Higgs production in association with bottom quarks at NLO+PS

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Motivations for $b\bar{b}H$

Measurement of bottom Yukawa y_b from $H \to b\bar{b}$ decay tough experimentally: Higgs width extremely small and huge QCD background.

Processes featuring $b\bar{b}H$ vertex are a viable alternative.

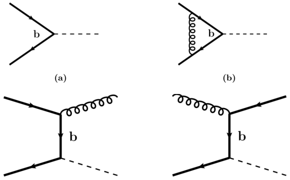
- Largest contribution: interference of bottom and top loops in $gg \to H$.
- Second largest: associated $b\bar{b}H$ production.
- $b\bar{b}H$ rate much smaller than gluon fusion, but it emerges after b tagging.

Beyond the SM, coupling of scalars to b's may be highly enhanced by factors of $\tan\beta$.

Detailed study of the $b\bar{b}H$ mode may help constraining the scalar sector in BSM models.

Two ways of computing $b\bar{b}H$: 4- and 5-flavour schemes

5-flavour scheme (5FS)



- Simple $2 \to 1$ process at LO: b massless, associated PDF.
- Partonic cross section does not depend on m_b.
- Dependence introduced through threshold conditions; logarithms of m_b/Q resummed through DGLAP evolution of the b PDF.
- Important when dominated by large $log(m_b/Q)$.
- Less so for ones exclusive in b's.
- Matching to showers improves the b-kinematics description.

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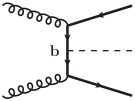
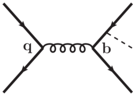
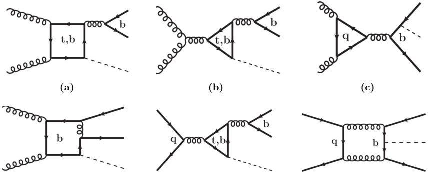
4-flavour scheme (4FS)







- More complex $2 \to 3$ process at LO: b massive.
- Partonic cross section depends on m_b; it contains m_b/Q power terms and the first few logarithms of the tower.
- Important for b observables; realistic b tags already at LO.
- Top loops generate $\alpha_S^3 y_b y_t$ terms: interference between $b\bar{b}H$ and gluon fusion.

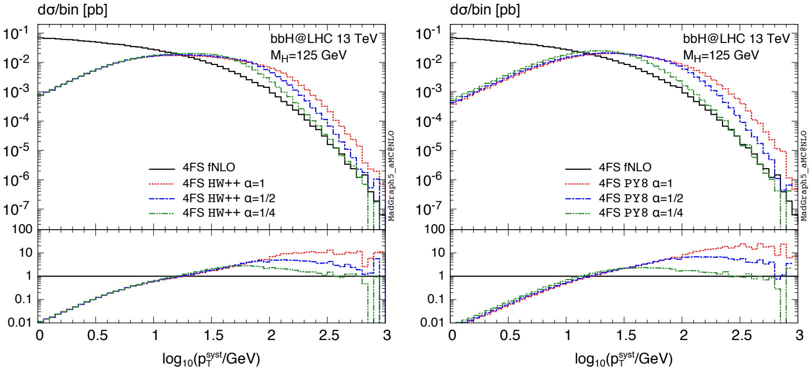
Status of the computations (in the SM)

- 5FS
  Inclusive NNLO [Harlander, Kilgore '03]
  N^3LO matrix elements [Ahmed, Mandal, Rana, Ravindran '14], [Gehrmann, Kara '14]
  Exclusive $H + b$ at NLO [Campbell, Ellis, Maltoni, Willenbrock '03]
  Exclusive NNLO [Buehler, Herzog, Lazopoulos, Mueller '12]
  NNLO+NNLL for p_t^H [Harlander, Tripathi, Wiesemann '14]
  NLO+PS [Wiesemann, Frederix, Hirschi, Maltoni, PT '14]: this talk
- 4FS
  Inclusive (exclusive) NLO [Dittmaier, Kramer, Spira '04]
  NLO+PS [Wiesemann, Frederix, Hirschi, Maltoni, PT '14], [Jaeger, Reina, Wackeroth '15]: this talk
- Matched 4FS-5FS
  NLO+NLL cross section [Forte, Napoletano, Ubiali '16], [Bonvini, Papanastasiou, Tackmann '16]

Matching systematics

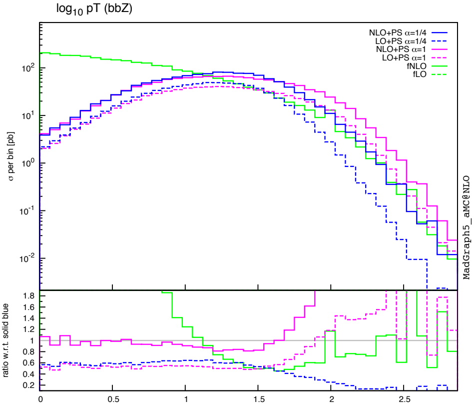
- In MC@NLO one can choose Q_{sh}, the upper bound for shower hardness.
- Q_{sh} bounds the region where the PS resummation extends, similar in spirit to a resummation scale.
- Dependence on Q_{sh} beyond formal accuracy.
- Default in the `MadGraph5_aMC@NLO` code is to chose Q_{sh} dynamically in the range $0.1\alpha\sqrt{s_0} < Q_{sh} < \alpha\sqrt{s_0}$, with $\alpha = 1$ and $\sqrt{s_0}$ = Born CM energy.
- But these are just default values: one should always check if they are sensible for the process at hand.

Matching systematics in the 4FS



- p_t of the Born 'system': an observable to expose Q_{sh} dependence.
- $\alpha = 1$ corresponds in this setup to $\langle Q_{sh} \rangle \sim 180\,\text{GeV}$, way too large for $b\bar{b}H$, where scales $\sim m_H/4$ are sensible.
- We use $\alpha = 1/4$ as baseline for the 4FS results.
- Confirmed by the largely improved agreement between different showers.

Matching systematics in MC@NLO: more in general



- Here for example $b\bar{b}Z$ 4FS production.
- Green=fixed NLO (fNLO), solid (non green)= NLO+PS, dashed=LO+PS.

- Good practice for getting sensible shower scales: compare LO+PS with fixed NLO.
- With too large shower scales LO+PS overshoots fNLO at medium-high p_t: parton shower stretched out of its defining approximations.
- Shower scales that dampen LO+PS at p_t lower than the fNLO get matching systematics under control at NLO+PS (warning: too low scales are dangerous too).
- In POWHEG analogous systematics due to the `hdamp` parameter.

Setup

1409.5301: MadGraph5_aMC@NLO

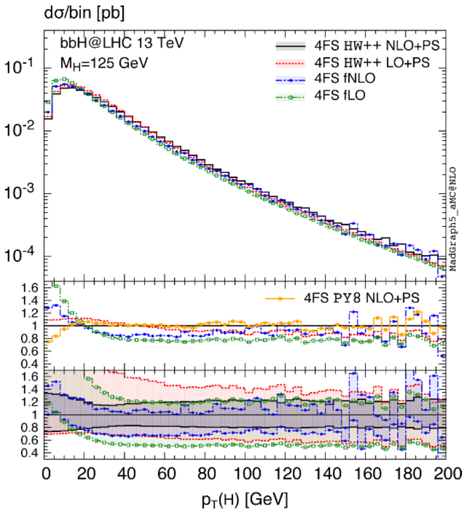
- Automated NLO+PS with the MC@NLO method at the 13 TeV LHC.
- y_b renormalised in the $\overline{\text{MS}}$ scheme.
- Showering with Pythia8 and Herwig++.
- Central value for scales $\mu_{R,F} = \frac{1}{4} \sum_{i=final} m_{t,i}$.
- Results in the 4FS with $\alpha = 1/4$ from here on.
- Results in the 5FS with $\alpha = 1$, as there $\sqrt{s_0} = m_H$ induces small scales: small matching systematics in that case.
- Results shown for the y_b^2 term only, if not stated otherwise.
- Uncertainty band from independent 9-point μ_R and μ_F variation.

1509.05843: POWHEG-BOX

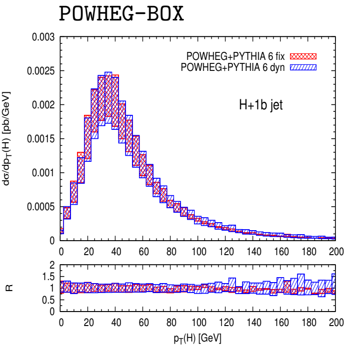
- Very similar setup.
- Showering with Pythia6.

Differential distributions

Inclusive Higgs p_t in the 4FS, `MadGraph5_aMC@NLO`

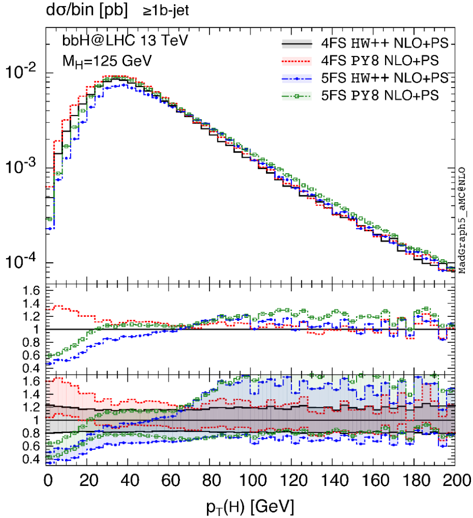


- Good agreement overall, especially at $p_t^H > 20\,\text{GeV}$ shape wise.
- Uncertainty reduction from LO to NLO.
- Still sizeable $\sim \pm 20\%$.



Differential distributions

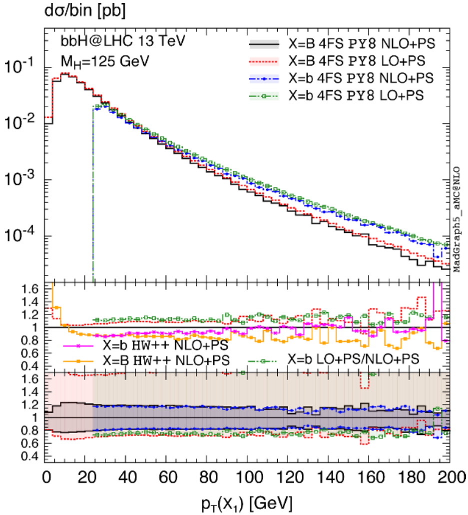
Higgs p_t: 4FS vs 5FS requiring at least a b-jet ($p_t(j_b) > 25\,\text{GeV}$, $|\eta(j_b)| < 2.5$).



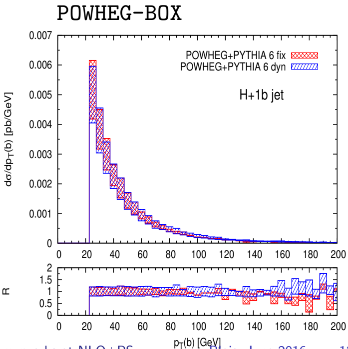
- Reasonable agreement at $p_t^{\mathrm{H}} > 40\,\text{GeV}$.
- Differences between 4FS and 5FS at small p_t^{H}, and between different showers in the same scheme.
- 4FS expected to be superior here, but would be interesting to investigate using data.

Differential distributions

Exclusive in the b's: p_t of the hardest b 'object' (b=b-jet, B=b-hadron)

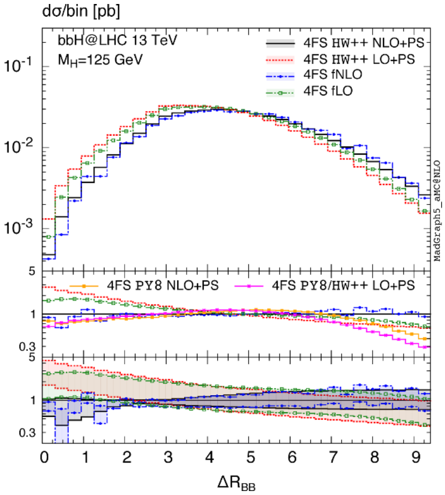


- Little NLO corrections on shapes, but massive uncertainty reduction.
- Agreement between showers at medium-large p_t.
- Small p_t for B hadrons: Herwig++ visibly larger.



Differential distributions

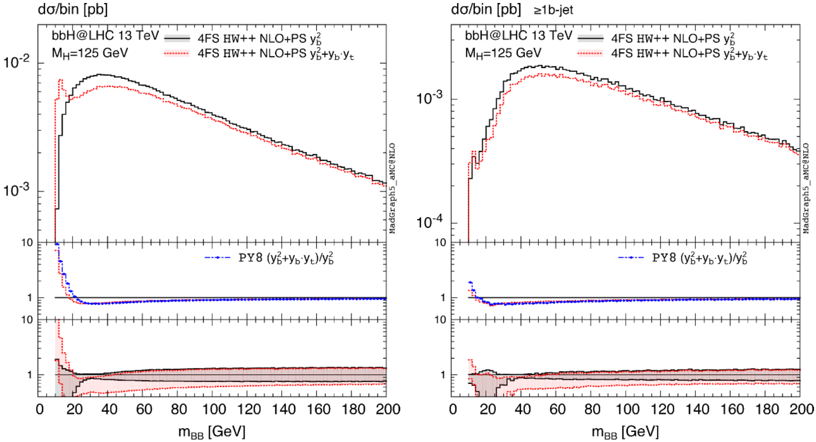
ΔR_{BB} in the 4FS.



- $B = b$ quarks at f(N)LO, $B =$ hardest b-hadrons at (N)LO+PS.
- Huge consistency improvement from LO+PS to NLO+PS at small ΔR_{BB}.
- Stil sizeable shower dependence at large ΔR_{BB}.
- Comparison of different PS: powerful handle on systematics of the shower modelling.

Differential distributions

Effect of the $y_b y_t$ term on m_{BB}.



- $y_b y_t$ term gives a flat contribution $\sim -10\%$ to most of the observables.
- Striking counter-example: peak structure at small m_{BB}, due to nearly collinear $g \to b\bar{b}$ splitting from diagrams with y_t (left).
- Requiring one b-tag washes most of the effect away (right).

Conclusions

- $b\bar{b}H$ useful for probing y_b. Necessary to have accurate differential predictions for this process.
- NLO+PS predictions in the 4FS significant for giving a reliable description and for reducing theoretical uncertainties.
- In general, good agreement between different showers, with exceptions that could be used to improve the shower modelling.
- Matching systematics under control but necessary to choose reasonable starting conditions. Comparing LO+PS and fNLO gives some suggestion on how to do it in general in MC@NLO.

Thank you for your attention