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V1.3_200108

Exotic New Physics Searches

Alexander Oh
University of Manchester

on behalf of the **ATLAS Collaboration**

Searches

- Severely constraining the parameter space for BSM physics at the LHC.
- This talk focusses on recent updates, many with full run-2 data sets.

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

$$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$$

ATLAS Preliminary

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

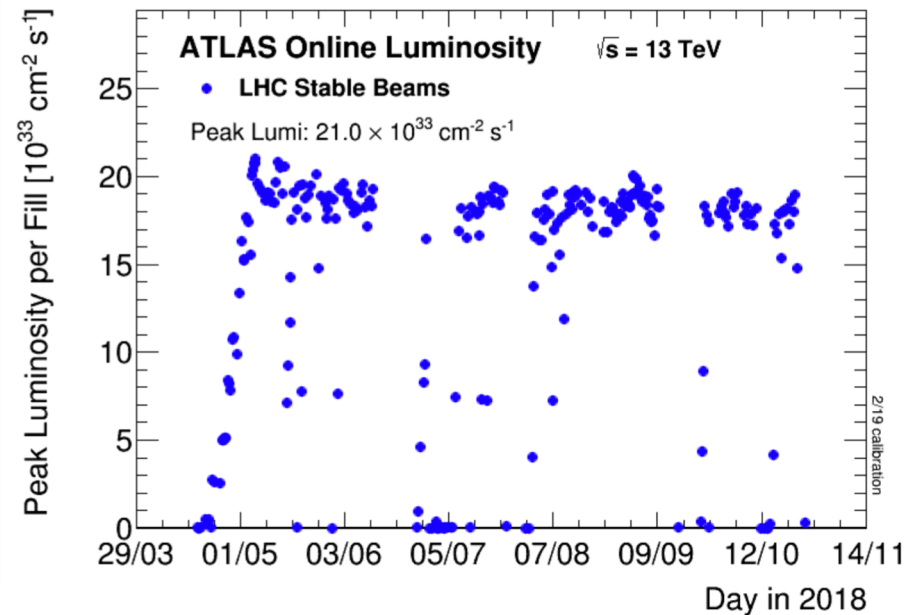
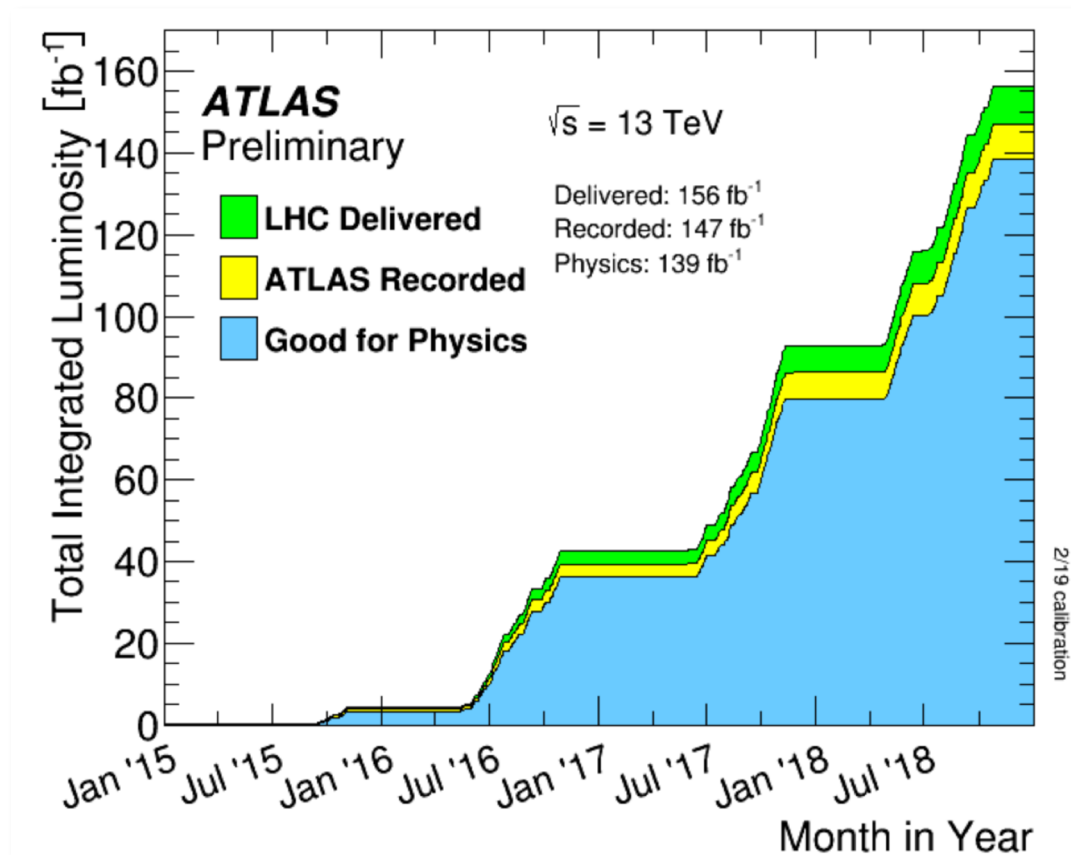
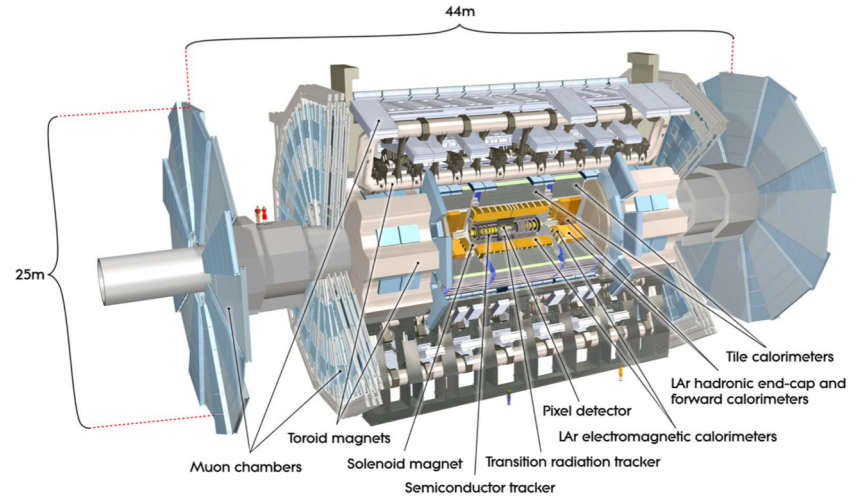
Model	ℓ, γ	Jets†	$E_{\text{T}}^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/g$	$0 e, \mu$	$1-4 j$	Yes	36.1	M_D 7.7 TeV	$n=2$ 1711.03301
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_s 8.6 TeV	$n=3$ HLZ NLO 1707.04147
	ADD QBH	-	$2 j$	-	37.0	M_{BH} 8.9 TeV	$n=6$ 1703.09127
	ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	M_{BH} 8.2 TeV	$n=6, M_D=3 \text{ TeV}$, rot BH 1606.02265
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{BH} 9.55 TeV	$n=6, M_D=3 \text{ TeV}$, rot BH 1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	36.7	G_{KK} mass 4.1 TeV	$k/\bar{M}_{Pl} = 0.1$ 1707.04147
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV	$k/\bar{M}_{Pl} = 1.0$ 1808.02380
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qqqq$	$0 e, \mu$	$2 J$	-	139	G_{KK} mass 1.6 TeV	$k/\bar{M}_{Pl} = 1.0$ ATLAS-CONF-2019-003
	Bulk RS $G_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	36.1	G_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$ 1804.10823
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$ 1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 5.1 TeV	$\Gamma/m = 1\%$ 1903.06248
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass 2.42 TeV	1709.07242
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	36.1	Z' mass 2.1 TeV	1805.09299
	Leptophobic $Z' \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	36.1	Z' mass 3.0 TeV	1804.10823
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	139	W' mass 6.0 TeV	CERN-EP-2019-100
	SSM $W' \rightarrow \tau\nu$	1τ	-	Yes	36.1	W' mass 3.7 TeV	1801.06992
	HVT $V' \rightarrow WZ \rightarrow qqqq$ model B	$0 e, \mu$	$2 J$	-	139	V' mass 3.6 TeV	$g_V = 3$ ATLAS-CONF-2019-003
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	V' mass 2.93 TeV	$\gamma = 3$ 1712.05518
LRSM $W_R \rightarrow tb$	multi-channel	-	-	36.1	W_R mass 3.25 TeV	1807.10473	
LRSM $W_R \rightarrow \mu N_R$	2μ	$1 J$	-	80	W_R mass 5.0 TeV	$m(N_R) = 0.5 \text{ TeV}$, $g_L = g_R$ 1904.12679	
CI	CI $qqqq$	-	$2 j$	-	37.0	Λ 21.8 TeV	η_{LL} 1703.09127
	CI $\ell\ell qq$	$2 e, \mu$	-	-	36.1	Λ 40.0 TeV	η_{LL} 1707.02424
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Λ 2.57 TeV	$ C_{q\ell} = 4\pi$ 1811.02305
DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$1-4 j$	Yes	36.1	m_{DM} 1.55 TeV	$g_a=0.25, g_s=1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301
	Colored scalar mediator (Dirac DM)	$0 e, \mu$	$1-4 j$	Yes	36.1	m_{DM} 1.67 TeV	$g=1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301
	$VV_{\chi\chi}$ EFT (Dirac DM)	$0 e, \mu$	$1 J, \leq 1 j$	Yes	3.2	M_s 700 GeV	$m(\chi) < 150 \text{ GeV}$ 1608.02372
Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)	$0-1 e, \mu$	$1 b, 0-1 J$	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4, \lambda = 0.2, m(\chi) = 10 \text{ GeV}$ 1812.09743	
LQ	Scalar LQ 1 st gen	$1, 2 e$	$\geq 2 j$	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$ 1902.00377
	Scalar LQ 2 nd gen	$1, 2 \mu$	$\geq 2 j$	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$ 1902.00377
	Scalar LQ 3 rd gen	2τ	$2 b$	-	36.1	LQ_3^+ mass 1.03 TeV	$\mathcal{B}(LQ_3^+ \rightarrow b\tau) = 1$ 1902.08103
	Scalar LQ 3 rd gen	$0-1 e, \mu$	$2 b$	Yes	36.1	LQ_3^+ mass 970 GeV	$\mathcal{B}(LQ_3^+ \rightarrow t\tau) = 0$ 1902.08103
Heavy quarks	VLO $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV	SU(2) doublet 1808.02343
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet 1808.02343
	VLO $T_{3/3} T_{3/3} T_{3/3} \rightarrow Wt + X$	$2(SS) \geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	$T_{3/3}$ mass 1.64 TeV	$\mathcal{B}(T_{3/3} \rightarrow Wt) = 1, c(T_{3/3} Wt) = 1$ 1807.11893	
	VLO $Y \rightarrow Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$ 1812.07343
VLO $B \rightarrow Hb + X$	$0 e, \mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV	$k_B = 0.5$ ATLAS-CONF-2018-024	
VLO $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4 j$	Yes	20.3	Q mass 690 GeV	1509.04261	
Excited fermions	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	139	q^* mass 6.7 TeV	only u^* and d^* , $\Lambda = m(q^*)$ ATLAS-CONF-2019-007
	Excited quark $q^* \rightarrow q\gamma$	1γ	$1 j$	-	36.7	q^* mass 5.3 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1709.10440
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	36.1	b^* mass 2.6 TeV	1805.09299
	Excited lepton ℓ^*	$3 e, \mu$	-	-	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$ 1411.2921
Excited lepton ν^*	$3 e, \mu, \tau$	-	-	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921	
Other	Type III Seesaw	$1 e, \mu$	$\geq 2 j$	Yes	79.8	N^0 mass 560 GeV	$m(W_R) = 4.1 \text{ TeV}$, $g_L = g_R$ 1809.11105
	LRSM Majorana ν	2μ	$2 j$	-	36.1	N_R mass 3.2 TeV	DY production 1710.09748
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow t\tau) = 1$ 1411.2921
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $ q = 5e$ 1812.03673
	Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV	DY production, $ g = 1g_D$, spin 1/2 1905.10130
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 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).

Run-2 data sample

- Run-2 data-set 139 fb^{-1} at $\sqrt{s}=13 \text{ TeV}$.
- Peak luminosity $2.1 \text{ e}34 \text{ cm}^{-2} \text{ s}^{-1}$



Di-boson resonance

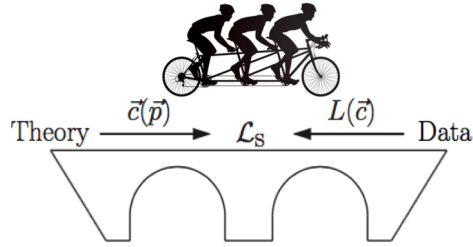
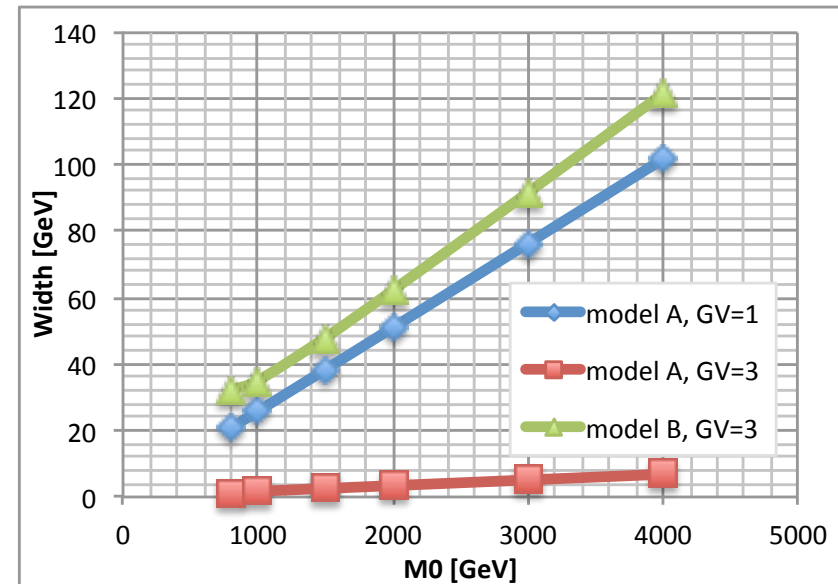
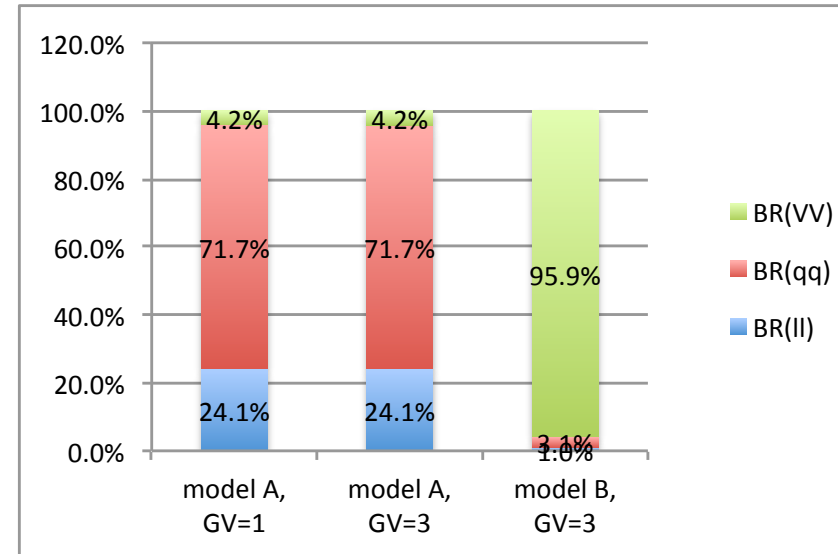


Figure 1.1: Pictorial view of the Bridge Method.

■ Heavy Vector Triplet

arXiv:1402.4431v2

- Effective Lagrangian with additional fields $V^{+,0,-}$.
- Can tune mass, couplings to fermions and bosons.
- Two benchmark scenarios
 - **A**: weakly coupled extended gauge symmetry
 - **B**: strongly coupled minimal composite higgs model

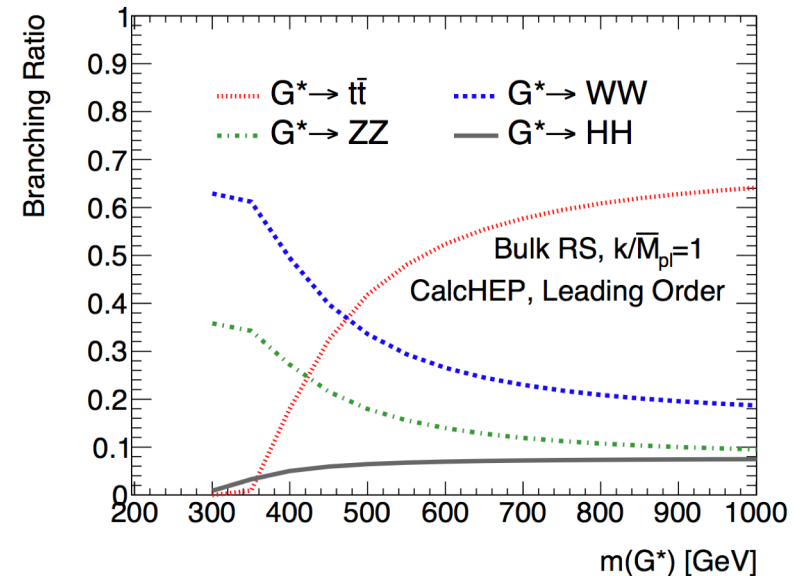
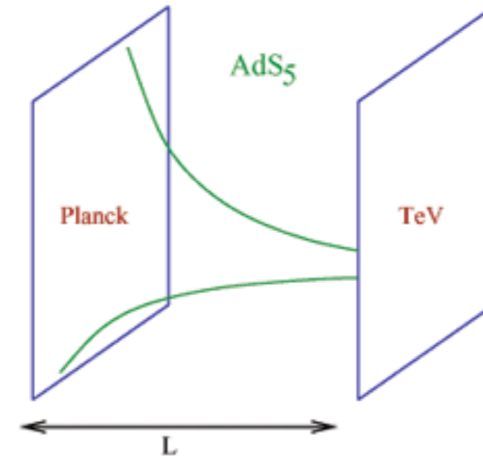


Di-boson resonance

- “bulk” RS graviton with warped extra dimension

Phys.Rev.D76:036006,2007

- Extension of KK graviton in RS1 framework with SM particles extending into the “bulk”.
- Couplings to light fermions suppressed.
- gg fusion dominant production channel.
- High BR of $G^* \rightarrow VV$.



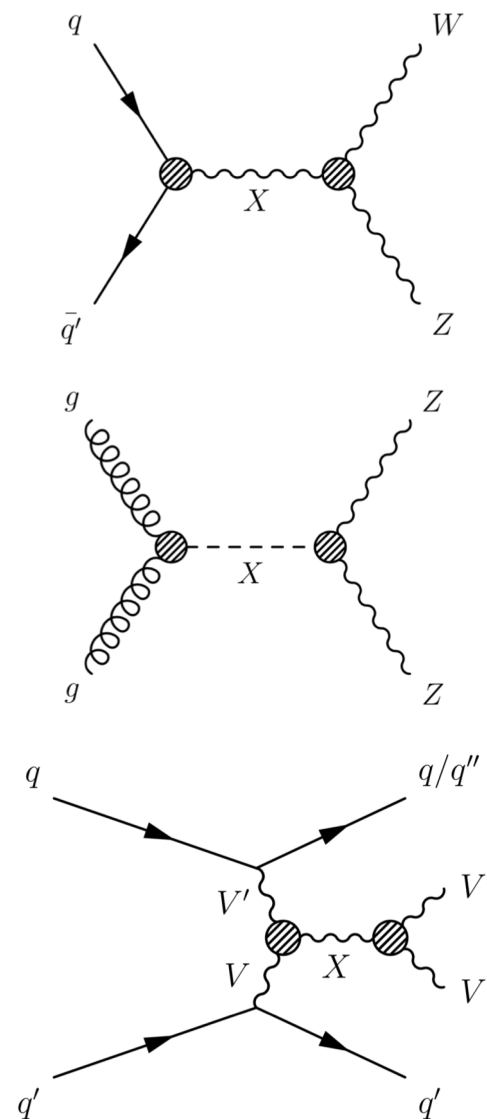
Narrow di-boson resonances

■ Production and decay of heavy resonances:

- quark-antiquark annihilation
- gluon—gluon fusion
- Vector Boson Fusion

■ Experimental signatures

- Semi-leptonic final state
 - $\nu\nu qq$, $l\nu qq$, $ll qq$
- Topologies:
 - Boosted: $V \rightarrow J$ large-R jet
 - Resolved: $V \rightarrow jj$ small-R jets
- **fully hadronic JJ**



VV->JJ resonances

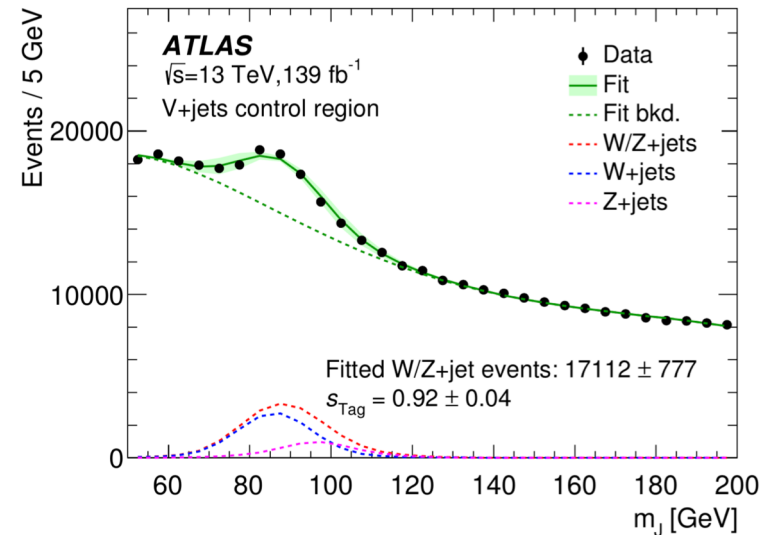
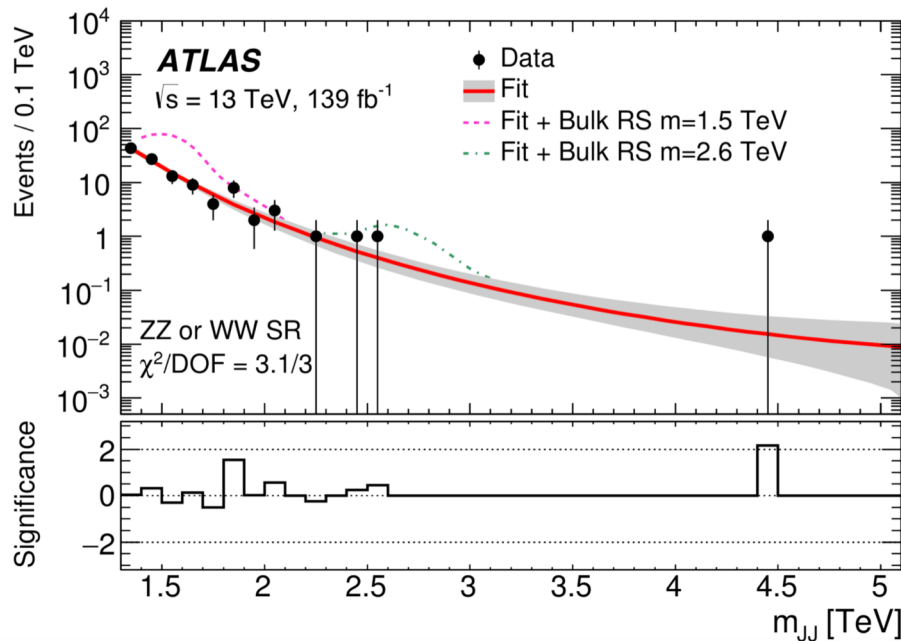
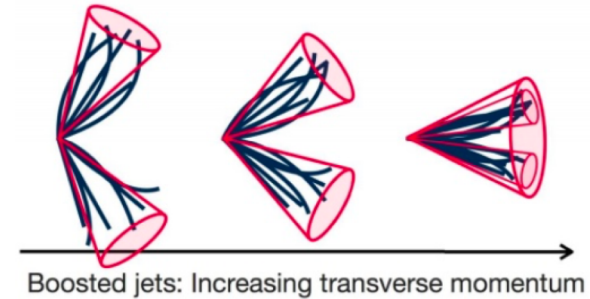
arXiv:1906.08589

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sqrt(s) = 13 TeV
L = 139 fb⁻¹
FS = JJ

Fully hadronic final state.

- Look for two large R jets, consistent with hadronically decaying W or Z.
- Sensitive to resonances above about 1.4 TeV



- Bump hunt in di-jet invariant mass spectrum.

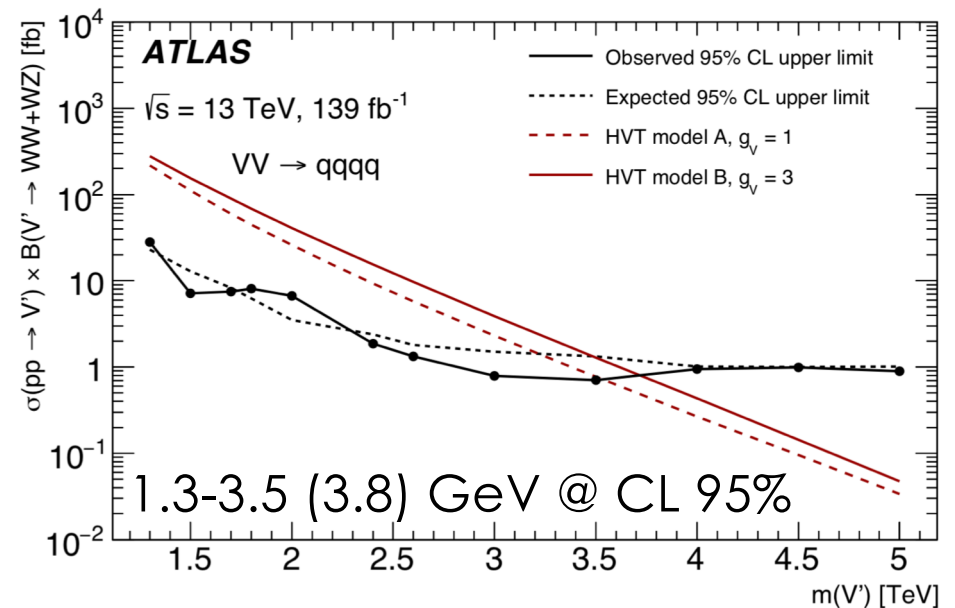
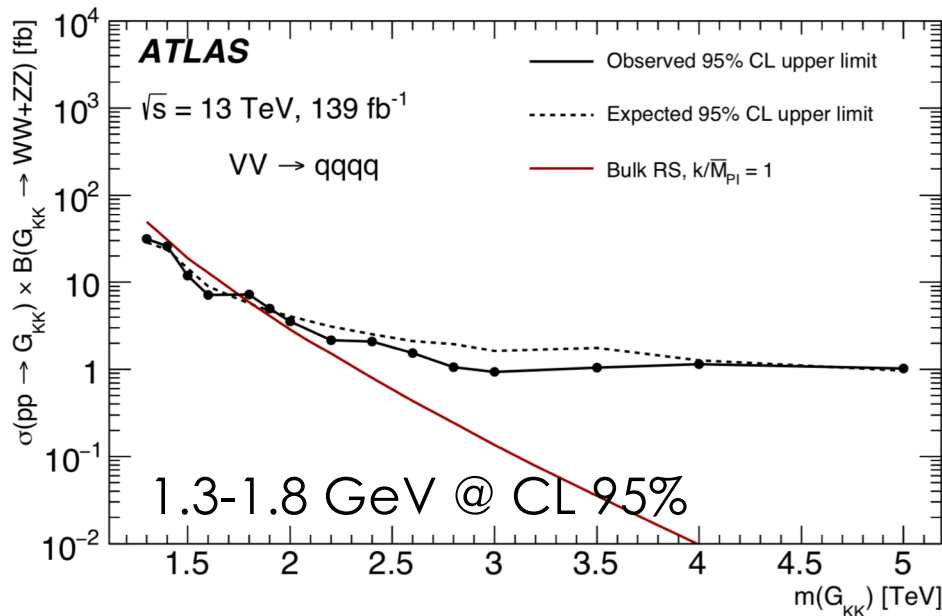
VV- \rightarrow JJ resonances

arXiv:1906.08589

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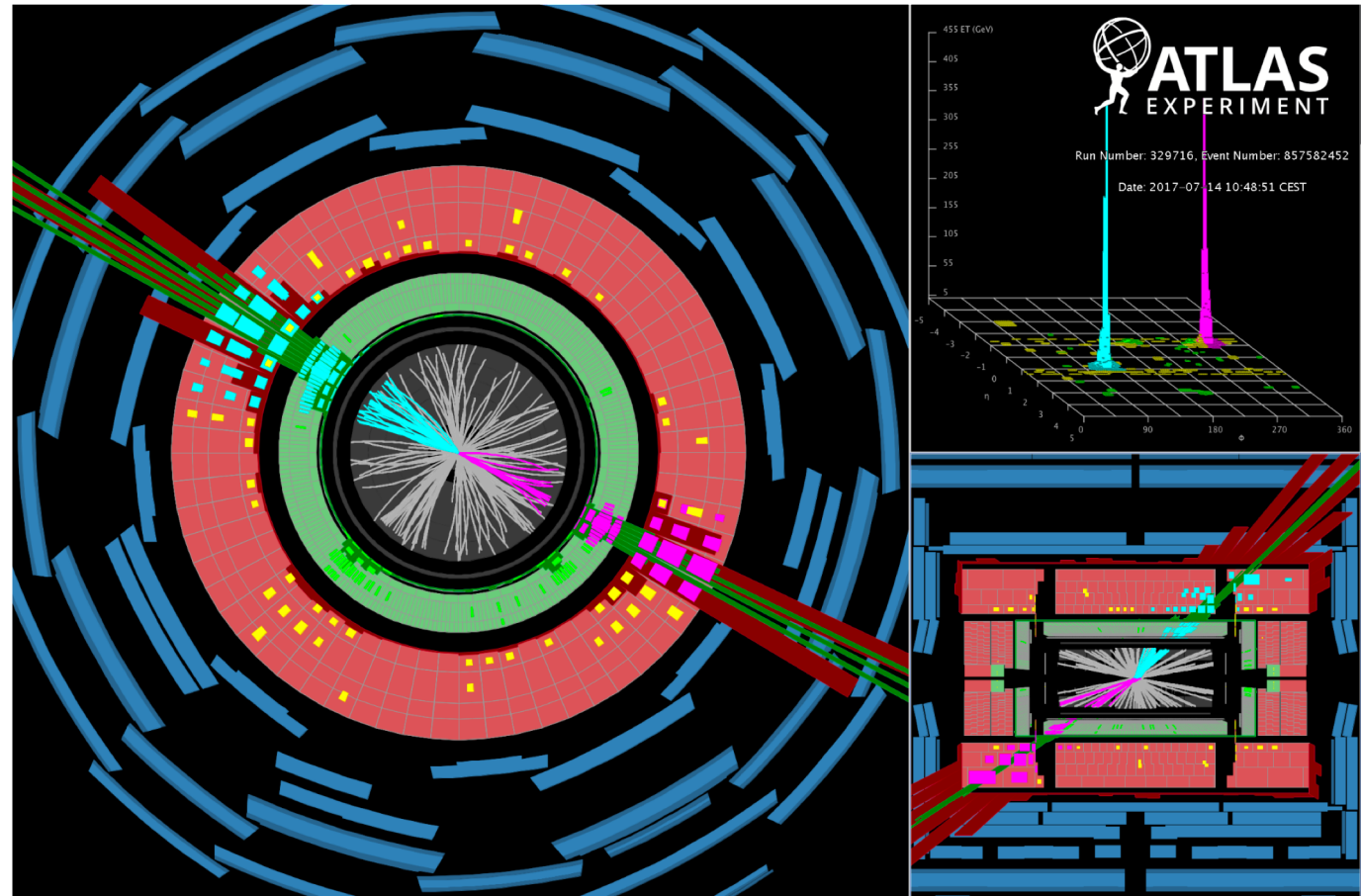
- **No excess observed**
- **Limits** on HVT (spin-1) Graviton models (spin-2)
- Competitive limits compared to combination of 36fb^{-1} analysis on (all channels). arXiv:1808.02380

Model	Signal Region	Excluded mass range [TeV]
HVT model A, $g_V = 1$	WW	1.3–2.9
	WZ	1.3–3.4
	WW + WZ	1.3–3.5
HVT model B, $g_V = 3$	WW	1.3–3.1
	WZ	1.3–3.6
	WW + WZ	1.3–3.8
Bulk RS, $k/\bar{M}_{\text{Pl}} = 1$	WW	1.3–1.6
	ZZ	none
	WW + ZZ	1.3–1.8



Di-jet

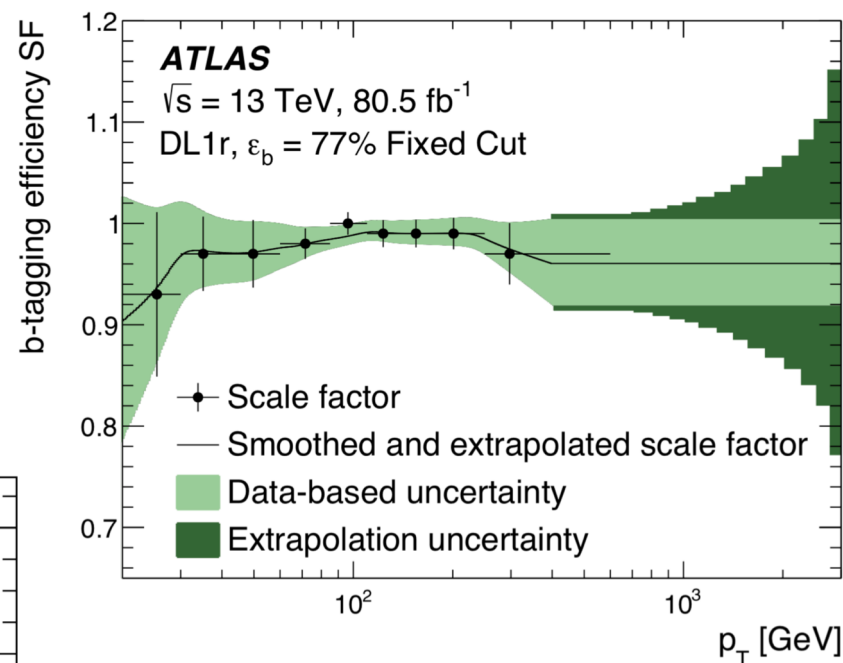
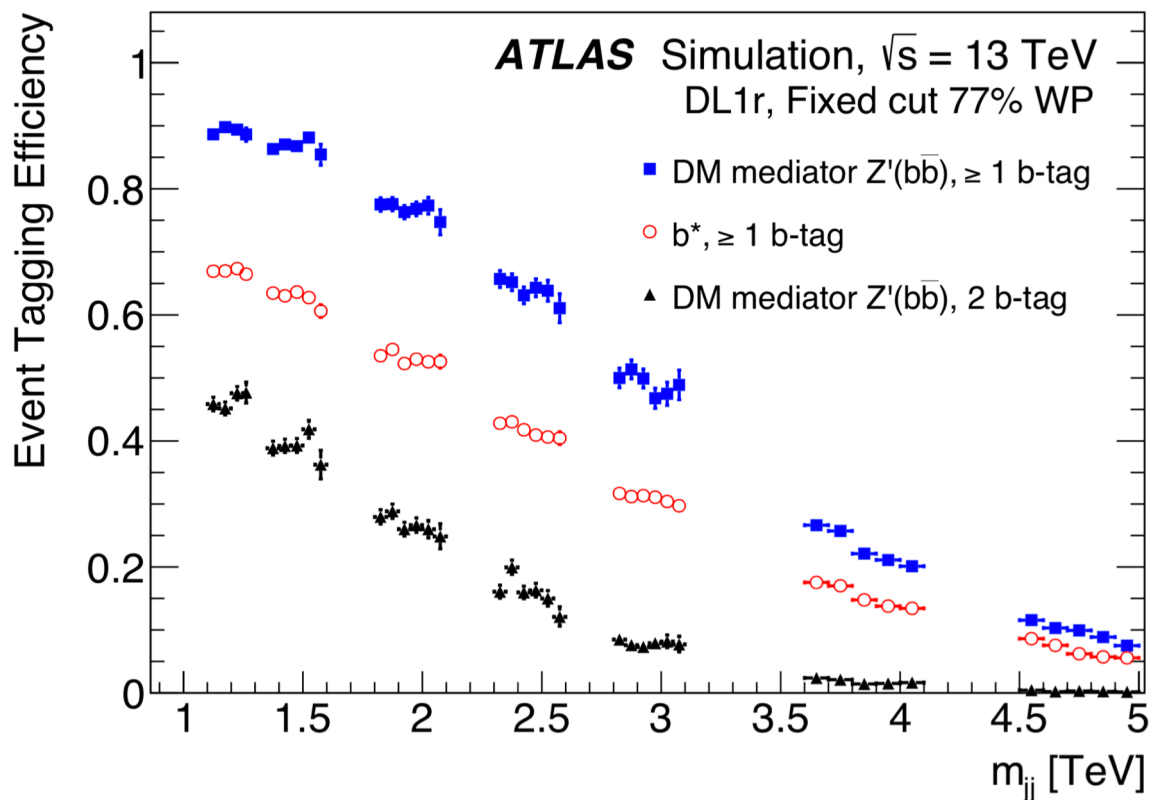
- Search for di-jet resonances.
- Full Run-2 data-set, 139fb^{-1}
- Inclusive di-jet search and dedicated di-b-jet signature.



di-jet event with $m_{jj}=9.5\text{ TeV}$

Di-jet

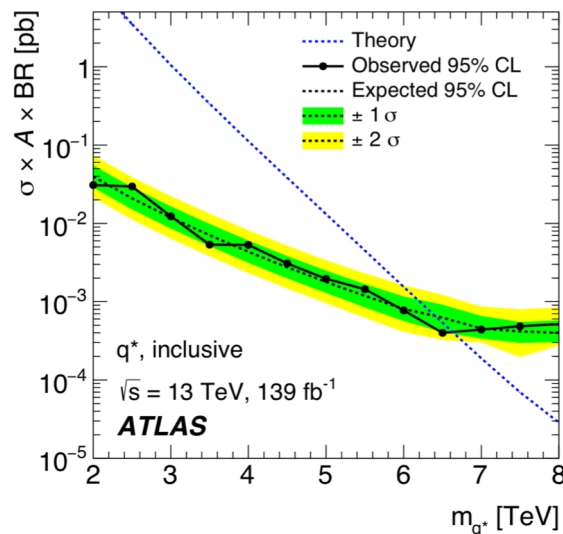
- **Improved b tagging:**
b-jets identified with deep-learning neural networks, operating point $\epsilon_b=77\%$ (for $t\bar{t}$ events).
- Correction factors for $\epsilon_b(p_T)$ derived from data and MC.



- Event tagging efficiency mass and model dependent.
- Reduce dominant QCD background by cutting on rapidity separation of jets.

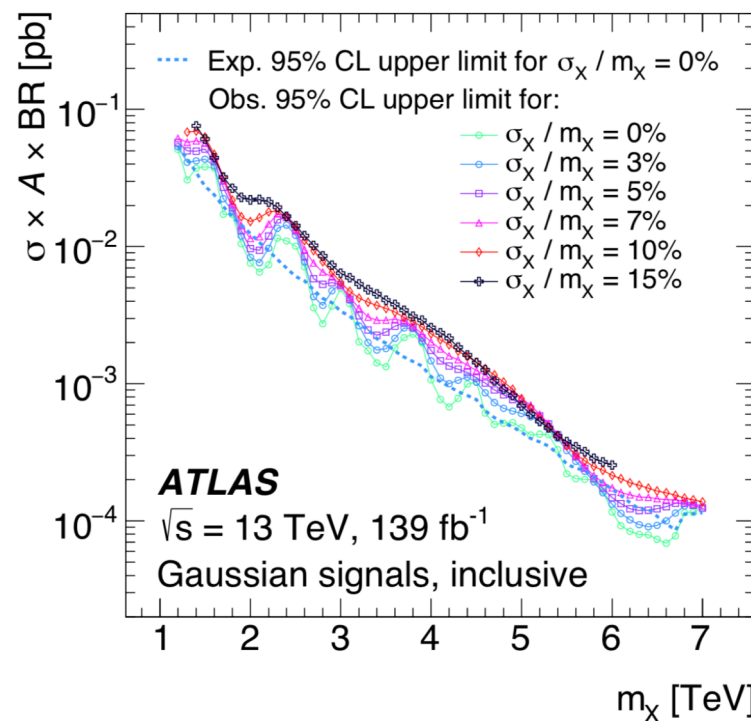
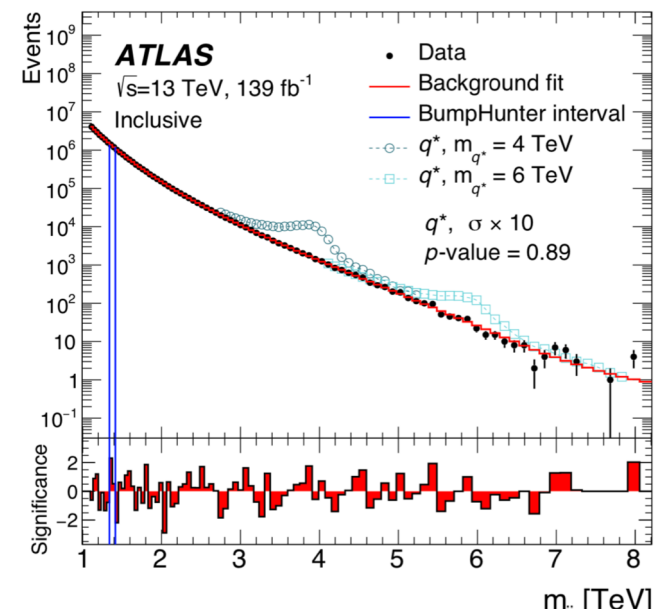
Di-jet

- SM Di-jet mass spectrum described with parametric function and validated with data-driven methods.
- For b-tagged jets CR are defined with inverted b-tag requirements.
- Quantify significance of any excess with *bump-hunter*.
- No excess found.
- Set limits on BSM models & Gaussian signals



[arXiv:1910.08447](https://arxiv.org/abs/1910.08447)

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Di-jet

- No excess found, set limits on BSM models.

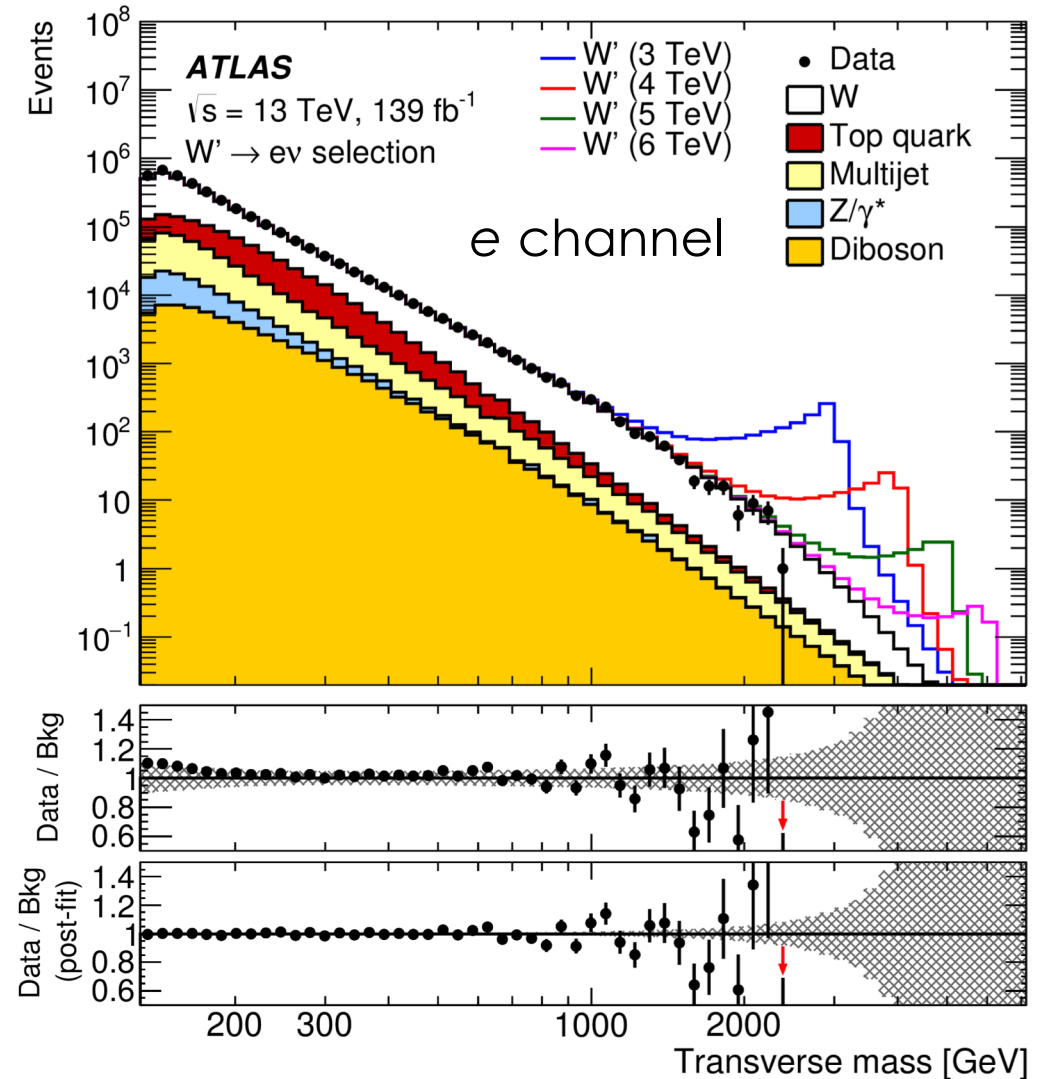
Table 2: The lower limits on the masses of benchmark signals at 95% CL.

Category	Model	Lower limit on signal mass at 95% CL	
		Observed	Expected
Inclusive	q^*	6.7 TeV	6.4 TeV
	QBH	9.4 TeV	9.4 TeV
	W'	4.0 TeV	4.2 TeV
	W^*	3.9 TeV	4.1 TeV
	DM mediator Z' , $g_q = 0.20$	3.8 TeV	3.8 TeV
	DM mediator Z' , $g_q = 0.50$	4.6 TeV	4.9 TeV
$1b$	b^*	3.2 TeV	3.1 TeV
$2b$	DM mediator Z' , $g_q = 0.20$	2.8 TeV	2.8 TeV
	DM mediator Z' , $g_q = 0.25$	2.9 TeV	3.0 TeV
	SSM Z' ,	2.7 TeV	2.7 TeV
	graviton, $k/\overline{M}_{\text{PL}} = 0.2$	2.8 TeV	2.9 TeV

- Search for resonances in transverse mass $m_T^{(*)}$ in lepton (e, μ) + MET channel.
- Full Run-2 data-set, 139fb⁻¹
- Acceptance between 79% and 44% depending on channel and W' mass.
 - high pT muon selection optimised.
- No excess observed, limits on W' models.

(*)

$$m_T = \sqrt{2 p_T E_T^{\text{miss}} (1 - \cos \phi_{\ell\nu})}$$



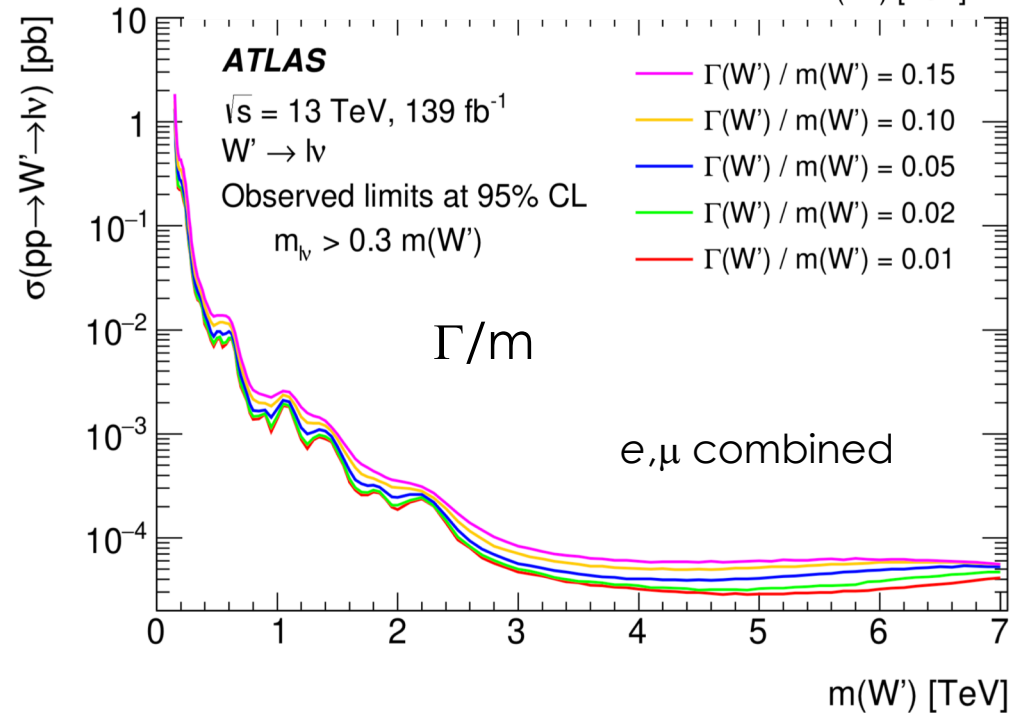
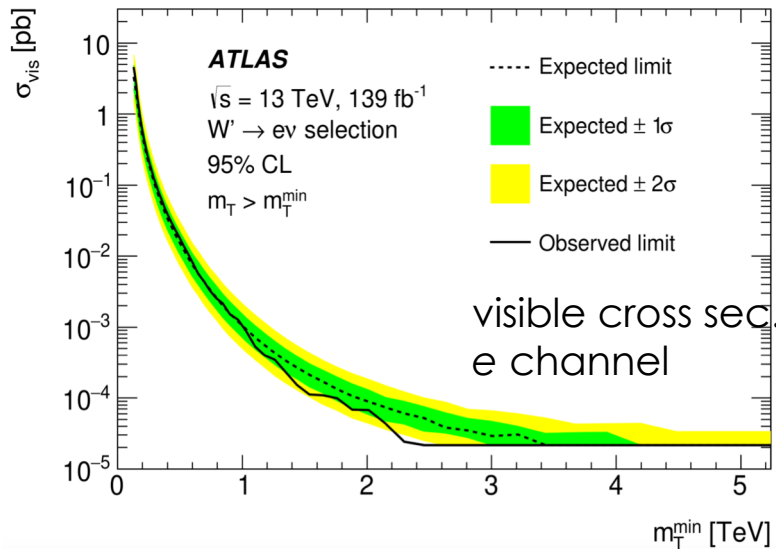
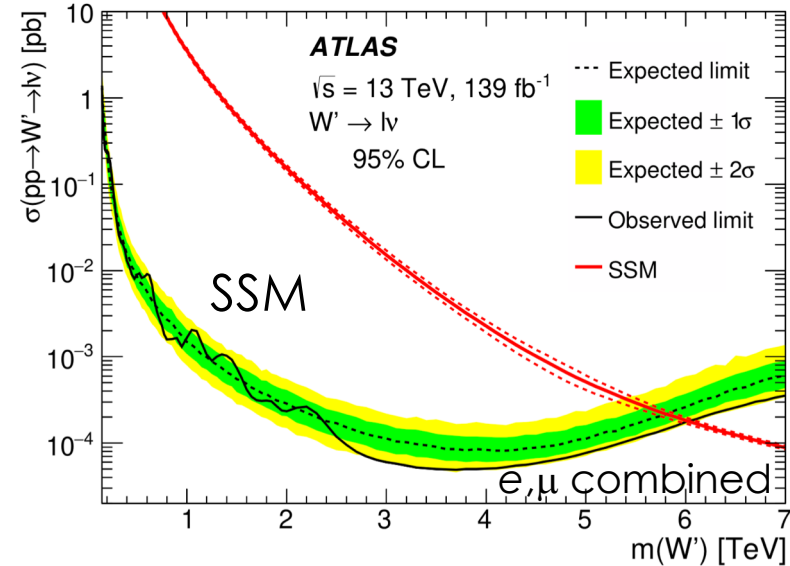


W'

■ Limits on

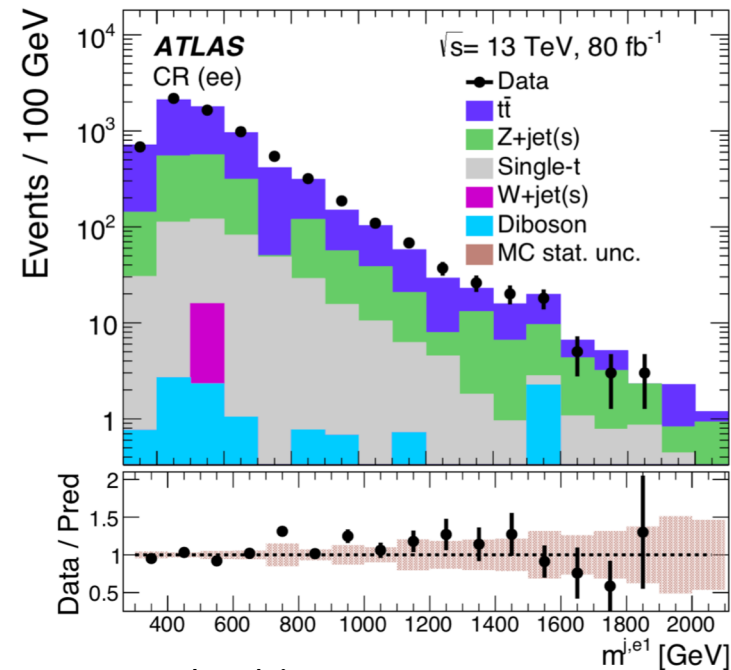
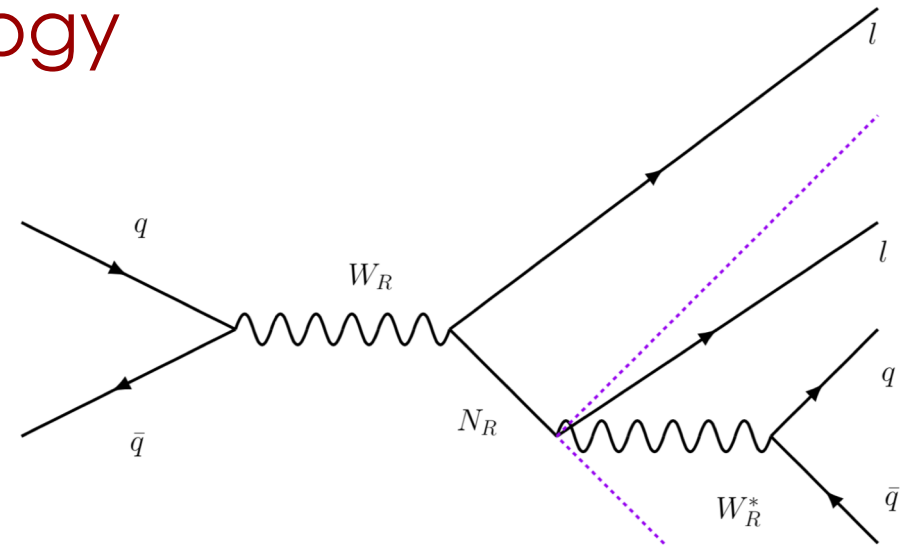
- SSM model W' (6.0 TeV observed, 5.8 TeV expected)
- Varying Γ/m ratios (1% to 15%)
- Visible cross section above m_T threshold.

Decay	$m(W')$ lower limit [TeV]	
	Observed	Expected
$W' \rightarrow e\nu$	6.0	5.7
$W' \rightarrow \mu\nu$	5.1	5.1
$W' \rightarrow \ell\nu$	6.0	5.8



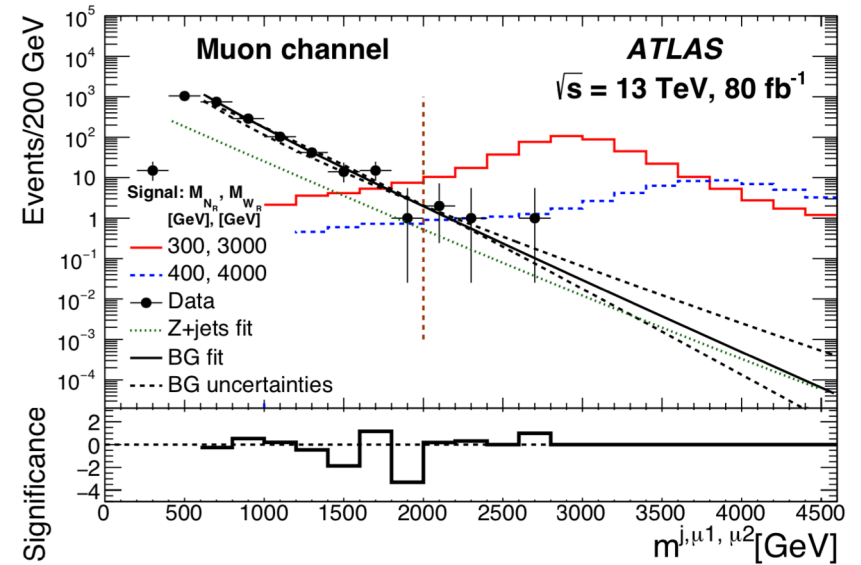
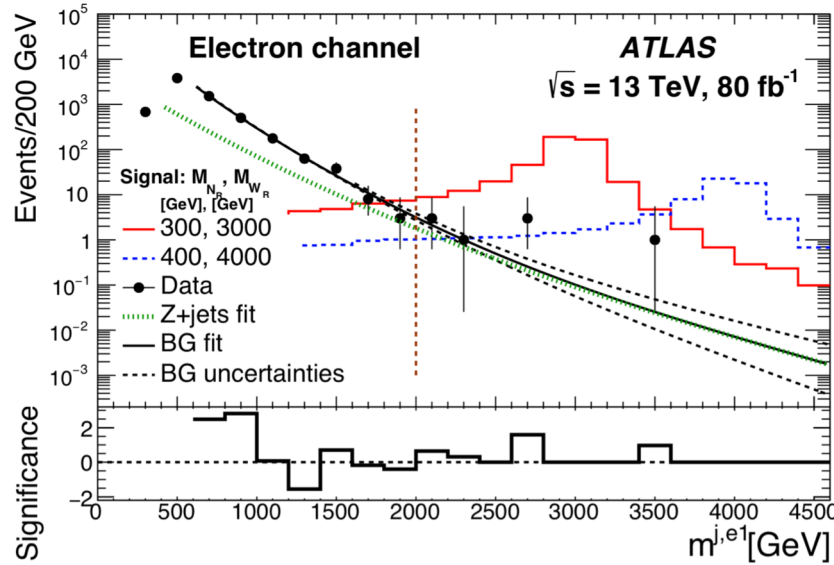
Heavy Neutrino search in boosted topology

- Seesaw mechanism to explain neutrino masses, models predict right-handed heavy W'_R and a heavy neutrino N_R .
- This search for $m(W_R) \gg m(N_R)$.
 - N_R boosted decay.
 - Signature same isolated lepton and fat-jet + embedded lepton, same flavour.
 - Observable $m_{inv}(J, l_1, l_2)$:



$m(W_R)$ in control region $< 2\text{TeV}$

Heavy Neutrino search in boosted topology

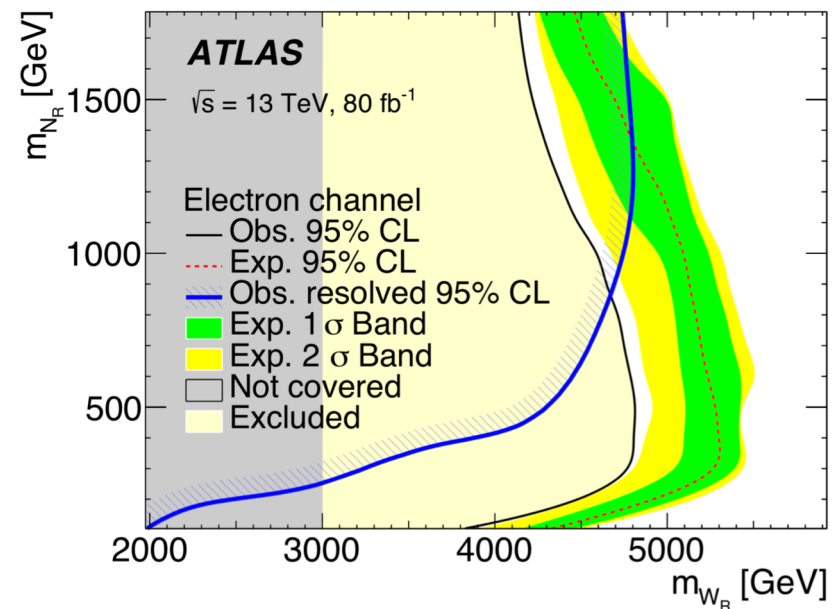
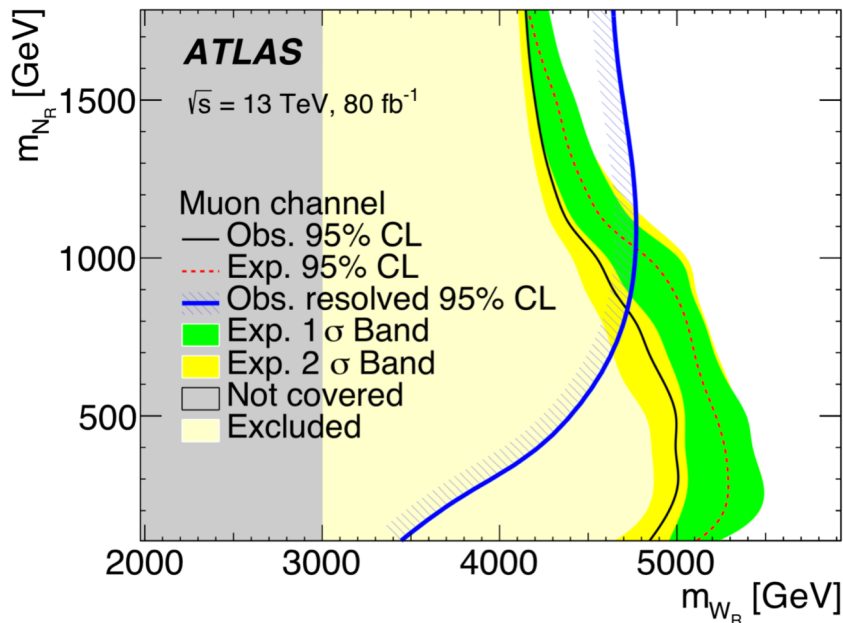


- Event count in signal region consistent with background expectation.
- Derive mass limits on N_R and W_R .

	Electron Channel	Muon Channel
Signal ($m_{W_R} = 3 \text{ TeV}, m_{N_R} = 150 \text{ GeV}$)	346^{+48}_{-75}	411^{+36}_{-48}
Signal ($m_{W_R} = 3 \text{ TeV}, m_{N_R} = 300 \text{ GeV}$)	471^{+42}_{-69}	429^{+29}_{-40}
Signal ($m_{W_R} = 4 \text{ TeV}, m_{N_R} = 400 \text{ GeV}$)	66^{+6}_{-10}	57^{+4}_{-4}
Expected background	$2.8^{+0.5}_{-0.7}$	$1.9^{+0.5}_{-0.7}$
Observed events	8	4
Significance	2.4σ	1.2σ
p -value	0.0082	0.12

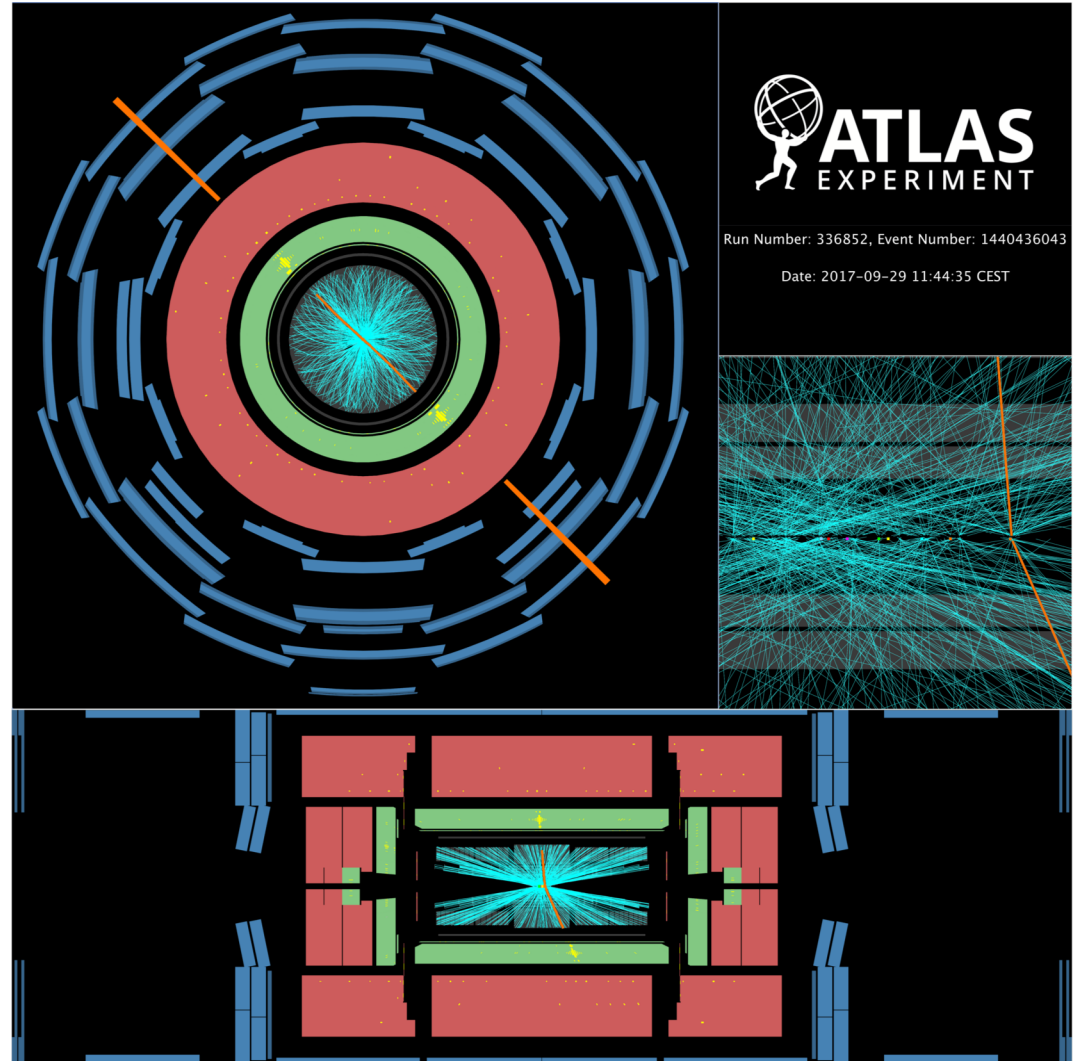
Heavy Neutrino search in boosted topology

- Derive mass limits on N_R and W_R .
 - $m(W_R) > 4.8$ TeV (e- channel)
 - $m(W_R) > 5.0$ TeV (μ - channel)
- Complementary results to previous analysis using resolved jets.



Z'

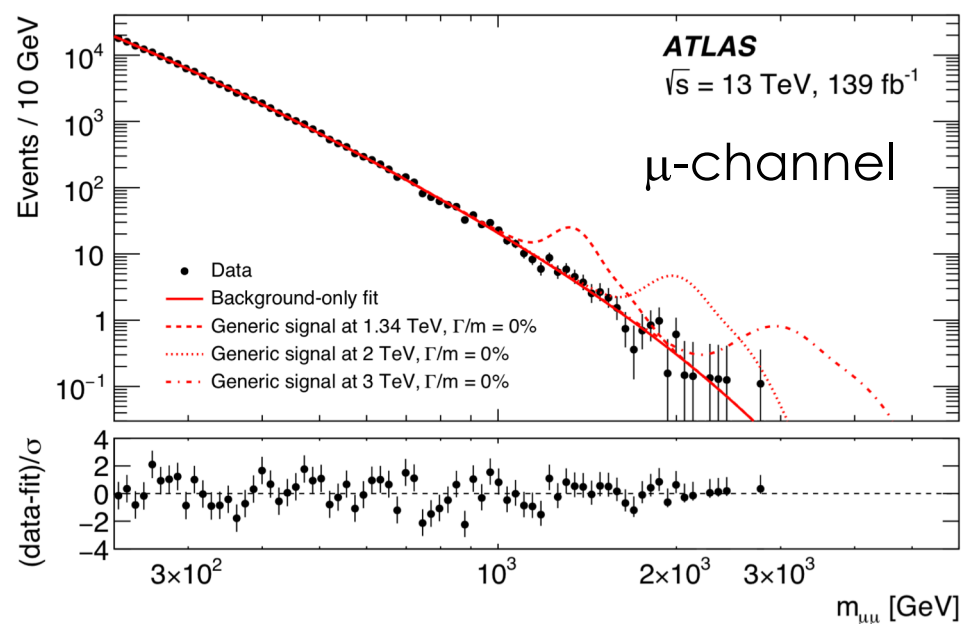
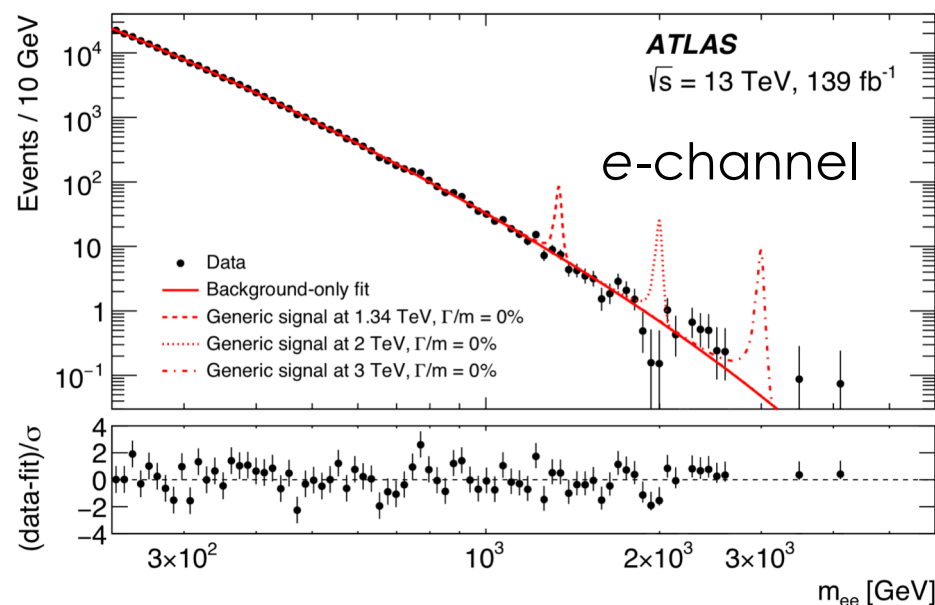
- Search for **narrow resonances** in the dilepton (electron or muon) invariant **mass spectrum**
- Signal models:
 - **generic Breit-Wigner signals**
 - Z' (ψ , X , SSM), **Heavy Vector Triplet** model
- Selection of two high p_T isolated leptons.



$$m_{ee} = 4.06\text{TeV}$$

Z'

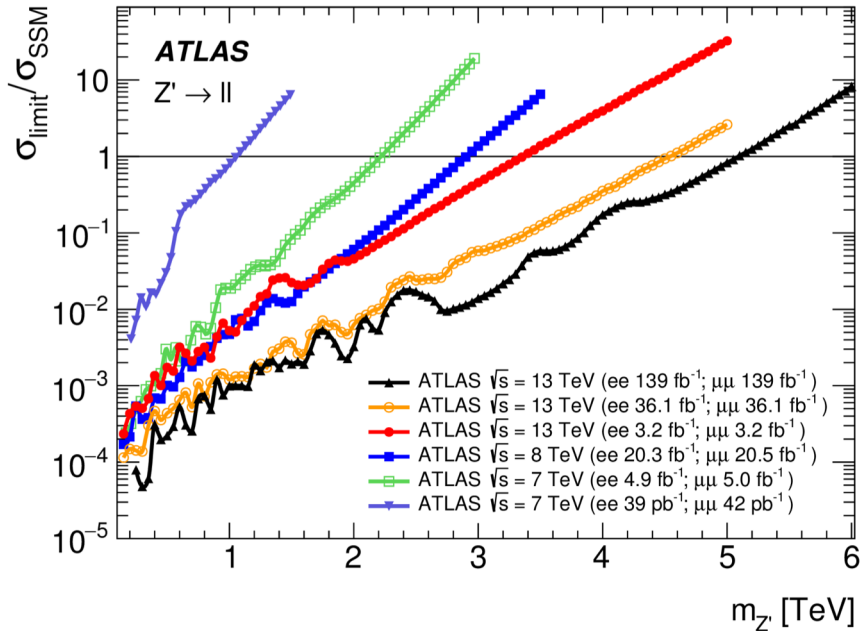
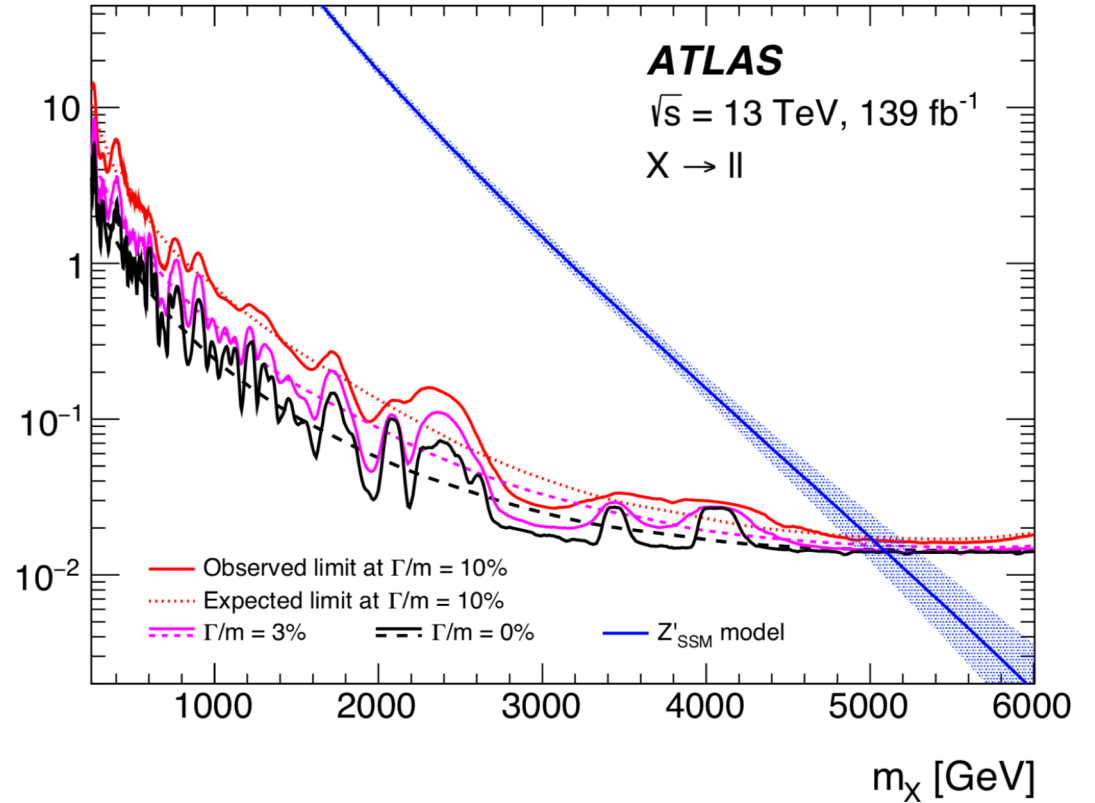
- Improvements in lepton reconstruction.
 - Improved ECAL cell-clustering.
 - ID and muon tracking alignment.
- Main background Drell-Yan Z production.
- Background estimation with fit, functional form determined from template fits.
- Dominant uncertainty:
 - "spurious signal"/background modelling.
 - Electron ID, muon quality



Z'

- Better limits compared to previous studies
 - data-set increased 4 fold
 - optimization of lepton reconstruction

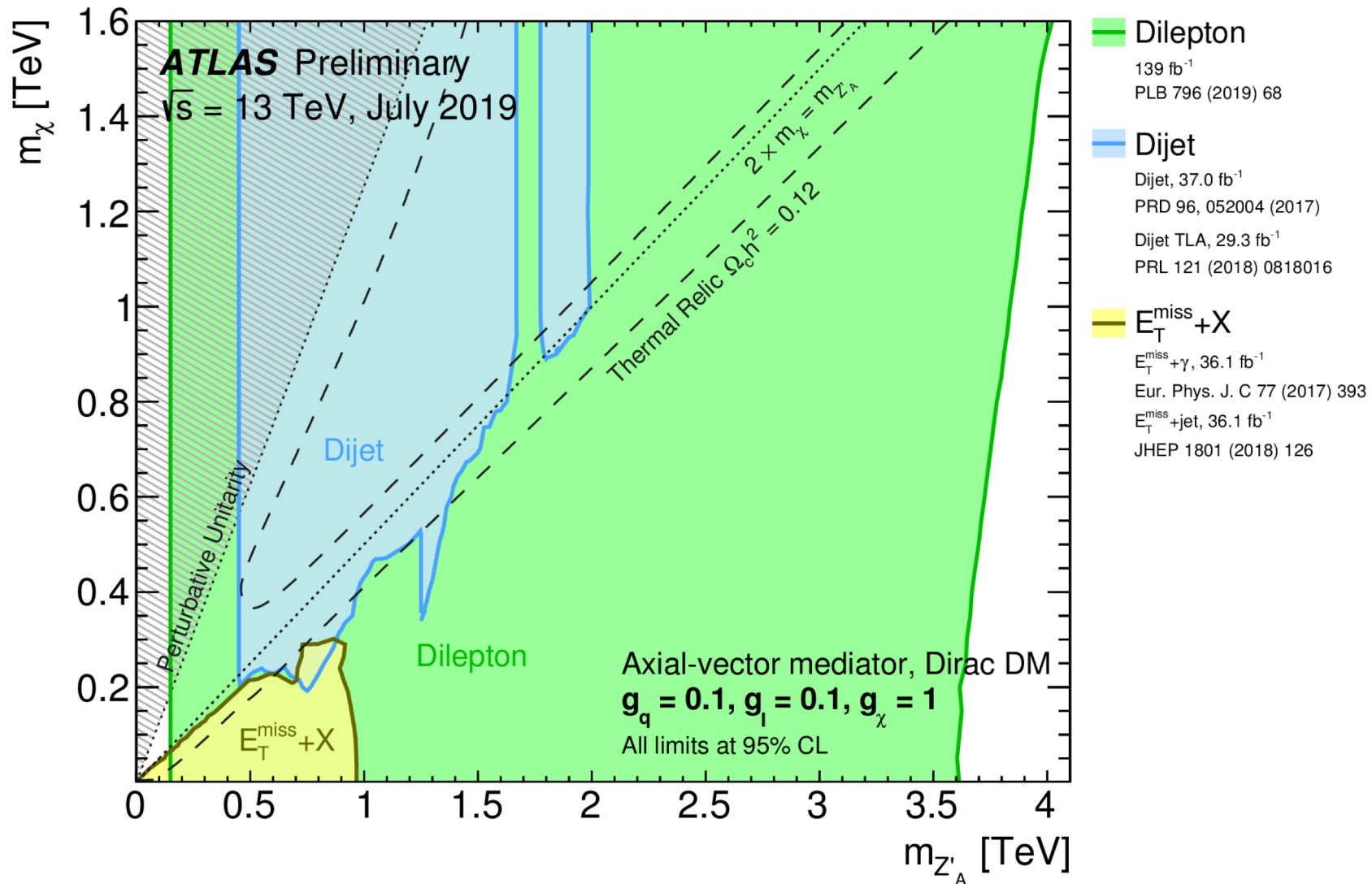
$\sigma_{\text{fid}} \times B$ [fb]



Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_{ψ}	4.1	4.3	4.0	4.0	4.5	4.5
Z'_{χ}	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1

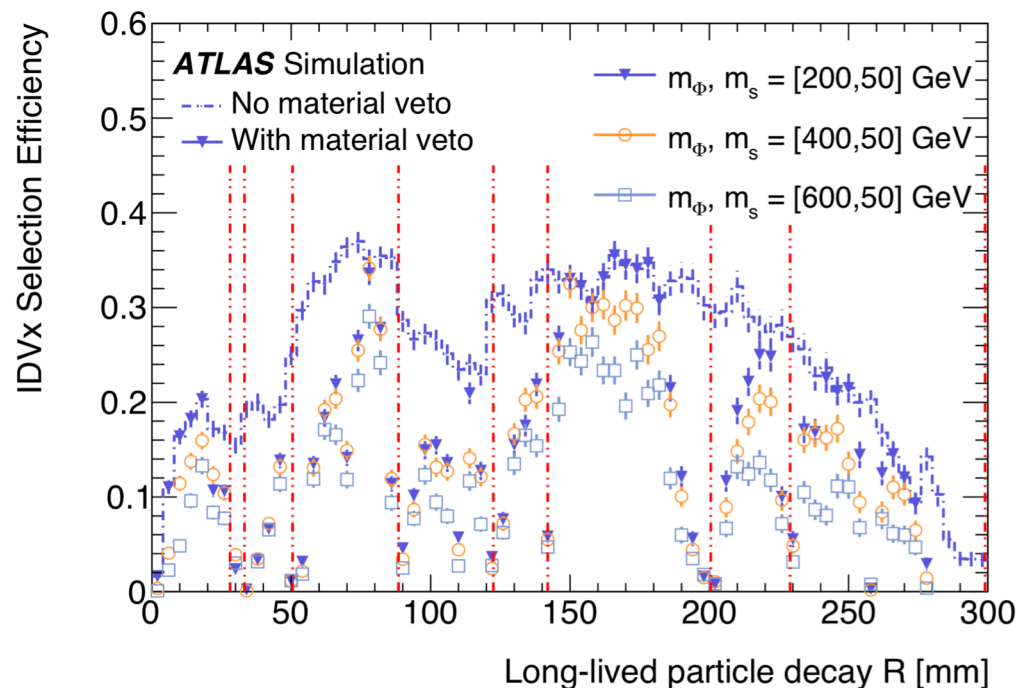
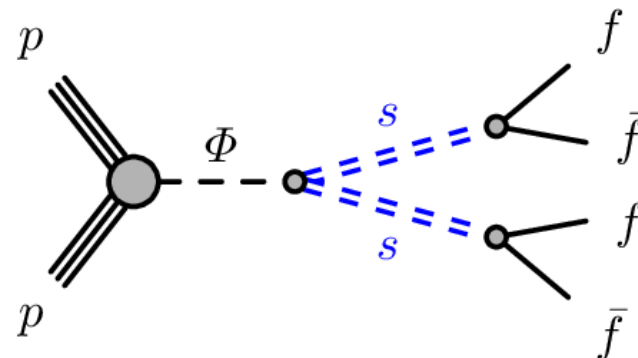
Dark Matter Summary

- Summary plot including di-jet (37fb^{-1}), di-lepton and E_T miss.



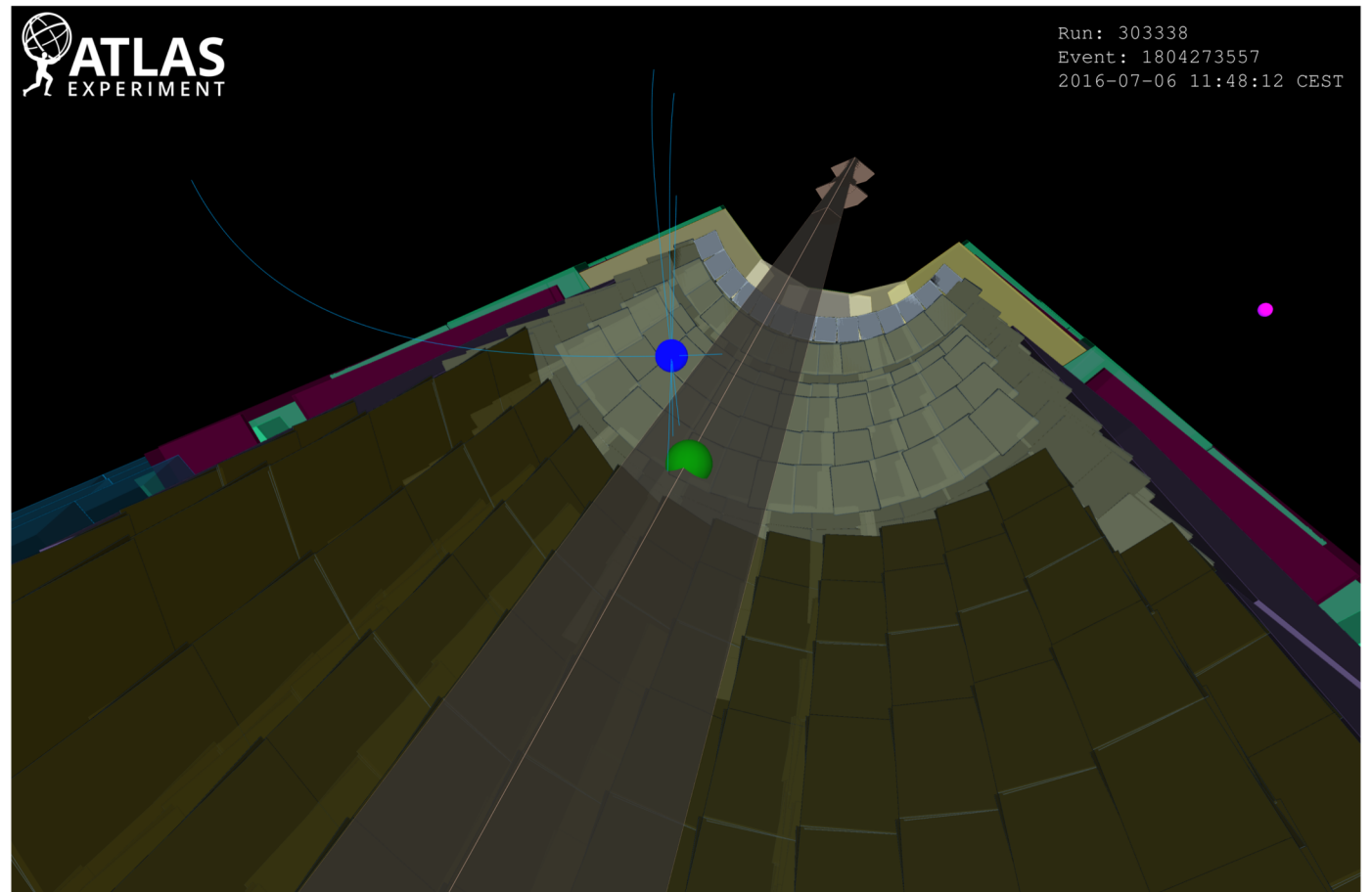
Displaced jets

- Search for long-lived particles, predicted by many BSM models (eg. SUSY, hidden sector, neutral naturalness)
- Dataset 33fb⁻¹ at 13 TeV.
- Topology: one s decay in ID, and one s decay in muon spectrometer (MS).
 - s decay preferable to $bb, cc, \tau\tau$
 - Use special reconstruction methods, dedicated trigger chains.
 - Sensitive for $O(\text{cm}) < c\tau < O(\text{m})$.
- Main backgrounds:
 - ID: material interactions
 - MS: Multi-jet, punch through



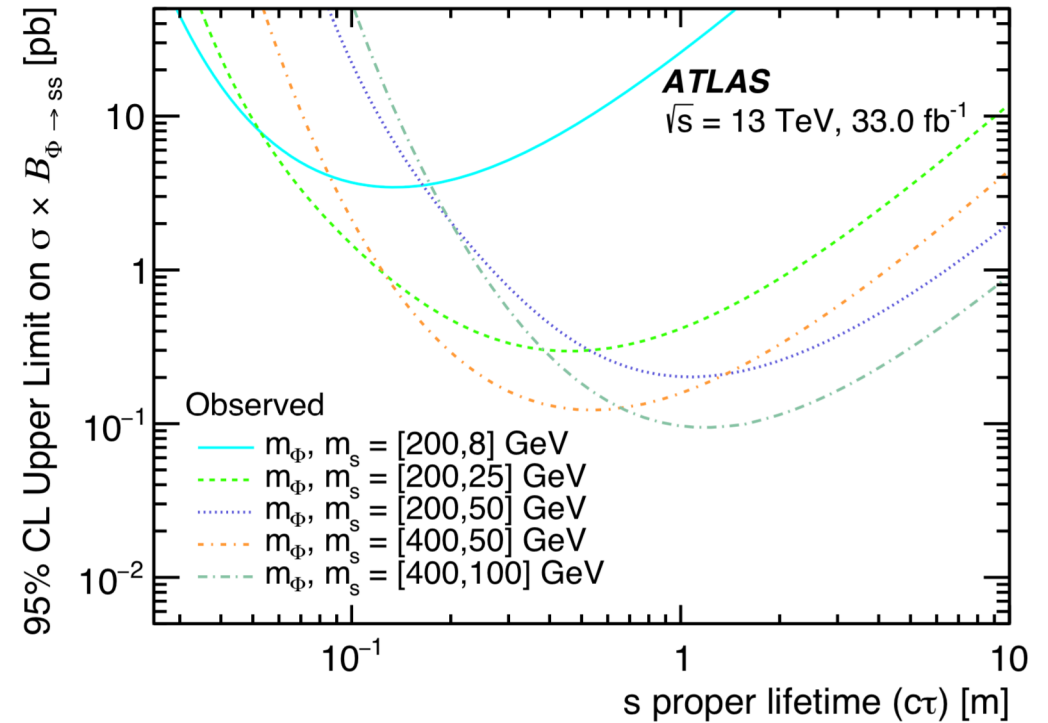
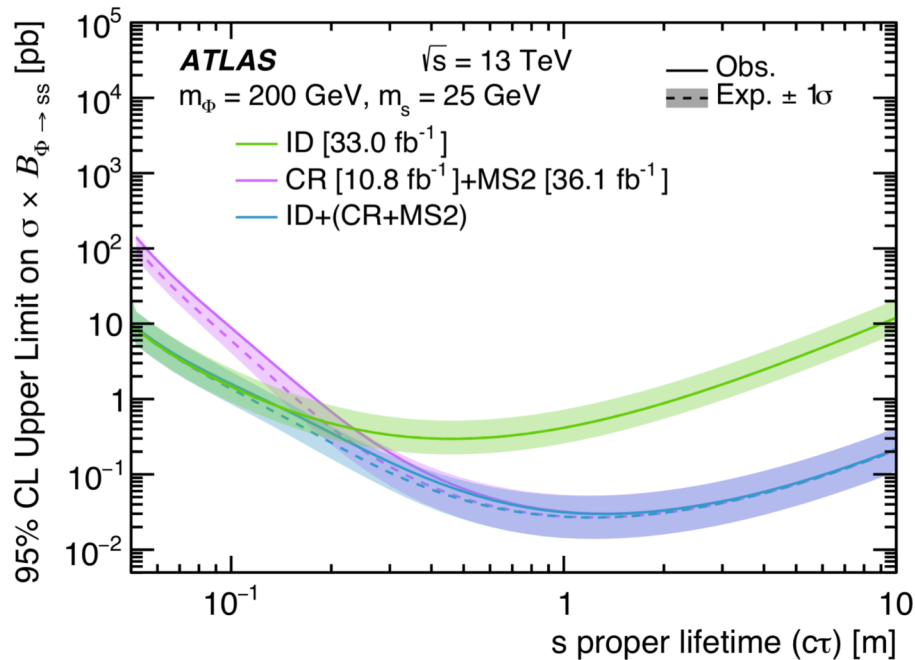
Displaced jets

- Background estimated from data with CR: 1.2 ± 0.2 (stat) ± 0.3 (sys)
- Main signal systematic from displaced vertex reco.
- Observe 1 event passing all signal criteria in data.



Displaced jets

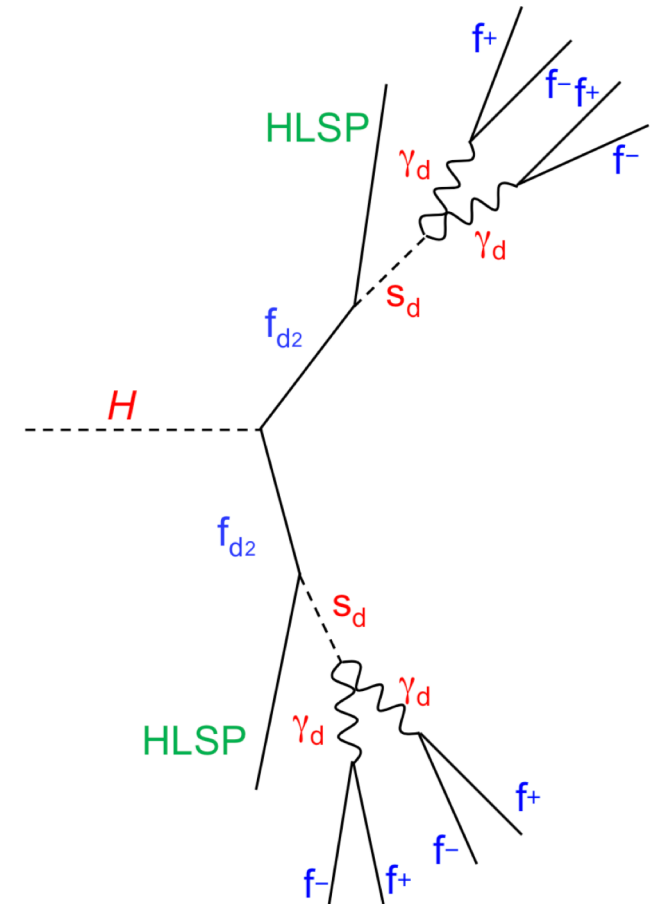
- Derive limits on $(\sigma \text{ BR})$ on various signal masses.
- Orthogonal to MS and ID only analyses.



- Combination with MS and ID only analyses improves limits.

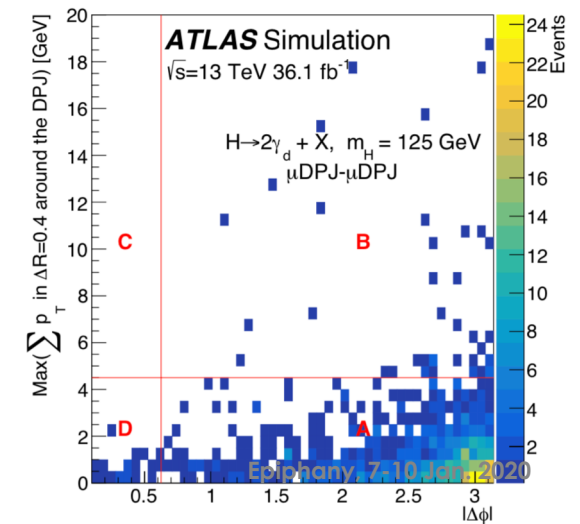
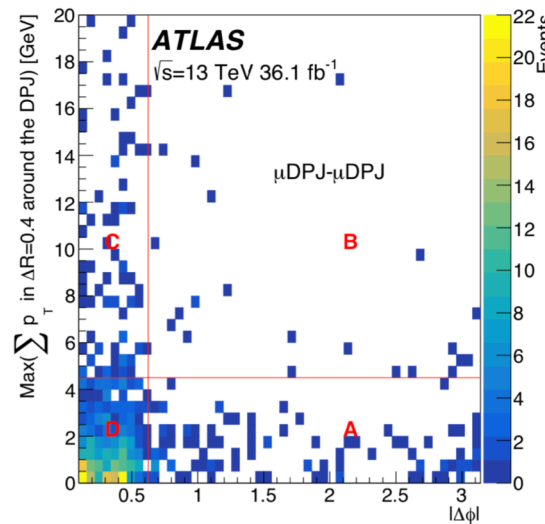
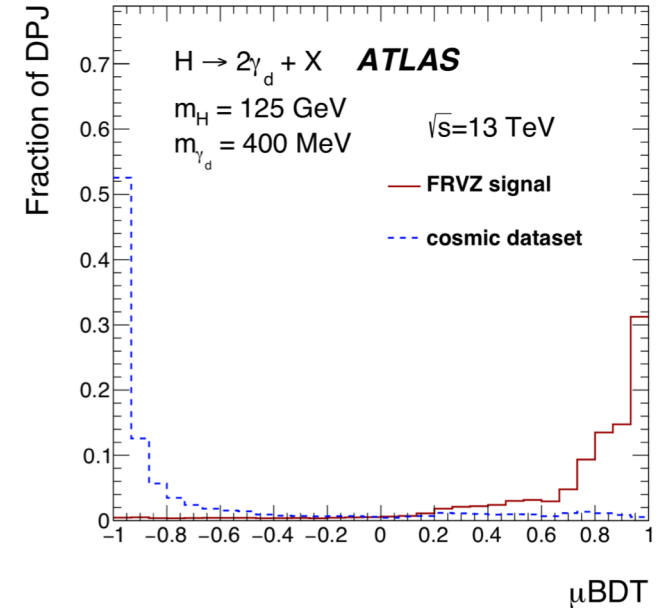
Collimated fermion jets

- Search for long-lived dark photons produced from the decay of a Higgs boson or a heavy scalar boson.
- Dataset 36fb^{-1} at 13 TeV.
- Decaying into displaced collimated Standard Model fermions (leptons or hadrons).
- Improved background rejection makes fully hadronic channel accessible.



Collimated fermion jets

- Dark Photon signature searched for in outer calorimeter/MS
 - muons: look for 2 close by muons in MS
 - hadrons/electrons: look for jets with large Had/EM ratio.
- Selection based on BDT on DP jet candidate:
 - muonic jet, main background cosmics.
 - hadronic jet, main background multijet production.
- Data driven background estimation with CR.

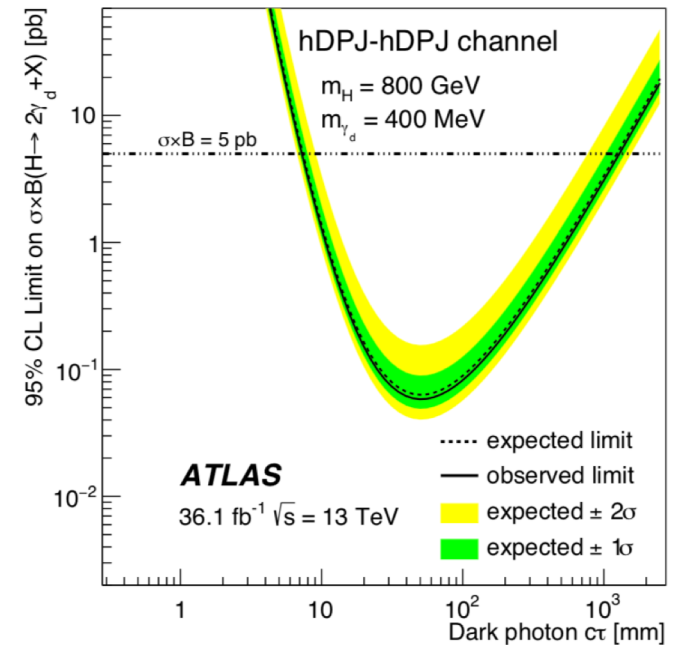
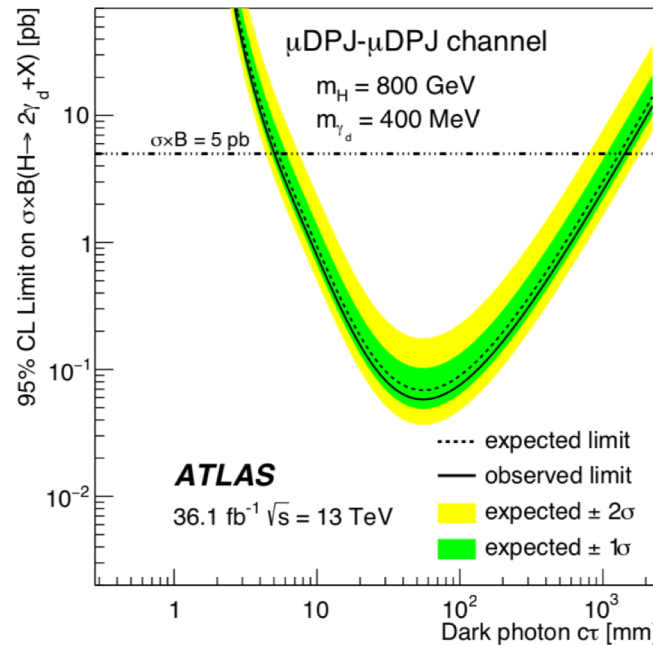
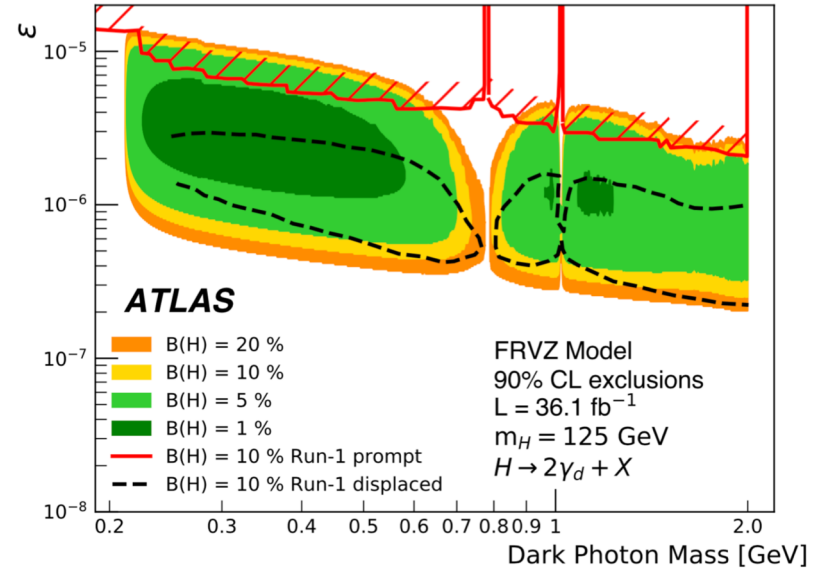


Collimated fermion jets

- No excess observed.
- Limits on kinetic mixing parameter ϵ vs dark photon mass.

$$\tau \propto \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100 \text{ MeV}}{m_{\gamma_d}}\right)$$

- Limits on production cross section times BR.





Summary

- Discussed a few recent updates:
 - VV- \rightarrow JJ resonances (arXiv:1906.08589)
 - Di-jet resonances (arXiv:1910.08447)
 - W' (arXiv:1906.05609)
 - Heavy neutrino (arXiv:1904.12679)
 - Z' (arXiv:1903.06248)
 - Displaced jets (arXiv:1911.12575)
 - Collimated fermion jets (arXiv:1909.01246)
- Many more results with different final states expected with the full run-2 dataset.
- Run-3 increase centre-of-mass energy and luminosity.
 - Exploit upgrades in detector and trigger capabilities!
- Awaiting the unexpected!