



VBF Higgs Measurements Decaying to Bottom and Charm Quarks

A Summary of Run 2 Results and Future Outlook for Run 3 Measurements

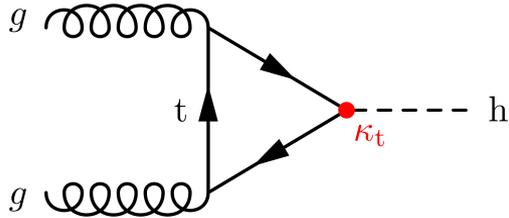
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Lepton Photon 2025 Madison, Wisconsin
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Higgs Production At the LHC

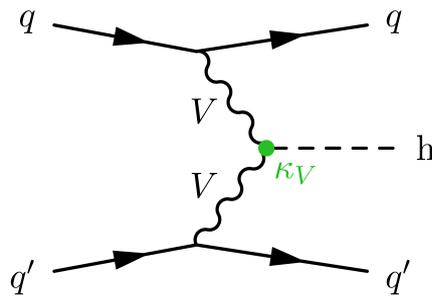


Gluon-Gluon Fusion



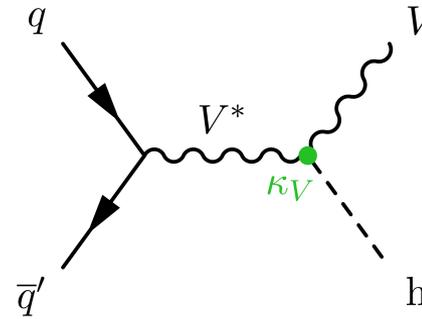
$$\sigma_{ggF} \approx 50 \text{ pb}$$

Vector Boson Fusion



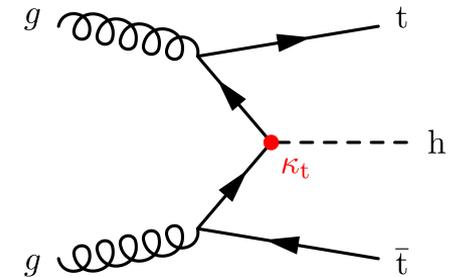
$$\sigma_{VBF} \approx 4 \text{ pb}$$

Higgs Strahlung



$$\sigma_{VH} \approx 2.5 \text{ pb}$$

ttH



$$\sigma_{ttH} \approx 0.5 \text{ pb}$$

- Vector Boson Fusion is the second largest higgs production mechanism at the LHC.
- Can directly probe coupling to vector bosons, κ_V .
- VBF has very unique signature in the detector.

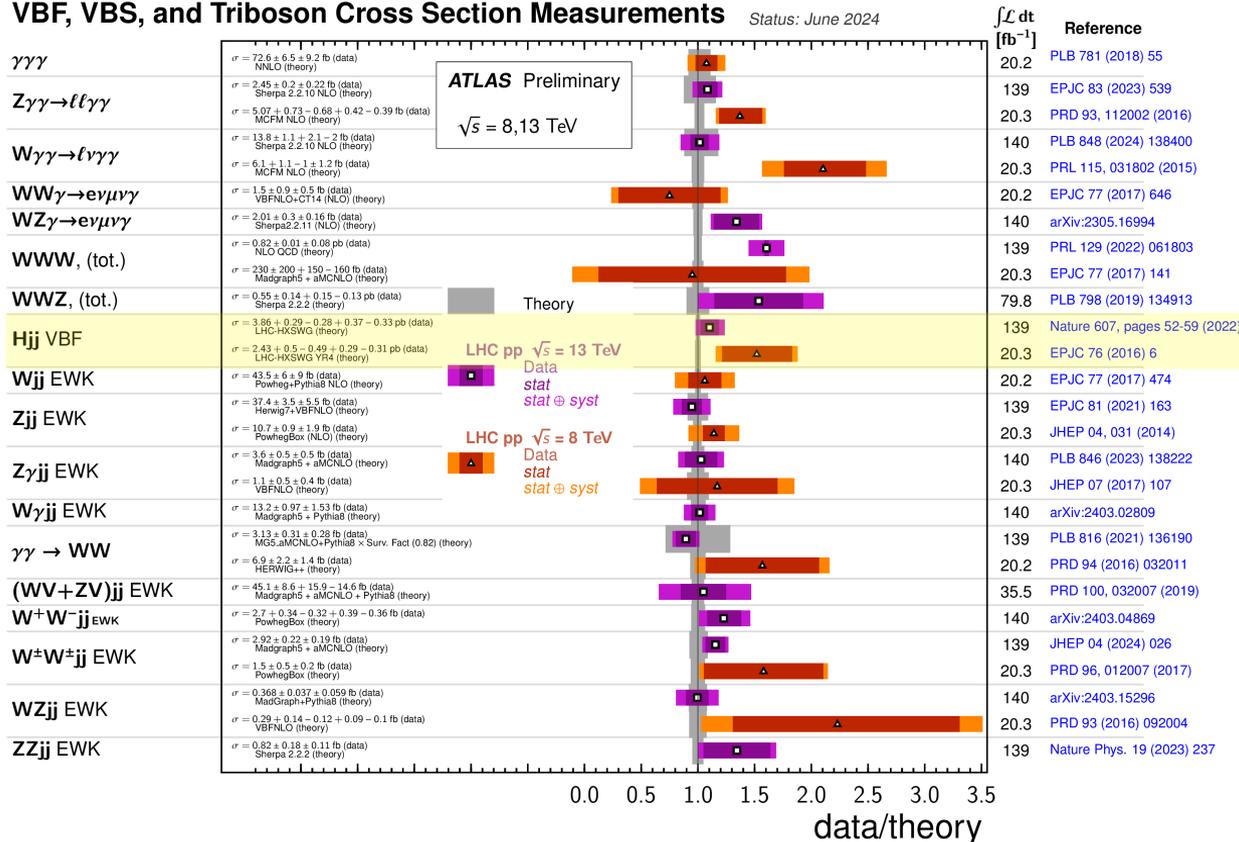
Cross Sections at 13 TeV from *Handbook of LHC Higgs cross sections* [1610.07922](#)

Statistically Dominated VBF Measurements



VBF, VBS, and Triboson Cross Section Measurements

Status: June 2024



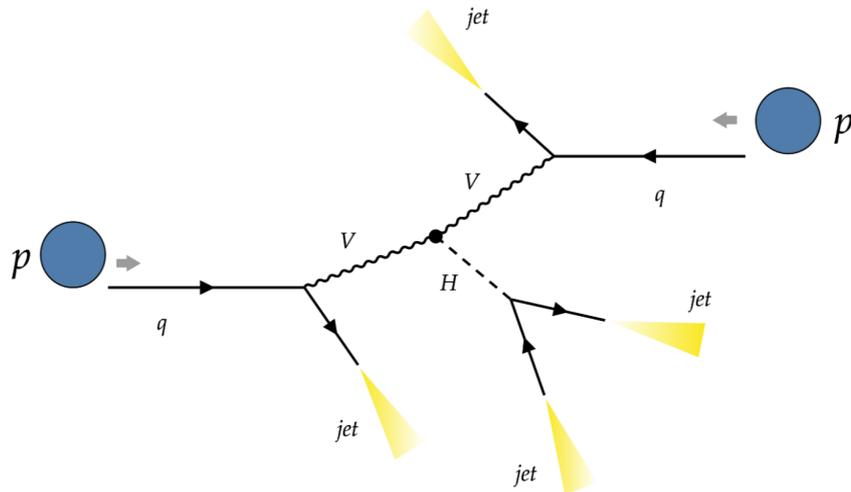
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-Nearly all VBF, VBS, and Triboson measurements are stat limited.

-Run 3 will significantly increase stats which allows to probe SM more effectively.

-This talk will focus on VBF Hjj results.

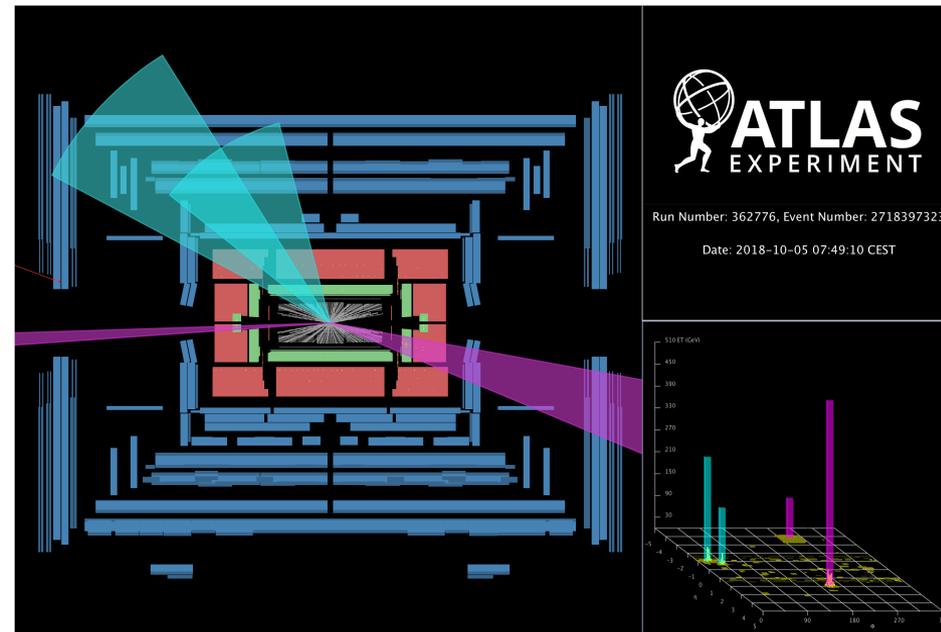
Experimental VBF Signatures



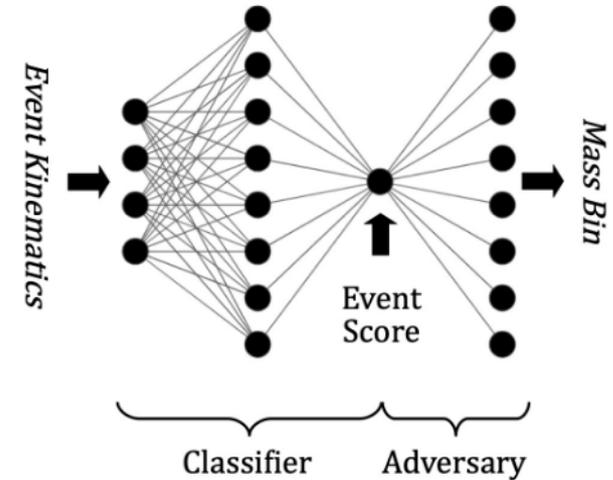
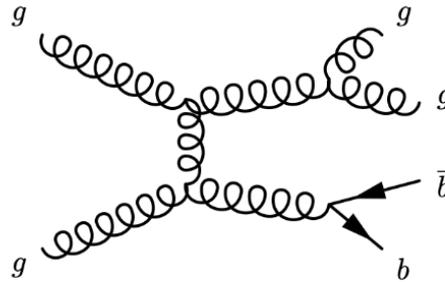
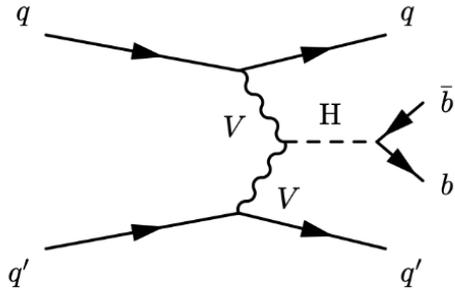
-VBF topologies are selected by the presence of two VBF jets in the mid-forward region.

-In hadronic Higgs decay, there typically exists two b or c tagged jets in the central region.

Candidate VBF Hbb Event at 13TeV



Analysis Strategy: Signal vs Background



-Dominant background is non-resonant QCD which can be hard to model with MC.

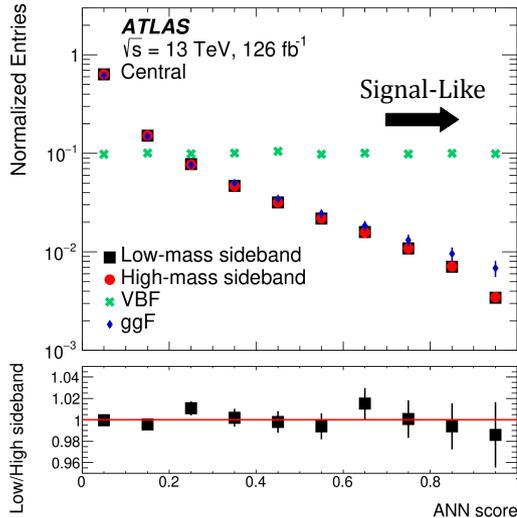
-NN is used to discriminate signal vs sideband data. Where sideband data is outside signal mass window $100 < m_{bb} < 140$ GeV.

-An adversarial loss term is applied to ensure output of the model is completely decorrelated from m_{bb} .

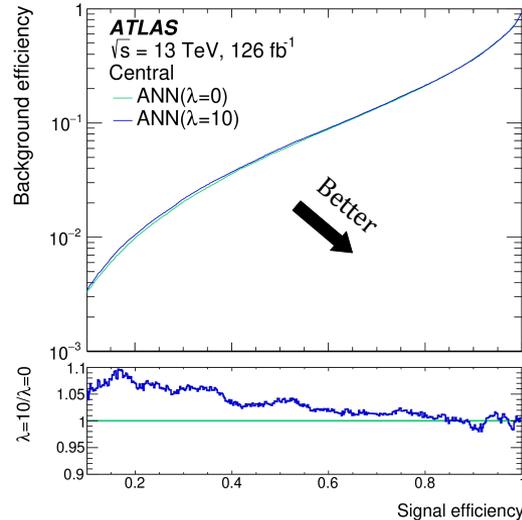
$$L = L_{cl} - \lambda L_{ad}$$

Adversarial Neural Network Output

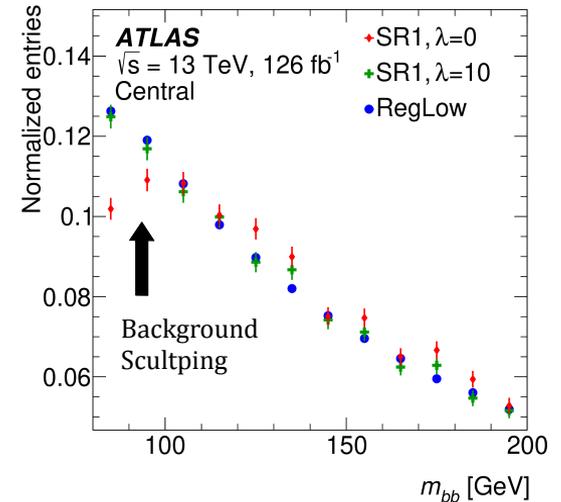
HIGG-2019-04



-Output scores of the ANN. Signal regions are defined by cutting on this score.



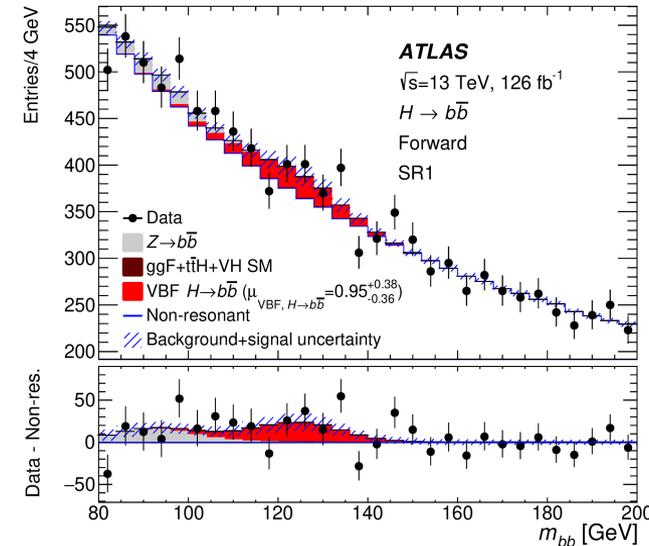
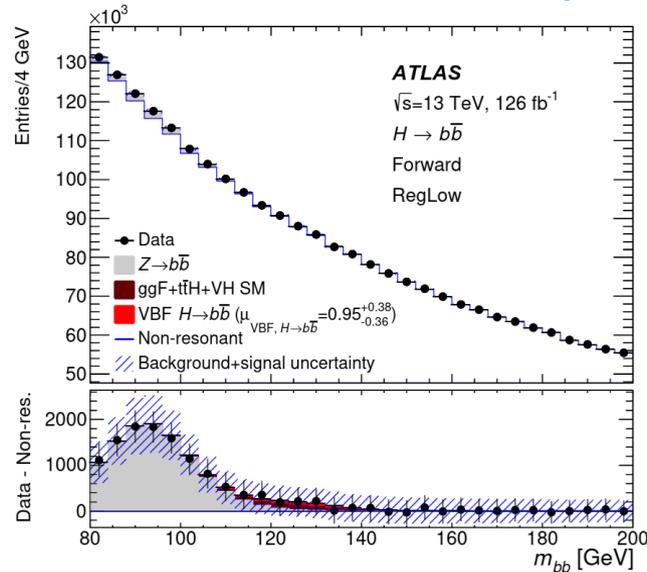
-As the strength of the adversary increases, λ , the performance of the classifier slightly decreases.



-Sidebands in SR1 are less sculpted when $\lambda=10$ which shows that the NN is decorrelated from m_{bb} .

Low Score and High Score Regions

Eur. Phys. J. C 81 (2021) 537

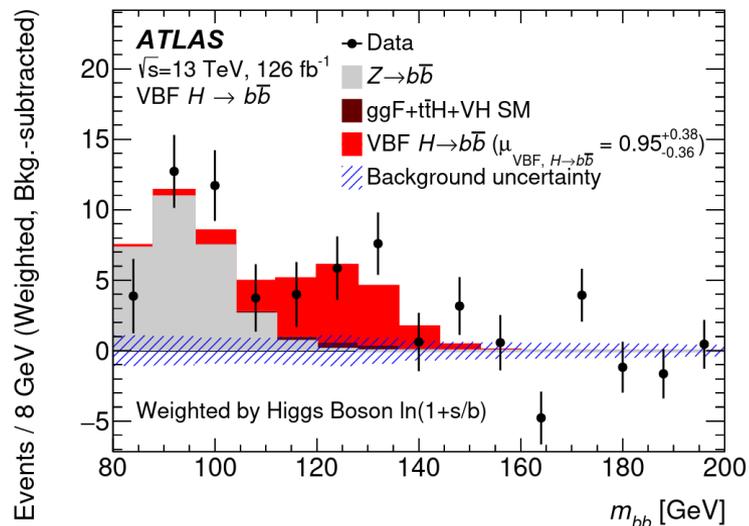


- Low score region (left) and high score region (right) are determined by the output of the ANN.
- The non-resonant background shape is determined from the data in low score region and the same shape is used in all higher score regions.
- ANN is decorrelated from mass, so the non-resonant background shape remains unsculpted.

ATLAS Run 2 Resolved VBF Hbb



Eur. Phys. J. C 81 (2021) 537



-Subtracting the non-resonant background, we can see resonant Z peak and Higgs peak.

-Significance is slightly below 3σ with dominant stat uncertainty.

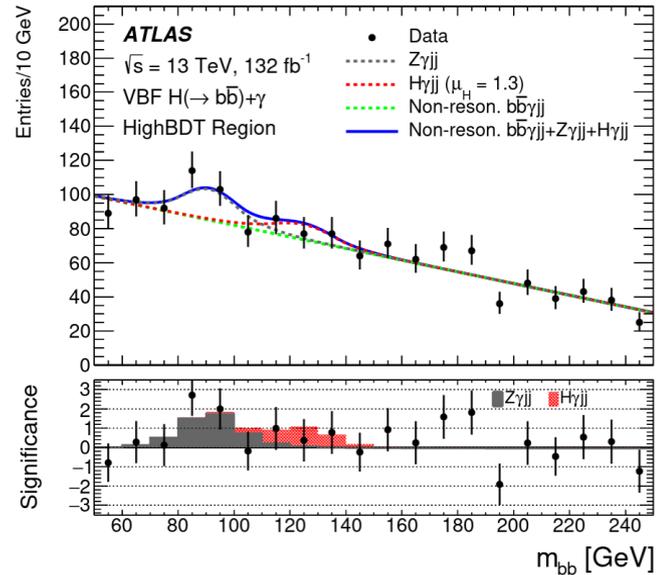
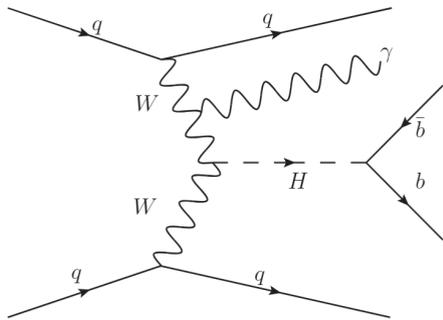
Uncertainty	$\sigma(\mu_{\text{VBF}, H \rightarrow b\bar{b}})$
Statistics	± 0.32
NR Background Bias	± 0.15
Embedded Z	± 0.05
Experimental	$+0.10 / -0.06$
Trigger	$+0.07 / -0.03$
Jet	$+0.07 / -0.04$
Flavor Tagging	$+0.02 / -0.01$
Other	$+0.03 / -0.02$
Signal Theory	$+0.06 / -0.03$

Results	VBF Production	Inclusive Production	$p_T > 200 \text{ GeV}$
Expected significance	2.8σ	2.9σ	2.3σ
Observed significance	2.6σ	2.7σ	2.2σ
Expected signal strength	$1.00^{+0.38}_{-0.37}$	$1.00^{+0.37}_{-0.36}$	$1.00^{+0.45}_{-0.43}$
Observed signal strength	$0.95^{+0.38}_{-0.36}$	$0.95^{+0.37}_{-0.35}$	$0.93^{+0.45}_{-0.43}$

ATLAS Run 2 Resolved VBF Hbb + γ



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Source of absolute uncertainty	$\sigma(\mu_H)$ down	$\sigma(\mu_H)$ up
Statistical		
Data statistical	-0.78	+0.80
Bkg. fit shapes	-0.19	+0.22
Bkg. fit normalizations	-0.51	+0.52
Z boson normalizations	-0.15	+0.14
Systematic		
Spurious signal	-0.24	+0.21
Theoretical	-0.01	+0.08
Photon	-0.01	+0.03
Jet	-0.06	+0.20
b-tagging	-0.02	+0.11
Auxiliary	-0.01	+0.04
Total	-0.99	+1.04
Total statistical	-0.96	+0.99
Total systematic	-0.25	+0.32

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-The VBF signal strength μ_{VBF} is 1.3 ± 1.0 corresponding to an observed (expected) significance of 1.3 (1.0).

-Combine VBF Hbb (previous slide) with VBF Hbb + γ for an observed significance of 2.9σ !

Results	VBF production	Inclusive production
Expected significance	2.9σ	3.0σ
Observed significance	2.9σ	3.0σ
Expected signal strength	$1.00^{+0.36}_{-0.34}$	$1.00^{+0.35}_{-0.34}$
Observed signal strength	$0.99^{+0.36}_{-0.34}$	$0.99^{+0.35}_{-0.33}$

Summary of Current Results



Table of Current Results in ATLAS and CMS

		<i>Observed</i>		<i>Expected</i>	
	<i>Integrated Luminosity</i>	<i>Signal Strength</i>	<i>Significance</i>	<i>Signal Strength</i>	<i>Significance</i>
<i>ATLAS VBF Hbb Resolved</i> <i>Eur. Phys. J. C 81 (2021) 537</i>	126 fb ⁻¹	0.95 ^{+0.38} _{-0.36}	2.6σ	1.0 ^{+0.38} _{-0.37}	2.8σ
<i>ATLAS VBF Hbb + γ</i> <i>JHEP 03 (2021) 268</i>	132 fb ⁻¹	1.3 ^{+1.0} _{-1.0}	1.3σ	1.0 ^{+1.0} _{-1.0}	1.0σ
<i>ATLAS VBF Combined</i> <i>Eur. Phys. J. C 81 (2021) 537</i>	126 fb ⁻¹	0.99 ^{+0.36} _{-0.34}	2.9σ	1.0 ^{+0.36} _{-0.34}	2.9σ
<i>CMS VBF Hbb Resolved</i> <i>JHEP 01 (2024) 173</i>	91 fb ⁻¹	1.01 ^{+0.39} _{-0.24}	2.4σ	1.0 ^{+?} _{-?}	2.7σ
<i>CMS VBF Hbb Boosted</i> <i>JHEP 12 (2024) 035</i>	138 fb ⁻¹	4.9 ^{+1.9} _{-1.6}	2.7σ	1.0 ^{+1.4} _{-1.3}	0.9σ



Summary of Run 3 Improvements

New Inclusive VBF Trigger, Improvements in Flavor Tagging, and New Q/G Tagger





Inclusive VBF Trigger

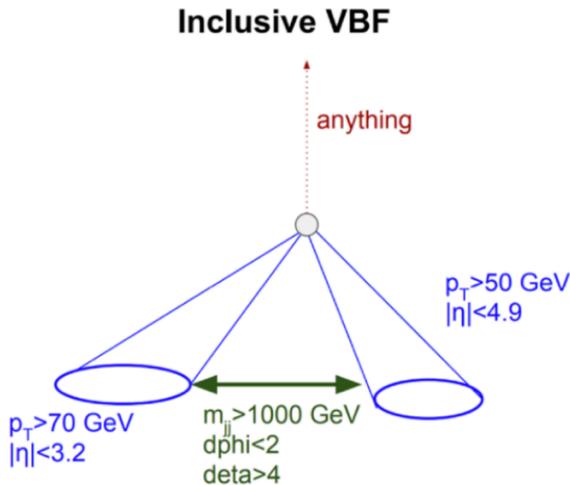


-Inclusive VBF trigger imposes requirements on VBF jets without requirements on the Higgs decay.

-Uses a delayed trigger stream to reconstruct events when resources allow it. Rates shown in table.

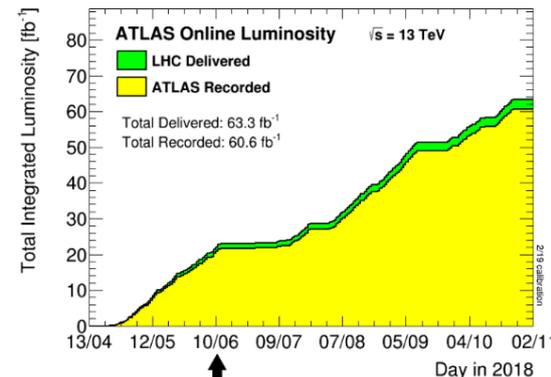
-Allows for Hcc analysis.

-Full Run 3 will deliver large amount of statistics!



Trigger	p_T threshold [GeV]	Rate [Hz]
VBF di-jet	70 ($ \eta < 3.2$), 50 ($ \eta < 4.9$)	270
Two jets, two b -jets ($\epsilon = 77\%$)	80, 55, 28, 20	160
Six jets	6×35	140
Five jets, one b -jet	$5 \times 35, 25$	50
B -physics di-muon	11, 6	40
$B \rightarrow K^* ee$	5, 5	170

TRIG-2022-01



VBF Trigger Installed

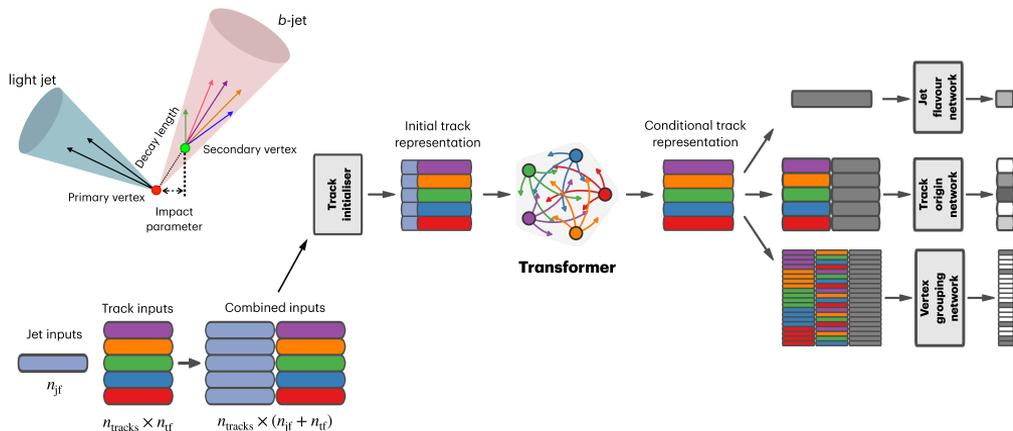
	ATLAS Recorded
2018	~40 fb ⁻¹
2022	35.7 fb ⁻¹
2023	29.7 fb ⁻¹
2024	117.6 fb ⁻¹
2025	>50 fb ⁻¹
Total	~273 fb⁻¹



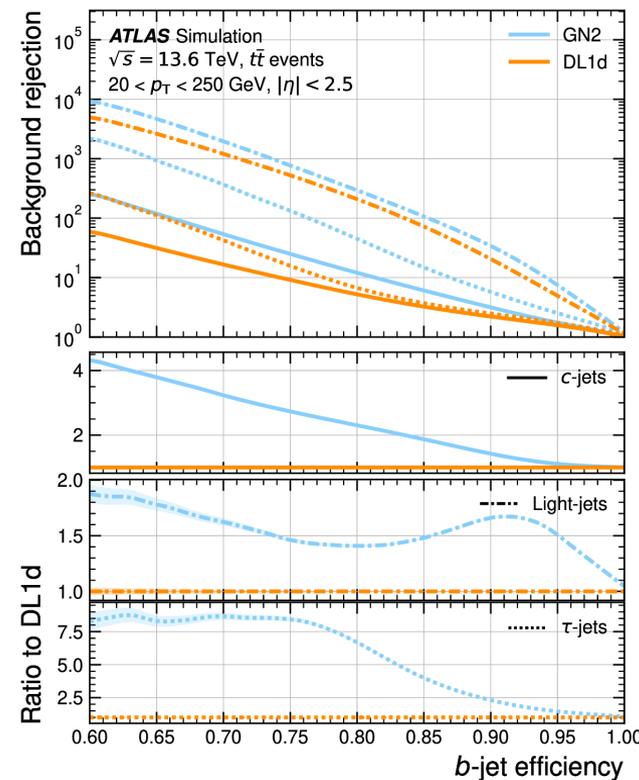
Flavor Tagging Improvements



FTAG-2023-05



$$D_b = \log \left(\frac{p_b}{f_c p_c + f_\tau p_\tau + (1 - f_c - f_\tau) p_u} \right)$$



-The introduction of Graph and Attention based models in ATLAS has drastically improved c-jet and light-jet rejection.

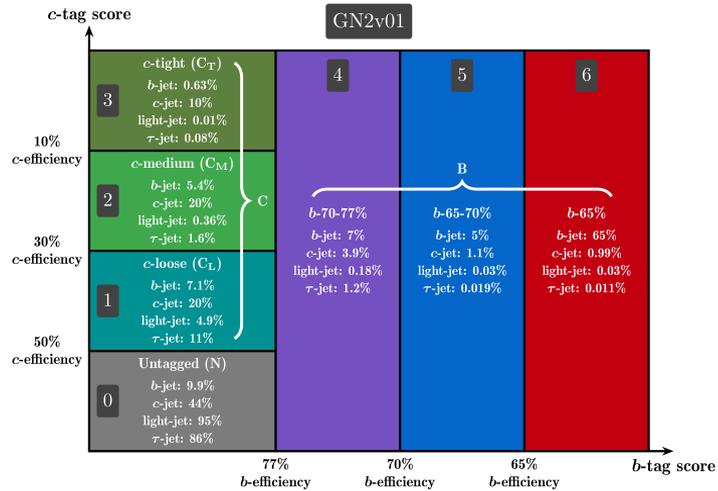
-ROC curves for b-jet efficiency showing background rejection for c-jet (solid), light-jet (dotted-dashed), τ -jet (dashed). Major improvements over previous generation DL1d.



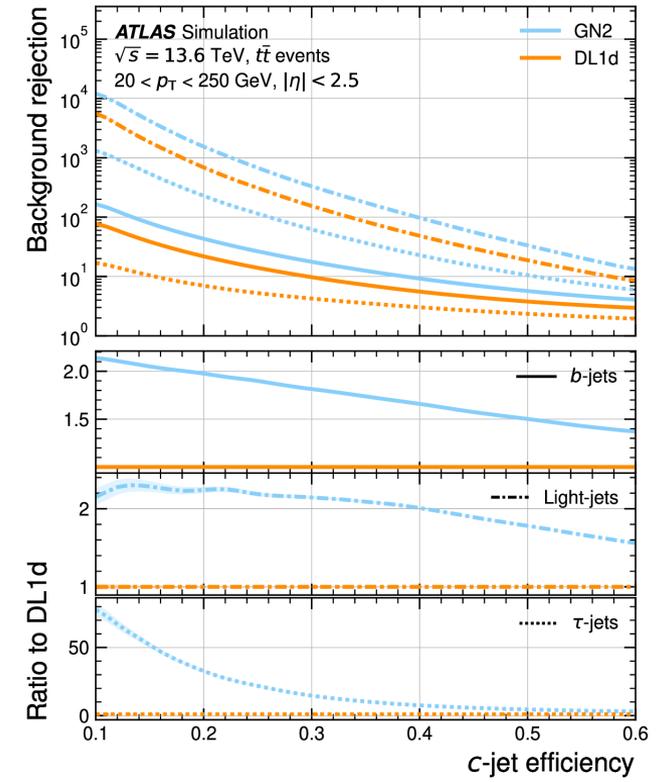
C-tagging Performance and Calibrations



FTAG-2023-05



$$D_c = \log \left(\frac{p_c}{f_b p_b + f_\tau p_\tau + (1 - f_b - f_\tau) p_u} \right)$$



-New c-tagging calibrations for GN2 has allowed for a Run 3 VBF Hcc analysis!

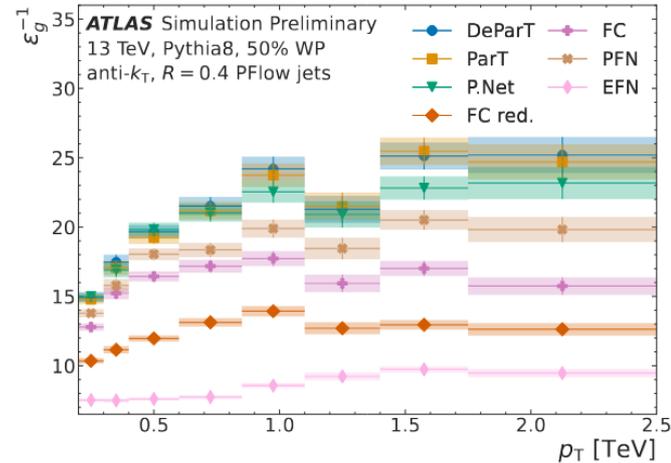
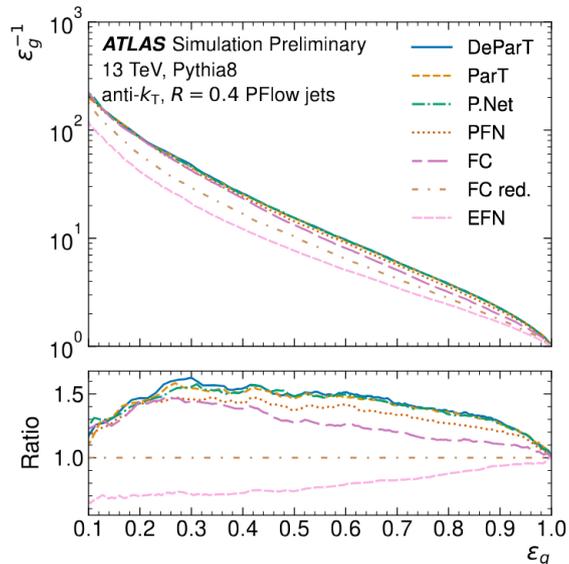
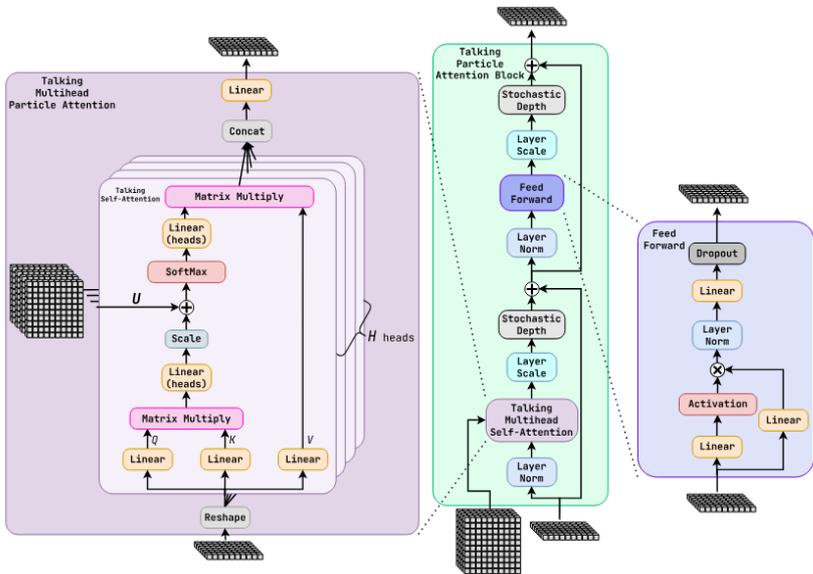
-ROC curves for c-jet efficiency showing background rejection for b-jet (solid), light-jet (dotted-dashed), τ-jet (dashed).



Q/G Tagging Improvements



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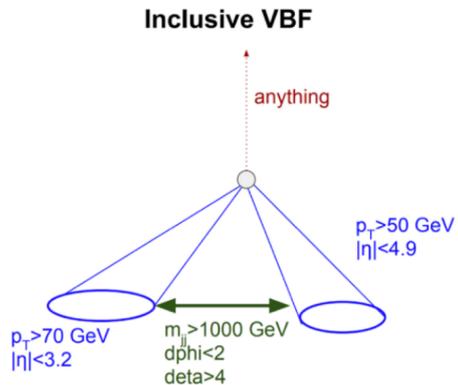
-A Dynamically Enhanced Particle Transformer, DeParT, is trained on a Q/G tagging task.

-DeParT outperforms other models on the Q/G tagging task.

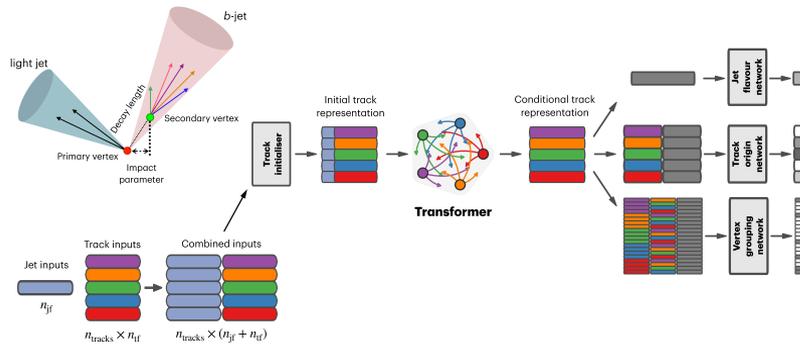
-DeParT maintains good performance across the entire p_T spectrum.



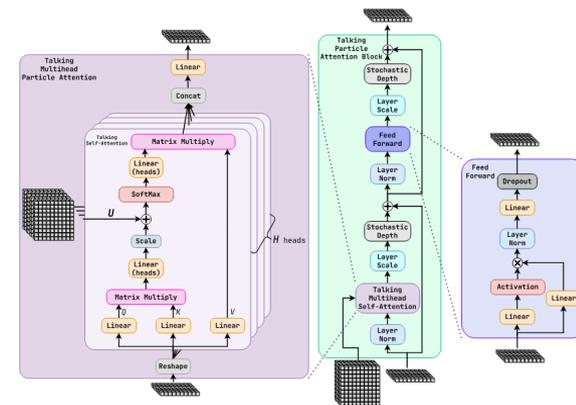
Run 3 VBF Improvements



(1)



(2)



(3)

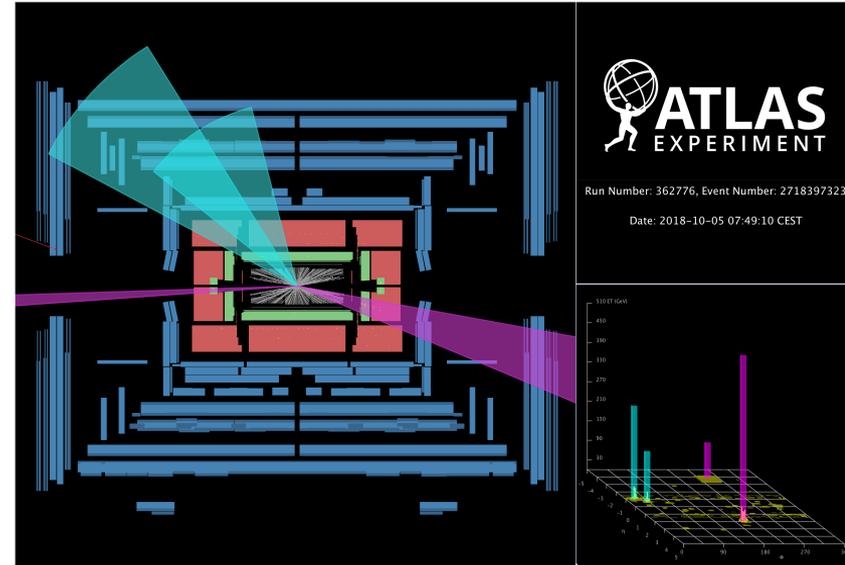
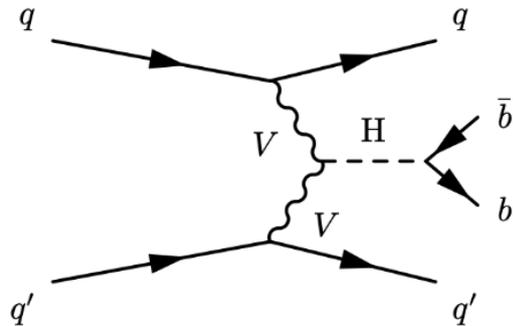
Run 3 VBF analyses will benefit from improvements in:

- (1) New inclusive VBF trigger allowing for Hcc analysis.
- (2) Flavor Tagging improvements and new c-tagging calibrations.
- (3) Improved Q/G taggers to help suppress QCD background.

Conclusions

-VBF topology is very unique topology that enables crucial SM measurements.

-VBF measurements are often limited by statistics, and Run 3 will help deliver the statistics needed to probe the SM more precisely than ever before.



-A new dedicated inclusive VBF trigger, improvements in flavor tagging, and new c-tagging calibration opens up new potential for Run 3 VBF analyses.

Acknowledgments



I'd like to acknowledge the US Department of Energy for providing funding to Okstate for HEP-Ex research.

Many thanks to ATLAS Collaboration and CERN.





Backup

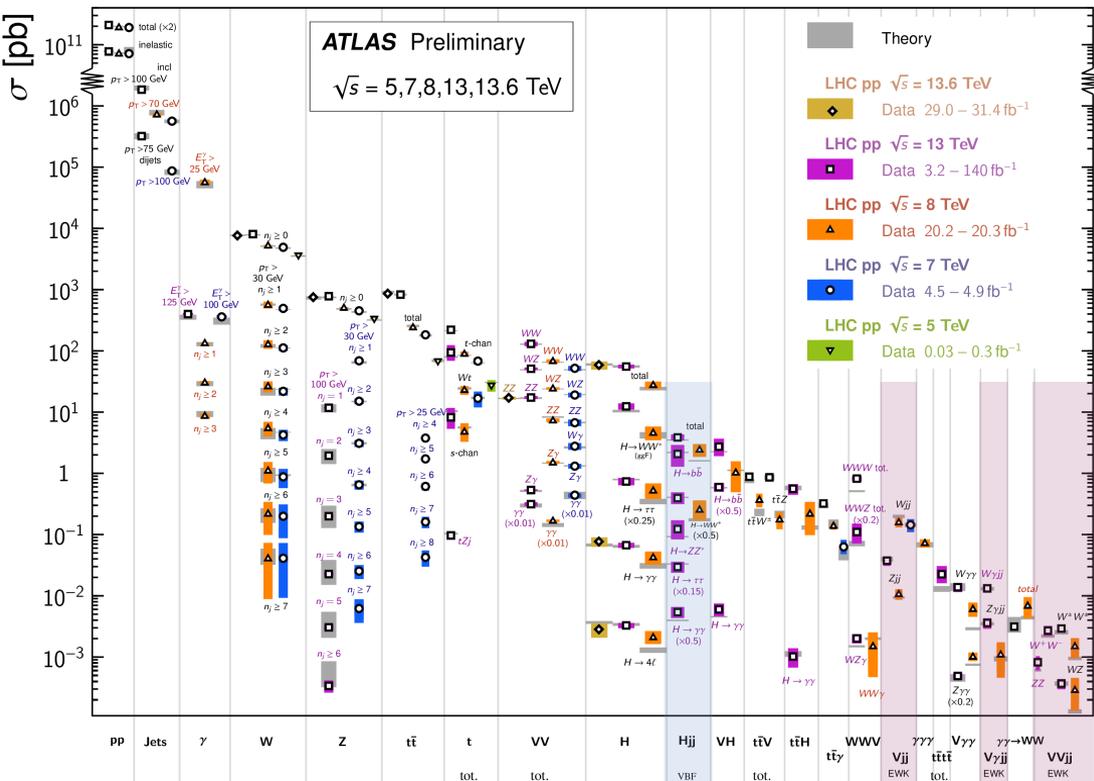


Low Cross Sections Processes



Standard Model Production Cross Section Measurements

Status: June 2024



-VBF topology allows for measurements of low cross section processes.

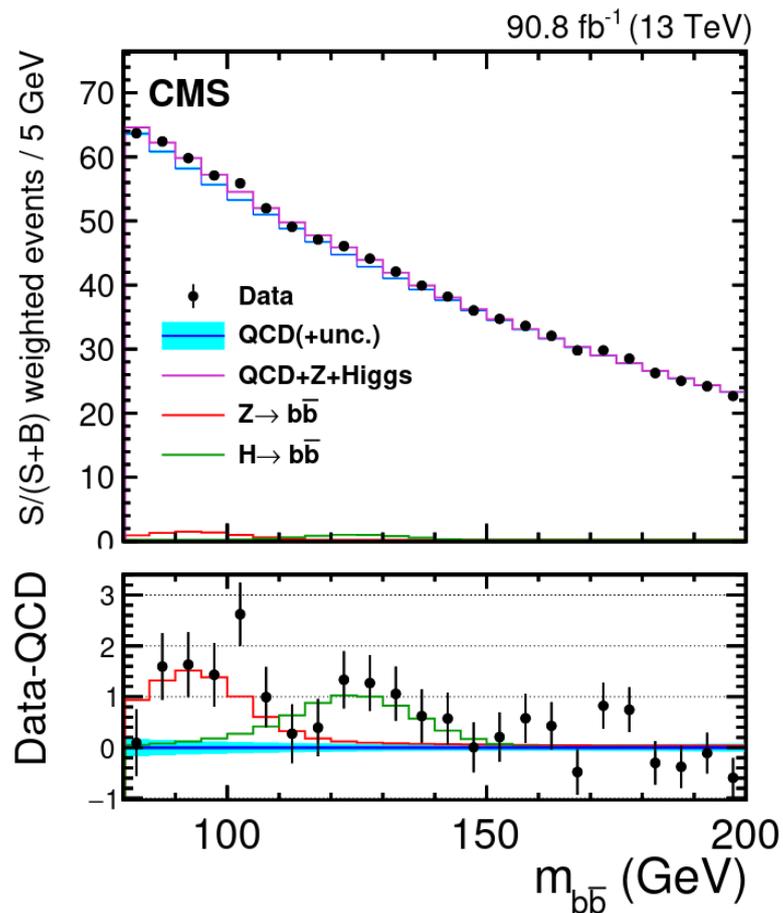
-These measurements are statistically limited. Exciting time for Run 3!

-Triggering on VBF/VBS topologies is crucial for Run 3 precision measurements.

■ VBF Higgs Signatures

■ VBF/VBS EWK Signatures

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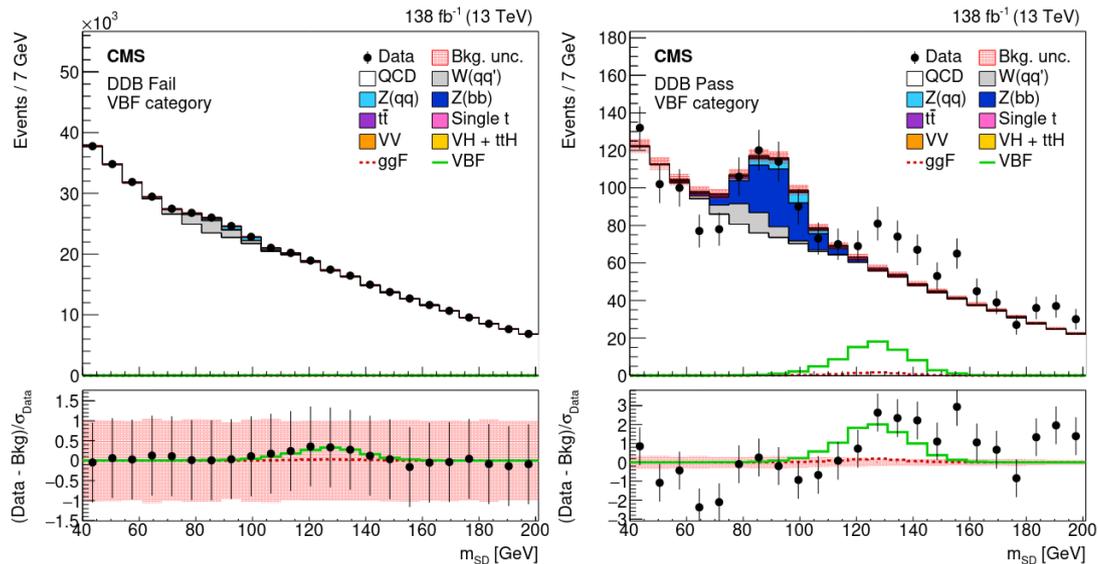
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$$\mu_{Hb\bar{b}}^{qqH} = 1.01_{-0.24}^{+0.39} (\text{syst}) \pm 0.39 (\text{stat}),$$

$$\mu_{Zb\bar{b}} = 0.96 \pm 0.21 (\text{syst}) \pm 0.23 (\text{stat})$$

The VBF signal is observed with a significance of 2.4σ . The expected significance is 2.7σ .

Source of systematic uncertainty	Impact on signal strength [%]
VBF parton shower	13.0
Jet energy scale	7.7
Trigger efficiency	6.7
Parton shower (final-state radiation)	5.6
b jet regression smearing	3.3
b tagging efficiency	3.0
Pileup modeling	2.3
b jet regression scale	2.0
Jet energy resolution	1.5



JHEP 12 (2024) 035

-CMS performed a search for VBF Higgs produced with $p_T > 450 \text{ GeV}$.

-DeepDoubleBVL-V2 (DDB) is used to perform Hbb tagging.

-Signal strength for VBF and ggF is measured by year on Run 2 dataset. Large variations between years.

	\mathcal{L} [fb^{-1}]	VBF signal strength	ggF signal strength
Early 2016	19.5	$5.2^{+4.6}_{-3.8}$ ($+3.9$ stat)	$2.5^{+4.7}_{-4.3}$ ($+3.8$ stat)
Late 2016	16.8	$5.6^{+5.8}_{-4.2}$ ($+4.5$ stat)	$0.6^{+4.4}_{-4.8}$ (± 3.8 stat)
2017	41.5	$0.8^{+2.8}_{-2.5}$ ($+2.7$ stat)	$3.3^{+3.1}_{-2.7}$ (± 2.5 stat)
2018	59.8	$8.3^{+3.9}_{-3.0}$ ($+2.8$ stat)	$0.4^{+2.6}_{-2.7}$ (± 2.3 stat)
Combined	138	$4.9^{+1.9}_{-1.6}$ (± 1.5 stat)	$1.6^{+1.7}_{-1.5}$ (± 1.4 stat)

Higgs Branching Ratios



Decay channel	Branching ratio	Rel. uncertainty
$H \rightarrow \gamma\gamma$	2.27×10^{-3}	2.1%
$H \rightarrow ZZ$	2.62×10^{-2}	$\pm 1.5\%$
$H \rightarrow W^+W^-$	2.14×10^{-1}	$\pm 1.5\%$
$H \rightarrow \tau^+\tau^-$	6.27×10^{-2}	$\pm 1.6\%$
$H \rightarrow b\bar{b}$	5.82×10^{-1}	+1.2% -1.3%
$H \rightarrow c\bar{c}$	2.89×10^{-2}	+5.5% -2.0%
$H \rightarrow Z\gamma$	1.53×10^{-3}	$\pm 5.8\%$
$H \rightarrow \mu^+\mu^-$	2.18×10^{-4}	$\pm 1.7\%$