Combination of searches for heavy spin-1 resonances with the ATLAS detector

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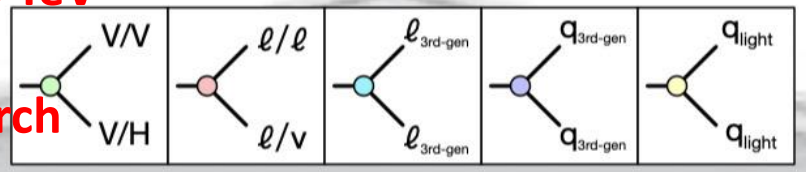
Overview

Full Run-2 data, 139 fb^{-1}, $\sqrt{s}$ = 13 TeV

spin-1 resonances (W', Z') research

In VV, VH, ll, lv, $t\bar{t}$, tb, qq, $b\bar{b}$ types



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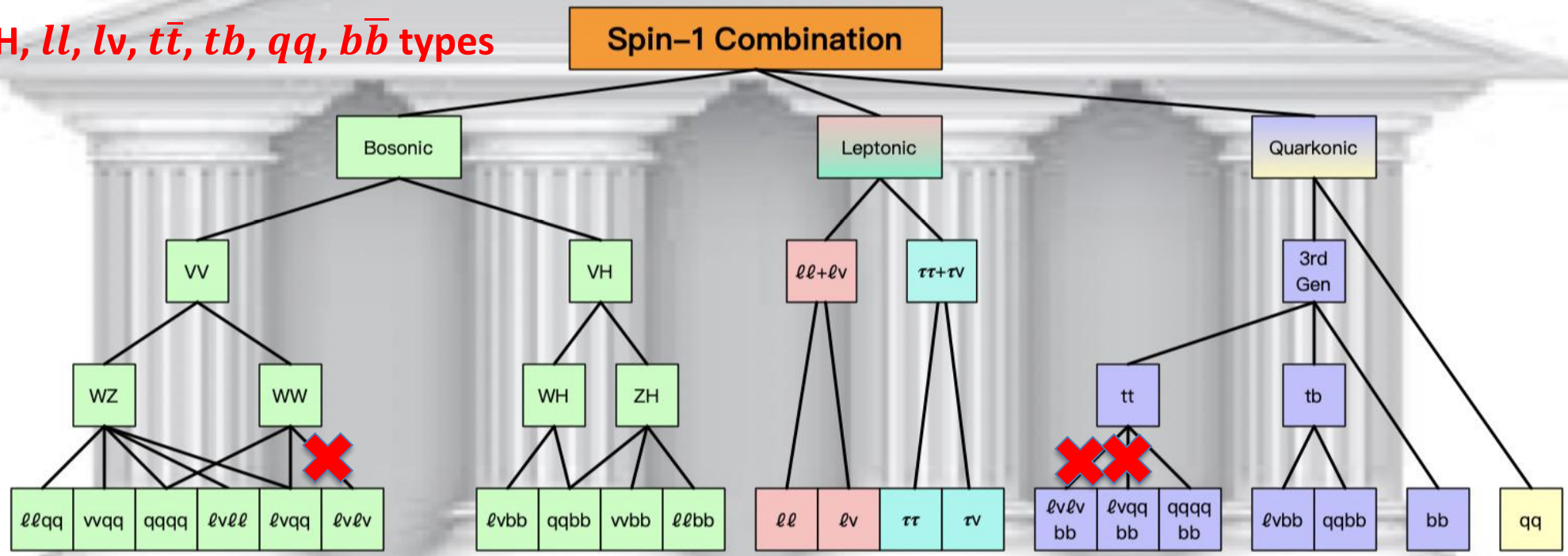


HVT $\mathcal{W}_\mu^a[g_\ell(\bar{\ell}_L\gamma^\mu\tau_a\ell_L)+g_{\ell_3}(\bar{\ell}_L^3\gamma^\mu\tau_a\ell_L^3)+g_q(\bar{q}_L\gamma^\mu\tau_a q_L)+g_{q3}(\bar{q}_L^3\gamma^\mu\tau_a q_L^3)+g_\phi(\phi^\dagger\tau_a iD^\mu\phi)]$

Signal model

- A phenomenological Heavy Vector Triplet (HVT) model with nearly degenerate W'/Z' and SM couplings as free parameters

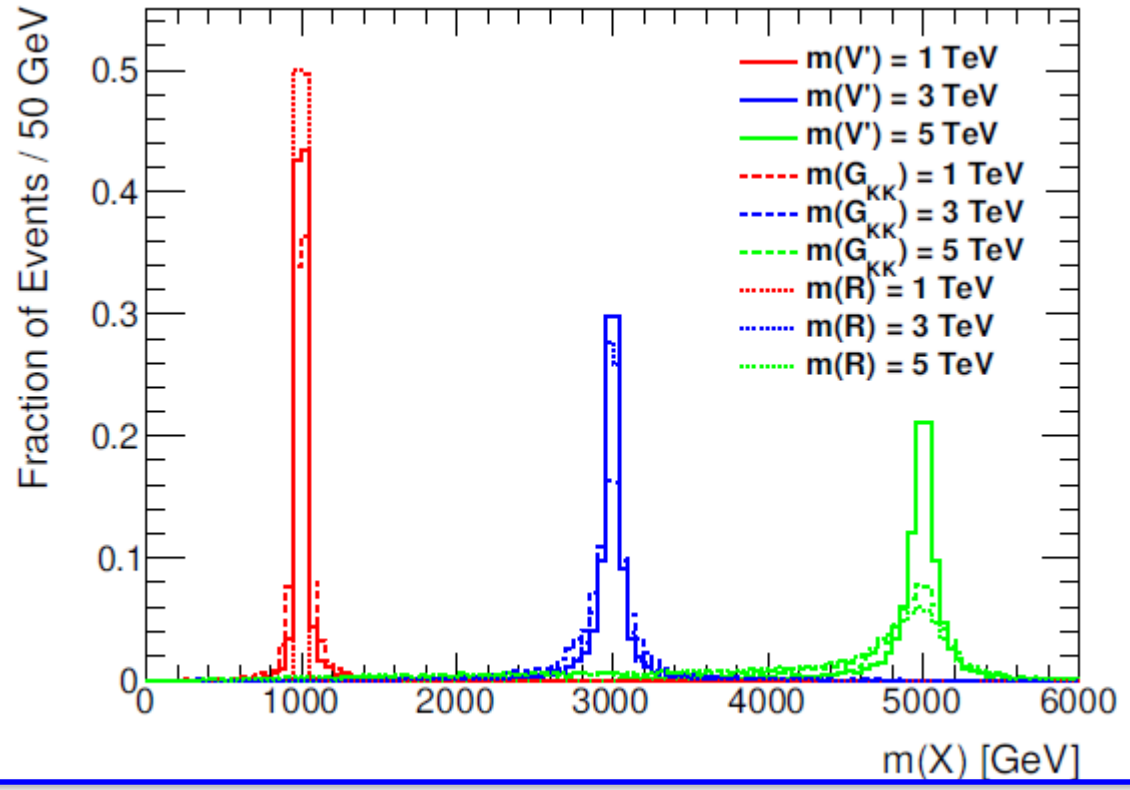
$$\mathcal{L}_{\mathcal{W}}^{\text{int}} = -g_q \mathcal{W}_\mu^a \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - g_\ell \mathcal{W}_\mu^a \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - g_H \left(\mathcal{W}_\mu^a H^\dagger \frac{\sigma_a}{2} i D^\mu H + \text{h.c.} \right)$$

- Three typical models in two production modes:
  - $q\bar{q}$ production
    - Model A: weakly-coupled scenario, g_H = -0.56, g_f = -0.55
    - Model B: strongly-coupled scenario, g_H = -2.9, g_f = 0.14
  - VBF production
    - Model C: g_H = 1, g_f = 0

Signal templates

- Most signal samples: MG5_aMC@NLO+Py8
- Mass points of the signal samples are shown below

qqA	0.3-1.0 [0.1], 1.0-3.0 [0.2], 3.0-5.0 [0.5], 5.0-8.0 [1.0]
VBF	0.3-0.8 [0.1], 0.8, 1.0, 1.2, 1.5, 1.8, 2.0, 2.4, 2.6, 3.0, 3.5, 4.0



Combination analysis strategy

- Check the orthogonality among those analysis signal regions
  - A series of operations are applied to reduce the overlap

- Combine analyses

- Set limits in 1D and 2 D
  - 1D: exclusion of cross section as function of m_V,
  - 2D: coupling planes
    - $\{g_H, g_f\}, \{g_q, g_l\}$
    - $\{g_H, g_{q3}\}, \{g_{q3}, g_{l3}\}, \{g_{q12}, g_{q3}\}$

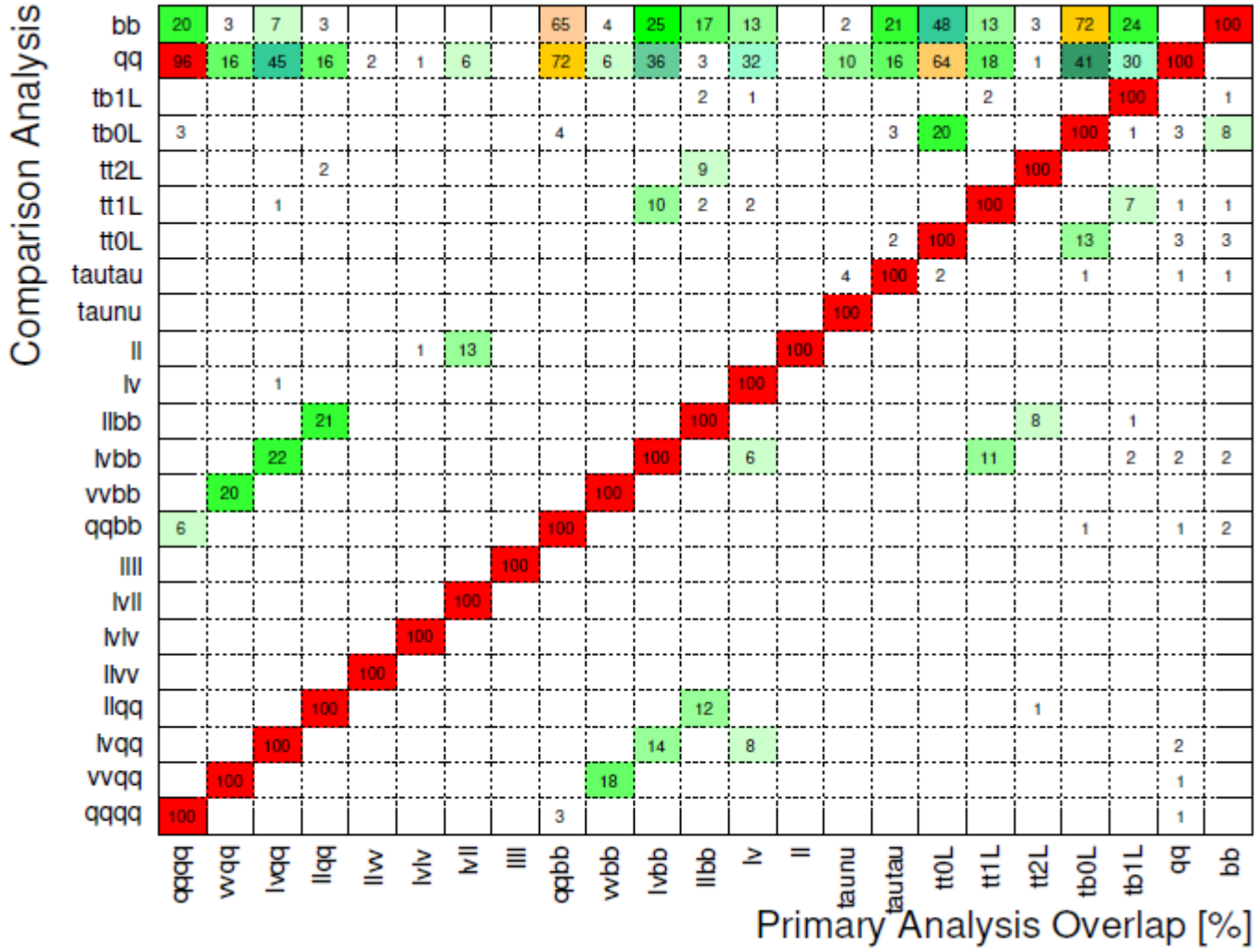
With request on rest coupling

Event selection

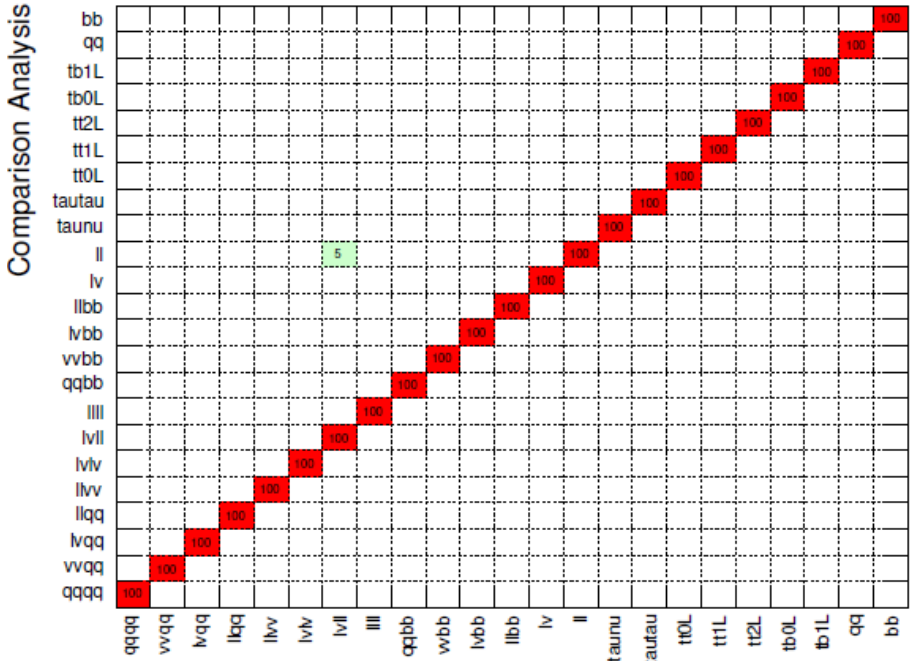
Analysis	Leptons	$E_{\mathrm{T}}^{\mathrm{miss}}$	Jets	b-tags	Top-tags	VBF	Discr.	Ref.
$WW/WZ \to qqqq$	0	Veto	$\geq$2J	-	-	-	m_{VV}	[9]
$WW/WZ \to \ell\nu qq$	$1e$, 1μ	Yes	$\geq$2j, $\geq$1J	0, 1, 2	-	Yes	m_{VV}	[10]
$WZ \to qq\nu\nu$	0	Yes	$\geq$1J	0	-	Yes	m_{VV}	[10]
$WZ \to qq\ell\ell$	$2e$, 2μ	-	$\geq$2j, $\geq$1J	0	-	Yes	m_{VV}	[10]
$WZ \to \ell\nu\ell\ell$	$3 \subset (e, \mu)$	Yes	-	0	-	Yes	m_{VV}	[11]
$WH/ZH \to qqbb$	0	Veto	$\geq$2J	1, 2	-	-	m_{VH}	[12]
$ZH \to \nu\nu bb$	0	Yes	$\geq$2j, $\geq$1J	1, 2	-	-	m_{VH}	[13]
$WH \to \ell\nu bb$	$1e$, 1μ	Yes	$\geq$2j, $\geq$1J	1, 2	-	-	m_{VH}	[13]
$ZH \to \ell\ell bb$	$2e$, 2μ	Veto	$\geq$2j, $\geq$1J	1, 2	-	-	m_{VH}	[13]
$\ell\nu$	$1e$, 1μ	Yes	-	-	-	-	m_{T}	[15]
$\tau\nu$	1τ	Yes	-	-	-	-	m_{T}	[16]
$\ell\ell$	$\geq 2e$, $\geq 2\mu$	-	-	-	-	-	$m_{\ell\ell}$	[14]
$\tau\tau$	0, $1e$, 1μ	Yes	-	0, $\geq$1	-	-	$m_{\tau\tau}$	[17]
tt0L	0	-	2J	1, 2	2	-	m_{tt}	[19]
tb0L	0	-	$\geq$(1j+1J)	$\geq$1	1	-	m_{tb}	[20]
tb1L	$1e$, 1μ	Yes	2j, 3j	1, 2	-	-	m_{tb}	[20]
qq	0	-	2j	0	-	-	m_{jj}	[18]
bb	0	-	2j	1, 2	-	-	m_{bb}	[18]

Generally orthogonal

Orthogonality

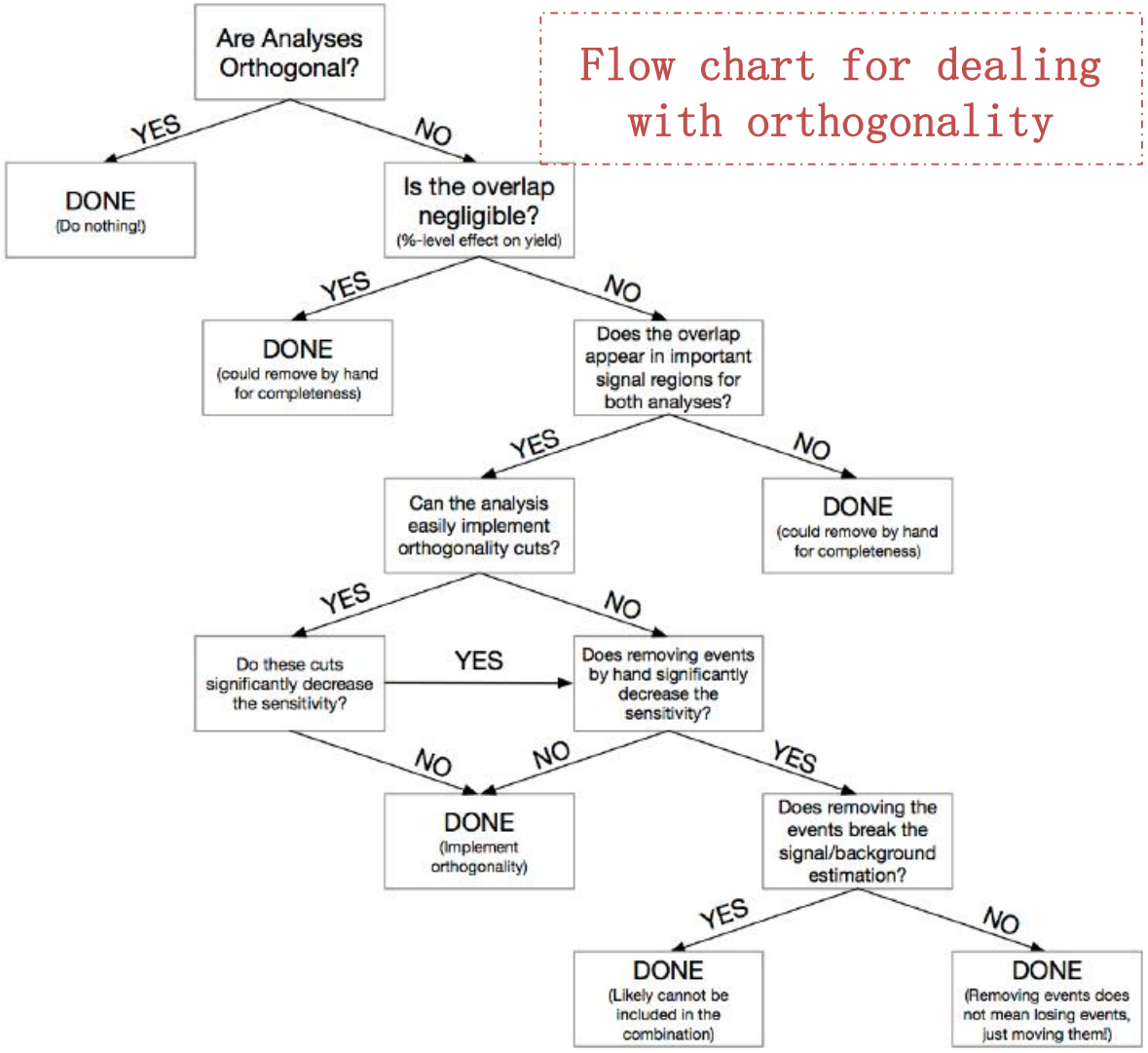


- Use MC sample to check the orthogonality
- The contents of each cell indicate the percentage of MC events common to the analysis selection of each corresponding row and column (y/x).



Final check with data

Orthogonality



Flow chart for dealing with orthogonality

- Minimal additional requirements are applied to achieve orthogonality
- Complementary kinematic cuts are applied
- An analysis priority order is established to preferentially remove
- Only in signal regions

Analysis	Original Selection	Additional Selection
$VH \to \nu\nu bb$	m(jj) or m(J) window	$m(jj) > 100$ GeV
$VH \to \ell\nu bb$	m(jj) or m(J) window	$m(jj) > 106$ GeV
$VH \to \ell\ell bb$	m(jj) or m(J) window	$m(jj) > 100$ GeV
$VH \to qqbb$	$p_T(J)$ dependent	$m(J) > 106$ GeV
tb0L	-	Second W and top-tag veto
tb1L	-	Second W and top-tag veto
qq	-	Remove overlapping events
bb	-	Remove overlapping events

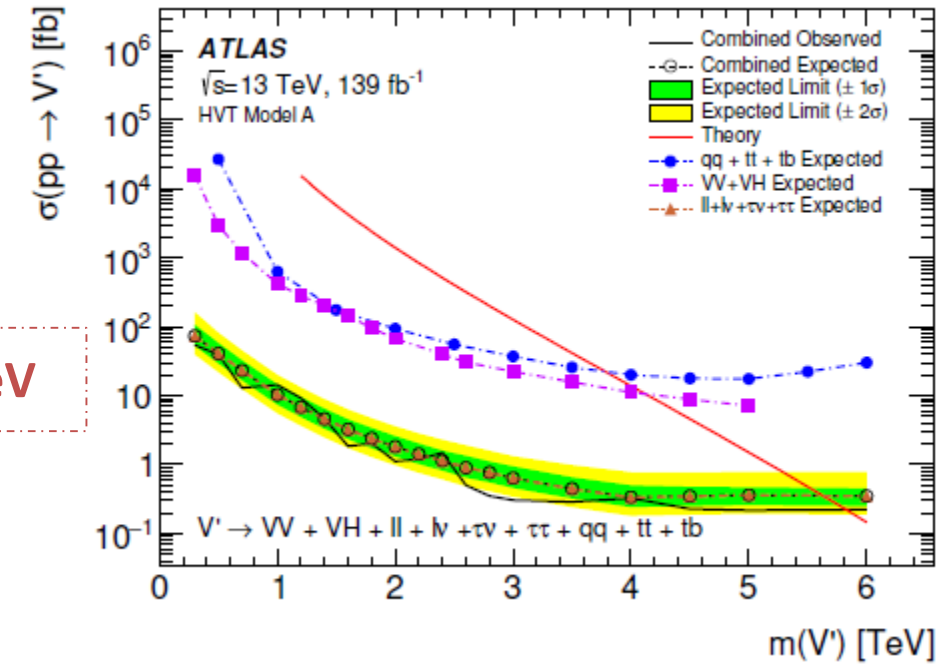
Systematics

- Experimental systematic uncertainties are correlated in different channels if they are exactly same, otherwise treated as uncorrelated
- Theoretical uncertainties are treated correlated or not should depend on the process
- Systematic uncertainties weaken the upper limit on the cross-section by up to20%

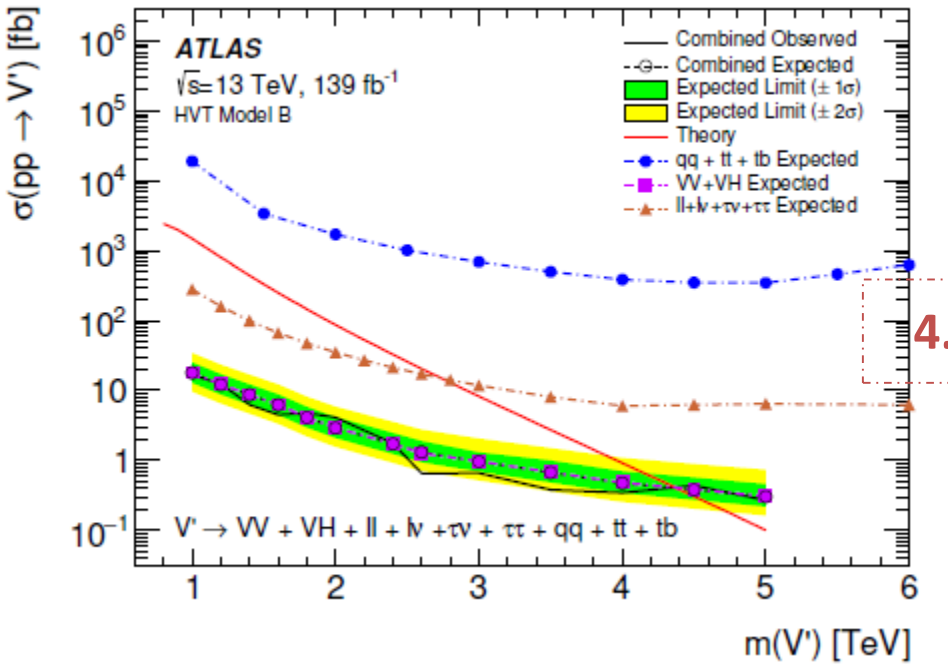
Systematic Source	$WW(\ell\nu\ell\nu)$	$WW(\ell\nu qq)$	$WZ(\ell\ell qq)$	$WZ(\nu\nu qq)$	$WZ(\ell\ell\ell\nu)$	$WH(\ell\nu bb)$	$WH(\nu\nu bb)$	$\ell\nu$	$\tau\nu$	$\tau\tau$	qq	$tt1L$	$tt2L$	$tb0L$	$tb1L$
Small-R jet energy resolution	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B
Small-R jet energy scale	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B
Small-R jet flavor	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B		S+B	S+B	S+B	S+B
Small-R jet pileup	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B			S+B	S+B	S+B	S+B
Small-R jet punch-through	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B			S+B	S+B	S+B	S+B
Small-R jet JVT	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B				S+B	S+B	S+B	S+B

Systematic Source	$WW(\ell\nu\ell\nu)$	$WW(\ell\nu qq)$	$WZ(\ell\ell qq)$	$WZ(\ell\ell\ell\nu)$	$WH(\ell\nu bb)$	$ZH(\ell\ell bb)$	$\ell\ell$	$\ell\nu$	$tt1L$	$tt2L$	$tb1L$
Electron energy resolution	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	
Electron energy scale	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B
Electron identification	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B
Electron reconstruction	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B			
Electron isolation	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B			
Electron trigger	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B			
Muon momentum resolution	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B
Muon momentum scale	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B
Muon reconstruction	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	
Muon isolation	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B			
Muon trigger	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	
Muon Sagitta	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B	S+B

1D Result: Model A&B



5.8 (5.6) TeV



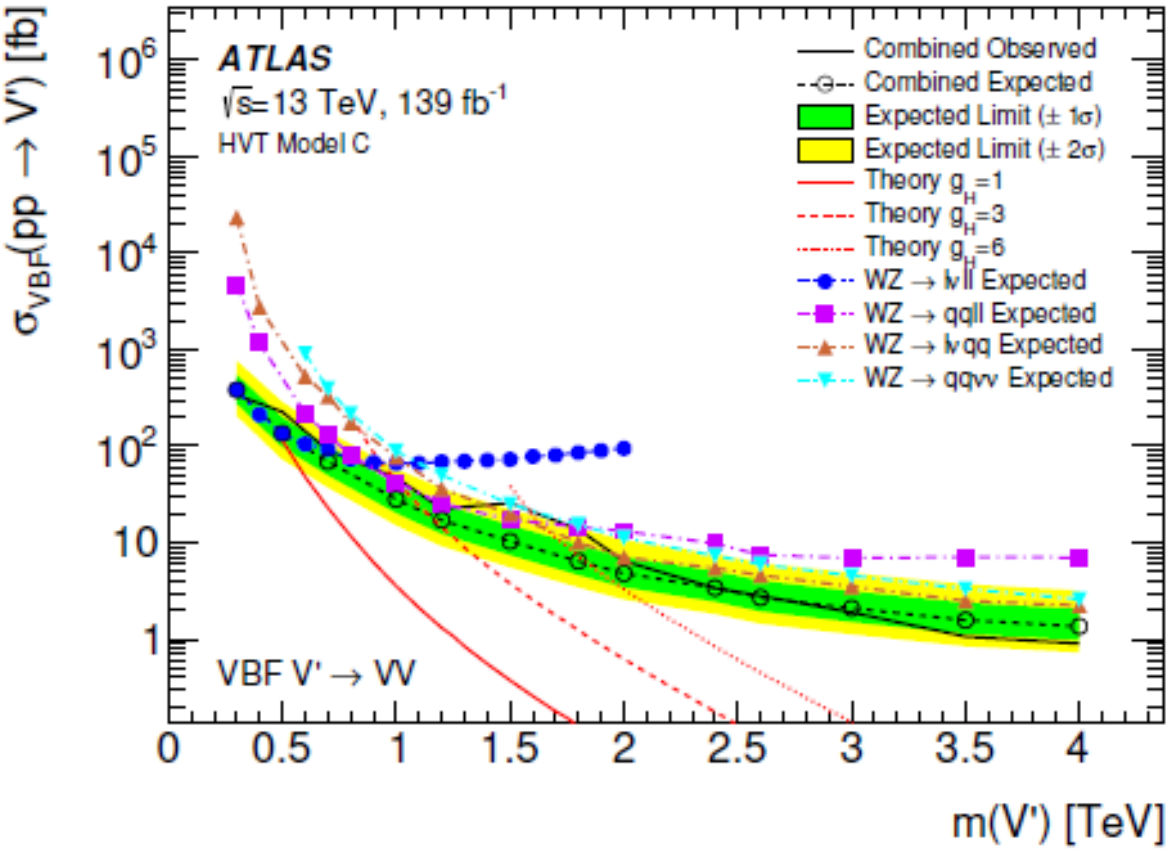
4.4 (4.4) TeV

Channel	HVT model A exclusion limit		HVT model B exclusion limit	
	Observed [TeV]	Expected [TeV]	Observed [TeV]	Expected [TeV]
VV	4.1	4.0	4.3	4.2
VH	3.6	3.5	3.9	3.9
Bosonic	4.3	4.1	4.4	4.4
Leptonic	5.8	5.6	3.2	2.7
Quarkonic	4.1	3.8	-	-
Full combination	5.8	5.6	4.4	4.4

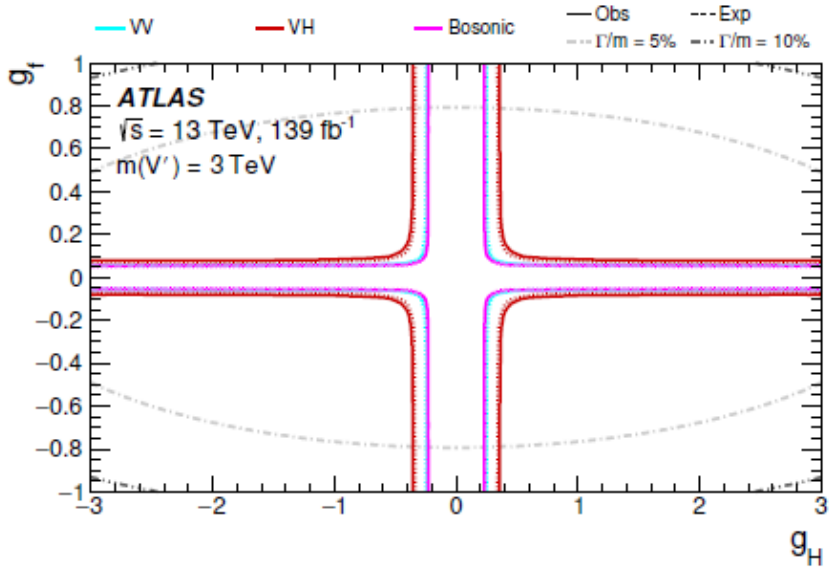
No significant excess is observed

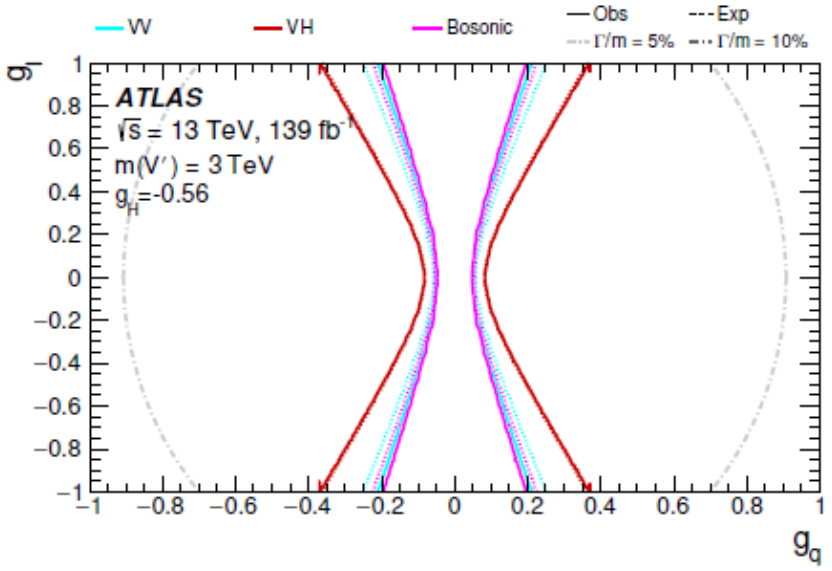
1D Result: VBF

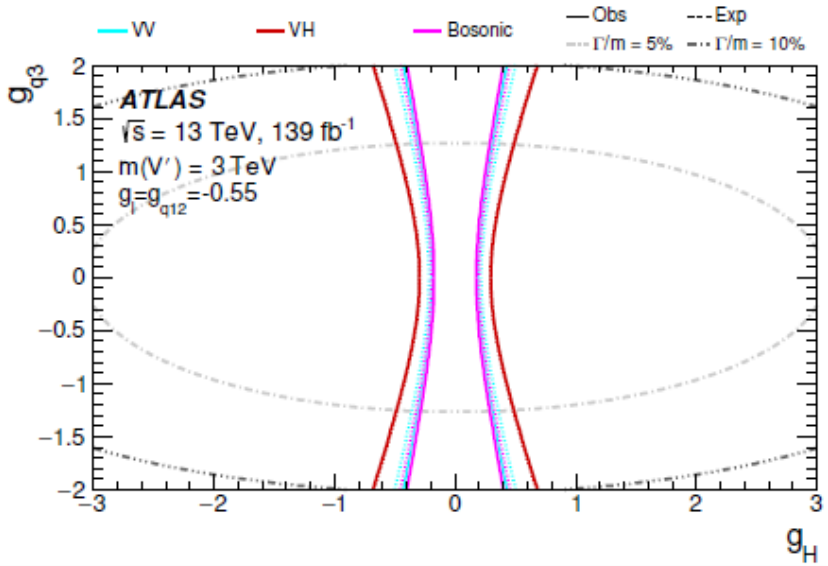
0.4 (0.5) TeV



2D Result: Bosonic subcombination

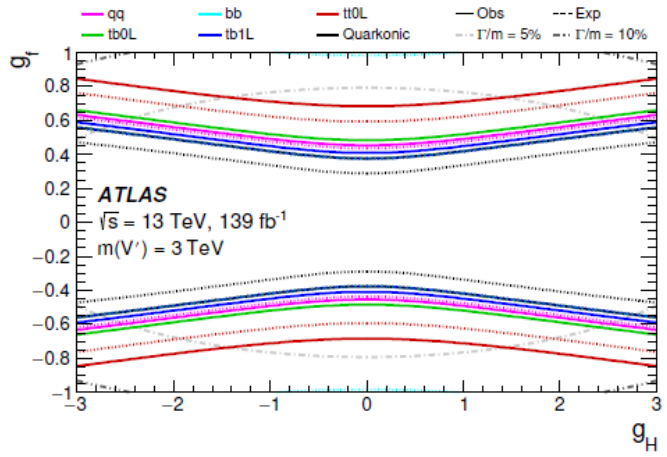


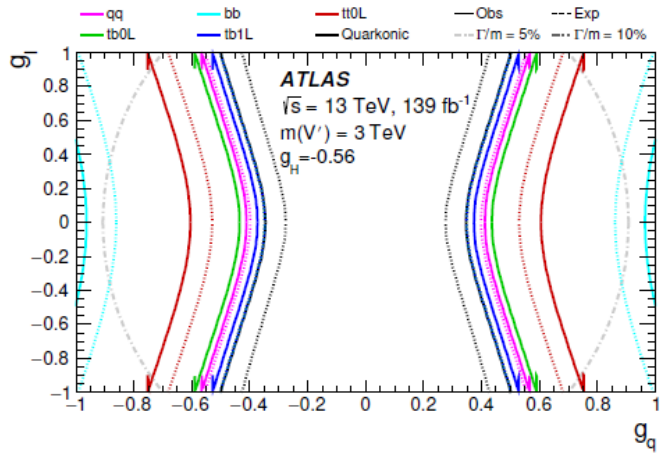


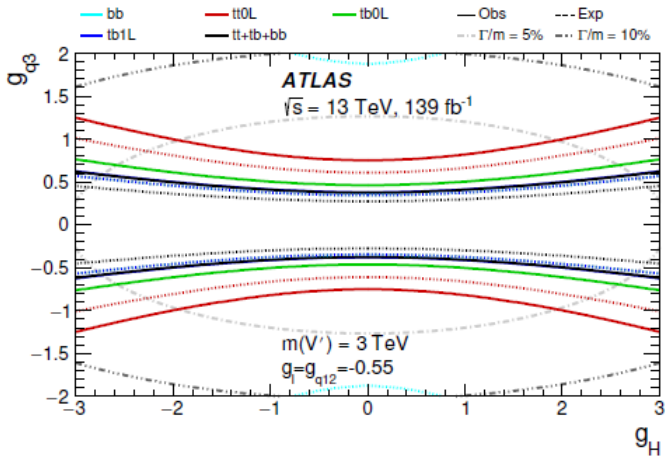


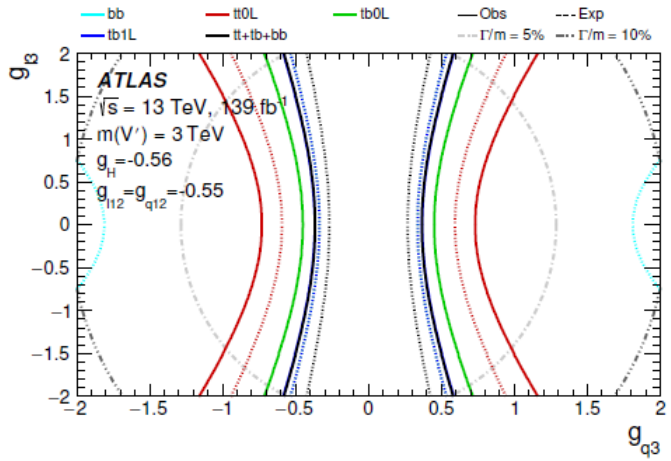
3 TeV

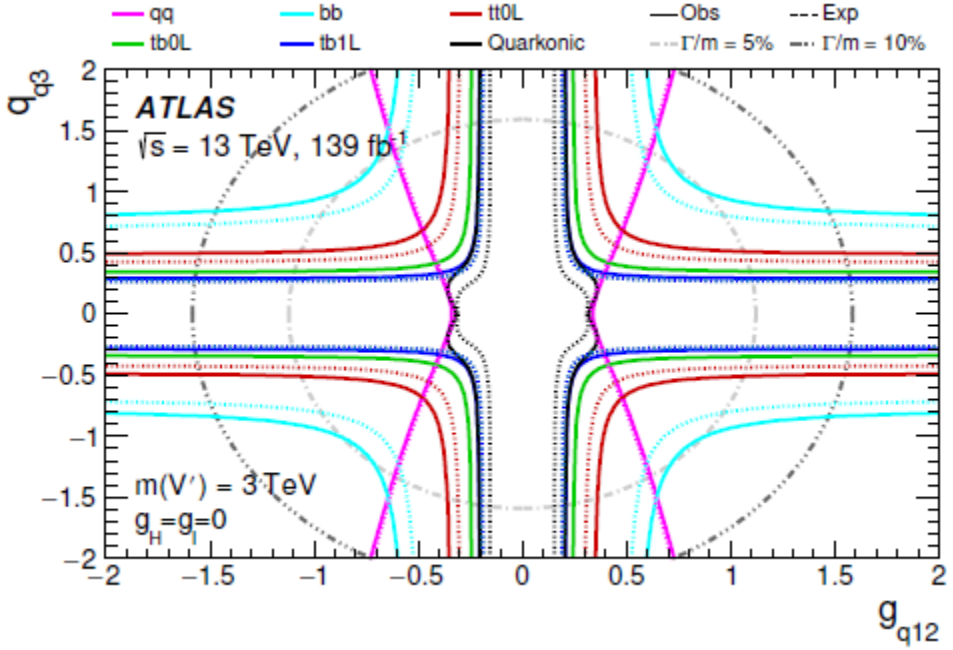
2D Result: Quarkonic subcombination





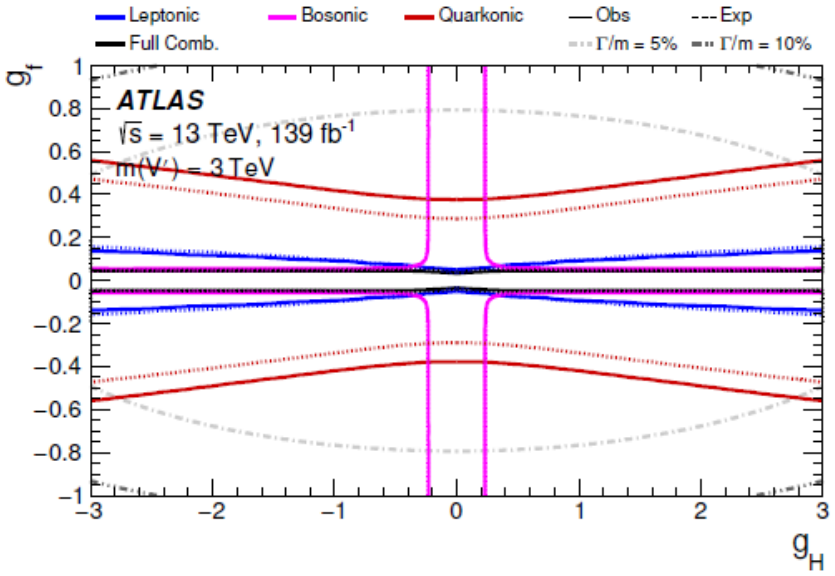


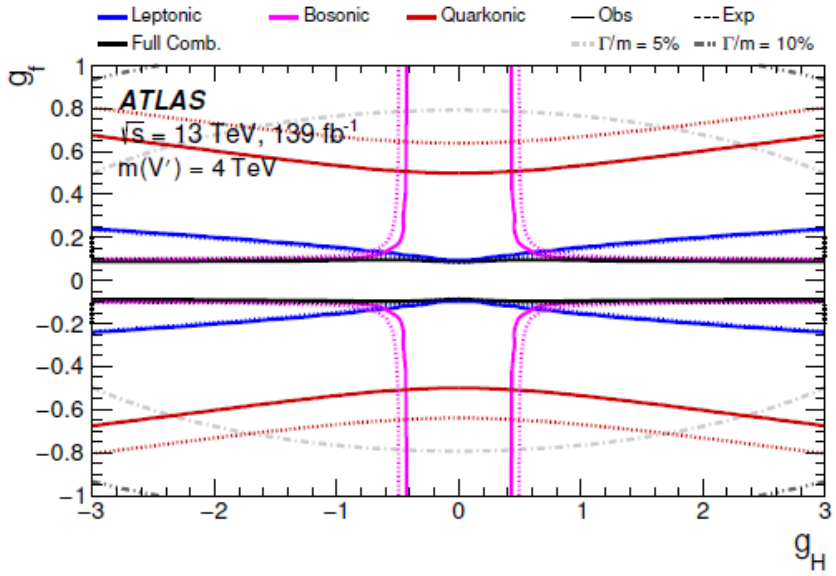


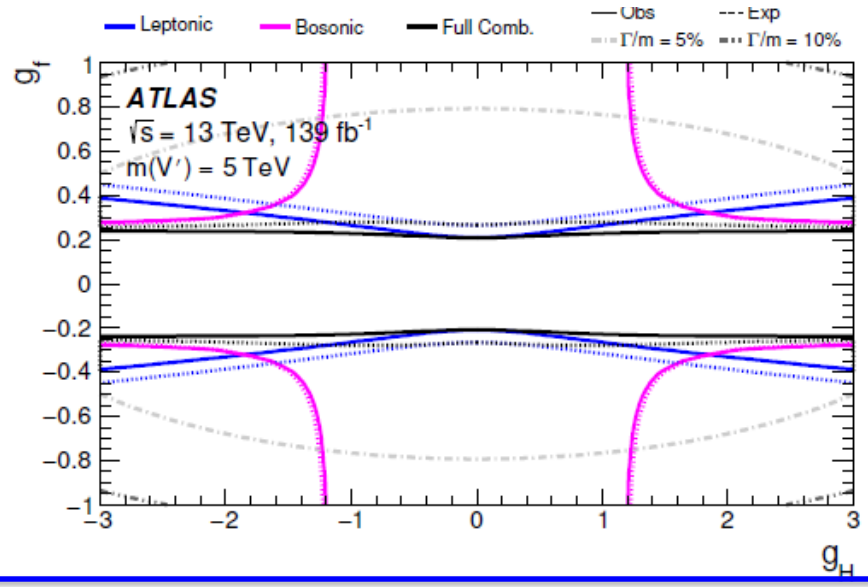


Different channels provide complementary sensitivity

2D Result: Full combination

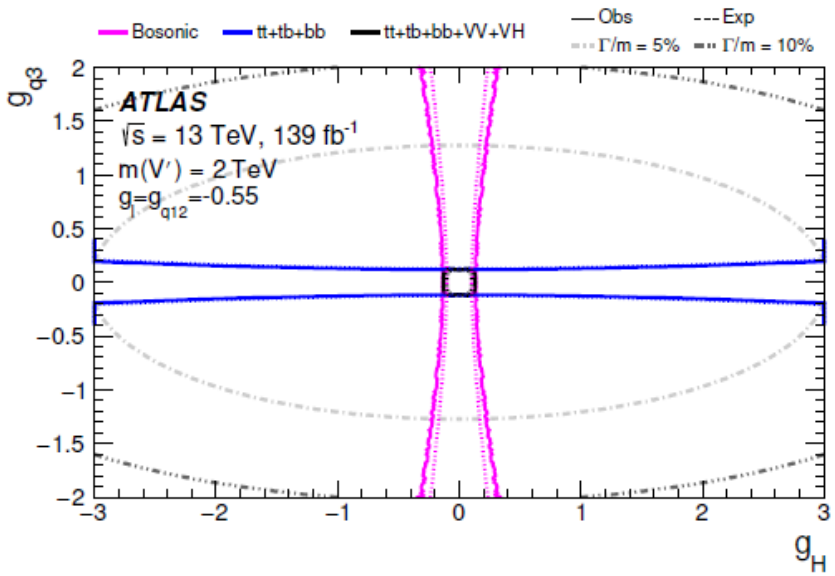


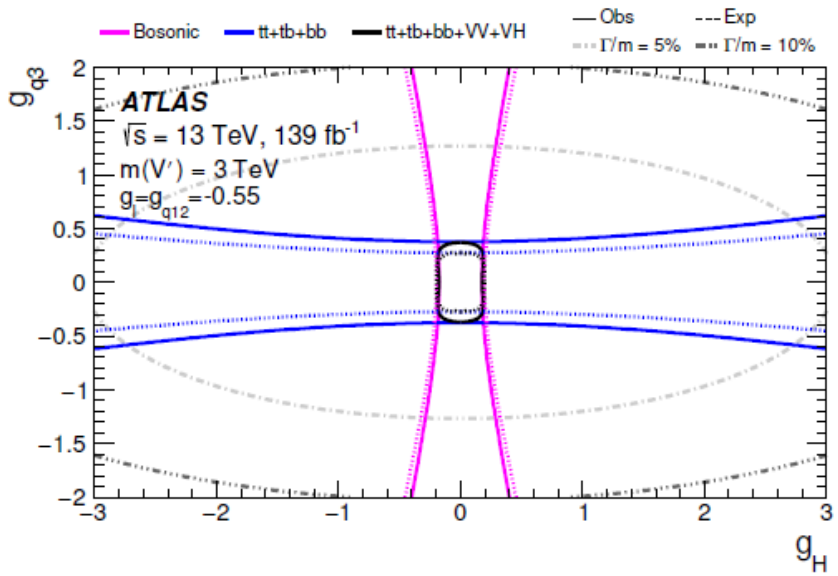


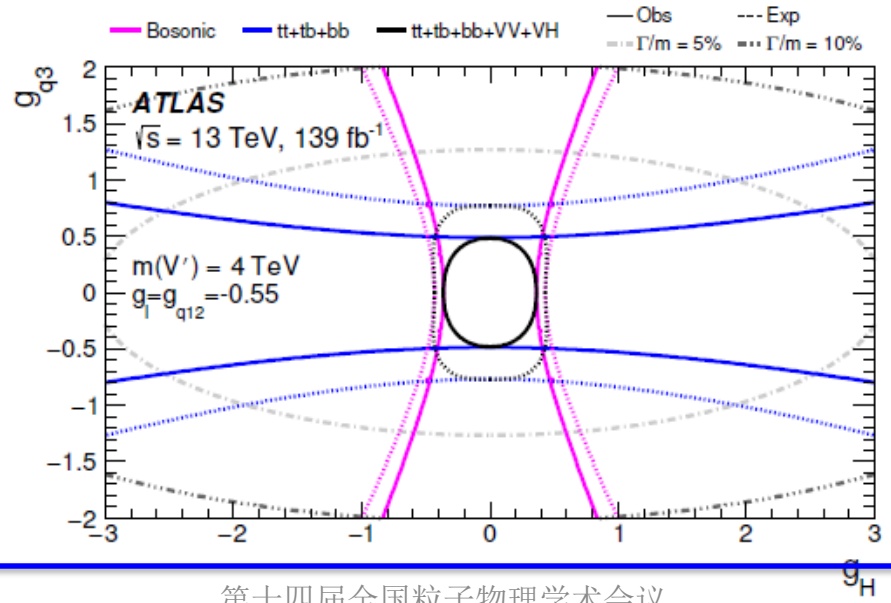


$\{g_H, g_f\}$

2D Result: Full combination

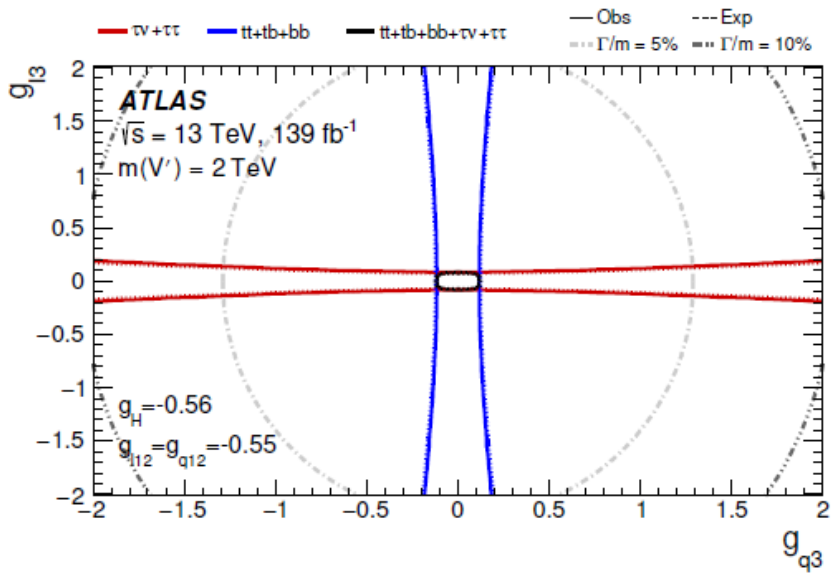


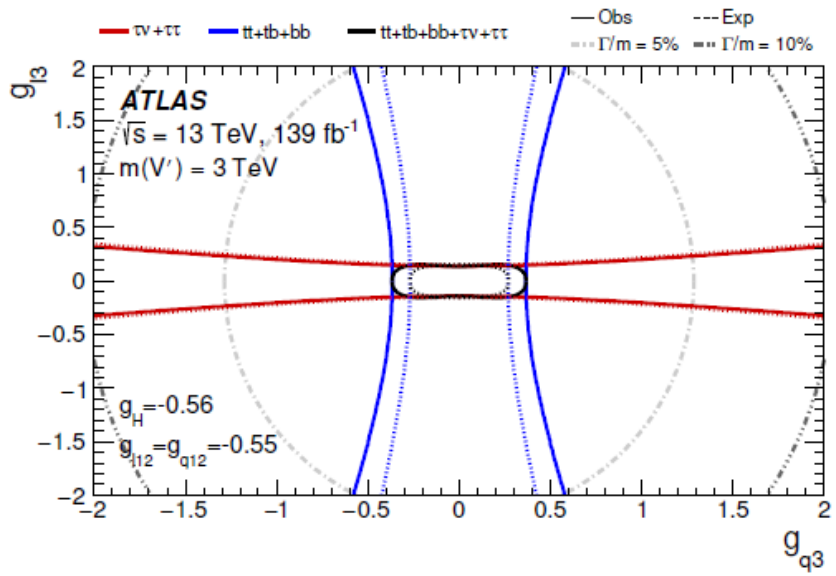


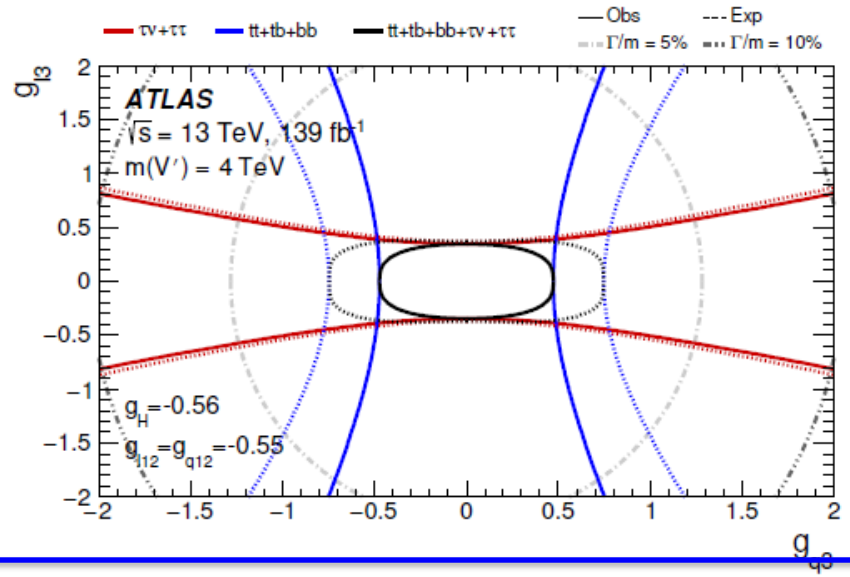


$\{g_H, g_{q3}\}$

2D Result: Full combination







$\{g_{q3}, g_{l3}\}$

Summary

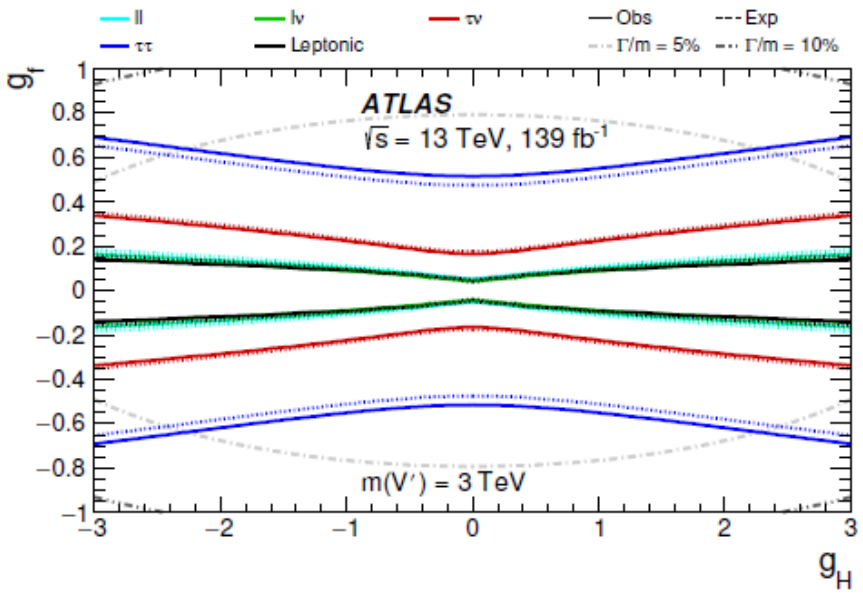
- Combination of searches for heavy spin-1 resonances analysis is done by using ATLAS full Run-II $139fb^{-1}$ data
  - Include 18 final states

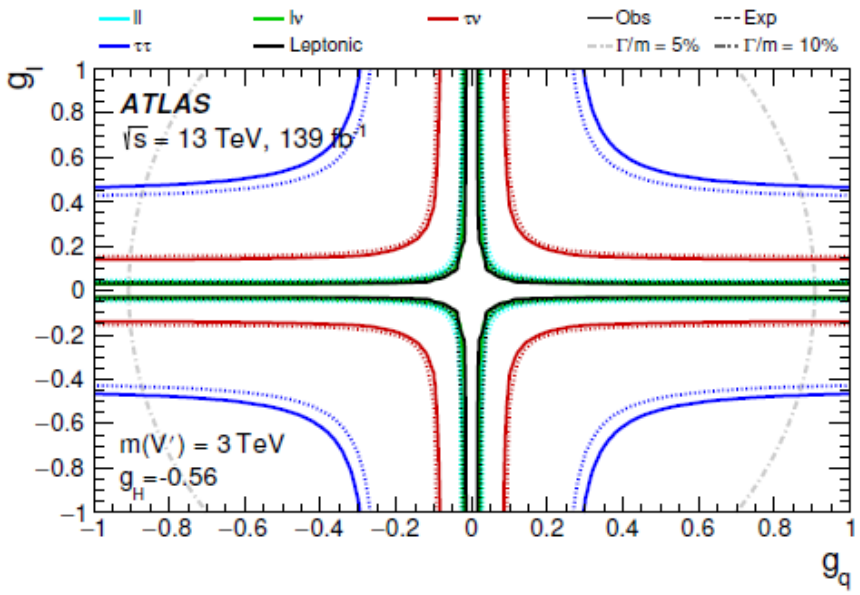
- No significant excess is observed

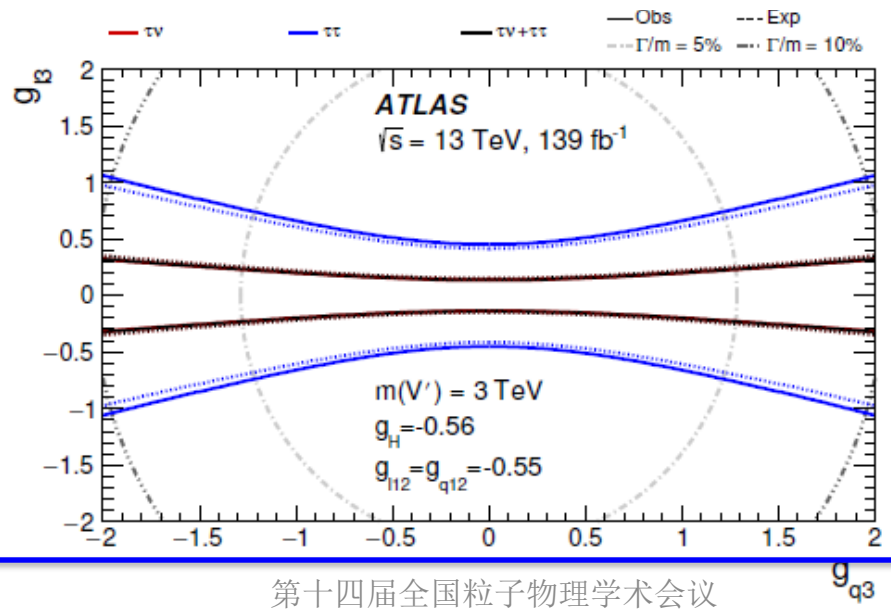
- HVT models are used for interpretation
  - 1D limits: m_V, is excluded up to 5.8 TeV and 4.4 TeV for Model A and B respectively, for Model C, results for several g_H choices are shown
  - 2D limits: multiple 2D planes explored

Backup

2D Result: Leptonic subcombination

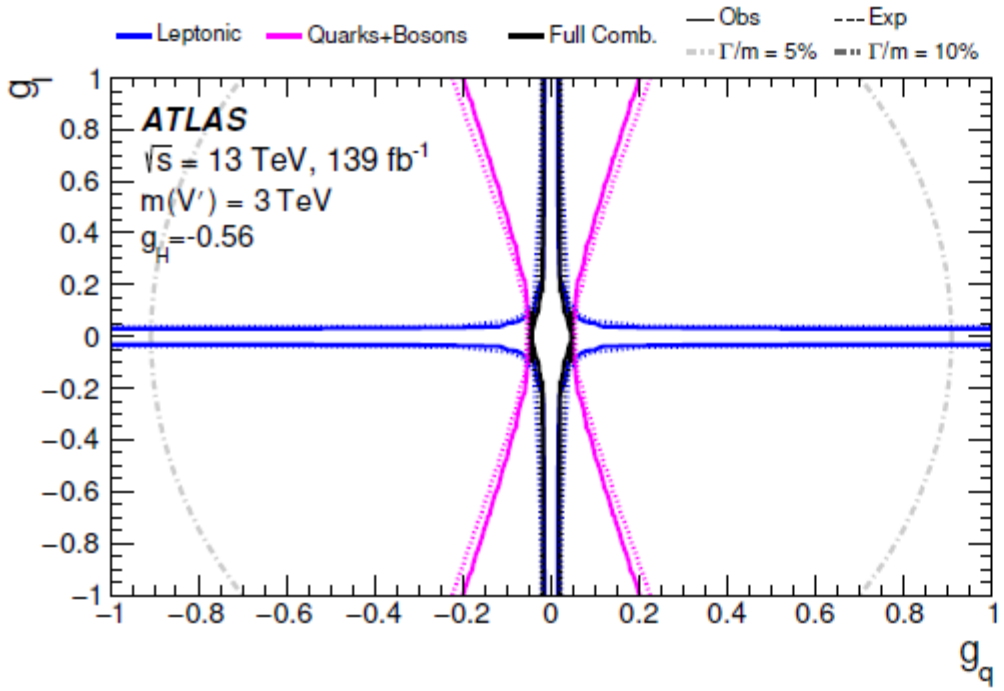


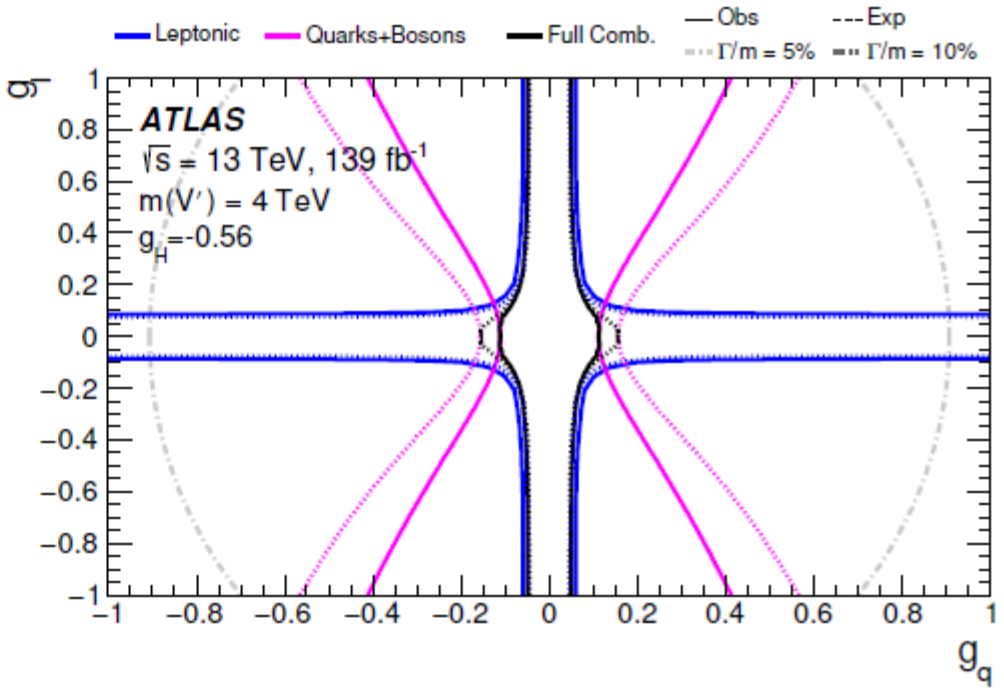




3 TeV

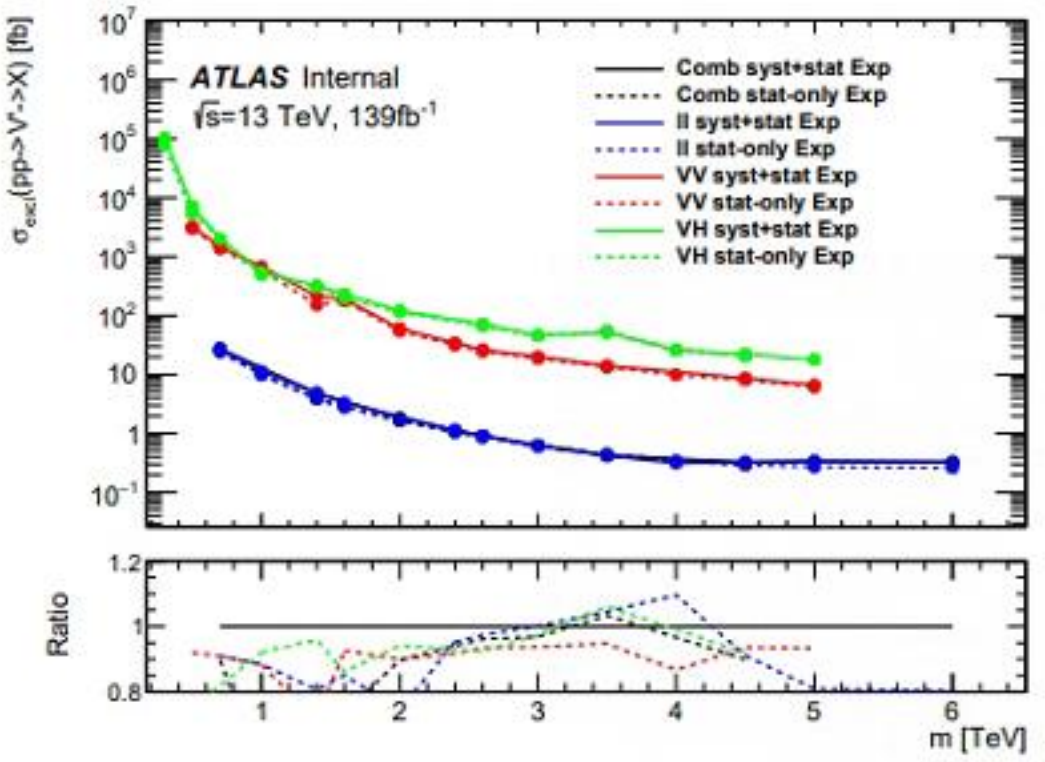
2D Result: Full combination

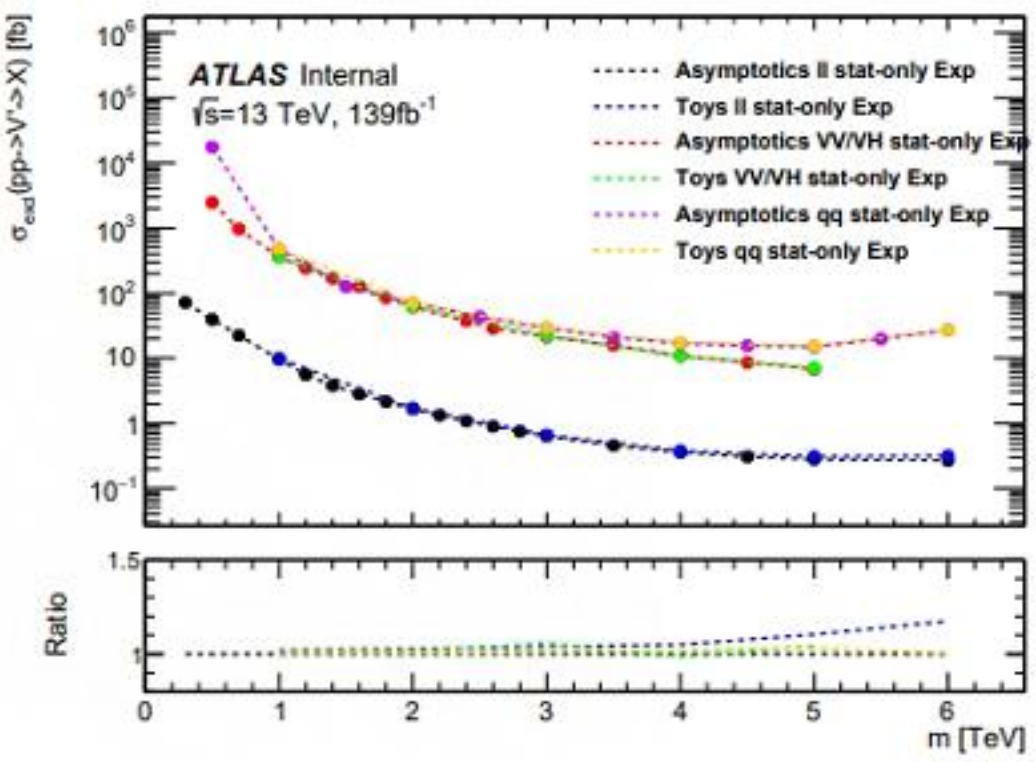




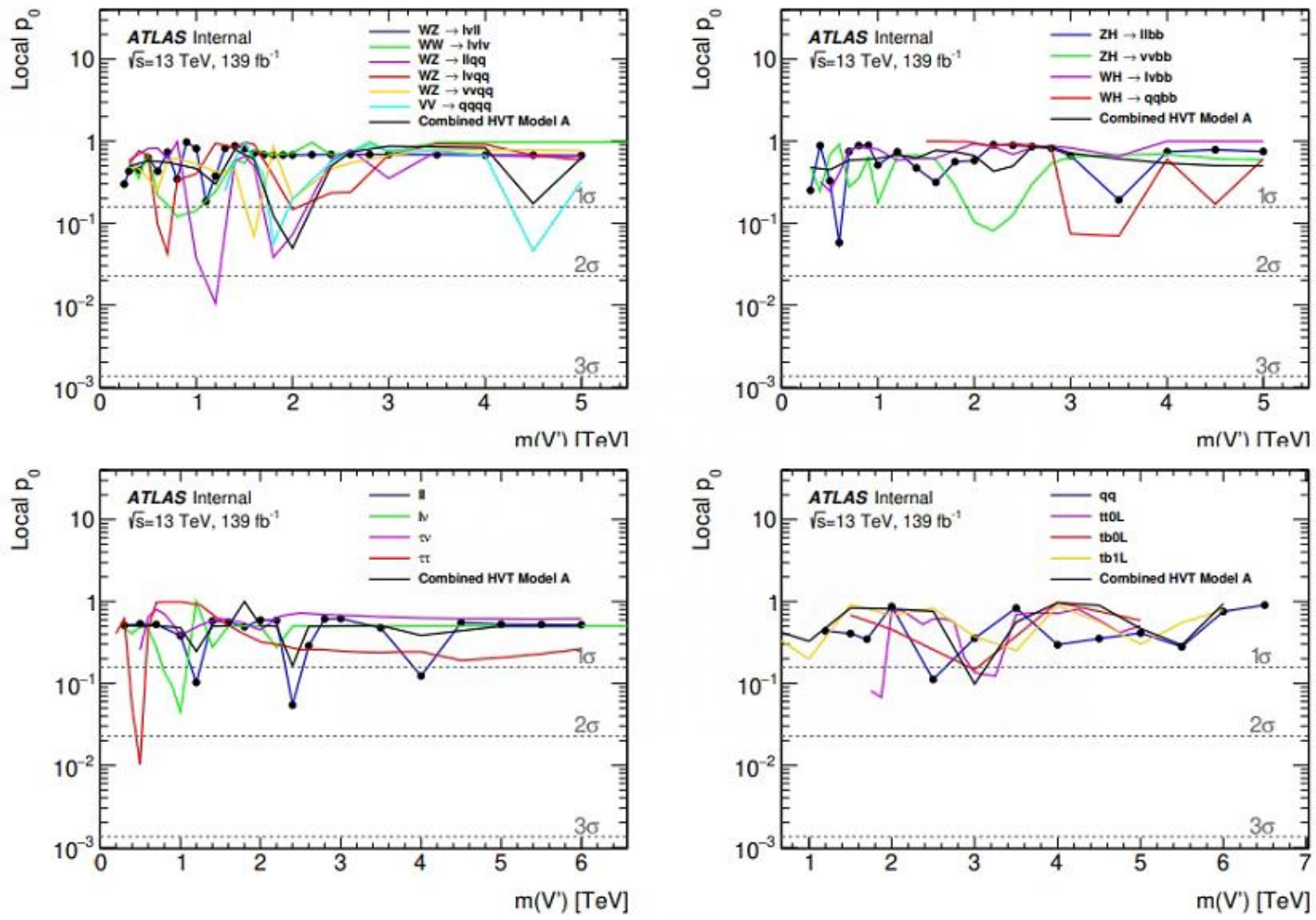
$\{g_q, g_l\}$

Toy


ATLAS Internal
√s=13 TeV, 139fb-1
Comb syst+stat Exp
Comb stat-only Exp
ll syst+stat Exp
ll stat-only Exp
VV syst+stat Exp
VV stat-only Exp
VH syst+stat Exp
VH stat-only Exp
σexcl(pp->V'->X) [fb]
Ratio
m [TeV]


ATLAS Internal
√s=13 TeV, 139fb-1
Asymptotics ll stat-only Exp
Toys ll stat-only Exp
Asymptotics VV/VH stat-only Exp
Toys VV/VH stat-only Exp
Asymptotics qq stat-only Exp
Toys qq stat-only Exp
σexcl(pp->V'->X) [fb]
Ratio
m [TeV]

P-value


ATLAS Internal
√s=13 TeV, 139 fb-1
WZ → lνll
WW → lνlν
WZ → llqq
WZ → lνqq
WZ → ννqq
VV → qqqq
Combined HVT Model A
ZH → llbb
ZH → ννbb
WH → lνbb
WH → qqbb
ll
lν
νν
ττ
qq
tt0L
tb0L
tb1L
Local p0
m(V') [TeV]
1σ
2σ
3σ