

Overview of ATLAS Exotics Group Analyses and Interpretive Models

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Overview

- Overview of ATLAS Exotics group structure & analyses
 - Group organization aligned by signature-based search strategies
- Organization of generic interpretations
 - Spanning signature-based efforts
- Summary of interpretive paradigms and results
 - Heavy Gauge Bosons
 - Extra Dimensions
 - Heavy Quarks
 - Excited Fermions
 - Contact Interactions
 - And more

ATLAS Exotics Results

ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2016

ATLAS Preliminary

$\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$

$\sqrt{s} = 8, 13 \text{ TeV}$

Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	$\geq 1j$	Yes	3.2	M_D 6.86 TeV	$n = 2$ Preliminary	
	ADD non-resonant $\ell\ell$	$2e, \mu$	-	20.3	M_S 4.7 TeV	$n = 3 \text{ HLZ}$ 1407.2410	
	ADD QBH $\rightarrow \ell q$	$1e, \mu$	$1j$	-	20.3	M_{th} 5.2 TeV	1311.2006
	ADD QBH	-	$2j$	-	3.6	M_{th} 8.3 TeV	$n = 6$ 1512.01530
	ADD BH high $\sum p_T$	$\geq 1e, \mu$	$\geq 2j$	-	3.2	M_{th} 8.2 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$ ATLAS-CONF-2016-006
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_{th} 9.55 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$ 1512.02586
	RS1 $G_{KK} \rightarrow \ell\ell$	$2e, \mu$	-	-	20.3	$G_{KK} \text{ mass}$ 2.68 TeV	$k/\overline{M}_{pl} = 0.1$ 1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	20.3	$G_{KK} \text{ mass}$ 2.66 TeV	$k/\overline{M}_{pl} = 0.1$ 1504.05511
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1e, \mu$	$1J$	Yes	3.2	$G_{KK} \text{ mass}$ 1.06 TeV	$k/\overline{M}_{pl} = 1.0$ ATLAS-CONF-2015-075
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	-	$4b$	-	3.2	$G_{KK} \text{ mass}$ 475-785 GeV	$k/\overline{M}_{pl} = 1.0$ ATLAS-CONF-2016-017
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	2UED / RPP	$1e, \mu$	$\geq 2b, \geq 4j$	Yes	3.2	$KK \text{ mass}$ 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \rightarrow tt$) = 1 ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2e, \mu$	-	-	3.2	$Z' \text{ mass}$ 3.4 TeV	ATLAS-CONF-2015-070
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	19.5	$Z' \text{ mass}$ 2.02 TeV	1502.07177
	Leptophobic $Z' \rightarrow bb$	-	$2b$	-	3.2	$Z' \text{ mass}$ 1.5 TeV	Preliminary
	SSM $W' \rightarrow \ell\nu$	$1e, \mu$	-	Yes	3.2	$W' \text{ mass}$ 4.07 TeV	ATLAS-CONF-2015-063
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A	$0e, \mu$	$1J$	Yes	3.2	$W' \text{ mass}$ 1.6 TeV	$g_V = 1$ ATLAS-CONF-2015-068
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A	-	$2J$	-	3.2	$W' \text{ mass}$ 1.38-1.6 TeV	$g_V = 1$ ATLAS-CONF-2015-073
	HVT $W' \rightarrow WH \rightarrow \ell\nu bb$ model B	$1e, \mu$	$1-2b, 1-0j$	Yes	3.2	$W' \text{ mass}$ 1.62 TeV	$g_V = 3$ ATLAS-CONF-2015-074
	HVT $Z' \rightarrow ZH \rightarrow \nu\nu bb$ model B	$0e, \mu$	$1-2b, 1-0j$	Yes	3.2	$Z' \text{ mass}$ 1.76 TeV	$g_V = 3$ ATLAS-CONF-2015-074
	LRSM $W'_R \rightarrow tb$	$1e, \mu$	$2b, 0-1j$	Yes	20.3	$W' \text{ mass}$ 1.92 TeV	1410.4103
	LRSM $W'_R \rightarrow tb$	$0e, \mu$	$\geq 1b, 1J$	-	20.3	$W' \text{ mass}$ 1.76 TeV	1408.0886
CI	CI $qqqq$	-	$2j$	-	3.6	Λ 17.5 TeV	$\eta_{LL} = -1$ 1512.01530
	CI $qq\ell\ell$	$2e, \mu$	-	-	3.2	Λ 23.1 TeV	$\eta_{LL} = -1$ ATLAS-CONF-2015-070
	CI $uutt$	$2e, \mu$ (SS)	$\geq 1b, 1-4j$	Yes	20.3	Λ 4.3 TeV	$ C_{LL} = 1$ 1504.04605
DM	Axial-vector mediator (Dirac DM)	$0e, \mu$	$\geq 1j$	Yes	3.2	m_A 1.0 TeV	$g_q = 0.25, g_\nu = 1.0, m(\chi) < 140 \text{ GeV}$ Preliminary
	Axial-vector mediator (Dirac DM)	$0e, \mu, 1\gamma$	$1j$	Yes	3.2	m_A 650 GeV	$g_q = 0.25, g_\nu = 1.0, m(\chi) < 10 \text{ GeV}$ Preliminary
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LQ	Scalar LQ 1 st gen	$2e$	$\geq 2j$	-	3.2	LQ mass 1.07 TeV	$\beta = 1$ Preliminary
	Scalar LQ 2 nd gen	2μ	$\geq 2j$	-	3.2	LQ mass 1.03 TeV	$\beta = 1$ Preliminary
	Scalar LQ 3 rd gen	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	LQ mass 640 GeV	$\beta = 0$ 1508.04735
Heavy quarks	VLQ $TT \rightarrow Ht + X$	$1e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	T mass 855 GeV	T in (T,B) doublet 1505.04306
	VLQ $YY \rightarrow Wb + X$	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet 1505.04306
	VLQ $BB \rightarrow Hb + X$	$1e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	B mass 735 GeV	isospin singlet 1505.04306
	VLQ $BB \rightarrow Zb + X$	$2/3e, \mu$	$\geq 2/1b$	-	20.3	B mass 755 GeV	B in (B,Y) doublet 1409.5500
	VLQ $QQ \rightarrow WqWq$	$1e, \mu$	$\geq 4j$	Yes	20.3	Q mass 690 GeV	1509.04261
	$T_{5/3} \rightarrow Wt$	$1e, \mu$	$\geq 1b, \geq 5j$	Yes	20.3	$T_{5/3} \text{ mass}$ 840 GeV	1503.05425
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1γ	$1j$	-	3.2	$q^* \text{ mass}$ 4.4 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1512.05910
	Excited quark $q^* \rightarrow qg$	-	$2j$	-	3.6	$q^* \text{ mass}$ 5.2 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1512.01530
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	Excited quark $b^* \rightarrow Wt$	1 or $2e, \mu$	$1b, 2-0j$	Yes	20.3	$b^* \text{ mass}$ 1.5 TeV	$f_L = f_t = f_R = 1$ 1510.02664
	Excited lepton ℓ^*	$3e, \mu$	-	-	20.3	$\ell^* \text{ mass}$ 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$ 1411.2921
	Excited lepton ν^*	$3e, \mu, \tau$	-	-	20.3	$\nu^* \text{ mass}$ 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921
Other	LSTC $a_T \rightarrow W\gamma$	$1e, \mu, 1\gamma$	-	Yes	20.3	$a_T \text{ mass}$ 960 GeV	1407.8150
	LRSM Majorana ν	$2e, \mu$	$2j$	-	20.3	$N^0 \text{ mass}$ 2.0 TeV	$m(W_R) = 2.4 \text{ TeV, no mixing}$ 1506.06020
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	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3e, \mu, \tau$	-	-	20.3	$H^{\pm\pm} \text{ mass}$ 400 GeV	DY production, BR($H^{\pm\pm} \rightarrow \ell\tau$)=1 1411.2921
	Monotop (non-res prod)	$1e, \mu$	$1b$	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$ 1410.5404
	Multi-charged particles	-	-	-	20.3	multi-charged particle mass 785 GeV	DY production, $ q = 5e$ 1504.04188
	Magnetic monopoles	-	-	-	7.0	monopole mass 1.34 TeV	DY production, $ g = 1g_D, \text{spin } 1/2$ 1509.08059

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Example: Heavy Gauge Bosons

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10^{-1}

1

10

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Extra Dimension Interpretations

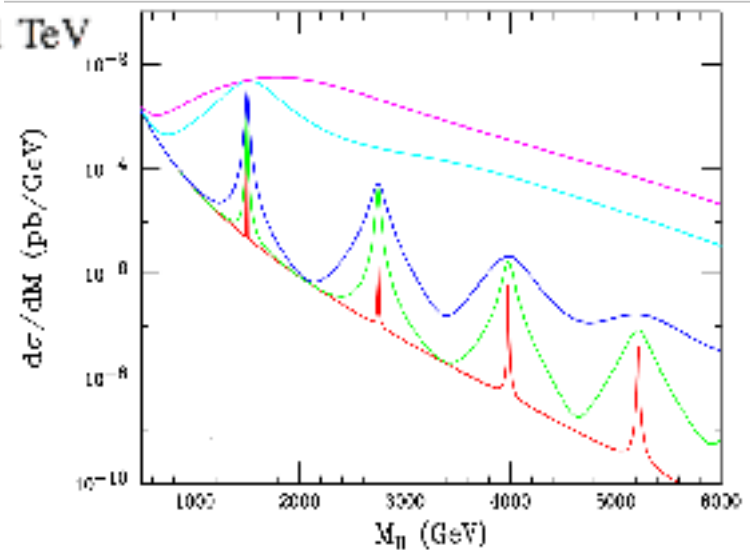
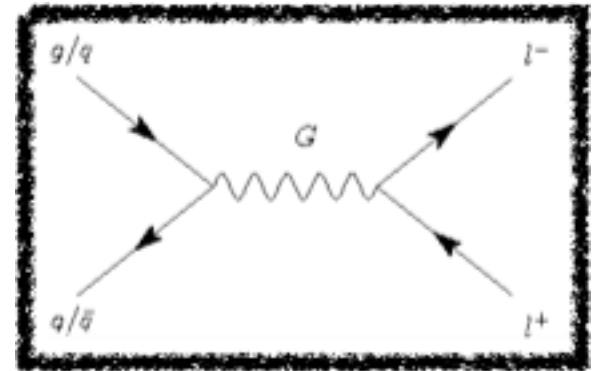
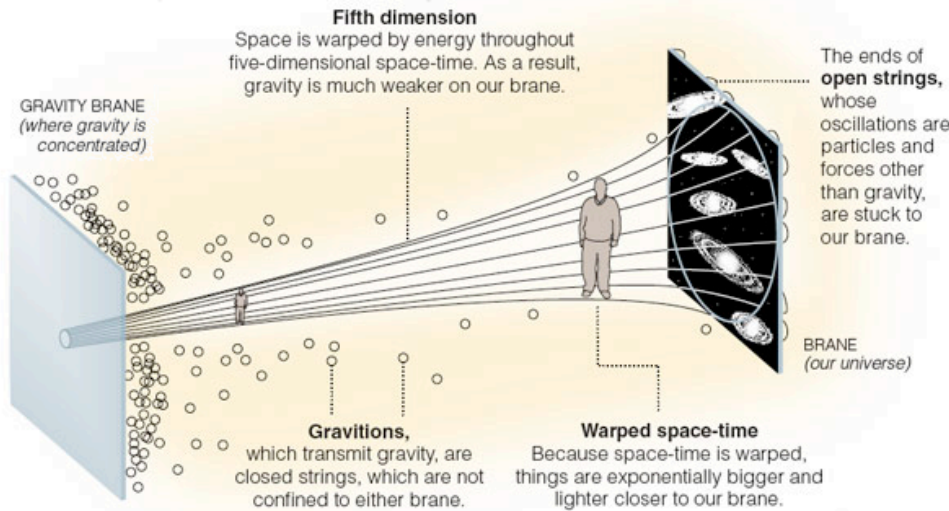
Extra Dimension Interpretations

- Extra Dimensions (ED) are proposed in many BSM theories to help explain the apparent weakness of Gravity, invoking a **Spin-2 Tensor Boson (G^*)**.
- Two models broadly used in ATLAS searches are **Randall-Sundrum (RS1 & RS2)**, and **Arkani, Dimopoulos, Dvali (ADD)**:

RS Graviton

- **Warped ED** allow access to physics at the Planck Scale from the TeV Scale.
- Search for resonances, where the width and cross-section depends on the **warping factor, k** .

$$\mathcal{L} = - \left(\frac{G_0^{\mu\nu}}{\bar{M}_{Pl}} + \sum_{n>0} \frac{G_n^{\mu\nu}}{\Lambda_\pi} \right) T_{\mu\nu}, \text{ where } \Lambda_\pi = \bar{M}_{Pl} e^{-\pi k R} \sim 1 \text{ TeV}$$



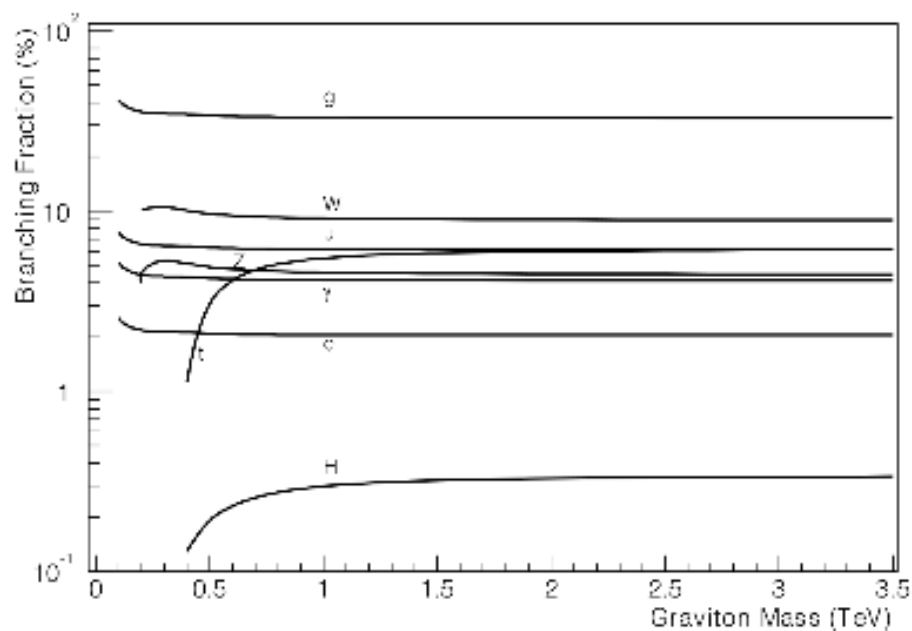
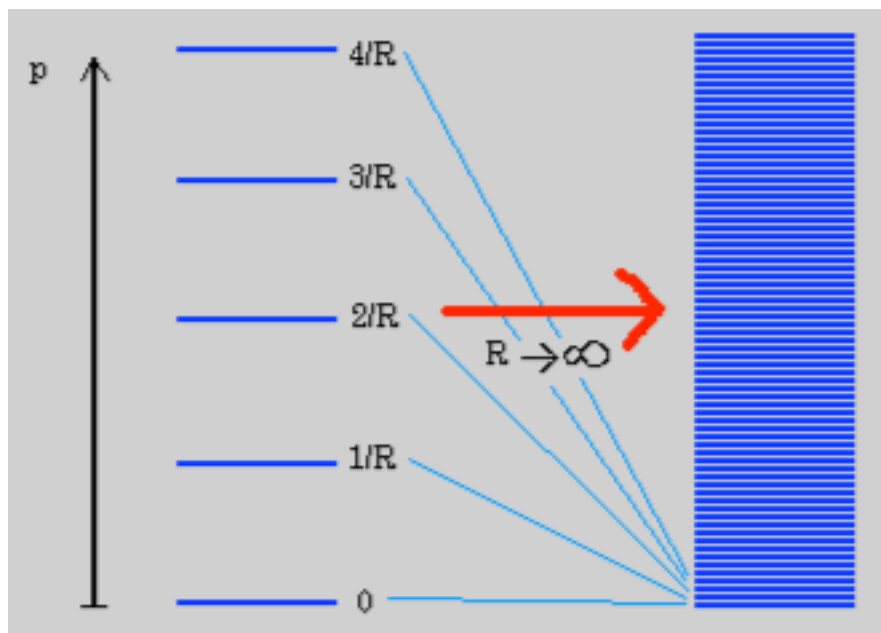
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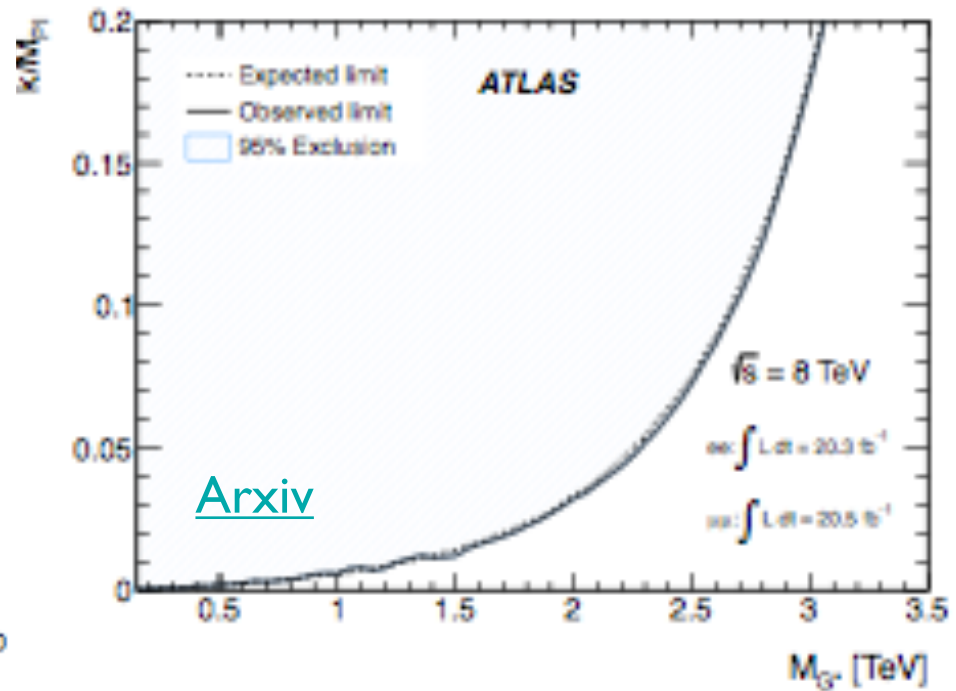
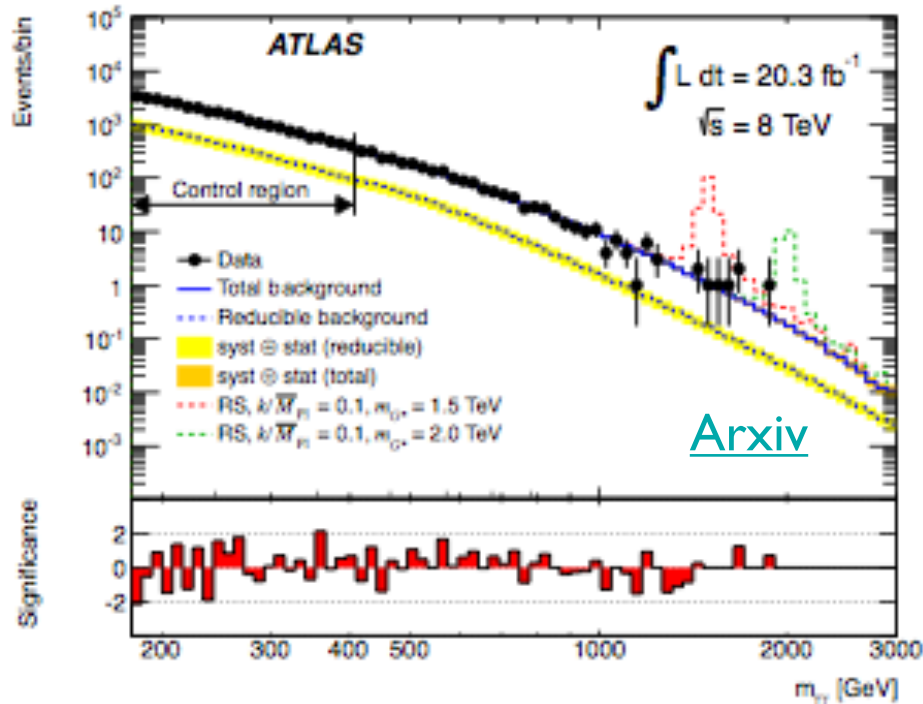
ADD Graviton

- If the ED were **large ($> \mu\text{m}$) and flat**, the spacing between the Kaluza-Klein towers is reduced, and eventually the resonances become a **non-resonant excess**.



Extra Dimension Interpretations

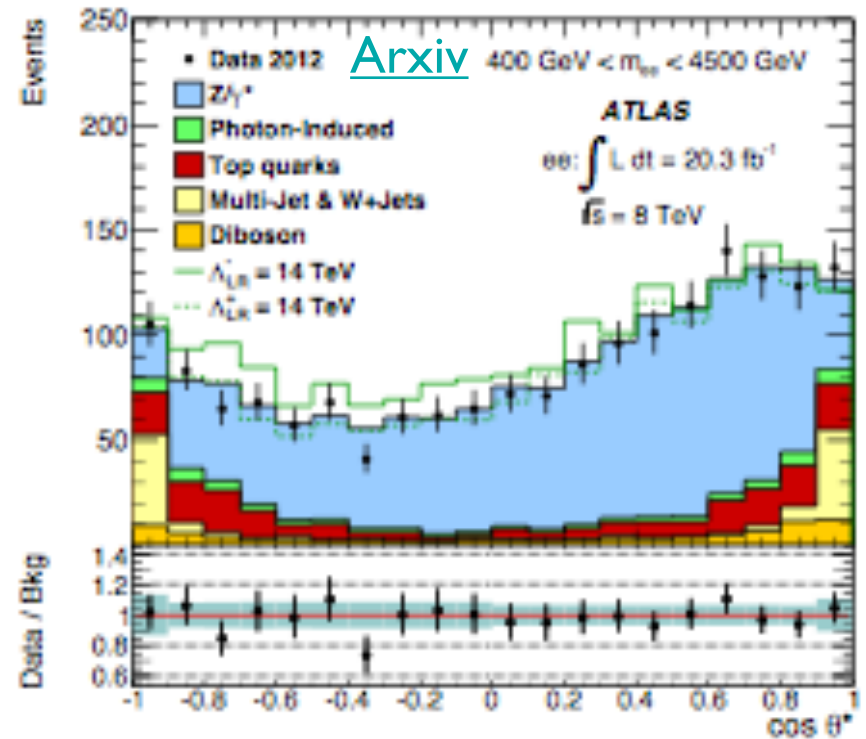
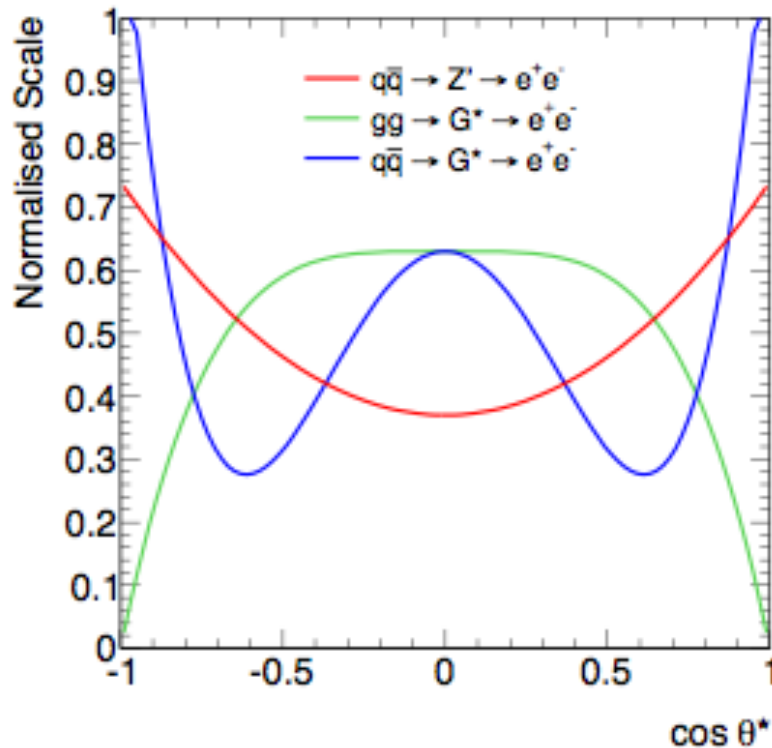
- These models are searches for in many channels at ATLAS, such as:
 - Dilepton: 7, 8 TeV, planned again for 13 TeV. RS1 and ADD Models.
 - Diphoton: 7, 8, and 13 TeV (combined with dilepton at 8 TeV!).
 - Dibosons [WW, ZZ]: 7, 8, and 13 TeV. RS2 model (SM fields in Bulk).
- Clean signatures with relatively small, well understood backgrounds.



Extra Dimension Interpretations

- What handles do we have to probe new physics?
- What do analyses provide to help theorists (and others) interpret the results?

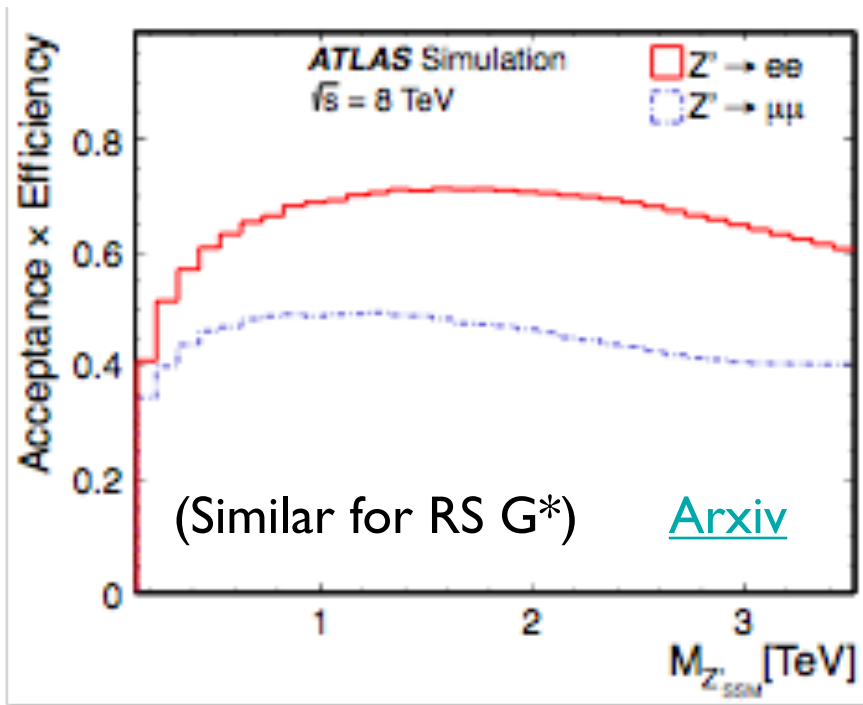
Angular Distributions



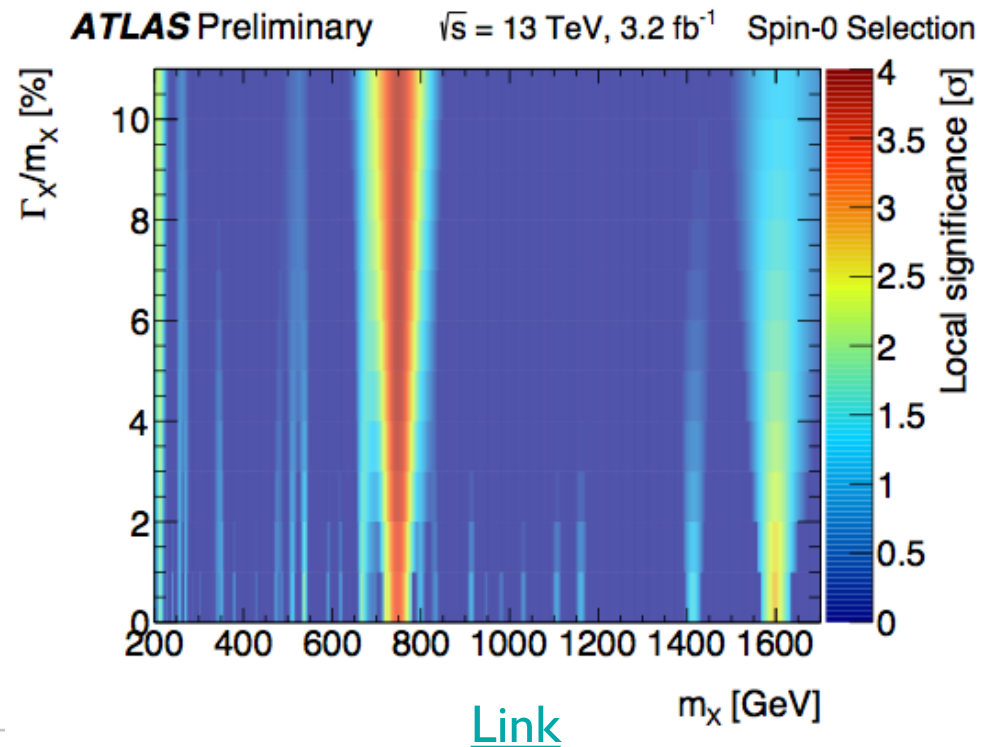
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Acceptance x Efficiency



Width Scans



Heavy Gauge Boson Interpretations

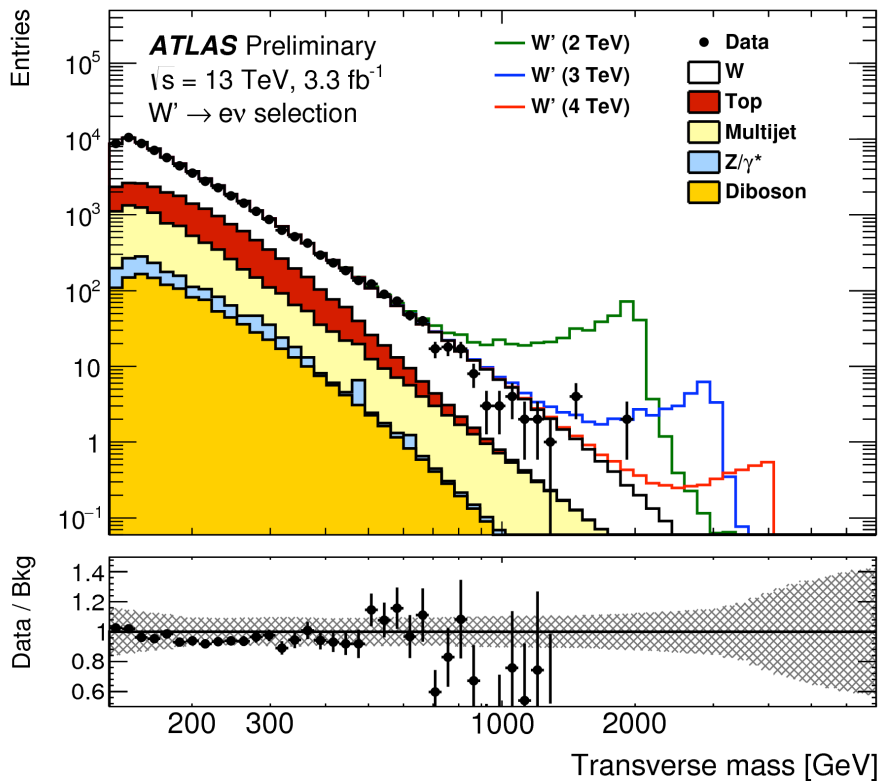
Heavy Gauge Boson Interpretations

- Several BSM models predict heavy gauge bosons:
 - Extended Gauge Models (EGM)
 - Technicolour
 - Composite Higgs models
 - Little Higgs
 - Theories with universal extra dimensions (e.g. Kaluza-Klein)
 - Sequential Standard Model (SSM)
 - Randall-Sundrum (RS) Graviton model
 - Heavy Vector Triplet (HVT).

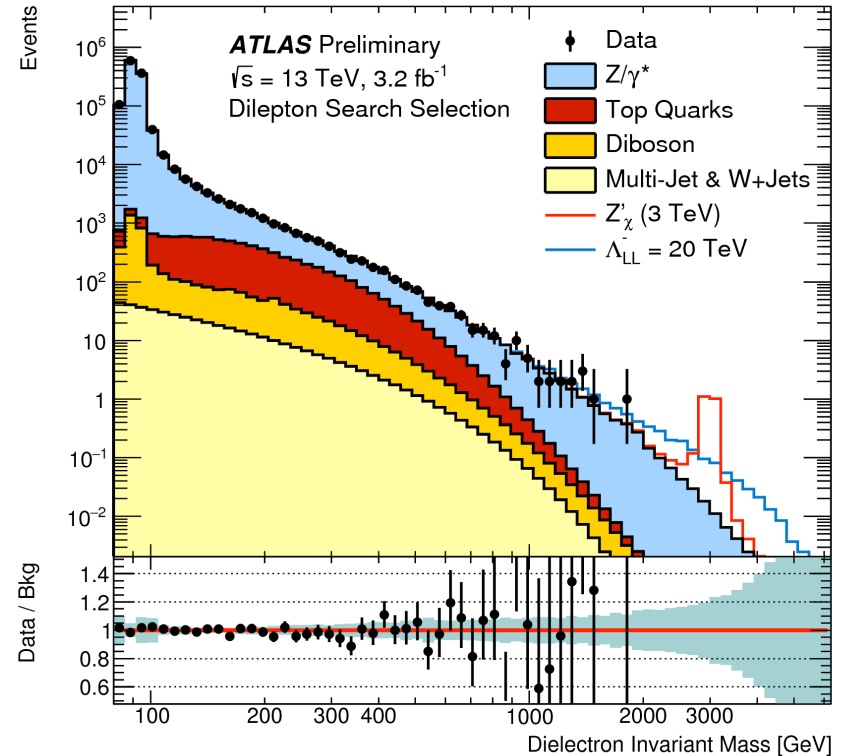
W' and Z' to leptons

- Relatively “clean” background
- Benchmark model : W' (SSM), Z' (SSM and E₆).

ATLAS-CONF-2015-063



ATLAS-CONF-2015-070

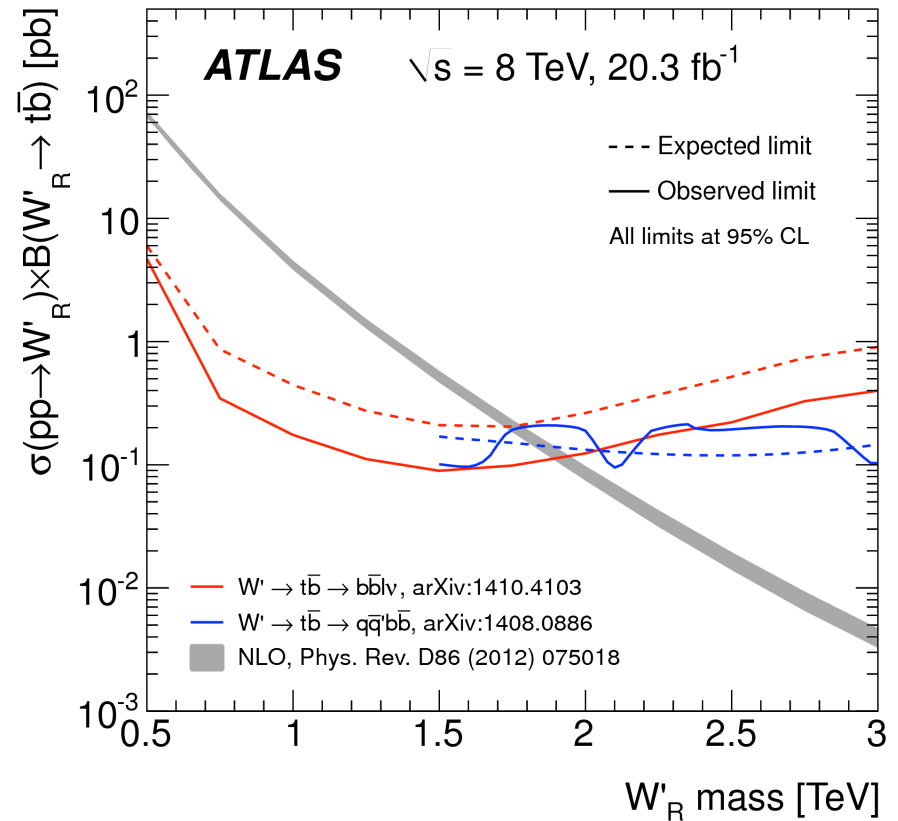
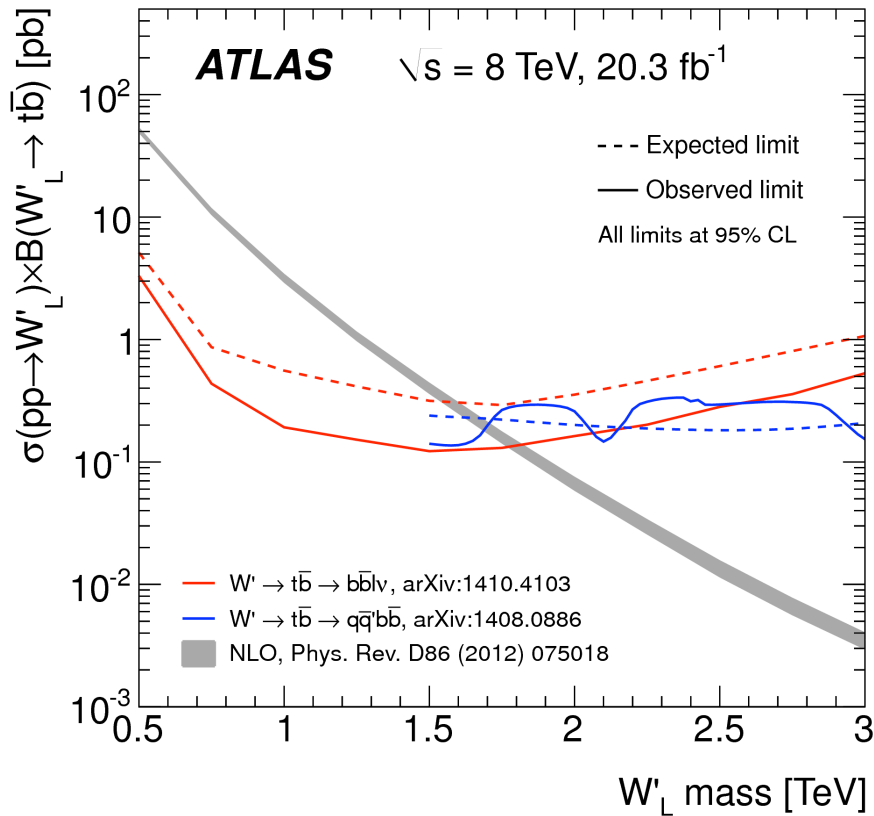


$W' \rightarrow t\bar{b}$

- Complementarity :

- Theories with extension of fundamental symmetries of the SM predict W'_R
- Not always seen by other channels. No decay to charged lepton and ν_R if $m_\nu > m_{W'}$

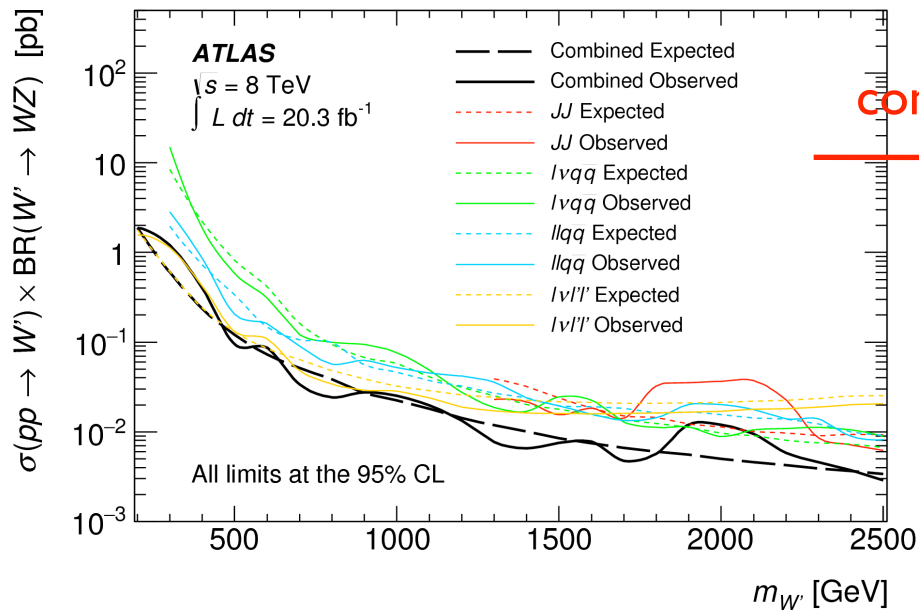
arXiv:1410.4103



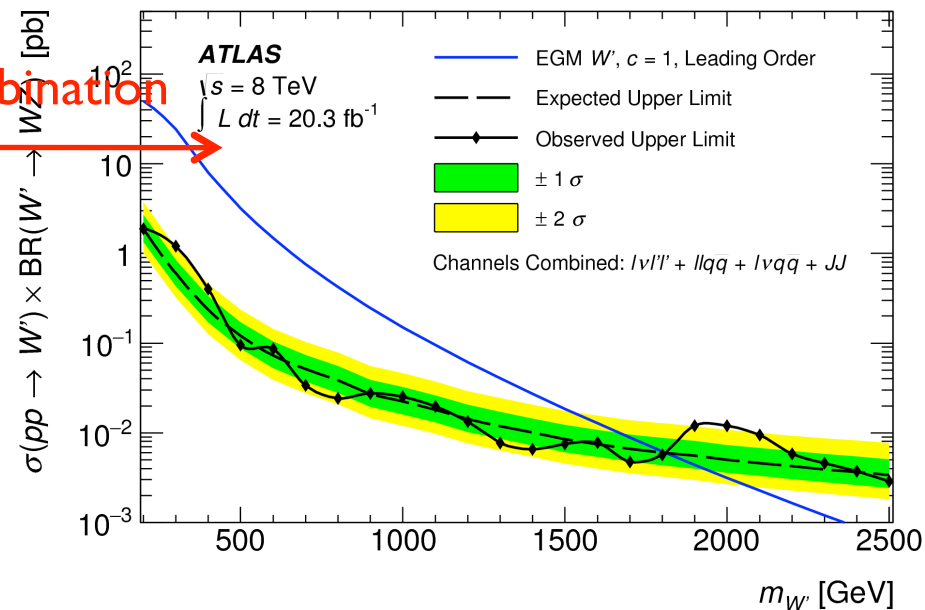
W' and Z' to WW

- Benchmark models:
 - Extended Gauge Model
 - Randall-Sundrum (RS) gravitation model
- EGM vs SSM \rightarrow check of $W'WZ$ coupling

arXiv:1512.05099



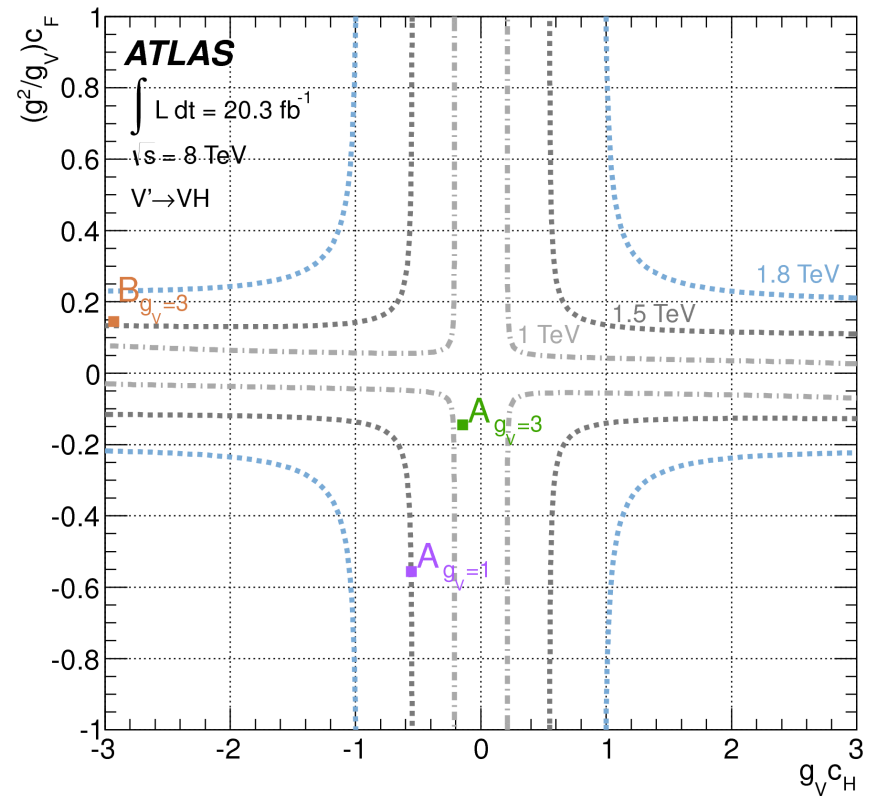
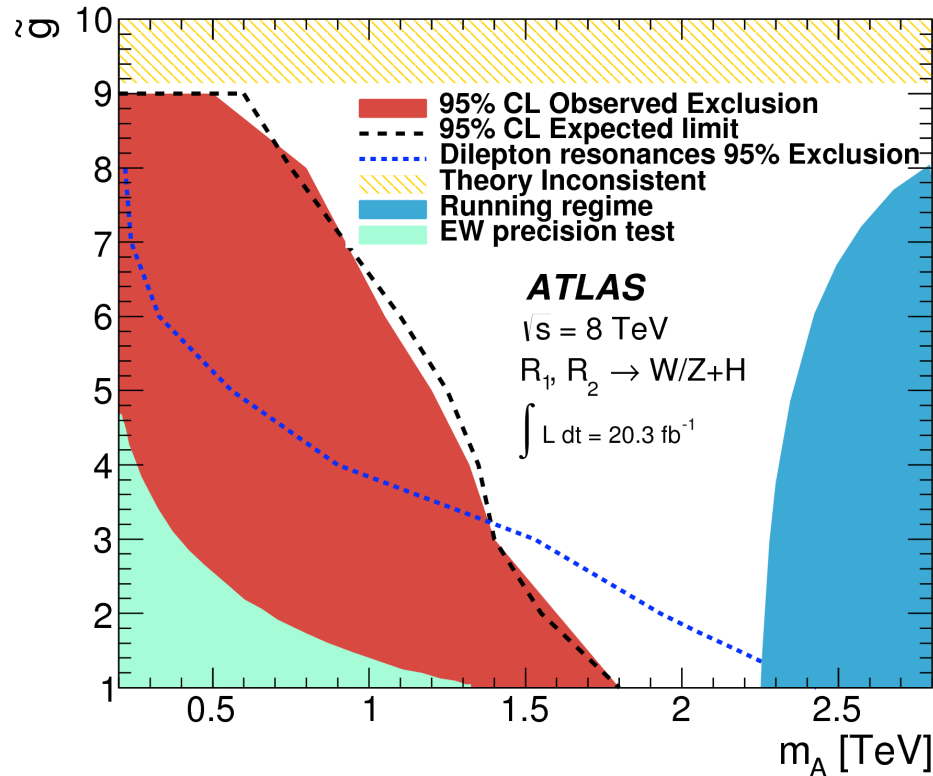
combination \rightarrow



W' and Z' to VH

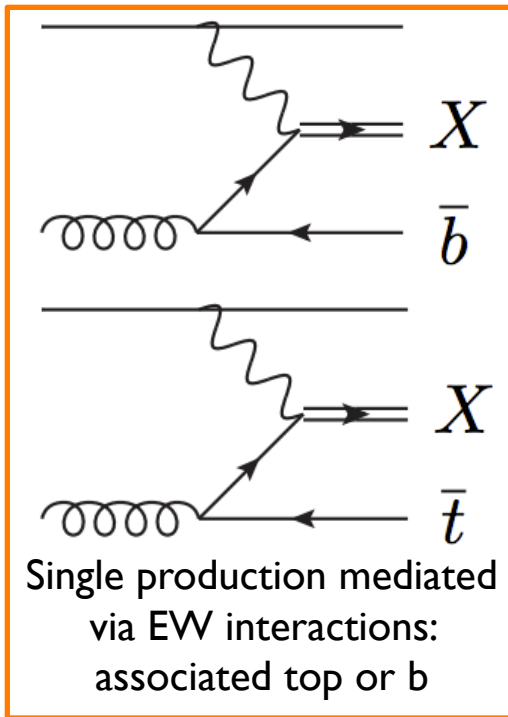
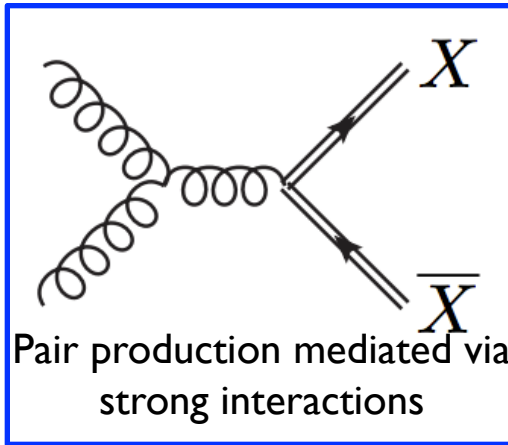
- Similar search for $V' \rightarrow VH$ interpreted in Heavy Vector Triplet model and Minimal Walking Technicolor.

arXiv:1503.08089

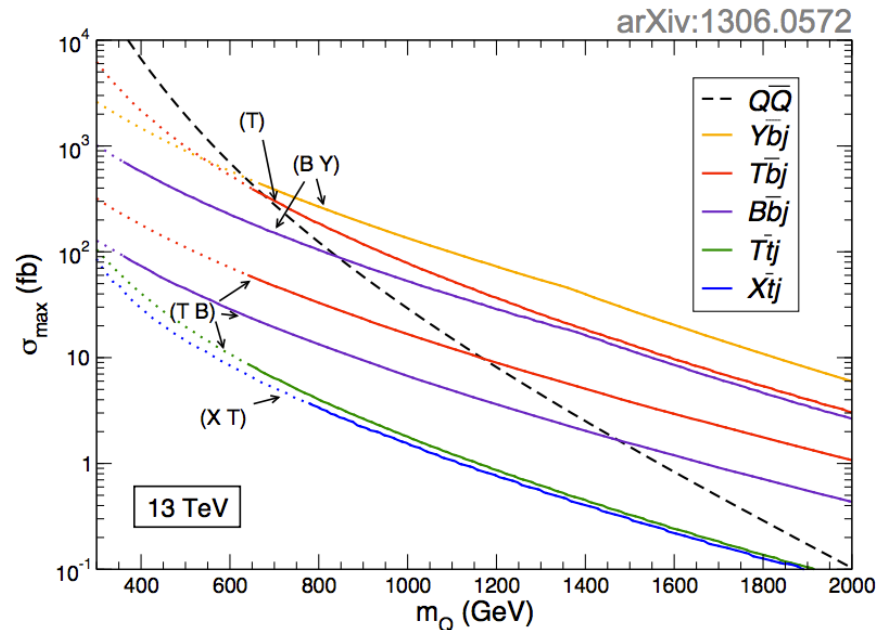


Vector-Like Quark Interpretations

Vector-Like Quark Pair Searches



- Present in many BSM models (eg. Composite Higgs), contain useful top-partner
- Search strategies are generally designed by production mode
- Pair production dominates at lower masses, mostly model independent
- Single production pdf-favored at high mass, sensitive to mixing with SM quarks (generally taken to be 3rd gen only)



Vector-Like Quark Pair Searches

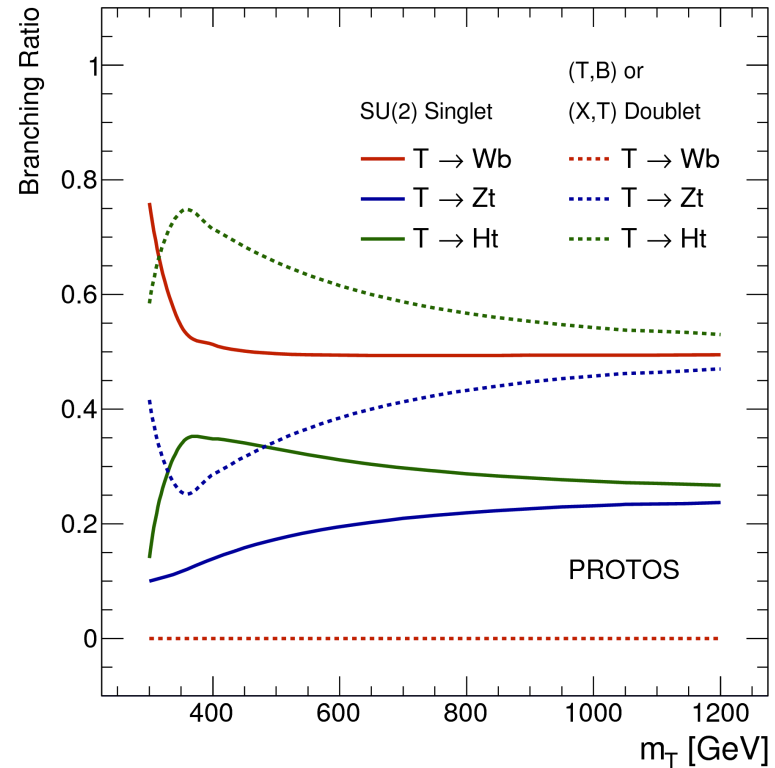
- Models can be built in increasing steps of phenomenological complexity
 - Mixing with SM quarks can modify couplings to V/H bosons and lead to FCNCs
 - Leads to a potentially complex overlap of production/decay modes in experimental searches. Complicates interpretation to some degree.

	SM $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	Singlets $(T)_{L,R}$ $(B)_{L,R}$	Doublets $(X, T)_{L,R}$ $(T, B)_{L,R}$ $(B, Y)_{L,R}$	Triplets $(X, T, B)_{L,R}$ $(T, B, Y)_{L,R}$
$SU(2)_L$	2 and 1	1	2	3
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3 -1/3	7/6 1/6 -5/6	2/3 -1/3
\mathcal{L}_Y	$-\frac{y_u^i v}{\sqrt{2}} \bar{u}_L^i u_R^i$ $-\frac{y_d^i v}{\sqrt{2}} \bar{d}_L^i V_{CKM}^{ij} d_R^j$	$-\frac{\lambda_u^i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\frac{\lambda_d^i v}{\sqrt{2}} \bar{d}_L^i D_R$	$-\frac{\lambda_u^i v}{\sqrt{2}} U_L u_R^i$ $-\frac{\lambda_d^i v}{\sqrt{2}} D_L d_R^i$	$-\frac{\lambda_i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\lambda_i v \bar{d}_L^i D_R$

Vector-Like Quark Pair Searches

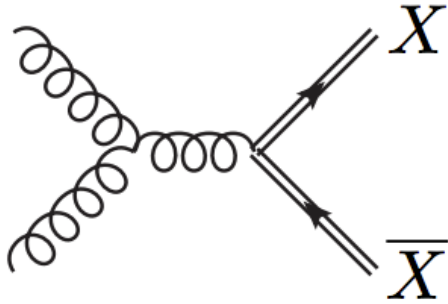
- Models can be built in increasing steps of phenomenological complexity
- Mixing with SM quarks can modify couplings to V/H bosons and lead to FCNCs
- Leads to a potentially complex overlap of production/decay modes in experimental searches. Complicates interpretation to some degree.

	charge	decay modes
T singlet	+2/3	$T \rightarrow Wb, Ht, Zt$
B singlet	-1/3	$B \rightarrow Wt, Hb, Zb$
(T,B) doublet	(+2/3, -1/3)	$T \rightarrow Wb, Ht, Zt$ $B \rightarrow Wt, Hb, Zb$
(X,T) doublet	(+5/3, +2/3)	$X \rightarrow Wt$ $T \rightarrow Ht, Zt$
(B,Y) doublet	(-1/3, -4/3)	$B \rightarrow Hb, Zb$ $Y \rightarrow Wt$

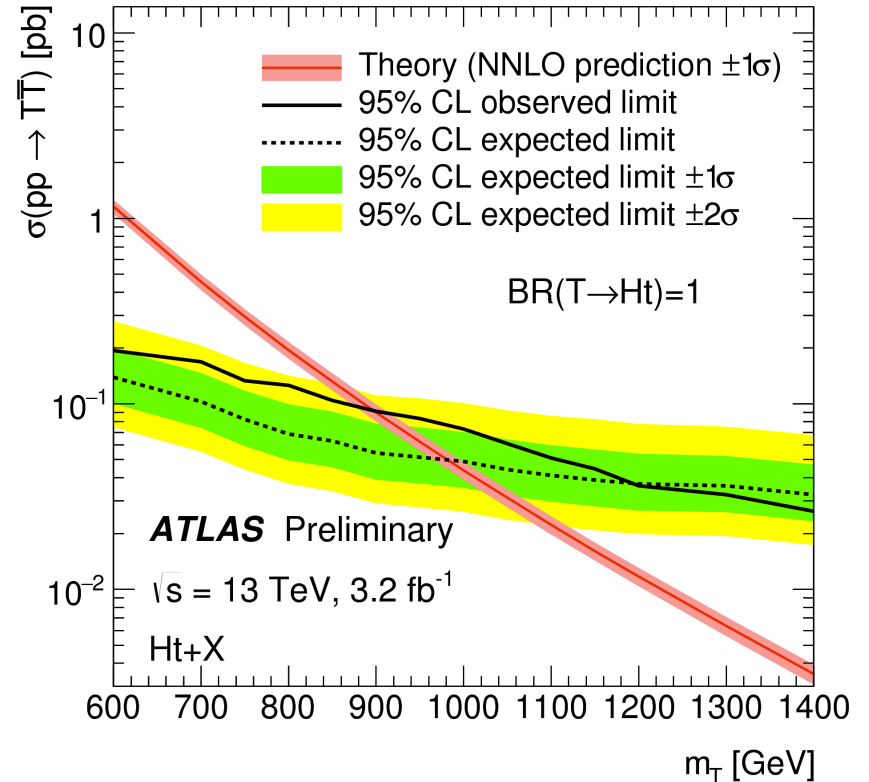
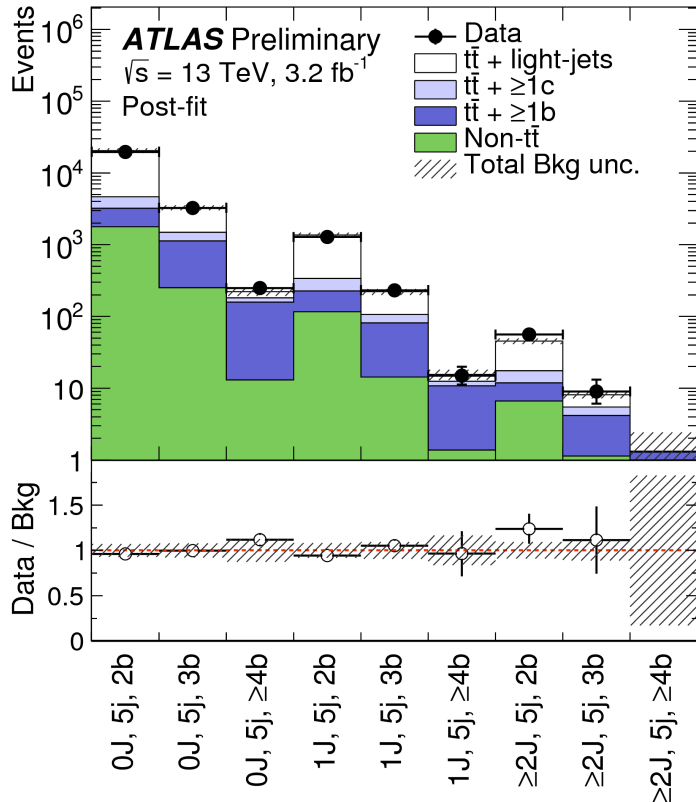


Vector-Like Quark Pair Searches

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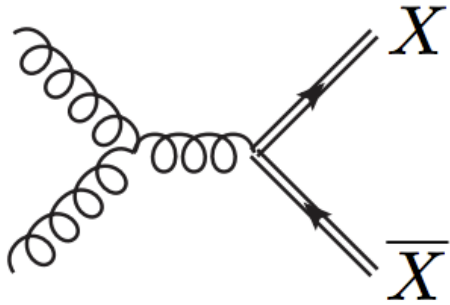


- Vector-like top pair production search
- Divided by identified jets (small-R and large-R) and b-tags
- Limits on total rate compared yield mass exclusions at $O(1 \text{ TeV})$ for $BR(T \rightarrow Ht)=1$

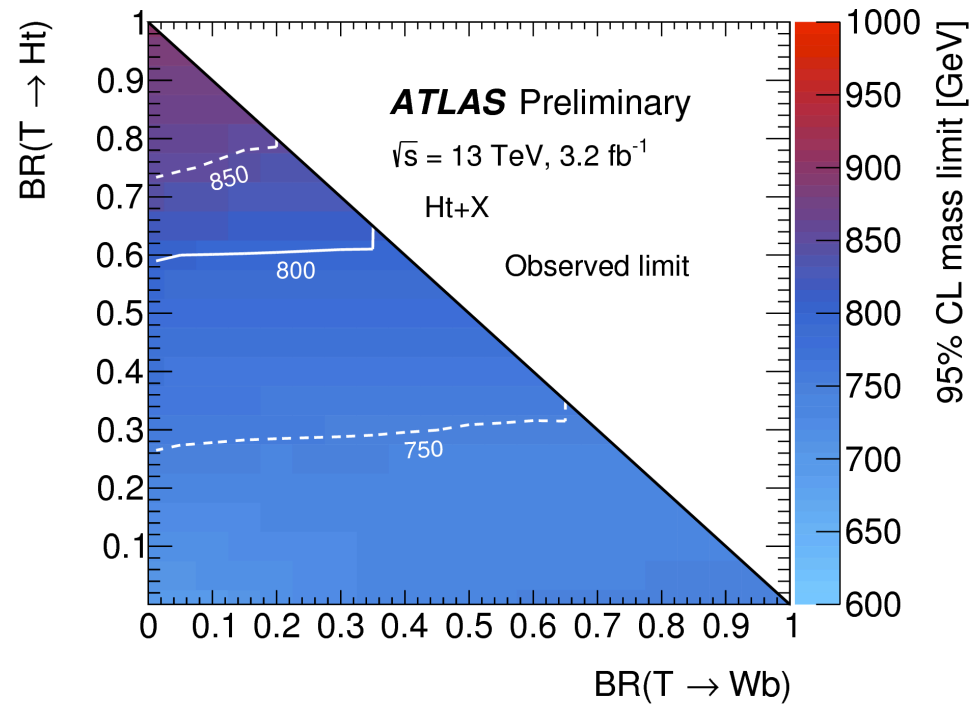
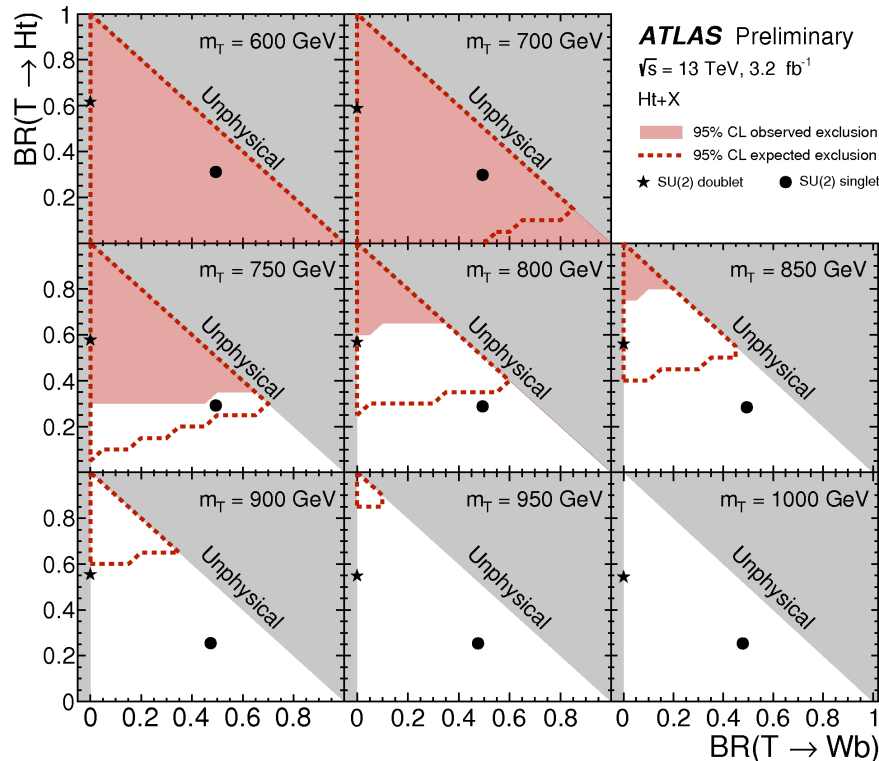


Vector-Like Quark Pair Searches

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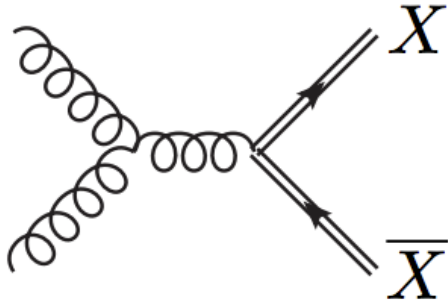


- Mass limits weaken as $BR(T \rightarrow Ht)$ decreases
- Limits for fixed mass predictions can be mapped to the 2D BR plane for vector-like tops

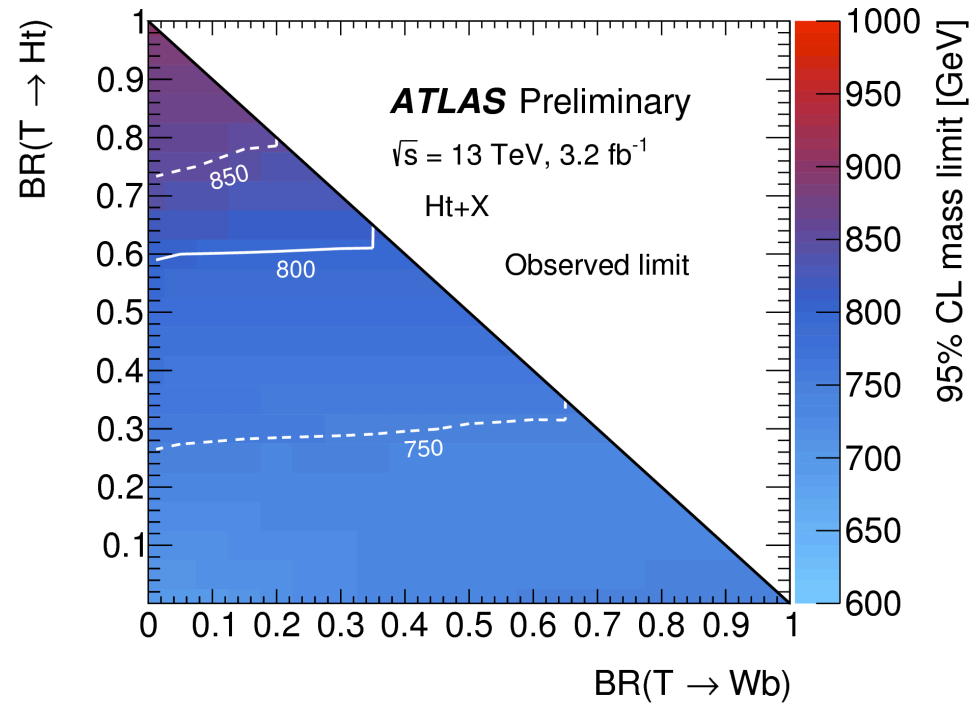
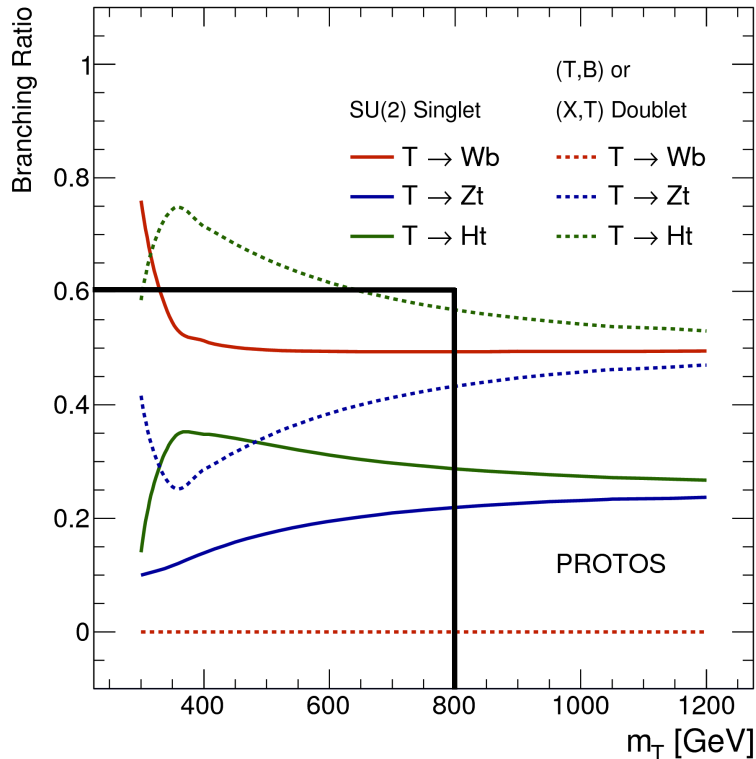


Vector-Like Quark Pair Searches

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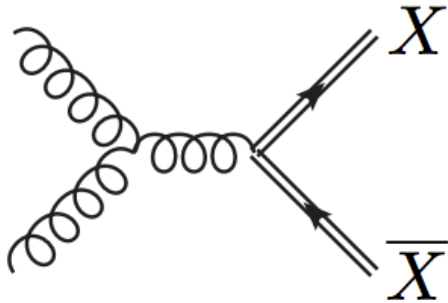


- Mass limits weaken as $BR(T \rightarrow Ht)$ decreases
- Limits for fixed mass predictions can be mapped to the 2D BR plane for vector-like tops
- Limits can be mapped back to BR/M space where the difference between model structure becomes apparent

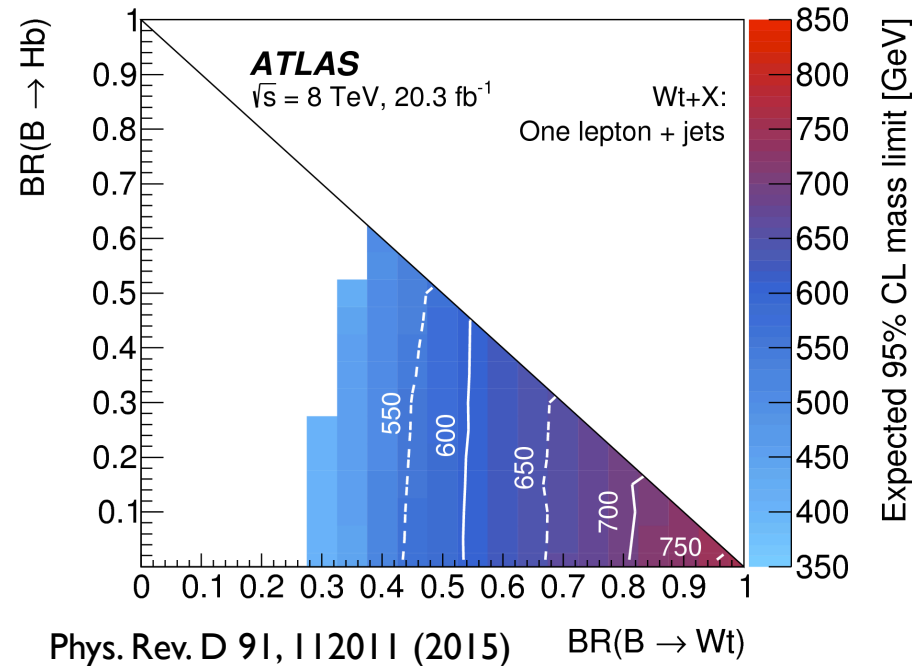


Vector-Like Quark Pair Searches

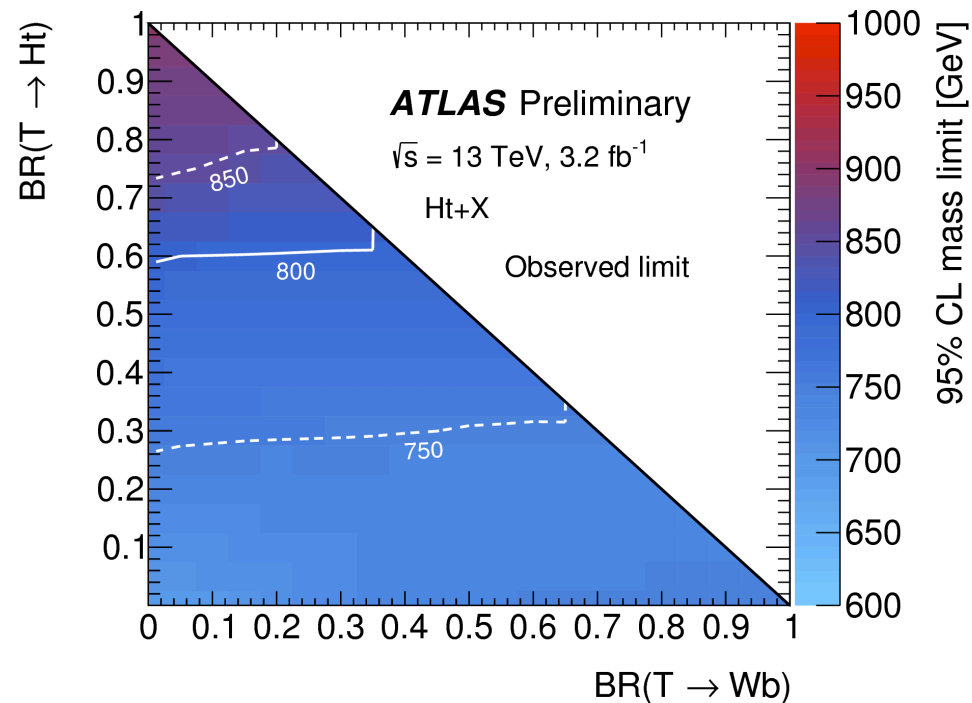
ATLAS-CONF-2016-013



- Mass limits weaken as $BR(T \rightarrow Ht)$ decreases
- Limits for fixed mass predictions can be mapped to the 2D BR plane for vector-like tops
- Limits can be mapped back to BR/M space where the difference between model structure becomes apparent
- A similar behavior is observed when the search is aimed at $B \rightarrow Wt$

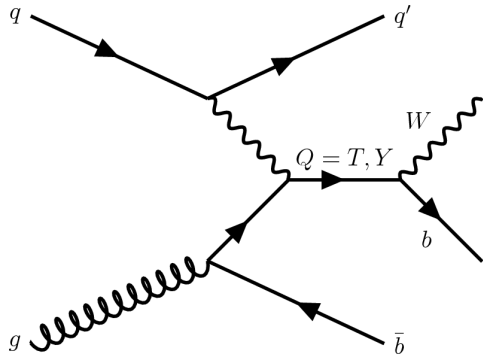


Phys. Rev. D 91, 112011 (2015) $BR(B \rightarrow Wt)$

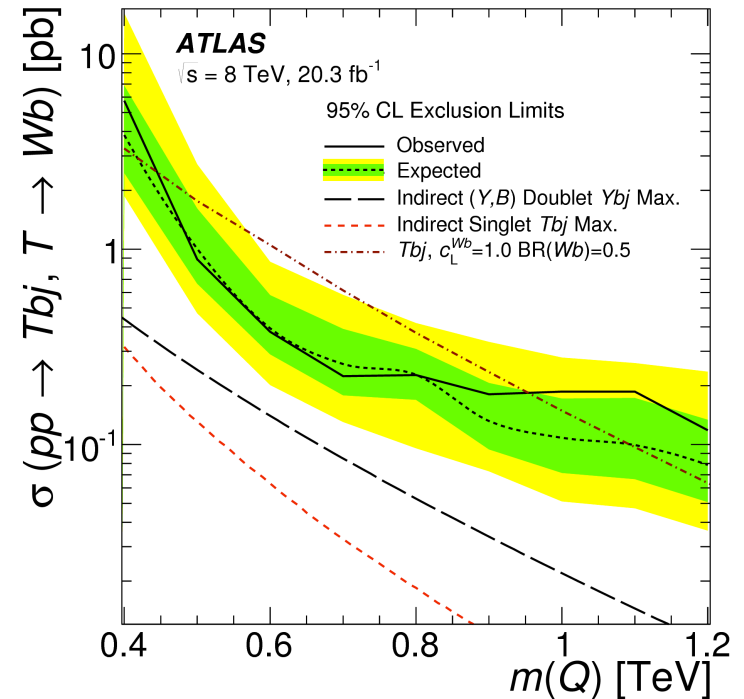
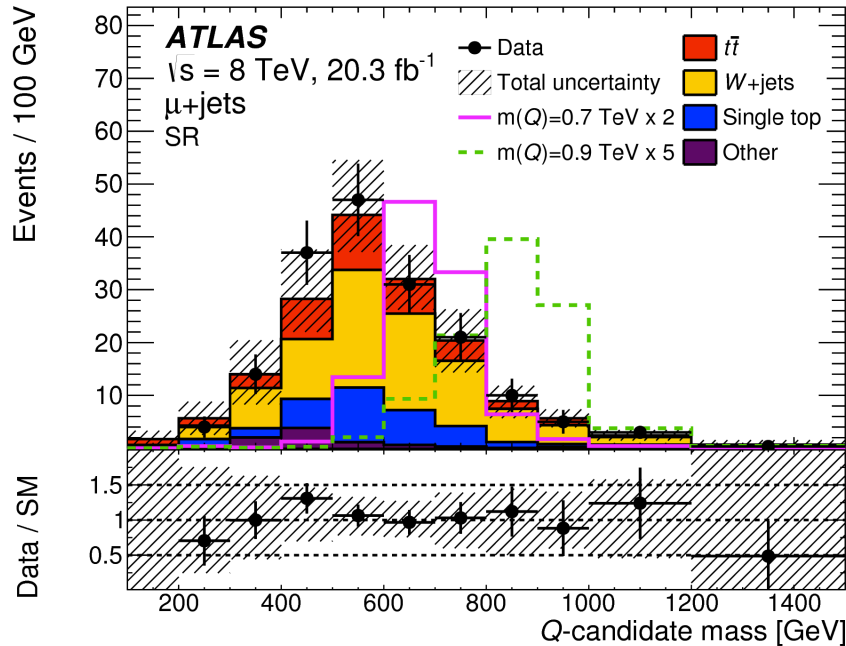


Singly-Produced VLQs

Submitted to EPJC
arxiv:1602.05606

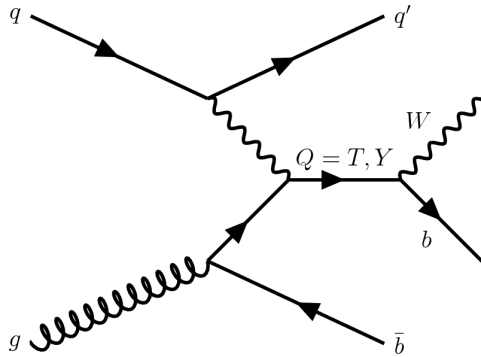


- Search for singly-produced vector-like quarks decaying to Wb
- Limits on total rate derived from reconstructed VLQ candidate mass and compared to benchmark models

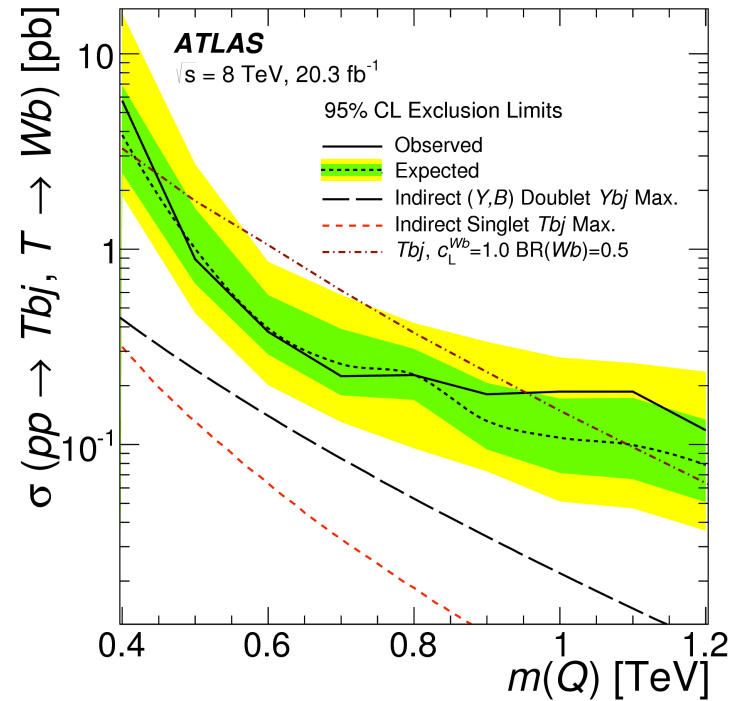
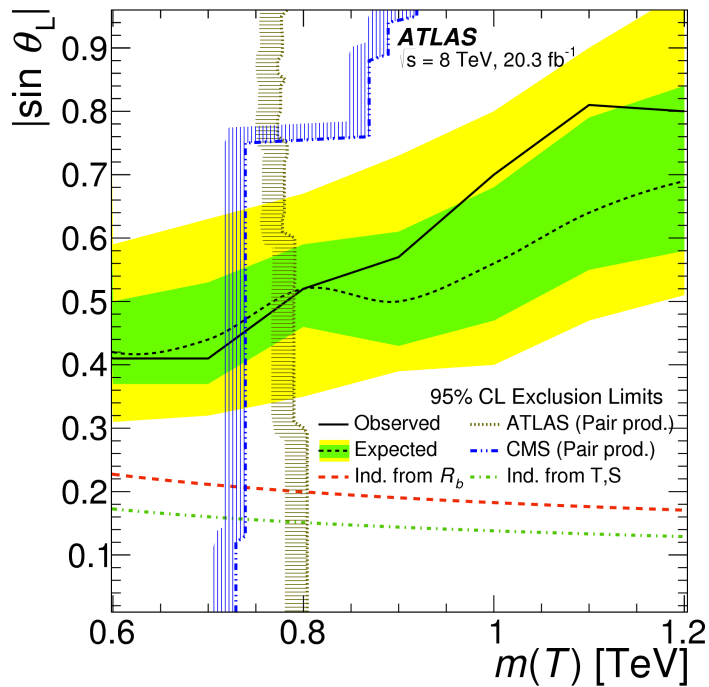


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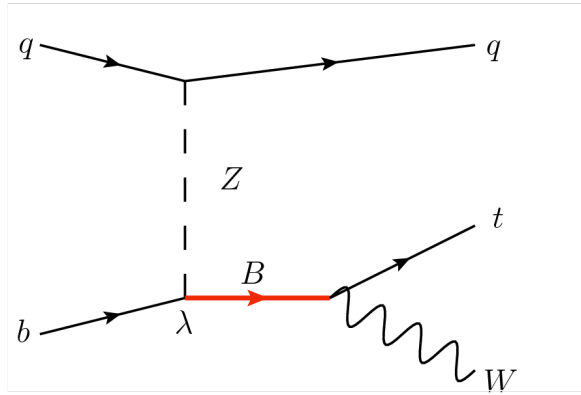


- Search for singly-produced vector-like quarks decaying to Wb
- Limits on total rate derived from reconstructed VLQ candidate mass and compared to benchmark models
- Limits on rate can be translated to VLQ/SM mixing angle for a given VLQ flavor. Facilitates comparison with pair prod. searches.

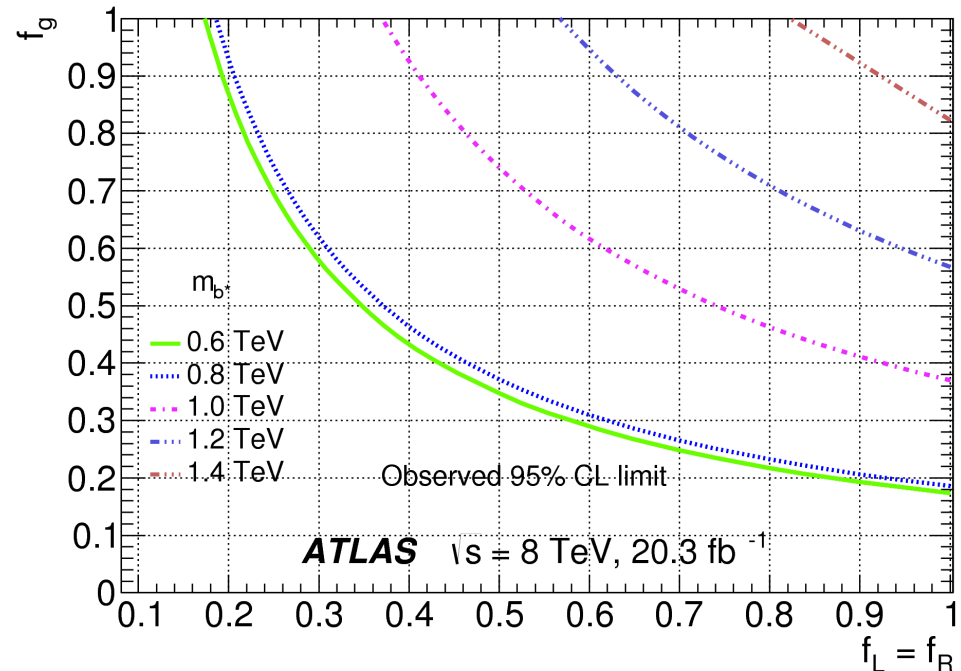
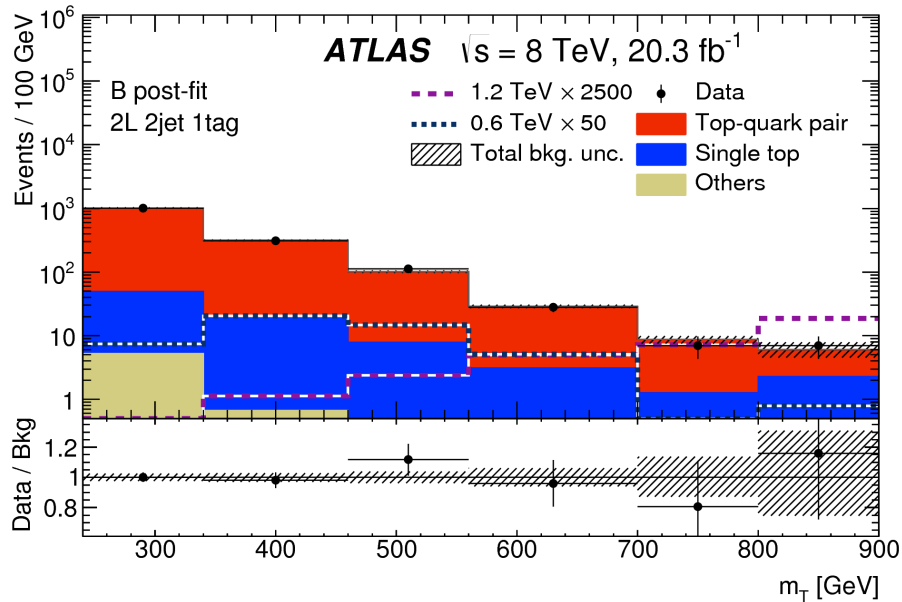


Singly-Produced VLQs

JHEP02(2016)110



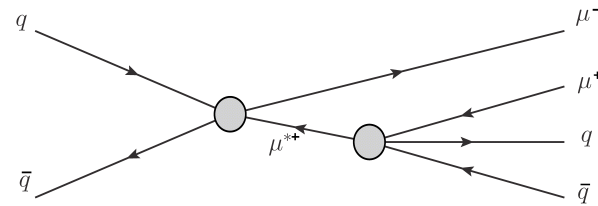
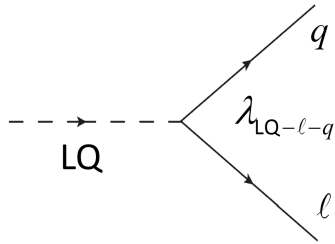
- Search for singly-produced vector-like quarks decaying to Wt
- Limits on total rate derived from reconstructed VLQ candidate transverse mass, similar to Wb search
- Limits on coupling factors for gluon- b and Wt can be derived as a function of VLQ mass



Other Interpretations

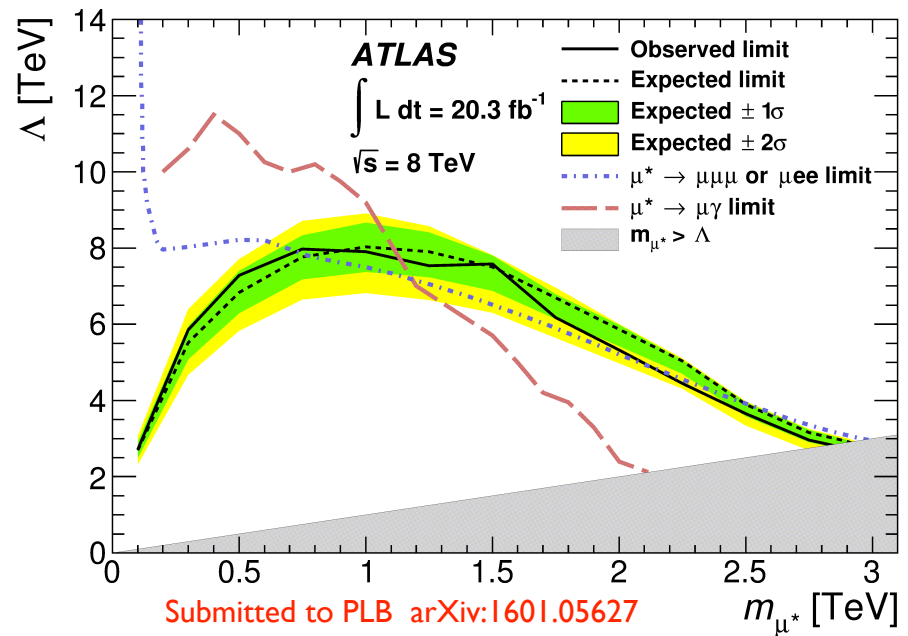
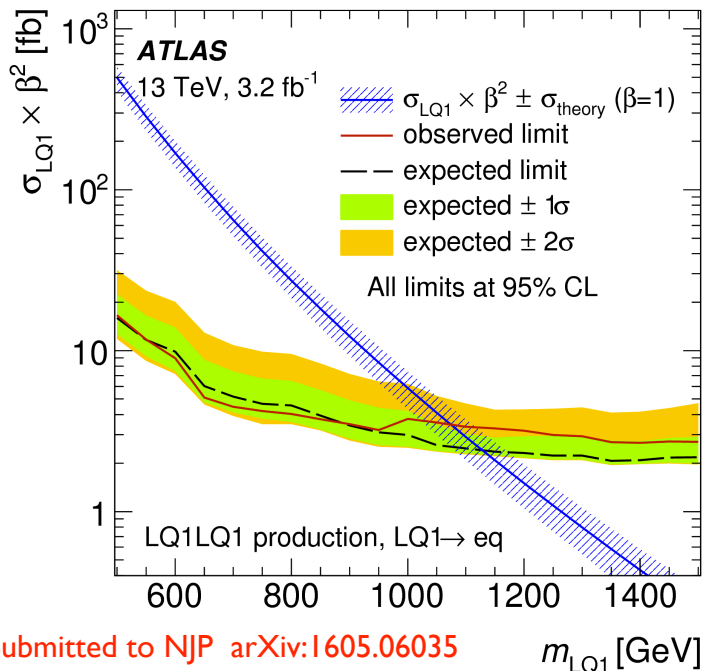
- There are many more ATLAS Exotics interpretive efforts that we cannot cover in detail for this talk
 - Contact Interaction Interpretations
 - Lepto-quarks
 - Dark Matter
 - Excited Fermions
 - Higgs triplet
 - LRSM w/ Majorana neutrino
 - Monopoles
 - Multi-charge
 - And more!
- We will do a quick fly-by pass of these, but it's not a comprehensive summary

LeptoQuarks and Excited Fermions



- Search for scalar leptoquarks
- Production rate depends primarily on LQ mass, decay rate to lepton+quark depends on Yukawa coupling. Leads to relatively model-independent limits.

- Search for excited muons
- Effective Lagrangian predicts rates that depend on lepton compositeness scale (Λ) and excited fermion mass.



Contact Interactions

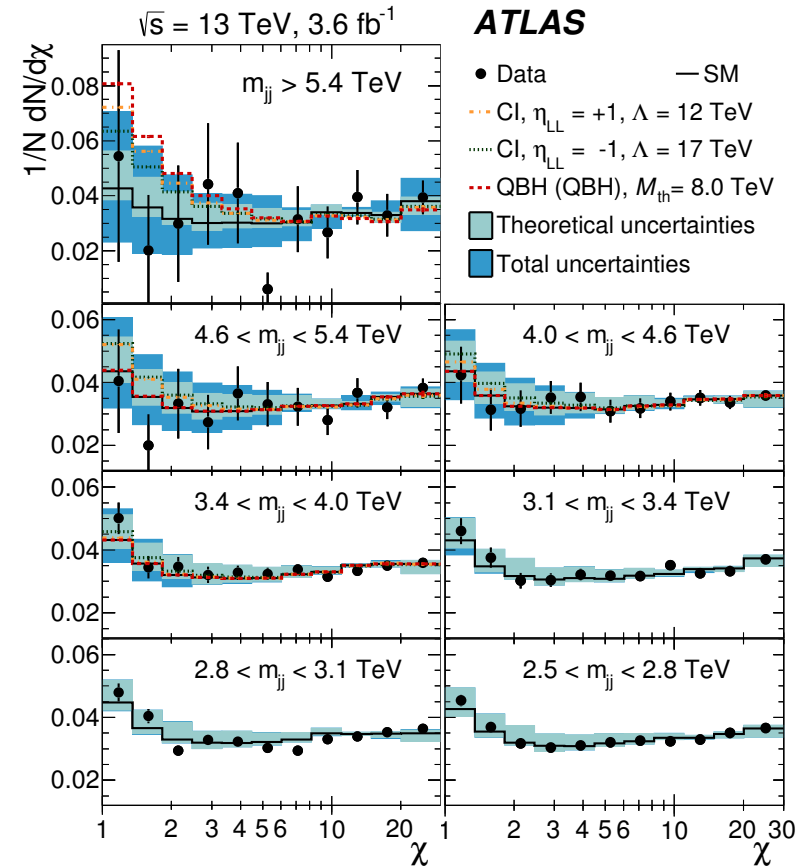
$$\mathcal{L} = \frac{g^2}{\Lambda^2} [\eta_{LL} (\bar{q}_L \gamma_\mu q_L) (\bar{\ell}_L \gamma^\mu \ell_L) + \eta_{RR} (\bar{q}_R \gamma_\mu q_R) (\bar{\ell}_R \gamma^\mu \ell_R) + \eta_{LR} (\bar{q}_L \gamma_\mu q_L) (\bar{\ell}_R \gamma^\mu \ell_R) + \eta_{RL} (\bar{q}_R \gamma_\mu q_R) (\bar{\ell}_L \gamma^\mu \ell_L)],$$

$$\frac{d\sigma}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} - \eta \frac{F_I}{\Lambda^2} + \frac{F_C}{\Lambda^4}$$

- qqll and qqqq: four-fermion effective field theories considered in ATLAS searches. Compositeness, depending on energy scale, Λ .
- Broad excess over the SM invariant mass spectrum, and forward-backward asymmetry in angular distributions.
- Interaction describes a color and isospin singlet with couplings to L/R-handed fermion states.
- η_{XY} describes whether the interference is constructive (-), or destructive (+), and the couplings i.e. $\eta_{LL} = 1$, $\eta_{RR} = \eta_{LR} = 0$

Dijet: arXiv:1512.01530

Dilepton: CONF

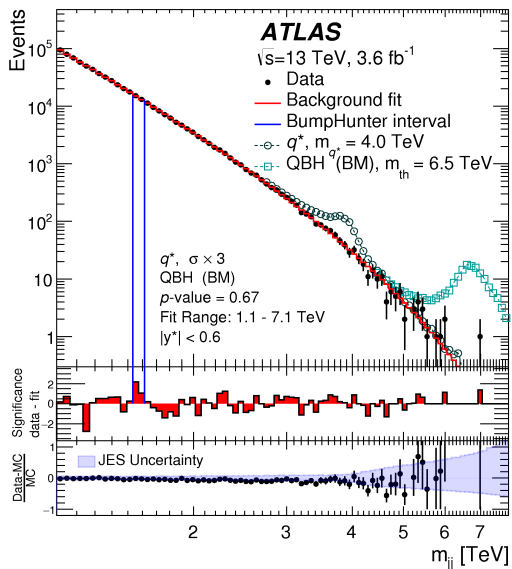


$$\chi = e^{2|y^*|} \sim \frac{1 + \cos \theta^*}{1 - \cos \theta^*},$$

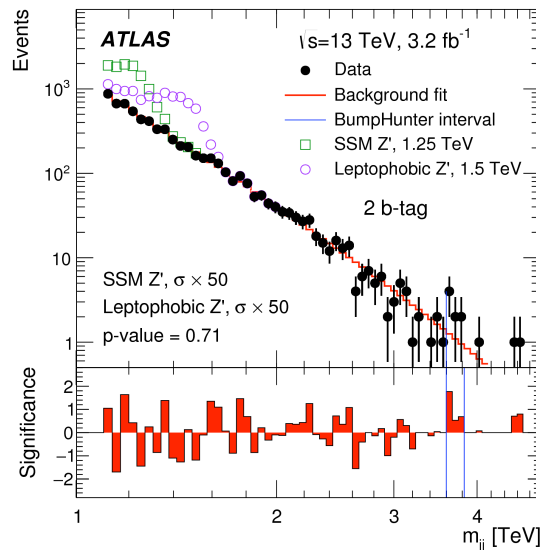
Di-jets, di-b-jets, ttbar

- Dijet resonances \rightarrow exclude quantum black holes (QBH) in benchmark models : $m_{\text{QBH}} < 8.3$ GeV (excited quarks), $m_{\text{QBH}} < 8.1$ GeV (W' model), and $m_{\text{QBH}} < 5.3$ GeV (Z' model)
- $bb\bar{b}$, bq , bg resonances : Sequential Standard Model (SSM) and Leptophobic Z'
- $tt\bar{b}$: topcolour-assisted-technicolour $\rightarrow Z'$ boson production

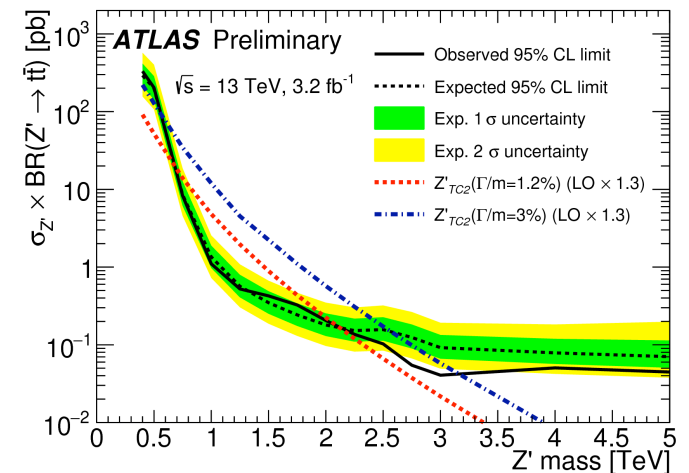
arXiv:1512.01530



arXiv:1603.08791



ATLAS-CONF-2016-014



Summary / Conclusions

- ATLAS Exotics group searches cover a broad range of BSM signatures
 - Benchmark interpretations are applied to compare sensitivities for similar searches, but are not always trivial to compare/combine for coherent groups
 - Where possible, try to provide acceptance and efficiency curves, fiducial cross-section limits, etc, to help with theorist re-interpretation. Use of Rivet too.
- Broad classes of interpretive models lead to a loose organization of signature-based searches
 - For example, Composite Higgs models can predict BSM signatures across experimental observables: leptons, jets, MET, etc.
- Potential for expansion of interpretative efforts where useful and/or feasible
 - Though a generic set of models common to many signatures and agreed with CMS helps streamline the experimental effort.