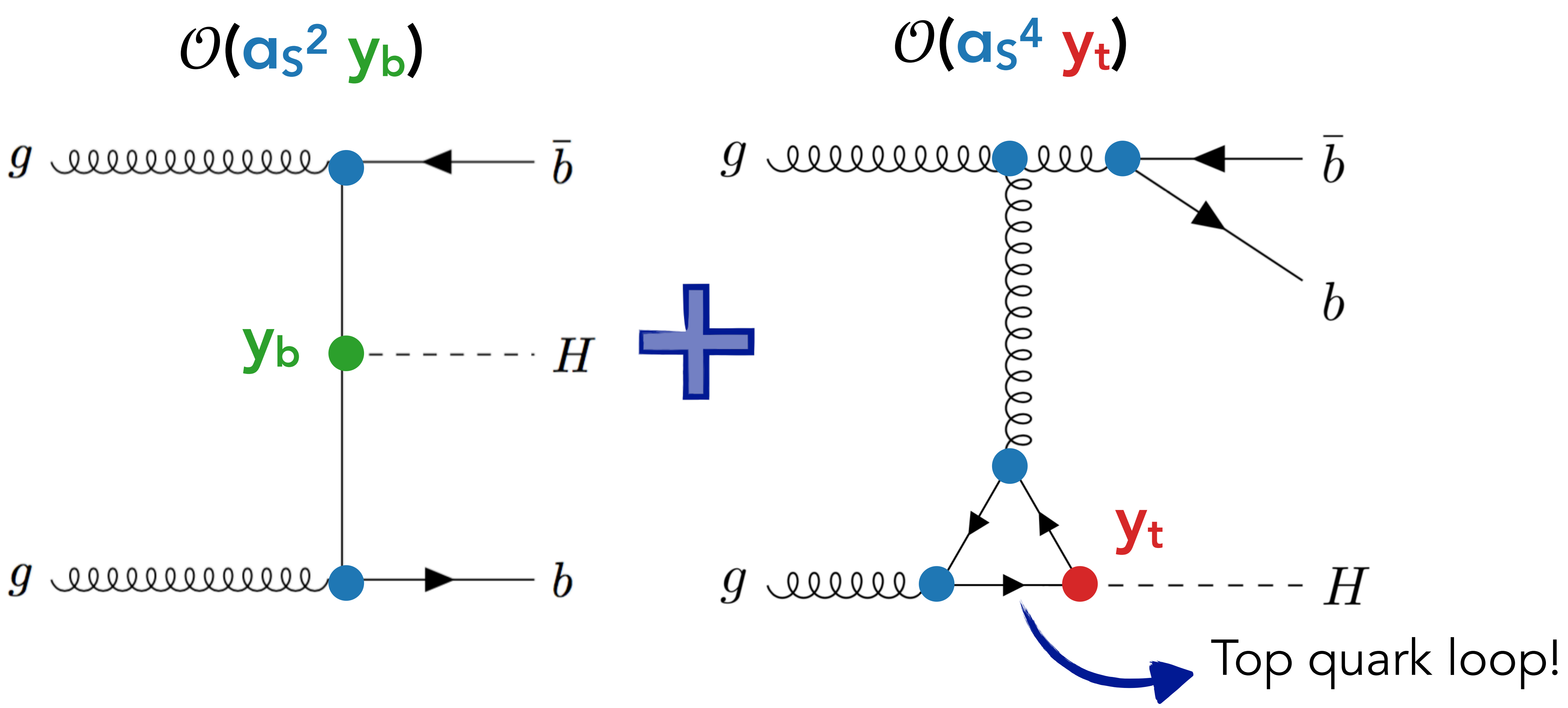


- According to current projections, an **observation** of **SM *HH*** production could be possible only at the end of **HL-LHC**.

The *bbH* background for *HH* searches

The **most sensitive** HH channels all involve the ***H→bb* decay**.

➡ **Single Higgs boson production + bb** (= *bbH*) is an irreducible bkg. for all these searches!



= **ggF H** production + **bb**
generated via QCD radiation.

➡ $d\sigma\ (bbH) \propto |\mathcal{O}(\alpha_S^2\ y_b) + \mathcal{O}(\alpha_S^4\ y_t)|^2$
$\propto \mathcal{O}(y_b^2) + \mathcal{O}(y_t^2) + \mathcal{O}(y_b y_t)$.

- ***bbH* rate comparable** to **SM HH signal** in ***HH* phase space**.
- **y_t^2 contribution** currently simulated by the experiments using **ggF NNLOPS (ATLAS)** or **MiNLO (CMS):**
  - ➡ Within 5-flavor scheme (5FS) = Massless bottom quarks.
  - Only at most LO-accurate for **ggF Higgs + 2 jets**.
- ATLAS *HH* searches assign a **100% uncertainty** to the **ggF H + bb background**.
  - ➡ Also motivated by data - MC disagreement in other analyses (see JHEP 08 (2022) 027 and Eur. Phys. J. C 80 (2020) 942).
  - Now the **primary systematic uncertainty** for ***HH* searches**, **affecting** the **current constraints on HH production from ATLAS** by **25%**!

= Crucial to have **better description** of the ***bbH* background** for the **next generation of *HH* searches**!

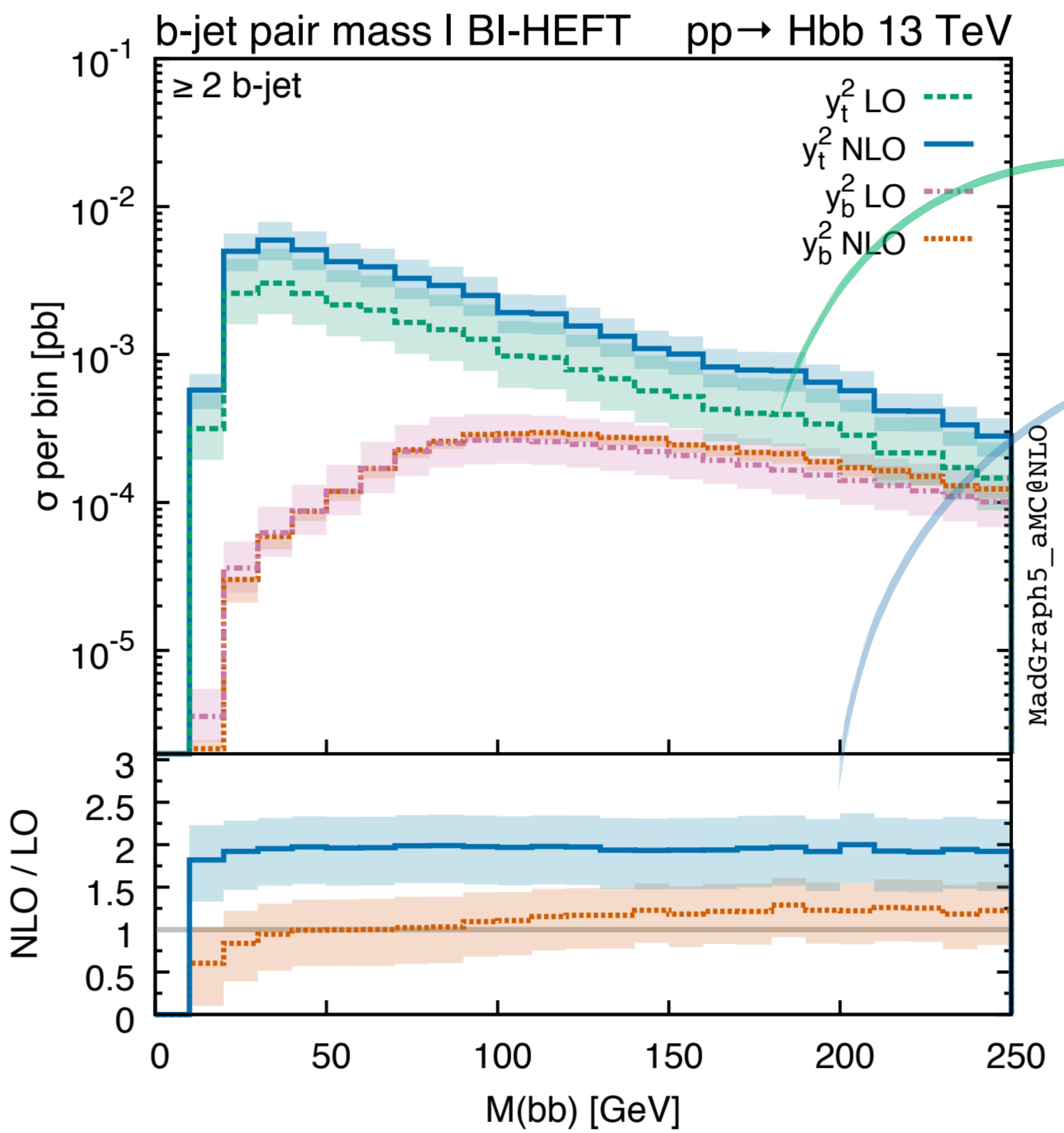
The *bbH* process @ NLO

JHEP 07 (2019) 054, N. Deutschmann, F. Maltoni, M. Wiesemann, M. Zaro, 2019.

The (fiducial) rates for the ***bbH*** process was computed **@ NLO** in the **4-flavor scheme (4FS)**, using `MadGraph5_aMC@NLO`.

Including the $\propto y_b^2$ and the $\propto y_t^2$ **contributions** and the **interference** ($\propto y_b y_t$).

= Massive bottom quarks.



- The y_t^2 **contribution** to the *bbH* cross-section is **dominant already @ LO**.
  - Becomes even **larger @ NLO**, with **K-factors = 2 - 3**.
- **Large NLO / LO K-factors** for both y_t^2 and y_b^2 components, with **strong dependence** on the **differential distributions**.
  - Critical to have **reliable** predictions for the ***bbH* process @ NLO**.
- The **interference** term is **subdominant** (= **5-10%** w.r.t. the total).
  - Subleading w.r.t. the relatively large scale uncertainties (**≈ 50%**).

The *bbH* process @ NLO + PS (4FS) in the phase space of *HH*→*bbγγ*

We present a simulation of ***bbH* process @ NLO + matching to parton shower (PS) in the 4FS** + dedicated analysis targeting the *HH* phase space! → Using the *HH*→*bbγγ* search as a representative case. JHEP 09 (2023) 179

Setup

- **Same approach & settings** as JHEP 07 (2019) 054.
  - m_b = 4.92 GeV, m_t = 172.5 GeV, m_H = 125 GeV.
  - PDF set `NNPDF31_nlo_as_0118_nf_4`.
  - Central scales $\mu_R = \mu_F = \mu_{Sh} = H_T / 4$.
- We simulate only the y_b^2 and y_t^2 contributions (= the $y_b y_t$ **interference** is **ignored**).
- **Fiducial cuts** inspired by *HH*→*bbγγ* analysis (JHEP 01 (2024) 066).
  - Consider **di-photon decay** of the **Higgs boson**.
  - **Anti-k$_T$ jets** with R = 0.4, with $p_T > 25$ GeV and $|\eta| < 2.5$.
  - At least **2 photons** and exactly **2 *b*-jets** (= jets containing at least one B-hadron).
  - **Photon cuts**: $p_T(\gamma_{1(2)}) > 0.35\ (0.25) \times m_{\gamma\gamma}$, $|\eta(\gamma)| < 2.37$, $105 < m_{\gamma\gamma} < 160$ GeV. → Targeting the *H*→γγ kinematics.
  - ***b*-jet cuts**: $80 < m_{bb} < 140$ GeV. → Targeting the *H*→*bb* kinematics.

The *bbH* process @ NLO + PS (4FS) in the phase space of *HH*→*bbγγ*

We present a simulation of ***bbH* process @ NLO + matching to parton shower (PS) in the 4FS** + dedicated analysis targeting the *HH* phase space! → Using the *HH*→*bbγγ* search as a representative case.

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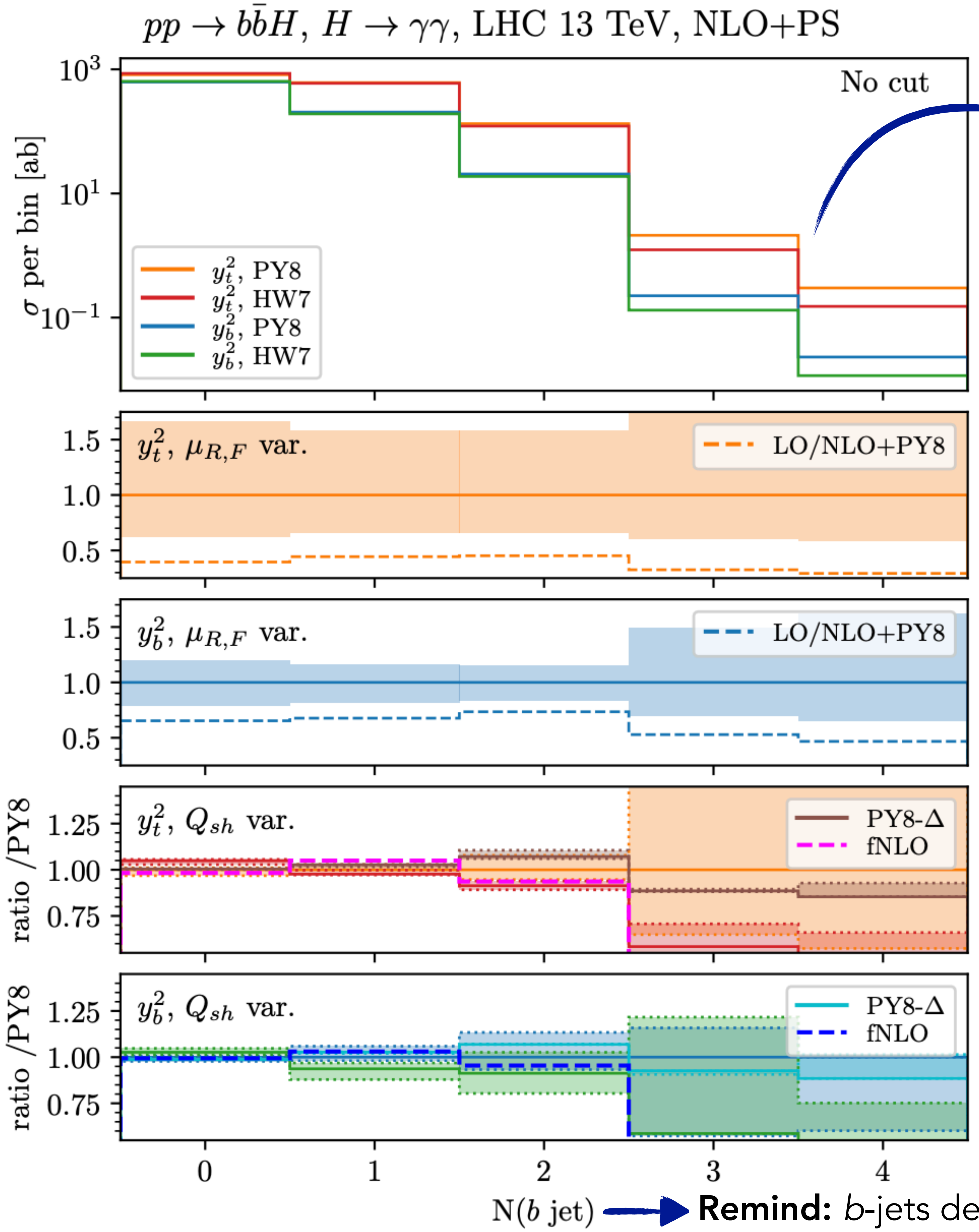
Fiducial cross-sections

Cut	Contr.	Run	LO	NLO	$\delta\mu_{R,F}$	δQ_{sh}	NNLOPS (y_t^2 LO)	HH signal
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		$^{+4\%}_{-6\%}$		

- The NLO **corrections** to the bbH rates are **very large**! →
  - y_b^2 = +50%.
  - y_t^2 = +150%.
- The scale uncertainties @ NLO are still **sizeable** (especially for y_t^2, where they are within **~60%**).
- The **impact of the PS** (`Pythia8` or `Herwig7`) on the *bbH* NLO rates is within ~10% (= **subdominant** w.r.t. the **scale uncertainties**!).
- The ***bbH* background rate** is **comparable** with the **SM HH signal**.
- The **ggF 5FS NNLOPS** simulation provides *bbH* cross-sections **larger** by a **factor ~2** w.r.t. our 4FS bbH @ NLO prediction.
  - Could be traced back to the **g→bb splittings** in the PS.
  - When turning these off, the **ggF 5FS NNLOPS rates drops to half** its nominal prediction. → More details in the next slides.

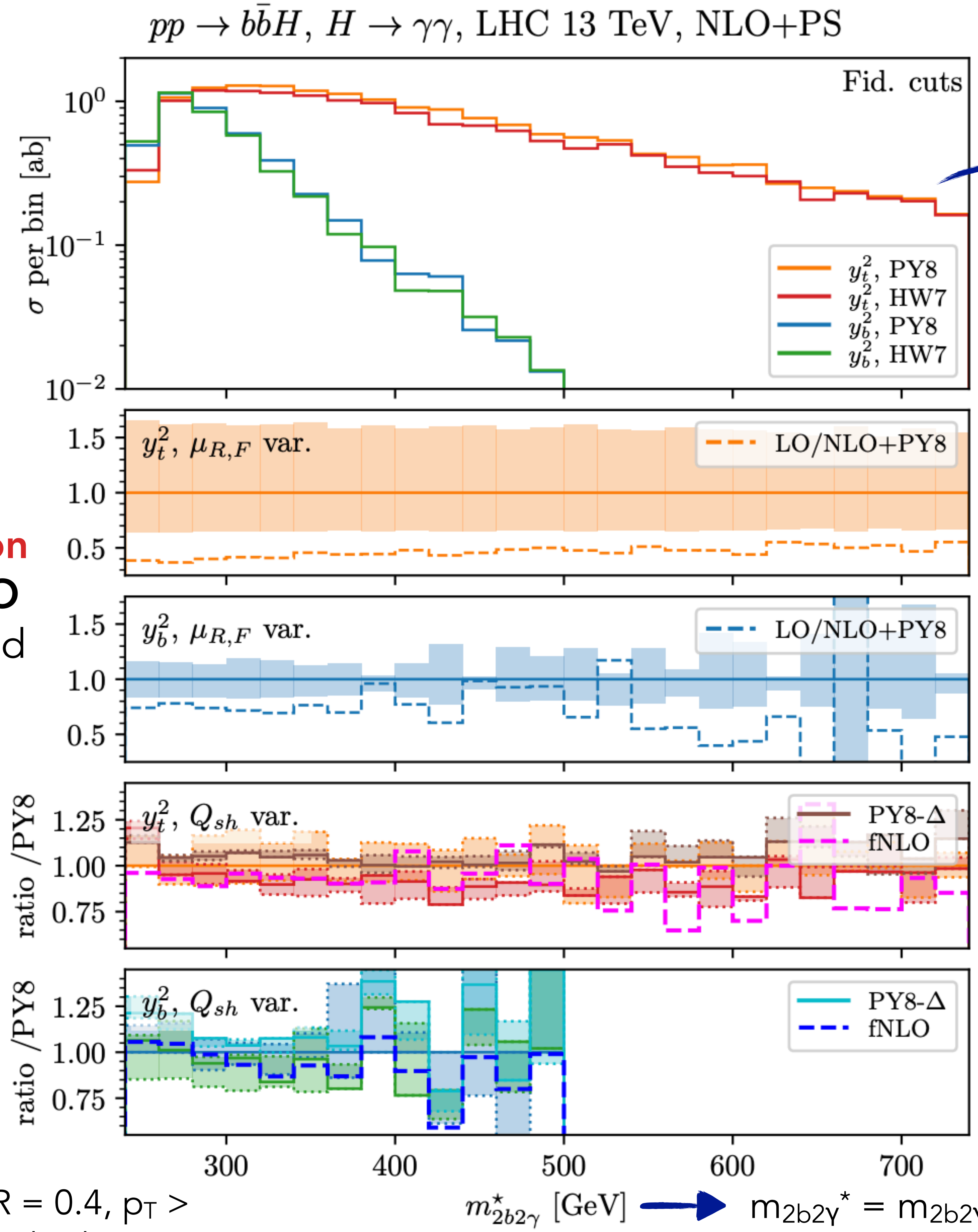
Differential distributions



y_t^2 contribution increasingly larger w.r.t. the **y_b^2 contribution**.

y_t^2 contribution has **larger NLO corrections** and **scale unc.**.

PS unc. become **larger** for N (b jet) ≥ 3.



y_b^2 contribution (= **softer** bottom quarks) **comparable** to **y_t^2 contribution** (= **harder** bottom quarks generated by **hard gluon** recoiling against the Higgs) at **low $m_{2b2\gamma}^*$**, and strongly **suppressed** at **larger $m_{2b2\gamma}^*$**.

N(b jet) → **Remind:** *b*-jets defined as anti-k_T jets with R = 0.4, p_T > 25 GeV and |η|<2.5, including at least one B-hadron.

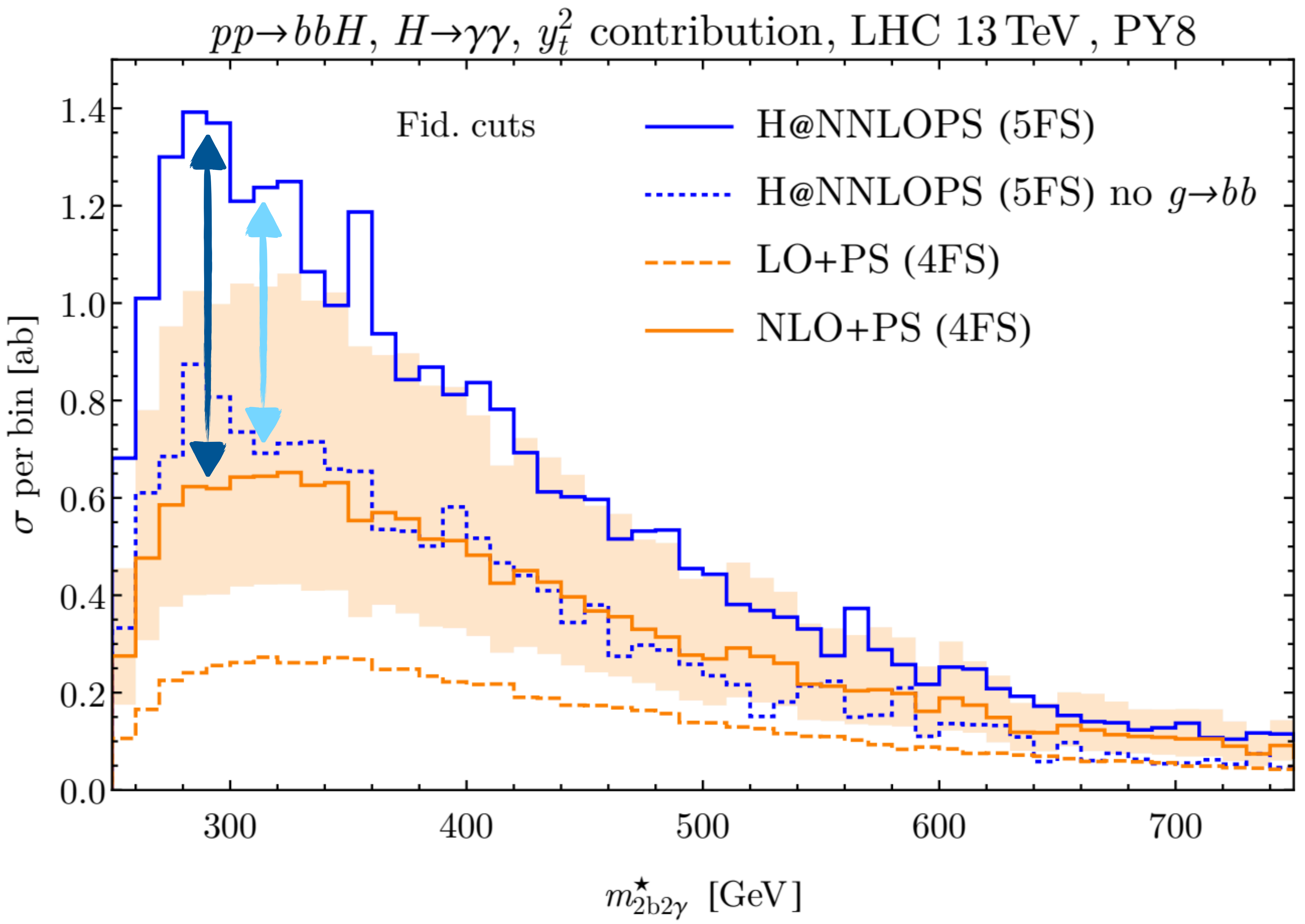
$m^{\star}_{2b2\gamma}$ [GeV] → $m_{2b2\gamma}^* = m_{2b2\gamma} - m_{bb} - m_{\gamma\gamma} + 2m_H$.

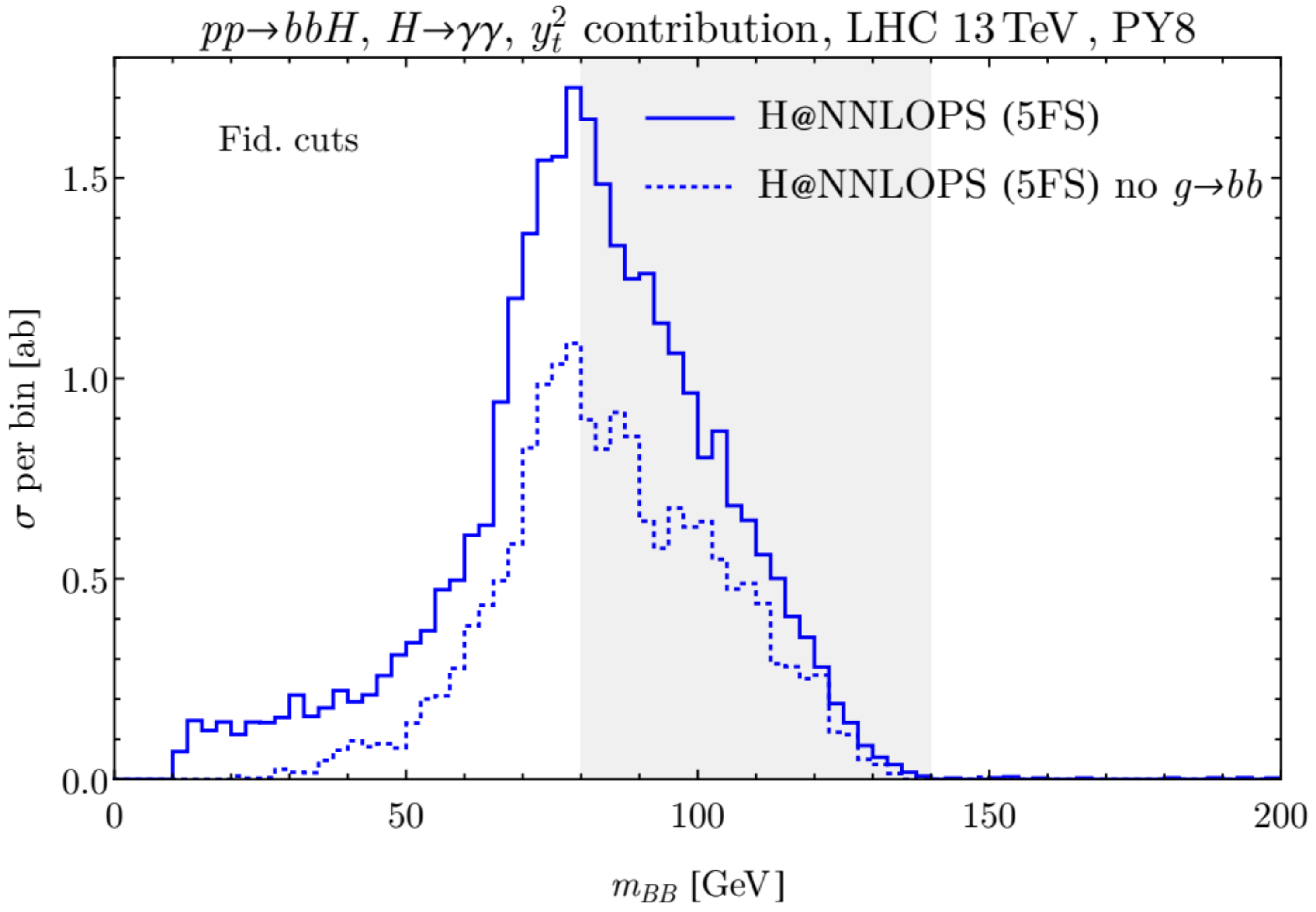
Comparison and combination with inclusive NNLOPS prediction

- The *bbH* **cross-sections** provided by the **ggF 5FS NNLOPS** simulation are **larger** by a **factor ~2** w.r.t. our **4FS bbH @ NLO** prediction.
- This **discrepancy** is **recovered** if we **turn off** the **g→bb splittings** in the PS.

➡ **Question**: why does the **g→bb splittings generate** a large amount of events with **2 hard and central** (p_T > 25 GeV, |η| < 2.5) ***b*-jets**?

➡ 1. Maybe **soft wide-angle bottom quarks** from **g→bb splittings** are **clustered** with **other hard partons** to form **two hard *b*-jets** (= pp→H + bb + jj events)?
2. Or maybe **g→bb splittings** are generating **hard**, **wide-angle bottom quarks**?





g→bb splittings populate region with **high B-hadron invariant mass**!

➡
- **g→bb splittings** are generating events with **hard B-hadrons!**
- Probably bottom quarks from **g→bb splittings** are hard and well separated.

➡
- Kinematics poorly described in soft / collinear approximation of the PS.
- The PS is acting outside of its validity range.

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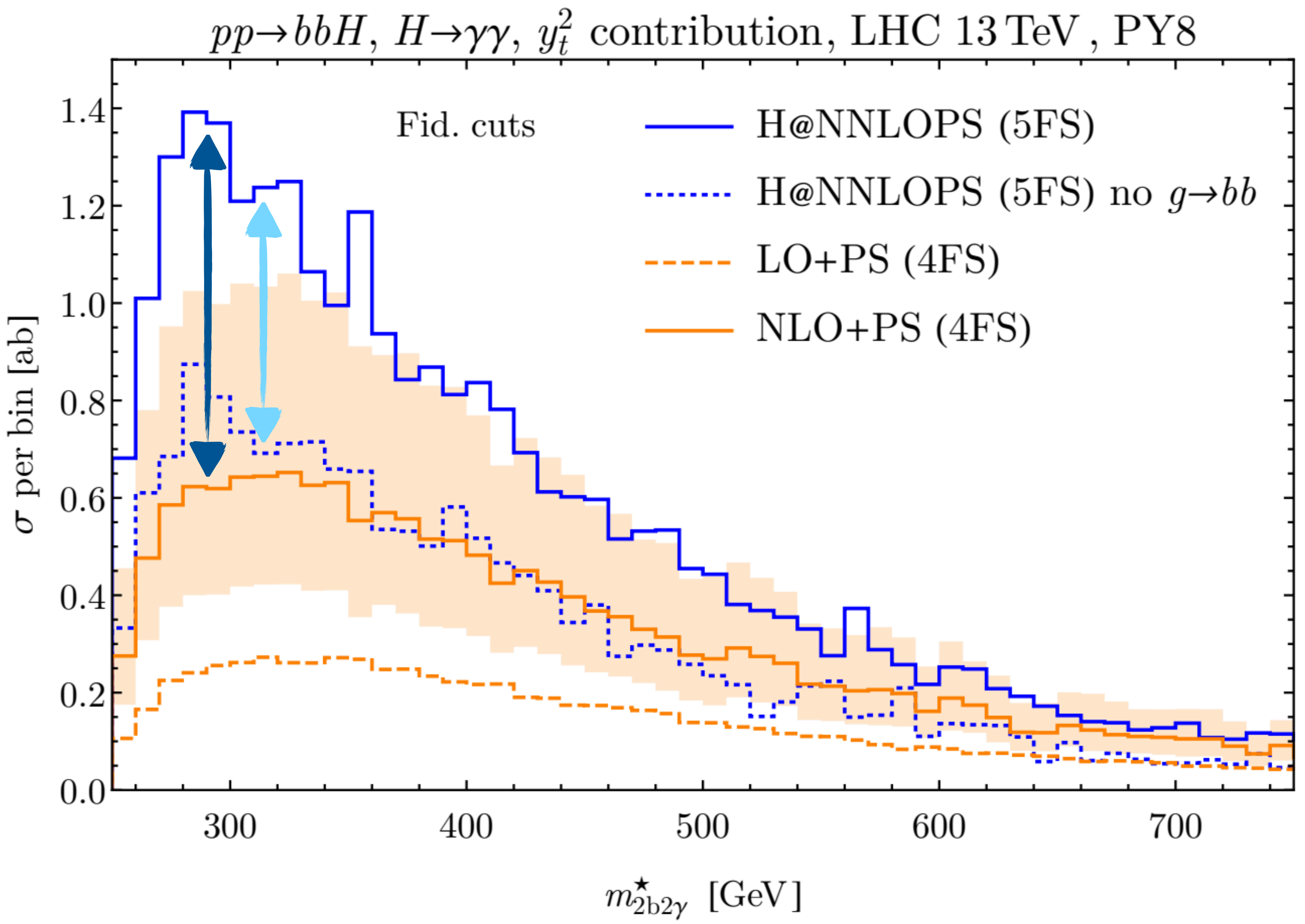

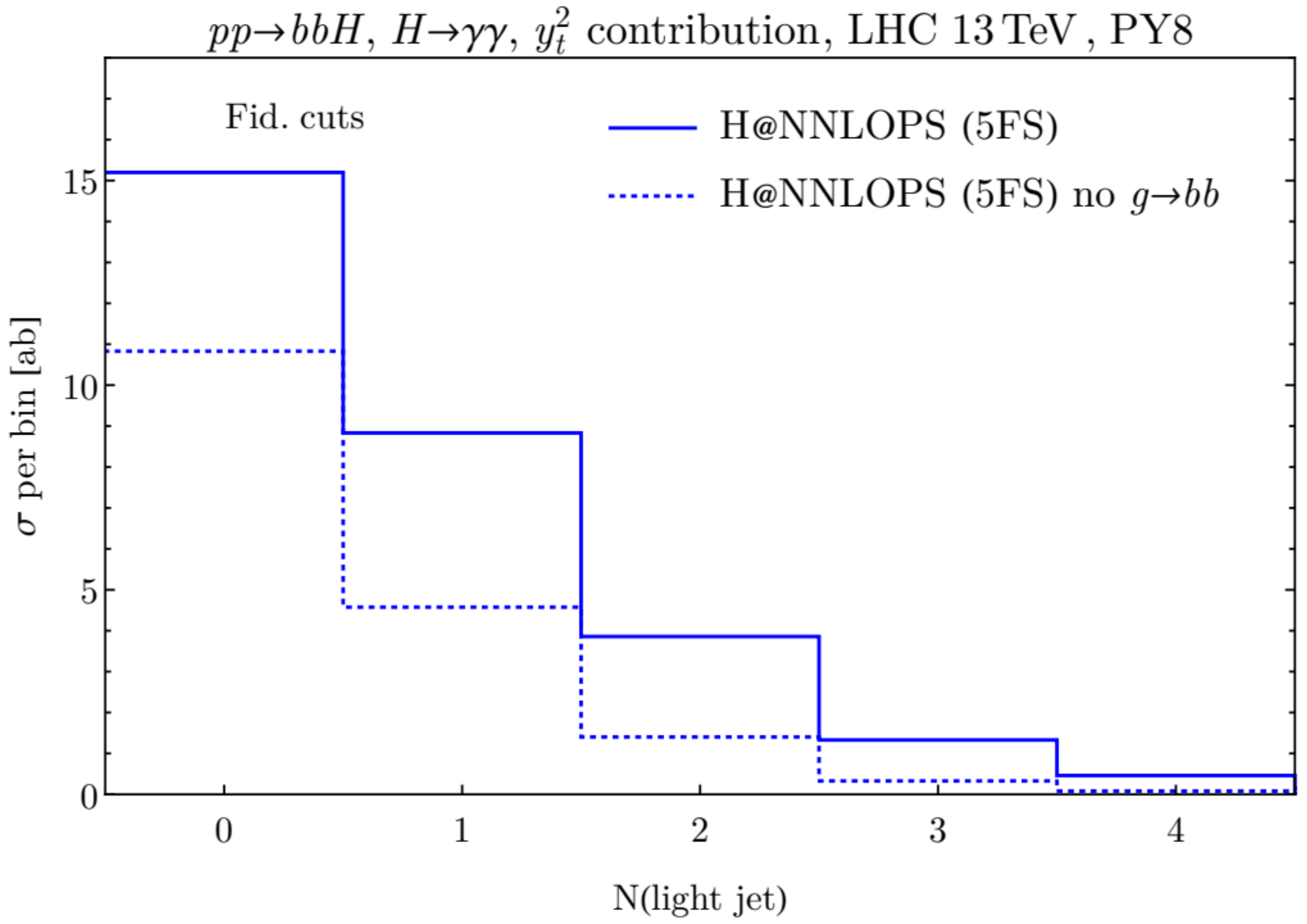

g→bb splittings populate region with **no light jets** (in addition to the two b-jets from the fiducial cuts).

- **g→bb splittings** are **not contributing** to ***pp→H + bb + jj* events** (i.e. N (light jets) = 2).
- **Potential double-counting** of *pp→H + bb* events (already covered by the Matrix-Element calculations in ggF NNLOPS 5FS simulation) from the **PS**.

Comparison and combination with inclusive NNLOPS prediction

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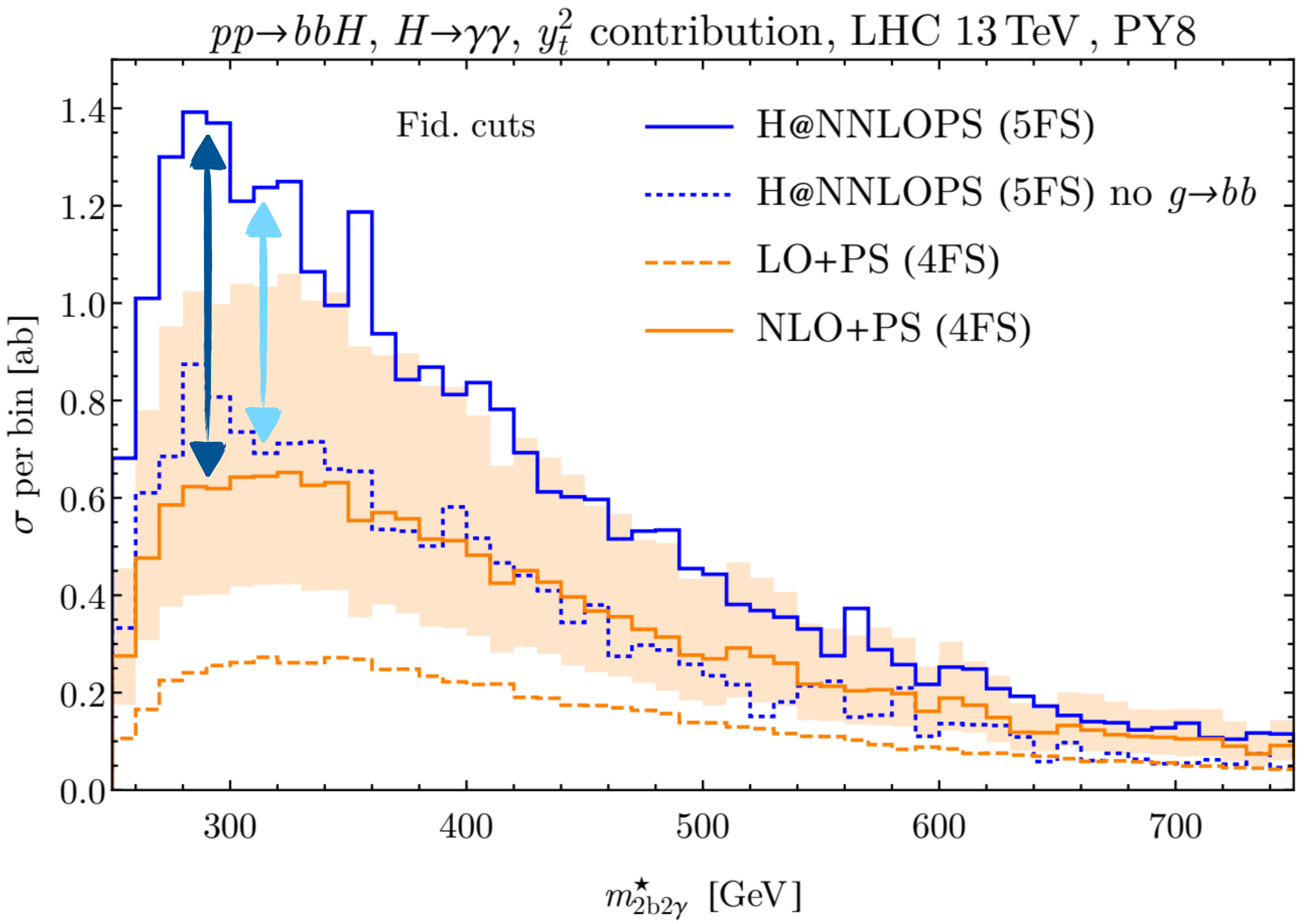
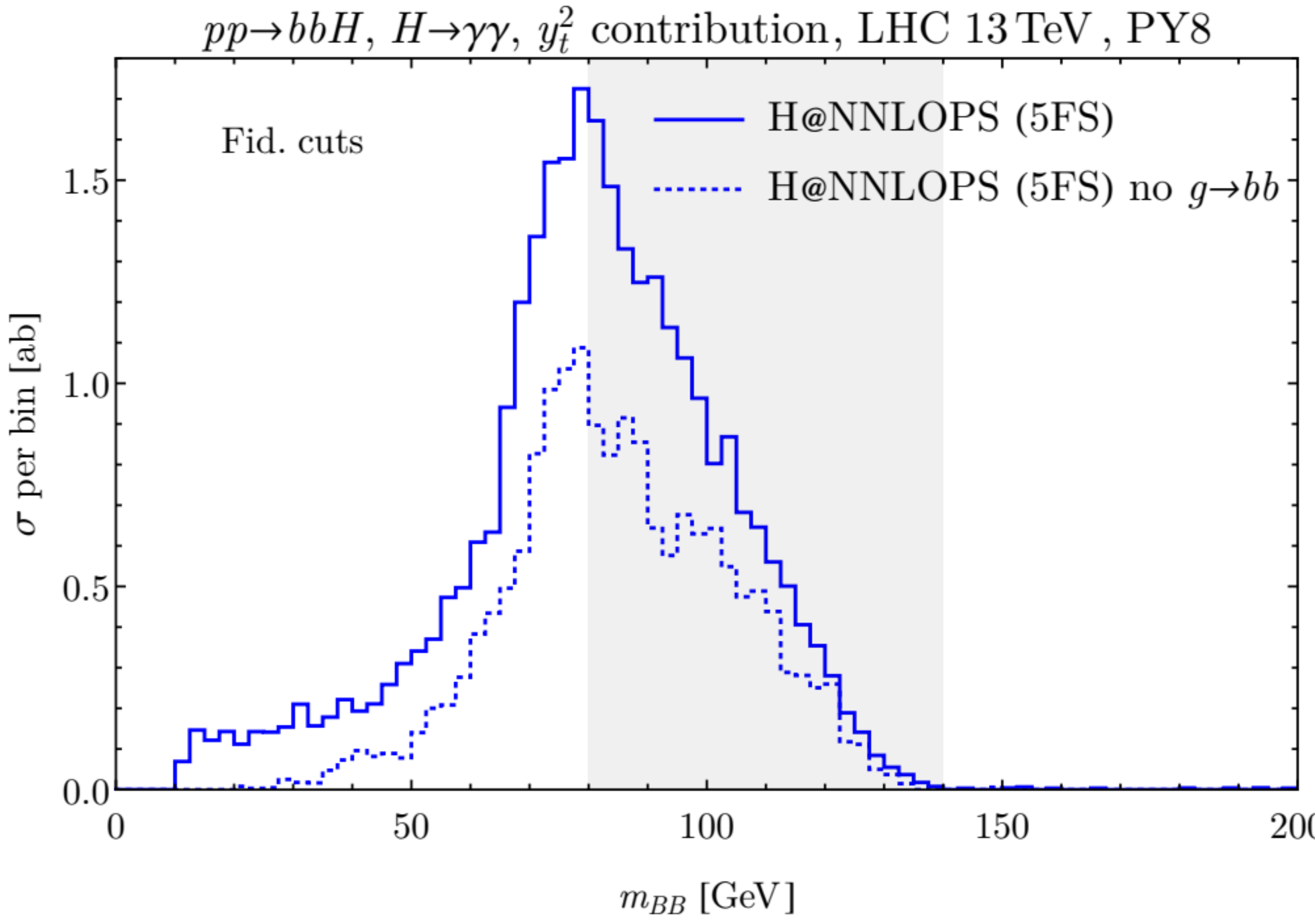
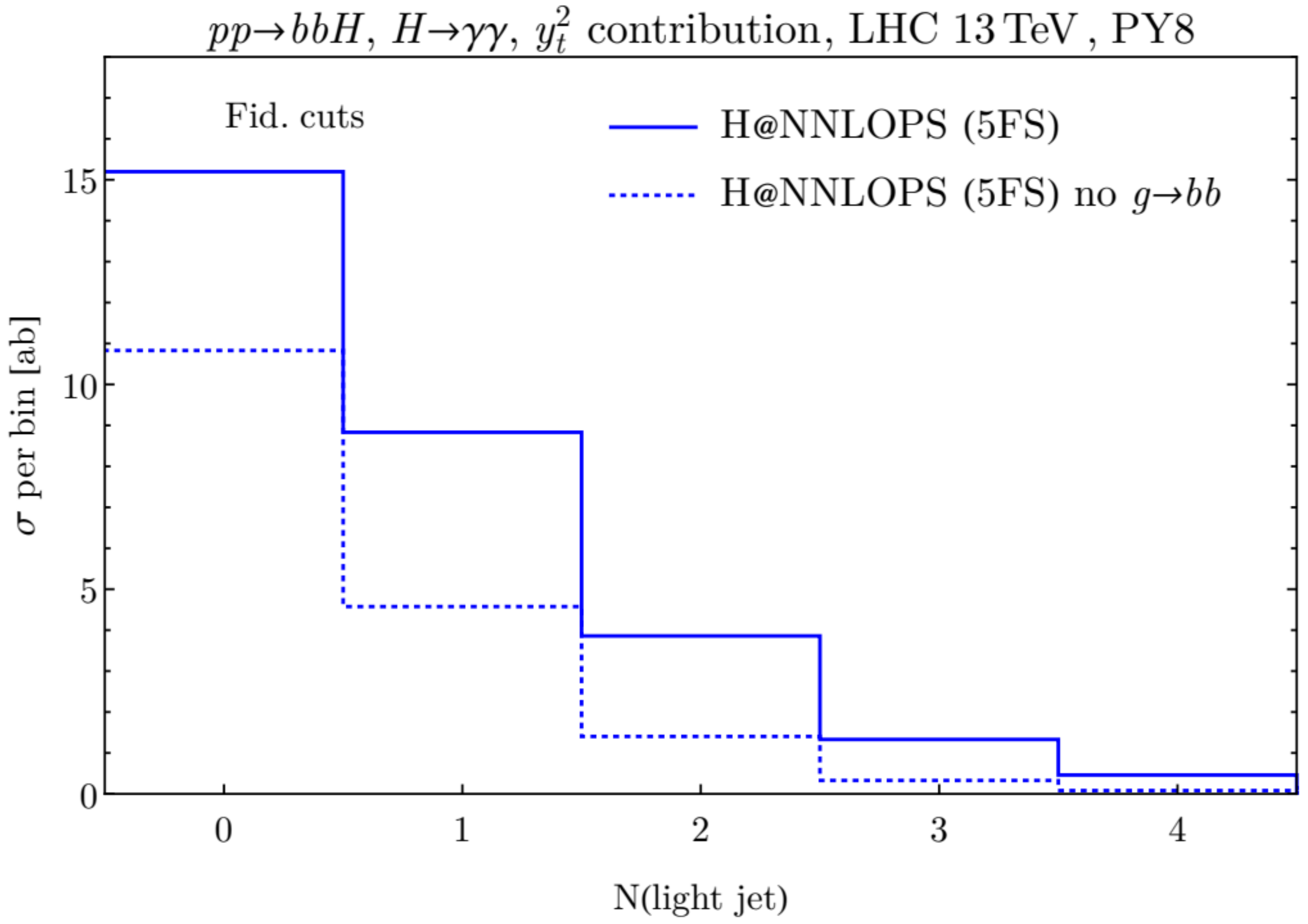






The **100% uncertainty** assigned to the ggF H + bb background by the HH searches is **probably adequate**.

Impact of new *bbH* modeling for *HH* searches

Question: what is the **impact** of the **new *bbH* modeling** from the *bbH* @ NLO (4FS) + PS for the ***HH* searches**?

➡ We have propagated the **new bbH rates** and **uncertainties** to **two *HH* searches** in the *bbγγ* and *bbττ* channels.

➡ Using full Run 2 ATLAS analyses as representative cases (= Phys. Rev. D 106 (2022) 052001 and JHEP 07 (2023) 040).

1. ***bbH* @ NLO (4FS) rates** ≈ 0.5 × **ggF NNLOPS (5FS)** rates.
   ➡ **Rates** of the *bbH* background from the two analyses ≈ **halved**.
2. **100% uncertainty** on ggF + bb bkg. **replaced** with **scale uncertainties** for ***bbH* @ NLO (4FS)** in fid. region (**≈ 50%**)
   ➡ **Uncertainty** on the *bbH* background **≈ halved**!

Positive impact on upper limits on HH production & HH discovery significance.

Impact of rates and uncertainties from *bbH* @ NLO + PS (4FS) on the **upper limits on HH production & HH discovery significance**.

	HH→*bbγγ*	HH→*bbττ*
Run 2	2%	5%
HL-LHC projection	10%	20%

➡ **Larger improvement for HH→*bbττ***, because the analysis is less statistically limited and because of the larger contribution of the *bbH* background.

Subtlety:

- The **ggF NNLOPS (5FS)** sample is also used to estimate the **bkg.** from single **Higgs + jets**, where light or c-jets are **mistagged as b-jets**.
- The new bbH @ NLO does not cover this!
- For this exercise, we **only rescaled** the **true b-jet contribution** (≈ **80%** of the ggF NNLOPS estimation).

Summary

- **Single Higgs boson production + bb** (***bbH***) is an **irreducible background** for the most sensitive ***HH* searches** (= all involving at least one ***H→bb* decay**).
  - **Current predictions** adopted by ATLAS rely on the inclusive **ggF NNLOPS (5FS)** sample, and assign a **100% uncertainty**.

- We studied the ***bbH* process @ NLO (within the 4FS) + matching to PS** in a fiducial region **targeting** the ***HH* phase space**.
  - Simulated both the y_b^2 and the y_t^2 contributions using `MadGraph5_aMC@NLO`.
  - **Large NLO corrections** (especially for the y_t^2 case).
  - Still **sizable scale uncertainties** @ NLO, especially for the y_t^2 contribution (= $^{+58\%}_{-34\%}$).

- We **compared** the **new *bbH* @ NLO simulation (4FS)** with the **current ggF NNLOPS (5FS)** sample.
  - The **rates** from the **ggF NNLOPS (5FS)** prediction appear to be **largely influenced** by the **g→bb splittings in the PS** (= probably acting **outside** of its **validity range**!).

- We estimated the **impact** of the **new *bbH* @ NLO (4FS) predictions** to **HH searches** (using HH→*bbγγ* and HH→*bbττ* analyses as representative cases).
  - Propagating **lower rates** and **smaller uncertainties**.
  - **2% - 20% improvement** on upper limits on HH cross-section / HH discovery significance, depending on the HH channel and the luminosity.

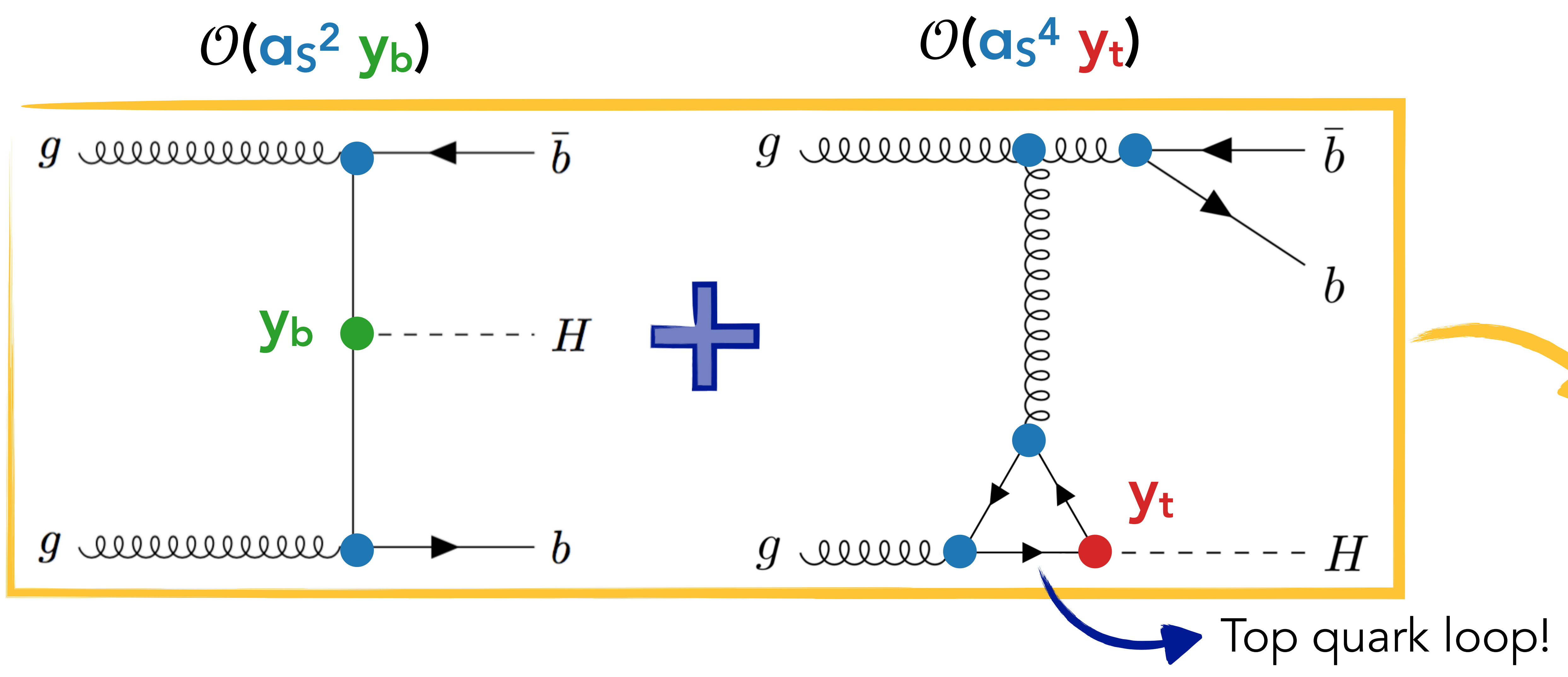
Thank you for your attention!

Backup

The *bbH* background for *HH* searches

The **most sensitive** HH channels all involve the ***H→bb* decay**.

- **Single Higgs boson production + bb** (= *bbH*) is an irreducible bkg. for all these searches!

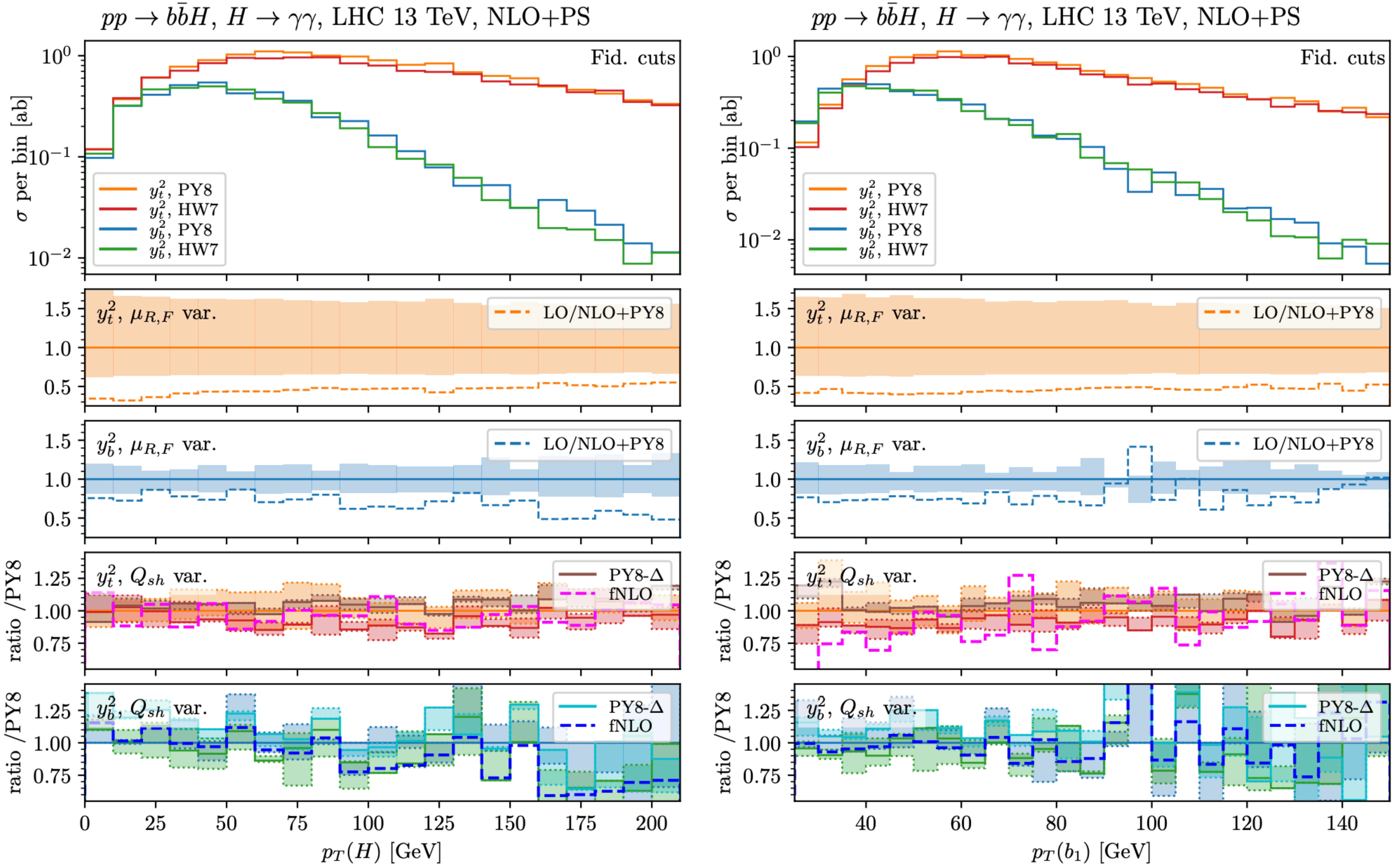


ATLAS Run 2 *HH→bbγγ* search (JHEP 01 (2024) 066)

	High Mass 1	High Mass 2	High Mass 3	Low Mass 1	Low Mass 2	Low Mass 3	Low Mass 4
SM $HH(\kappa_\lambda = 1)$ signal	$0.26^{+0.03}_{-0.04}$	$0.194^{+0.021}_{-0.032}$	$0.84^{+0.10}_{-0.14}$	$0.048^{+0.007}_{-0.008}$	$0.038^{+0.004}_{-0.006}$	$0.039^{+0.004}_{-0.006}$	$0.032^{+0.004}_{-0.004}$
ggF	$0.25^{+0.03}_{-0.04}$	$0.188^{+0.021}_{-0.032}$	$0.81^{+0.10}_{-0.14}$	$0.046^{+0.007}_{-0.008}$	$0.036^{+0.004}_{-0.006}$	$0.037^{+0.004}_{-0.006}$	$0.025^{+0.004}_{-0.004}$
VBF $[10^{-3}]$	$7.9^{+0.6}_{-0.5}$	$5.3^{+0.5}_{-0.4}$	29^{+4}_{-3}	$1.98^{+0.28}_{-0.24}$	$1.71^{+0.16}_{-0.14}$	$1.96^{+0.21}_{-0.19}$	$7.4^{+0.6}_{-0.5}$
Alternative $HH(\kappa_\lambda = 10)$ signal	$2.5^{+0.4}_{-0.3}$	$1.81^{+0.25}_{-0.20}$	$6.2^{+0.8}_{-0.6}$	$5.0^{+1.2}_{-0.9}$	$3.8^{+0.7}_{-0.5}$	$3.7^{+0.7}_{-0.6}$	$3.6^{+0.4}_{-0.4}$
ggF	$2.3^{+0.4}_{-0.3}$	$1.64^{+0.25}_{-0.19}$	$4.9^{+0.8}_{-0.6}$	$4.7^{+1.0}_{-0.8}$	$3.6^{+0.7}_{-0.6}$	$3.3^{+0.7}_{-0.5}$	$2.04^{+0.34}_{-0.27}$
VBF	$0.231^{+0.019}_{-0.017}$	$0.170^{+0.019}_{-0.017}$	$1.29^{+0.15}_{-0.14}$	$0.28^{+0.20}_{-0.11}$	$0.23^{+0.23}_{-0.12}$	$0.36^{+0.10}_{-0.08}$	$1.57^{+0.17}_{-0.16}$
Alternative VBF $HH(\kappa_{2V} = 3)$ signal	$0.23^{+0.04}_{-0.04}$	$0.20^{+0.05}_{-0.04}$	$3.8^{+0.7}_{-0.6}$	$0.03^{+0.04}_{-0.02}$	$0.03^{+0.06}_{-0.02}$	$0.048^{+0.023}_{-0.015}$	$0.17^{+0.04}_{-0.03}$
Single Higgs boson background	$1.5^{+0.5}_{-0.3}$	$0.48^{+0.21}_{-0.10}$	$0.57^{+0.25}_{-0.14}$	$1.72^{+0.31}_{-0.19}$	$0.53^{+0.08}_{-0.06}$	$0.29^{+0.14}_{-0.07}$	$0.16^{+0.06}_{-0.03}$
ggF	$0.5^{+0.5}_{-0.2}$	$0.14^{+0.21}_{-0.09}$	$0.25^{+0.25}_{-0.12}$	$0.29^{+0.31}_{-0.15}$	$0.08^{+0.08}_{-0.04}$	$0.07^{+0.13}_{-0.06}$	$0.04^{+0.06}_{-0.03}$
$t\bar{t}H$	$0.302^{+0.034}_{-0.032}$	$0.069^{+0.009}_{-0.008}$	$0.063^{+0.008}_{-0.007}$	$0.77^{+0.09}_{-0.08}$	$0.214^{+0.029}_{-0.026}$	$0.100^{+0.012}_{-0.012}$	$0.048^{+0.005}_{-0.005}$
ZH	$0.61^{+0.06}_{-0.05}$	$0.174^{+0.020}_{-0.016}$	$0.188^{+0.035}_{-0.029}$	$0.49^{+0.05}_{-0.04}$	$0.149^{+0.028}_{-0.025}$	$0.069^{+0.033}_{-0.023}$	$0.028^{+0.010}_{-0.007}$
Rest	$0.17^{+0.08}_{-0.04}$	$0.089^{+0.030}_{-0.016}$	$0.07^{+0.04}_{-0.02}$	$0.181^{+0.030}_{-0.019}$	$0.089^{+0.016}_{-0.009}$	$0.046^{+0.007}_{-0.004}$	$0.039^{+0.008}_{-0.004}$
Continuum background	$11.3^{+1.5}_{-1.6}$	$3.2^{+0.8}_{-0.8}$	$2.8^{+0.8}_{-0.8}$	$37.2^{+2.9}_{-2.9}$	$10.8^{+1.5}_{-1.5}$	$4.4^{+0.9}_{-1.0}$	$1.1^{+0.5}_{-0.5}$
Total background	$12.8^{+1.6}_{-1.6}$	$3.7^{+0.9}_{-0.8}$	$3.4^{+0.8}_{-0.8}$	$38.9^{+2.9}_{-2.9}$	$11.3^{+1.5}_{-1.5}$	$4.7^{+0.9}_{-1.0}$	$1.3^{+0.5}_{-0.5}$
Data	12	4	1	29	8	5	4

- The ***bbH* background** is **not negligible** w.r.t. the **SM HH signal**!
  - **Example of ATLAS Run 2 *HH→bbγγ* search**: ***bbH* background comparable** with **SM HH signal** in **most sensitive analysis categories** (= High Mass 3 and Low Mass 4).

Differential distributions



The shape difference between the y_b^2 **contribution** and the y_t^2 **contribution** for $p_T(H)$ and $p_T(b_1)$ confirms that the y_t^2 **contribution** favors **harder spectra** for the **Higgs boson** and **bottom quarks**.

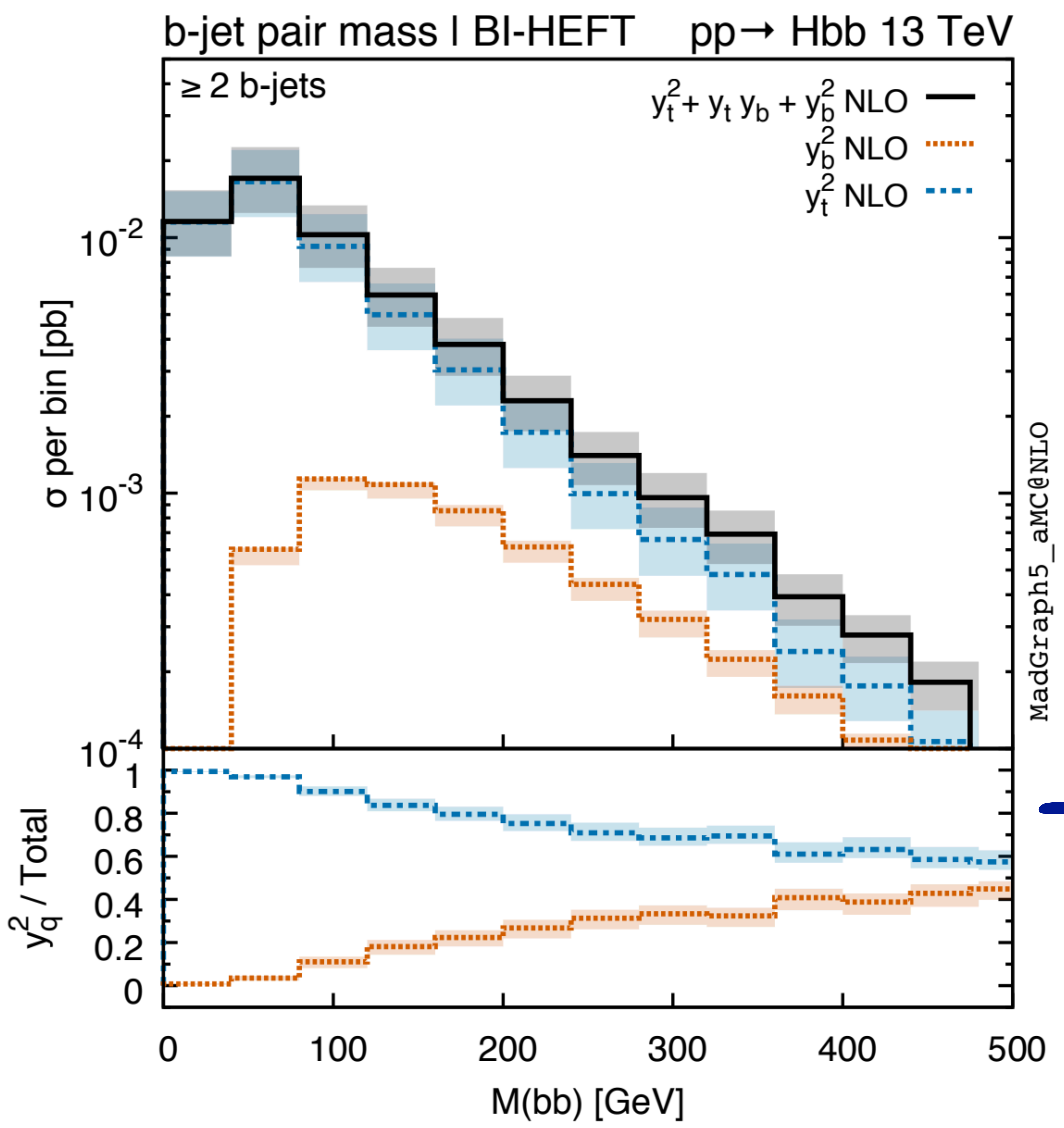
The *bbH* process @ NLO

The (fiducial) rates for the ***bbH*** process was computed **@ NLO** in the **4-flavor scheme (4FS)**, using `MadGraph5_aMC@NLO`.

= Massive bottom quarks.

- Including the $\propto y_b^2$ and the $\propto y_t^2$ **contributions** and the **interference** ($\propto y_b y_t$).
- **Heavy top approximation** (**HTL**) adopted for the **NLO corrections** to the y_t^2 component.

Verified to be reliable from a comparison @ LO.



The relative contribution of the **interference** ($\propto y_b y_t$) **corresponds to 1 - y_b^2 - y_t^2.**

The *bbH* process @ NLO + PS (4FS) in the phase space of *HH*→*bbγγ*

We present a simulation of *bbH* process @ NLO + matching to parton shower (PS) + dedicated analysis targeting the *HH* phase space! → Using the *HH*→*bbγγ* search as a representative case.

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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	[illegible] −20%	+0% +0%	4867; $g \to b\bar{b}$: 2140	82.1
		PY8-Δ		848		+0% +0%		
		HW7	561	851		+0% +0%		
	y_t^2	PY8	655	1565	+61% −35%	+0% +0%		
		PY8-Δ		1595		+0% +0%		
		HW7	655	1578		+0% +0%		
	sum	PY8	1217	2414	+46% −29%	+0% +0%		
		PY8-Δ		2443		+0% +0%		
		HW7	1216	2429		+0% +0%		
Fid. cuts	y_b^2	PY8	3.15	4.22	[illegible] −15%	+10% −4%	29.9; $g \to b\bar{b}$: 17.2	22.7
		PY8-Δ		4.75		+0% −2%		
		HW7	2.59	4.08		+8% −12%		
	y_t^2	PY8	8.24	18.1	+58% −34%	+10% −7%		
		PY8-Δ		19.2		+3% −1%		
		HW7	6.83	16.6		+4% −5%		
	sum	PY8	11.4	22.3	+50% −30%	+10% −6%		
		PY8-Δ		23.9		+2% −1%		
		HW7	9.42	20.7		+4% −6%		
Fid. cuts + $m^{\star}_{2b2\gamma} < 500$ GeV	y_b^2	PY8	3.11	4.15	[illegible] −15%	+11% −4%	22.3; $g \to b\bar{b}$: 13.3	15.7
		PY8-Δ		4.69		+0% −2%		
		HW7	2.56	4.02		+8% −13%		
	y_t^2	PY8	5.33	12.3	+60% −34%	+12% −8%		
		PY8-Δ		12.8		+2% −1%		
		HW7	4.31	11.3		+5% −5%		
	sum	PY8	8.44	16.5	+49% −29%	+12% −7%		
		PY8-Δ		17.5		+1% −1%		
		HW7	6.86	15.3		+6% −7%		
Fid. cuts + $m^{\star}_{2b2\gamma} < 350$ GeV	y_b^2	PY8	2.71	3.65	[illegible] −16%	+9% −4%	11.5; $g \to b\bar{b}$: 6.82	2.84
		PY8-Δ		4.11		+0% −2%		
		HW7	2.22	3.54		+8% −15%		
	y_t^2	PY8	2.32	5.78	+61% −34%	+13% −9%		
		PY8-Δ		6.05		+1% +0%		
		HW7	1.88	5.43		+5% −3%		
	sum	PY8	5.03	9.43	+44% −27%	+12% −7%		
		PY8-Δ		10.2		+0% +0%		
		HW7	4.10	8.97		+6% −6%		

Fiducial cross-sections (before cuts and in $m_{2b2\gamma}^*$ categories)

- The *bbH* rates were evaluated also **before the fiducial cuts**, and in **three** categories, based on cuts on the **$m_{2b2\gamma}^*$ variable (on top of the fiducial selection).**

  ➔ $m_{2b2\gamma}^* < \infty$, **$m_{2b2\gamma}^* < 500$ GeV**, and **$m_{2b2\gamma}^* < 350$ GeV**.

- The ***bbH* cross-section changes** substantially **depending on the cuts**!

  ➔
  - After applying the **fiducial cuts**, the *bbH* cross-section drops of a factor ~100!
  - In the fiducial region, the ***bbH* background rate** is **comparable** with the **SM HH signal**, and becomes **dominant** in the **$m_{2b2\gamma}^* < 350$ GeV category**.

- The relative contributions of the **y_b^2** and **y_t^2** components changes with the cuts.

  ➔ The **y_b^2 contribution** is **subleading** w.r.t **y_t^2** in all categories, **except** in the **$m_{2b2\gamma}^* < 350$ GeV category**, where the **two contributions are similar**.

The *bbH* process: the state of the art

References (TWiki and ongoing work)

- Higgs radiation off bottom quarks at the Tevatron and the LHC [S. Dittmaier, M. Kramer, M. Spira, arXiv:hep-ph/0309204]
- Exclusive Higgs boson production with bottom quarks at hadron colliders [S. Dawson, C. B. Jackson, L. Reina, D. Wackeroth, arXiv:hep-ph/0311067]
- Higgs boson production in bottom quark fusion at next-to-next-to-leading order [R. V. Harlander, W. B. Kilgore, arXiv:hep-ph/0304035]
- Higgs production in bottom-quark fusion in a matched scheme [S. Forte, D. Napoletano, M. Ubiali, arXiv:1508.01529].
- Higgs production in bottom-quark fusion: matching beyond leading order [S. Forte, D. Napoletano, M. Ubiali, arXiv:1607.00389]
- Resummation and matching of *b*-quark mass effects in bbH production [M. Bonvini, A. S. Papanastasiou, F. J. Tackmann, arXiv:1508.03288]
- Matched predictions for the bbH cross section at the 13 TeV LHC [M. Bonvini, A. S. Papanastasiou, F. J. Tackmann, arXiv:1605.01733]
- Higgs production in association with bottom quarks. [M. Wiesemann, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, P. Torrielli, arXiv:1409.5301]
- Higgs boson production in association with *b*-jets in the POWHEG BOX [B. Jager , L. Reina, D. Wackeroth, arXiv:1509.05843]
- Simulating *b*-associated production of Z and Higgs bosons with SHERPA [F. Krauss, D. Napoletano, S. Schumann, arXiv:1612.04640]
- Top-Yukawa contributions to *bbH* production at the LHC [N. Deutschmann, F. Maltoni, M. Wiesemann, M. Zaro, arXiv:1808.01660]
- NNLO+PS predictions for Higgs production through bottom-quark fusion [C. Biello, A. Sankar, M. Wiesemann, G. Zanderighi, arXiv:2407.08864]