NLO QCD Corrections to  $Wb\bar{b}$  Production with Many Jets at the LHC

A Study of  $H(\rightarrow b\bar{b})W$  Backgrounds

Fernando Febres Cordero Department of Physics, University of Freiburg

ICHEP, Seoul, July 2018

Based on arXiv:1712.05721, with F.R. Anger, H. Ita and V. Sotnikov





# $HW \rightarrow b\bar{b}W$ production at the LHC

 $\sim 58\%~Hbb~$ BR makes it a key signature. Constrain Higgs sector/BSM. Associated production necessary to tame backgrounds!

Early  $H(\rightarrow b\bar{b})V$  evidence from Tevatron and ATLAS+CMS Run I combined data. Run II data should finally deliver discovery

Very complex multi-scale multi-channel signature. Example  $m^W_{\rm T}$  distribution. Here we focus on the  $Wb\bar{b}+{\rm jets}$  backgrounds





1s=13 TeV, 36.1 fb

(Tot.) (Stat., Syst.)

SM VM -+ VM

(+0.40 +0.55 (-0.38 + -0.45

VH, H(bb)

-Stat

ALI Contributions

6% ± 2.5% (stat.) + 1.0

ATLAS

WH

ZH

Comb

-Total

# Precisions studies of $Wb\bar{b} + n$ -jet production

NLO QCD $n = 0, m_b = 0$ (1999)	Ellis, Veseli (Bern, Dixon, Kosower)	35	$W^+ b\bar{b}$ — NLO Inc — NLO Exc — LO
NLO QCD n = 0 on-shell (2006)	FFC, Reina, Wackeroth	[qd] 20 b 15 10	
NLO QCD $n = 0$ (2011)	Badger, Campbell, Ellis; Oleari, Reina	5 -	
NLO QCD $n = 1 w. PS$ (2015)	Luisoni, Oleari, Tramontano (Reina, Schutzmeier)	20	$W \overline{b} \overline{b}$ — Total — qq gg
NLO QCD $n \leq 3$ w. excl. sums (2018)	Anger, FFC, Ita, Sotnikov	٩d	arXiv:0906.1923
		5	A STATE AND A STAT

0.5

Mass effects exploited in more inclusive sample studies!

2

 $p_t > 25 \text{ GeV} |\eta| < 2.5$ 

 $\mu / \mu_0$ 

# Massive high-multiplicity NLO QCD with BlackHat/Sherpa

- New version of the BlackHat library which can handle massive fermions
- Using numerical unitarity and its extension to massive quarks (Ellis, Giele, Kunszt, Melnikov), exploiting a map to 4-D algebra (Anger, Sotnikov)
- We observe similar properties for numerical stability as in previous massless studies
- Inclusion of massive close loops have percent-level effects in total cross sections and similar impact over distributions (see related work by Campbell and Ellis)
- We use the automated massive-dipole subtraction (Catani, Dittmaier, Seymour, Trocsanyi) in Sherpa for computing full NLO QCD corrections



[Anger, FFC, Ita, Sotnikov arXiv:1712.05721]

# NLO QCD corrections and theoretical uncertainties

- Importance of quantum corrections across multiplicities
- Release of kinematical constrains; opening of initial-state channels
- Scale sensitivity reduction at NLO
- Cross sections dominated by virtual contributions
- NLO scale plateau relatively low
- Differences with V+light-jet behavior due to difference in leading subprocesses



[Anger, FFC, Ita, Sotnikov arXiv:1712.05721]

# NLO QCD corrections and theoretical uncertainties

- Importance of quantum corrections across multiplicities
- Release of kinematical constrains; opening of initial-state channels
- Scale sensitivity reduction at NLO
- Cross sections dominated by virtual contributions
- NLO scale plateau relatively low
- Differences with V+light-jet behavior due to difference in leading subprocesses



## Exclusive sums from fixed-order multi-jet predictions

As a means to reduce quantum corrections when large tree-like real-radiation contributions are found, exclusive studies have been proposed, but the sensitivity to  $p_T^{\text{veto}}$  can spoil perturbative convergence! Here we propose the usage of exclusive sums

## Exclusive sums from fixed-order multi-jet predictions

As a means to reduce quantum corrections when large tree-like real-radiation contributions are found, exclusive studies have been proposed, but the sensitivity to  $p_T^{\text{veto}}$  can spoil perturbative convergence! Here we propose the usage of exclusive sums

Consider NLO QCD *inclusive* and *exclusive* cross secs with n light jets:

$$\sigma_n^{\rm inc}, \qquad \sigma_n^{\rm exc}$$

Then, considering  $Wb\bar{b}$  production, we define two exclusive sums by:

$$\begin{split} \sigma^{\rm NLO+} &= \sigma_0^{\rm exc} + \sigma_1^{\rm inc} \ , \\ \sigma^{\rm NLO++} &= \sigma_0^{\rm exc} + \sigma_1^{\rm exc} + \sigma_2^{\rm inc} \end{split}$$



# Key observables for $H(\rightarrow b\bar{b})W$

#### [Anger, FFC, Ita, Sotnikov arXiv:1712.05721]

- A key irreducible background to  $H(\rightarrow b\bar{b})W$ measurement are QCD production of  $Wb\bar{b}$ +jets
- This signature gives access to y<sub>b</sub>
- NLO+ a exclusive sum: adds NLO corrections to hard contributions
- From NLO++ and  $\sim 10\% \ p_T^{\rm veto}$  sensitivity deduce need for NNLO QCD

Similar results studied for the observables  $p_T^W$  and  $M_{b\bar{b}}$ 



# Conclusions

- ► We have presented a precision study of Wbb + n-jet production at the LHC and showed that NLO QCD correction are needed for numerically reliable results
- We studied the impact of our results for  $H(\rightarrow b\bar{b})W$ phenomenology, in particular for measurements of the bottom Yukawa coupling
- ► As a means to avoid jet p<sub>T</sub><sup>veto</sup> dependencies and to improve predictions from high-multiplicities fixed-order results we used exclusive sums
- ▶  $Wb\bar{b}$  production might well be one of the most pressing cases for NNLO QCD corrections for  $2 \rightarrow 3$  processes at the LHC



# Conclusions

- ► We have presented a precision study of Wbb + n-jet production at the LHC and showed that NLO QCD correction are needed for numerically reliable results
- We studied the impact of our results for  $H(\rightarrow b\bar{b})W$ phenomenology, in particular for measurements of the bottom Yukawa coupling
- ► As a means to avoid jet p<sub>T</sub><sup>veto</sup> dependencies and to improve predictions from high-multiplicities fixed-order results we used exclusive sums
- ▶  $Wb\bar{b}$  production might well be one of the most pressing cases for NNLO QCD corrections for 2 → 3 processes at the LHC





### Extra slide

## Phenomenological setup employed [Anger, FFC, Ita, Sotnikov arXiv:1712.05721]

We employ a dynamical scale  $\mu = \mu_r = \mu_f = \hat{H}'_T/2$  and the CT14\_NF4 PDF sets, together with the pseudo-PDF error set PDF4LHC15\_nlo\_nf4\_30. We set  $m_b = 4.75$  GeV,  $m_t = 172$  GeV,  $M_W = 80.385$  GeV,  $\Gamma_W = 2.085$  GeV. Impose the kin. cuts:

- $\blacktriangleright \ p_{\rm T}^l > 25 \ {\rm GeV}$
- $\bullet |\eta^l| < 2.5$
- ▶  $p_{\mathrm{T}}^{\nu} > 20~\mathrm{GeV}$
- ▶  $M_{\mathrm{T}}^W > 20~\mathrm{GeV}$

- Anti-k<sub>T</sub> jets with IR-safe flavor tag
- ► R = 0.4

▶ 
$$p_{\mathrm{T}}^{\mathrm{jet}} > 25 \; \mathrm{GeV}$$

• 
$$|\eta^{\rm jet}| < 2.4$$

We have collected results for  $W^{\pm}b\bar{b} + n$ -jet production (n = 0, 1, 2, 3) at the LHC  $\sqrt{s} = 13$  TeV as *n*-tuple files that can be used for computing generic IR safe observables