

Associated Higgs- and Gauge-boson production at the LHC

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Run 2 Higgs measurements: a huge success

See also, CMS-HIG-19-005

ATLAS Conf 2021 053



The VH channel: currently statistically limited

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LHC / HL-LHC Plan





VH Higgs measurements will become systematic limited

ATLAS, arXiv:2007.02873

Source of uncertainty		VH	$\sigma_{\mu} \ WH$	ZH
Total	Total		0.260	0.240
Statistical		0.115	0.182	0.171
Systematic		0.134	0.186	0.168
Statistical un	certainties			
Data statistical		0.108	0.171	0.157
$t\bar{t} \ e\mu$ control	$t\bar{t} e\mu$ control region		0.003	0.026
Floating normalisations		0.034	0.061	0.045
Experimental uncertainties				
Jets		0.043	0.050	0.057
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.015	0.045	0.013
Leptons		0.004	0.015	0.005
	b-jets	0.045	0.025	0.064
<i>b</i> -tagging	<i>c</i> -jets	0.035	0.068	0.010
	light-flavour jets	0.009	0.004	0.014
Pile-up		0.003	0.002	0.007
Luminosity		0.016	0.016	0.016
Theoretical and modelling uncertainties				
Signal		0.072	0.060	0.107



The theory modelling of the SM process a bottleneck **Goal**: improve the theoretical understanding of this process **VH** selection categories



Introduction to QCD corrections

Results for the VH+jet processes

Outlook / conclusions





97.2

1.1

1.7

The VH($\rightarrow bb$) channel selections



The VH($\rightarrow b\bar{b}$) channel selections

$$\sigma_{AB} = \sum_{ab} \int_{0}^{1} dx_{a} \int_{0}^{1} dx_{b} f_{a|A}(x_{a}) f_{b|B}(x_{b}) \hat{\sigma}_{ab}(x_{a}, x_{b}) (1 + O(\Lambda_{QCD}/Q))$$
barton distribution functions (PDFs)
non-perturbative, data-driven
hard scattering
perturbation theory

$$d\hat{\sigma}_{ab\to VH+..} = d\hat{\sigma}_{ab\to VH+..}^{LO} + \alpha_s d\hat{\sigma}_{ab\to VH+..}^{NLO} + \alpha_s^2 d\hat{\sigma}_{ab\to VH+..}^{NNLO} + \dots$$



Integrate this numerically (and convolute with PDFs)



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To go to NNLO QCD, need:

- I. All of the various [squared] amplitudes (RR, RV, VV)
- 2. A method to numerically integrate (4d) these things

Perturbative corrections: VH+jet

 $d\hat{\sigma}_{ab \to VH+..} = d\hat{\sigma}_{ab \to VH+..}^{LO} + \alpha_s d\hat{\sigma}_{ab \to VH+..}^{NLO} + \alpha_s^2 d\hat{\sigma}_{ab \to VH+..}^{NNLO} + \dots$



Non-trivial cancellation of IRC divergences

Perturbative corrections: VH+jet $d\hat{\sigma}_{ab\to VH+..} = d\hat{\sigma}_{ab\to VH+..}^{LO} + \alpha_s d\hat{\sigma}_{ab\to VH+..}^{NLO} + \alpha_s^2 d\hat{\sigma}_{ab\to VH+..}^{NNLO} + \dots$ $\sigma_{\rm NNLO} = \int_{\phi_{n+2}} \left(\mathrm{d}\sigma_{\rm NNLO}^{RR} - \mathrm{d}\sigma_{\rm NNLO}^{S} \right)$ $+ \int_{\mathcal{A}_{n+1}} \left(\mathrm{d}\sigma_{\mathrm{NNLO}}^{RV} - \mathrm{d}\sigma_{\mathrm{NNLO}}^{T} \right)$ mimic unresolved explicit pole $+\int_{\phi_{m+0}} \left(\mathrm{d}\sigma_{\mathrm{NNLO}}^{VV} - \mathrm{d}\sigma_{\mathrm{NNLO}}^{U} \right)$ cancellation subtraction) = Finite - 0Non-trivial cancellation of IRC divergences

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One must also consider 'heavy-quark' loop processes



These contributions 'easy' (no divergences) We take these from OpenLoops2 Buccioni et al., https://openloops.hepforge.org/process_library.php



All CC and NC processes to $\mathcal{O}(\alpha_s^3)$ computed with NNLOJET

Results: WH+1jet [exclusive]



Corrections negative, and -15%

Reduction of theory uncertainty by factor of two

Results: *ZH*+1jet [inclusive]



Run 3 + High Lumi LHC

Will enable high stats. measurements

Systematics will become bottleneck

ATLAS, arXiv:2007.02873

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Theoretical and modelling uncertainties

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Z + iets	0.032	0.013	0.059
W + jets	0.040	0.019	0.009
$t\overline{t}$	0.021	0.046	0.029
Single top quark	0.019	0.048	0.015
Diboson	0.033	0.033	0.039
Multi-jet	0.005	0.017	0.005

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Main messages

I. Including n_{jet} categories $(2, \equiv 3, \geq 3)$ is critical for exp.

ATLAS, arXiv:2007.02873Source of uncertainty σ_{μ} <td

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Including n_{jet} categories $(2, \equiv 3, \geq 3)$ is critical for exp.

- 2. Huge progress on theoretical side for VH+($n_{iet} > 1$)
 - NNLO QCD for WH+jet and ZH+jet
 RG, Gehrmann-De Ridder, Glover, Huss, Majer arXiv:2110.12292
 - Factor of two reduction in theory uncertainty

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• Factor of two reduction in theory uncertainty

Whiteboard

Extra distributions





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Standard scale variation, can have accidental cancellations.

Basically cancellation of those induced by p_T^{cut} Exclusive jet selection, Stewart, Tackmann: arXiv:1107.2117 Rhorry Gauld, 26/05/2021