# $b\bar{b}H$ report and future plans

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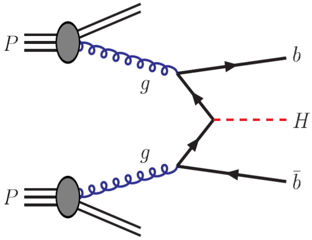
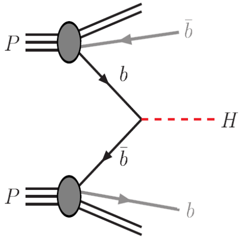
# Associated $H(b\bar{b})$ production

4-flavour scheme




- massive $b$'s
- potentially large logs $\ln(m_b/Q)$
- power terms $(m_b/Q)^n$
- involved $2 \to 3$ at LO
- 2 exclusive $b$'s at LO
- $b$(-tag) well defined

5-flavour scheme




- massless $b$'s
- resummation into $b$-PDFs
- —
- simple $2 \to 1$ at LO
- exclusive $b$'s at higher orders
- $b$ part of light jets

# 4FS vs. 5FS: Total cross section (New Recommendations)

4FS NLO:

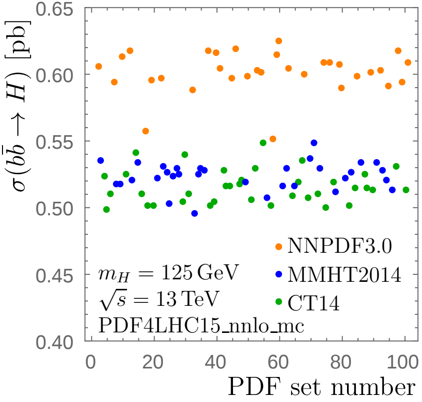
- $\mu_\mathrm{R} = \mu_\mathrm{F} = (m_H + 2\,m_b)/4$; 7-point variation
- 4-flavor set of PDF4LHC15 (PDF4LHC15_nlo_nf4_100)
- hybrid scheme for $b$ masses:
  - OS scheme for internal masses $m_b = 4.92\,\mathrm{GeV}$
  - $\overline{\mathrm{MS}}$ scheme for Yukawa
- OS top mass $m_t = 172.5\,\mathrm{GeV}$ for $y_b\,y_t$ term

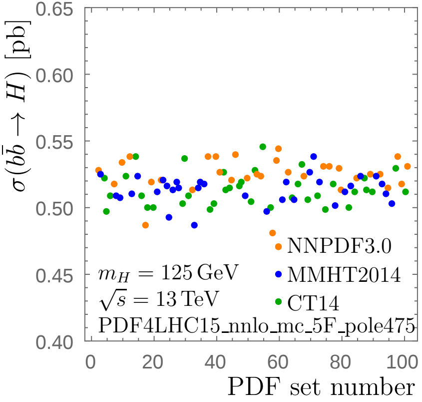
5FS NNLO:

- $\mu_\mathrm{R} = m_H$, $\mu_\mathrm{F} = m_H/4$; 7-point variation
- changed: ~~PDF4LHC15~~ → next slide
- $\overline{\mathrm{MS}}$ scheme for Yukawa

**prescription for $\overline{\mathrm{MS}}$ Yukawa mass:** (LHCHXSWG-INT-2015-006)
input: $m_b(\mu_R)$, evolved from $m_b(m_b) = 4.18\,\mathrm{GeV}$ with highest loop-order (4-loop) and flavor-number consistent with computation;
$\mu_R$ variations: running with loop-order consistent with computation

# NNLO 5FS Results ($m_H = 125\,\mathrm{GeV}$).




PDF4LHC_nnlo_mc out of the box

evolve from $Q = 2$ with $m_b^{\mathrm{pole}} = 4.75\,\mathrm{GeV}$

⇒ Difference seems entirely due to $m_b^{\mathrm{pole}} = 4.18\,\mathrm{GeV}$ in NNPDF3.0

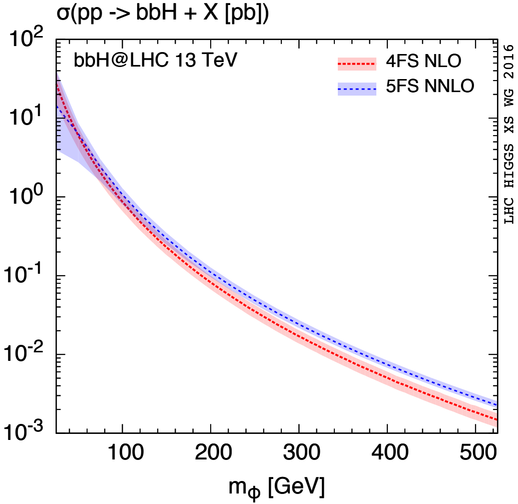
⇒ $f_g(Q = 2)$ agrees between all 3 sets within intrinsic PDF uncertainties

## 5FS PDF prescription:

- Use PDF4LHC15_nnlo 5FS set at $Q < m_b$ (ie, no $b$ PDF, only gluon/light quarks)
- Generate and evolve $b$-PDF with APFEL
- **use inputs:**
  - pole mass: $m_b^{\text{pole}} = 4.58\,\text{GeV}$
  - matching scale: $\mu_m = m_b^{\text{pole}}$
- **uncertainties:**
  - pole mass: $4.44\,\text{GeV} \leq m_b^{\text{pole}} \leq 4.72\,\text{GeV}$
  - matching scale: $m_b^{\text{pole}}/2 \leq \mu_m \leq 2\,m_b^{\text{pole}}$

(Thanks to Marco Bonvini, Stefano Forte, Stefan Liebler, Andrew Papanastasiou and Frank Tackmann; special thanks to Marco for providing the sets)

# 4FS vs. 5FS: Total cross section (New Grids)




4FS NLO:

[Dittmaier, Krämer, Spira '04]

[Dawson, Jackson, Reina, Wackeroth '04]

[MW, Frederix, Frixione, et al. '14]

new grids $m_\phi = 25 - 2025$ GeV for $y_b^2$ and $y_b\, y_t$ with MG5_aMC

5FS NNLO:

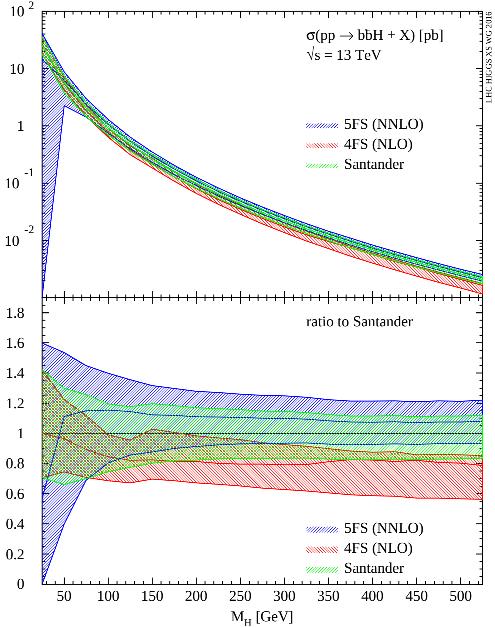
[Harlander, Kilgore '03]

[Harlander, Liebler, Mantler '13]

new grids $m_\phi = 25 - 2025$ GeV for $y_b^2$ produced with SusHi

MSSM: $\Delta_b$ approximation and resummation through $y_b$-reweighting (captures dominant effects) [Dawson, Jackson, Reina, Wackeroth '05], [Dittmaier, Häfliger, Krämer, Spira, Walser '14]

# 4+5FS combination: Santander matching




[Harlander, Krämer, Schumacher '11]

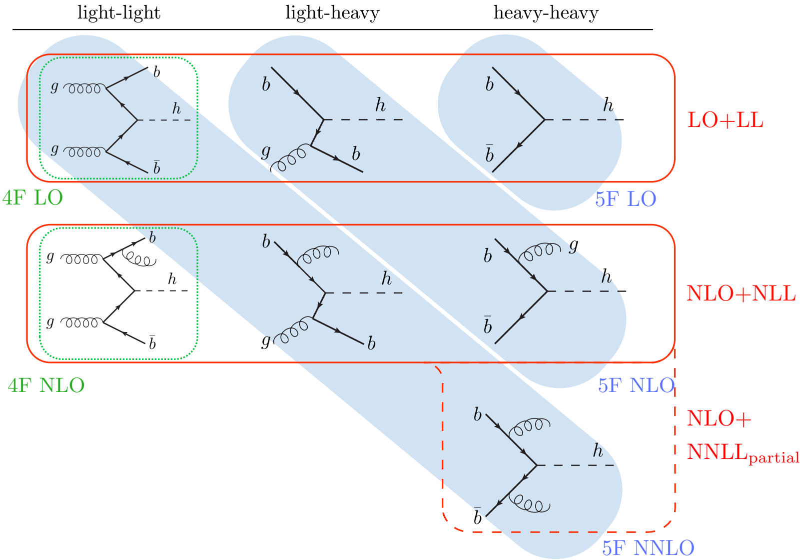
$$\sigma = \frac{\sigma^{4FS} + w\,\sigma^{5FS}}{1+w},$$
$$w = ln(m_\phi/m_b) - 2$$

combined grids available on:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG#Higgs_cross_sections_and_decay_b

– **now:** $y_b\,y_t$ included (crucial for large-$y_t$ scenarios)
– e.g, SM: $y_b\,y_t \sim -10\%$
– $y_t^2$ simply from gluon fusion

# 4+5FS combination: NLO+NNLL$_{\text{partial}}$

[Bonvini, Papanastasiou, Tackmann; '15]



# 4+5FS combination: FONLL

[Forte, Napoletano, Ubiali; '15]

FONLL-A:

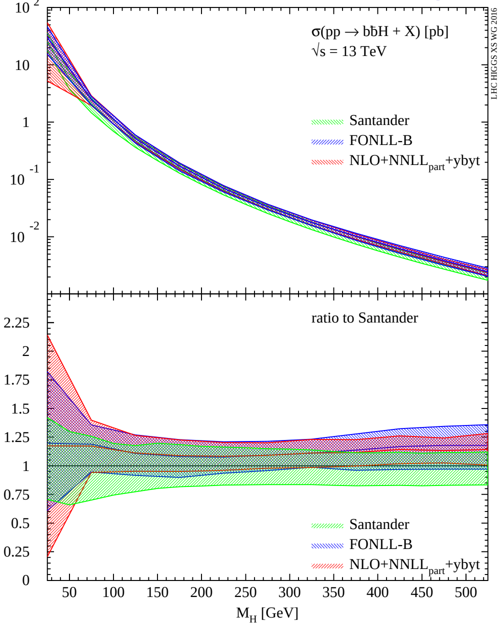
- 4FS mass effects at LO
- 5FS log resummation with NNLO information ($\text{NNLL}_{\text{partial}}$)
- Take 4FS and 5FS and write them as compatible expansions:
  - 5FS: express *b*-PDF by DGLAP through other PDFs
  - 4FS: change $\alpha_s$ and PDFs to five flavors
- add 4FS+5FS, but subtract double counted terms (these are logarithms that are already present in the 4FS)
- construct double counted terms from massless limit in 4FS

$$\sigma^{\text{FONLL}} = \sigma^{(4)} + \sigma^{(5)} - \text{double counting}$$

FONLL-B (new):

- same as FONLL-A but 4FS mass effects at NLO

# 4+5FS combination: Comparison of matching approaches




– $y_b\, y_t$ included in all predictions
– all predictions in agreement

consistently matched approaches:
*(FONLL-B and NLO+NNLL$_{\text{partial}}$)*
– perfect agreement among them
– decent agreement with Santander
– large $m_H$: tendency towards 5FS
– small $m_H$: no breakdown, closer to 4FS
– Santander now empirical

**New recommendations**

**uncertainties:**
envelope of FONLL-B and NLO+NNLL$_{\text{partial}}$ bands

**central prediction:**
central values of that envelope

# Tools for exclusive $b\bar{b}H$ cross section and distributions

- Higgs distributions (inclusive over $b$'s)
  - 5FS $y^H$ at NNLO: private code

    [Bühler, Herzog, Lazopoulos, Müller '12]
  - 5FS $p_T(H)$ at NNLO+NNLL: private code by M. Wiesemann

    [Harlander, Tripathi, MW '14]
- MCs for bbH signal simulation
  - MG5_aMC with $y_b^{\overline{MS}}$ at NLO+PS in 4FS

    https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/bbH

    [MW, Frederix, Frixione, Hirschi, Maltoni, Torielli '14]
  - POWHEG at NLO+PS in 4FS

    [Jäger, Reina, Wackeroth, '15]
  - Sherpa at NLO+PS in 4FS

    [Krauss, Napoletano, work in progress]
  - Sherpa merged 0,1,2 at NLO and 3-jet at LO in 5FS

    [Krauss, Napoletano, work in progress]

# Setup for MC comparison in YR4

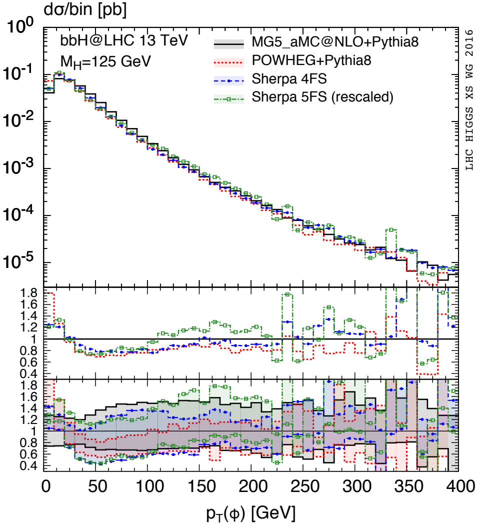
- **Scales**:
  - perturbative scales:
    $\mu_F = \mu_R = \frac{H_T^{\mathrm{Born}}}{4} \equiv \frac{1}{4} \sum_{i \in \{b,\bar{b},\phi\}} \sqrt{m_i^2 + p_T^2(i)}$
    (for `MG5_aMC+Pythia` 8 and `POWHEG+Pythia` 8)
  - shower scale:
    $\alpha = 1/4$ (MG5_aMC) and $h = \frac{m_\phi + 2\,m_b}{4}$ (POWHEG)
  - Sherpa scales according to reverse clustering scheme
- **uncertainties**:
  - 7-point $\mu_R$-$\mu_F$ variation
  - shower scale variation linearly added
- **Jet definition**:
  - anti-$k_T$, $R = 0.4$, $p_T > 25\,\mathrm{GeV}$ (all jets, including $b$'s)
  - b-jets: additionally $|y| < 2.5$ with at least one $B$-hadron

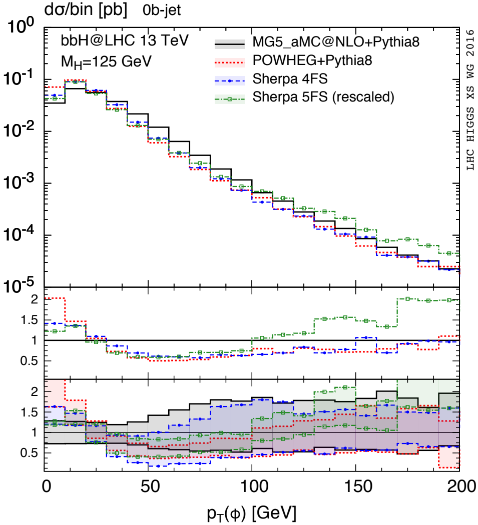
all other inputs as for total cross section...

# Comparison of MC generators: rates and acceptances

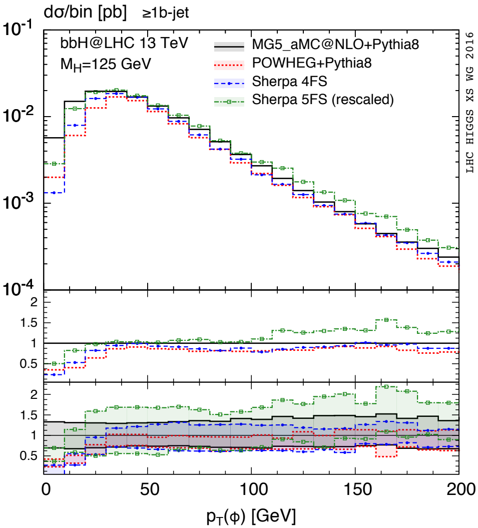
| | | inclusive | $0j_b$ | $\geq 1j_b$ | $\geq 2j_b$ | $1j_b$ |
|---|---|---|---|---|---|---|
| $\sigma$[pb] | MG5_aMC | $0.369^{+19.7\%}_{-18.8\%}$ | $0.243^{+22.5\%}_{-23.0\%}$ | $0.126^{+32.5\%}_{-28.3\%}$ | $0.0160^{+47.2\%}_{-39.8\%}$ | $0.110^{+30.4\%}_{-26.7\%}$ |
| | POWHEG | $0.375^{+20.3\%}_{-17.9\%}$ | $0.281^{+21.8\%}_{-18.6\%}$ | $0.0943^{+16.6\%}_{-16.5\%}$ | $0.00761^{+15.0\%}_{14.8\%}$ | $0.0867^{+16.8\%}_{-16.7\%}$ |
| | Sherpa 4FS | $0.370^{+15.4\%}_{-26.8\%}$ | $0.264^{+11.8\%}_{-26.0\%}$ | $0.105^{+26.9\%}_{-28.8\%}$ | $0.00955^{+74.9\%}_{-45.4\%}$ | $0.0952^{+22.2\%}_{-28.6\%}$ |
| | Sherpa 5FS | $0.586^{+30.4\%}_{-22.7\%}$ | $0.423^{+20.6\%}_{-15.7\%}$ | $0.162^{+56.1\%}_{-40.7\%}$ | $0.00773^{+68.9\%}_{-59.7\%}$ | $0.155^{+55.5\%}_{-40.4\%}$ |
| acceptance | MG5_aMC | 1 | 0.659 | 0.342 | 0.0432 | 0.298 |
| | POWHEG | 1 | 0.749 | 0.251 | 0.0203 | 0.231 |
| | Sherpa 4FS | 1 | 0.717 | 0.283 | 0.0258 | 0.258 |
| | Sherpa 5FS | 1 | 0.723 | 0.277 | 0.0132 | 0.264 |

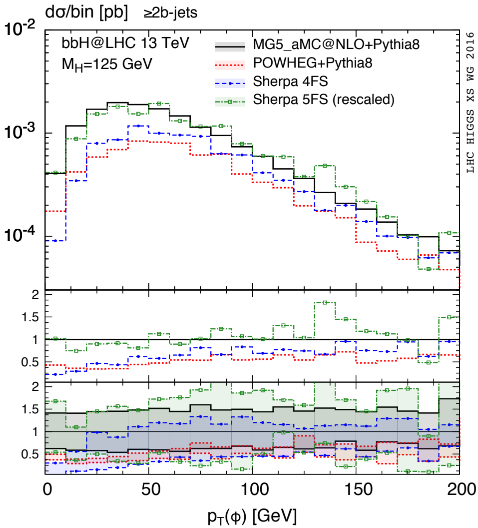
# Comparison of MC generators: Higgs $p_T$



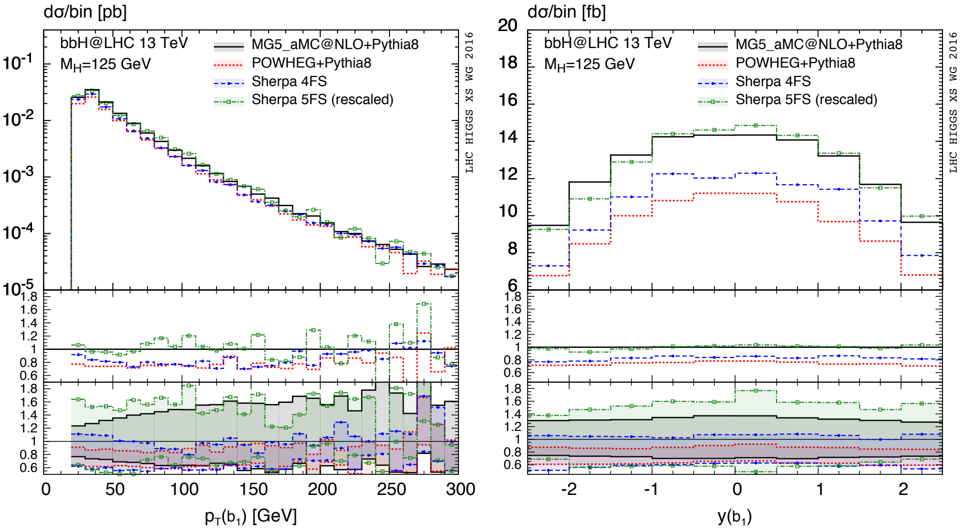



# Comparison of MC generators: Higgs $p_T$



# Comparison of MC generators: hardest $b$ jet



# Conclusions: Status

- **total cross section:**
  - total rates: new consistently matched 4+5FS predictions
  - two independent approaches in perfect agreement
  - good agreement with empirical Santander result
  - recommendation: use envelope of the two new computations
- **MC generation:**
  - use 4FS NLO+PS for bbH signal simulation
  - three MC generators available for bbH in 4FS
  - good agreement among them (in particular: shape-wise)
  - reasonable agreement with merged 5FS computation
  - recommendation: use at least two MCs to address systematics

# Future plans and outlook

There are more things to do...

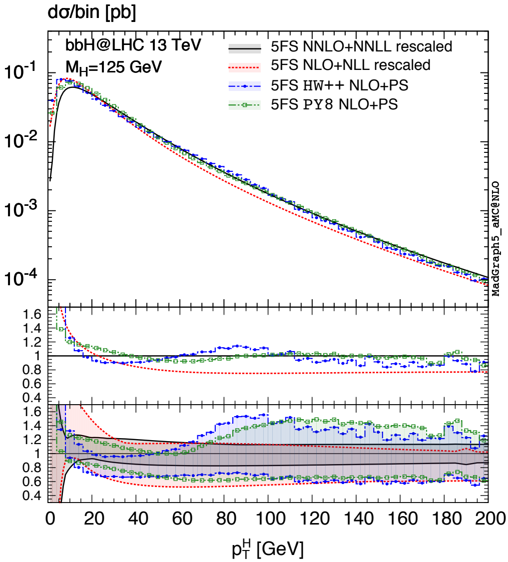
- **total cross section:**
  - redo cross section grids with new matching approaches (in progress: mandate given to the relevant people)
  - redefine (if necessary) relevant inputs and scale choices

- **MC generation:**
  - further understand MC systematics (and differences)
  - in particular: after settling other issues newest Sherpa 4FS results (beyond YR4) show significantly ($\sim 30\%$) smaller total cross section than POWHEG and MG5_aMC (and than previous Sherpa 4FS results)
  - redo MC comparison for heavier Higgs bosons
  - validate MCs with accurate Higgs $p_T$, $y$ results in 5FS
  - contribution from $ggF$ to exclusive $b\bar{b}H$ ($y_t^2$ terms)
  - validation of 4FS vs. 5FS with bbZ or single top

# BackUp

# $p_T^H$ in 5FS: NLO+PS vs. analytic resummation

[MW, Frederix, Frixione, Hirschi, Maltoni, Torielli '14]




analytic resummation:

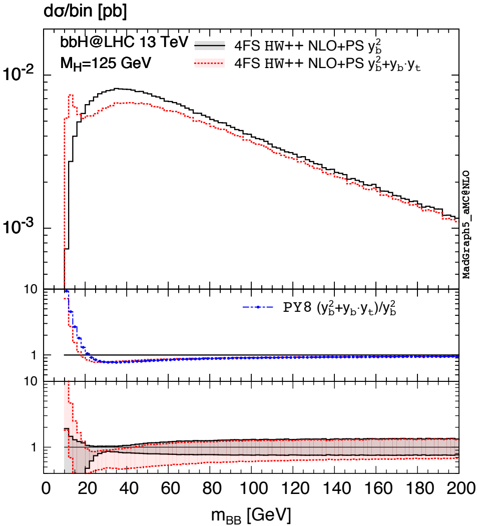
$\mu_F = \mu_R = m_T/4$

NLO+PS:

$\mu_F = \mu_R = H_T/4$

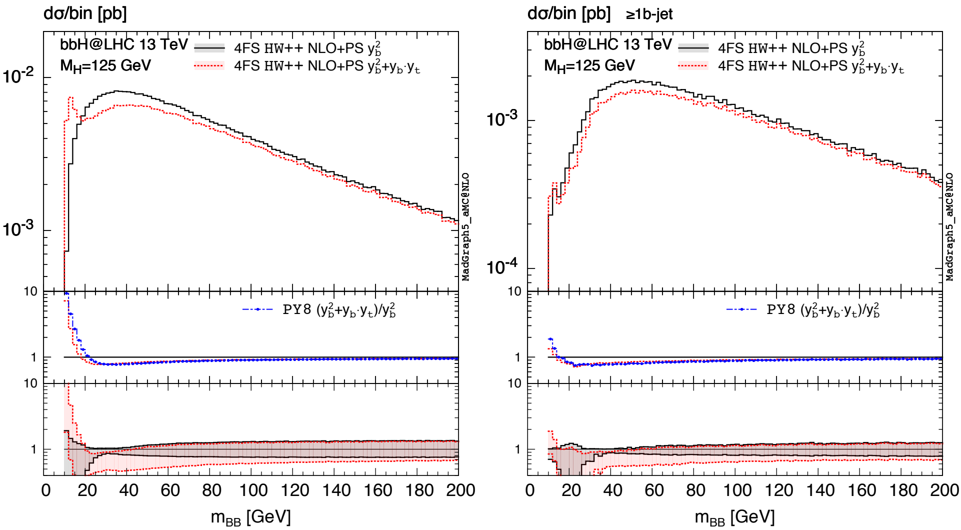
# $m_{BB}$: $y_b^2$ vs. $y_b\, y_t$ (4FS)

[MW, Frederix, Frixione, Hirschi, Maltoni, Torielli '14]



# $m_{BB}$: $y_b^2$ vs. $y_b\, y_t$ (4FS)

[MW, Frederix, Frixione, Hirschi, Maltoni, Torielli '14]



# Comparison of MC generators: hardest jet