Searches for Exotic New Physics at ATLAS and CMS

Mike Hance

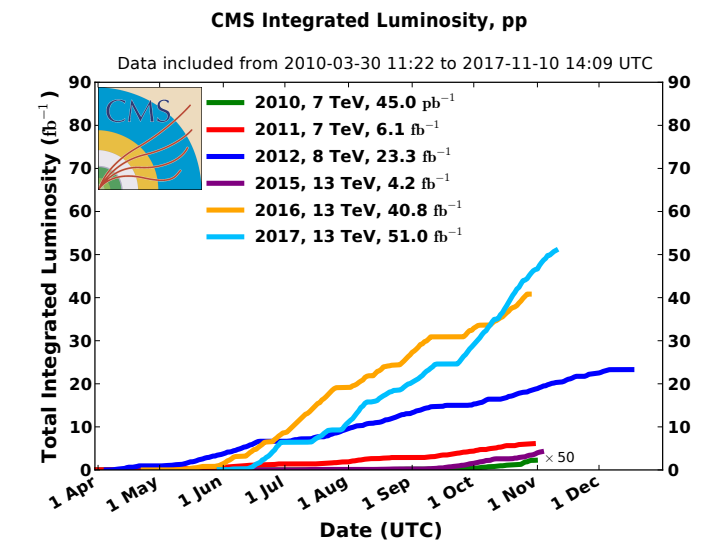
UC Santa Cruz

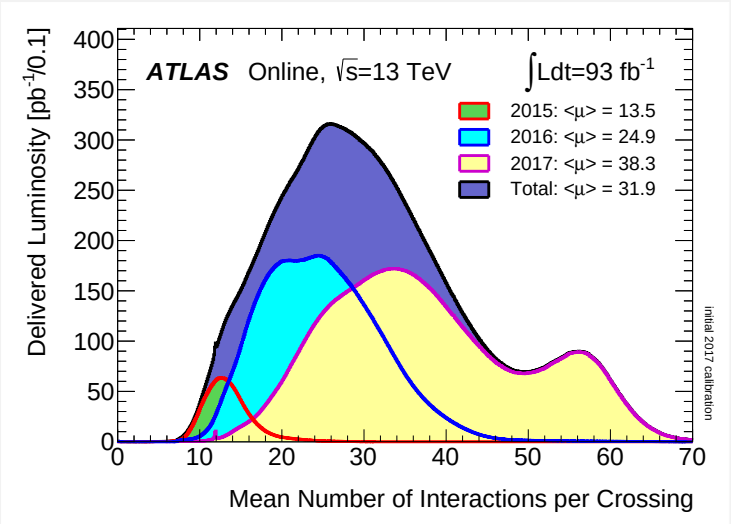
For the ATLAS and CMS Collaborations

SUSY17, December 11–15, 2017

Introduction

Run 2 in 2016: Potential for Discovery





CMS and ATLAS have been hard at work exploiting this potential:

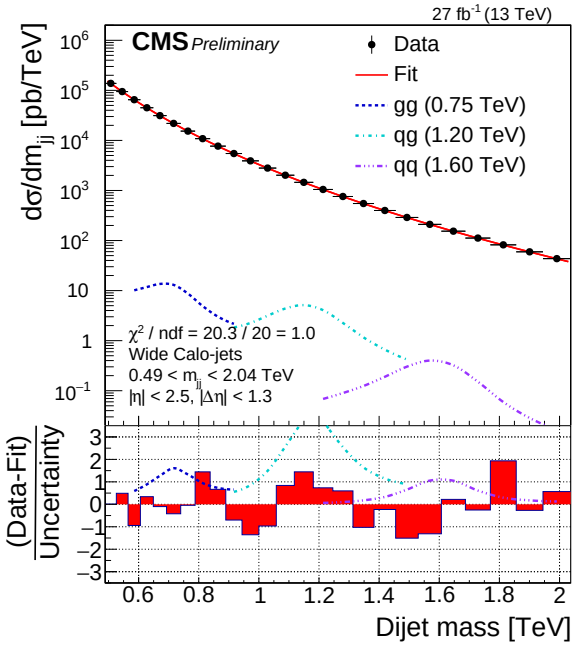
- **Over a hundred** search papers/notes with 2016 data
- Focus today on latest searches for **Exotica**
  - BSM Higgs covered on Monday by James Beacham
  - Dark Matter searches covered today by Henning Flächer
  - This talk: **heavy vectors**, **heavy fermions**, and other **high-scale new physics**

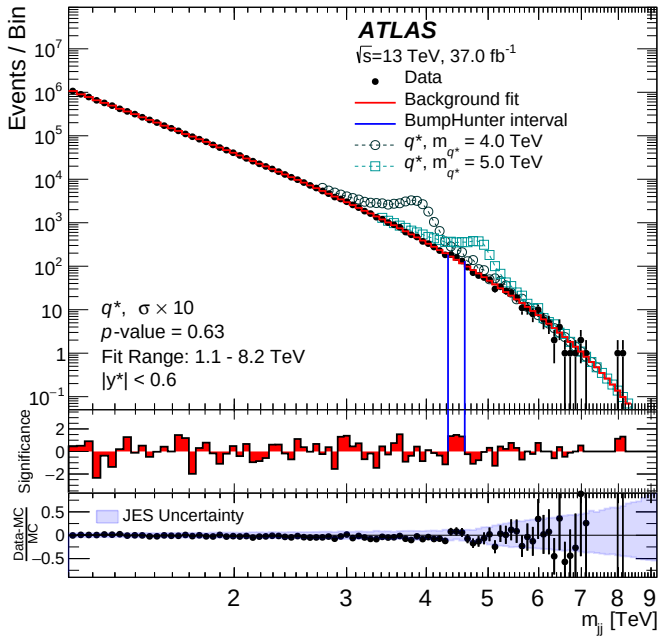
Dijets

Searches for dijet resonances

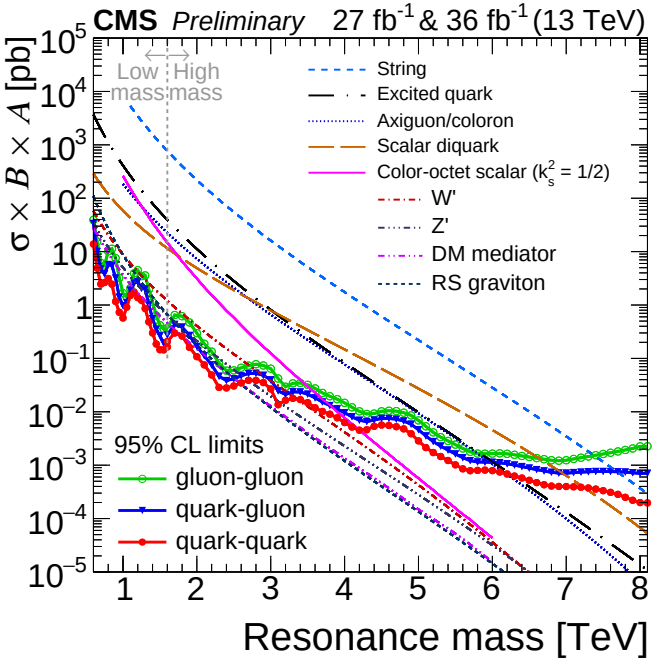
- Motivated by simple W'/Z' SM extensions...
- Quark compositeness...
- Dark Matter mediators

Also a proving ground for new analysis techniques: Trigger Level Analyses and Data Parking/Scouting.



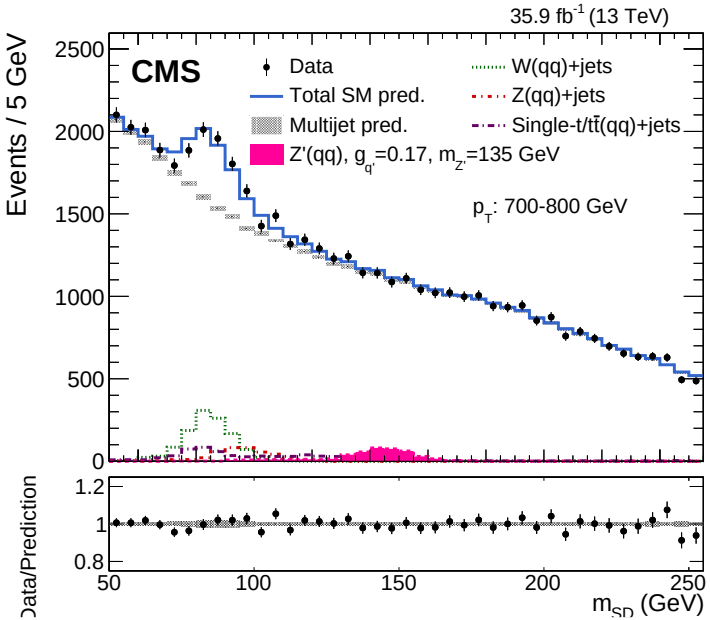


ATLAS-EXOT-2016-21



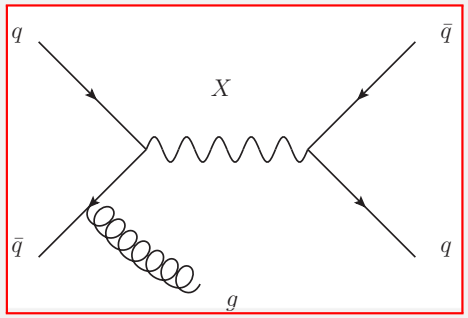
CMS-PAS-EXO-16-056

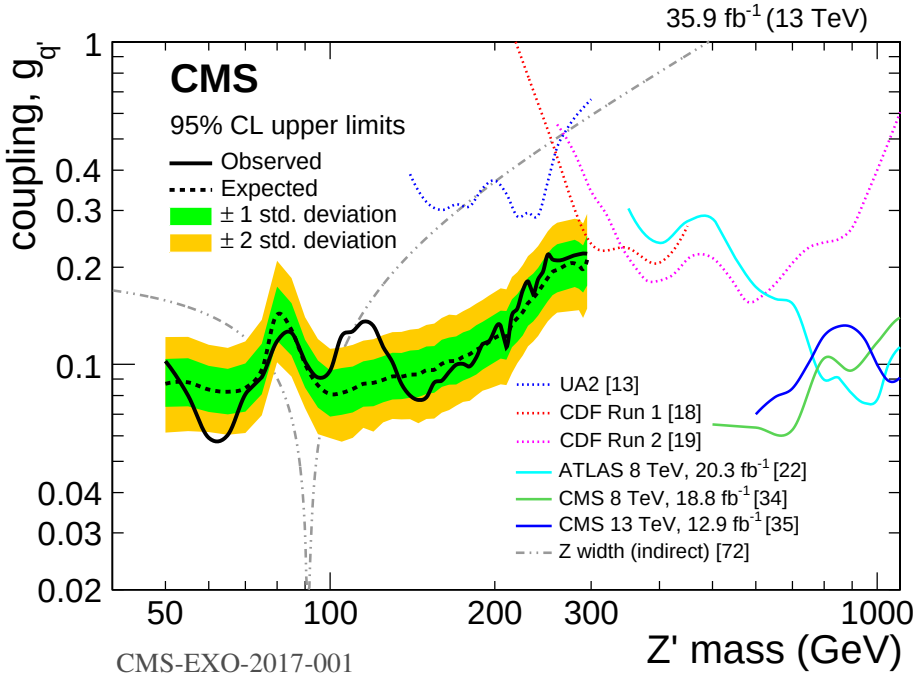
Low-mass dijets



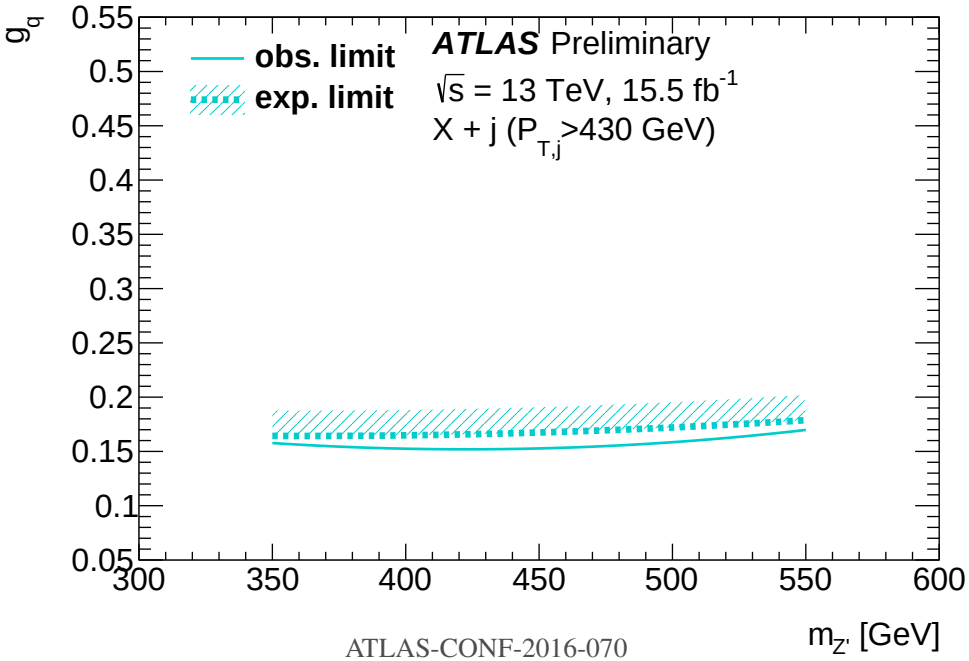
Creative searches at low-mass:

- ATLAS search with ISR γ/jet+dijet
- CMS search for boosted jj using substructure
- Extending low-mass limits from Tevatron and UA2





CMS-EXO-2017-001



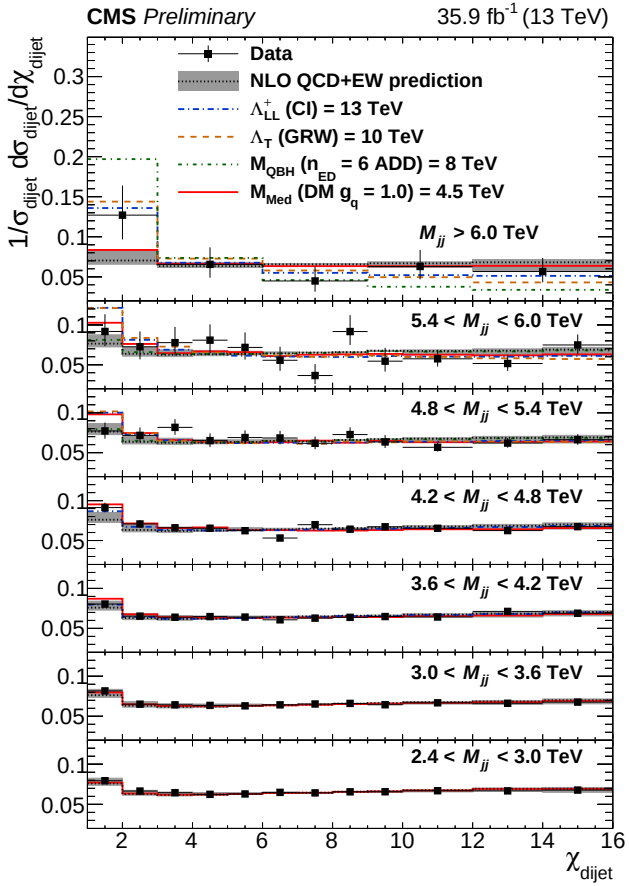
ATLAS-CONF-2016-070

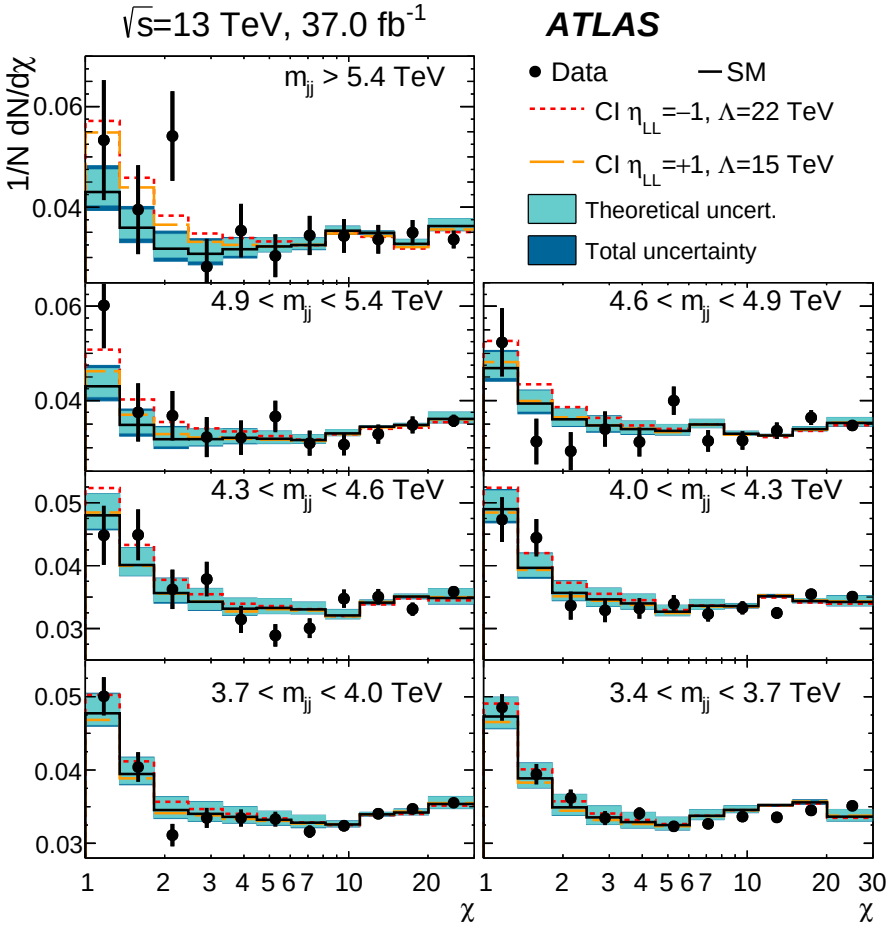
Dijet Angular Correlations

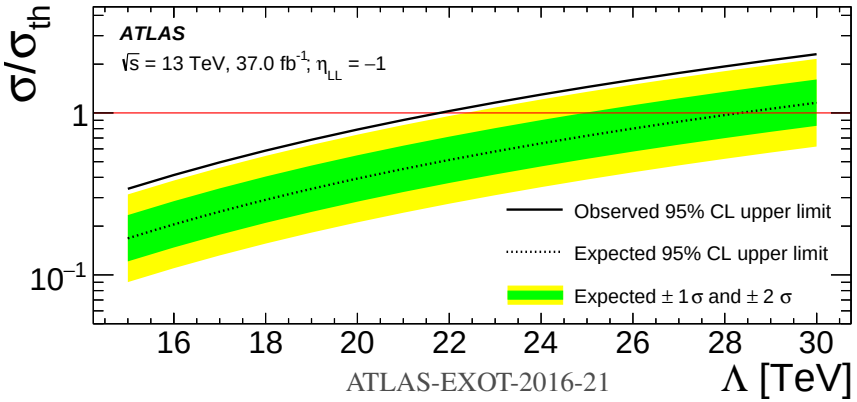
Complementary information about structure of interactions:

- Look for small values of $\chi = e^{|y_1 - y_2|}$

CMS-PAS-EXO-16-046





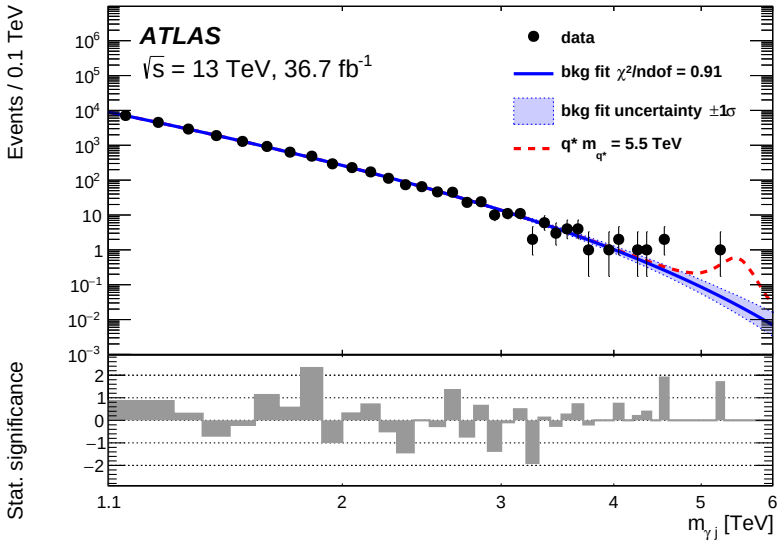


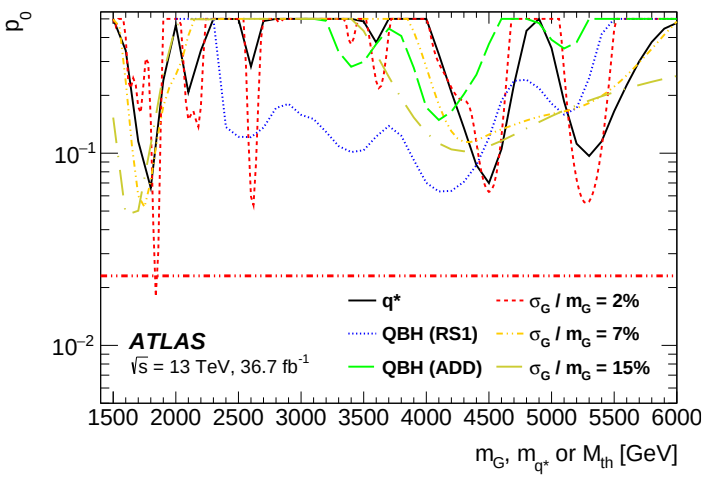
ATLAS-EXOT-2016-21

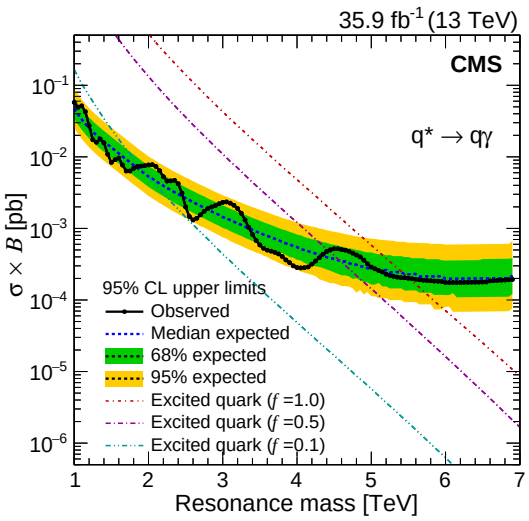
γ+jet resonances

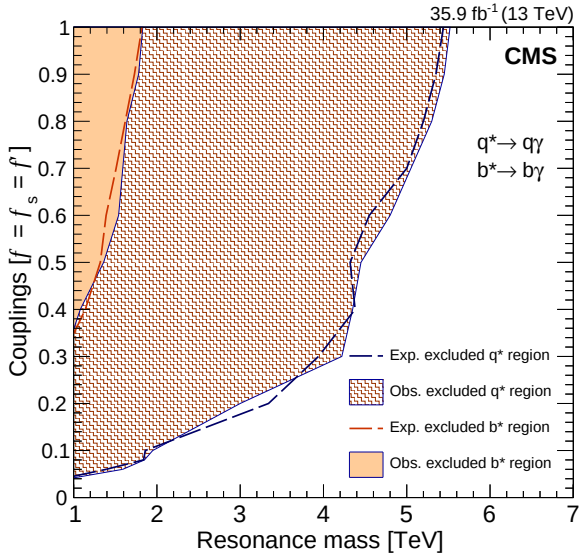
ATLAS-EXOT-2016-026

- γ-jet resonance searches sensitive to excited quarks
- Interpretation depends on couplings to SM particles
- b-tagging offers sensitivity to excited b^*









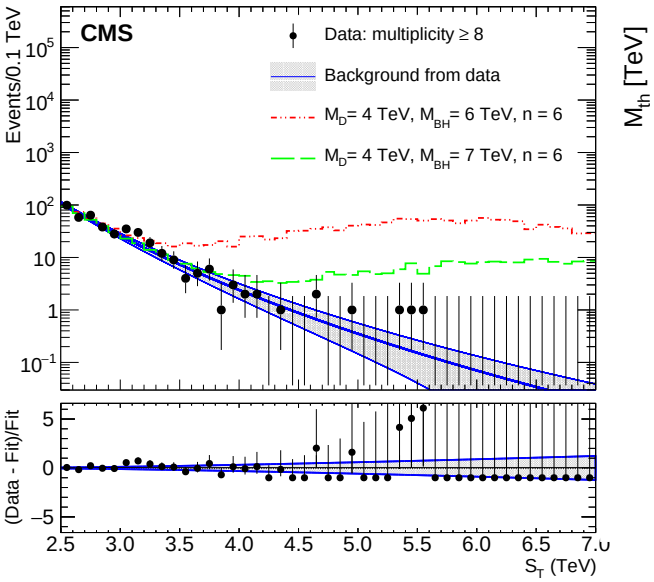
CMS-EXO-2017-002

Black Holes at the LHC?

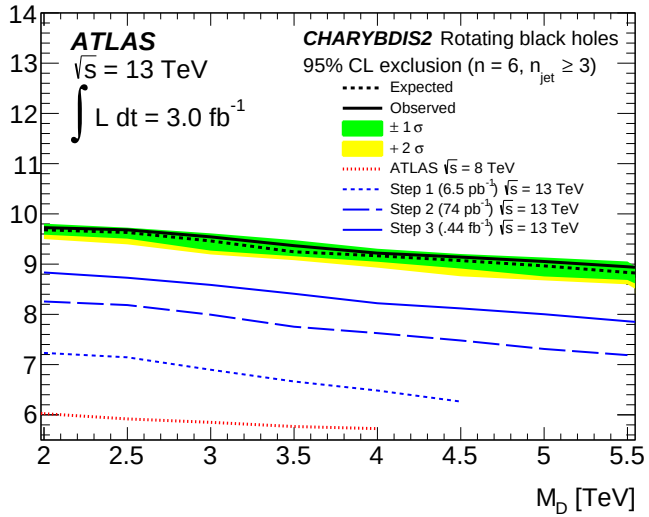
Not the end of the world as we know it.

- High-multiplicity, isotropic production of high-p_{T} objects
  - Can be with or without leptons
- Interpretations in several black hole, stringball, TeV-scale gravity models

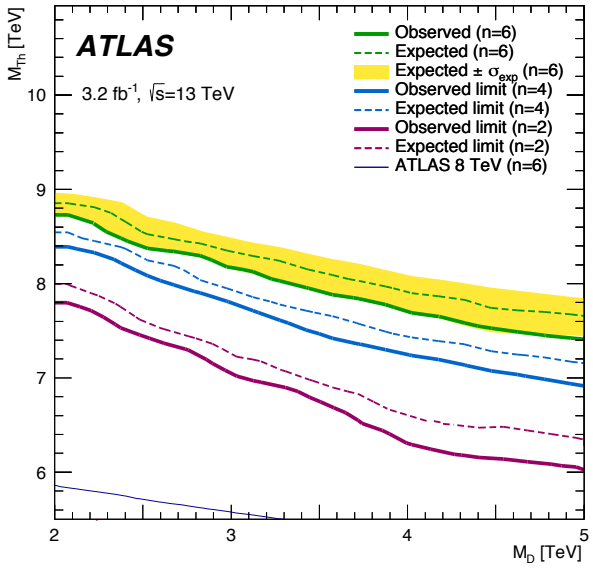
CMS-EXO-2015-007



ATLAS-EXOT-2015-09

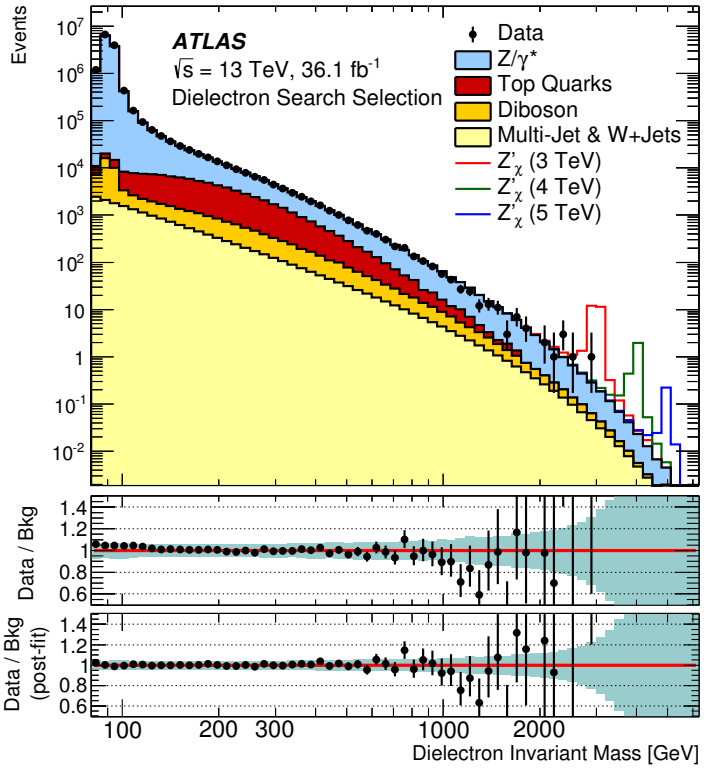


ATLAS-EXOT-2015-14

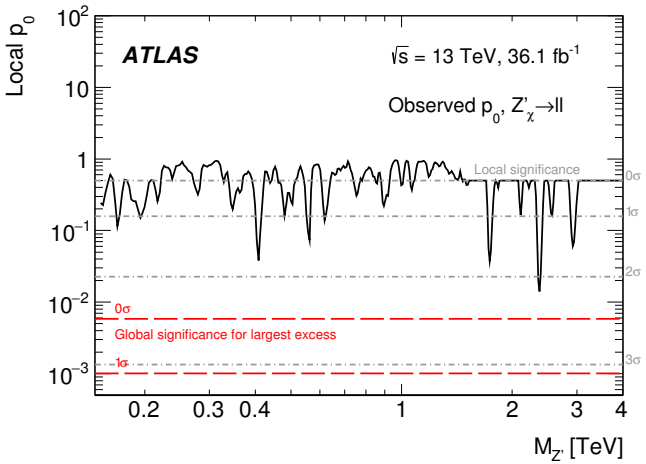


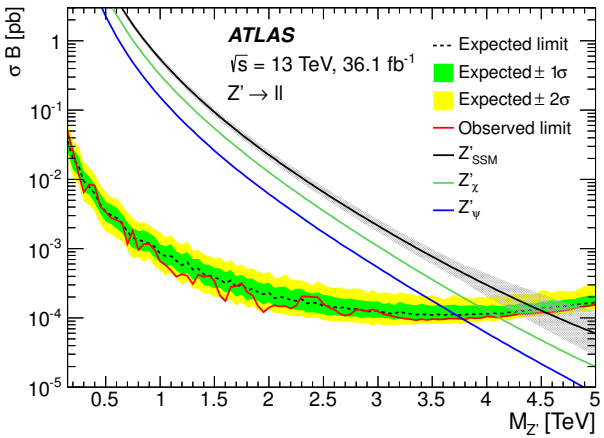
Limits from 2015 data still strong – unlikely to increase substantially at the LHC.

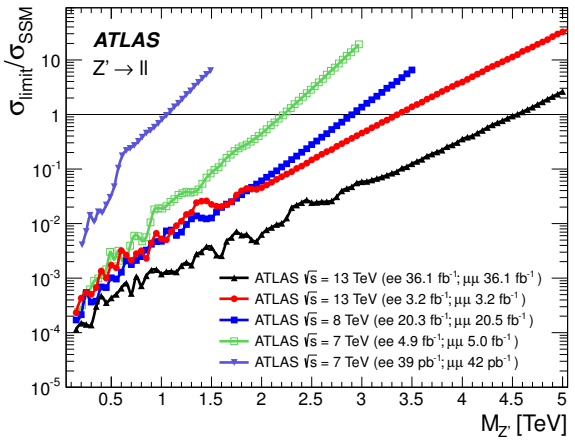
ATLAS-EXOT-2016-05



- $\mathcal{A} \times \varepsilon$ above 60%, resolution at 1% level for electrons
- Results available for varying widths, up to 32% of $M_{Z'}$.
- Excellent modeling for all data, up to 3 TeV!
- Constraints Z'_{SSM} can extend to ~5 TeV with 100 fb^{-1}
  - Collider Reach, no analysis improvements

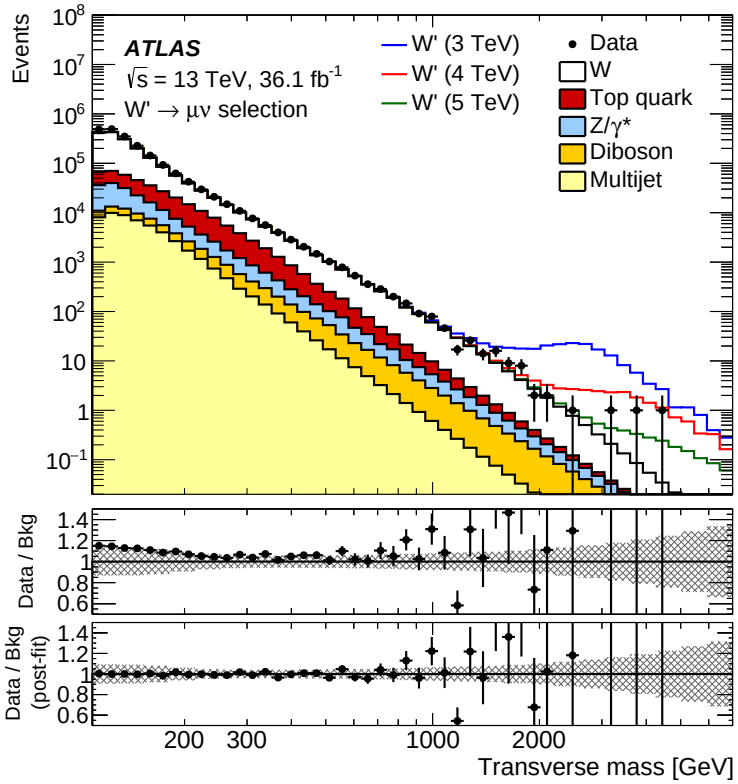


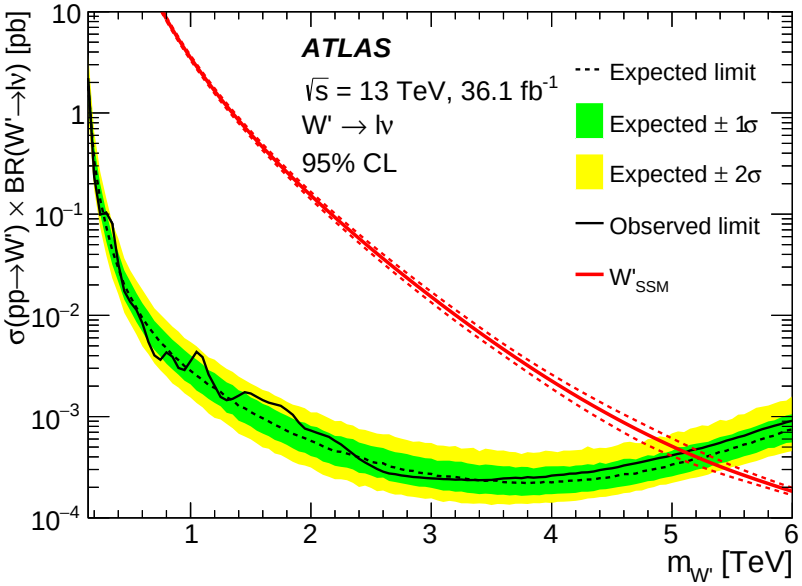


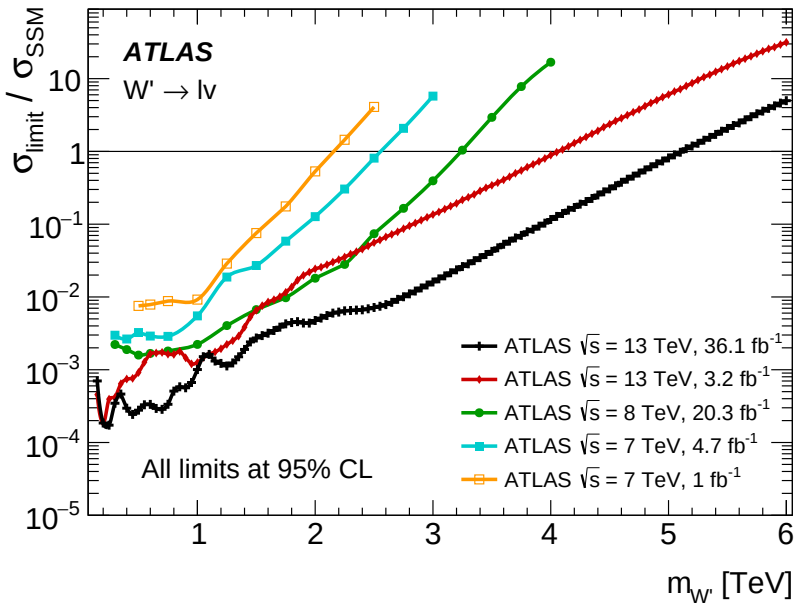


$W' \to \ell\nu$

ATLAS-EXOT-2016-06

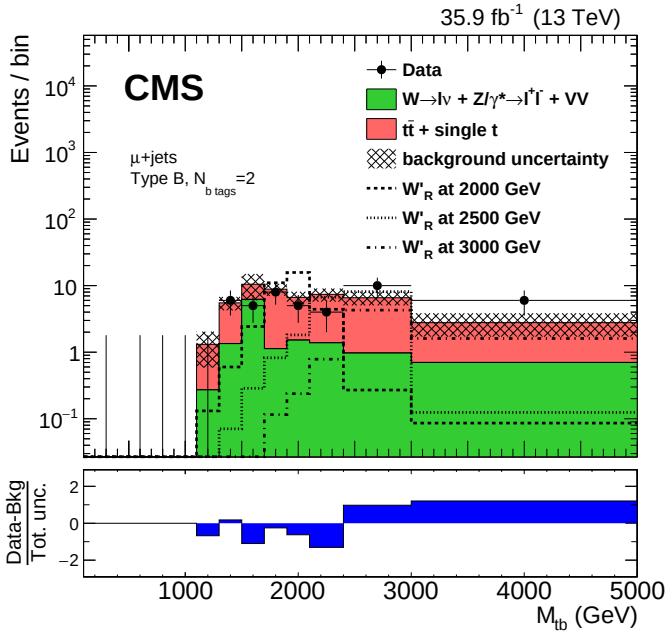






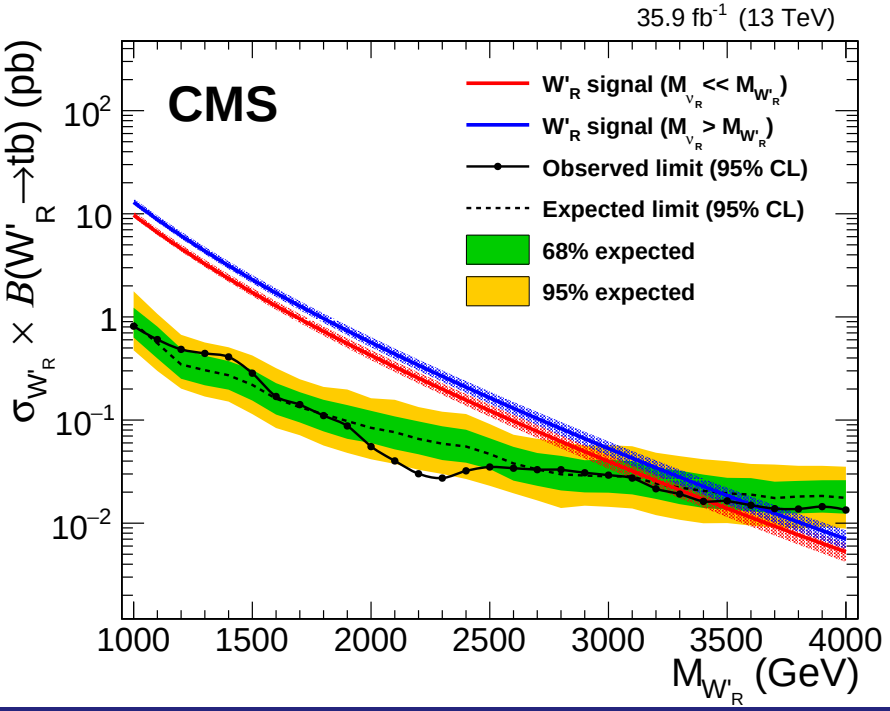
- Data up to $m_{\mathrm{T}} > 4$ TeV
- Constraints at low-mass continue to improve
- Limits can extend to 5.6 TeV with 100 fb^{-1}
  - Collider Reach, no analysis changes

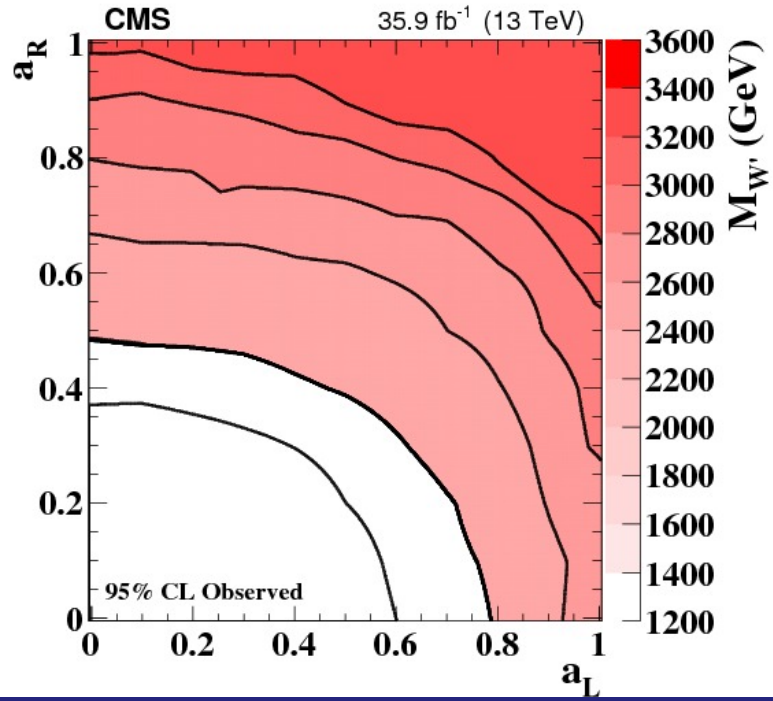
$W' \to tb$



- Decays to third-generation quarks also tightly constrained
- tb resonance search sensitive to both left-handed (a_{L}) and right-handed (a_{R}) couplings
- Similar mass scales reached with $\tau\tau qq$ final states in CMS-EXO-16-023

CMS-B2G-2017-010



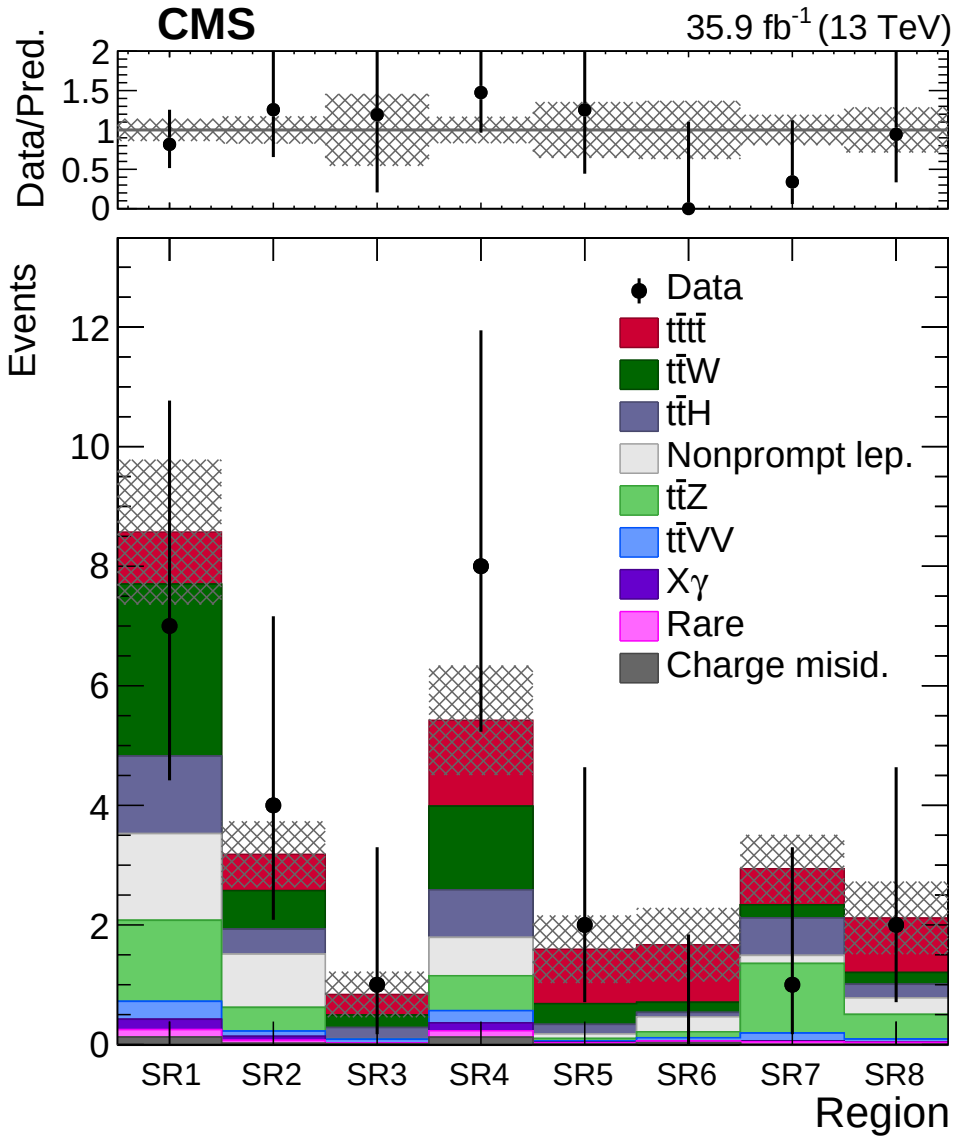


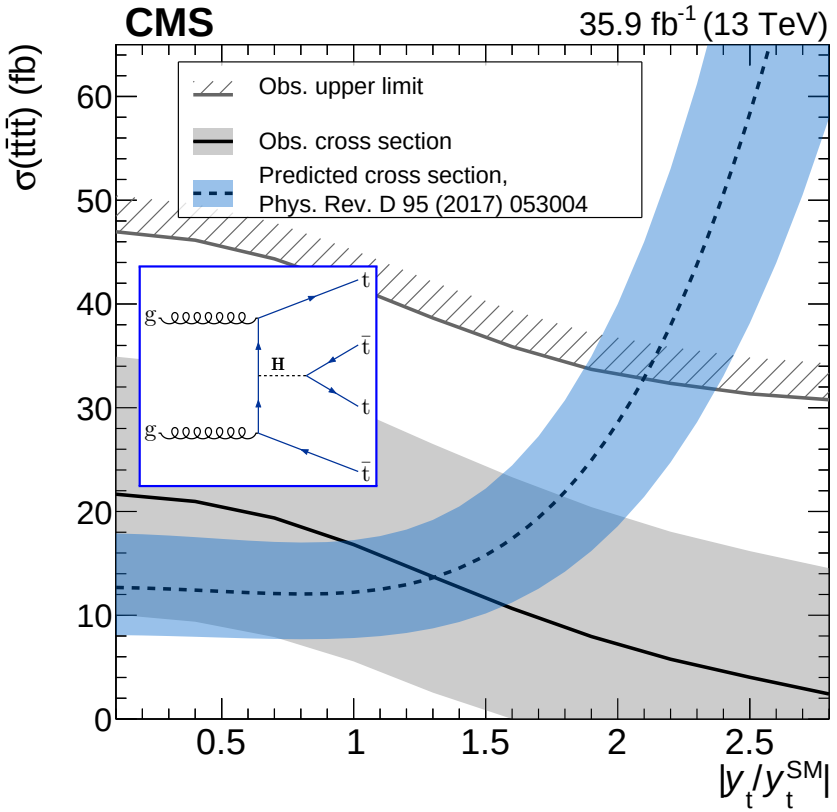
SM 4-top production

SM $t\bar{t}t\bar{t}$ production remains unobserved, could be enhanced in BSM models

- Multi-region search: bins in $N(\text{leptons})$, $N(b)$, $N(\text{jets})$

CMS-TOP-2017-009



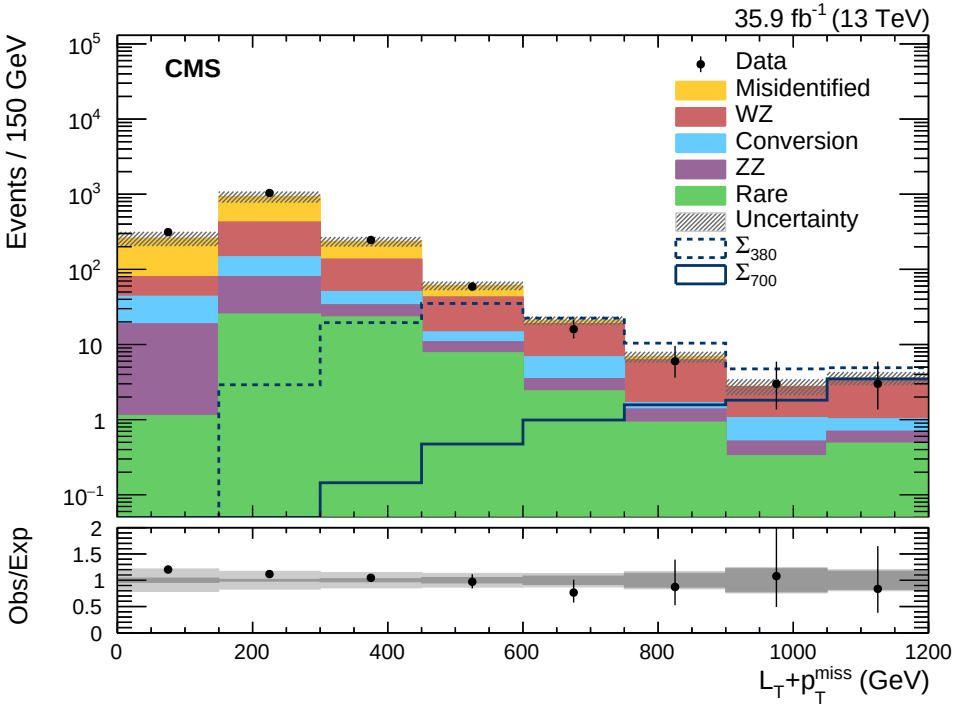


- SM Signal sensitivity: 1.6σ
- Interpreted as constraints on Higgs-top Yukawa

Type-III Seesaw

Similar to Type-I SS, but with new fermion triplet $(\Sigma^0, \Sigma^\pm)$.

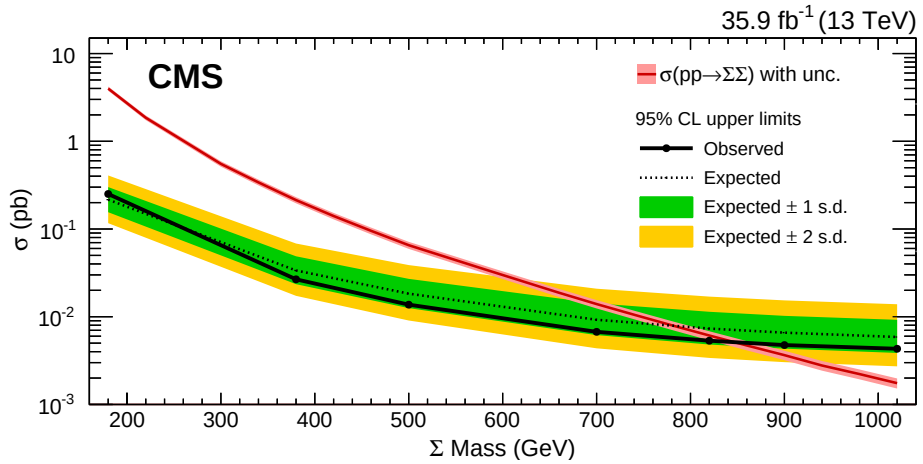
CMS-EXO-2017-006

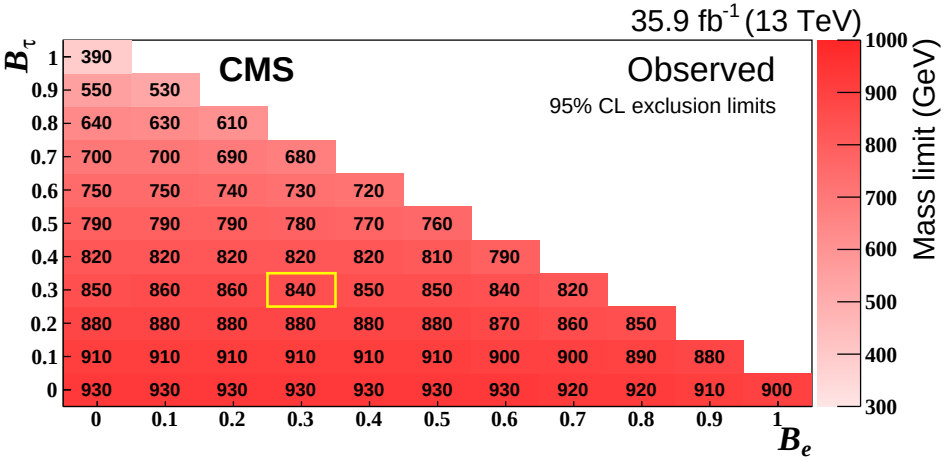


- $\Sigma^0\Sigma^\pm, \Sigma^\pm\Sigma^\mp \rightarrow \geq 3\ell^\pm$
- Discriminant is

$$\left(L_{\mathrm{T}} = \sum_{\mathrm{leptons}} p_{\mathrm{T}}^{\mathrm{lepton}} \right) + E_{\mathrm{T}}^{\mathrm{miss}}$$

- Cover all flavors (e, μ, τ) of heavy neutrino Σ^0

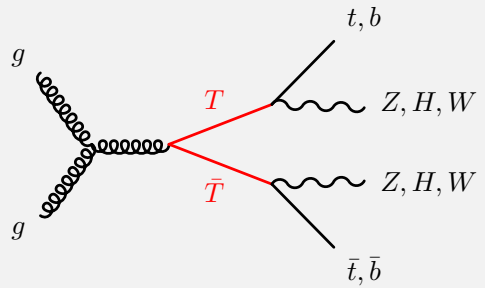


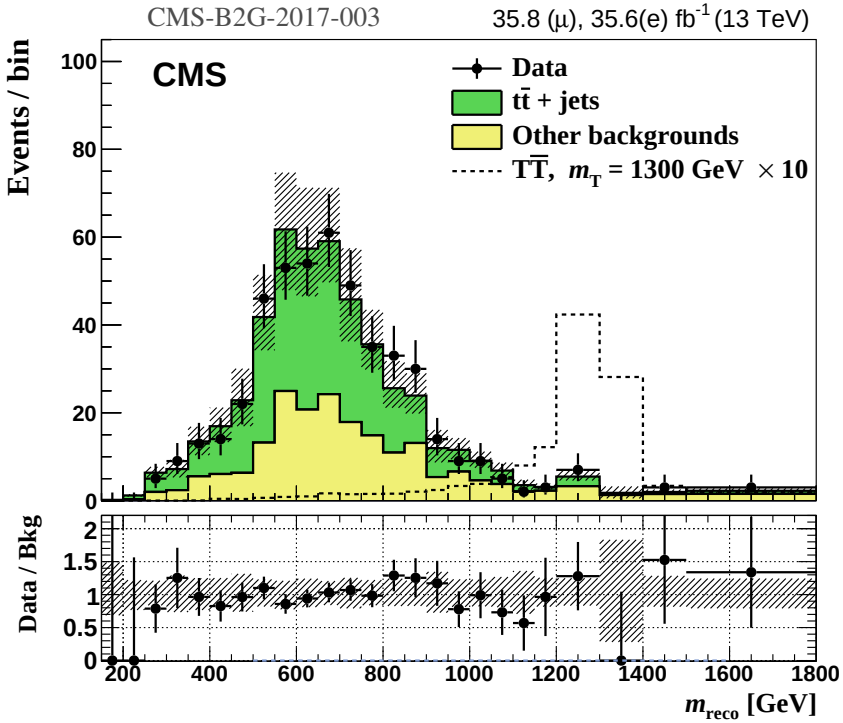


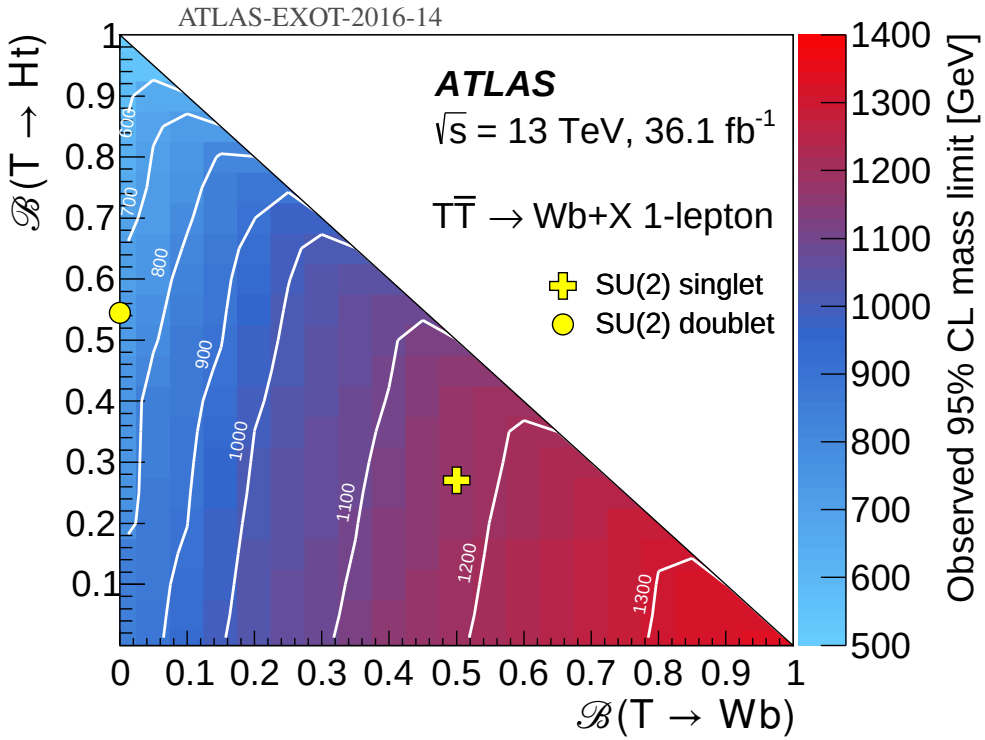
Vector-Like Quarks

Fourth-generation quark searches

- Chiral 4^{th} gen. excluded by Higgs
- Quarks with **vector-like** couplings can regulate Higgs mass in "natural" models

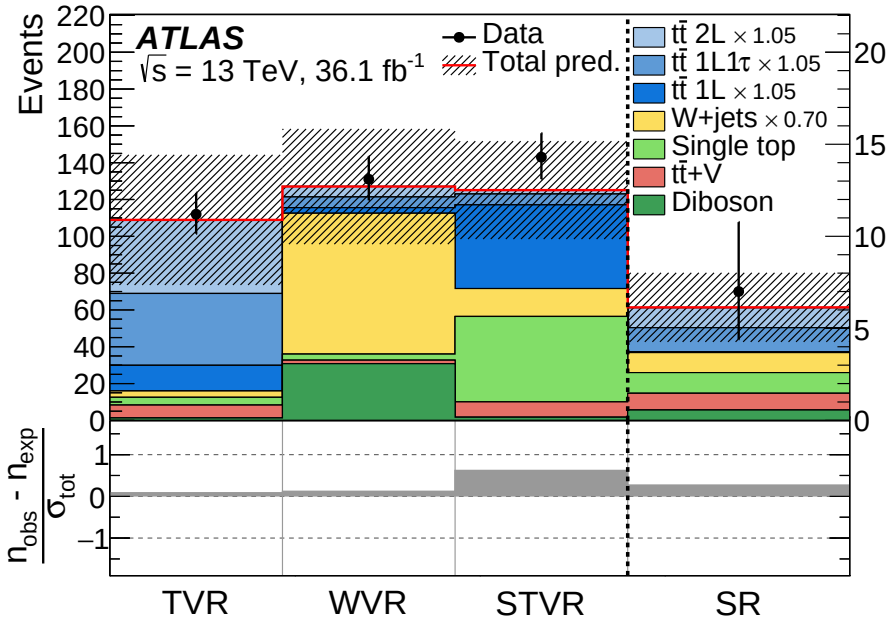


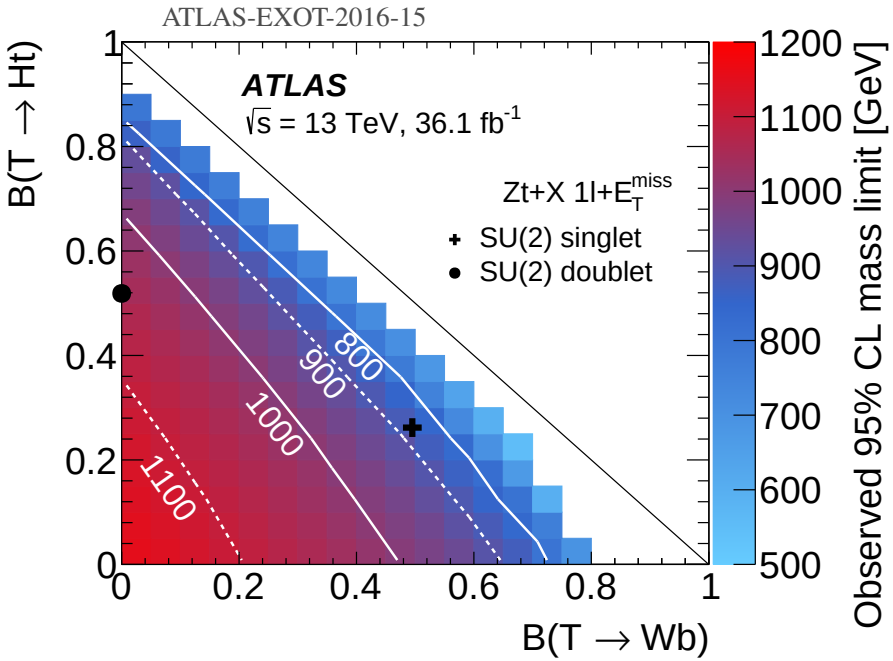




Limits pushing well above 1 TeV for most/all decay modes

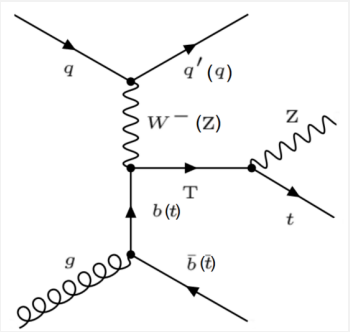
Vector-Like Quarks: $T \to Zt$

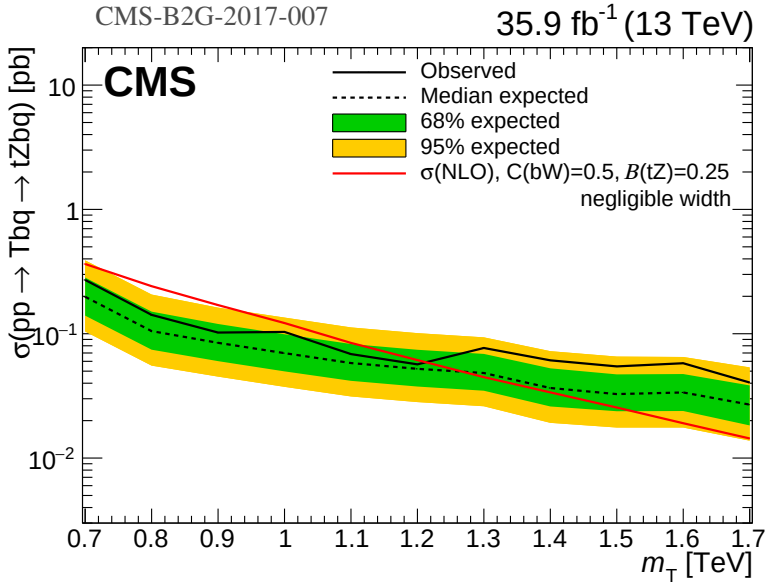




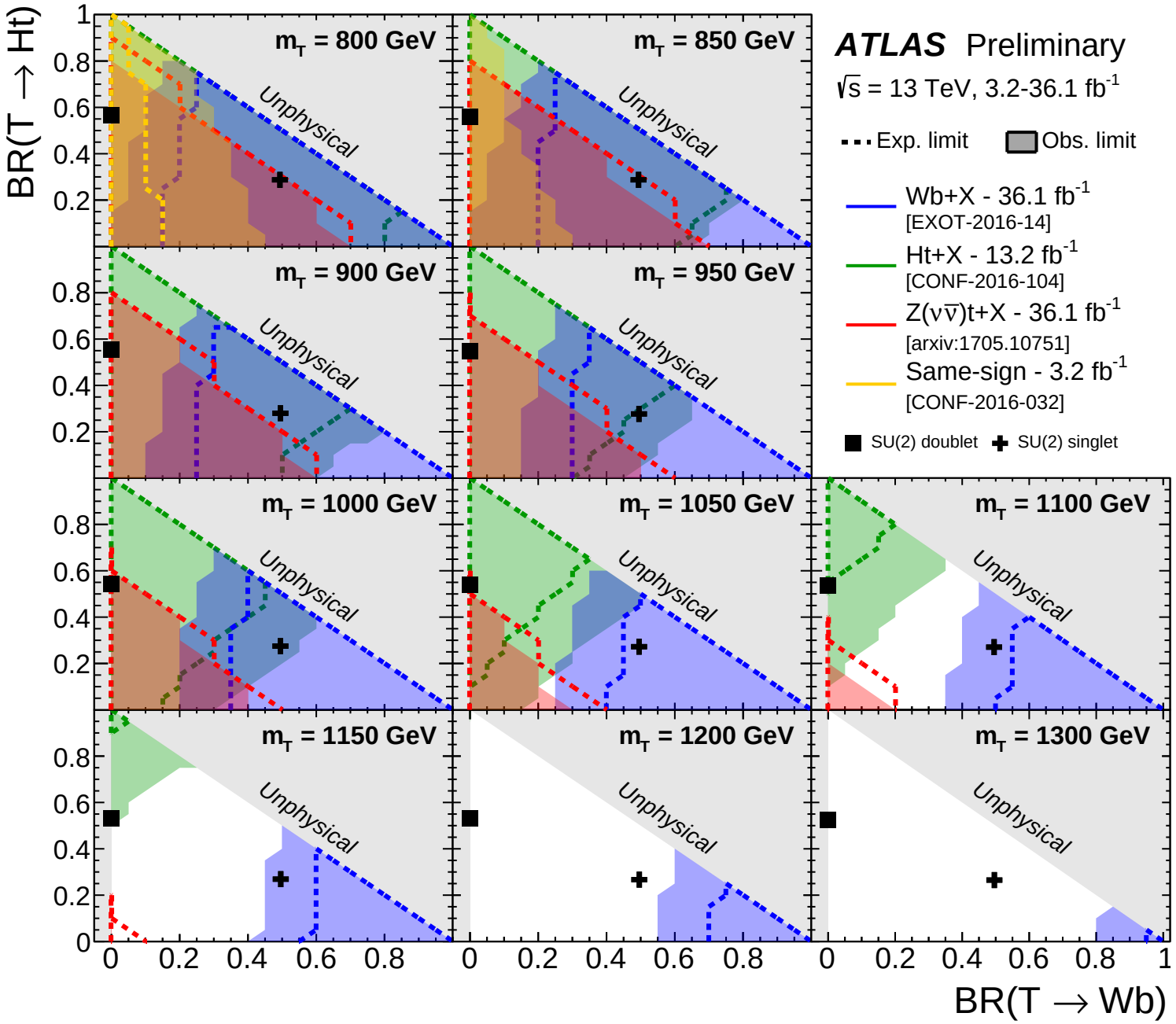
Strongest limits from pair-production:

- **single-production** will eventually be most sensitive at high mass
  - See also CMS $B \to Hb$: CMS-PAS-B2G-17-009





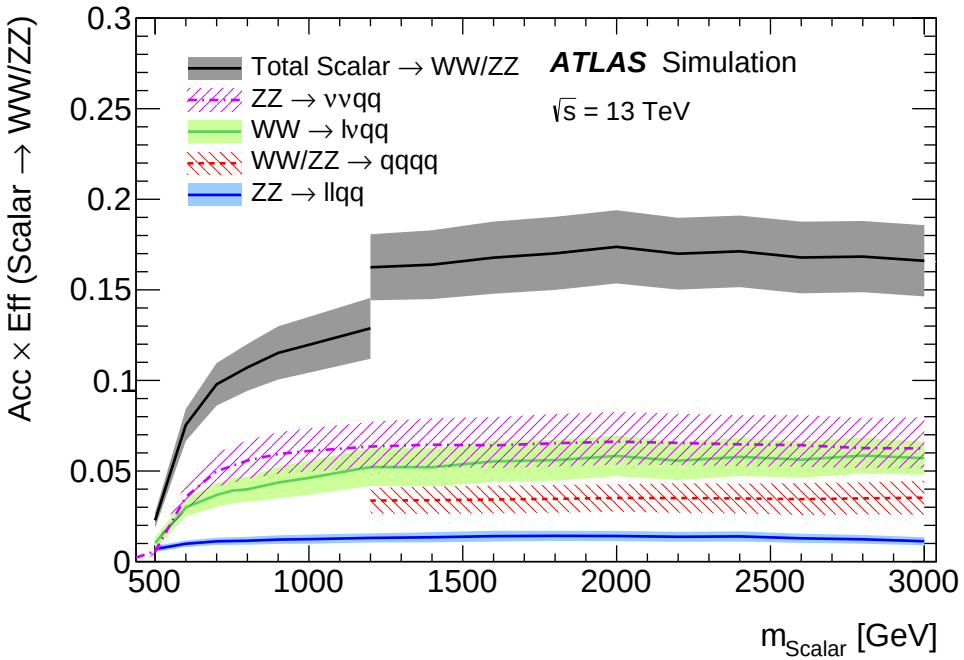
VLQ Summary

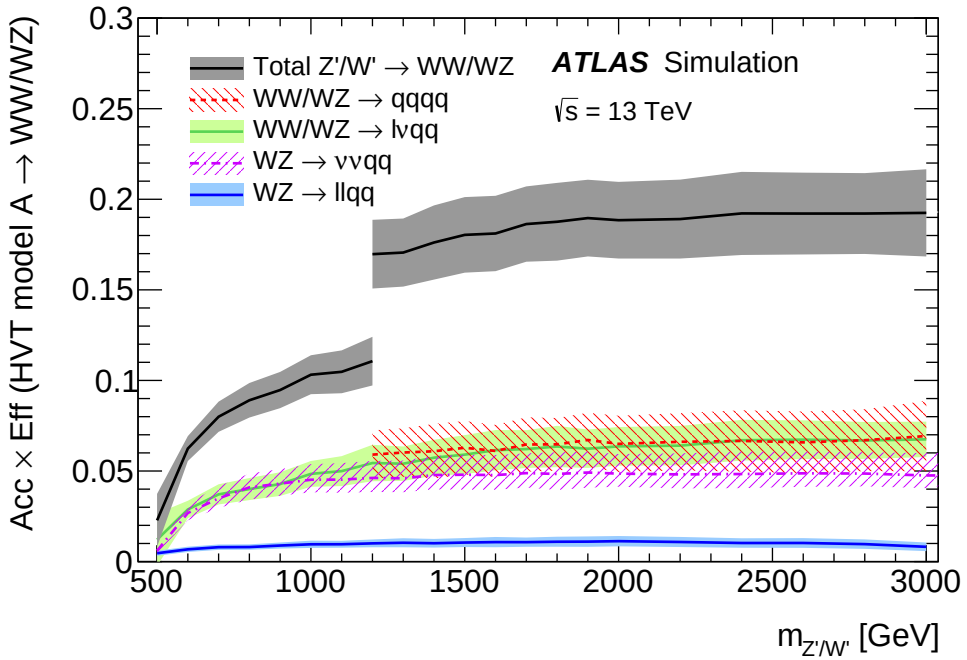

ATLAS Preliminary
√s = 13 TeV, 3.2-36.1 fb-1
Exp. limit
Obs. limit
Wb+X - 36.1 fb-1
[EXOT-2016-14]
Ht+X - 13.2 fb-1
[CONF-2016-104]
Z(νν̄)t+X - 36.1 fb-1
[arxiv:1705.10751]
Same-sign - 3.2 fb-1
[CONF-2016-032]
SU(2) doublet
SU(2) singlet
mT = 800 GeV
mT = 850 GeV
mT = 900 GeV
mT = 950 GeV
mT = 1000 GeV
mT = 1050 GeV
mT = 1100 GeV
mT = 1150 GeV
mT = 1200 GeV
mT = 1300 GeV
Unphysical
BR(T → Ht)
BR(T → Wb)

VV Resonances

A rich program of $WW/WZ/ZZ$ resonance searches:

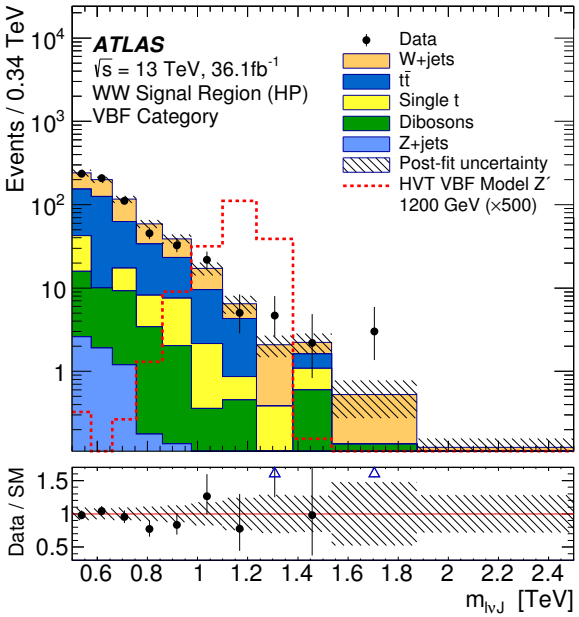
- **Spin-0** $S \to WW/ZZ$: Extended Higgs sectors, scalar singlet
- **Spin-1** $V' \to WZ/WW$: Heavy Vector Triplet, Composite Higgs
- **Spin-2** $G^* \to WW/ZZ$: Extra dimensions

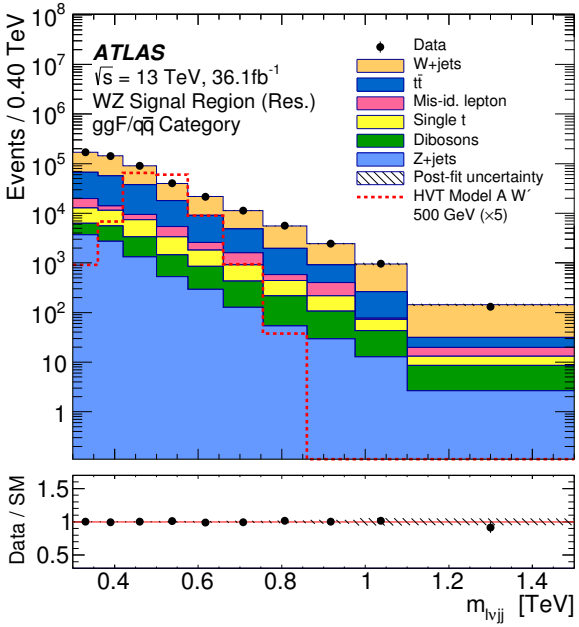


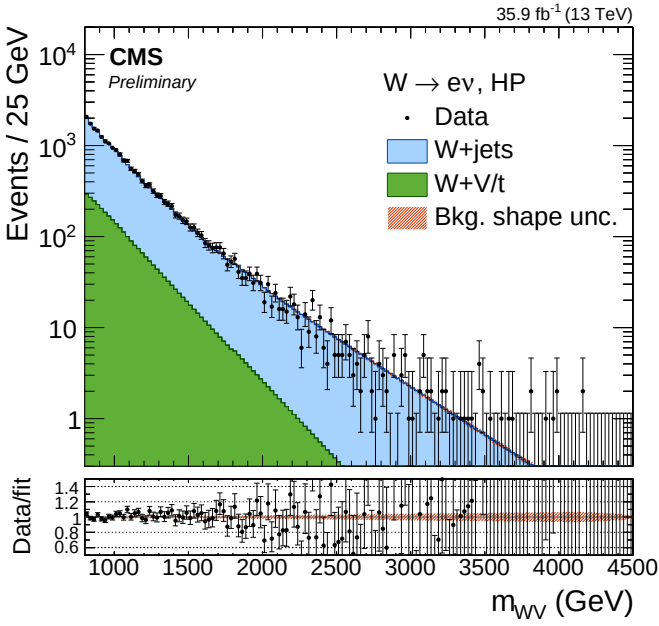


$WW/WZ \to \ell\nu qq$

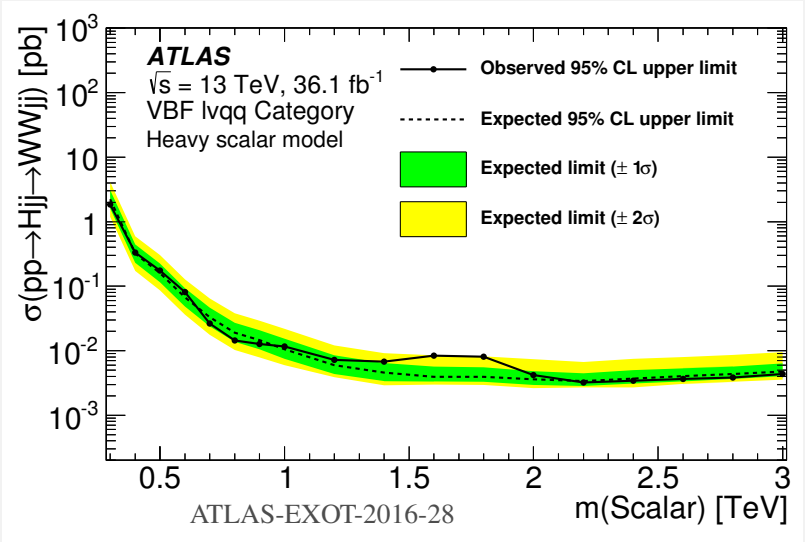
Resolved analysis at low-mass and **boosted boson tagging** for high-mass:



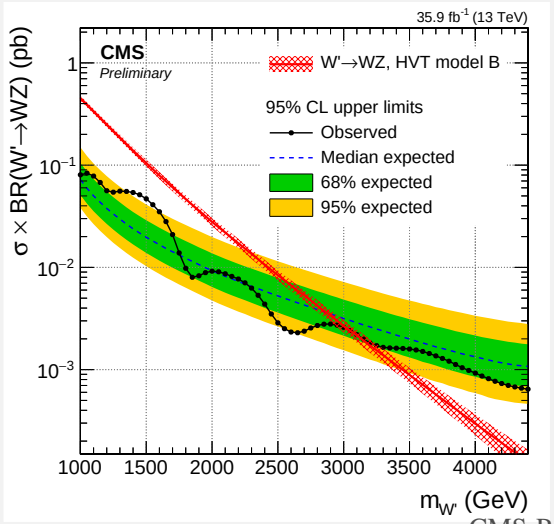




No excess: limits on both VBF and $q\bar{q}/gg$ production:



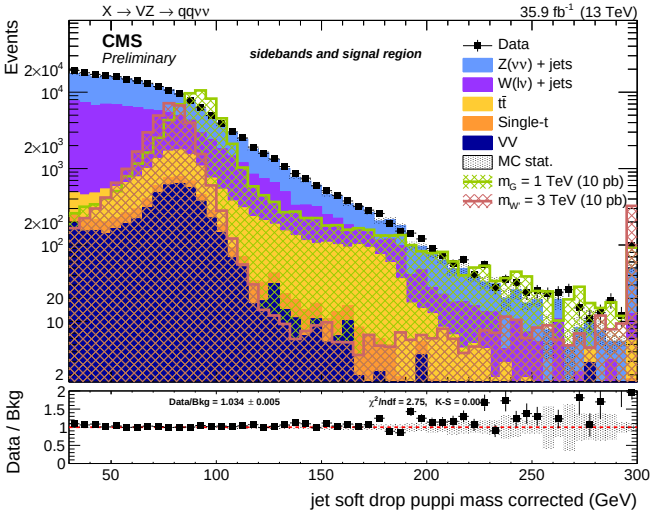
ATLAS-EXOT-2016-28

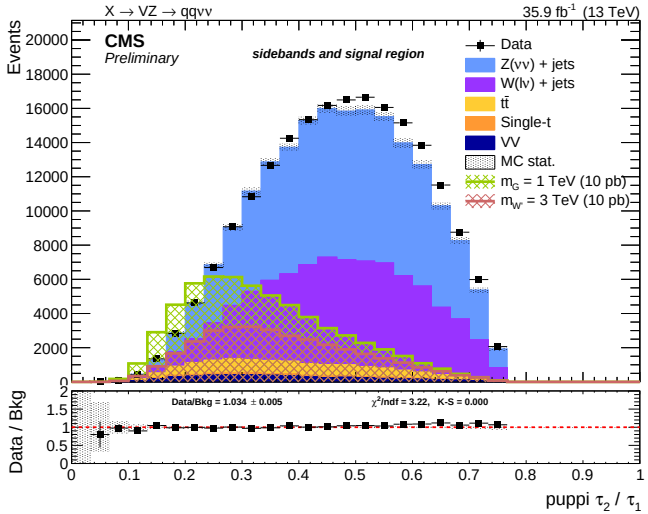


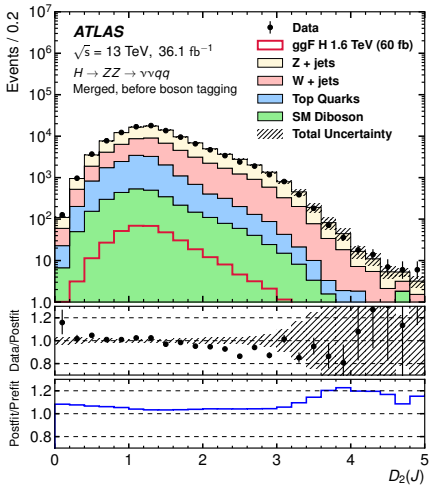
CMS-PAS-B2G-16-029

$ZW/ZZ \to \nu\nu qq/\ell\ell qq$

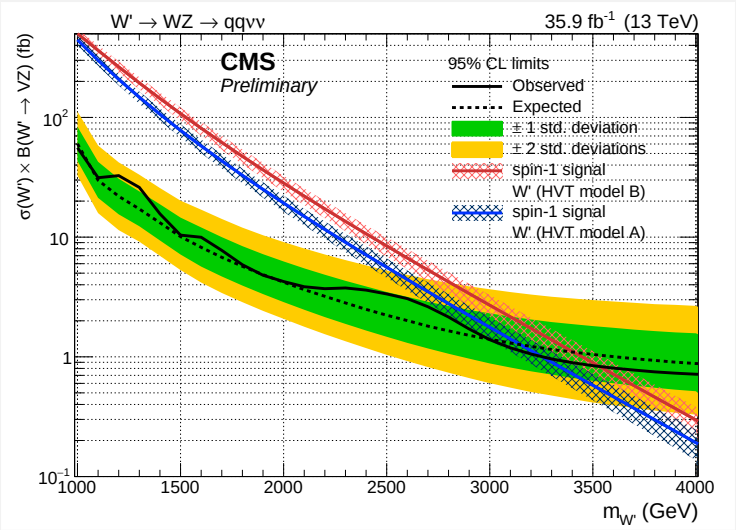
Heavy use of substructure (`puppi`, D_2) to suppress Z+jets backgrounds



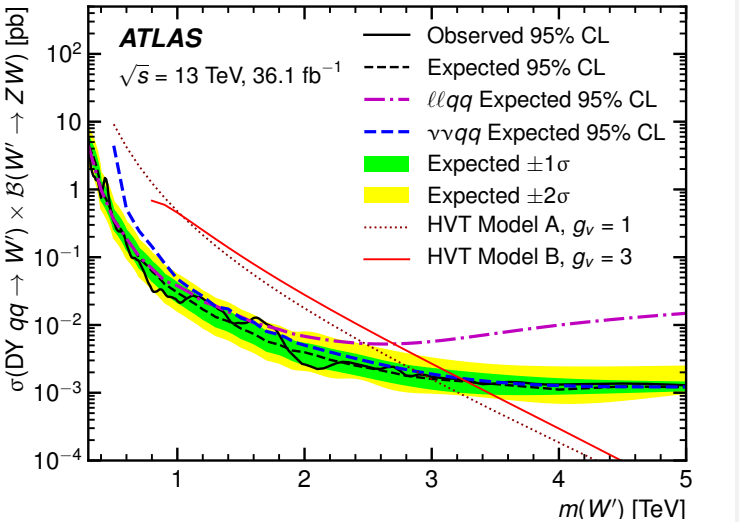




No excesses

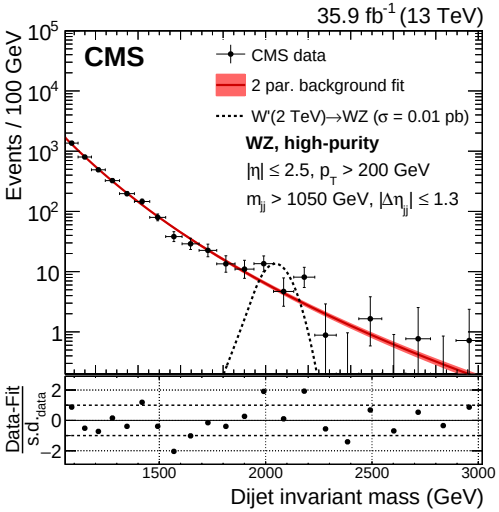


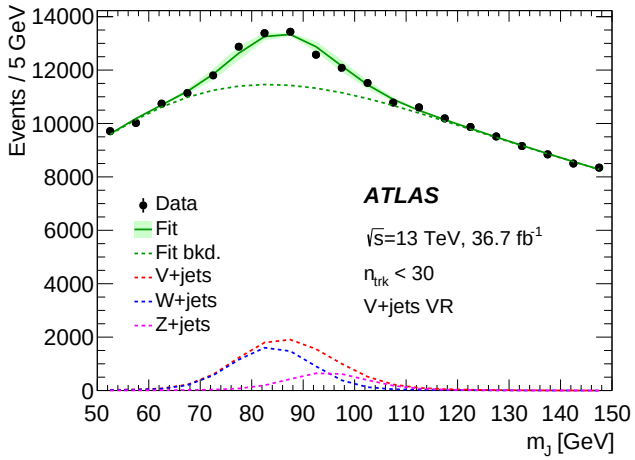
CMS-PAS-B2G-17-005

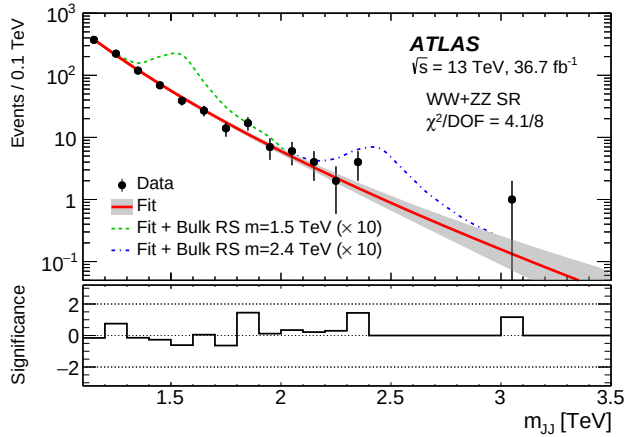


ATLAS-EXOT-2016-29

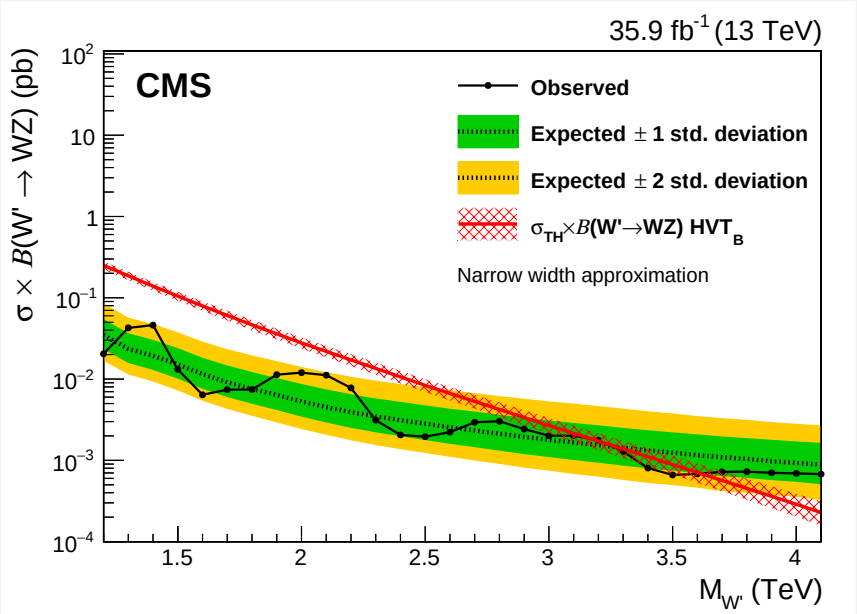
$VV \to q\bar{q}q\bar{q}$



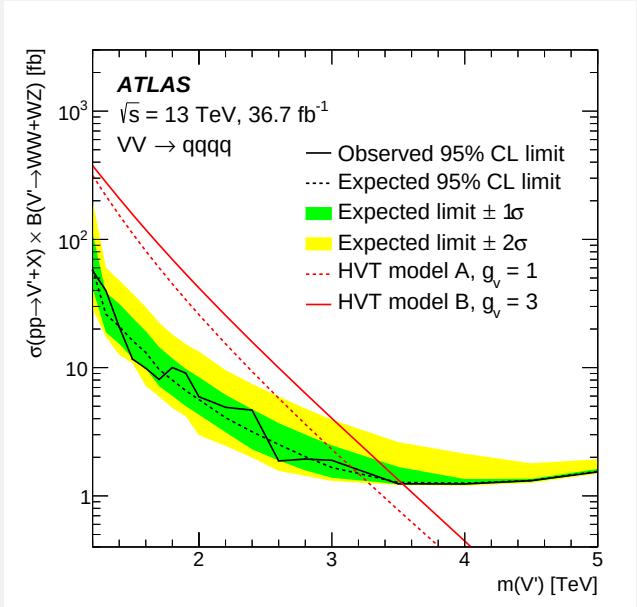




No excesses, limits well above 3 TeV!

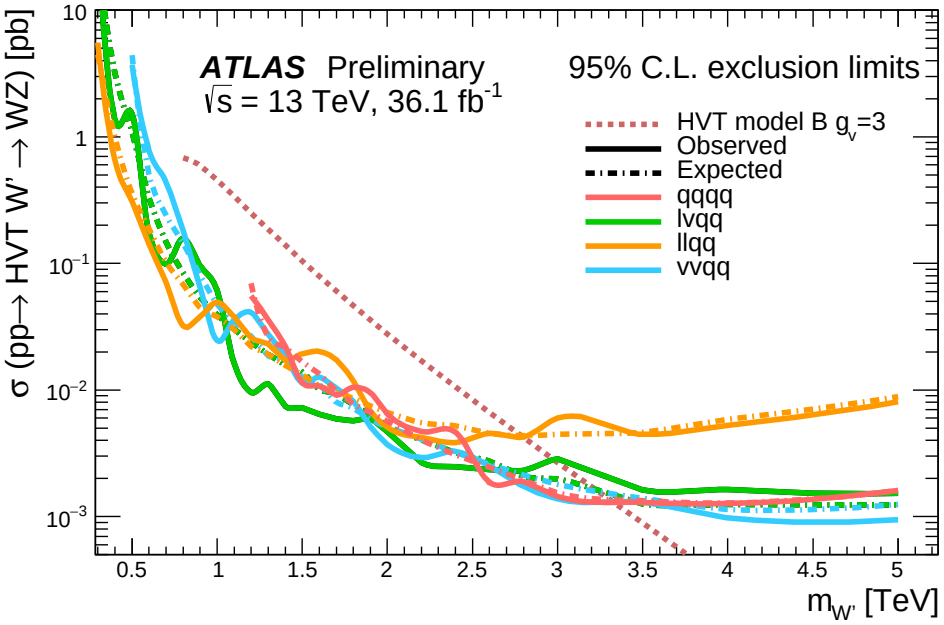


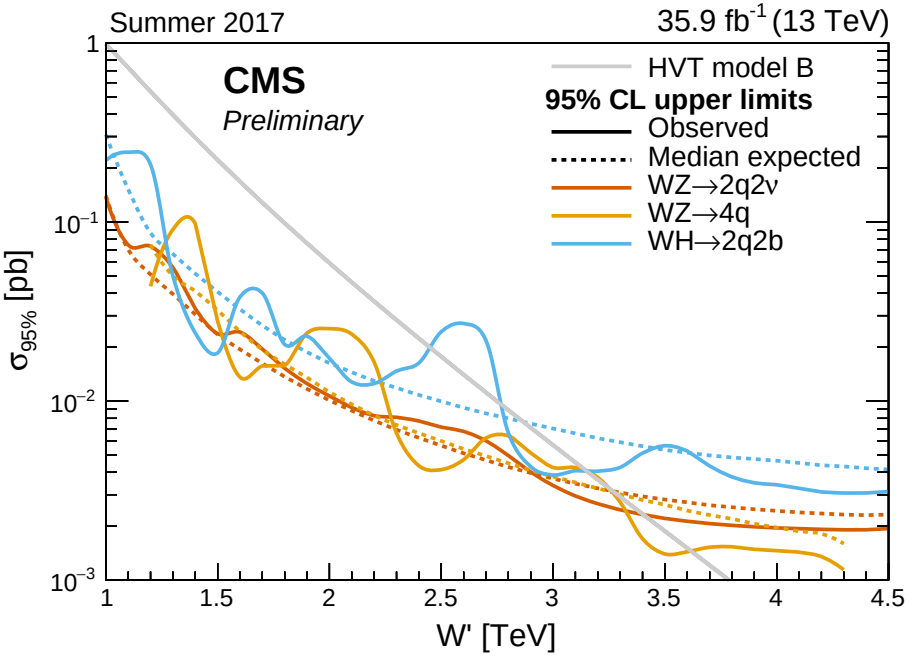
CMS-B2G-17-001



ATLAS-EXOT-2016-19

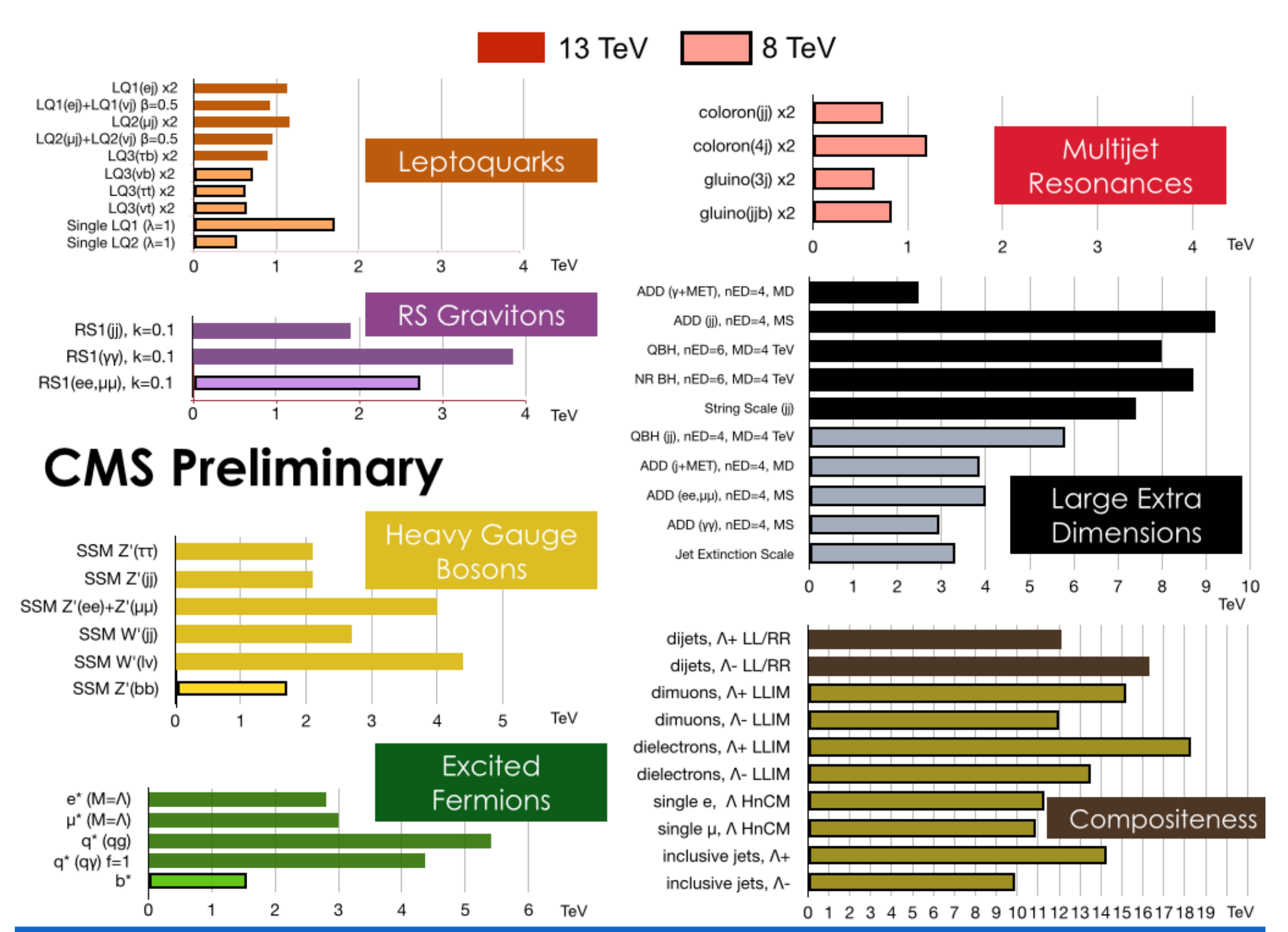
Diboson Summaries





Significant gains in sensitivity with respect to Run 1 and early Run 2:

- Improved boson-tagging algorithms at high-mass
- Pushing to low-mass searches with resolved channels
- Both experiments have previous combinations at 8 and 13 TeV, expect more to come


13 TeV
8 TeV
LQ1(ej) x2
LQ1(ej)+LQ1(νj) β=0.5
LQ2(μj) x2
LQ2(μj)+LQ2(νj) β=0.5
LQ3(τb) x2
LQ3(νb) x2
LQ3(ττ) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
Leptoquarks
0 1 2 3 4 TeV
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS Gravitons
0 1 2 3 4 TeV
CMS Preliminary
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
Heavy Gauge Bosons
0 1 2 3 4 5 TeV
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
Excited Fermions
0 1 2 3 4 5 6 TeV
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Multijet Resonances
0 1 2 3 4 TeV
ADD (γ+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
String Scale (jj)
QBH (jj), nED=4, MD=4 TeV
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
Jet Extinction Scale
Large Extra Dimensions
0 1 2 3 4 5 6 7 8 9 10 TeV
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Compositeness
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 TeV

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (3.2 – 37.0) fb^{-1} $\sqrt{s}$ = 8, 13 TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	36.1	G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	3.2	Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	36.1	W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	36.7	V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.1 TeV	η_{LL}^-	ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/≥ 3 e, μ	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e, μ, 1 γ	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/≥ 3 e, μ	$\geq 2/\geq 1$ b	–	20.3	B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	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, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

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

10^{-1} 1 10 **Mass scale [TeV]**

**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

Conclusion

Run 2 Search Program at Full Speed

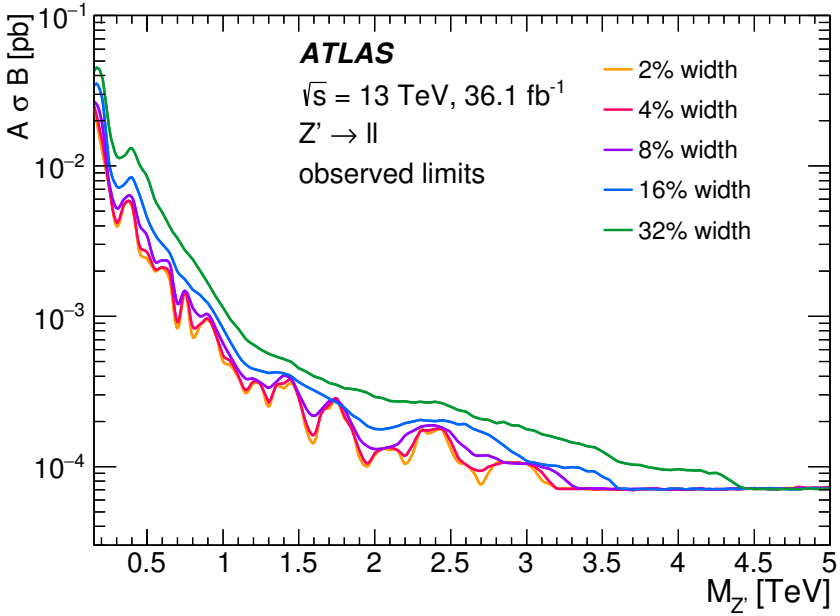
- Exotic searches for **new resonances** continue their drive to **multi-TeV** mass scales

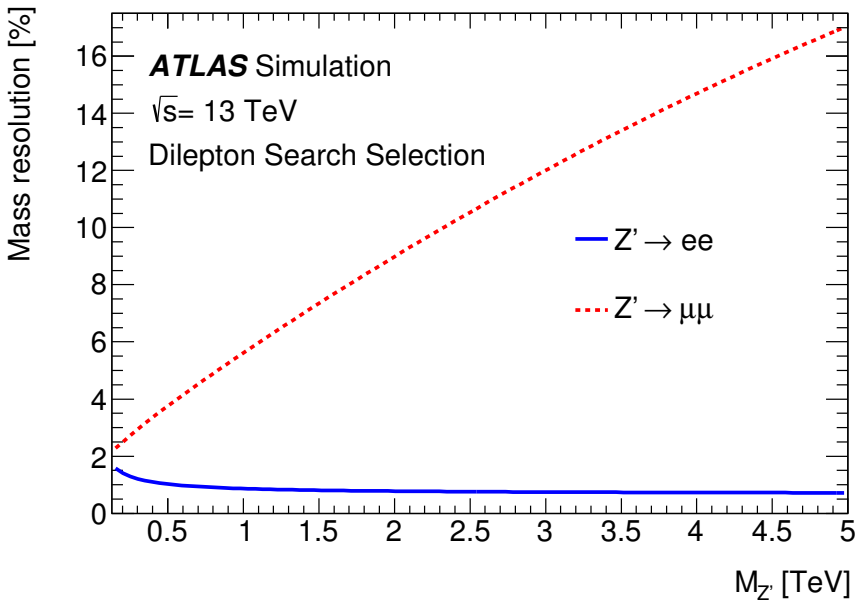
With $\gtrsim$70 fb^{-1} available for 2016+2017 analyses, many more updates to come in months ahead, with ever-increasing emphasis on:

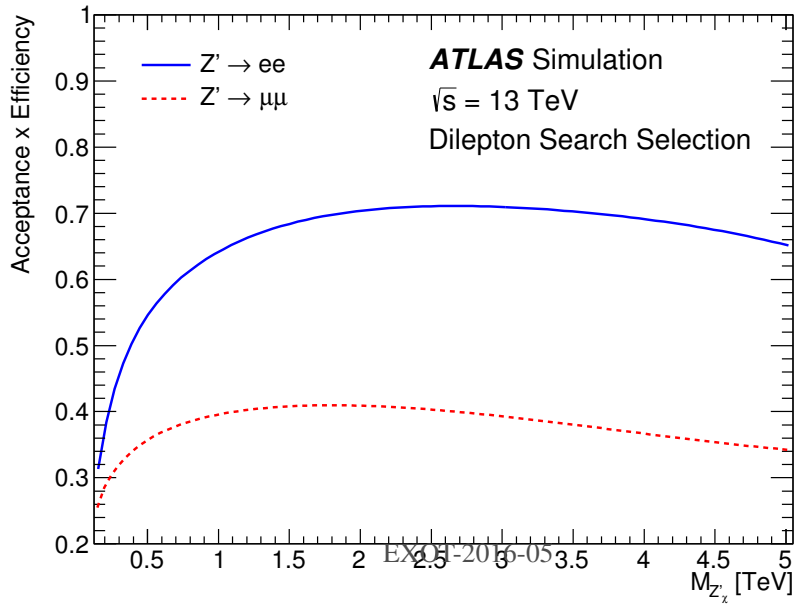
- Revisiting **low-mass** and other neglected parameter space
- Combinations (where appropriate)
- Lower-cross-section processes

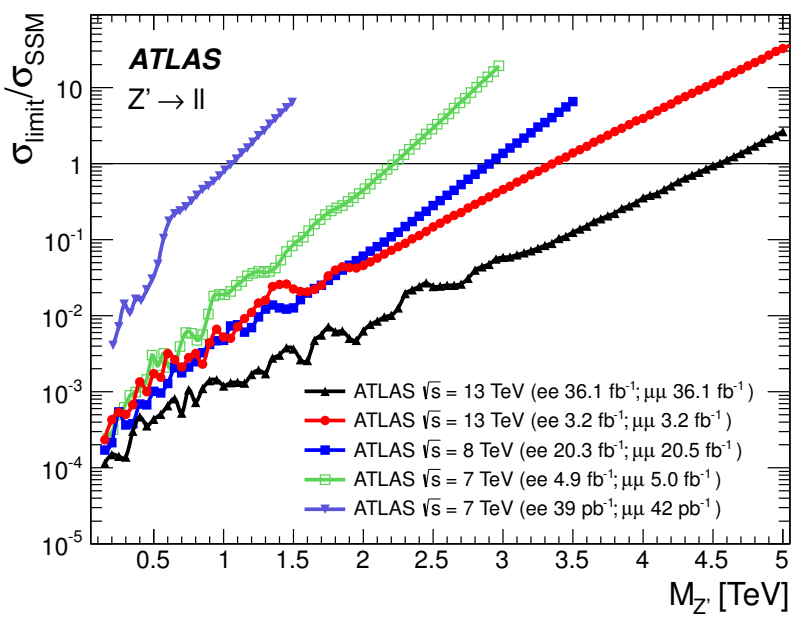
Bonus Slides

Dilepton Auxiliary



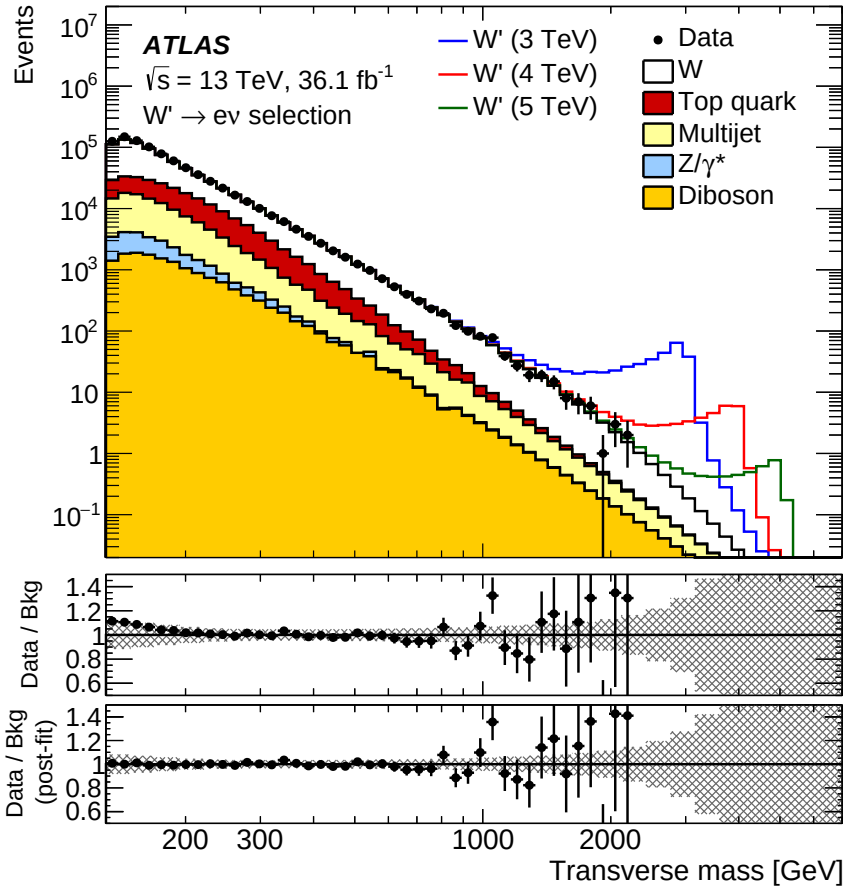


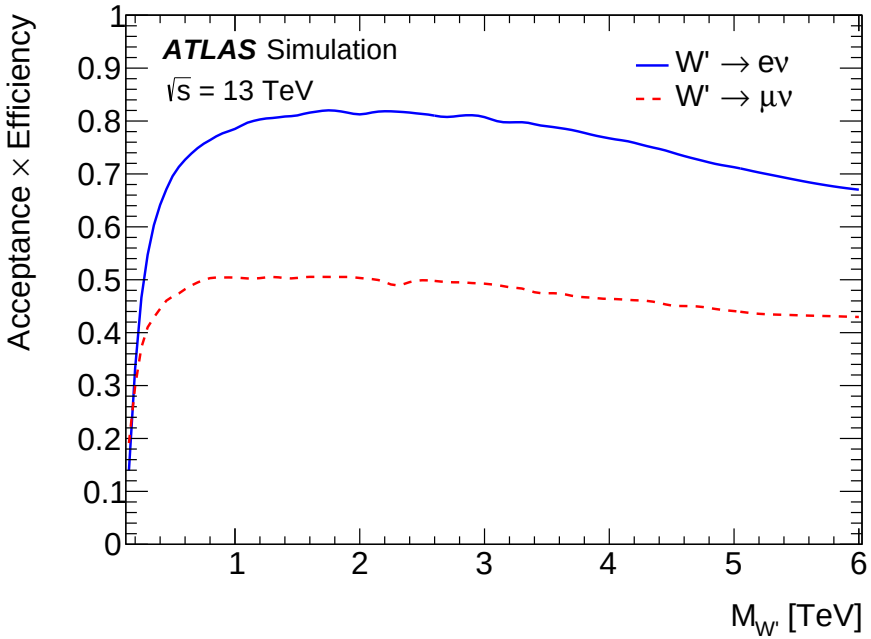




EXOT-2016-05

$W' \to \ell\nu$ Auxiliary

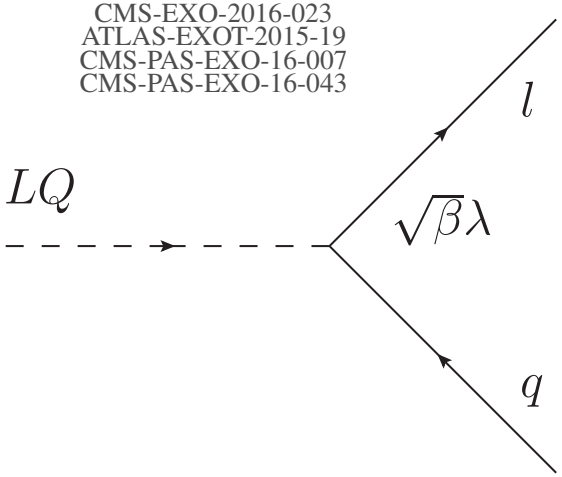




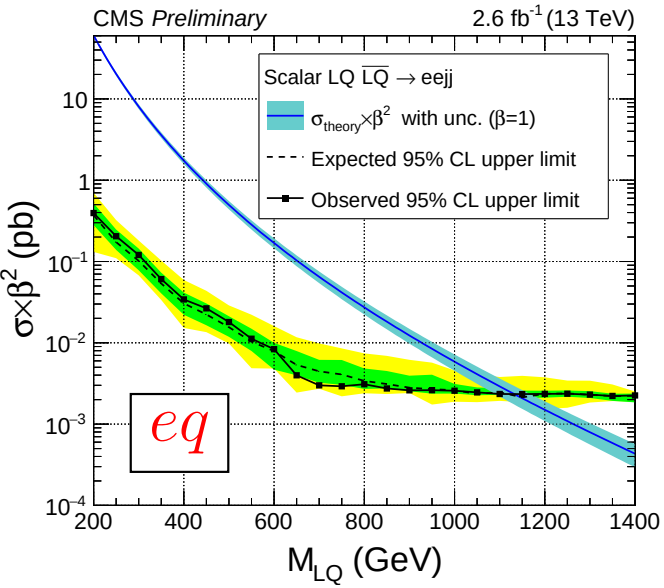
EXOT-2016-06

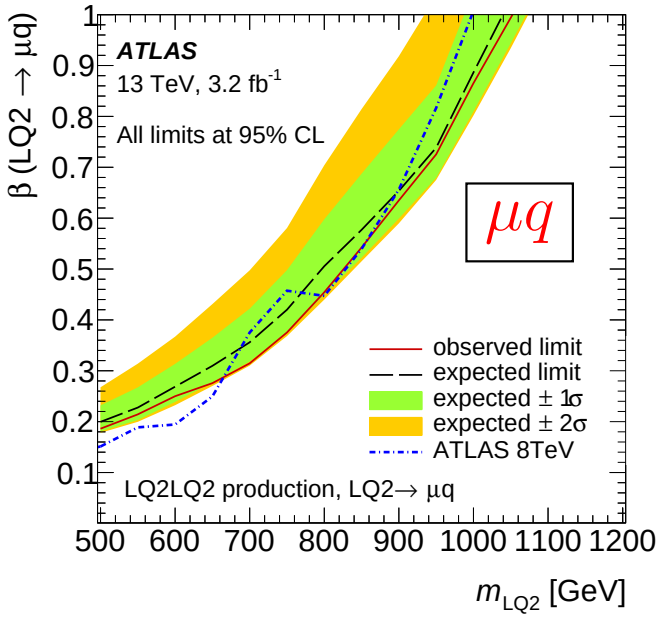
Leptoquarks

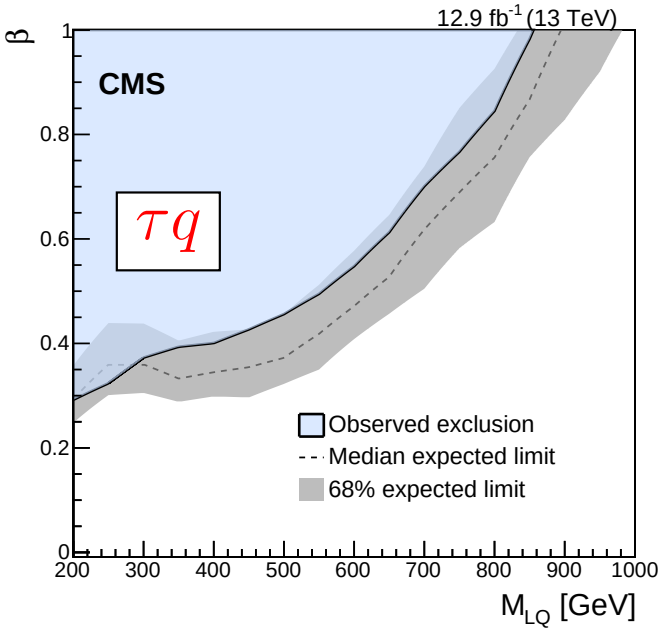
CMS-EXO-2016-023
ATLAS-EXOT-2015-19
CMS-PAS-EXO-16-007
CMS-PAS-EXO-16-043



- Searches for pair-produced 1^{st}, 2^{nd}, 3^{rd} gen. **scalar leptoquarks**
- Dominant backgrounds from Z+jets (eq and μq) or $t\bar{t}(\tau q)$



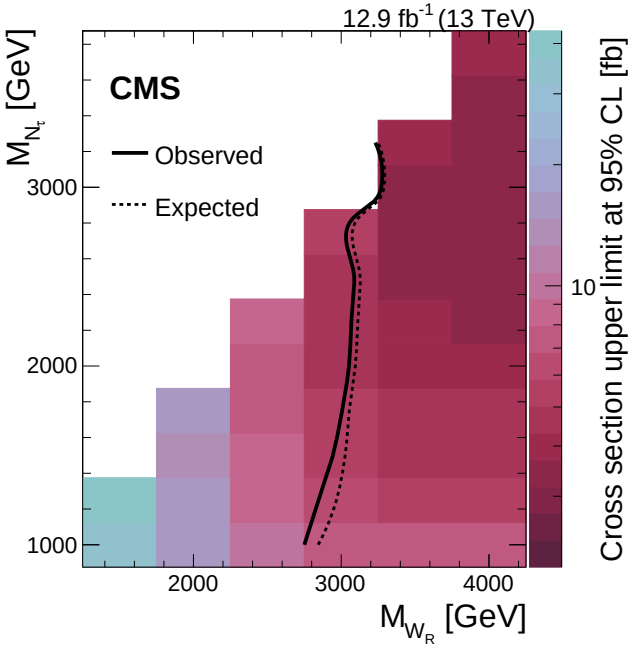


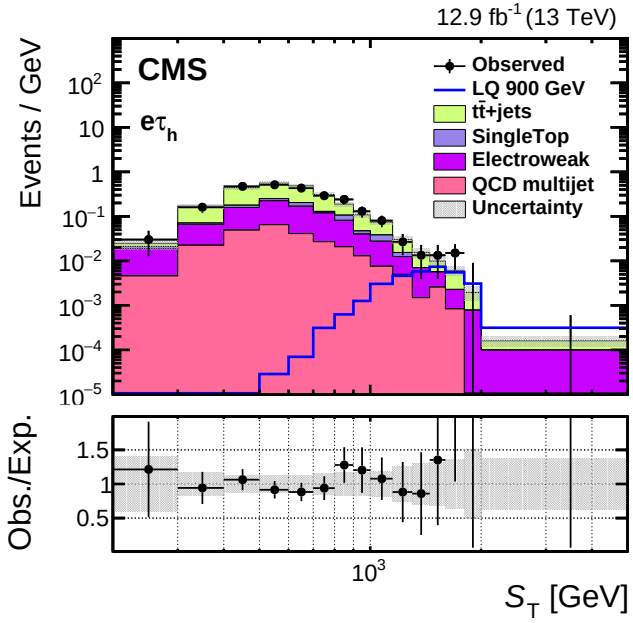


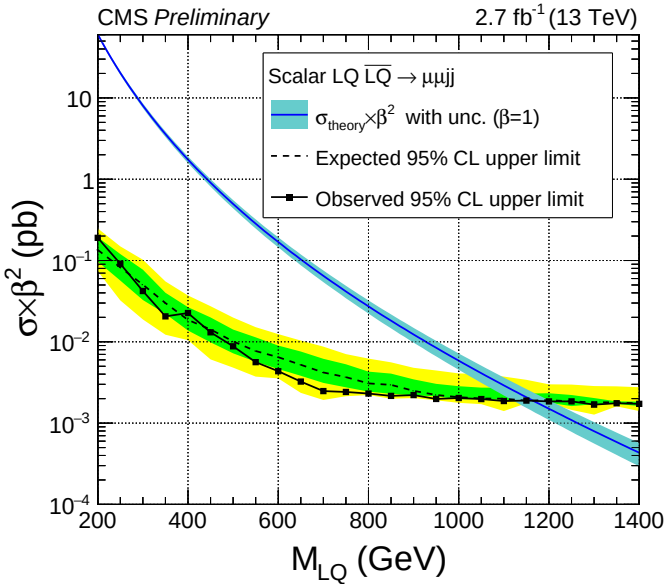
- No significant excesses observed in 2–13 fb^{-1}
- Results in terms of β =BR(LQ $\to \ell q$)

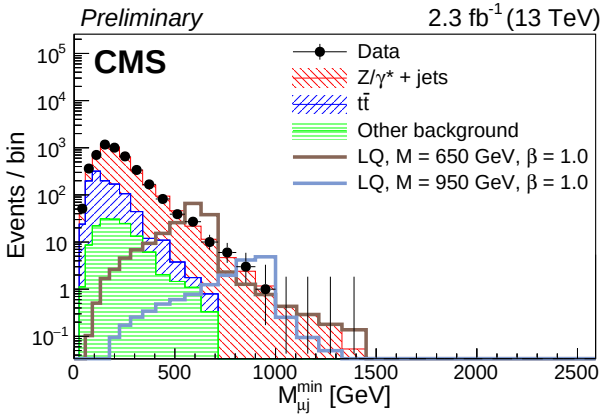
Leptoquarks

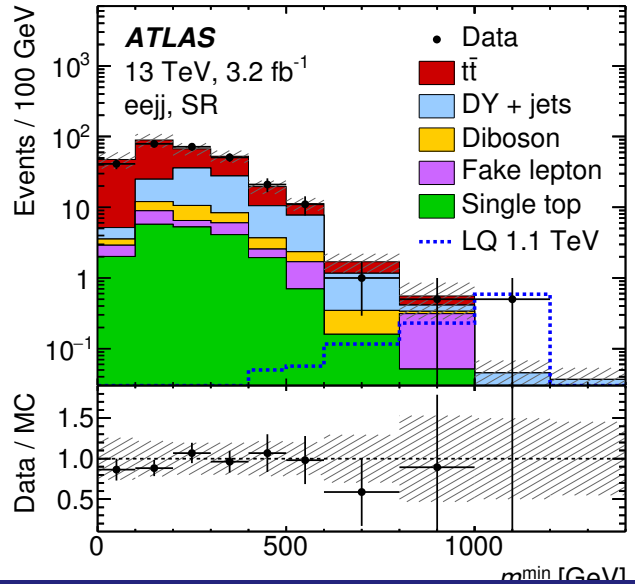
CMS-EXO-16-042
CMS-PAS-EXO-16-007

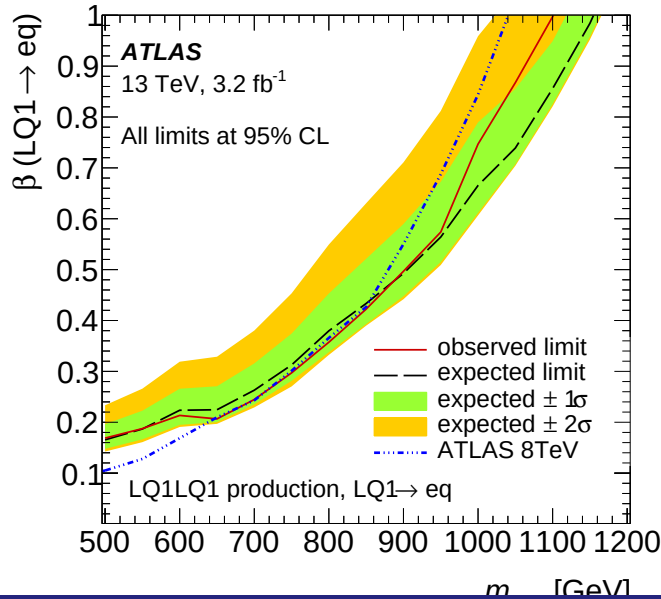




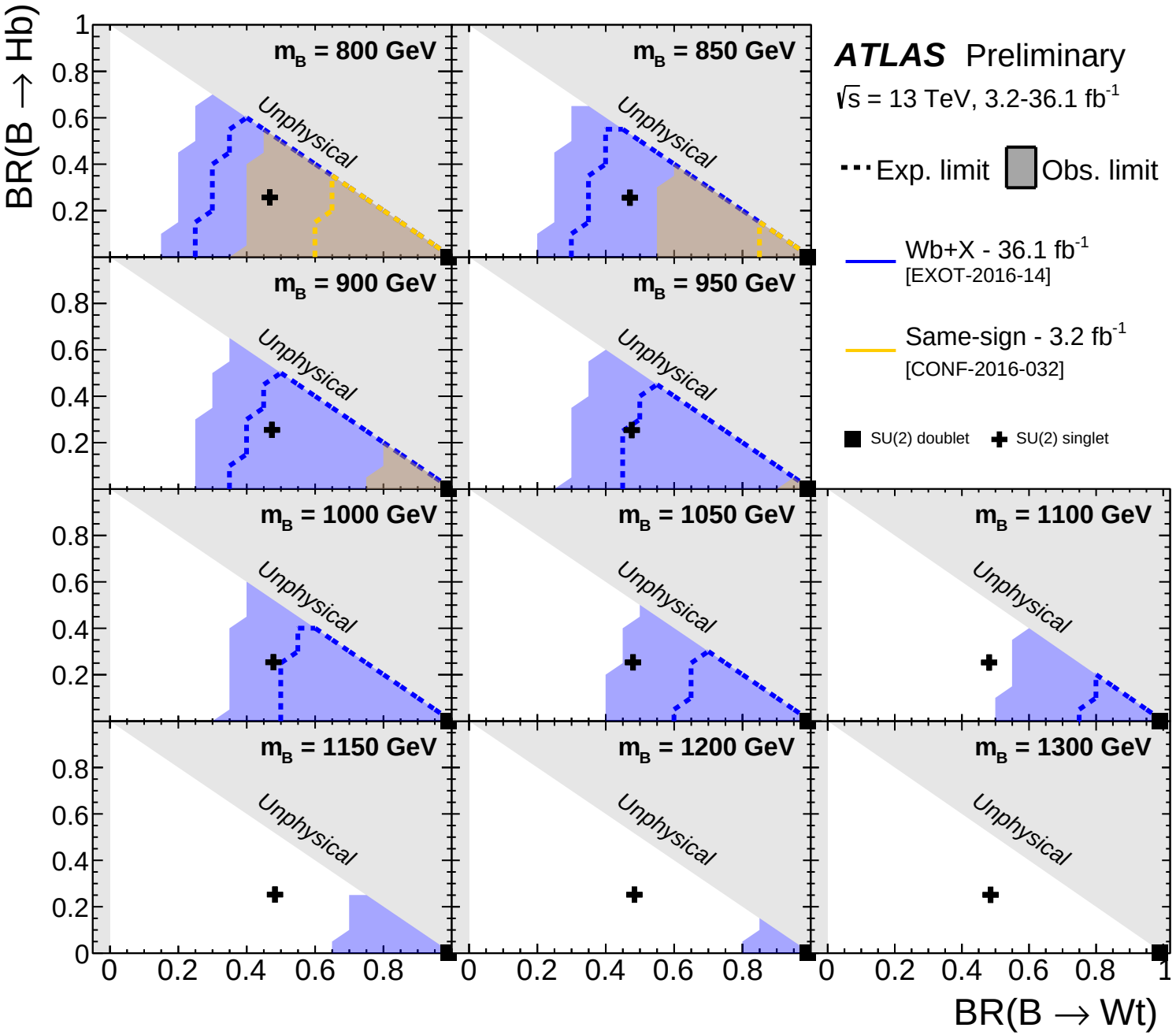








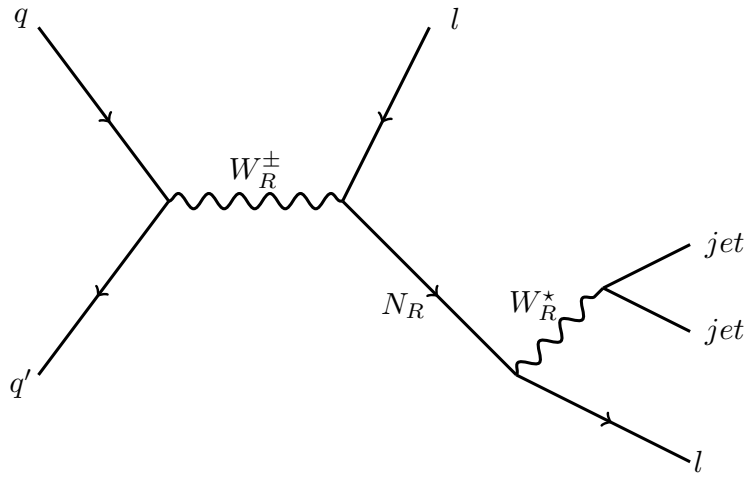
VLQ Summary

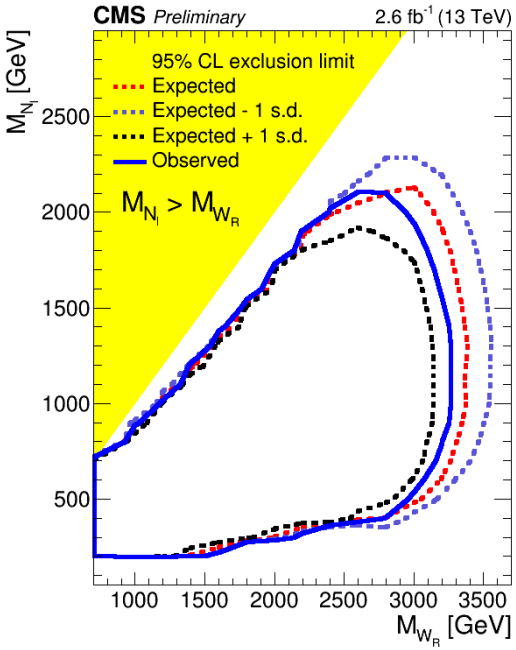

ATLAS Preliminary
√s = 13 TeV, 3.2-36.1 fb-1
Exp. limit
Obs. limit
Wb+X - 36.1 fb-1
[EXOT-2016-14]
Same-sign - 3.2 fb-1
[CONF-2016-032]
SU(2) doublet
SU(2) singlet
mB = 800 GeV
mB = 850 GeV
mB = 900 GeV
mB = 950 GeV
mB = 1000 GeV
mB = 1050 GeV
mB = 1100 GeV
mB = 1150 GeV
mB = 1200 GeV
mB = 1300 GeV
Unphysical
BR(B → Hb)
BR(B → Wt)

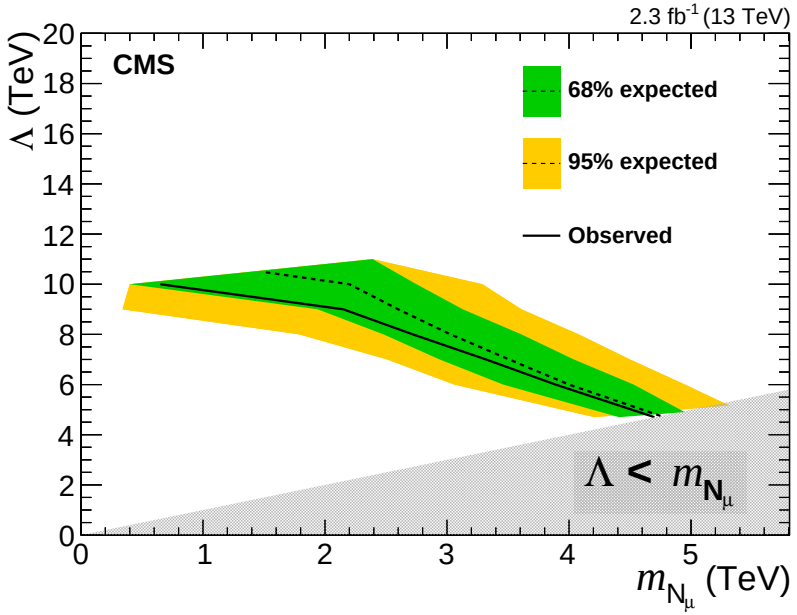
Heavy Neutrinos

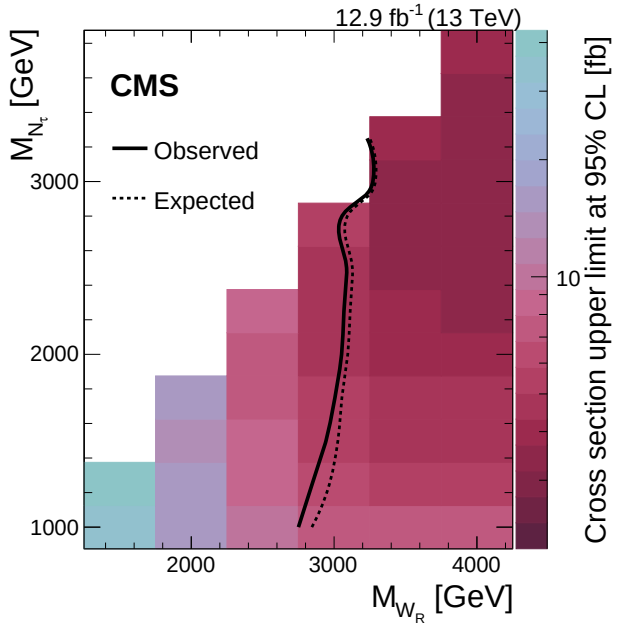
Similar signatures in **Type-I Seesaw**, **LRSM**, and **composite lepton** models

- Heavy ν_{R} "balance" light SM ν
- Seesaw/LRSM models also have W_{R}
- Signature: $\ell^+\ell^- jj$





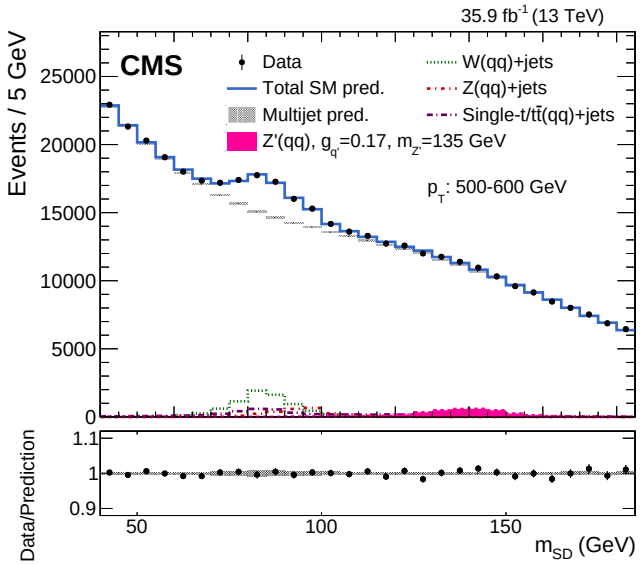


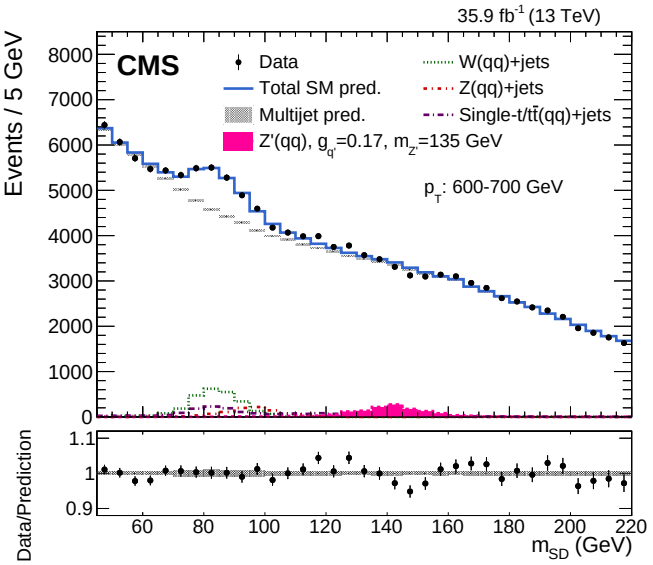


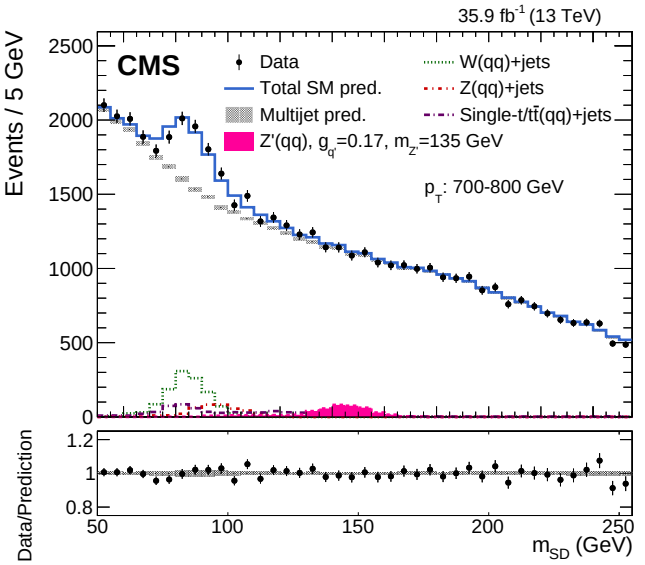
Constraints on heavy ν masses/interactions to >3 TeV

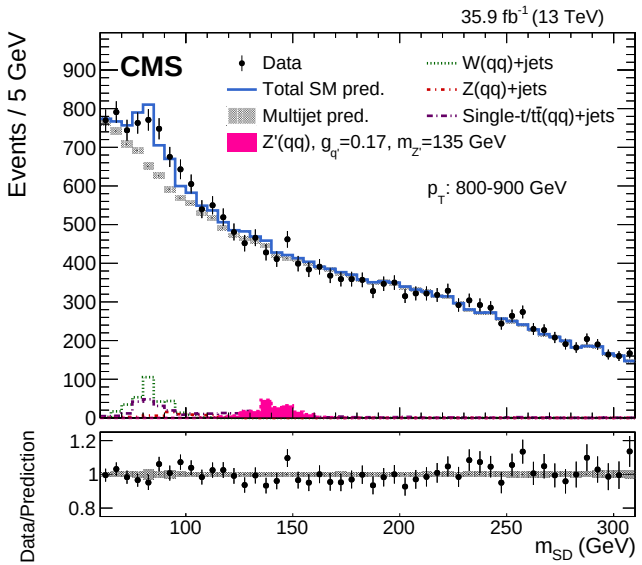
CMS-EXO-2016-026
CMS-EXO-2016-023
CMS-PAS-EXO-16-045

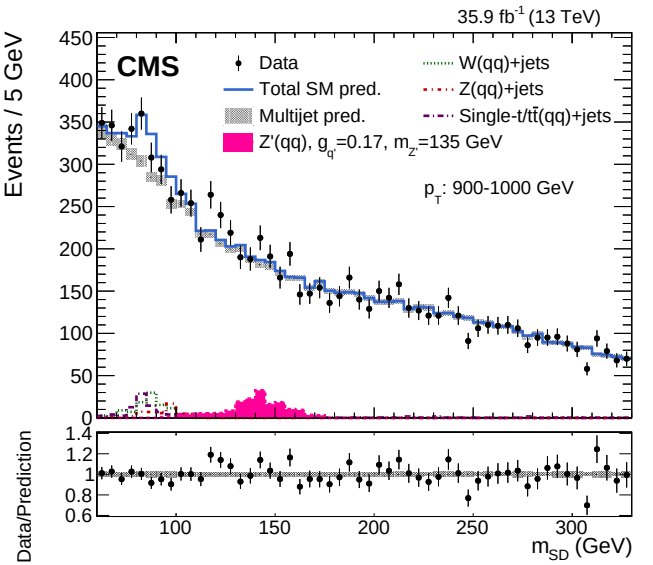
Low-mass dijets



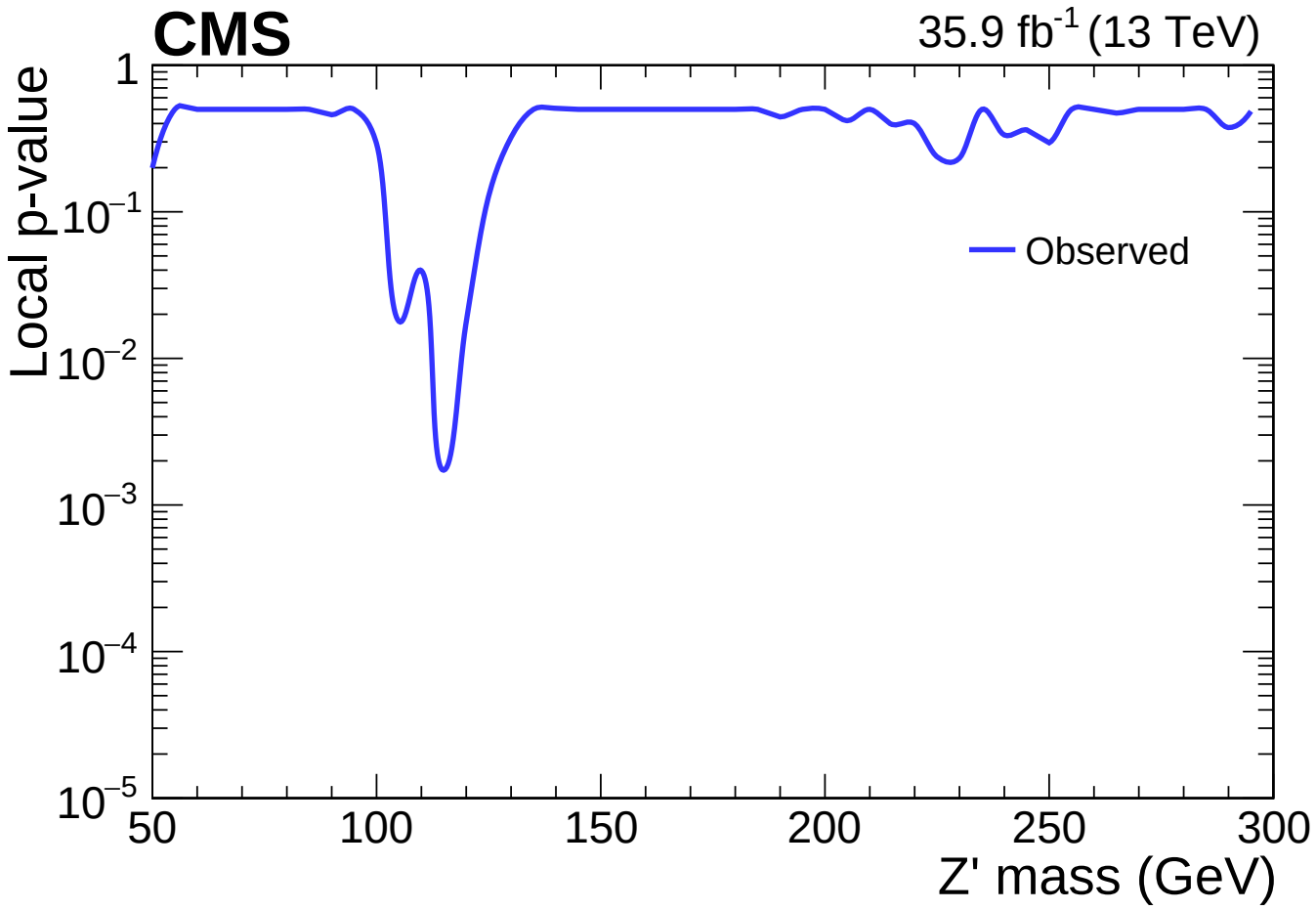








Low-mass dijets



Max significance at 115 GeV: 2.9σ local, 2.2σ global.