

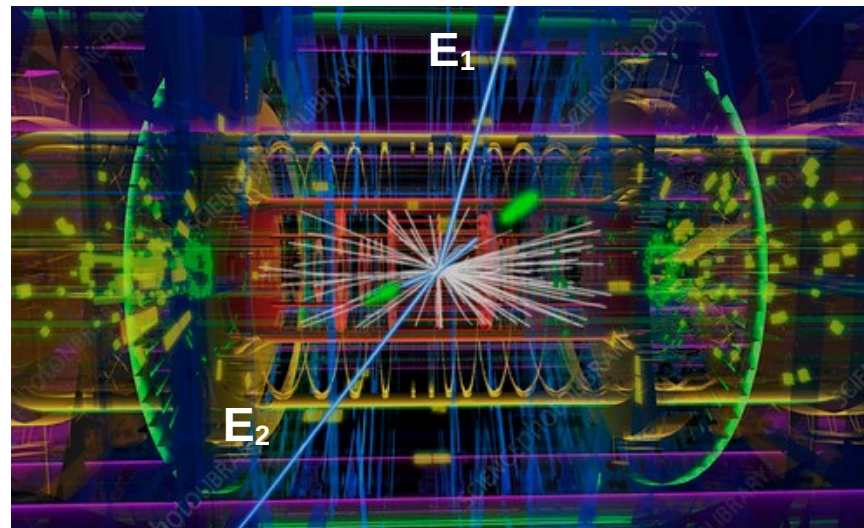
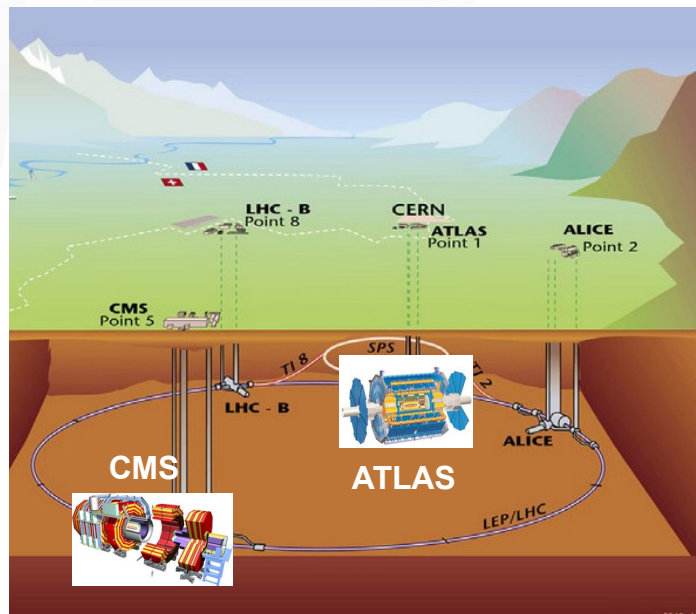
# Heavy Resonance Searches

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*On behalf of the ATLAS and CMS collaborations*

10th Edition of the Large Hadron Collider Physics Conference May 16-20, 2022 (Taipei, Taiwan)

## LHC experiments



# New particles at collider experiments

- Standard Model (SM) is successful for particle collisions
- Discrepancies may indicate new physics  $\equiv$  new particles/fields

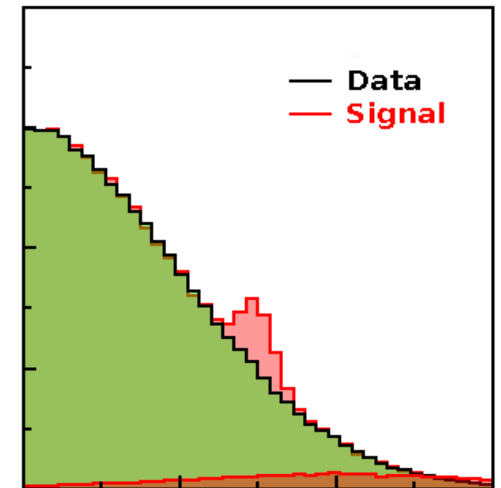
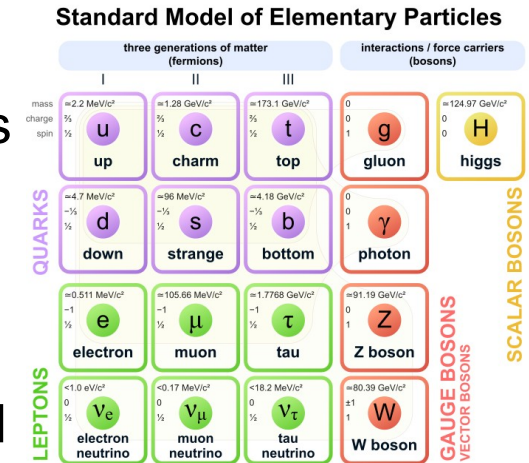
## Direct observations of new particles

- Combine known particles/jets to create “invariant masses” & search for “resonance” enhancements above background
- or observe through unusual signatures in detector (anomalously high  $dE/dx$  tracks etc)

## Indirect observations of new particles

- Compare SM predictions with data
- Search for any discrepancy with SM background
- Explain using theoretical frameworks beyond SM (BSM)

**No evidence yet but no shortage of models predicting exotic heavy particles**



$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$

Invariant mass from known particle/jet with energy  $E$  and  $\mathbf{p}$

# LHC limits for direct and indirect BSM searches

ATLAS

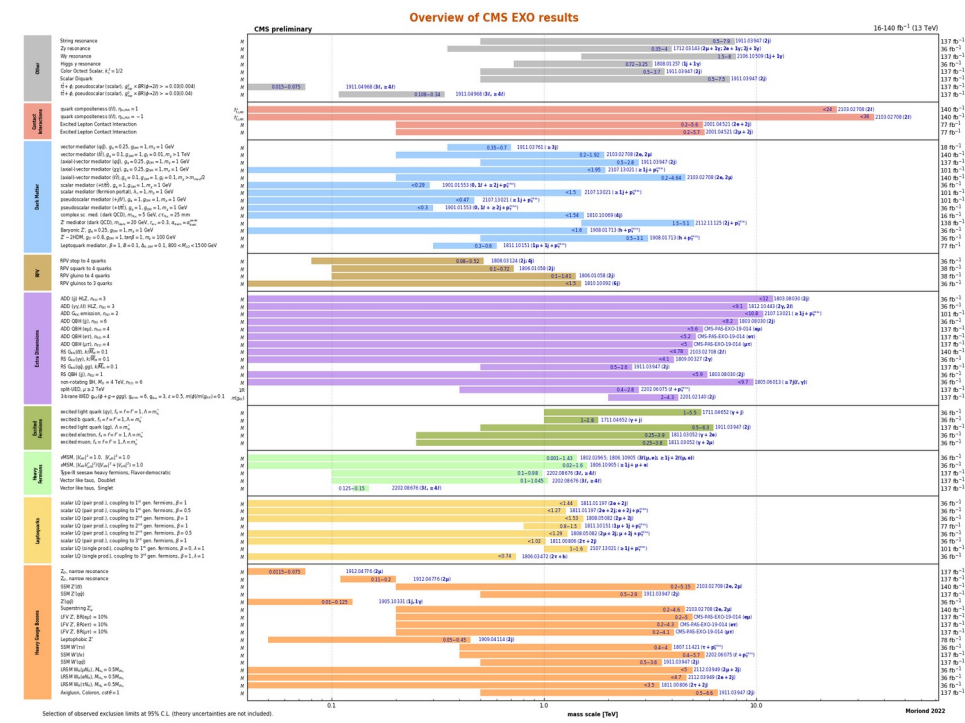
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CMS

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ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits  
Status: March 2022

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_{miss}^{\pm}$	$[\int \mathcal{L} dt] [fb^{-1}]$	Limit	Reference
<b>Extra dimensions</b>						
ADD $G_{KK} + g/\Lambda$	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	$M_s$ 11.2 TeV $n=2$	2102.10874
ADD non-resonant $\gamma\gamma$	$2\gamma$	-	-	36.7	$M_s$ 8.6 TeV $n=3$ HLZ NLO	1707.04147
ADD OH	-	2	-	37.0	$M_s$ 8.9 TeV	1703.09127
ADD BH multijet	-	$\geq 3$	-	3.6	$M_s$ $n=6, M_p = 3$ TeV, not BH	1512.02586
RS1 $G_{KK} \rightarrow \gamma\gamma$	$2\gamma$	-	-	139	$G_{KK}$ mass 4.5 TeV $k/\overline{M}_{Pl} = 0.1$	2102.13405
Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	139	$G_{KK}$ mass 3.6 TeV $k/\overline{M}_{Pl} = 1.0$	1808.02280
Bulk RS $G_{KK} \rightarrow W\gamma$	$1, e, \mu$	2   1   J	Yes	139	$k/\overline{M}_{Pl} = 1.0$	2004.14636
Bulk RS $G_{KK} \rightarrow t\bar{t}$	$1, e, \mu$	$\geq 1, b, \tau, 2   \geq 2$	Yes	36.1	$G_{KK}$ mass 2.0 TeV $f/m = 15\%$	1904.10823
2UED / RPP	$1, e, \mu$	$\geq 2, b, \tau   \geq 3$	Yes	36.1	$HK$ mass 1.8 TeV $\text{Tier } (1, 1), \mathcal{R}(\mathcal{A}^{(1)} \rightarrow t\bar{t}) = 1$	1803.09678
<b>Gauge bosons</b>						
SSM $Z' \rightarrow \ell\ell$	$2, e, \mu, \tau$	-	-	139	$Z'$ mass 5.1 TeV	1903.06248
SSM $Z' \rightarrow \tau\tau$	$2\tau$	-	-	36.1	$Z'$ mass 2.42 TeV	1709.07242
Leptophobic $Z' \rightarrow b\bar{b}$	-	$2b$	-	36.1	$Z'$ mass 2.1 TeV	1806.05099
Leptophobic $Z' \rightarrow t\bar{t}$	$0, e, \mu, \tau$	$\geq 1, b, \tau   \geq 2, J$	Yes	139	$Z'$ mass 4.1 TeV $\Gamma/m = 1.2\%$	2005.05138
SSM $W' \rightarrow \nu\bar{\nu}$	$1, e, \mu, \tau$	-	-	139	$W'$ mass 6.0 TeV	1906.05509
SSM $W' \rightarrow \nu\tau$	$1\tau$	-	-	139	$W'$ mass 5.0 TeV	ATLAS-CONF-2021-025
SSM $W' \rightarrow t\bar{b}$	-	$\geq 1, b, \tau   \geq 1, J$	Yes	139	$W'$ mass 4.4 TeV	ATLAS-CONF-2021-043
HVT $W' \rightarrow WZ \rightarrow \nu\ell\ell'$ model B	$1, e, \mu, \tau$	2   1   J	Yes	139	$W'$ mass 4.3 TeV	2004.14636
HVT $W' \rightarrow WZ \rightarrow \nu\ell\ell'$ model C	$3, e, \mu, \tau$	2   (VBF)	Yes	139	$W'$ mass 340 GeV	ATLAS-CONF-2022-005
HVT $W' \rightarrow WH$ model B	$2, e, \mu$	$\geq 1, b, \tau   \geq 2, J$	Yes	139	$W'$ mass 3.2 TeV	2007.05293
LRSM $W_R \rightarrow \mu R$	$2, e, \mu$	1   J	-	80	$W_R$ mass 5.0 TeV	1904.12679
<b>CI</b>						
CI $qqqq$	-	2   J	-	37.0	$A$ 21.8 TeV $\eta_{CI}$	1703.09127
CI $lqqq$	$2, e, \mu, \tau$	-	-	139	$A$ 35.8 TeV $\eta_{CI}$	2006.12946
CI $qqbb$	$2, e, \mu$	-	-	139	$A$ 1.8 TeV	2105.13847
CI $qqbb$	$2, \mu$	1   b	-	139	$A$ 2.0 TeV	2105.13847
CI $tttt$	$\geq 1, e, \mu, \tau$	$\geq 1, b, \tau   \geq 1, J$	Yes	36.1	$A$ 2.57 TeV $ k_{CI}  = 4\text{r}$	1811.02305
<b>DM</b>						
Axial-vector med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	$\overline{M}_{Pl}^2$ mass 376 GeV	2102.10874
Pseudo-scalar med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	$\overline{M}_{Pl}^2$ mass 3.1 TeV	2102.10874
Vector med. $Z'$ -2HDM (Dirac DM)	$0, e, \mu, \tau$	2   b	Yes	139	$\overline{M}_{Pl}^2$ mass 560 GeV	2108.13391
Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	$\overline{M}_{Pl}^2$ mass 3.1 TeV	ATLAS-CONF-2021-036
<b>LO</b>						
Scalar $LQ$ 1 <sup>st</sup> gen	$2, e$	$\geq 2$	Yes	139	$LQ$ mass 1.8 TeV $\beta = 1$	2006.05872
Scalar $LQ$ 2 <sup>nd</sup> gen	$2, \mu$	$\geq 2$	Yes	139	$LQ$ mass 1.7 TeV $\beta = 1$	2006.05872
Scalar $LQ$ 3 <sup>rd</sup> gen	$1, \tau$	$2b$	Yes	139	$LQ$ mass 1.24 TeV $\mathcal{R}(LQ \rightarrow \nu\bar{\nu}) = 1$	2108.07655
Scalar $LQ$ 3 <sup>rd</sup> gen	$0, e, \mu, \tau$	$\geq 2, \tau   \geq 2, b$	Yes	139	$LQ$ mass 1.24 TeV $\mathcal{R}(LQ \rightarrow \nu\bar{\nu}) = 1$	2101.11582
Scalar $LQ$ 3 <sup>rd</sup> gen	$\geq 2, e, \mu, \tau$	$\geq 1, \tau   \geq 1, b$	Yes	139	$LQ$ mass 1.43 TeV $\mathcal{R}(LQ \rightarrow \nu\bar{\nu}) = 1$	2101.12527
Scalar $LQ$ 3 <sup>rd</sup> gen	$0, e, \mu, \tau$	$\geq 1, \tau   \geq 0-2   \geq 2, b$	Yes	139	$LQ$ mass 1.26 TeV $\mathcal{R}(LQ \rightarrow \nu\bar{\nu}) = 1$	2108.07655
Vector $LQ$ 3 <sup>rd</sup> gen	$1, \tau$	$2b$	Yes	139	$LQ$ mass 1.77 TeV $\mathcal{R}(LQ \rightarrow \nu\bar{\nu}) = 0.5, YM$ coupl.	2108.07655
<b>Heavy quarks</b>						
VLQ $TT \rightarrow Z + X$	multi-channel	$\geq 1, b, \tau   \geq 1, J$	Yes	139	$V$ mass 1.4 TeV	SU(2) doublet
VLQ $BB \rightarrow W + Zb + X$	multi-channel	$\geq 1, b, \tau   \geq 1, J$	Yes	36.1	$B$ mass 1.34 TeV	SU(2) doublet
VLQ $T_{13} T_{33} W_{33} \rightarrow W + X$	$2(S)/\geq 3, e, \mu, \tau$	$\geq 1, b, \tau   \geq 1, J$	Yes	36.1	$T_{13}$ mass 1.64 TeV	$\mathcal{R}(T_{13} \rightarrow W\gamma) = 1, c(F_{13} = W) = 1$
VLQ $T \rightarrow H, Z, \gamma$	$1, e, \mu, \tau$	$\geq 1, b, \tau   \geq 1, J$	Yes	139	$V$ mass 1.8 TeV	SU(2) singlet, $\kappa = 0.5$
VLQ $Y \rightarrow Wb$	$1, e, \mu, \tau$	$\geq 1, b, \tau   \geq 1, J$	Yes	36.1	$Y$ mass 1.85 TeV	$\mathcal{R}(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$
VLQ $B \rightarrow Hb$	$0, e, \mu, \tau$	$\geq 2, b, \tau   \geq 1, J$	Yes	139	$B$ mass 2.0 TeV	SU(2) doublet, $\kappa = 0.3$
<b>Excited fermions</b>						
Excited quark $q^* \rightarrow qg$	-	2   J	-	139	$q^*$ mass 6.7 TeV	only $u'$ and $d'$ , $A = m(q^*)$
Excited quark $q^* \rightarrow q\gamma$	-	1   J	-	38.7	$q^*$ mass 3.2 TeV	only $u'$ and $d'$ , $A = m(q^*)$
Excited quark $b^* \rightarrow b\gamma$	-	1   b   J	-	36.1	$b^*$ mass 2.6 TeV	
Excited lepton $e^*$	$3, e, \mu, \tau$	-	-	20.3	$e^*$ mass 3.0 TeV	
Excited lepton $\nu^*$	$3, e, \mu, \tau$	-	-	20.3	$\nu^*$ mass 1.6 TeV	
<b>Other</b>						
Type II Seesaw	$2.3, 4, e, \mu, \tau$	$\geq 2$	Yes	139	$H^{\pm}$ mass 910 GeV	$m(W_2) = 4.1$ TeV, $g_L = g_R$
LRSM Majorana $\nu$	$2, \mu, \tau$	2   J	Yes	36.1	$N_{1,2}$ mass 3.2 TeV	
Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$	$2.3, 4, e, \mu, \tau$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2.3, 4, e, \mu, \tau$ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production, $\mathcal{R}(H^{\pm\pm} \rightarrow \nu\bar{\nu}) = 1$
Higgs triplet $H^{\pm\pm} \rightarrow \tau\tau$	$3, e, \mu, \tau$ (SS)	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $ \kappa  = 5e$
Multi-charged particles	-	-	-	36.1	multi-charged particle mass	DY production, $ \kappa  = 1g_0, \text{spin } 1/2$
Magnetic monopoles	-	-	-	34.4	monopole mass 1.22 TeV	
						1912.03673

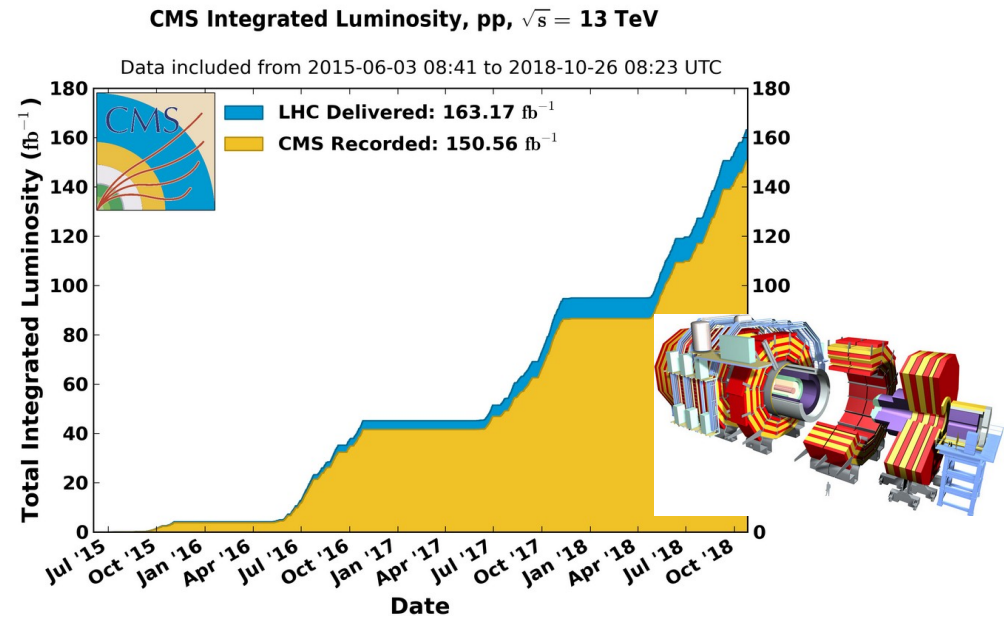
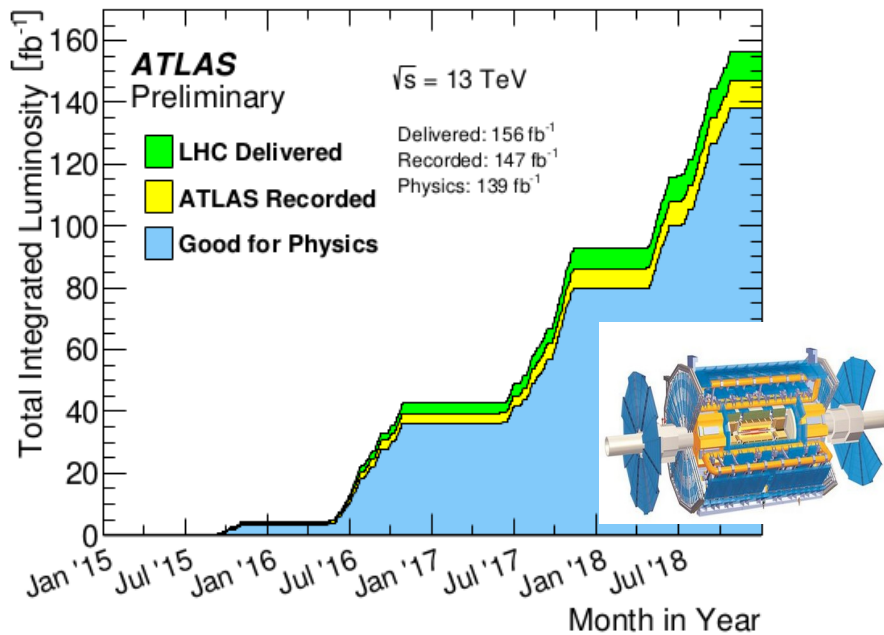


\*Only a selection of the available mass limits on new states or phenomena is shown.  
†Small-radius (large-radius) jets are denoted by the letter J (j).

- ~100 decay channels studied for various models that predict certain production rate (extra dimensions, gauge bosons, contact interactions, dark matter, heavy quarks, excited fermions, leptoquarks etc)
- Commonly excluded masses ~ 0.4 – 12 TeV
- But plenty of models that predict too small cross section for exclusion.



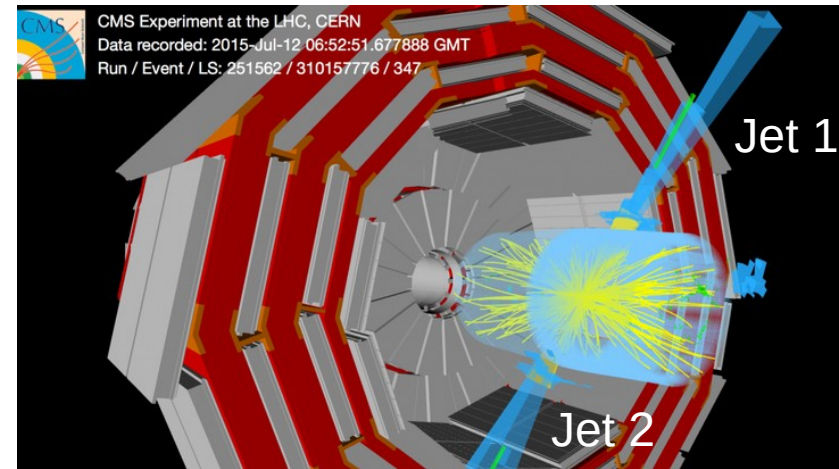
# LHC operation



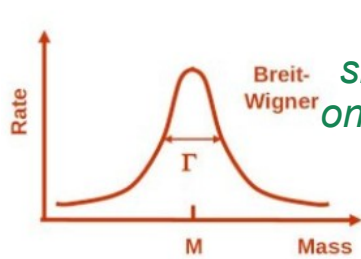
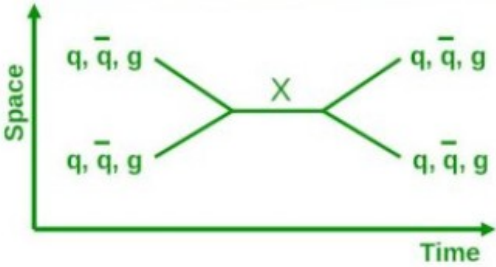
- Run2 pp collision data-set,  $\sqrt{s} = 13 \text{ TeV}$ .
- $\sim 140 \text{ fb}^{-1}$  used for this talk

## Typical search strategy:

- Select events with “X” (= jet,  $\gamma$ , Higgs, top, Z, W)
- Veto other activity ( $\mu, e, \dots$ )
- Measure missing transverse momentum (MET)
- Combine reconstructed objects  $\rightarrow$  compare with theory expectations



# Search for high mass dijet resonances



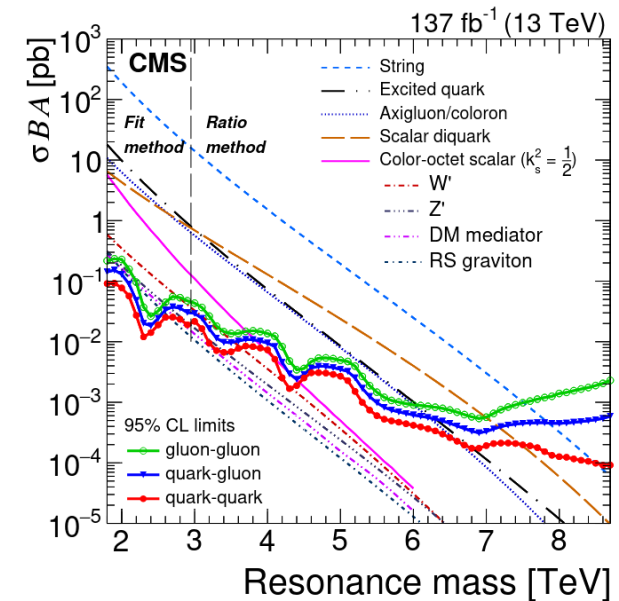
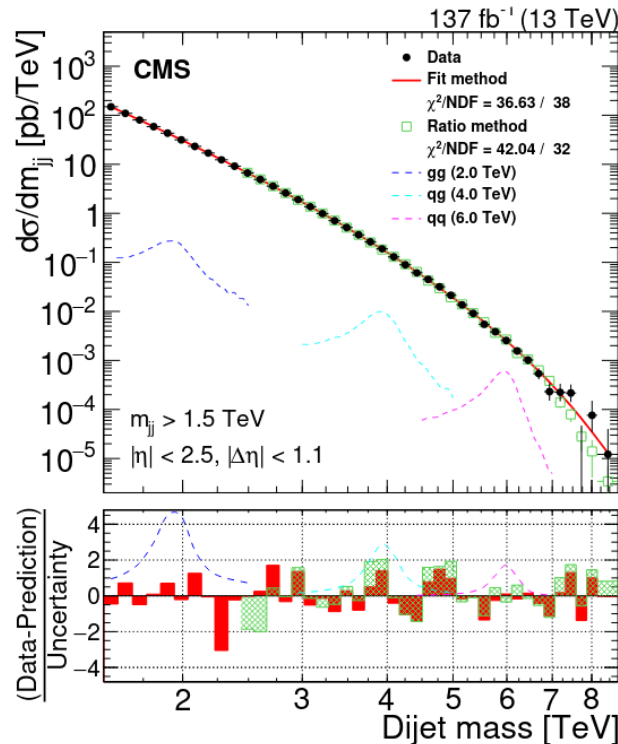
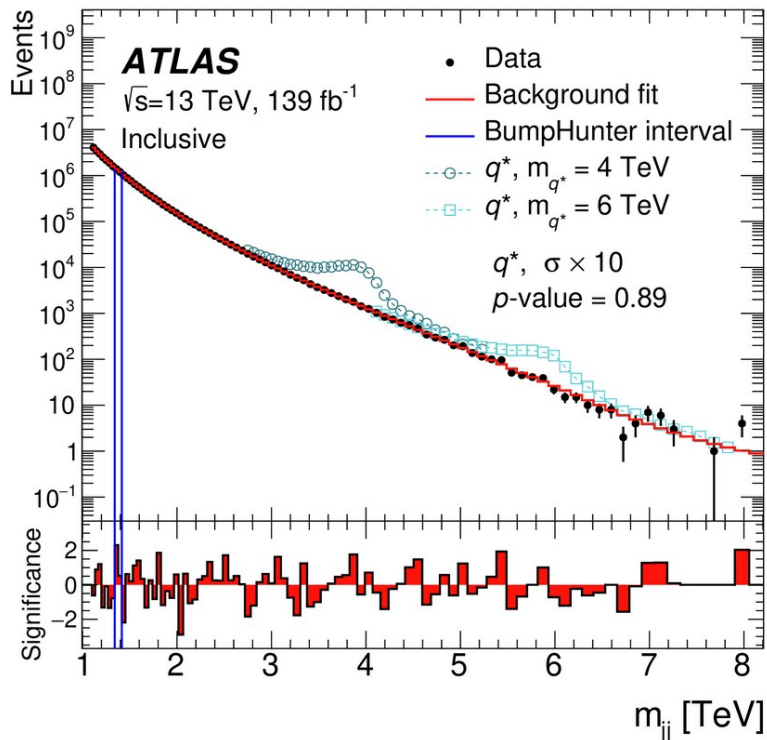
Resonance shapes depend on  $qq, qg$  and  $gg$  interactions

## Physics of Z'/W' bosons:

(review by P.Langacker [Rev.Mod.Phys.81:1199 \(2009\)](#))

- Similar to the SM W/Z bosons (but heavier)
- Extending SM to group  $SU(3) \times SU(2) \times U(1)$
- Sequential Standard Model
- Grand unified theories, fine tuning problem
- Extra dimensions
- Dark matter mediator etc. etc.

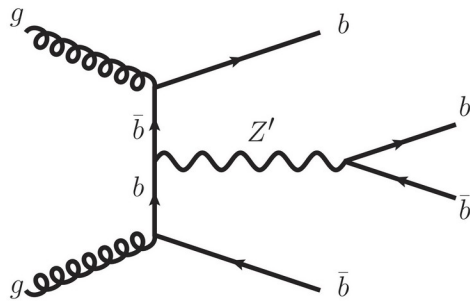
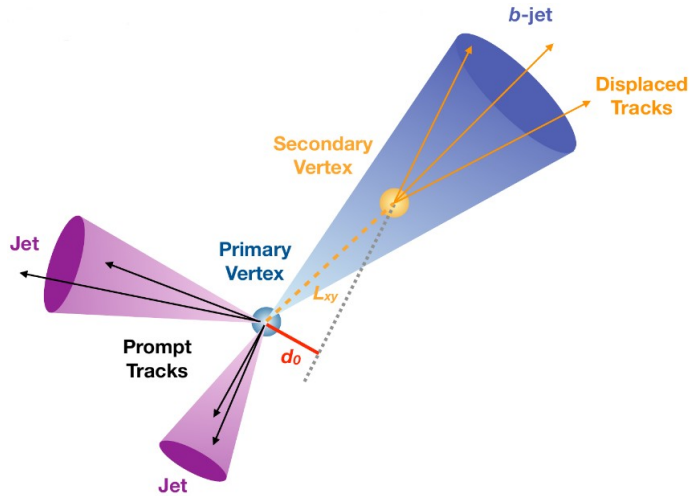
- Calculate invariant mass from 2 hadronic jets
- Fit with smooth analytic functions (red lines)
- Competitive limits up to  $\sim 8$  TeV



Observed and expected mass limits at 95% CL

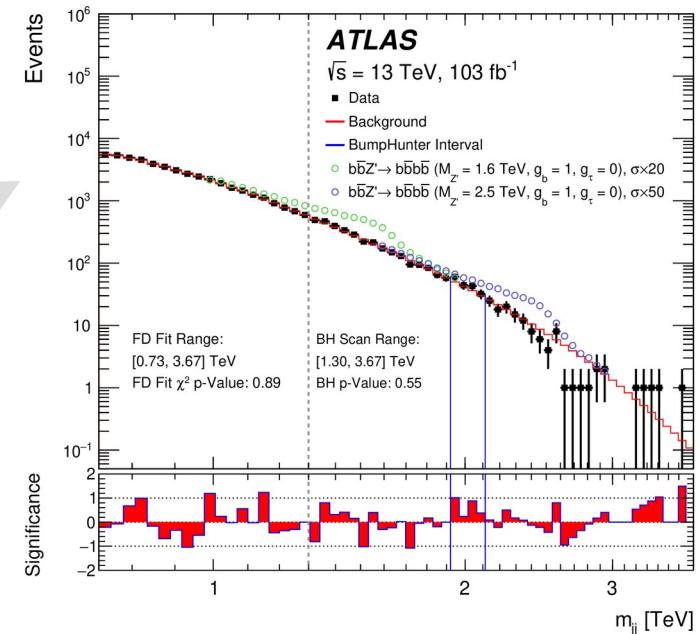
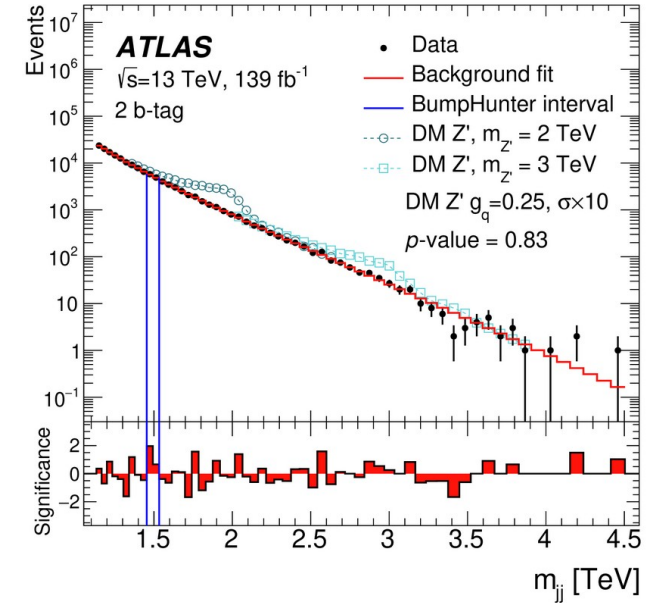
# Jets originating from b-quark

- Heavy  $Z'$  couples to SM particles (like  $q\bar{q}$ ) similar to Z-bosons
- “Leptophobic”  $Z'$  (does not decay to leptons), can couple to third-generation quarks for some modes
- All-jet searches may fail. Instead, search for  $Z' \rightarrow b\bar{b}$  by combining jets from b-quarks



2-b jet mass in all events

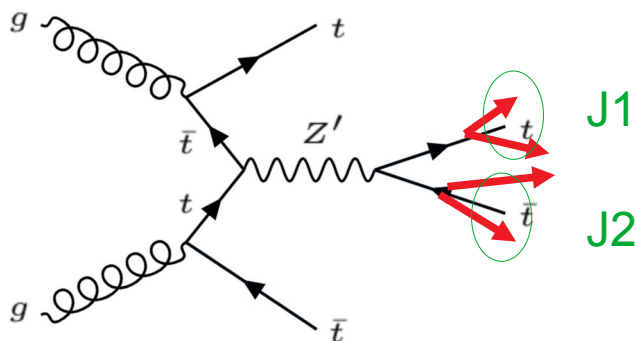
2-b jet mass in events with multiple b-quarks



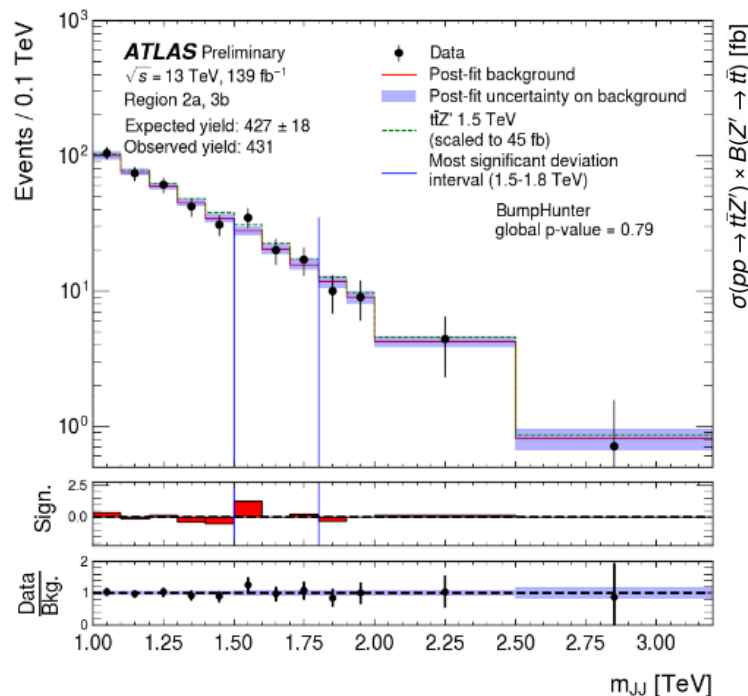
- No signals. Competitive limits for  $Z' \rightarrow b\bar{b}$  processes

- Some BSM models predict ‘top-philic’ vector resonances that couple mainly to top quark
- Best sensitivity  $\rightarrow$  both top quarks decay hadronically & spectator top decays semi-leptonically
- Use two large radius jets as proxies of the hadronically decaying top quarks (anti-kT with R=1)

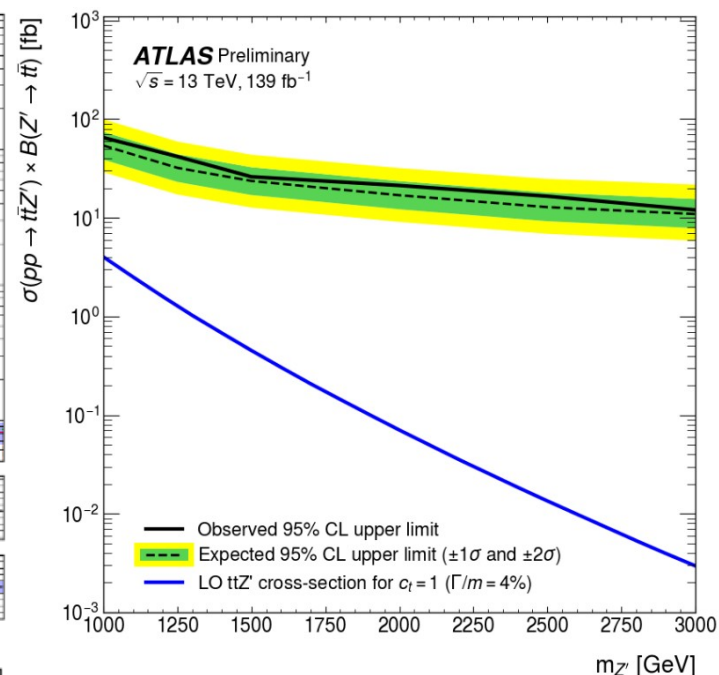
> 1 boosted jets  
> 2 b-tagged jets  
at least 1 lepton



Representative invariant mass of two large-radius jets



Experimental limits for  $t\bar{t}Z'$



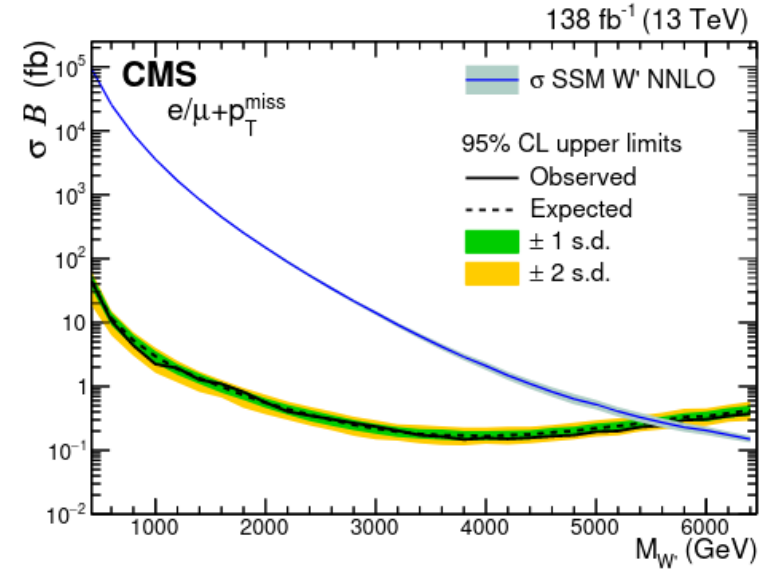
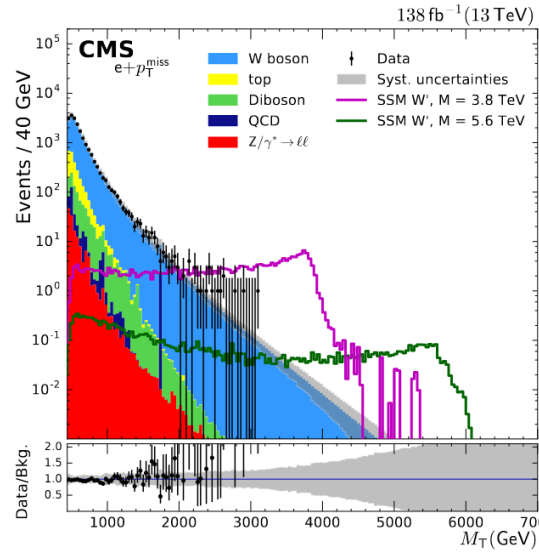
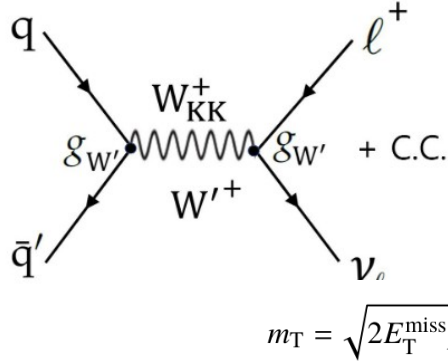
- No excess above the expected SM background
- Competitive Run II limits. Require more data to exclude  $t\bar{t}Z'$  production



# Searches for $W'$ heavy bosons - I

$W'$  is analog of  $W$  bosons in several BSM scenarios

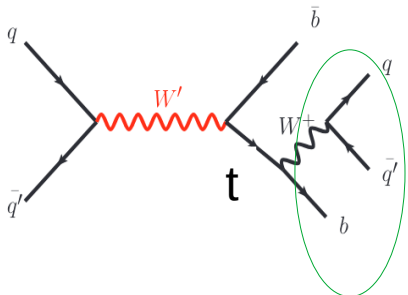
All leptonic  $W'$  ( $W_{KK}'$ )



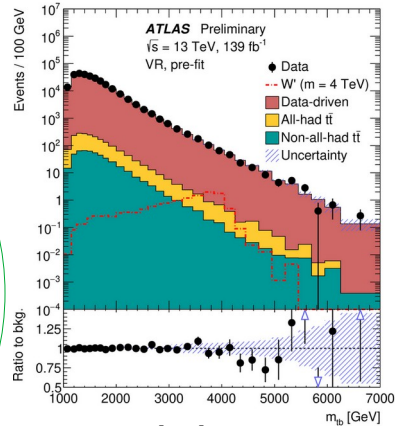
**CMS:** use transverse mass ( $m_T$ ) calculated from charged lepton and the missing transverse momenta

**ATLAS:** Search for heavy  $W'$  decaying to boosted top and b-quark

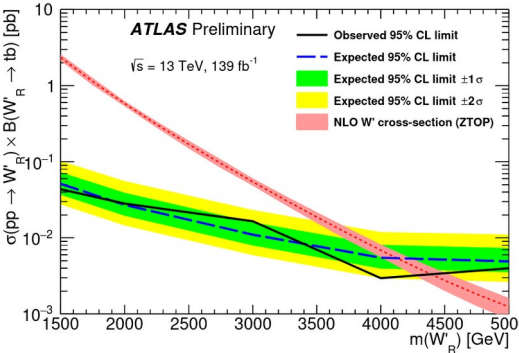
All-hadronic  $W'$



anti-kT with R=1



top+b jet mass



**LHC data exclude  $M(W')$ :**

< 5.7 TeV (lepton +  $\nu$ )

< 4.4 TeV (b-jet + boosted top)

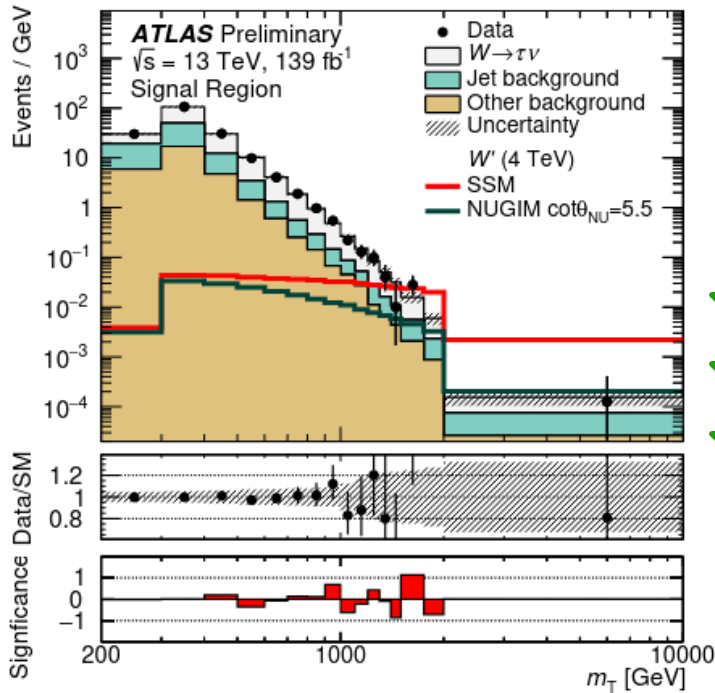
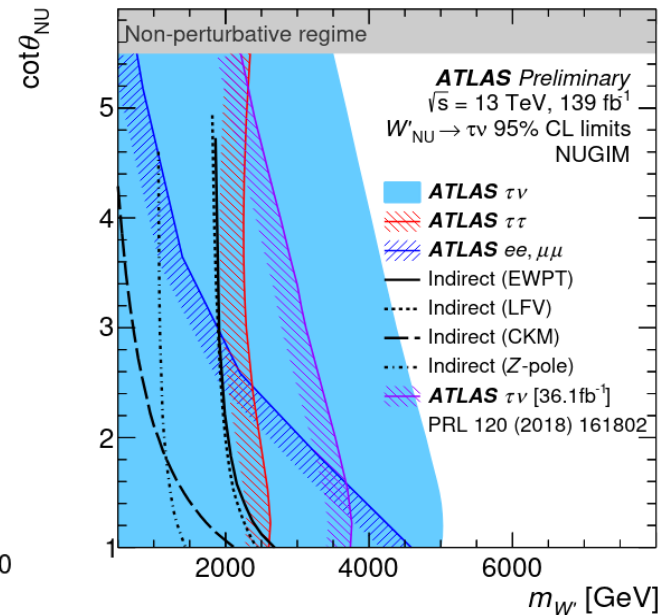
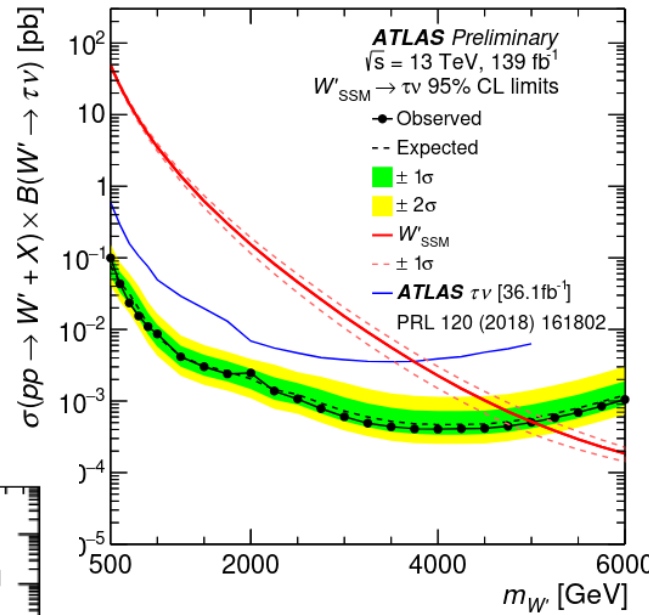
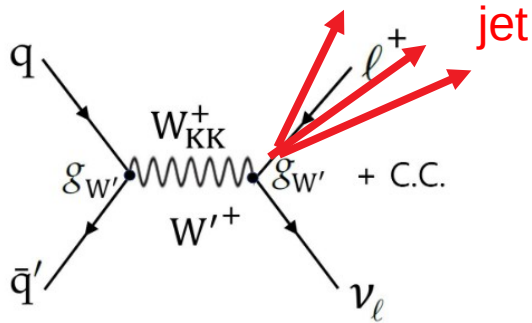
**Exclude BSM models:**

- ▶ Composite Higgs boson models
- ▶ Universal extra dimension
- ▶ Effective field theory (EFT)
- ▶ etc..



Hadronic decays of tau-leptons  
Challenging background!

→ use machine learning (ML)



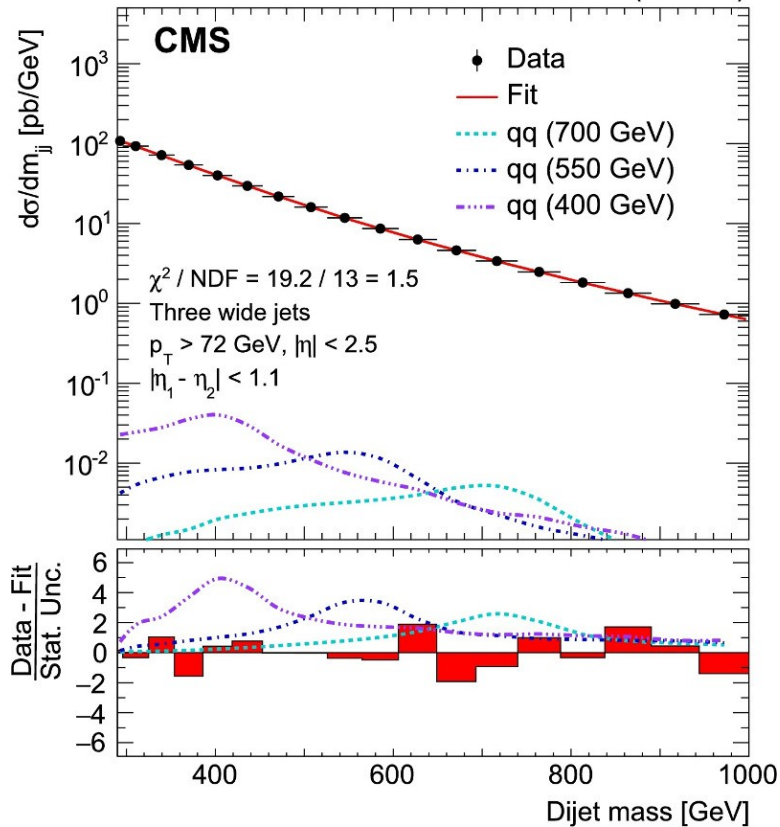
- Model independent limits
- <5 TeV 95% CL for Sequential Standard Model scenario
- Limits for Non-Universal Gauge Interaction Models (NUGIM) with additional parameter  $\cot \theta_{\text{NU}}$  used to scale the couplings to the first and second generations of fermions

# Searches using di-jets + X

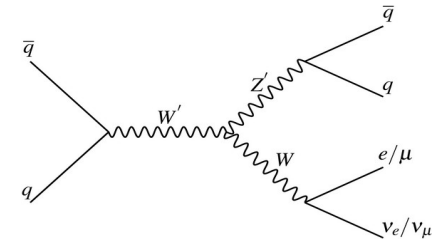
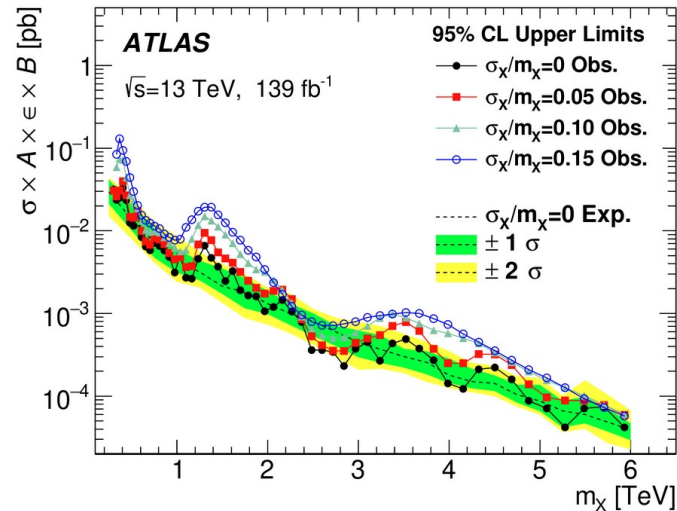
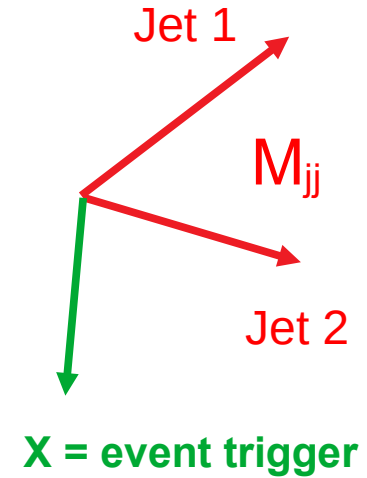
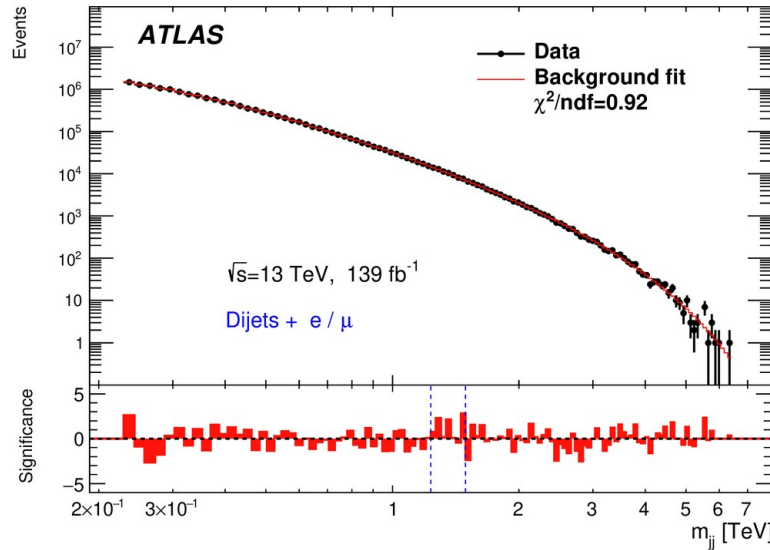
- Additional object X (lepton, jet, photon) helps triggering events with smaller masses (~ 300 GeV – 1 TeV)

X = 3<sup>rd</sup> jet

18.3 fb<sup>-1</sup> (13 TeV)



X = e, mu

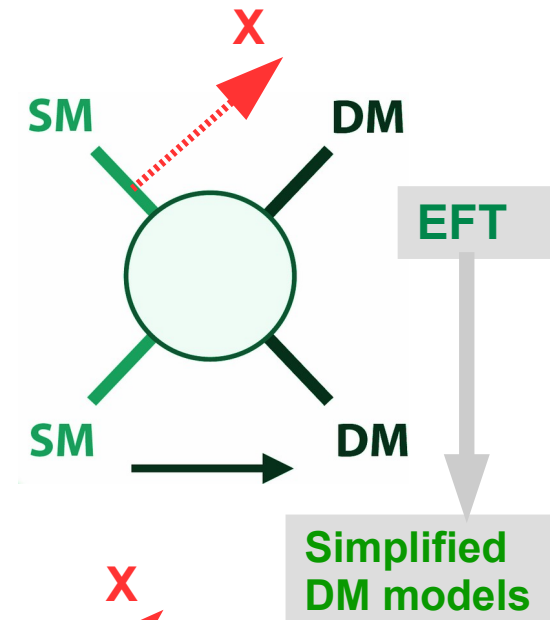


Limits on Sequential Standard model at 1.5 TeV

- Several specific models excluded, including technicolor, sequential SM, H<sup>±</sup>, DM with associated W

# Searches for Dark Matter (DM) at the LHC

- Overwhelming evidence for DM
- If new particle  $\rightarrow$  DM & SM particles in thermal equilibrium in the past
  - DM abundance determines annihilation cross section at freeze-out
  - DM is at electroweak scale?  $\rightarrow$  within LHC energy reach
- LHC collides pp under well-controlled conditions
  - SM particles can radiate other SM particles “X” (via ISR)
  - Undetected DM  $\rightarrow$  imbalance in transverse momentum

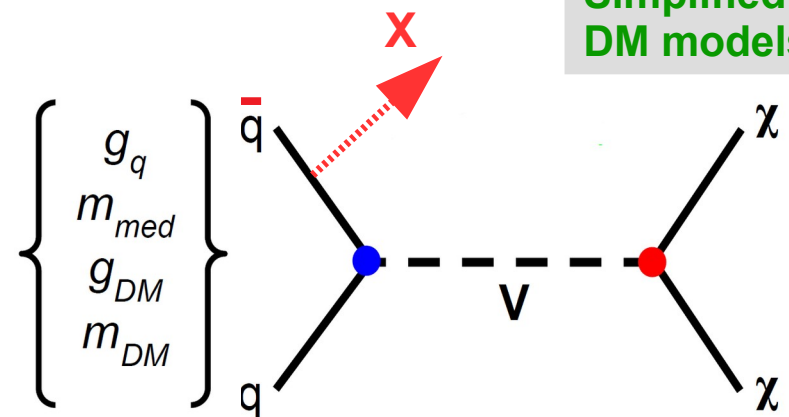


Adopt simplified DM model with a “mediator”  $V$

- $g_q$  ( $g_{DM}$ ) – mediator coupling to quarks (DM)
- $m_{med}$  ( $m_{DM}$ ) – mass of mediator (DM)

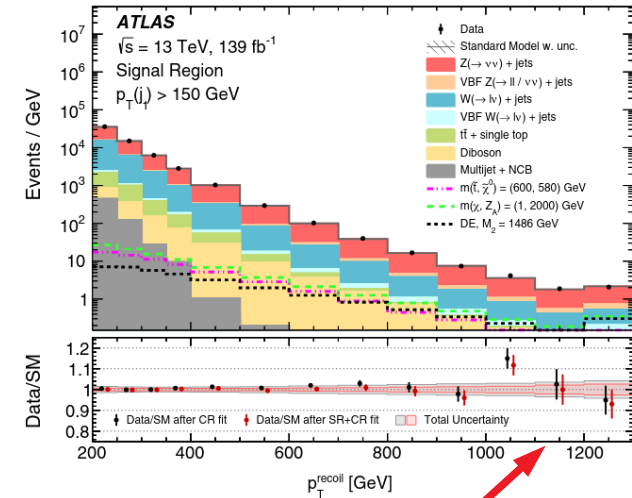
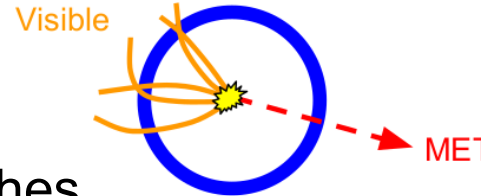
ATLAS & CMS:  $g_q=0.25$  (S=1),  $g_q=1$  (S=0),  $g_{DM}=1$

$\Gamma$ =minimum width formula



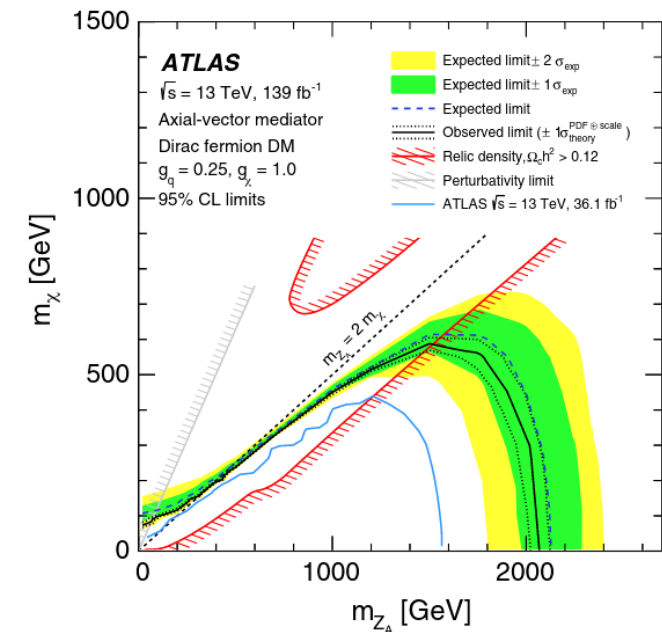


- ▼ Mono jet searches rely on MET
- ▼ MET > 200 GeV for typical searches
- ▼ Challenging pileup and non-collision background
- ▼ SM background:
  - ▼  $Z(\nu\nu)+j$  – irreducible (real MET) → MC with data on  $Z \rightarrow ll$
  - ▼  $W(l\nu)+j, t\bar{t}$  – reducible (loss of leptons from W) → MC
  - ▼ QCD multi-jet, non-collision BG → data driven

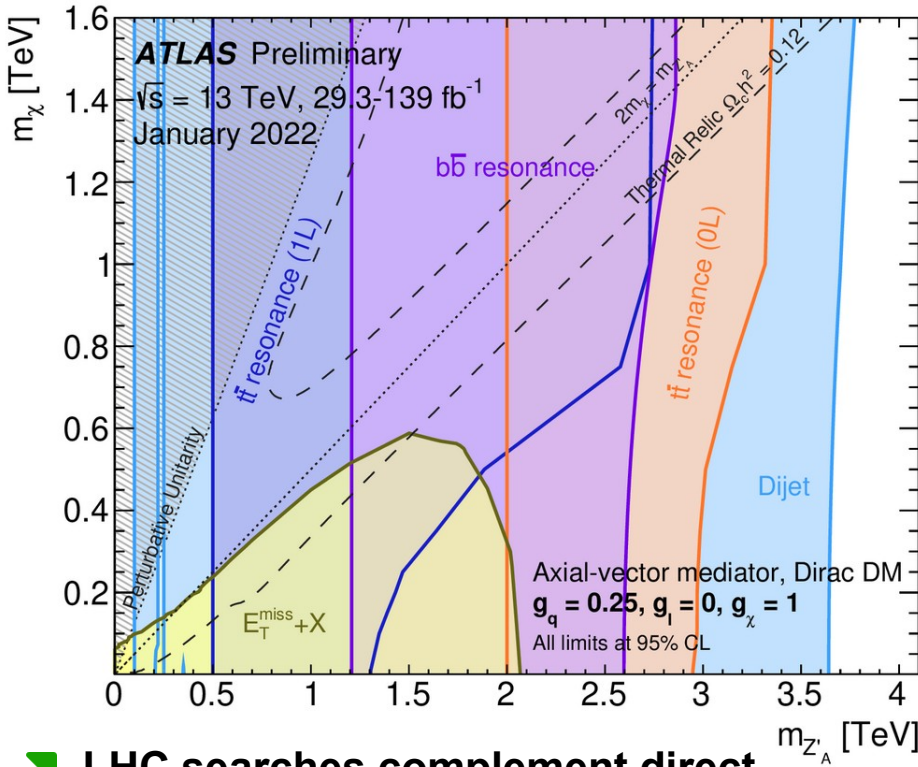


Typical precision for SM description

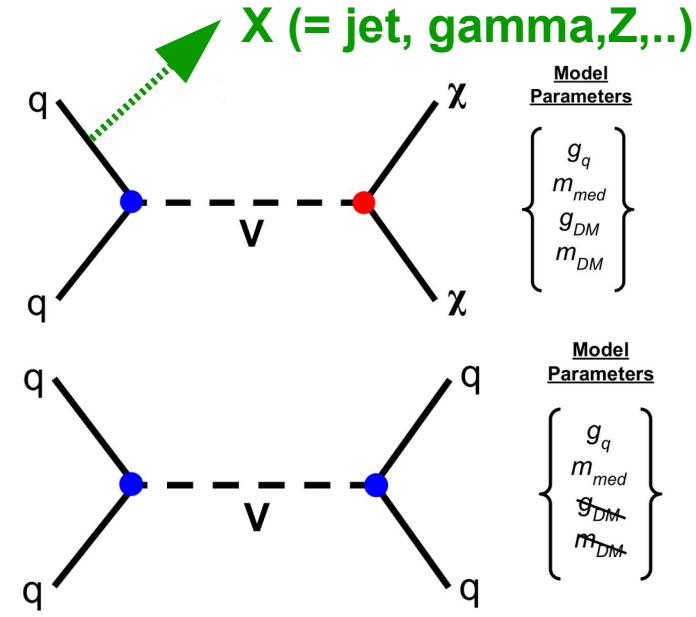
- ▼ Required high-precision SM measurements
- ▼ Examples:
  - ▼  $jet+\gamma$  – missing NNLO effects for  $Z(\nu\nu)$  (CMS)
  - ▼  $W+jet$  control region also for  $Z(\nu\nu)$  (ATLAS)



# Dark Matter summary plots

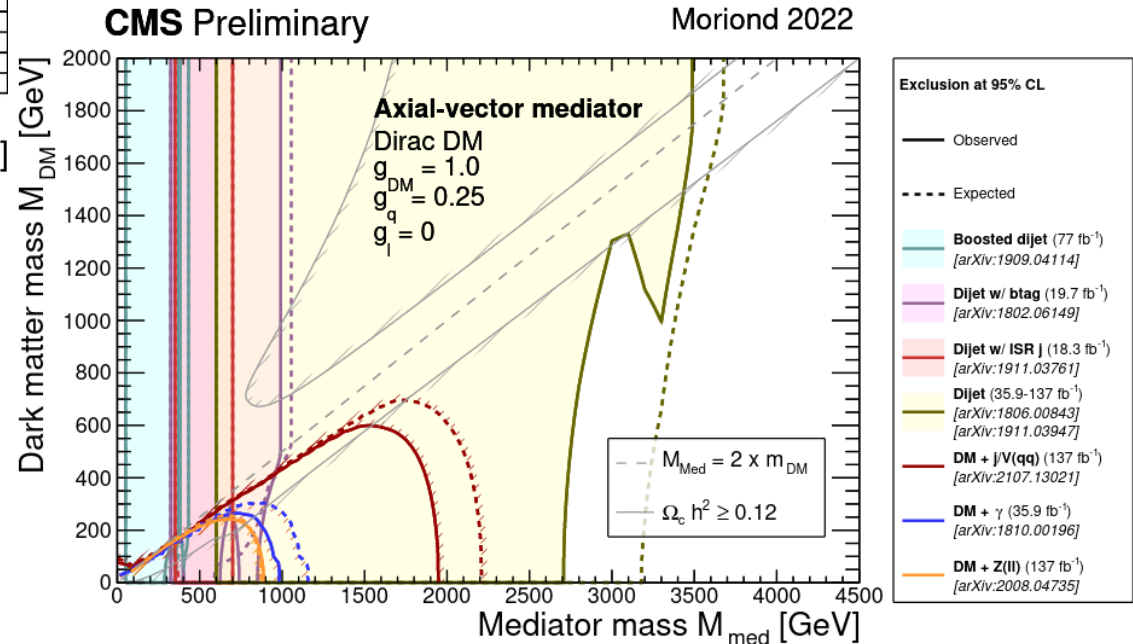


- Dijet**  
Dijet, 139 fb<sup>-1</sup>  
JHEP 03 (2020) 145  
Dijet TLA, 29.3 fb<sup>-1</sup>  
PRL 121 (2018) 081801  
Dijet+ISR, 79.8 fb<sup>-1</sup>  
PLB 795 (2019) 56  
Boosted dijet+ISR, 36.1 fb<sup>-1</sup>  
PLB 788 (2019) 316  
Boosted di-b+ISR, 80.5 fb<sup>-1</sup>  
ATLAS-CONF-2018-052
- t $\bar{t}$  resonance (1L)**  
36.1 fb<sup>-1</sup>  
EPJC 78 (2018) 565
- t $\bar{t}$  resonance (0L)**  
139 fb<sup>-1</sup>  
JHEP 10 (2020) 061
- b $\bar{b}$  resonance**  
139 fb<sup>-1</sup>  
JHEP 03 (2020) 145
- E<sub>T</sub><sup>miss</sup> + X**  
E<sub>T</sub><sup>miss</sup>+jet, 139 fb<sup>-1</sup>  
PRD 103 (2021) 112006



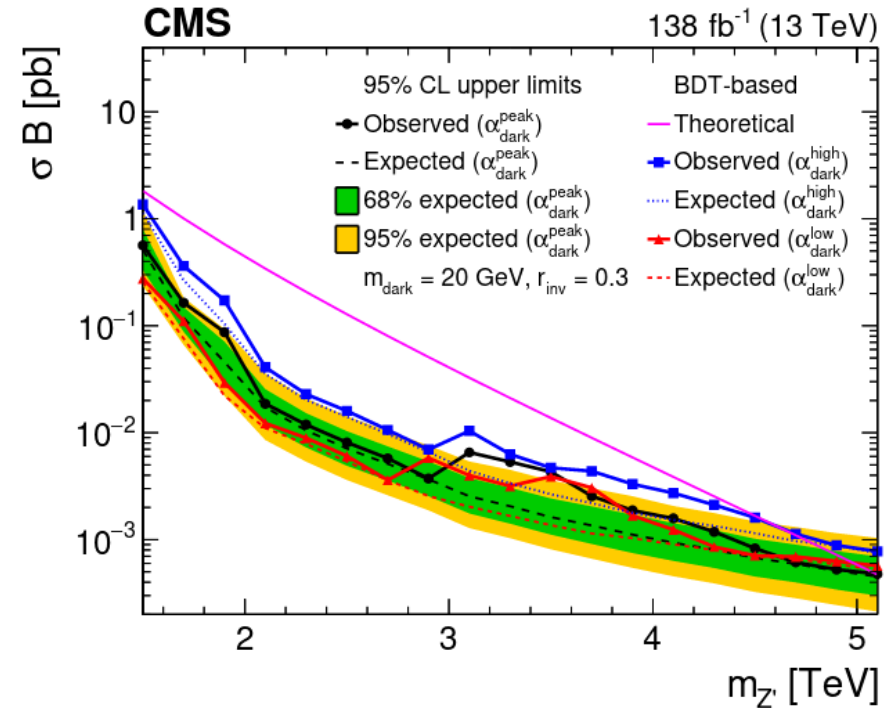
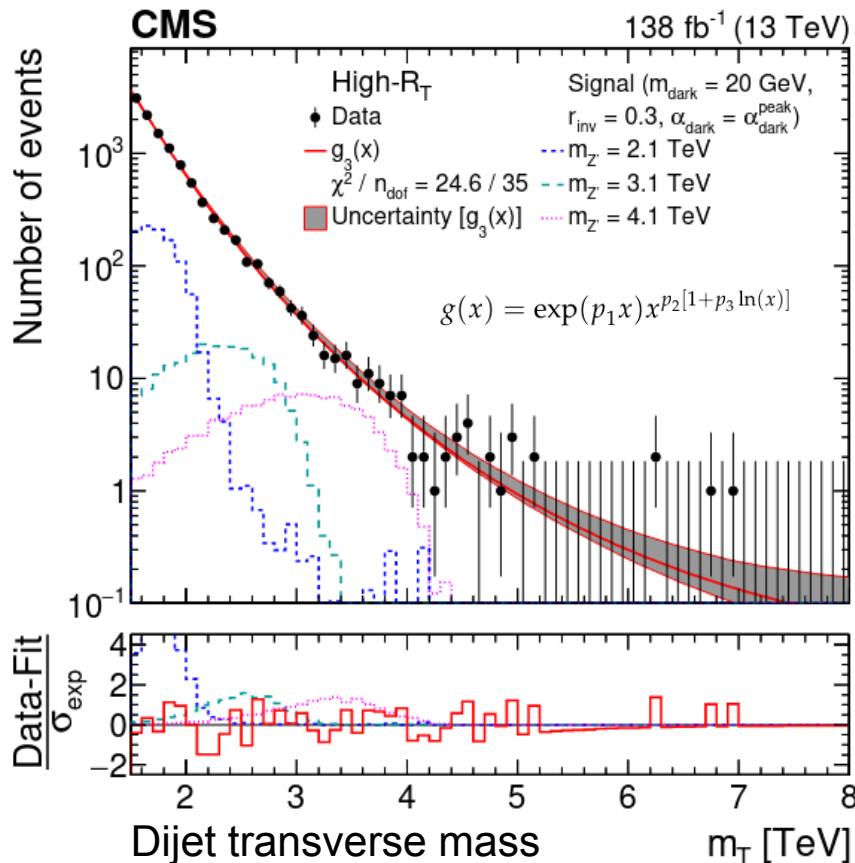
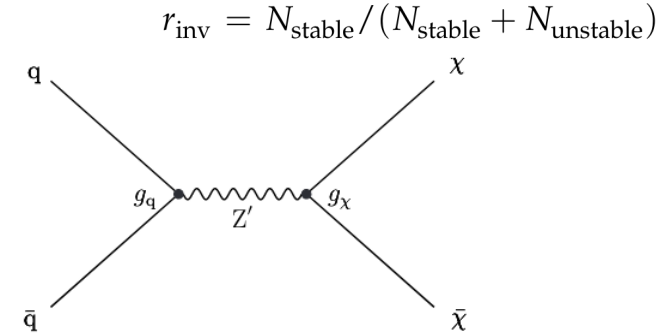
- Model Parameters**
- $g_q$
  - $m_{med}$
  - $g_{DM}$
  - $m_{DM}$
- Model Parameters**
- $g_q$
  - $m_{med}$
  - $g_{DM}$
  - $m_{DM}$

- ▶ **LHC searches complement direct detection experiments:**
  - ▶ Strong (model-dependent) limits for low mass  $m_{DM}$  (<10 GeV)
  - ▶ Strong limits for spin-dependent DM-nucleon cross section
  - ▶ Comprehensive searches for DM-SM mediators



- Exclusion at 95% CL**
- Observed
  - - - Expected
  - Boosted dijet (77 fb<sup>-1</sup>)  
[arXiv:1909.04114]
  - Dijet w/ btag (19.7 fb<sup>-1</sup>)  
[arXiv:1802.06149]
  - Dijet w/ ISR (18.3 fb<sup>-1</sup>)  
[arXiv:1911.03761]
  - Dijet (35.9-137 fb<sup>-1</sup>)  
[arXiv:1806.00843]
  - DM + J/V(qq) (137 fb<sup>-1</sup>)  
[arXiv:1911.03947]
  - DM +  $\gamma$  (35.9 fb<sup>-1</sup>)  
[arXiv:1810.00196]
  - DM + Z(ll) (137 fb<sup>-1</sup>)  
[arXiv:2008.04735]

- Heavy *leptophobic*  $Z'$  mediator decays to two "semi-visible" jets, containing both visible matter and invisible dark matter ("dark hadrons" from "dark quarks")
- Unstable dark hadrons decay to SM quarks while the stable dark hadrons are DM candidates
- Train BDT to separate SM and wider "semi-visible" jets



Limits for  $Z'$  mass for  $m_{\text{dark}}=20$  GeV and fraction of stable invisible dark hadrons

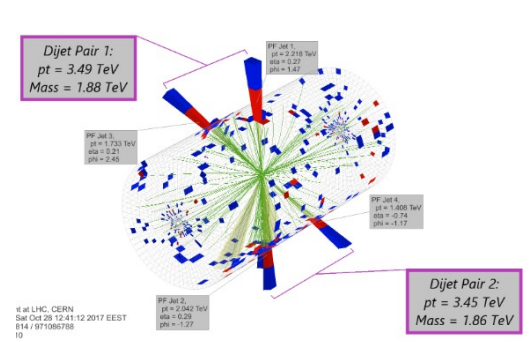
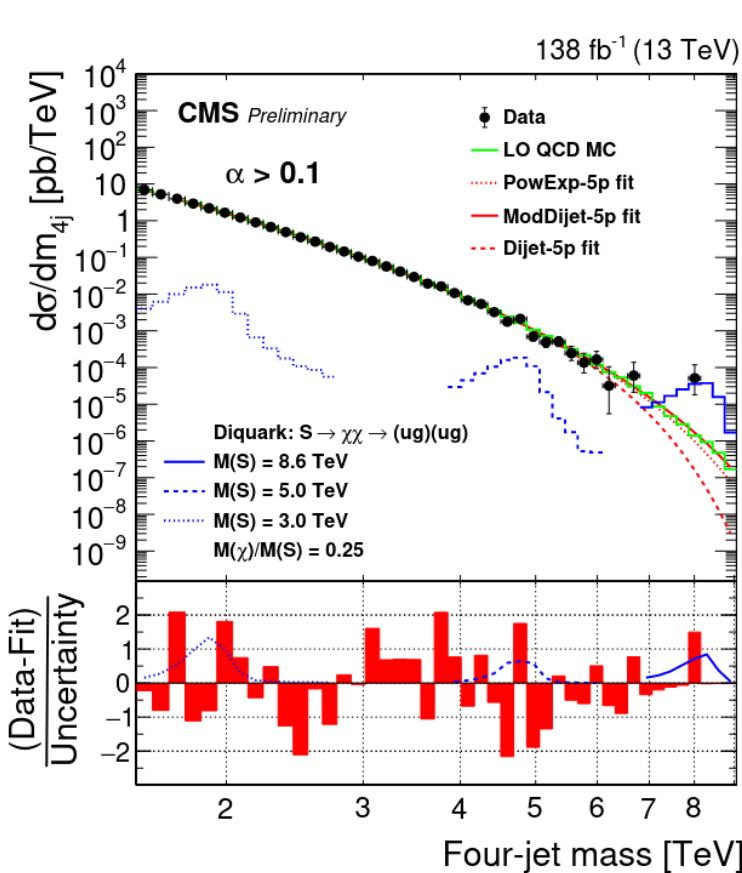
**Complement DM searches using missing momentum and initial-state radiation**



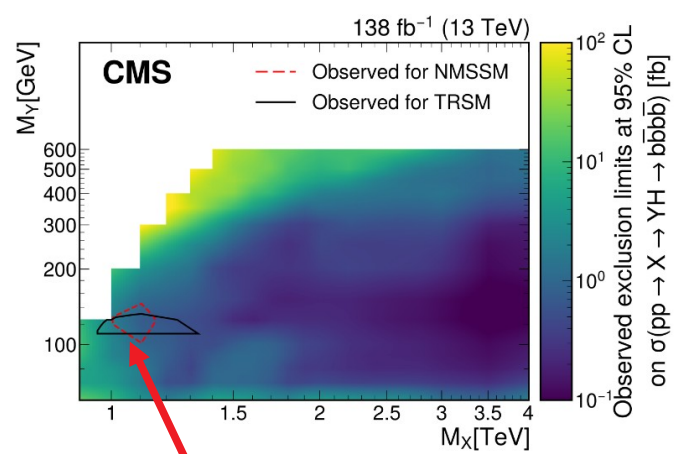
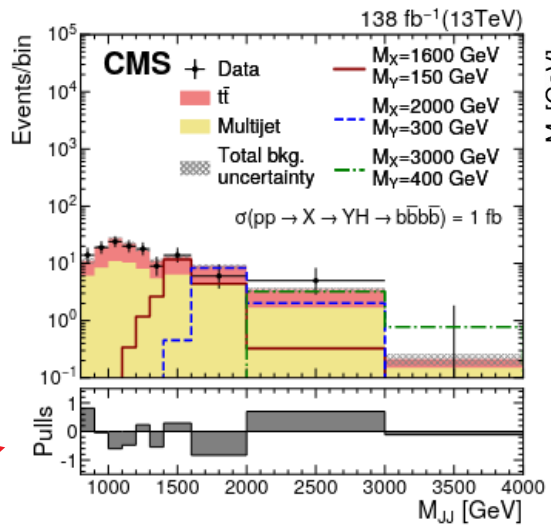
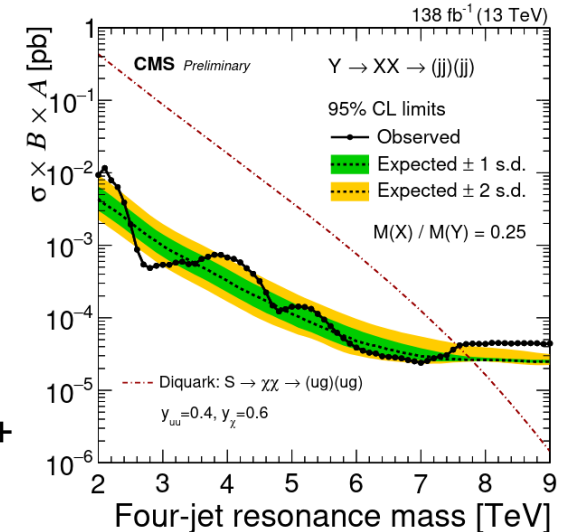
# BSM particles decaying $X \rightarrow YY / YH$

- Resonant  $pp \rightarrow X \rightarrow YY \rightarrow (jj) (jj)$  & Non-resonant  $pp \rightarrow YY \rightarrow (jj) (jj)$
- Scan  $\alpha$  (average mass of the two dijets divided by the four-jet mass)

Example: Scalar diquark:  
 $uu \rightarrow S(uu) \rightarrow \chi\chi \rightarrow (ug)(ug)$



First model-independent upper limits at 95% confidence levels + R-parity violating SUSY

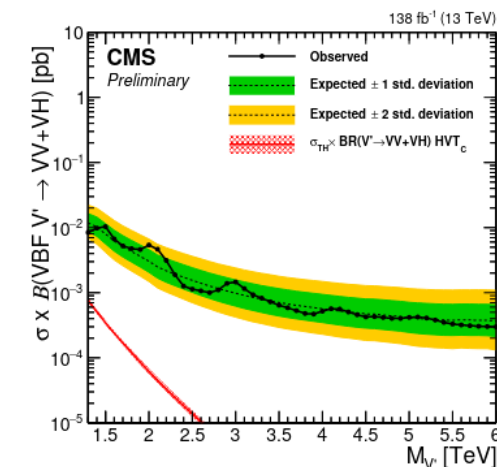
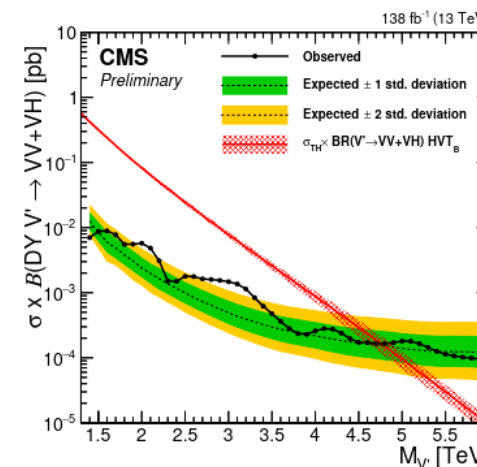
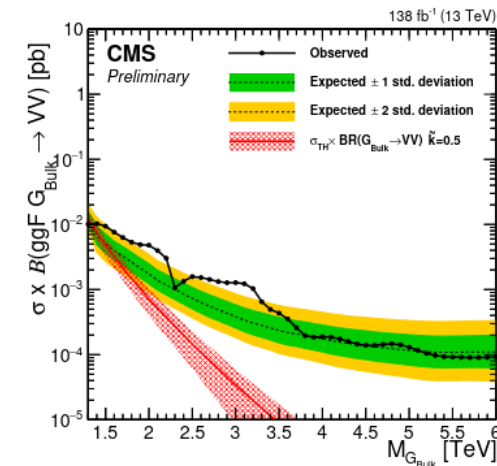
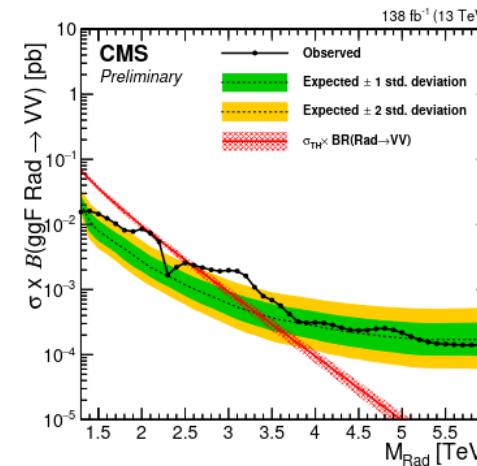
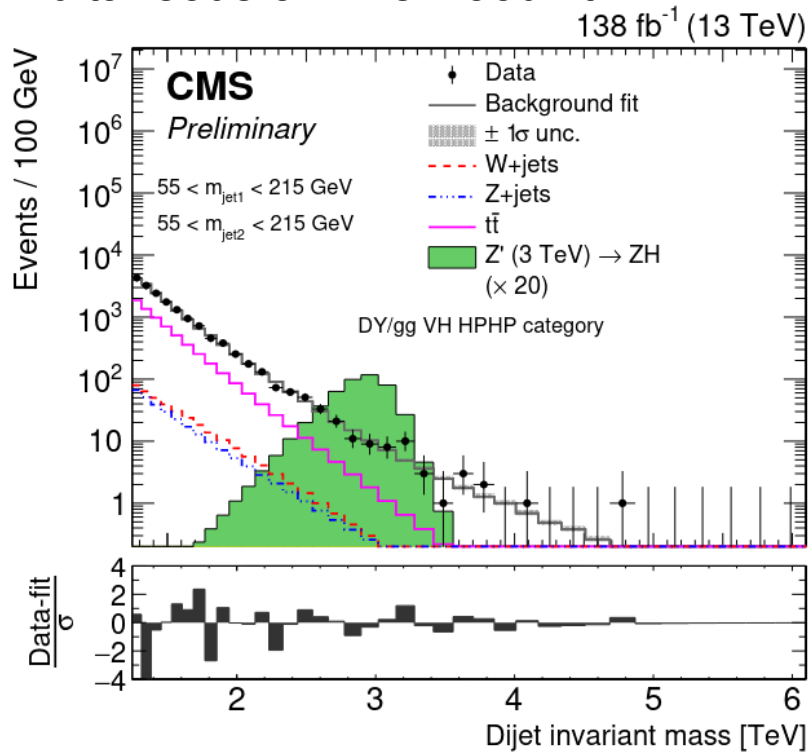
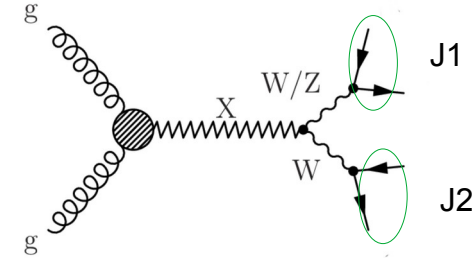


95% CL exclusions for  $M_X$  and  $M_Y$

- $pp \rightarrow X$  (scalar)  $\rightarrow YH \rightarrow bbb\bar{b}$
- Boosted regime: 2 large R-jets (AK8 = anti-kT R=0.8)

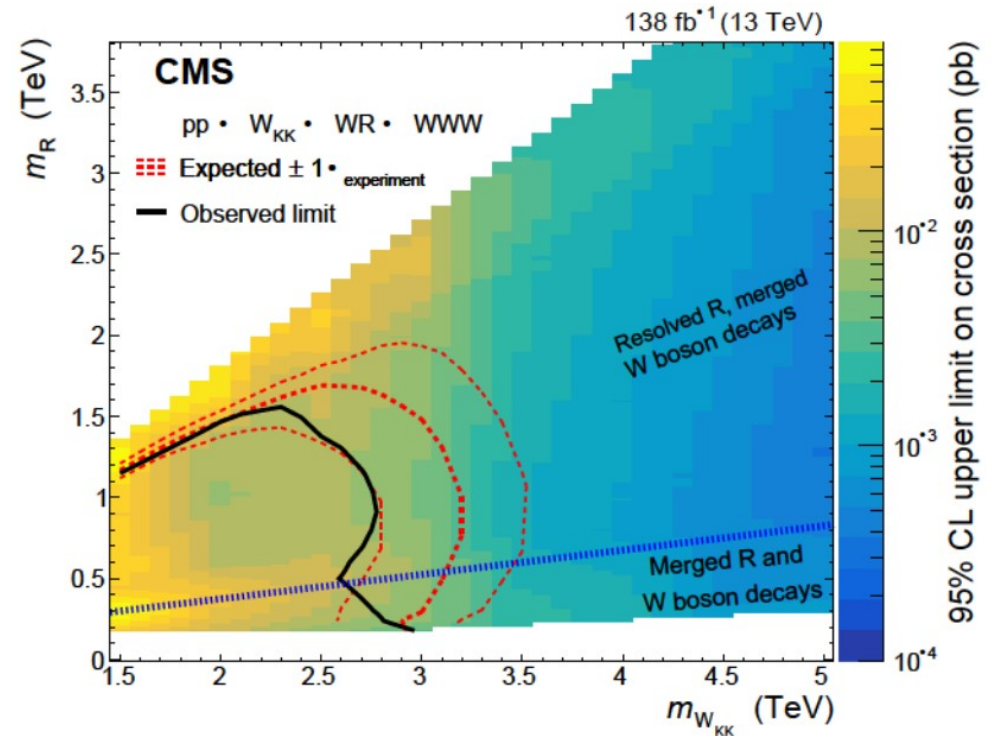
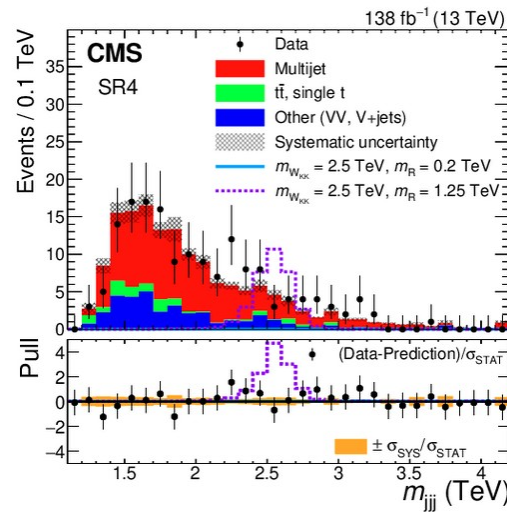
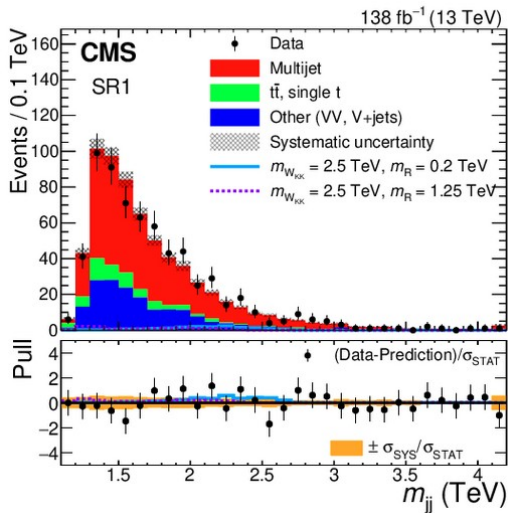
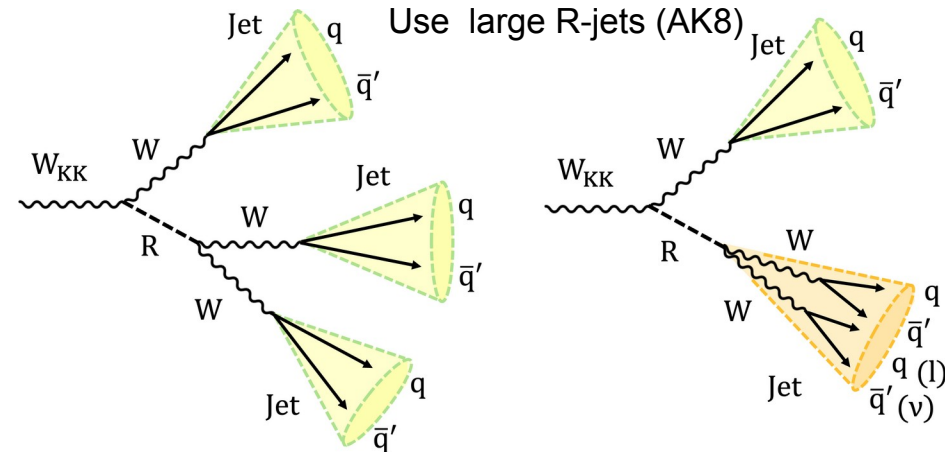
# X → WW, WZ, ZZ, WH or ZH

- W/Z/H decays to large R-jet (AK8) for heavy X
- Hadronic decays of W, Z, and H bosons identified using ML
- Measure masses of 2 jets ( $m_{J1}$ ,  $m_{J2}$ ) and dijet mass ( $m_{JJ}$ )
- Simultaneous 3D likelihood fit



- No evidence for new resonances
- Largest excess at ~2-3 TeV has ~2.3  $\sigma$  (global)
- Competitive limits for several BSM signals (including VBF mode)

- Search for Kaluza–Klein excited vector boson resonances,  $W_{KK} \rightarrow R W \rightarrow WWW$  (R is a scalar radion)
- No signal-like excess over the background

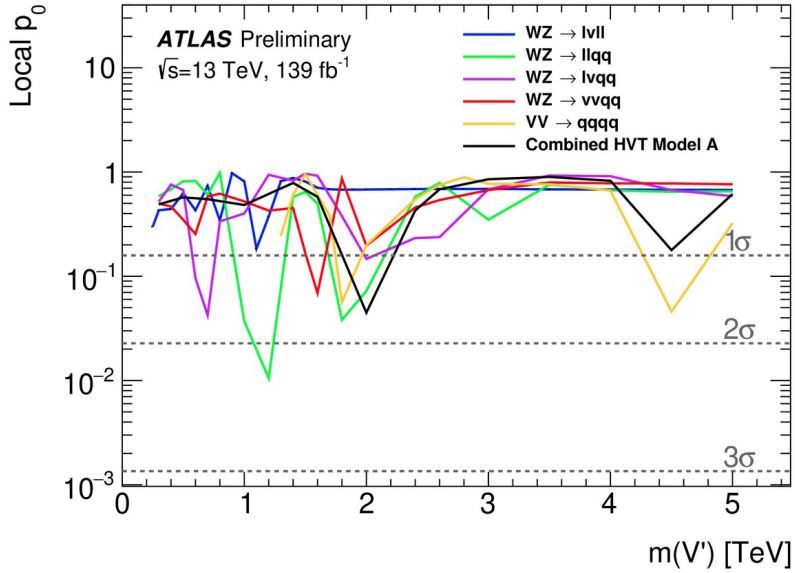


- First results using jet measurements
- Technical advances:
  - Novel jet substructure techniques
  - Dedicated “radion” taggers based on ML



- Uses 16 (orthogonal) ATLAS publications during 2018 - 2022
- Combine bosonic decay modes  $qqqq, \nu\nu qq, \ell\nu qq, \ell\ell qq, \ell\nu\ell\ell, qqbb, \nu\nu bb, \ell\nu bb$
- Results are interpreted in terms in the context of Spin-1 Heavy Vector Triplet (HVT)
  - $V'$  is collectively denotes  $W'^{\pm}$  and  $Z'$

Analysis	leptons	$E_{T_{miss}}$	jets	b-tags	Discr.
$WW/WZ/ZZ \rightarrow qqqq$	0	Veto	$\geq 2J$	-	$m_{VV}$
$WZ/ZZ \rightarrow \nu\nu qq$	0	Yes	$\geq 1J$	0	$m_{VV}$
$WW/WZ \rightarrow \ell\nu qq$	1e, 1 $\mu$	Yes	$\geq 2j, \geq 1J$	0, 1, 2	$m_{VV}$
$WZ/ZZ \rightarrow \ell\ell qq$	2e, 2 $\mu$	-	$\geq 2j, \geq 1J$	0	$m_{VV}$
$WZ \rightarrow \ell\nu\ell\ell$	3 $\subset$ (e, $\mu$ )	Yes	-	0	$m_{VV}$
$WH/ZH \rightarrow qqbb$	0	Veto	$\geq 2J$	1, 2	$m_{VH}$
$ZH \rightarrow \nu\nu bb$	0	Yes	$\geq 2j, \geq 1J$	1, 2	$m_{VH}$
$WH \rightarrow \ell\nu bb$	1e, 1 $\mu$	Yes	$\geq 2j, \geq 1J$	1, 2	$m_{VH}$
$ZH \rightarrow \ell\ell bb$	2e, 2 $\mu$	Veto	$\geq 2j, \geq 1J$	1, 2	$m_{VH}$
$\ell\nu$	1e, 1 $\mu$	Yes	-	-	$m_T$
$\tau\nu$	0	Yes	-	-	$m_T$
$\ell\ell$	$\geq 2e, \geq 2\mu$	-	-	-	$m_{\ell\ell}$

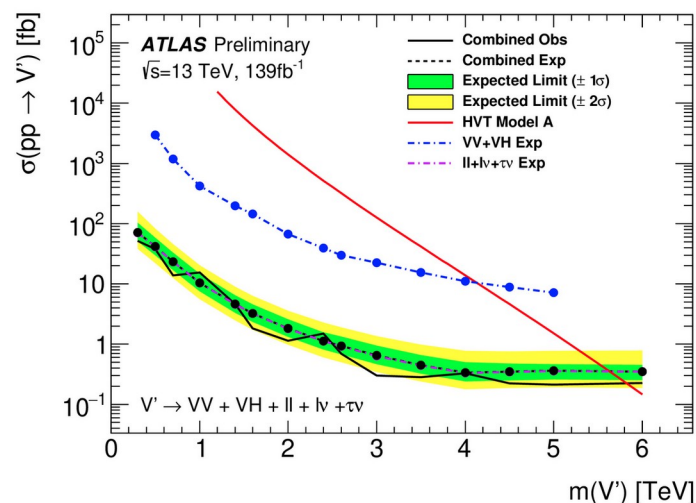


Typical example of p-value scan over the HVT pole masses up to 5 TeV

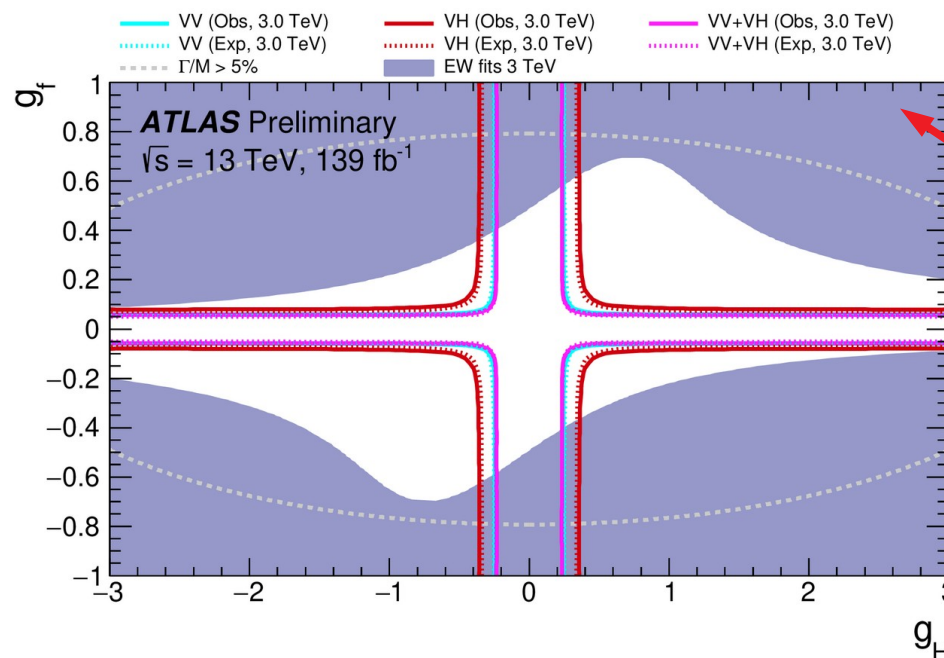
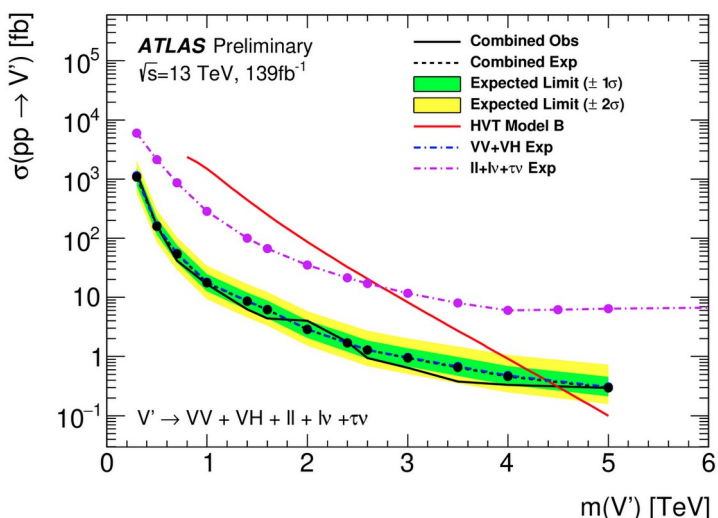
Scans for only-leptonic channel is extended up to 6 TeV (higher statistics!)

Results interpreted in terms of exclusions limits on masses and coupling constants

Weakly coupled HVT-A coupling



Strongly coupled HVT-A coupling



Constraints from EWK measurements

See other channels & masses in the original CONF note

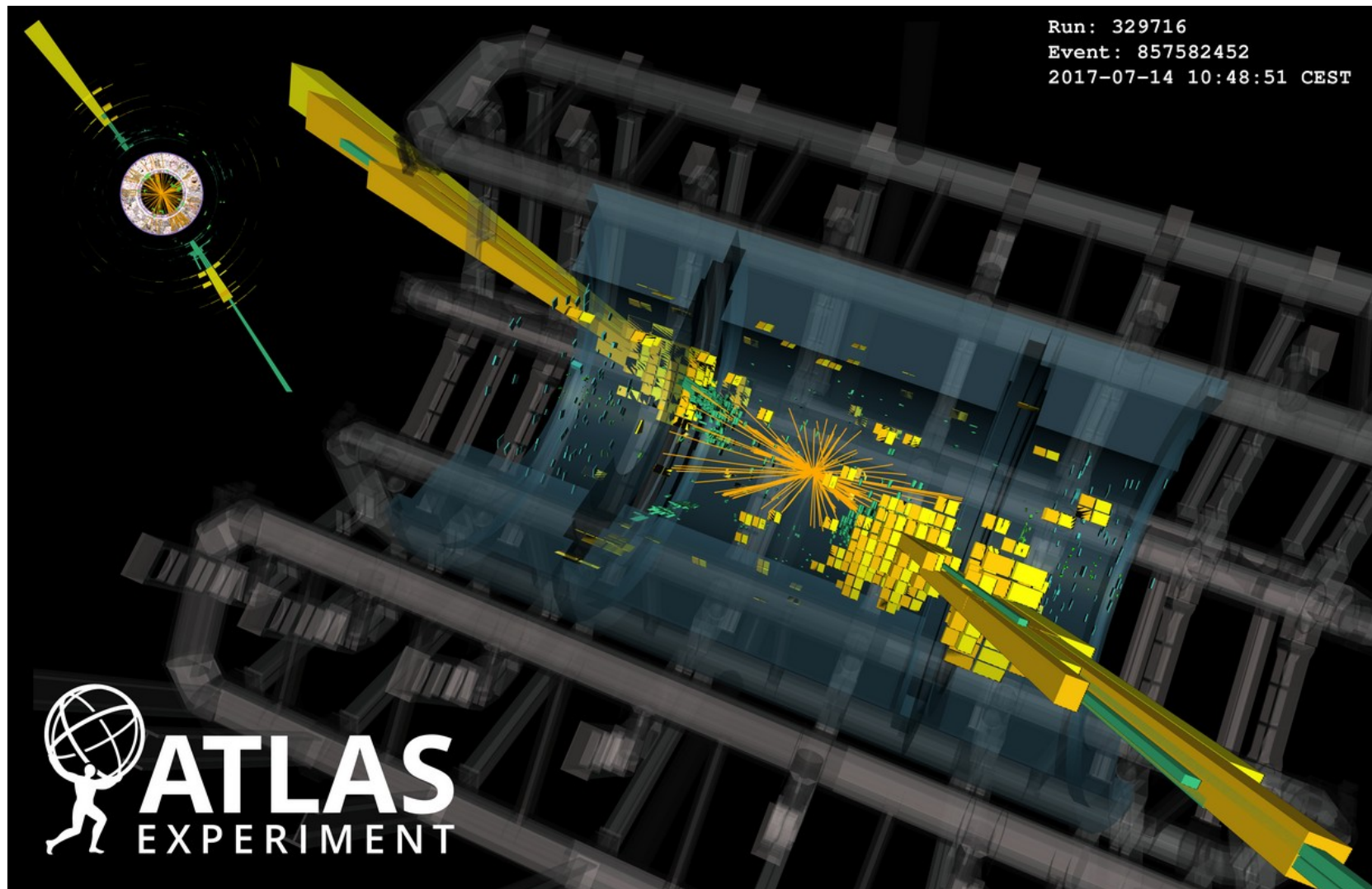
Typical exclusions for 3 TeV for  $\{g_V, g_H\}$  for  $q\bar{q}$  production mode

Combined results strengthen the constraints on BSM physics and allow expressions of constraints in terms of couplings to quarks, leptons and fermions

- ▼ Extensive program for searches for new heavy particles
- ▼ Refined studies with complex final state (jet, top,  $\gamma$ ,  $t\bar{t}$ , W, Higgs, etc)
- ▼ Mass reach extends up to 8 TeV for many inclusive jet/lepton studies
- ▼ Constraints on simplified DM models that complement direct detection experiments:
  - ▼ Strong (model-dependent) limits for low mass  $m_{\text{DM}}$  ( $<10$  GeV)
  - ▼ Strong limits for spin-dependent DM-nucleon cross section
  - ▼ Comprehensive searches for DM-SM mediators
- ▼ Combination of Run 2 searches for heavy resonances the context of HVT
- ▼ Stay tuned: Ongoing analysis using full Run 2 data
- ▼ Opportunities at Run 3:
  - ▼ 13 TeV  $\rightarrow$  13.6 TeV CM energy
  - ▼ Increase in luminosity (x 2, statistics!)
  - ▼ Cutting edge analysis techniques

**$\rightarrow$  Can translate to  $\sim 1$  TeV in mass reach for some channels**

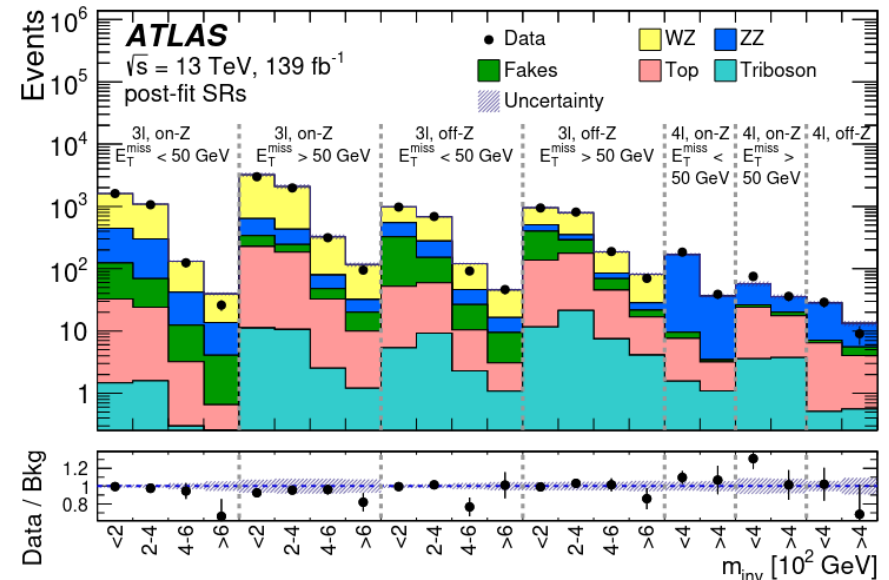
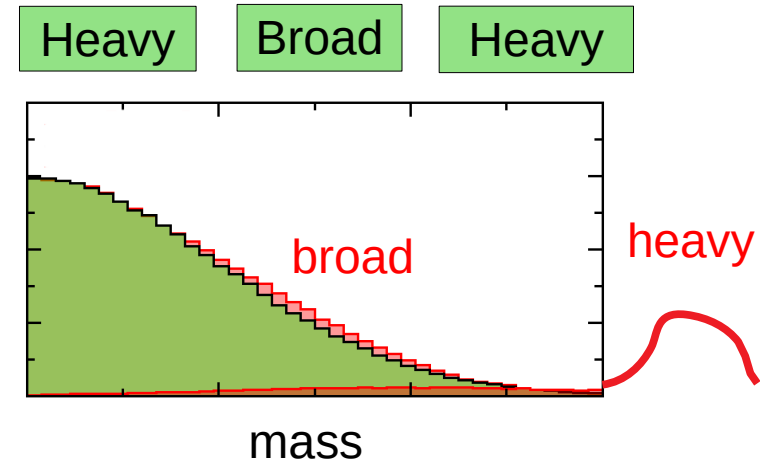
# Backup





## Non-resonant production

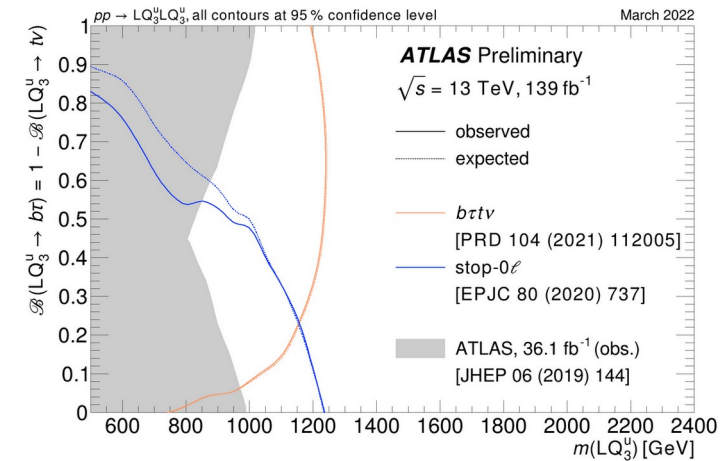
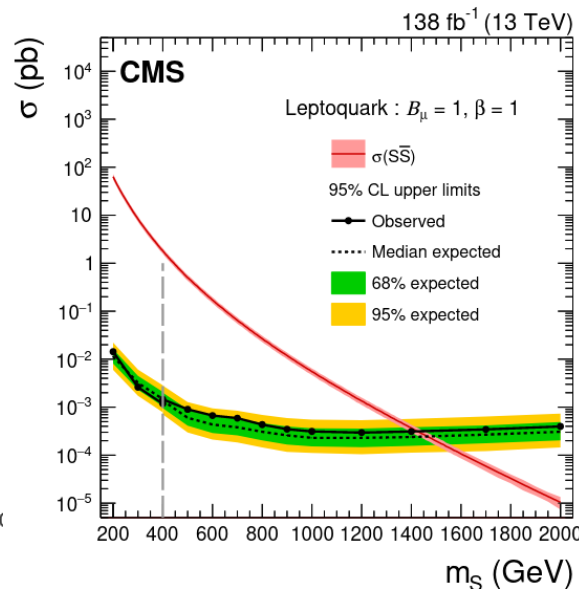
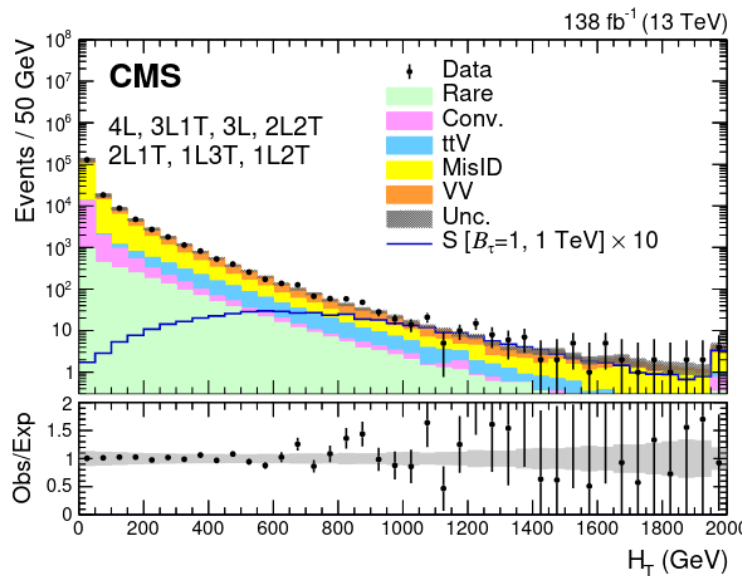
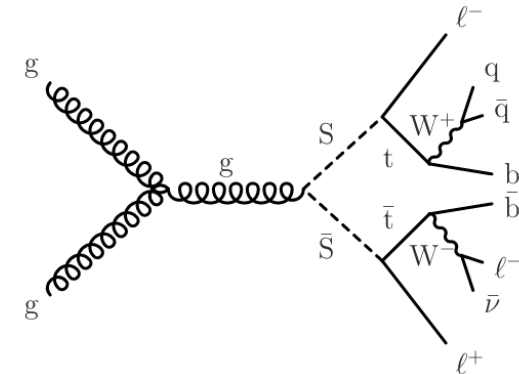
See M.Folgado & V.Sanz, Advances in High Energy Physics, Volume 2021, Article ID 2573471,



- ▶ New physics may show up in deviations over expected rates (wide resonances, non-resonant production etc)
- ▶ More elusive for direct production, but:
  - ▶ can have larger cross section
  - ▶ affects the measured distributions
- ▶ Look at production rate of 3 or 4 leptons
  - ▶ 22 event categories according to the number of leptons in the event, the missing transverse momentum, the invariant mass of the leptons
- ▶ No deviations from the Standard Model

- Events with at least 3 leptons
- Boosted decision tree to define signal regions.
- Observations are consistent with the SM
- 95% CL limits for Leptoquarks (<1.4 TeV), Type-III seesaw heavy fermions (<1 TeV), Vector-like fermions (<1 TeV)

## Example: Leptoquarks



ATLAS updated summary for pair-produced scalar third-generation up-type leptoquarks

$H_T$  is the scalar  $p_T$  sum of all jets