ATLAS Searches for VH/HH Resonances

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on behalf of the ATLAS Experiment

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Northern Illinois University

ATLAS EXPERIMENT

Motivation

The discovery of the Standard Model Higgs boson gives a powerful tool to search for new physics

- Massive particles interact with the Higgs field, natural place to search for resonances from physics beyond the Standard Model

Heavy Vector Triplets (HVT)

Addition of SU(2) Heavy Vector Triplet: W'^{+},W'^{-},Z'

Can be strongly coupled at high energy scale (Little Higgs, Composite Higgs)

Can answer **naturalness** problem

Two-Higgs Doublet Models (2HDM)

Addition of a second Higgs doublet gives 5 scalar states:

h - CP-even Higgs boson
H - CP-even Heavy Higgs
$H^{\pm}$ - Charged Higgs
A - CP-odd pseudoscalar

Can answer questions like **baryogensis, dark matter**

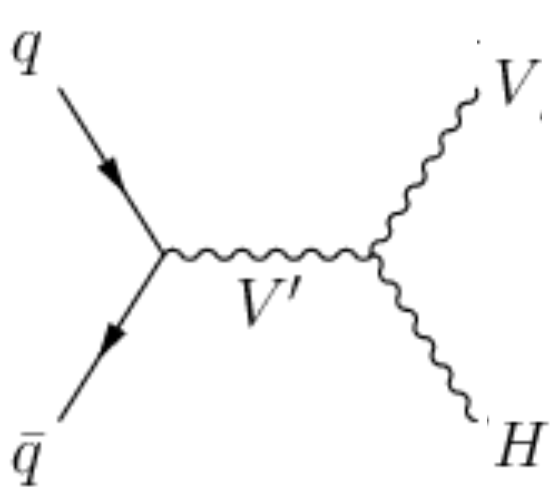
Randall-Sundrum Model

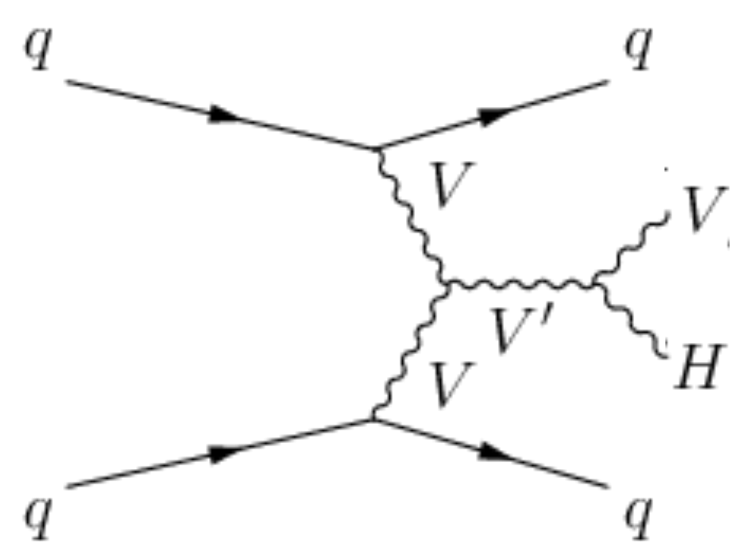
Warped Extra Dimensions model including spin-2 graviton, G_{KK}
Addresses **hierarchy** problem

VH Searches

- Semi-Leptonic VH
- Fully Hadronic VH
- Combination

- Models - Heavy Vector Triplet, 2HDM





Semi-Leptonic VH

J. High Energ. Phys. (2018) 2018: 51

All units on page are GeV

$$VH \rightarrow \nu\bar{\nu}b\bar{b},\ \ell^{\pm}\nu b\bar{b},\ \text{or}\ \ell^{+}\ell^{-}b\bar{b}$$

$b\bar{b}$

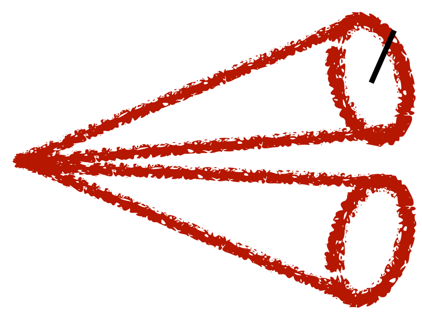
b-quark pair

from Higgs decay

H->bb BR = 0.58

Small R Jets

Resolved



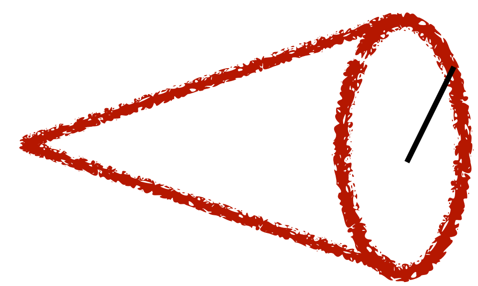
R=0.4

$p_{T1} > 45$

$p_{T2} > 20$

Large R Jet

Boosted



R = 1.0

$p_T > 250$

Pass 70% efficient b-tagging algorithm (MV2c10)

Resolved:

- Require m_{jj} between 110-140 GeV for the 0 and 1 lepton categories, 110-140 for 2 lepton
- Sensitive below 1 TeV

Boosted:

- Require m_J between 75-145 GeV
- Sensitive above 1 TeV

Semi-Leptonic VH

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All units on page are GeV

$$VH \rightarrow \nu\bar{\nu}b\bar{b},\ \ell^{\pm}\nu b\bar{b},\text{ or }\ \ell^{+}\ell^{-}b\bar{b}$$

		$\nu\bar{\nu}b\bar{b}$ 0-lepton	$\ell^{\pm}\nu b\bar{b}$ 1-lepton	$\ell^{+}\ell^{-}b\bar{b}$ 2-lepton
$\ell^{\pm}$ Leptons			$p_{T,\ell} > 27$	$p_{T,\ell_1} > 27$ $p_{T,\ell_2} > 7$
ν Neutrinos	(resolved)	$\vec{E}_T^{miss} > 150$	$\vec{E}_T^{miss} > 40$	Veto: $\vec{E}_T^{miss}/\sqrt{H_T} < 1.15 + 8 \times 10^{-3} \cdot m_{Vh}$
	(boosted)	$\vec{E}_T^{miss} > 200$	$\vec{E}_T^{miss} > 100$	

Background contamination varies by channel:

Channel	Dominant Backgrounds
0-lepton	Z+jets, ttbar
1-lepton	ttbar, single-top, W+jets
2-lepton	Z+jets, ttbar

Semi-Leptonic VH

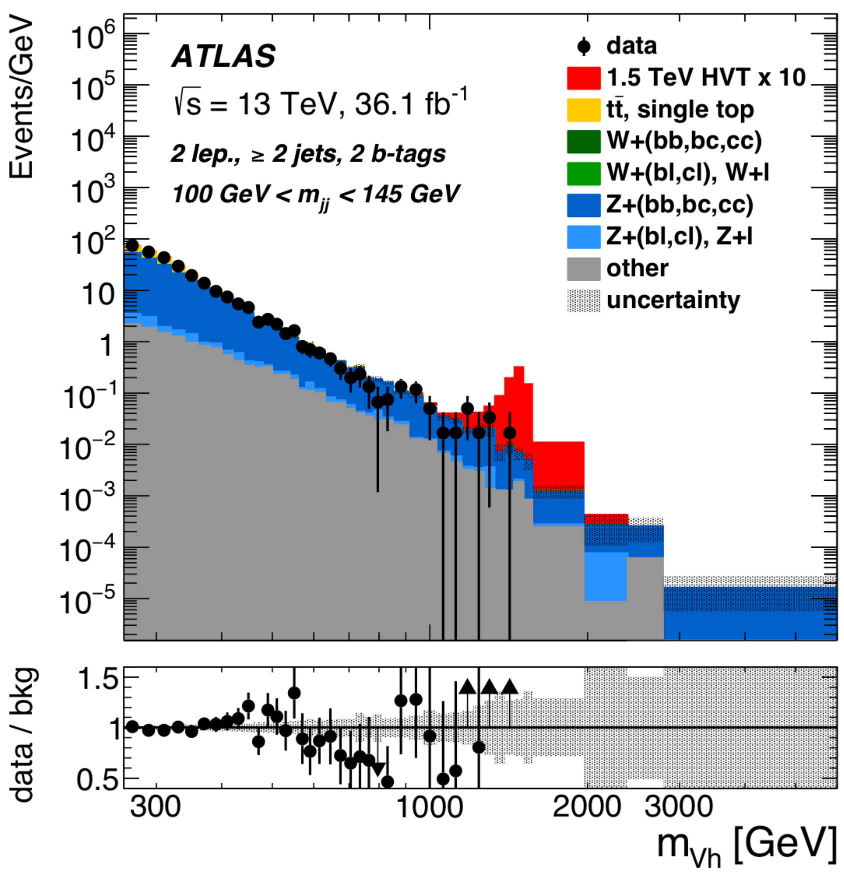
J. High Energ. Phys. (2018) 2018: 51

Fit m_{Vh} as the figure of merit

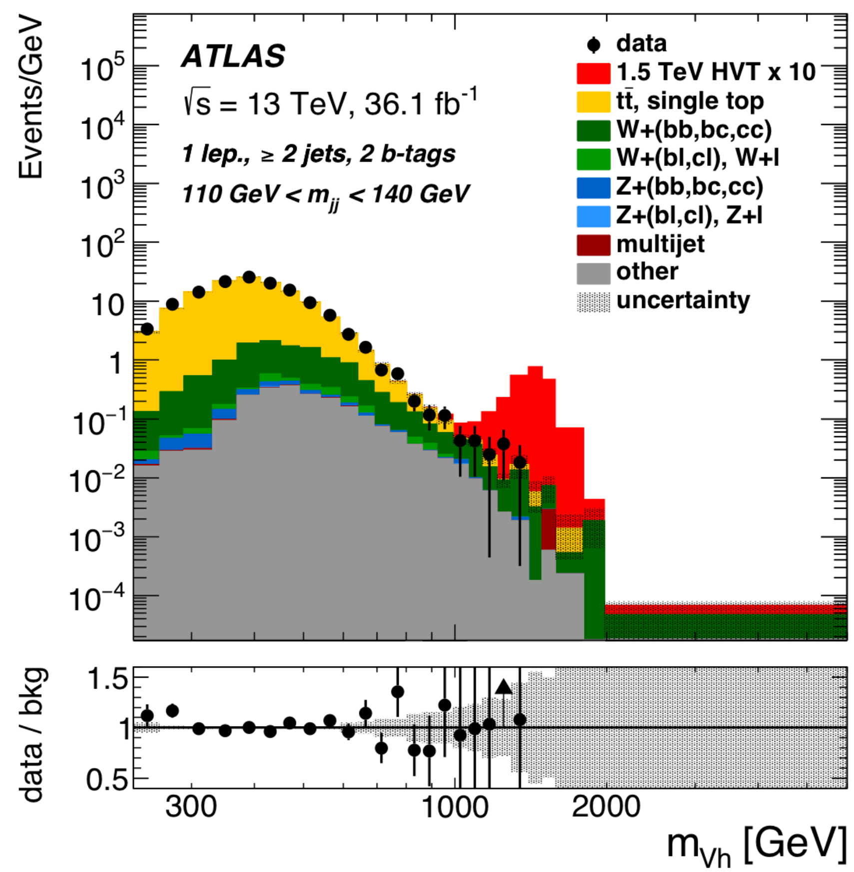
- In 0-lepton categories, where Zh cannot be reconstructed, fit $m_{T,Vh} = \sqrt{(E_T^h + E_T^{miss})^2 - (\vec{p}_T^{\,h} + E_T^{miss})^2}$
- In 1-lepton categories, the momentum of the neutrino is obtained by imposing a W mass constraint

Resolved

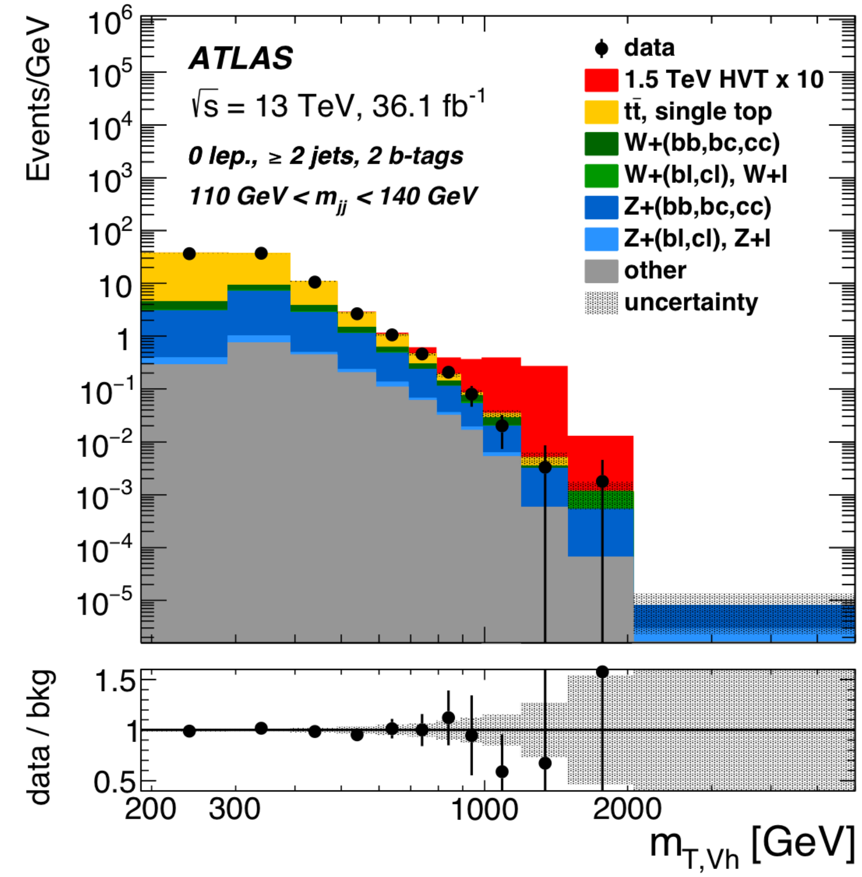
2-lepton



1-lepton



0-lepton



Semi-Leptonic VH

[J. High Energ. Phys. (2018) 2018: 51](#)

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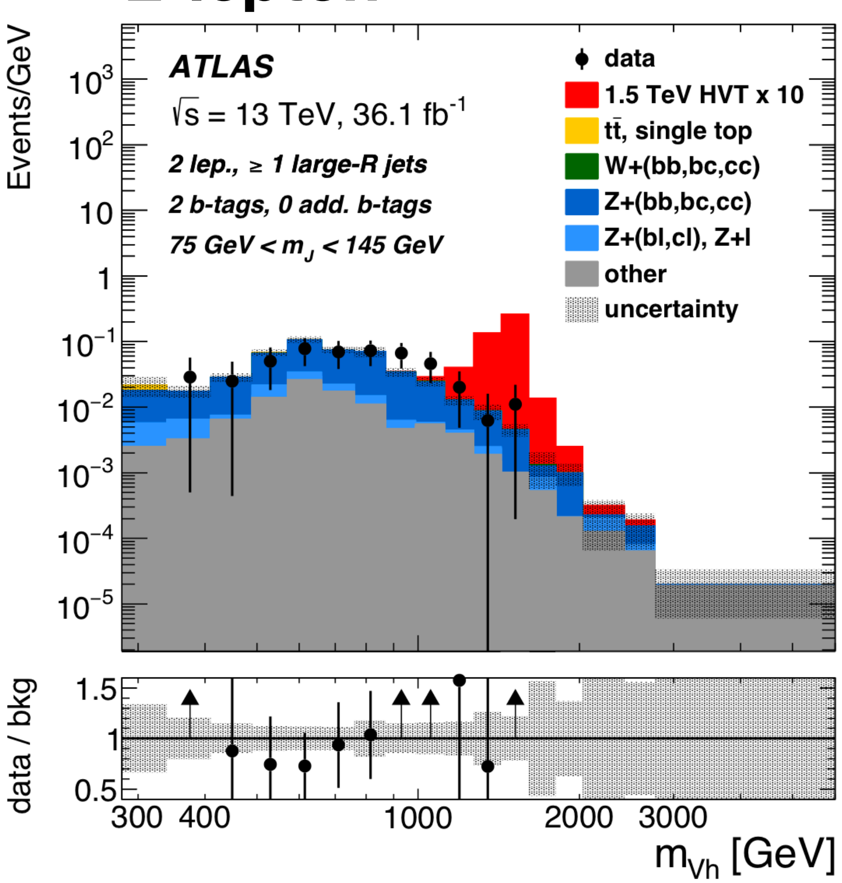
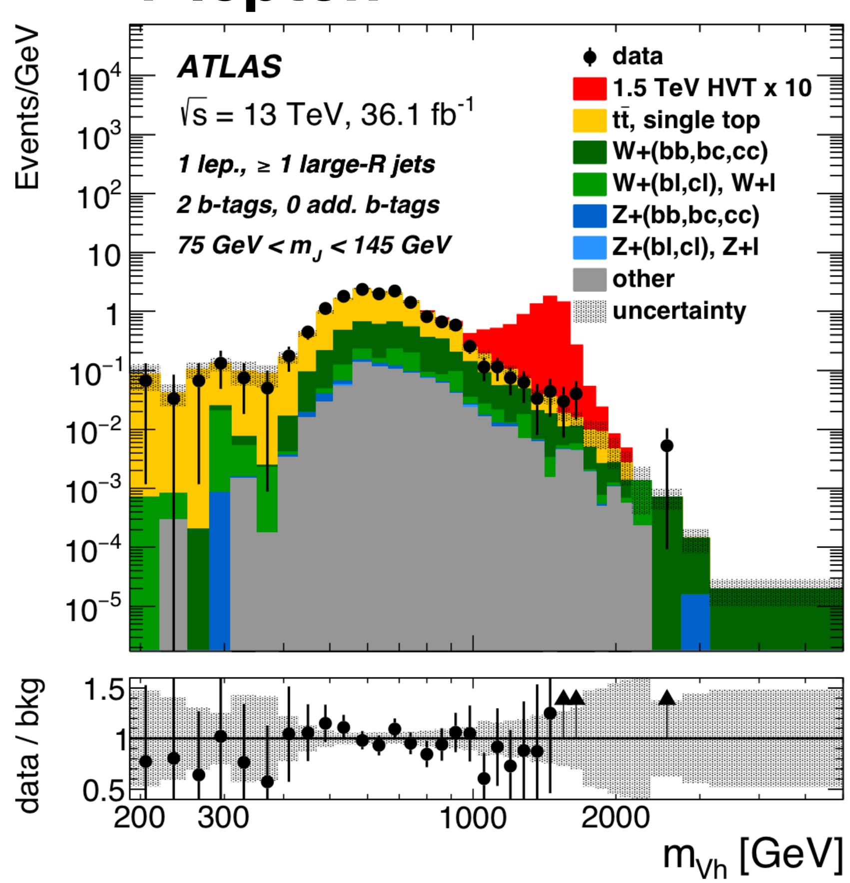
Boosted

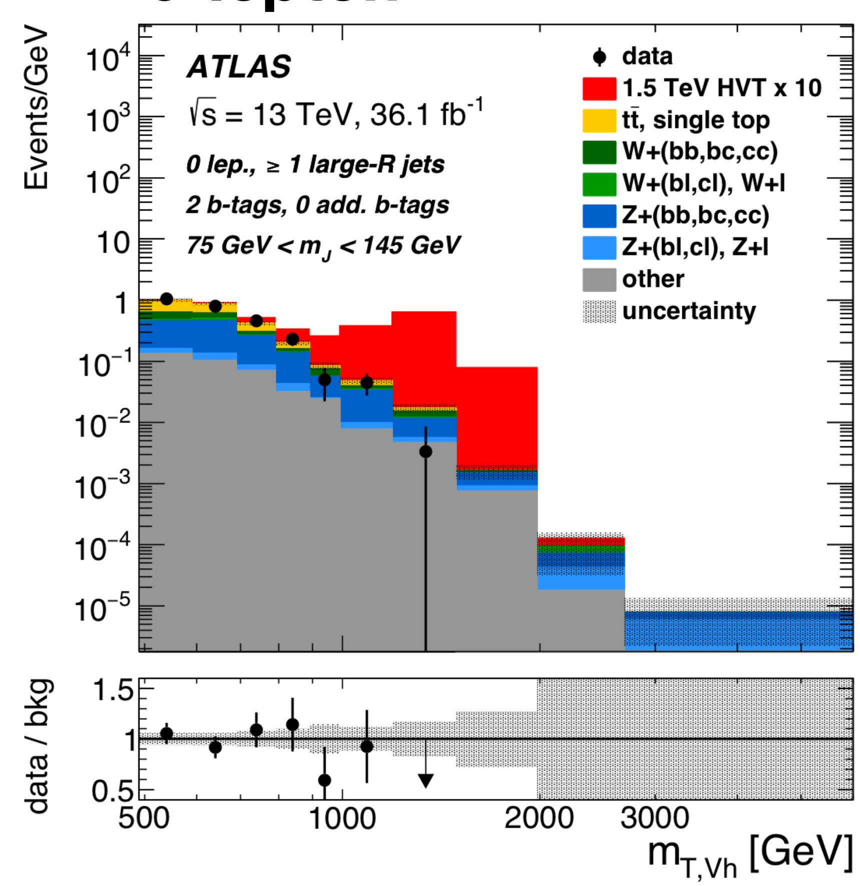
2-lepton



1-lepton



0-lepton



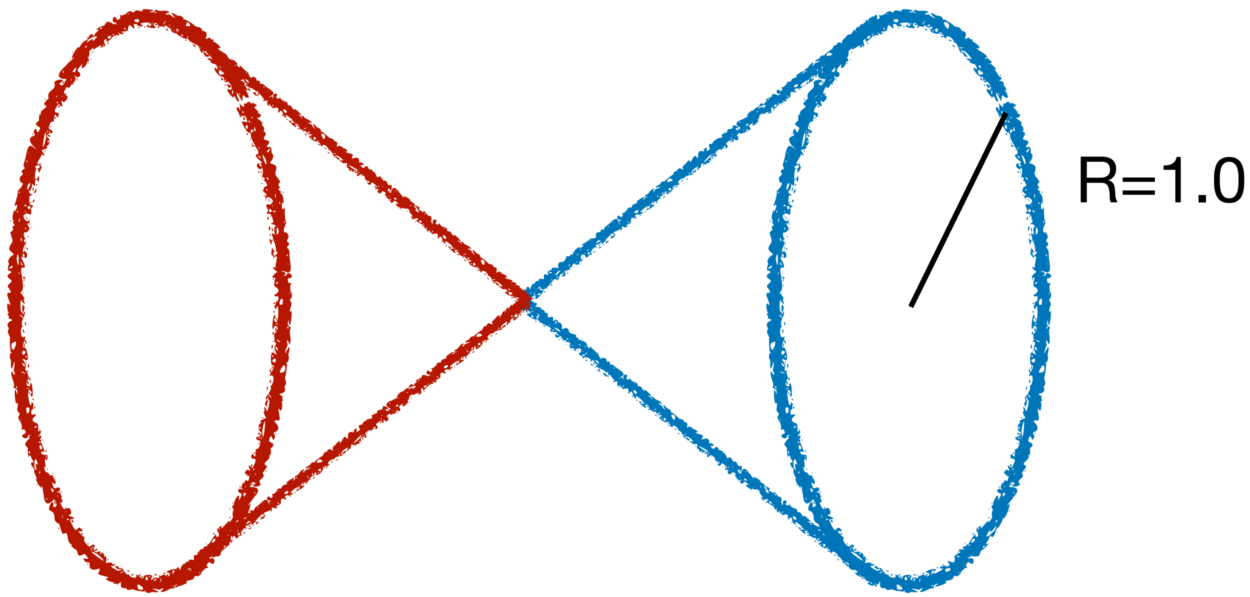
Fully Hadronic VH

Phys. Lett. B 774 (2017) 494-515

$$VH \rightarrow q\bar{q}b\bar{b}$$

Search at m_{VH} > 1 TeV, so probe **boosted** topologies

Search for **2 large R jets**



Higgs decay jet:

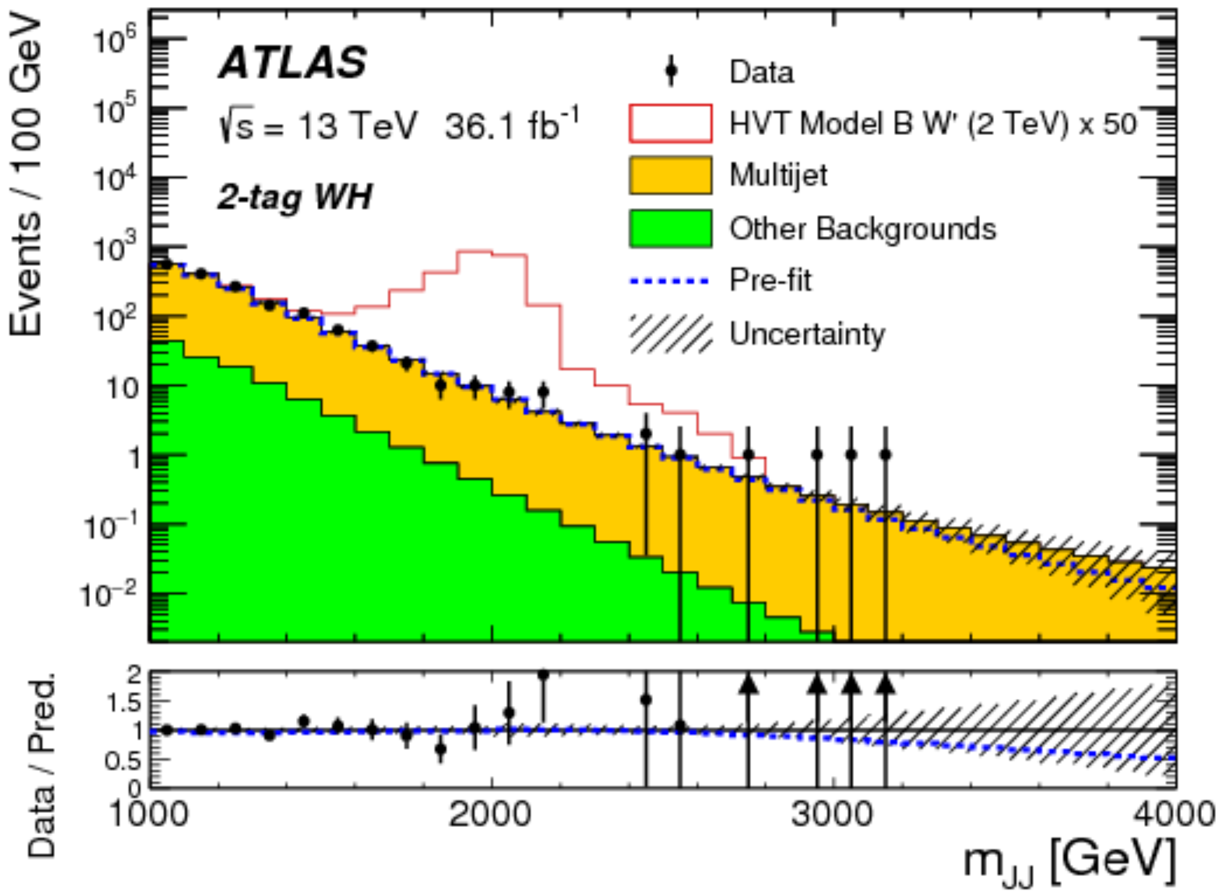
m_J between 75 and 145 GeV (90% efficient)
b-tagging requirements (77% efficient)

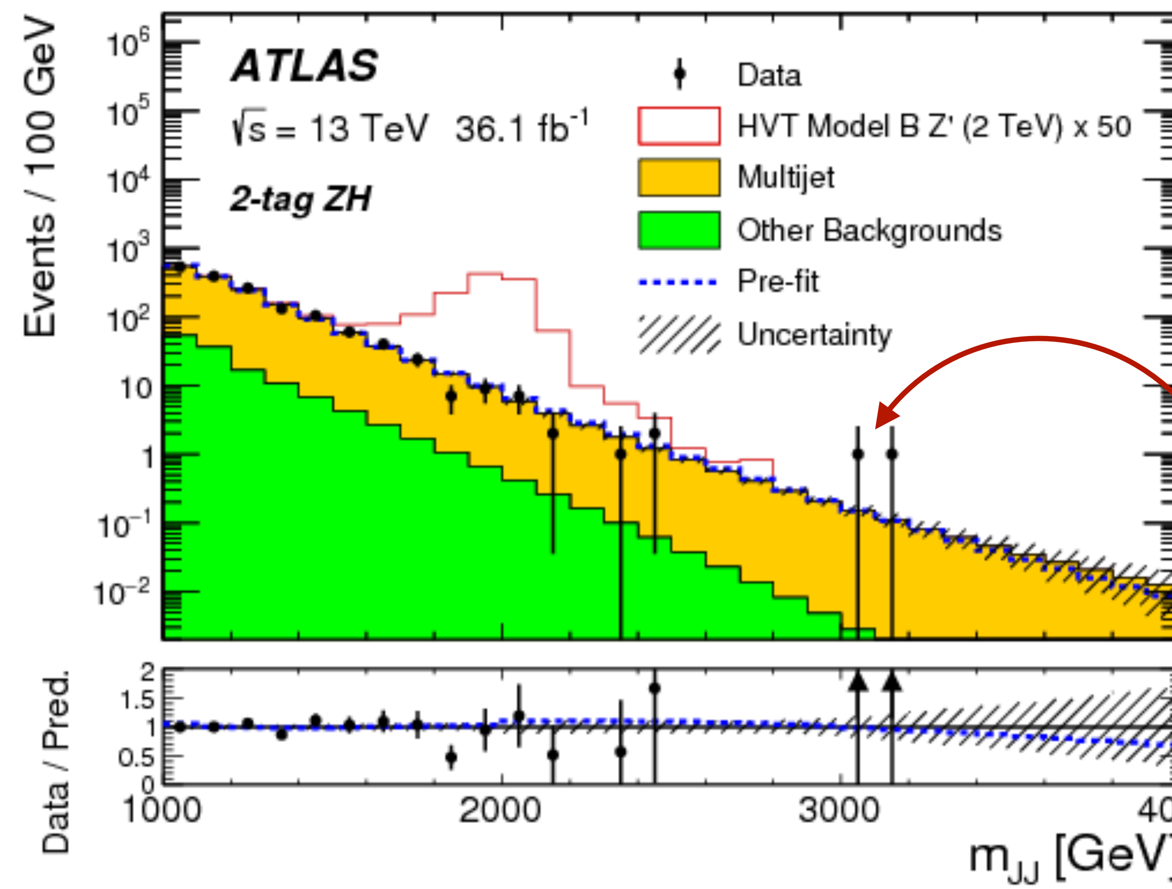
Vector Boson decay jet:

m_W between 67 and 95 GeV
m_Z between 75 and 107 GeV
D_2 selection (50% efficient, 2% multijet contamination) - Substructure variable to distinguish 2-prong jets, more here

Fully Hadronic VH

[Phys. Lett. B 774 (2017) 494-515]





Predominant background is from multijet events - modeled directly from data

- Use 0-tag sample, correct for kinematic differences in tagged regions, normalize using sidebands

Fit consistent with background-only hypothesis

- Largest deviation is in the ZH signal ~3 TeV
  - Local significance = 3.3σ
  - Global significance = 2.1σ

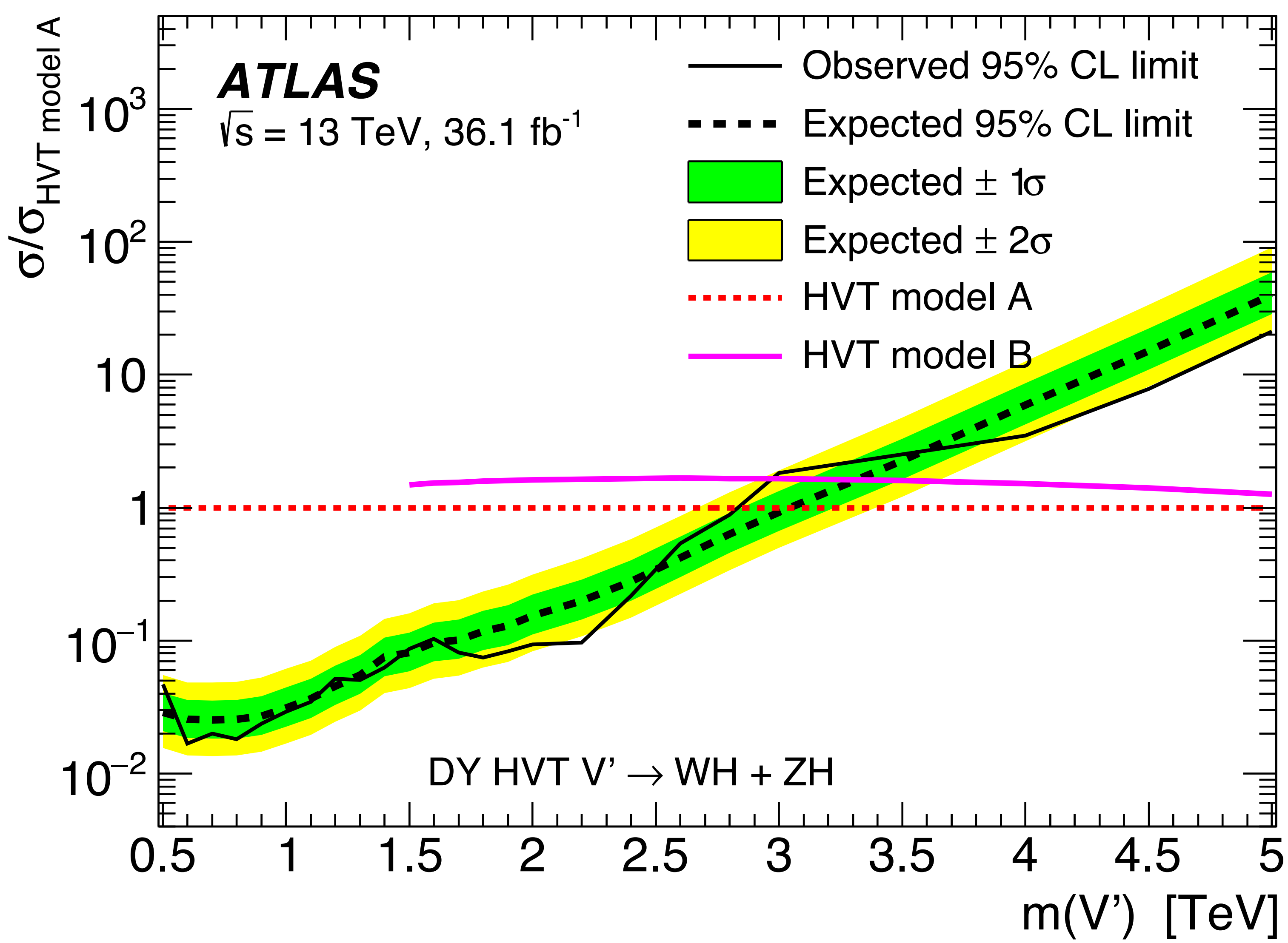
VH Combination

Phys. Rev. D 98, 052008

A combination of VH searches uses Heavy Vector Triplet models as benchmarks

Lower limits on resonance mass [TeV]

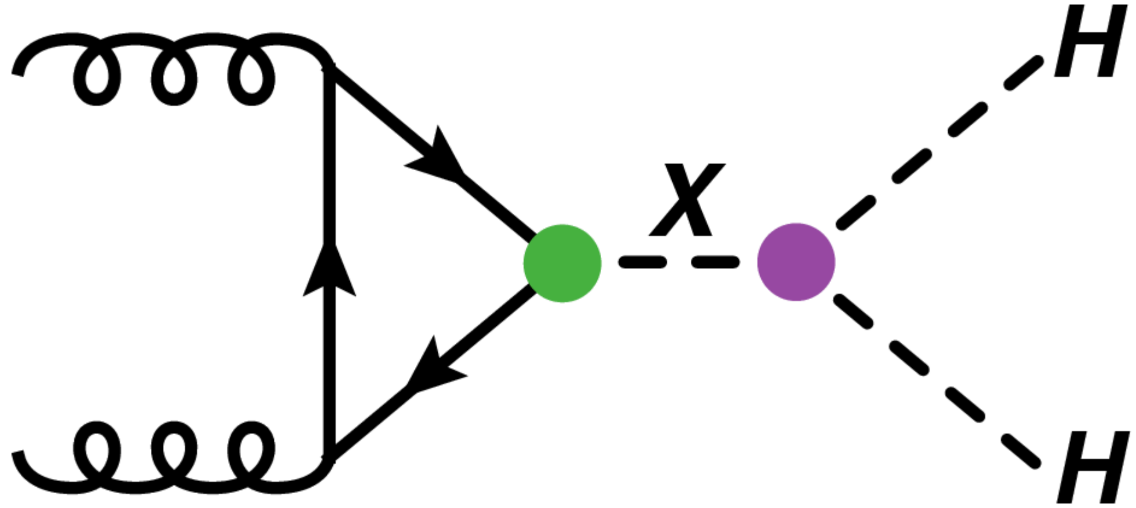
	Observed	Expected	Model Discription
Model A	2.8	3.1	BR to fermions and gauge bosons are comparable
Model B	3.0	3.4	fermionic couplings are suppressed



Di-Higgs Searches

- $bb\gamma\gamma$, bbττ, bbbb
- Combination

- Models - 2HDM, Randall-Sundrum



Di-Higgs Searches

JHEP 11 (2018) 040

Three predominant channels contribute to combined analysis

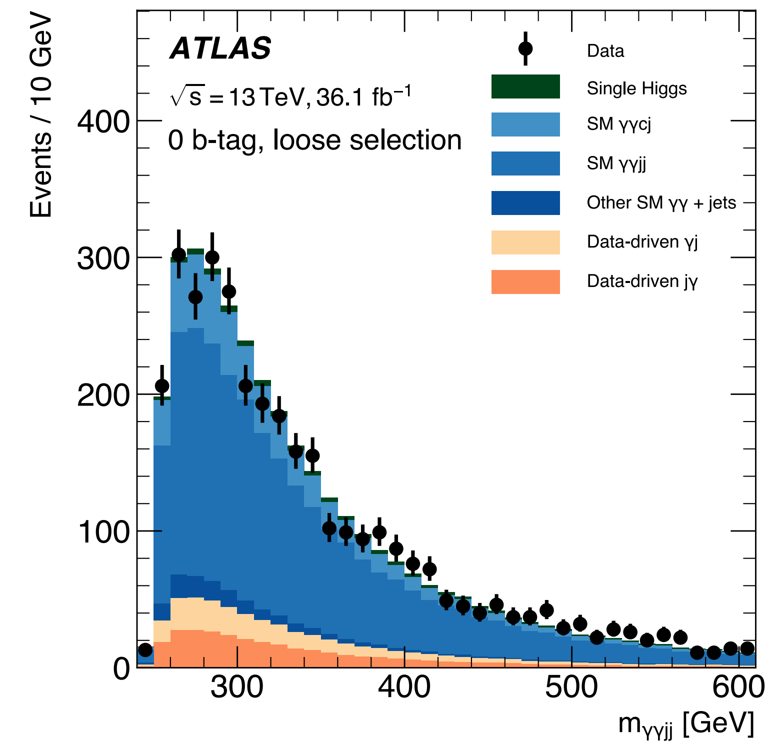
- Take advantage of high branching ratios and resolution of decay products

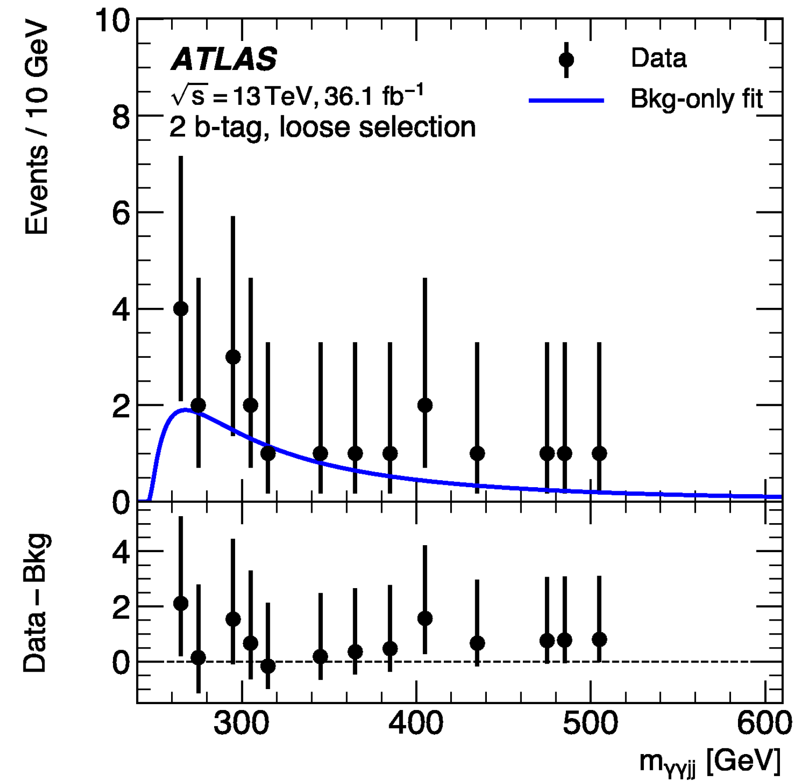
$HH \rightarrow b\bar{b}\gamma\gamma$

Fix m_{bb} to 125 GeV, cut $m_{\gamma\gamma}$ between 120 and 130 GeV, perform S+B fit in $m_{\gamma\gamma jj}$

Continuum $m_{\gamma\gamma}$ spectra background estimated from data

Particularly sensitive at low masses





Di-Higgs Searches

Phys. Rev. Lett. 121 (2018) 191801

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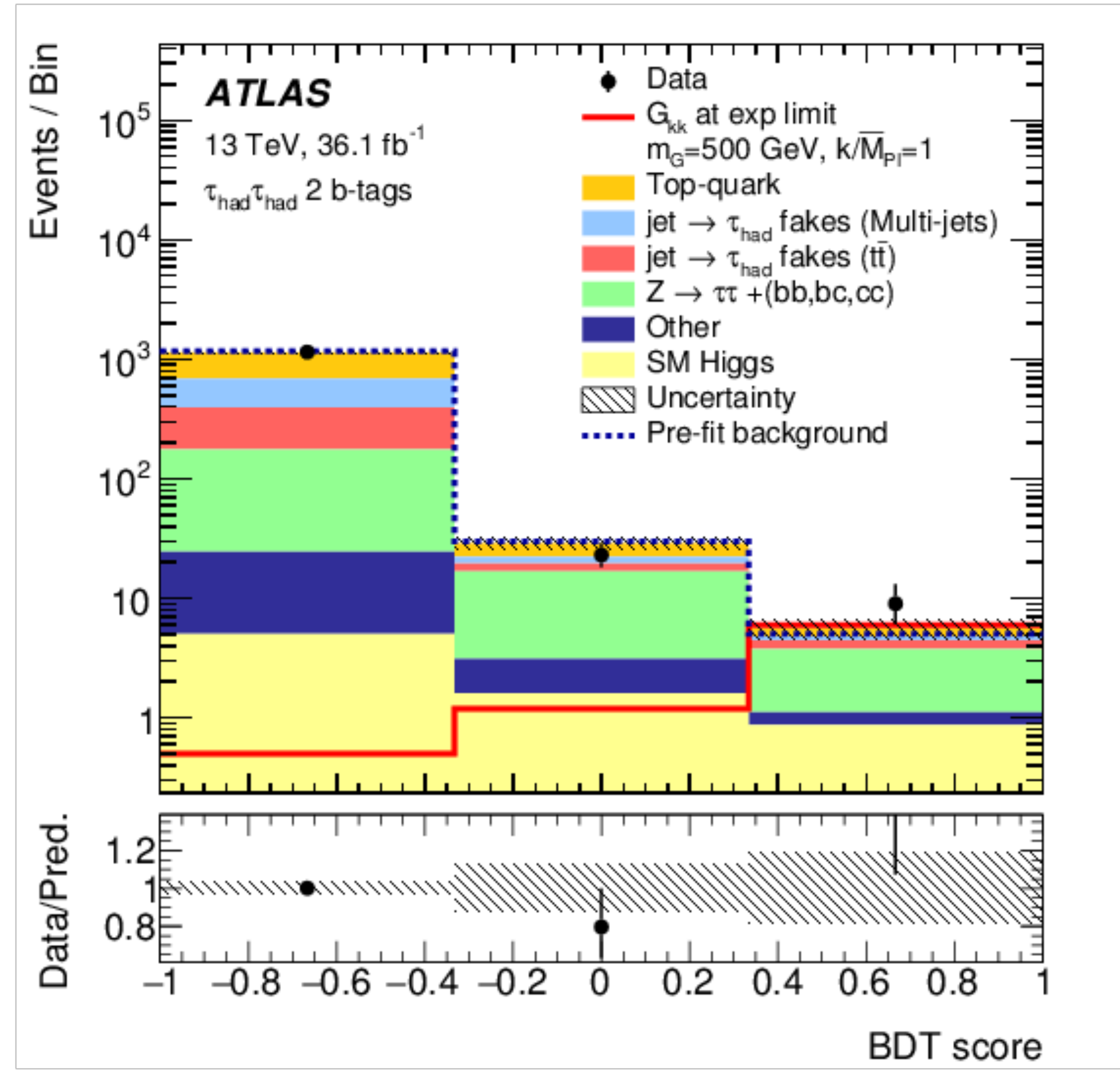
Continuum $m_{\gamma\gamma}$ spectra background estimated from data

Particularly sensitive at low masses

$HH \rightarrow b\bar{b}\tau\tau$

Train BDT to discriminate signal from backgrounds, fit BDT score distributions

- Dominant backgrounds: multijet, $t\bar{t}$, $Z \rightarrow \tau\tau$
- Separate BDT for each mass hypothesis



Di-Higgs Searches

JHEP 01 (2019) 030

Three predominant channels contribute to combined analysis

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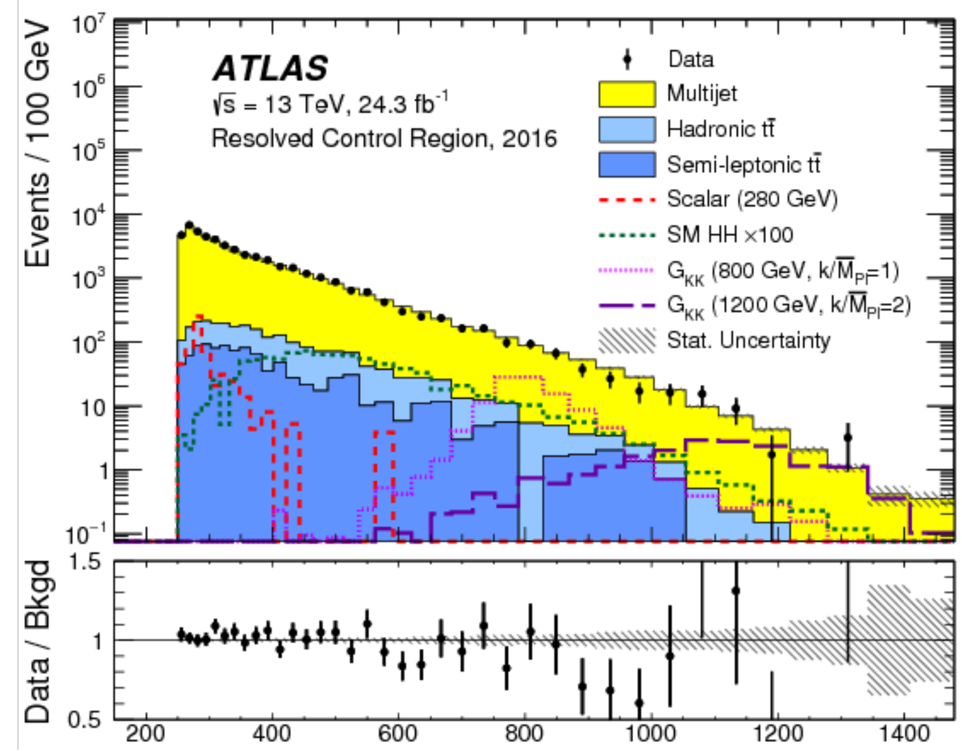

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Train BDT to discriminate signal from backgrounds, fit BDT score distributions

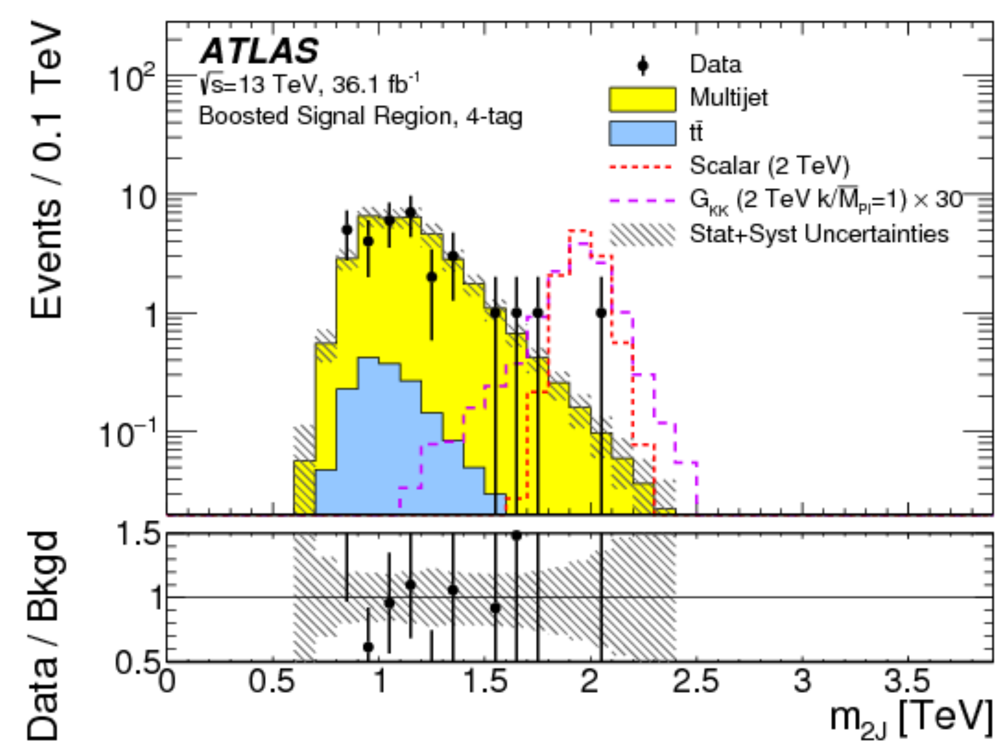
- Dominant backgrounds: multijet,
- Separate BDT for each mass hypothesis

$HH \rightarrow b\bar{b}b\bar{b}$

S+B fit to m_{4j} (m_{2J}) in the resolved (boosted) selection

Multijet background estimated from data

Especially sensitive in high mass region

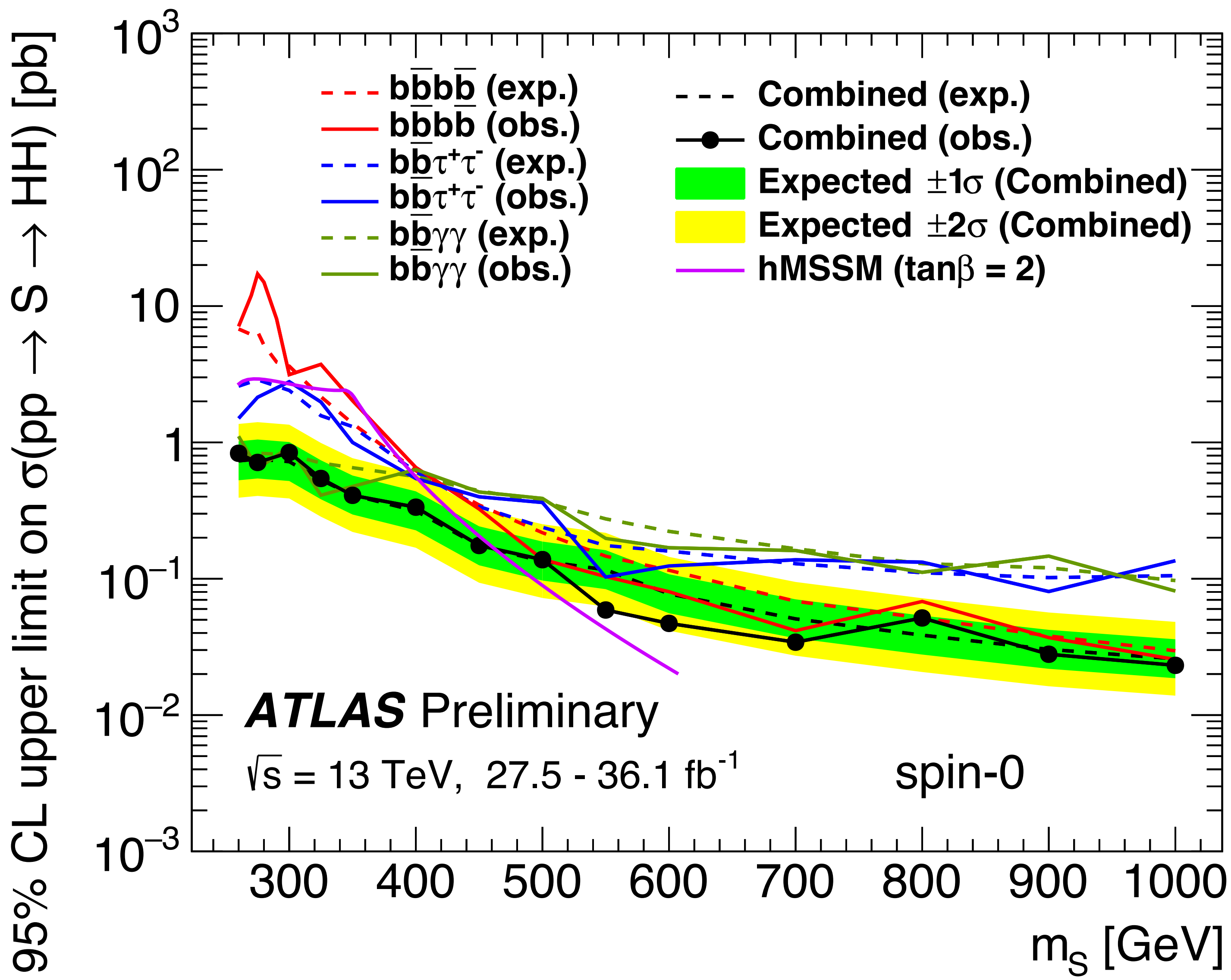


Di-Higgs Combination

ATLAS-CONF-2018-043

Combine channels to set limits on resonant HH production

Set limits on scalar resonance corresponding to CP-even heavy higgs in hMSSM (2HDM)



ATLAS-CONF-2018-043

hMSSM model with tanβ = 2, 260 < m_H/GeV< 462 is excluded at 95% CL

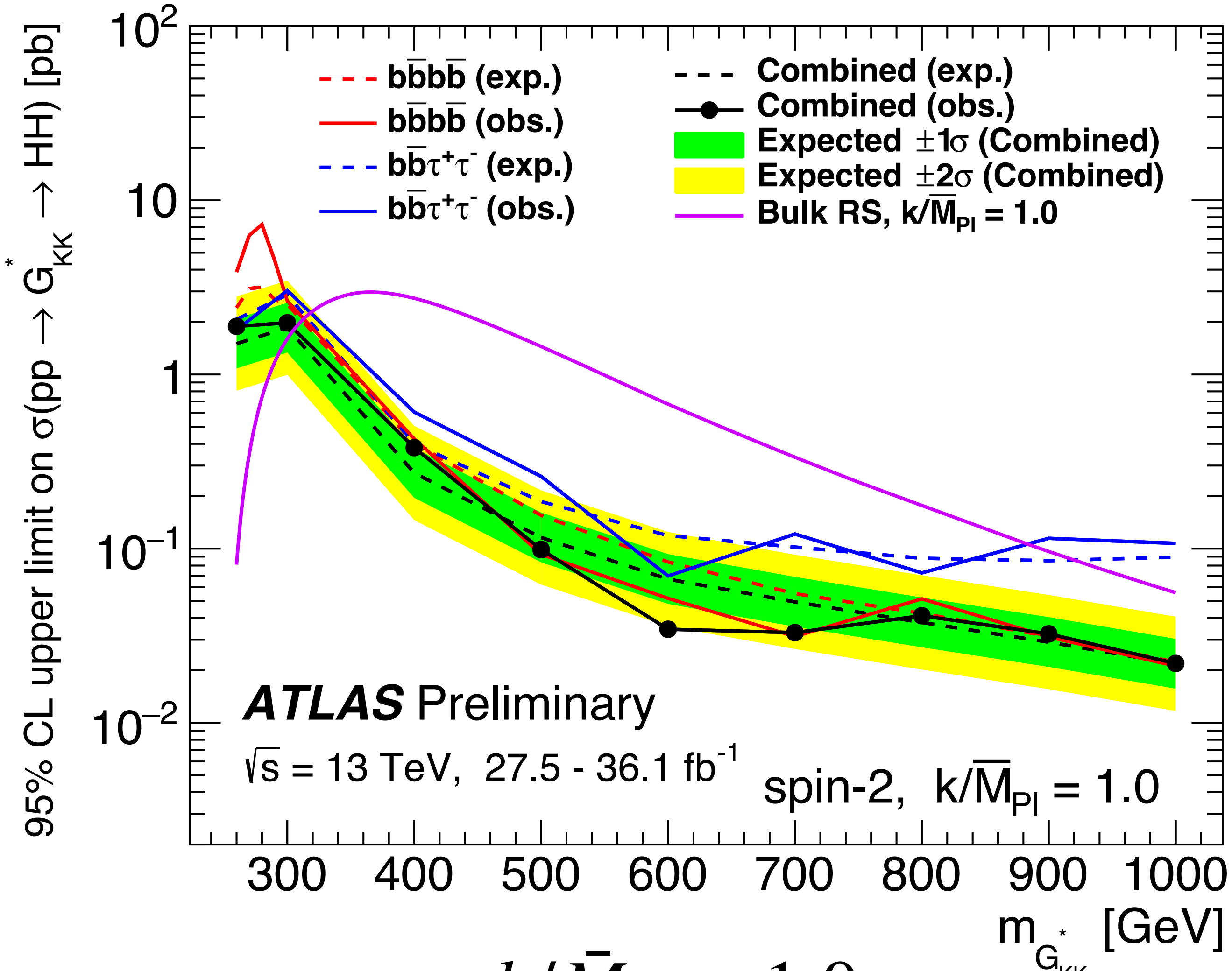
Di-Higgs Combination

ATLAS-CONF-2018-043

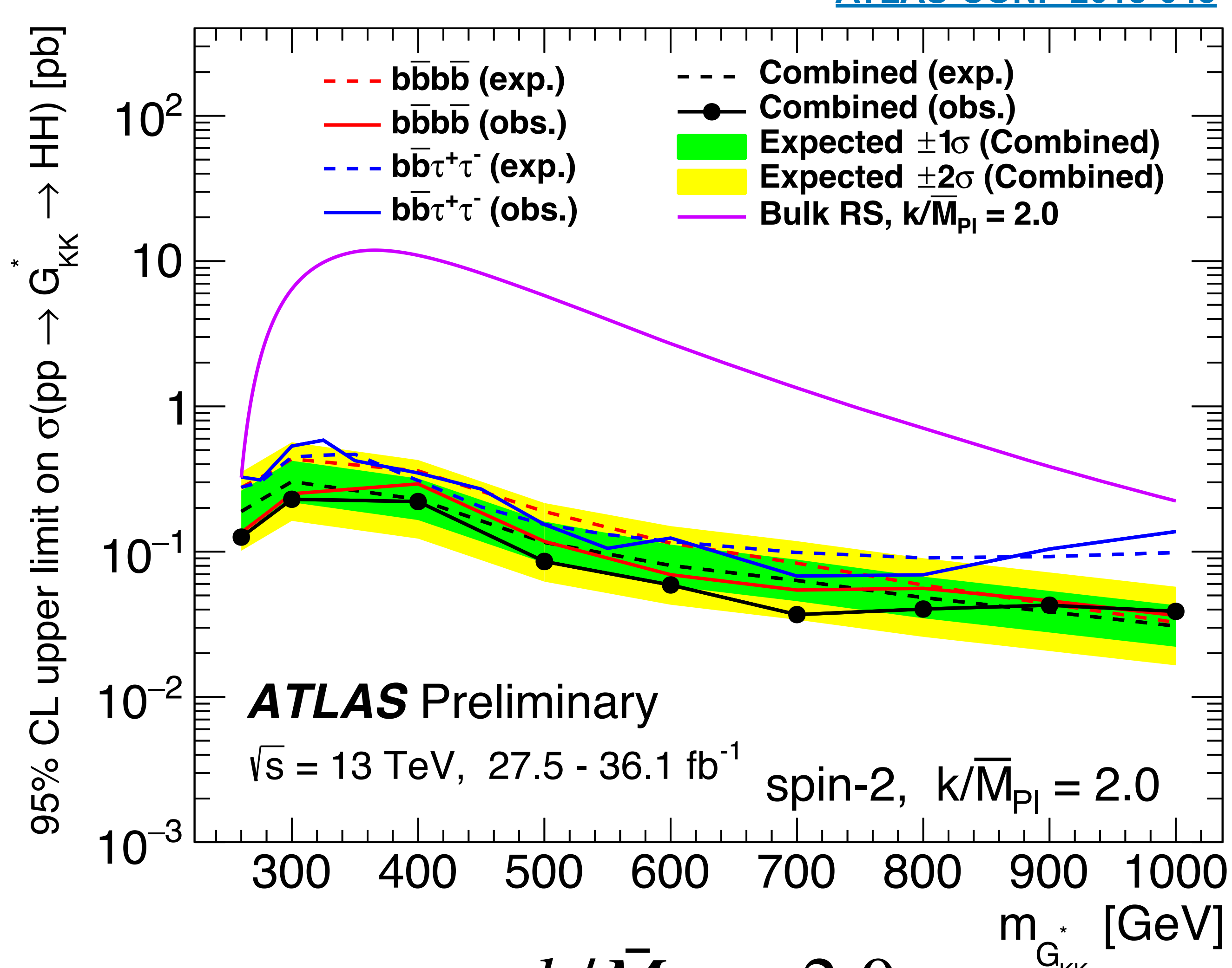
Combine channels to set limits on resonant HH production

Set limits on spin-2 resonance, corresponding to KK-graviton in Randall-Sundrum model

ATLAS-CONF-2018-043



$k/\bar{M}_{pl} = 1.0$



$k/\bar{M}_{pl} = 2.0$

307 < m_{GKK} < 1362 GeV excluded at 95% CL

m_{GKK} < 1744 GeV excluded at 95% CL

Conclusion

ATLAS searches for resonances decaying to VH or HH at 36.1 fb^{-1} have been presented

- VH searches set limits on Heavy Vector Triplet models
  - Semileptonic, fully hadronic, combination analyses presented
  - Lower observed limit of 2.8 TeV if branching ratio to fermions and gauge bosons are comparable
  - Lower observed limit of 3.0 TeV if fermionic couplings are suppressed

- HH searches set limits on Two-Higgs Doublet and Randall-Sundrum models
  - Individual channels $bb\gamma\gamma$, $bb\tau\tau$, bbbb and newest combination results presented
  - $260 < m_H/\text{GeV} < 462$ is excluded at 95% CL in 2HDM
  - $307 < m_{GKK}/\text{GeV} < 1362$ excluded for $k/M_{pl} = 1.0$ in RS model
  - $m_{GKK} < 1744$ GeV excluded for $k/M_{pl} = 2.0$ in RS model

Full Run 2 versions of these analyses with 140 fb^{-1} are underway!