

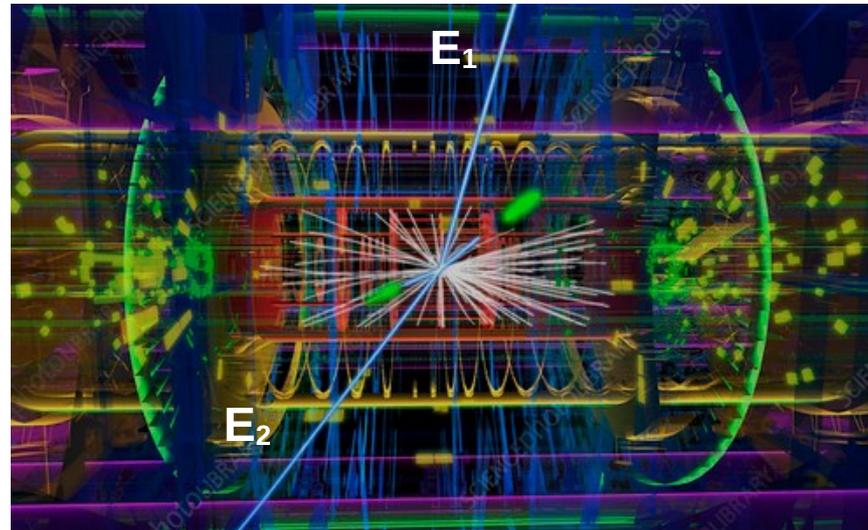
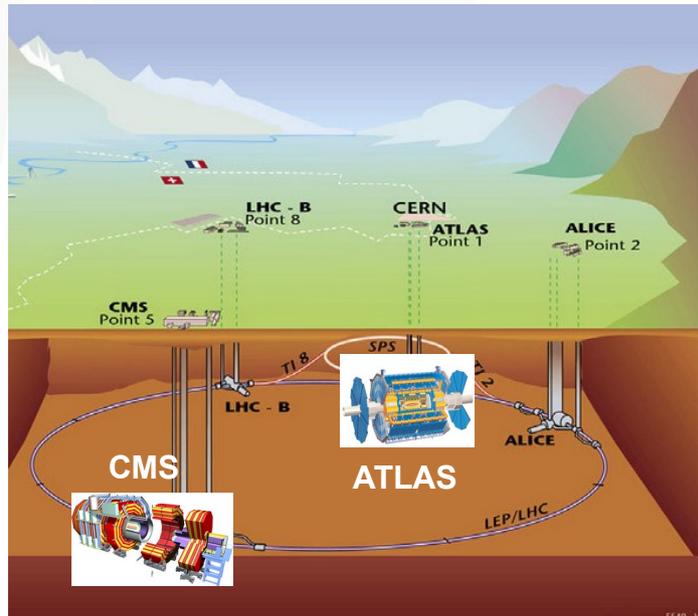
Heavy Resonance Searches

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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

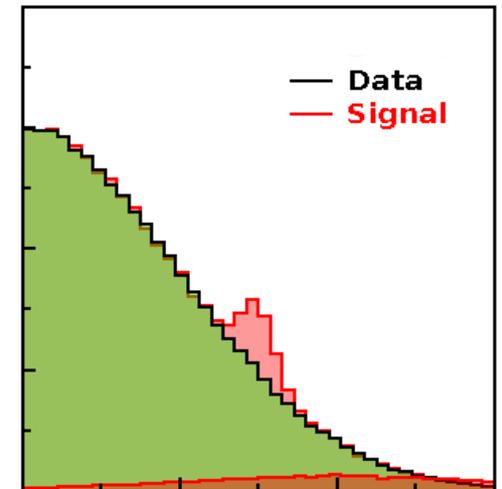
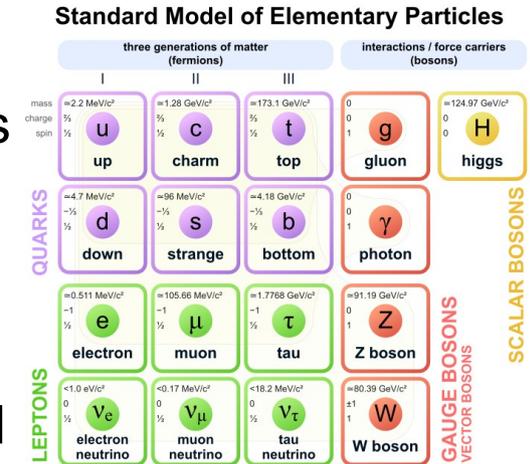
Direct observations of new particles

- 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

URL link to image

CMS

URL link to image

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2022

Model	ℓ, γ	Jets [†]	E_{miss}^{\pm}	$[\int \mathcal{L} dt] [fb^{-1}]$	Limit	Reference
Extra dimensions						
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 $\gamma\gamma$	2γ	-	-	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	-	≥ 3	-	3.6	M_s $n=6, M_p = 3$ TeV, not BH	1512.02566
RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	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 $G_{KK} \rightarrow W\gamma$	$1, e, \mu$	2/1/1 γ	Yes	139	G_{KK} mass 2.0 TeV $k/\overline{M}_{Pl} = 1.0$	2004.14636
Bulk RS $G_{KK} \rightarrow t\bar{t}$	$1, e, \mu$	$\geq 1, b, \geq 1, \geq 2$	Yes	36.1	G_{KK} mass 2.0 TeV $\Gamma/m = 15\%$	1904.10823
2UED / RPP	$1, e, \mu$	$\geq 2, b, \geq 3$	Yes	36.1	HK mass 1.8 TeV $Tier(1,1), R(A^{(1)} \rightarrow t\bar{t}) = 1$	1803.09678
Gauge bosons						
SSM $Z' \rightarrow \ell\ell$	$2, e, \mu, \tau$	-	-	139	Z' mass 5.1 TeV	1903.06248
SSM $Z' \rightarrow \tau\tau$	2τ	-	-	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 $Z' \rightarrow t\bar{t}$	$0, e, \mu, \tau$	$\geq 1, b, \geq 2, \gamma$	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 $W' \rightarrow \nu\tau$	$1, e, \mu, \tau$	-	-	139	W' mass 5.0 TeV	2004.14636
SSM $W' \rightarrow t\bar{b}$	-	$\geq 1, b, \geq 1, \gamma$	Yes	139	W' mass 4.4 TeV	ATLAS-CONF-2021-043
HVT $W' \rightarrow WZ \rightarrow \nu\ell\ell'$ model B	$1, e, \mu, \tau$	2/1/1 γ	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	$2, e, \mu, \tau$	$\geq 1, b, \geq 2, \gamma$	Yes	139	W' mass 3.2 TeV	2007.05293
LRSM $W_R \rightarrow \mu N_R$	$2, e, \mu, \tau$	1 γ	-	80	W_R mass 5.0 TeV $g_{\nu} = 3$	1904.12679
CI						
CI $qqqq$	-	2 γ	-	37.0	A 21.8 TeV η_{ℓ}	1703.09127
CI $\ell\ell qq$	$2, e, \mu, \tau$	-	-	139	A 35.8 TeV η_{ℓ}	2006.12946
CI $\ell\ell\ell\ell$	$2, e, \mu, \tau$	-	-	139	A 1.8 TeV	2106.13847
CI $\mu\mu\mu\mu$	$2, \mu$	1 b	-	139	A 2.0 TeV	2105.13847
CI $t\bar{t}t\bar{t}$	$\geq 1, e, \mu, \tau$	$\geq 1, b, \geq 1, \gamma$	Yes	36.1	A 2.57 TeV $ C_{\ell} = 4\pi$	1811.02305
DM						
Axial-vector med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	χ_{DM} mass 376 GeV	2102.10874
Pseudo-scalar med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	χ_{DM} mass 3.1 TeV	2102.10874
Vector med. Z' -2HDM (Dirac DM)	$0, e, \mu, \tau$	2 b	Yes	139	χ_{DM} mass 560 GeV	2108.13391
Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	χ_{DM} mass 3.1 TeV	ATLAS-CONF-2021-036
LO						
Scalar LQ 1 st gen	$2, e$	≥ 2	Yes	139	LQ mass 1.8 TeV $\beta = 1$	2006.05872
Scalar LQ 2 nd gen	$2, \mu$	≥ 2	Yes	139	LQ mass 1.7 TeV $\beta = 1$	2006.05872
Scalar LQ 3 rd gen	$1, \tau$	$2b$	Yes	139	LQ mass 1.24 TeV $2\mathcal{R}(LQ \rightarrow \nu\bar{\nu}) = 1$	2108.07665
Scalar LQ 3 rd gen	$0, e, \mu, \tau$	$\geq 2, \geq 2, b$	Yes	139	LQ mass 1.24 TeV $2\mathcal{R}(LQ \rightarrow \nu\bar{\nu}) = 1$	2004.14060
Scalar LQ 3 rd gen	$\geq 2, e, \mu, \tau$	$\geq 1, \tau, \geq 1, b, \geq 1, \gamma$	Yes	139	LQ mass 1.43 TeV $2\mathcal{R}(LQ \rightarrow \nu\bar{\nu}) = 1$	2101.11582
Scalar LQ 3 rd gen	$0, e, \mu, \tau$	$\geq 1, \tau, 0-2, \geq 2, b$	Yes	139	LQ mass 1.26 TeV $2\mathcal{R}(LQ \rightarrow \nu\bar{\nu}) = 1$	2101.12527
Vector LQ 3 rd gen	$1, \tau$	$2b$	Yes	139	LQ mass 1.77 TeV $2\mathcal{R}(LQ \rightarrow \nu\bar{\nu}) = 0.5, YM$ coupl.	2108.07665
Heavy quarks						
VLQ $TT \rightarrow Z + X$	multi-channel	$\geq 1, b, \geq 1, \gamma$	Yes	139	V mass 1.4 TeV	SU(2) doublet
VLQ $BB \rightarrow W + Z + X$	multi-channel	$\geq 1, b, \geq 1, \gamma$	Yes	36.1	B mass 1.34 TeV	SU(2) doublet
VLQ $T_{13} T_{33} W_{33} \rightarrow W + X$	$2\mathcal{R}(SU(3) \rightarrow 3, 3) \geq 1, b, \geq 1, \gamma$	Yes	36.1	T_{13} mass 1.64 TeV	$2(T_{13} \rightarrow W) = 1, c(F_{13} = W) = 1$	ATLAS-CONF-2021-040
VLQ $T \rightarrow H + Z$	$1, e, \mu, \tau$	$\geq 1, b, \geq 1, \gamma$	Yes	139	V mass 1.8 TeV	SU(2) singlet, $\kappa = 0.5$
VLQ $Y \rightarrow Wb$	$1, e, \mu, \tau$	$\geq 1, b, \geq 1, \gamma$	Yes	36.1	Y mass 1.85 TeV	$2(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$
VLQ $B \rightarrow Hb$	$0, e, \mu, \tau$	$\geq 2, b, \geq 1, \gamma$	Yes	139	B mass 2.0 TeV	SU(2) doublet, $\kappa = 0.3$
Excited fermions						
Excited quark $q^* \rightarrow qg$	-	2 γ	-	139	q^* mass 6.7 TeV	only u' and d' , $A = m(q^*)$
Excited quark $q^* \rightarrow q\gamma$	-	1 γ	-	38.7	q^* mass 3.2 TeV	only u' and d' , $A = m(q^*)$
Excited quark $b^* \rightarrow b\gamma$	-	1 $b, 1 \gamma$	-	36.1	b^* mass 2.6 TeV	
Excited lepton ℓ^*	$3, e, \mu, \tau$	-	-	20.3	ℓ^* mass 3.0 TeV	
Excited lepton ν^*	$3, e, \mu, \tau$	-	-	20.3	ν^* mass 1.6 TeV	
Other						
Type II Seesaw	$2.3, 4, e, \mu, \tau$	≥ 2	Yes	139	M^* mass 910 GeV	$m(W_{\Delta}) = 4.1$ TeV, $g_{\Delta} = g_{\Delta}$
LRSM Majorana ν	$2, \mu$	2 γ	Yes	36.1	N_{Δ} mass 3.2 TeV	ν production
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)	-	Yes	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production, $2\mathcal{R}(H^{\pm\pm} \rightarrow \nu\bar{\nu}) = 1$
Higgs triplet $H^{\pm\pm} \rightarrow \tau\tau$	$3, e, \mu, \tau$ (SS)	-	Yes	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $ \eta = 5e$
Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV	DY production, $ \eta = 1g_{\Delta}, \text{spin } 1/2$
Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	

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

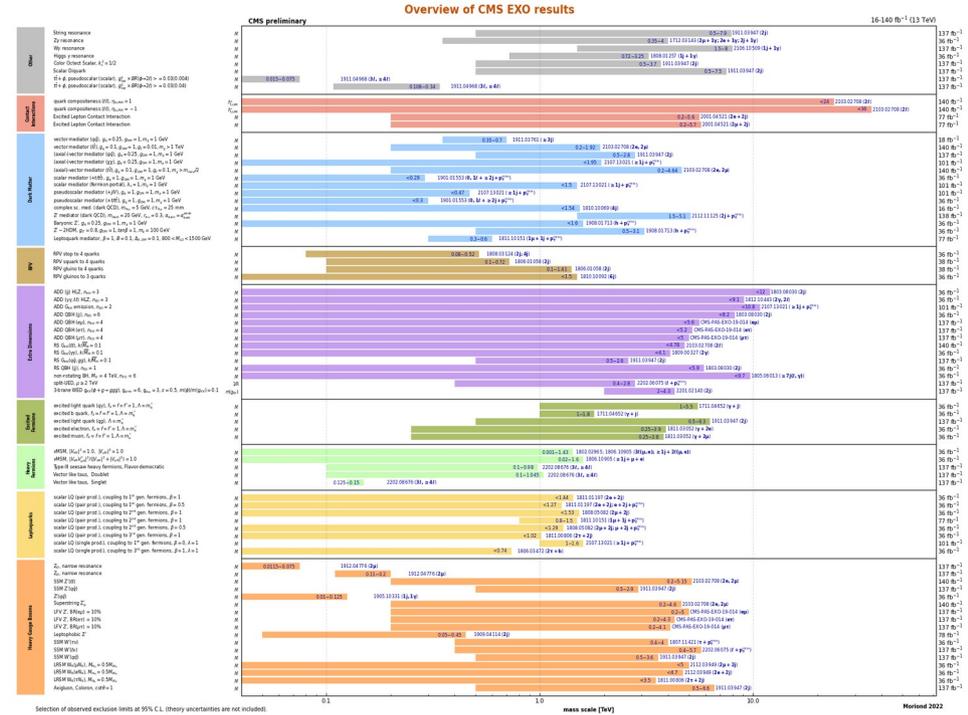
[†]Small-radius (large-radius) jets are denoted by the letter J (j).

~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

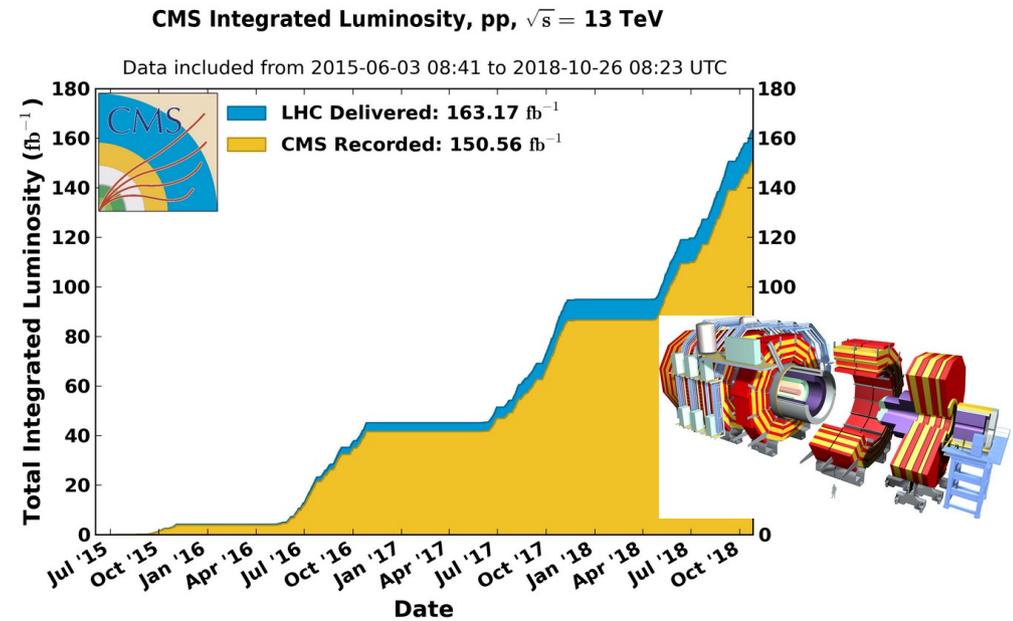
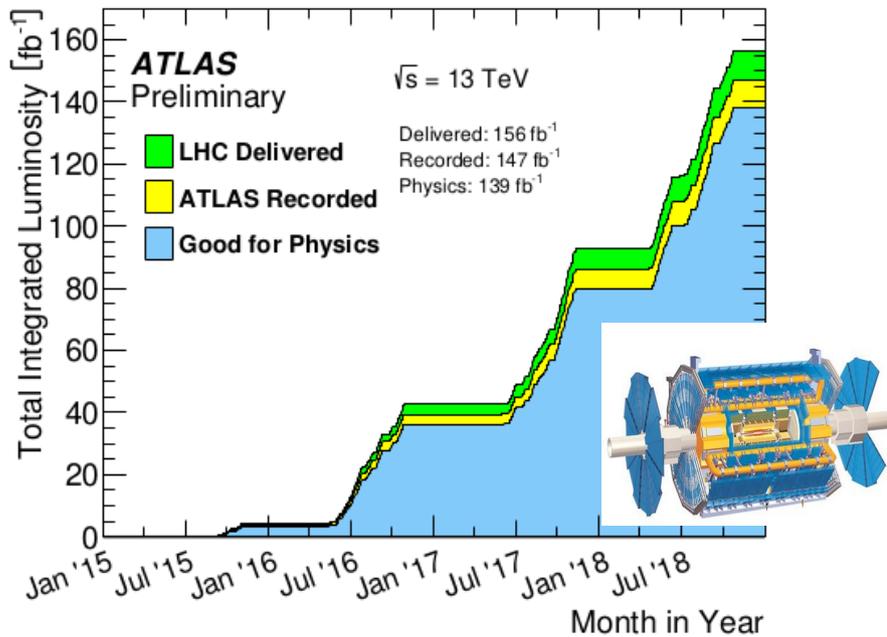
But plenty of models that predict too small cross section for exclusion.

ATLAS Preliminary
 $\int \mathcal{L} dt = (36 - 139) \text{ fb}^{-1}$
 $\sqrt{s} = 8, 13 \text{ TeV}$



Selection of observed exclusion limits at 95% CL. Theory uncertainties are not included.

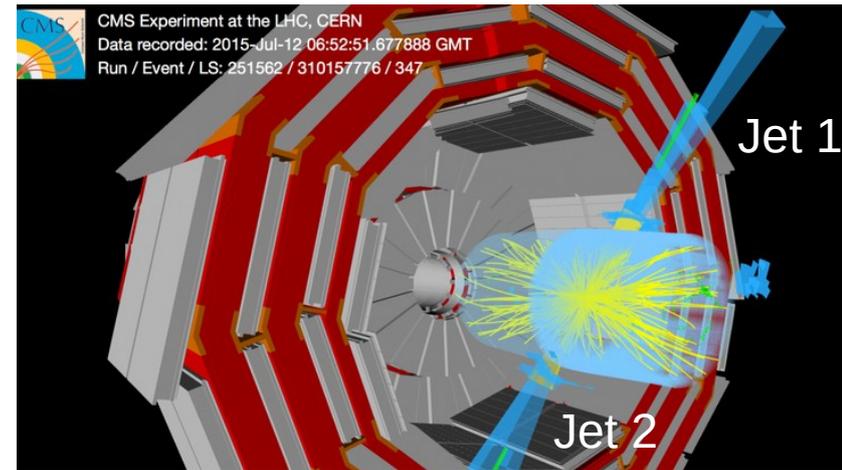
LHC operation



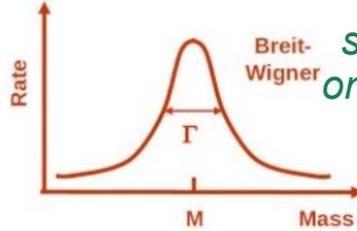
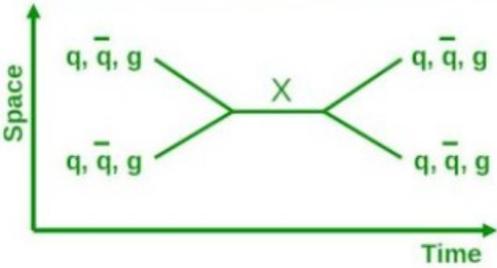
- Run2 pp collision data-set, $\sqrt{s} = 13 \text{ TeV}$.
- $\sim 140 \text{ fb}^{-1}$ used for this talk

Typical search strategy:

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



Search for high mass dijet resonances



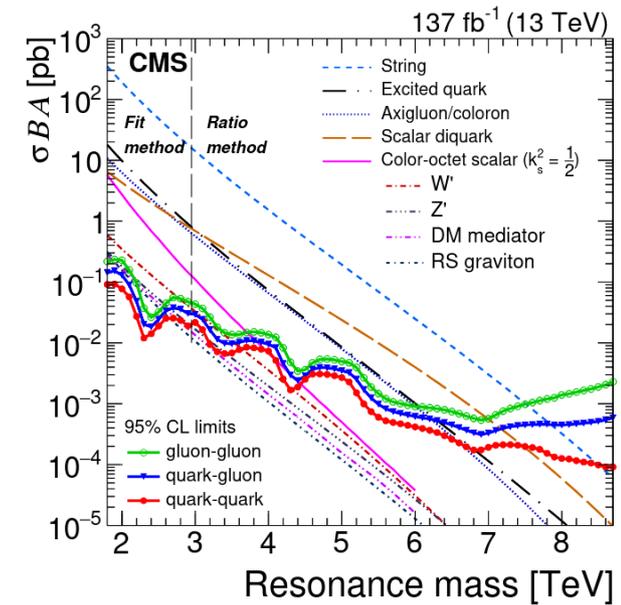
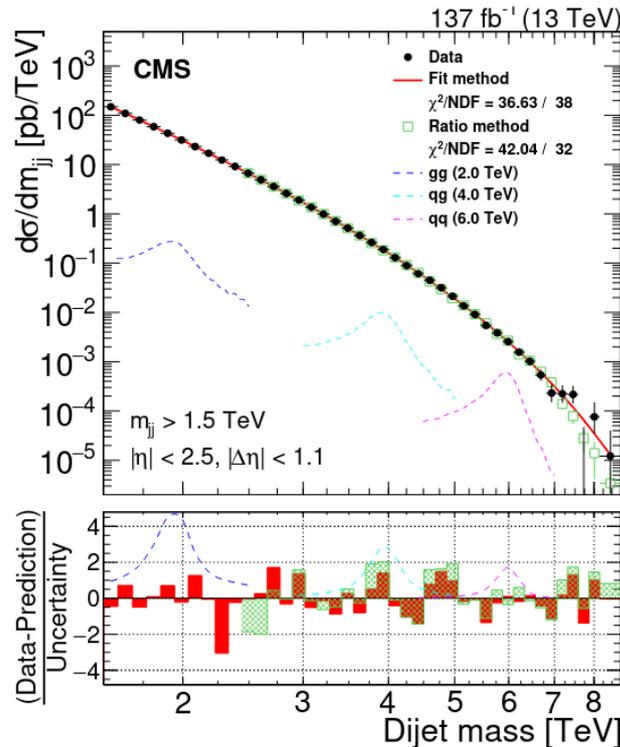
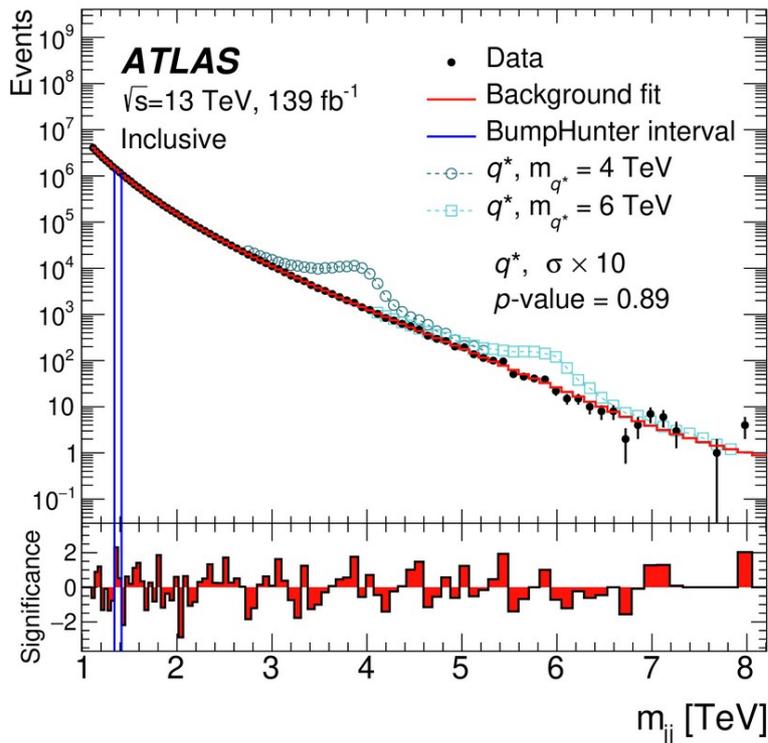
Resonance shapes depend on qq , qg and gg interactions

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.

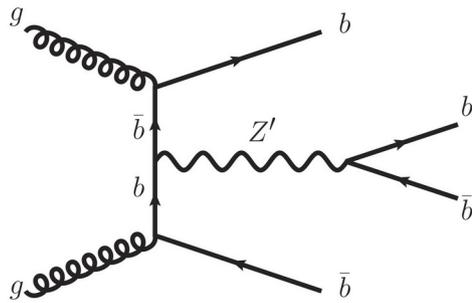
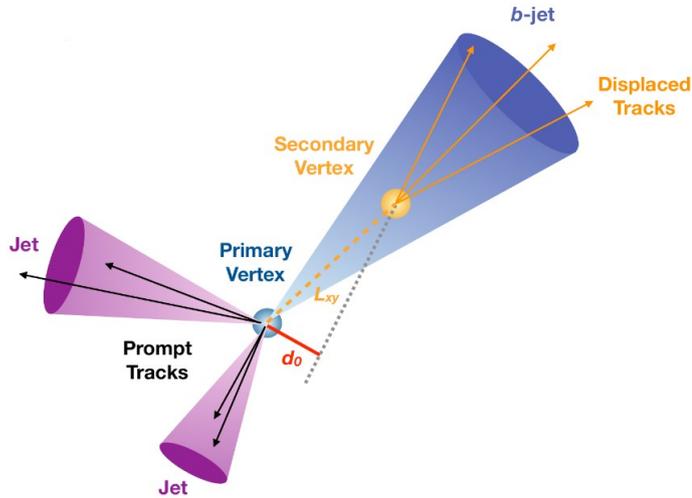
- Calculate invariant mass from 2 hadronic jets
- Fit with smooth analytic functions (red lines)
- Competitive limits up to ~ 8 TeV



Observed and expected mass limits at 95% CL

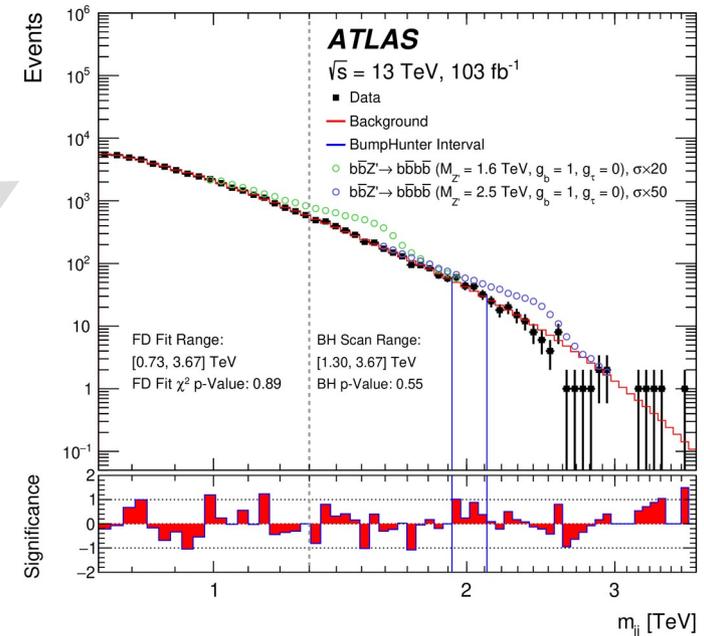
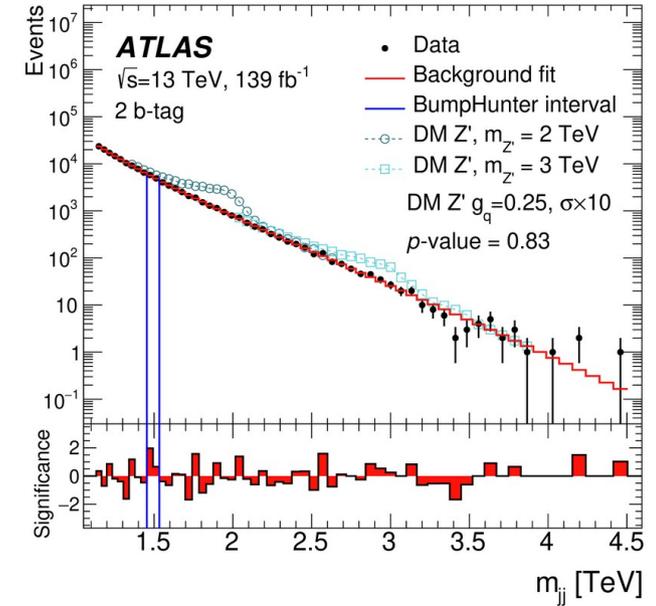
Jets originating from b-quark

- 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

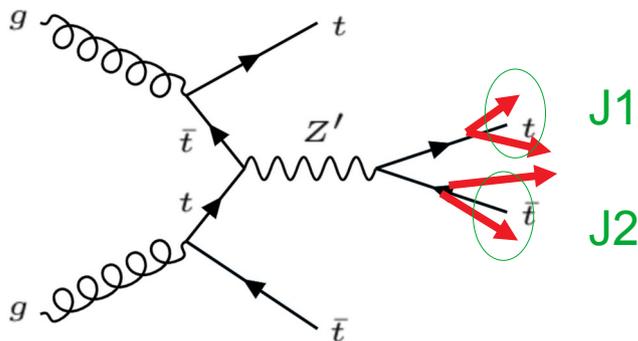
2-b jet mass in events with multiple b-quarks



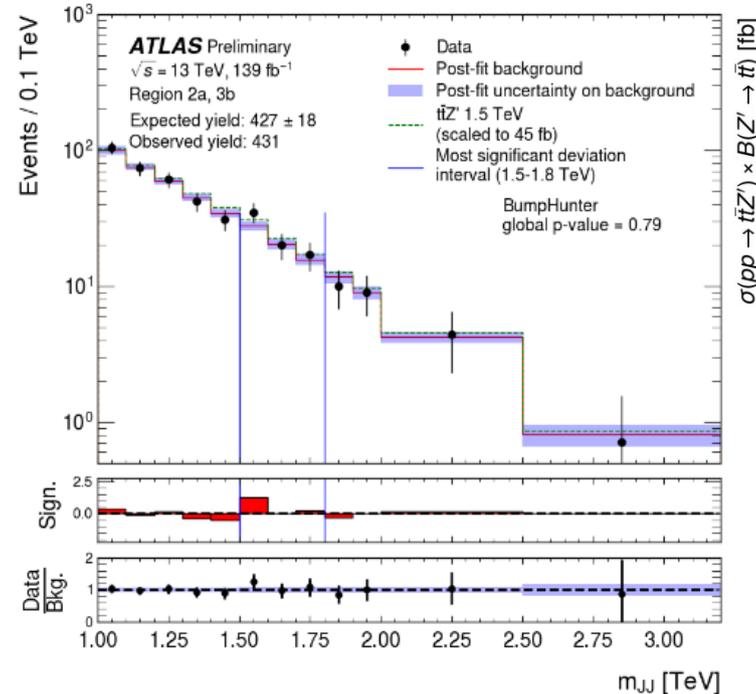
- No signals. Competitive limits for $Z' \rightarrow b\bar{b}$ processes

- 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)

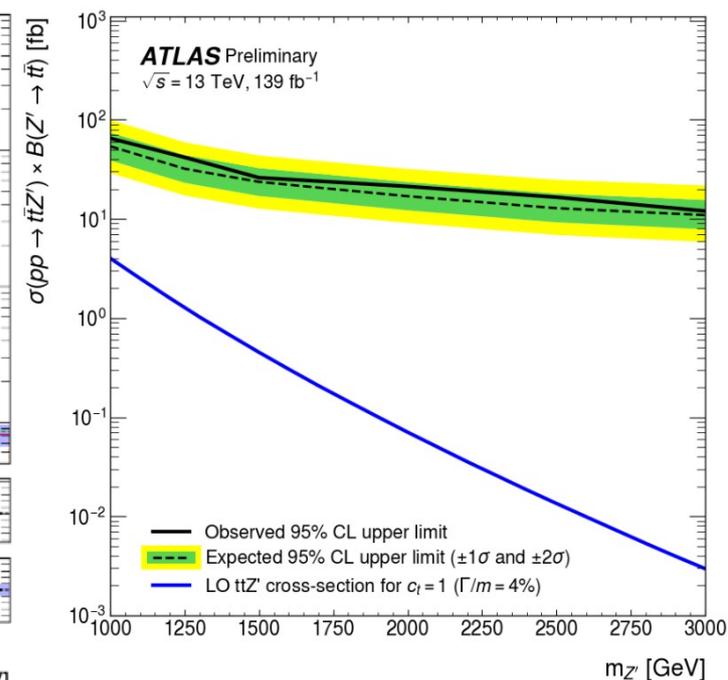
> 1 boosted jets
> 2 b-tagged jets
at least 1 lepton



Representative invariant mass of two large-radius jets



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

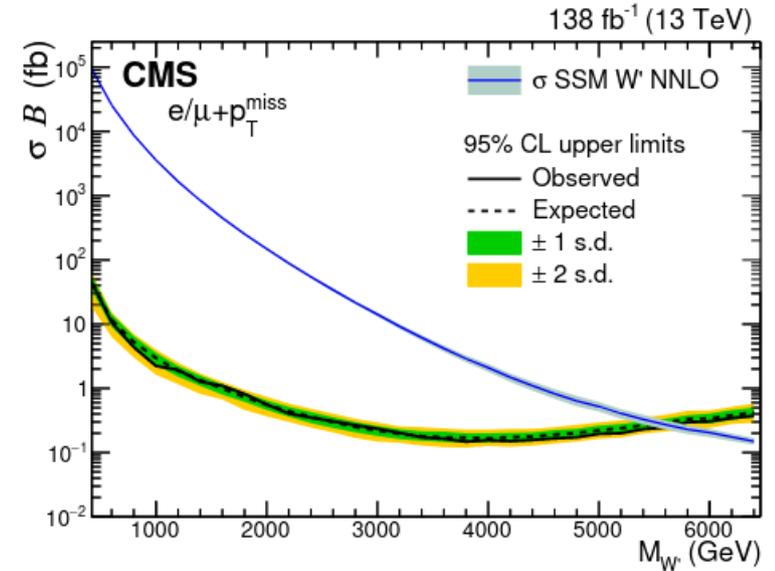
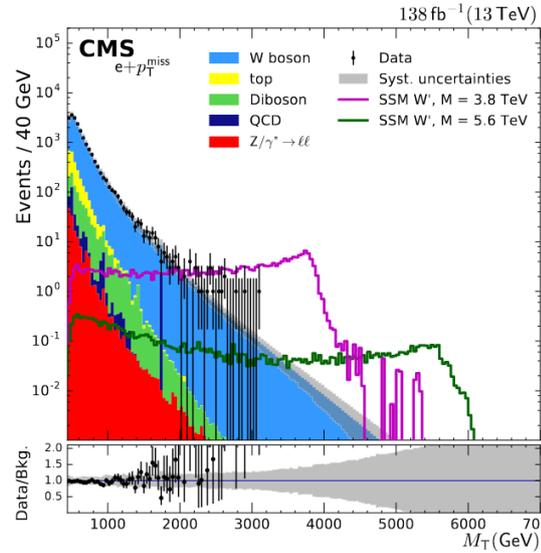
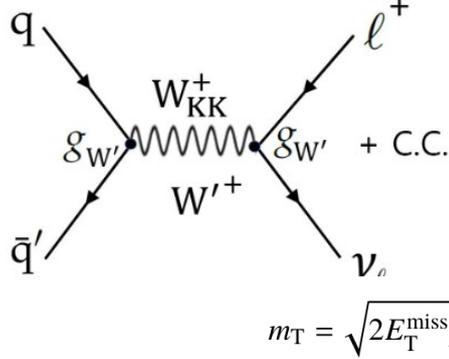


- No excess above the expected SM background
- Competitive Run II limits. Require more data to exclude $t\bar{t}Z'$ production

Searches for W' heavy bosons - I

W' is analog of W bosons in several BSM scenarios

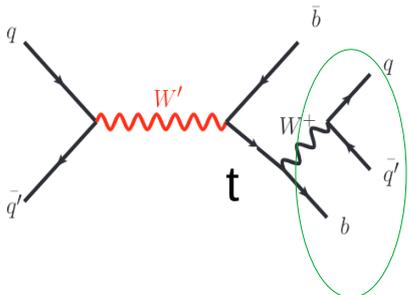
All leptonic W' (W_{KK'})



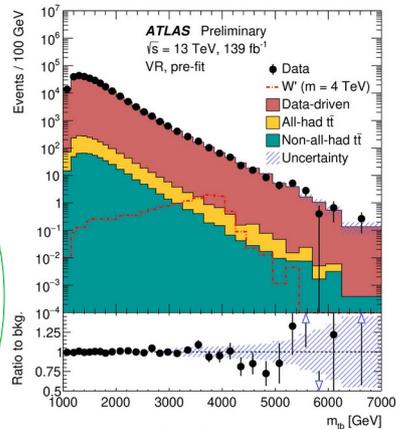
CMS: use transverse mass (m_T) calculated from charged lepton and the missing transverse momenta

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

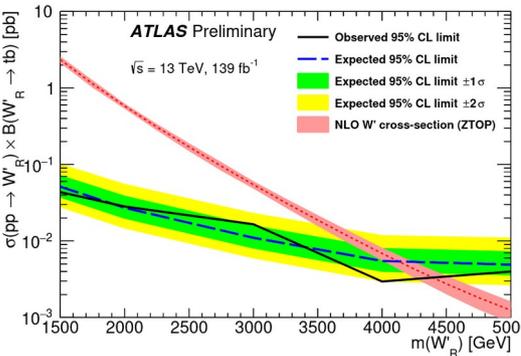
All-hadronic W'



anti-kT with R=1



top+b jet mass



LHC data exclude M(W'):

< 5.7 TeV (lepton + ν)

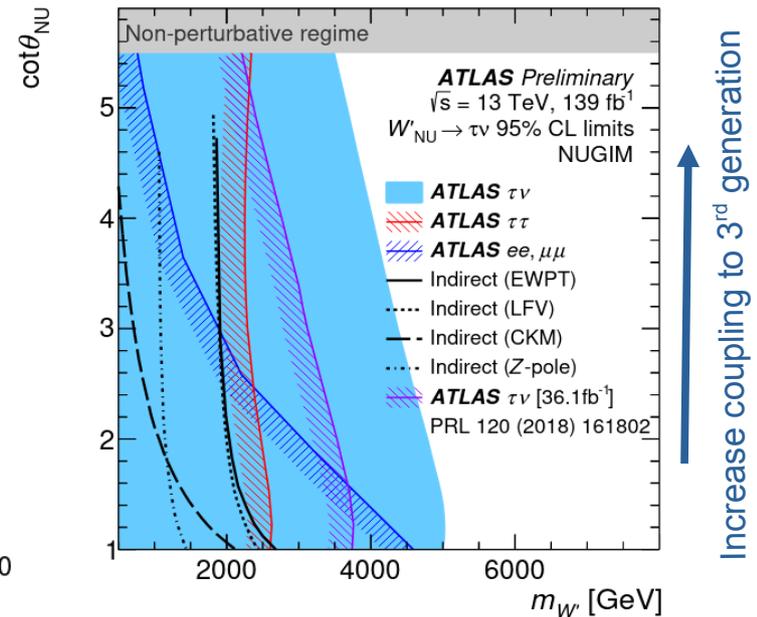
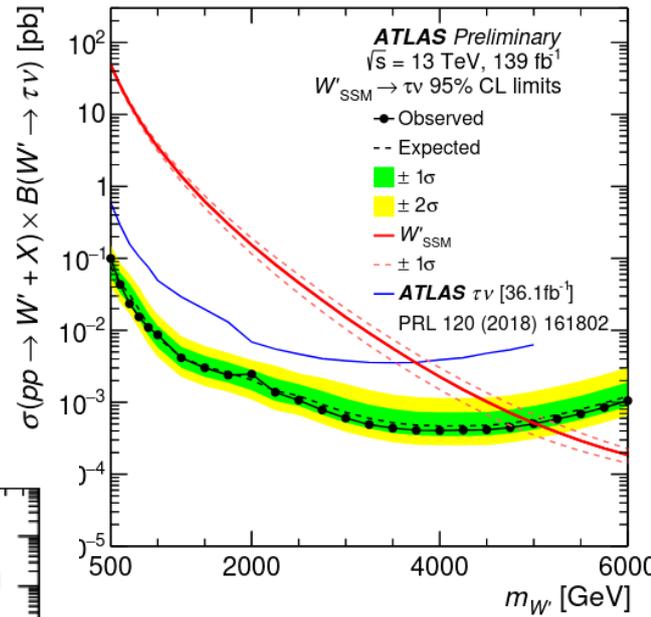
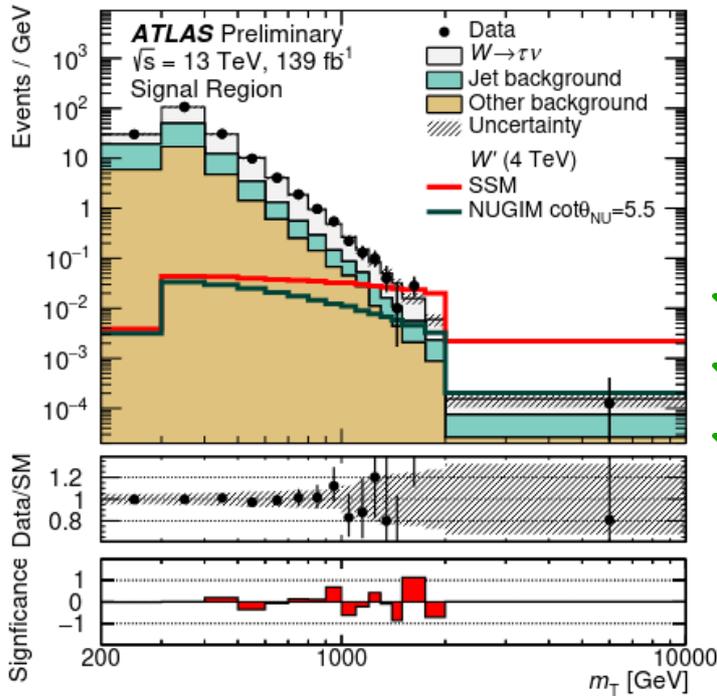
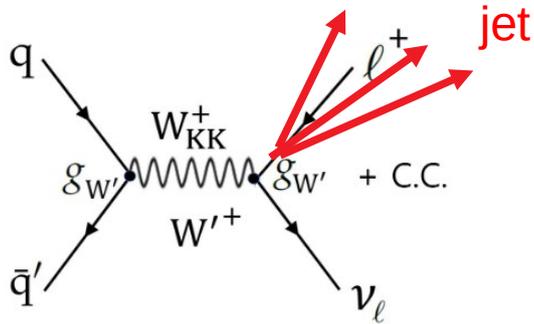
< 4.4 TeV (b-jet + boosted top)

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)



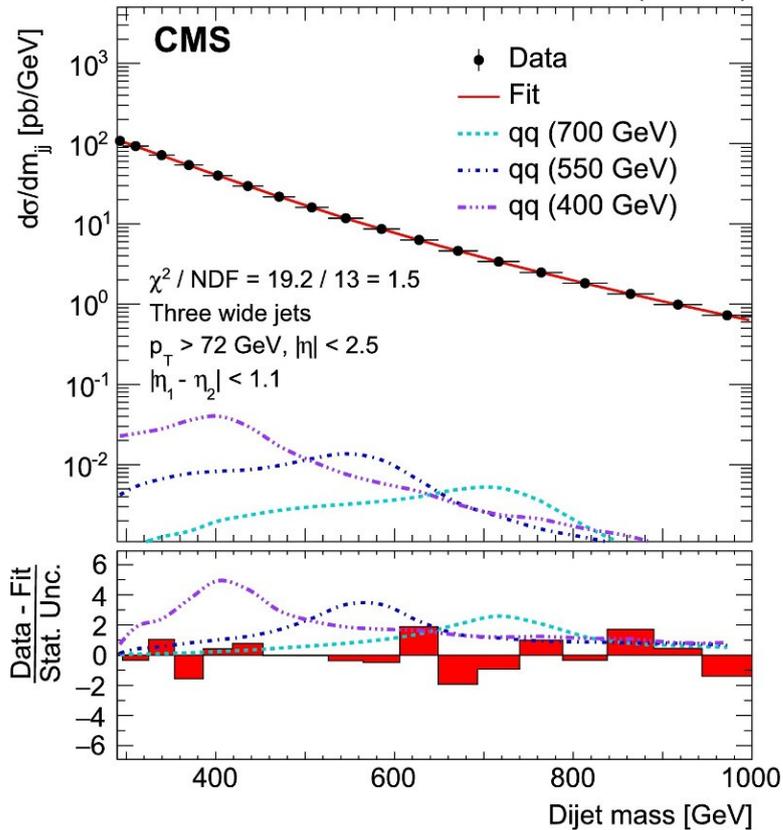
- Model independent limits
- <5 TeV 95% CL for Sequential Standard Model scenario
- Limits for Non-Universal Gauge Interaction Models (NUGIM) with additional parameter $\cot \theta_{NU}$ used to scale the couplings to the first and second generations of fermions

Searches using di-jets + X

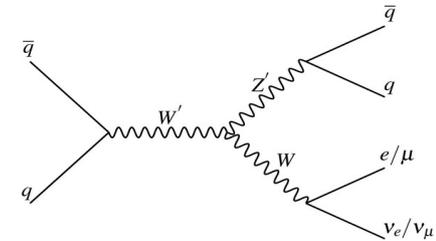
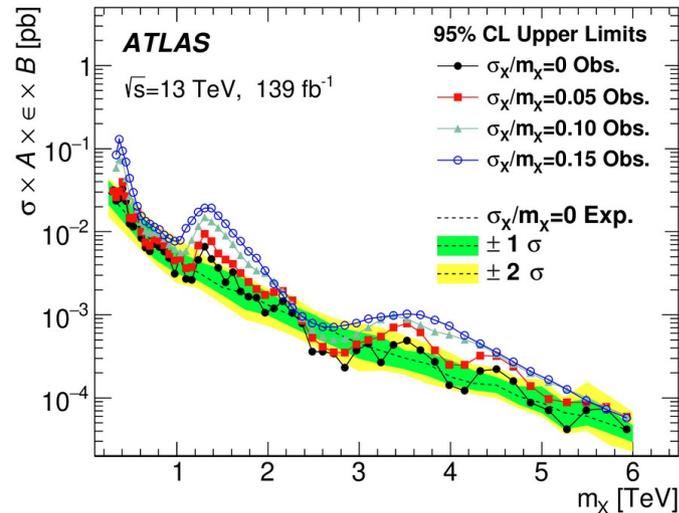
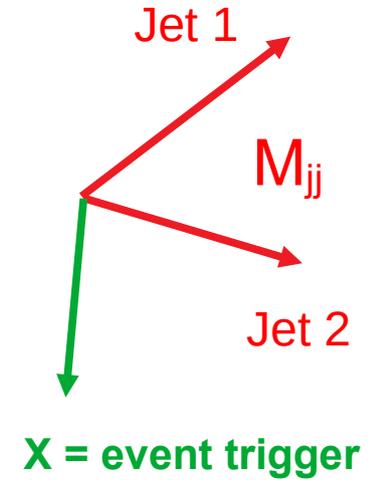
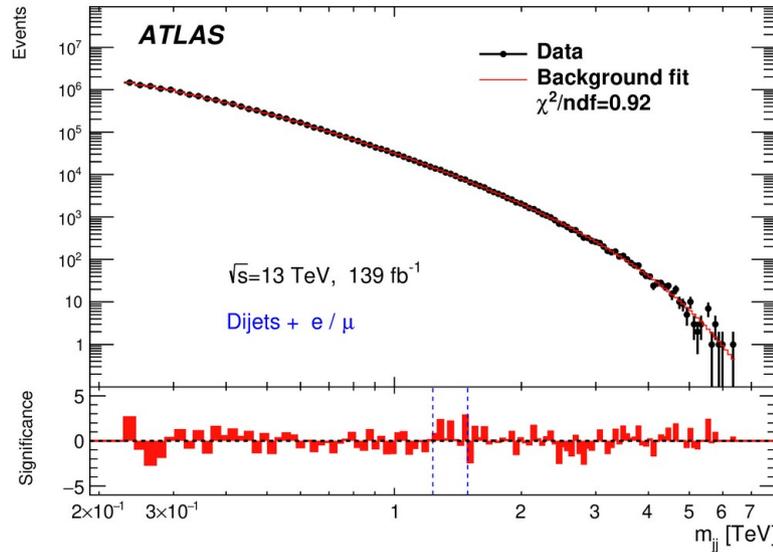
- Additional object X (lepton, jet, photon) helps triggering events with smaller masses (~ 300 GeV – 1 TeV)

X = 3rd jet

18.3 fb⁻¹ (13 TeV)



X = e, mu

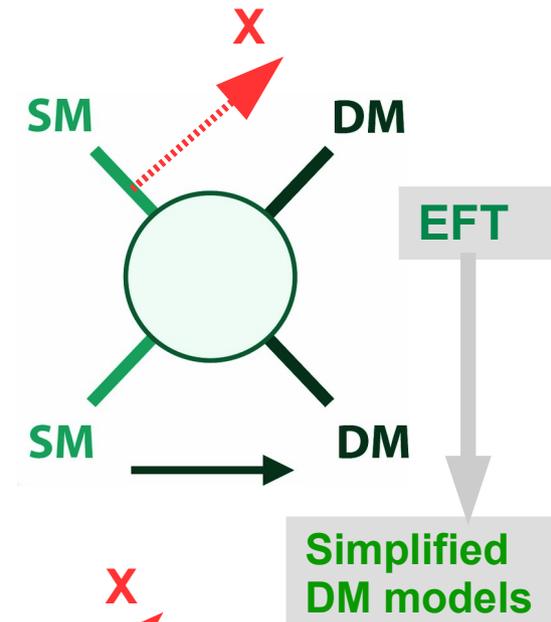


Limits on Sequential Standard model at 1.5 TeV

- Several specific models excluded, including technicolor, sequential SM, H[±], 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

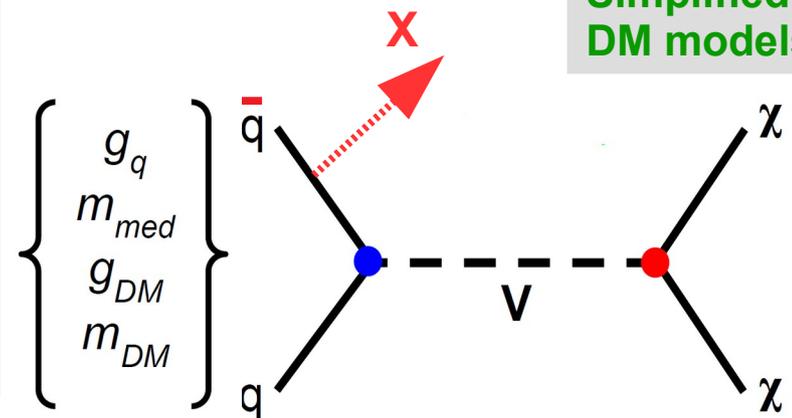


Adopt simplified DM model with a “mediator” V

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

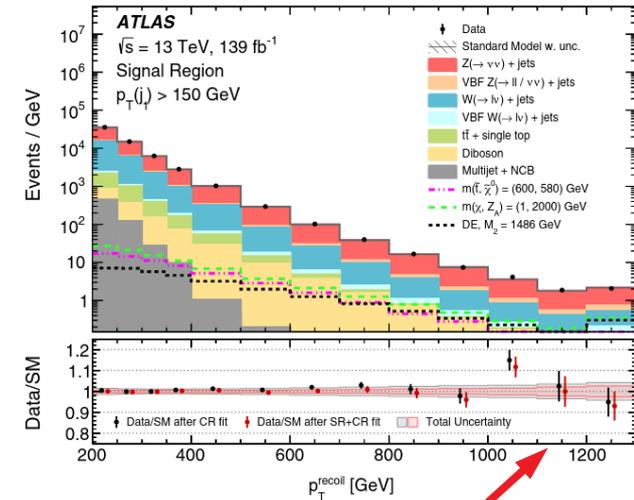
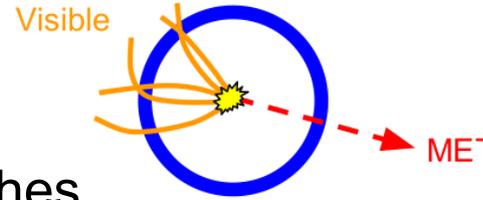
ATLAS & CMS: $g_q=0.25$ (S=1), $g_q=1$ (S=0), $g_{DM}=1$

Γ =minimum width formula



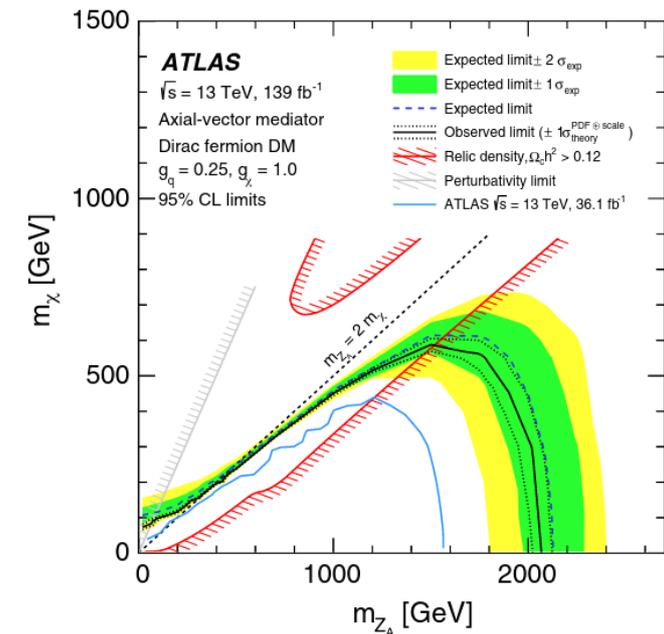
Mono jet searches

- ▼ 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

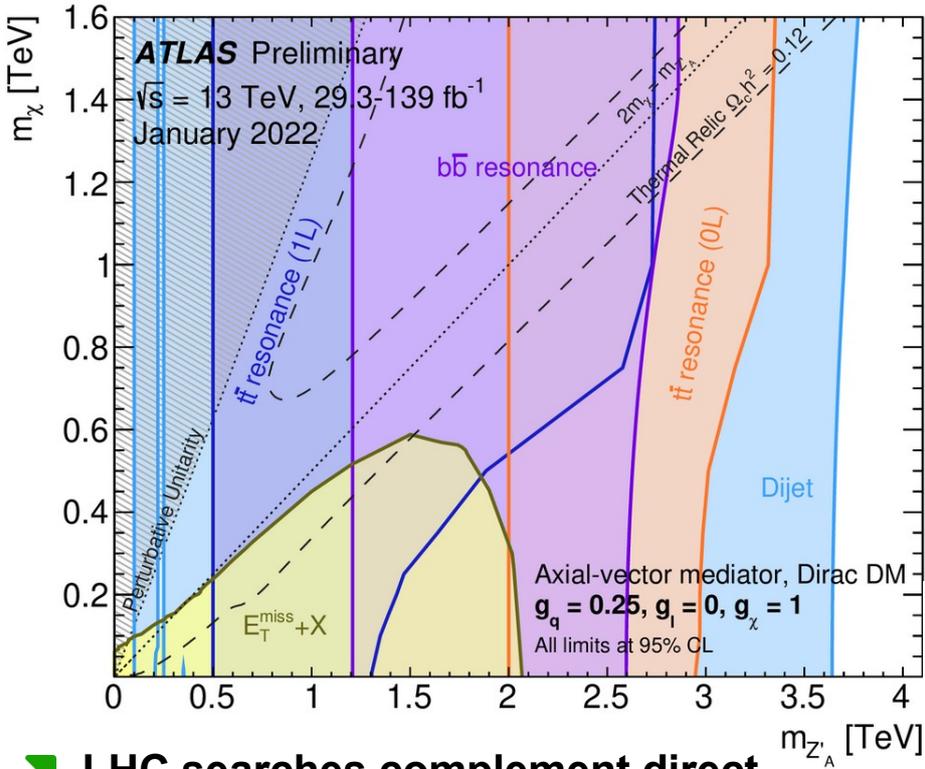


Typical precision for SM description

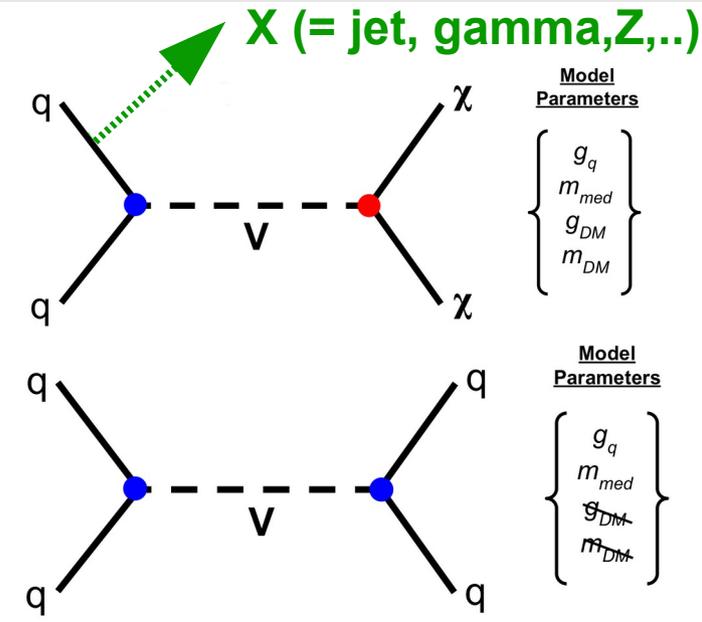
- ▼ Required high-precision SM measurements
- ▼ Examples:
 - ▼ $jet+\gamma$ – missing NNLO effects for $Z(\nu\nu)$ (CMS)
 - ▼ $W+jet$ control region also for $Z(\nu\nu)$ (ATLAS)



Dark Matter summary plots

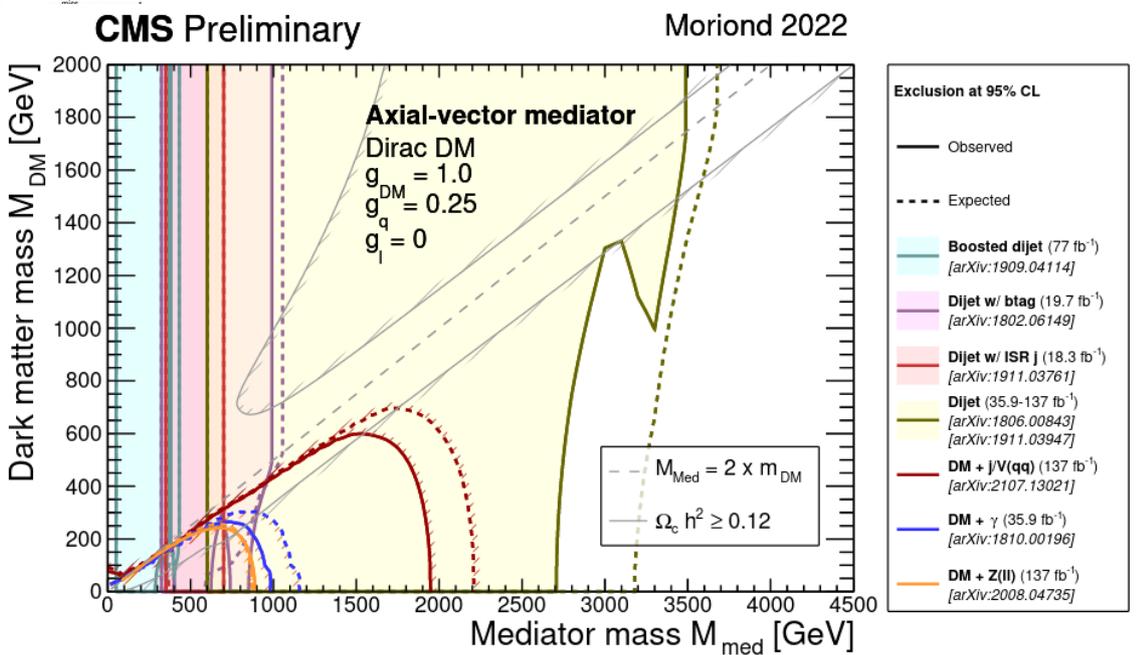


- Dijet**
Dijet, 139 fb⁻¹
JHEP 03 (2020) 145
Dijet TLA, 29.3 fb⁻¹
PRL 121 (2018) 081801
Dijet+ISR, 79.8 fb⁻¹
PLB 795 (2019) 56
Boosted dijet+ISR, 36.1 fb⁻¹
PLB 788 (2019) 316
Boosted di-b+ISR, 80.5 fb⁻¹
ATLAS-CONF-2018-052
- t-t resonance (1L)**
36.1 fb⁻¹
EPJC 78 (2018) 565
- t-t resonance (0L)**
139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



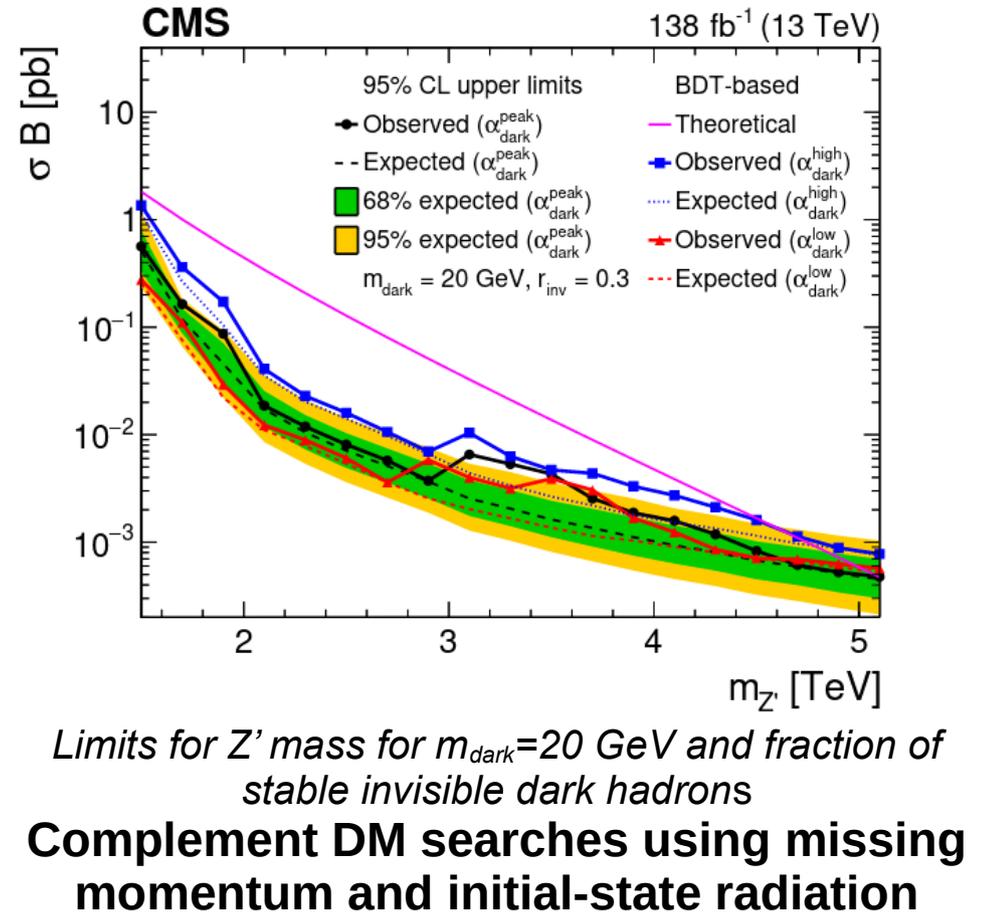
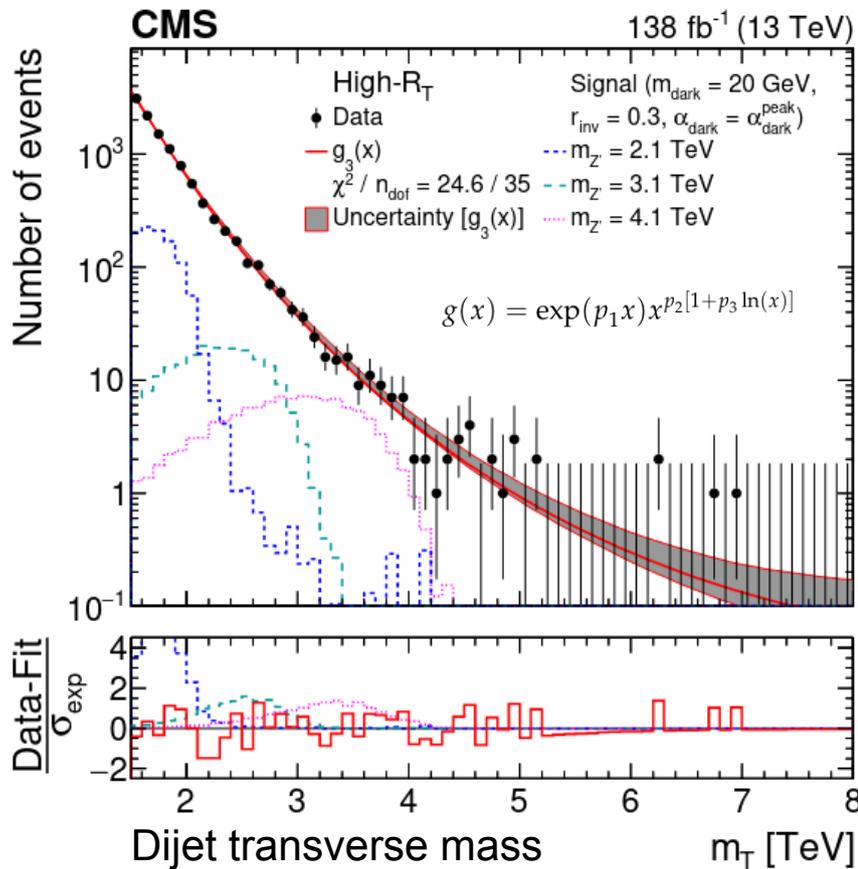
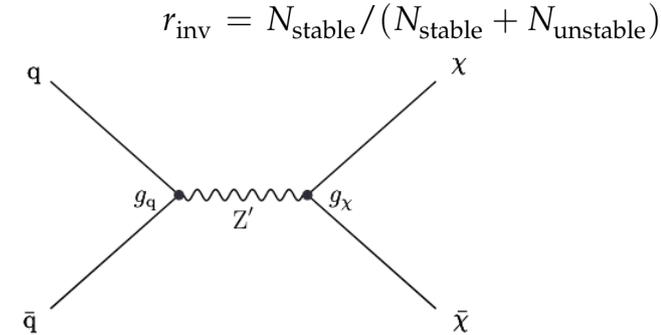
- Model Parameters**
- g_q
 - m_{med}
 - g_{DM}
 - m_{DM}
- Model Parameters**
- g_q
 - m_{med}
 - g_{DM}
 - m_{DM}

- **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⁻¹)
[arXiv:1909.04114]
 - Dijet w/ btag (19.7 fb⁻¹)
[arXiv:1802.06149]
 - Dijet w/ ISR (18.3 fb⁻¹)
[arXiv:1911.03761]
 - Dijet (35.9-137 fb⁻¹)
[arXiv:1806.00843]
 - DM + J/V(qq) (137 fb⁻¹)
[arXiv:1911.03947]
 - DM + gamma (35.9 fb⁻¹)
[arXiv:1810.00196]
 - DM + Z(l) (137 fb⁻¹)
[arXiv:2008.04735]

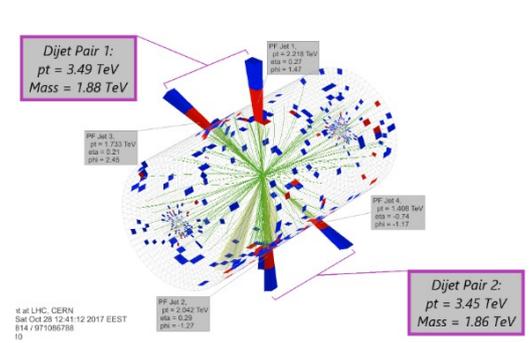
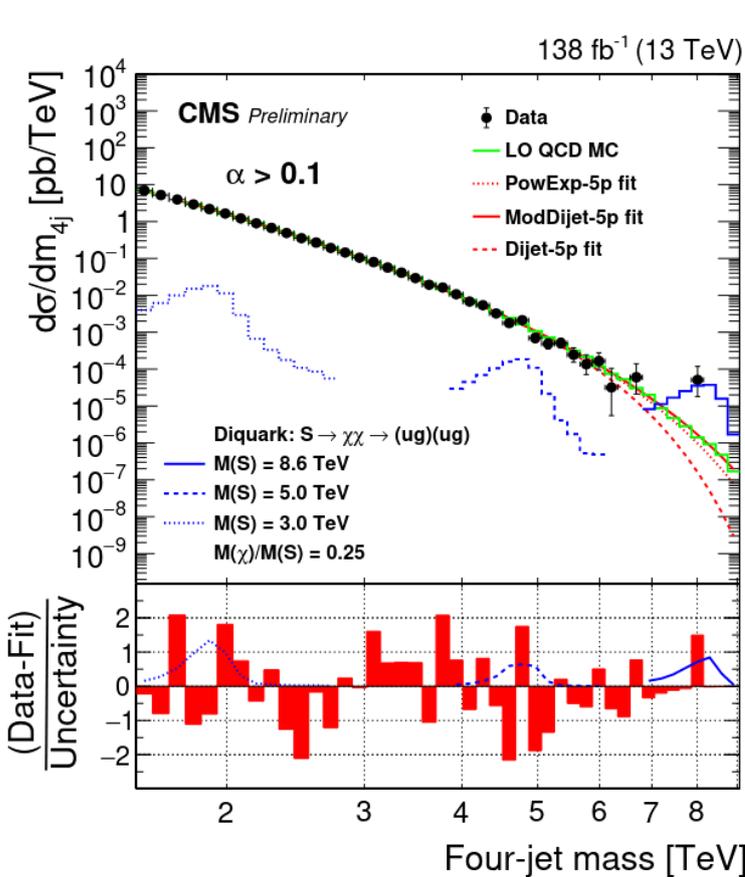
- Heavy *leptophobic* Z' mediator decays to two "semi-visible" jets, containing both visible matter and invisible dark matter ("dark hadrons" from "dark quarks")
- Unstable dark hadrons decay to SM quarks while the stable dark hadrons are DM candidates
- Train BDT to separate SM and wider "semi-visible"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



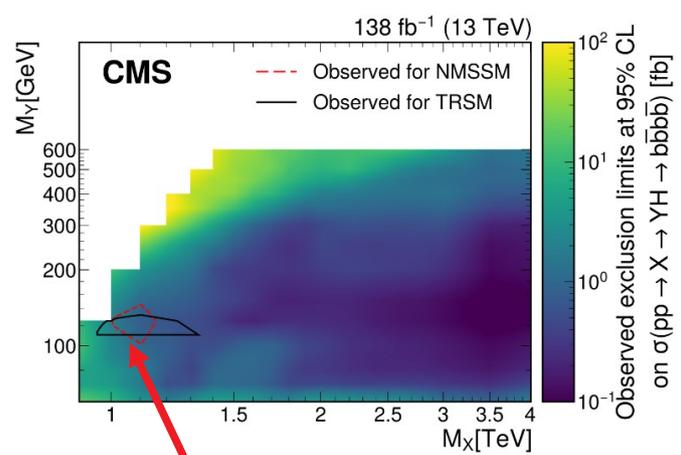
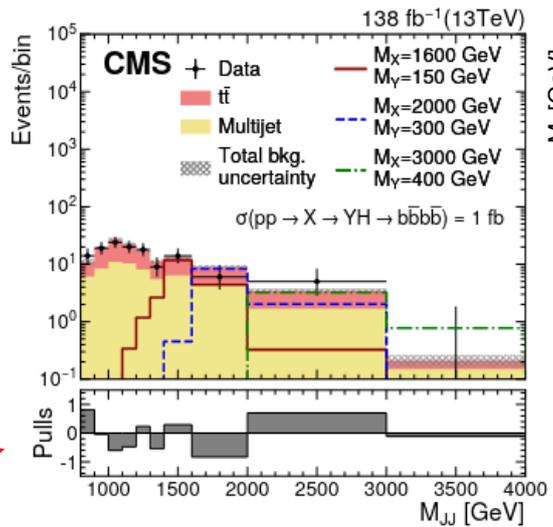
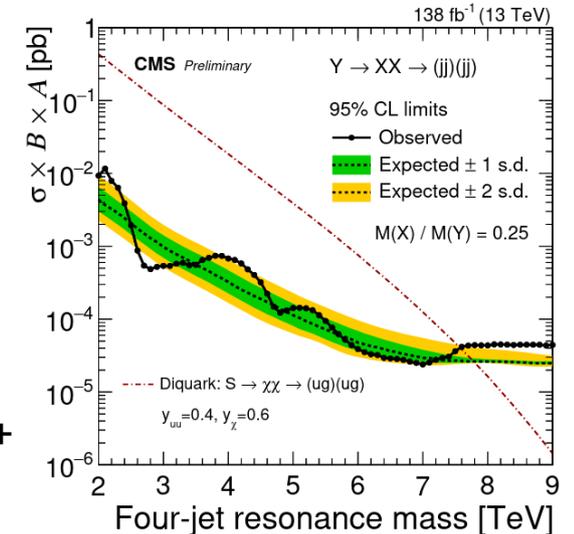
BSM particles decaying $X \rightarrow YY / YH$

- Resonant $pp \rightarrow X \rightarrow YY \rightarrow (jj)(jj)$ & Non-resonant $pp \rightarrow YY \rightarrow (jj)(jj)$
- Scan α (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

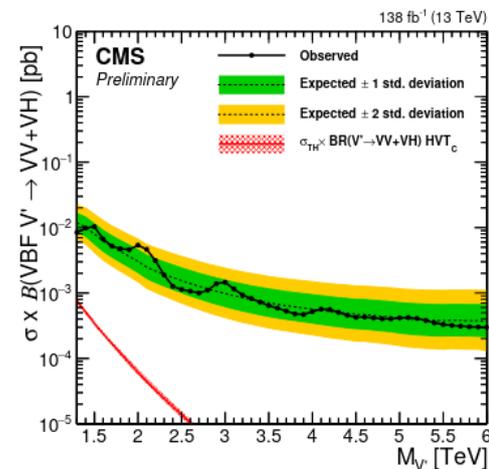
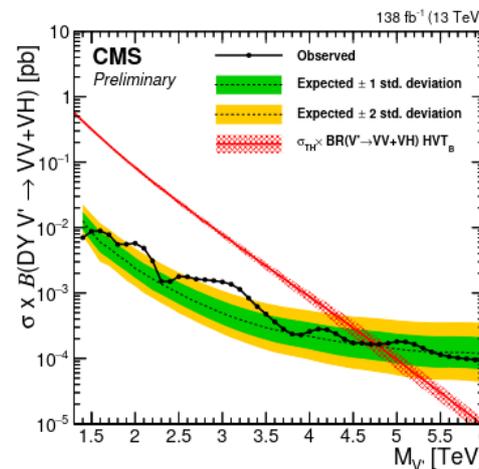
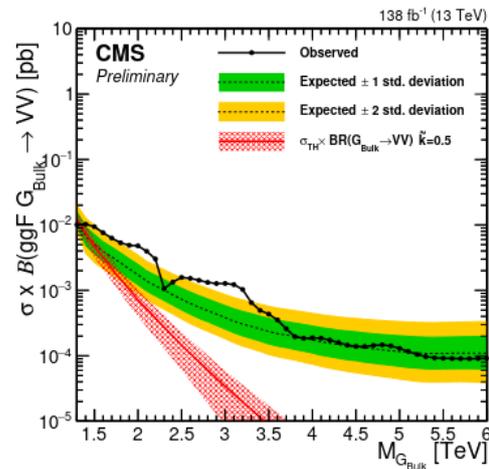
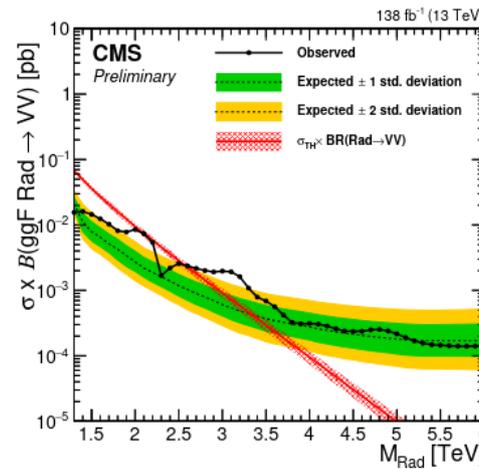
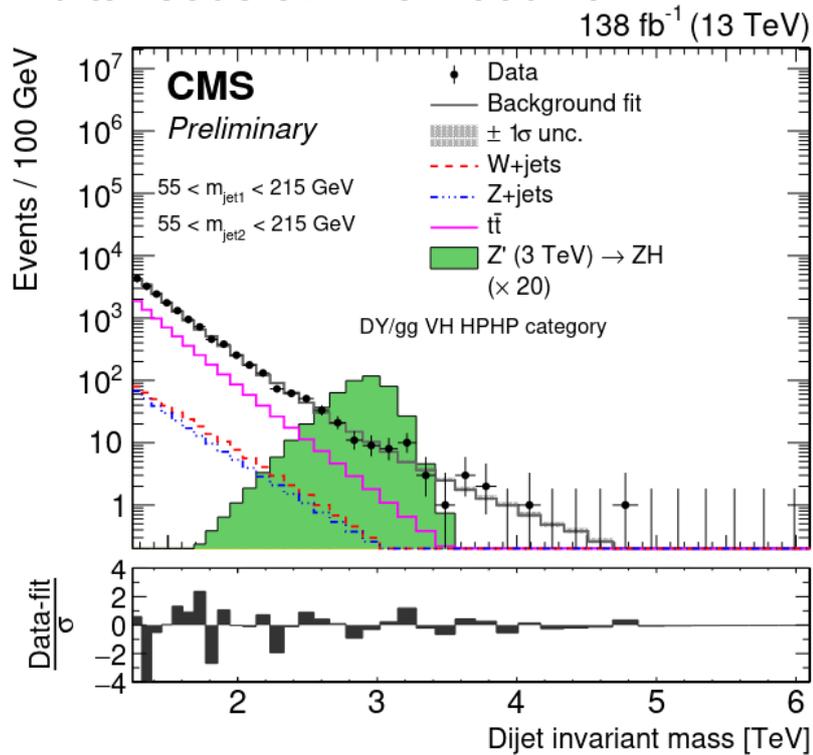
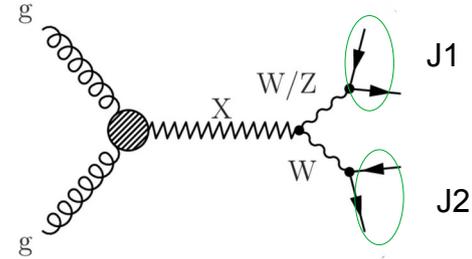


95% CL exclusions for M_X and M_Y

- $pp \rightarrow X$ (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

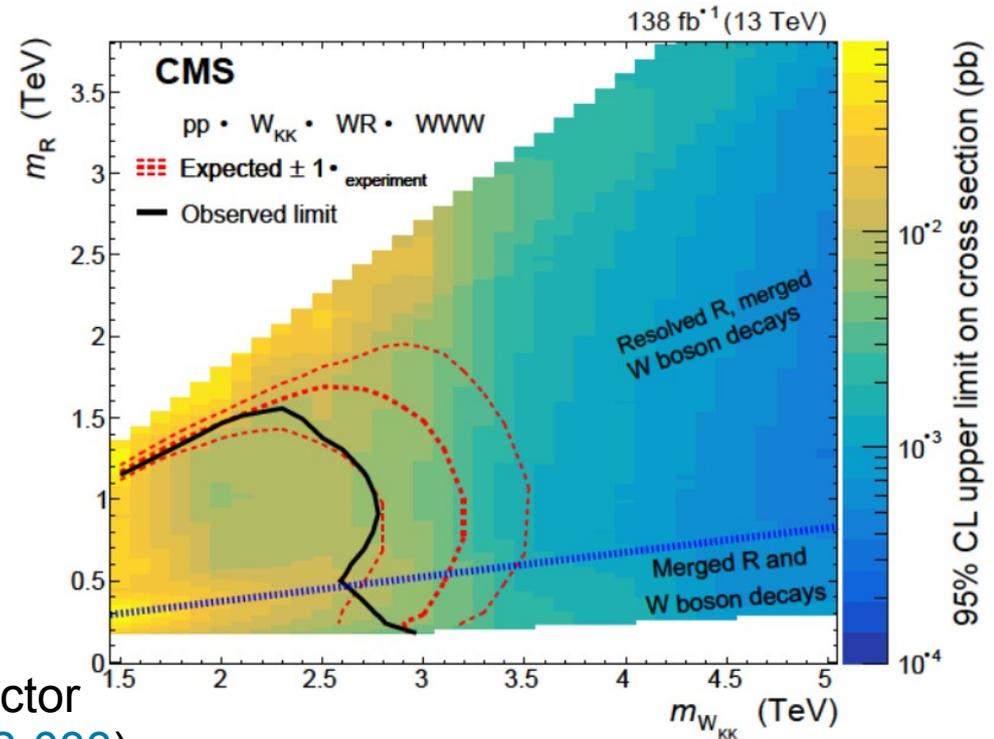
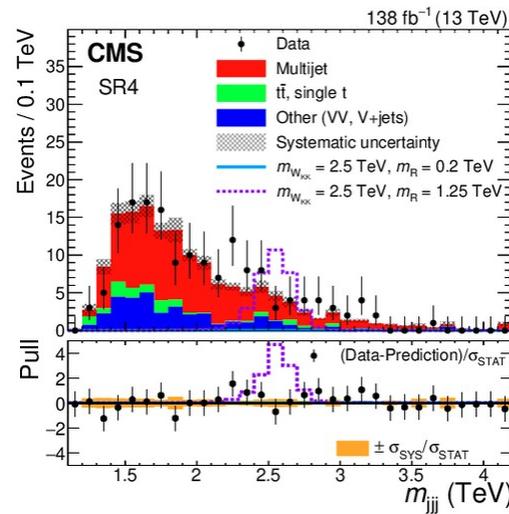
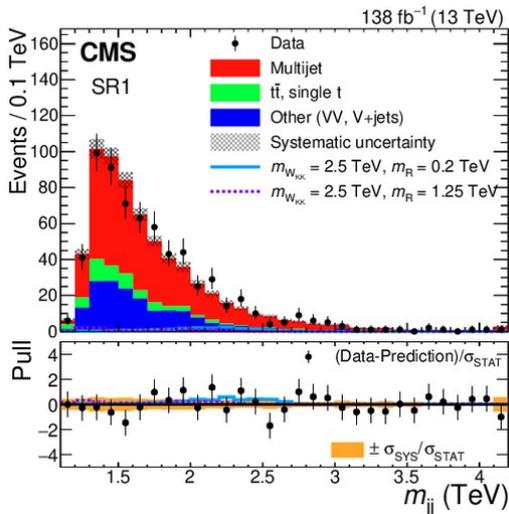
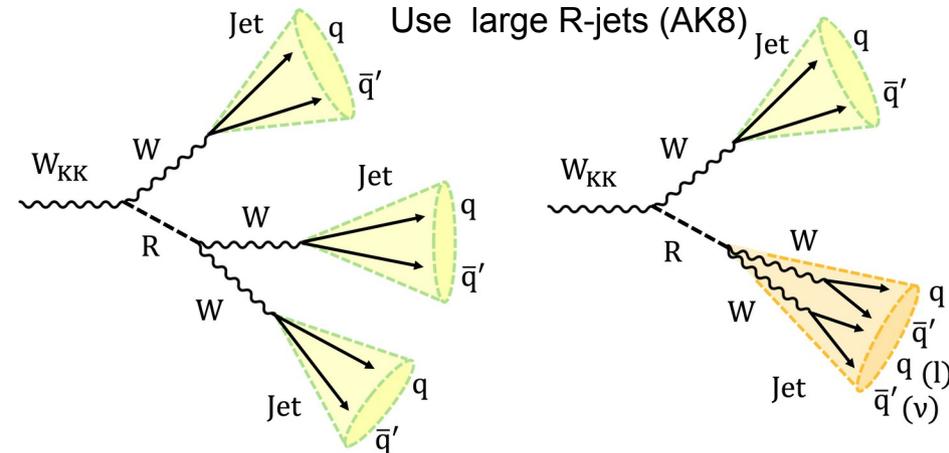
- W/Z/H decays to large R-jet (AK8) for heavy X
- Hadronic decays of W, Z, and H bosons identified using ML
- Measure masses of 2 jets (m_{J1} , m_{J2}) and dijet mass (m_{JJ})
- Simultaneous 3D likelihood fit



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

Resonances decaying to W bosons

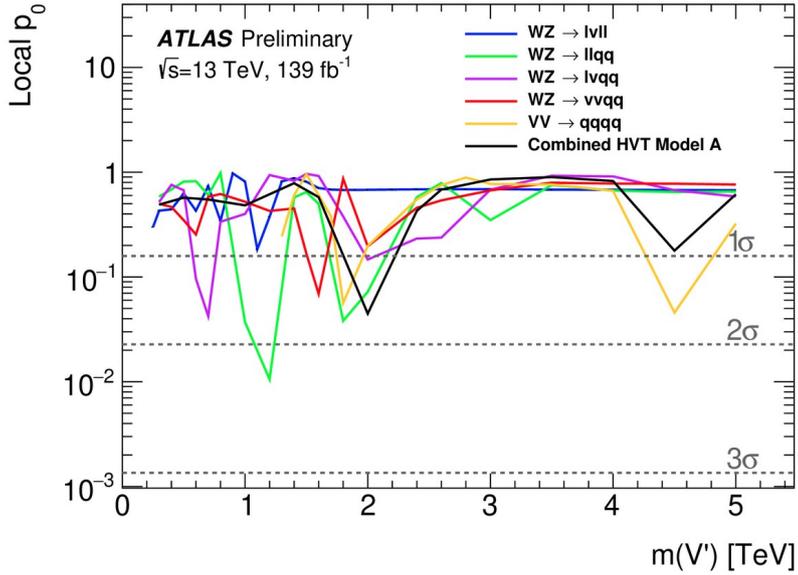
- Search for Kaluza–Klein excited vector boson resonances, $W_{KK} \rightarrow R W \rightarrow WWW$ (R is a scalar radion)
- No signal-like excess over the background



- First results using jet measurements
- Technical advances:
 - Novel jet substructure techniques
 - Dedicated “radion” taggers based on ML
- Also see heavy Higgs bosons decaying into vector bosons $W \rightarrow HW \rightarrow WWW$ ([ATLAS-CONF-2022-033](#))

- 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 μ	Yes	$\geq 2j, \geq 1J$	0, 1, 2	m_{VV}
$WZ/ZZ \rightarrow \ell\ell qq$	2e, 2 μ	-	$\geq 2j, \geq 1J$	0	m_{VV}
$WZ \rightarrow \ell\nu\ell\ell$	3 \subset (e, μ)	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 μ	Yes	$\geq 2j, \geq 1J$	1, 2	m_{VH}
$ZH \rightarrow \ell\ell bb$	2e, 2 μ	Veto	$\geq 2j, \geq 1J$	1, 2	m_{VH}
$\ell\nu$	1e, 1 μ	Yes	-	-	m_T
$\tau\nu$	0	Yes	-	-	m_T
$\ell\ell$	$\geq 2e, \geq 2\mu$	-	-	-	$m_{\ell\ell}$

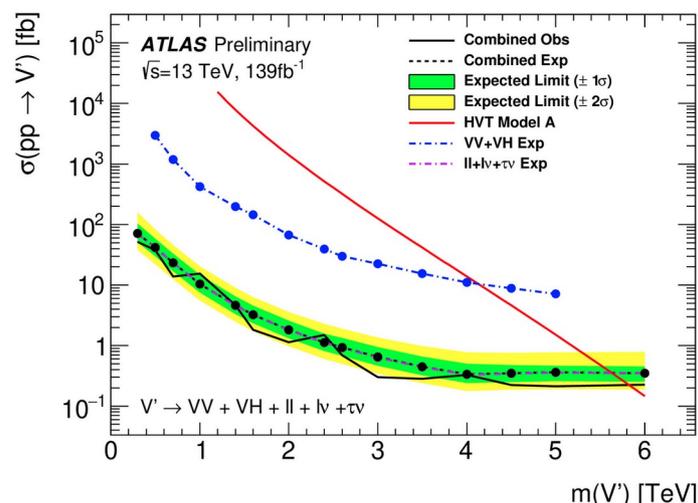


Typical example of p-value scan over the HVT pole masses up to 5 TeV

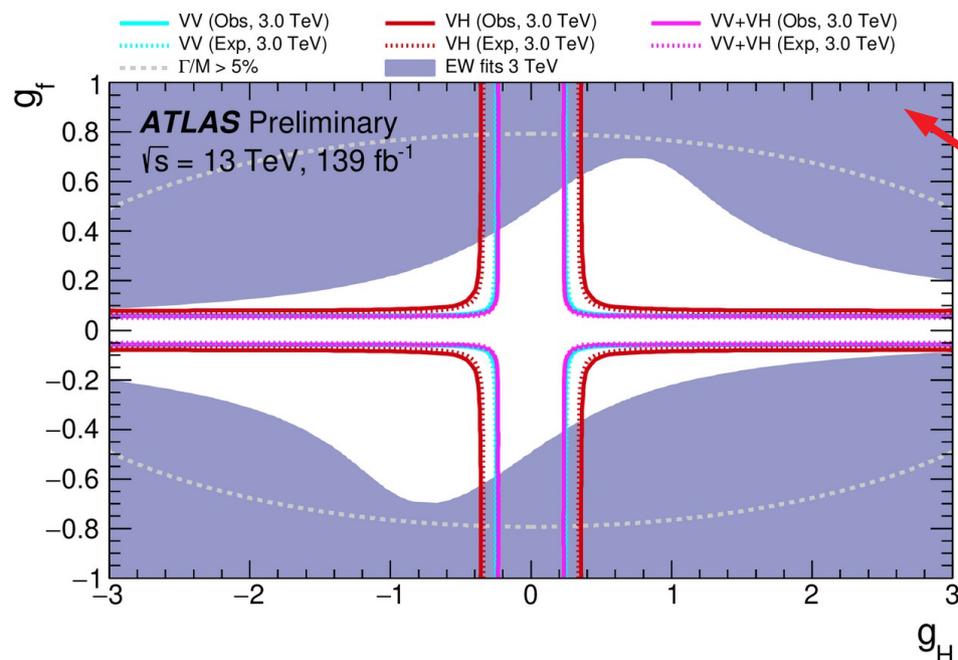
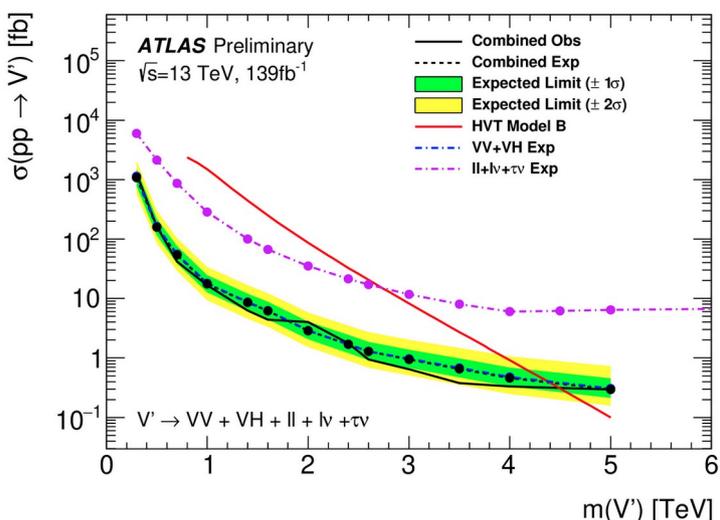
Scans for only-leptonic channel is extended up to 6 TeV (higher statistics!)

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

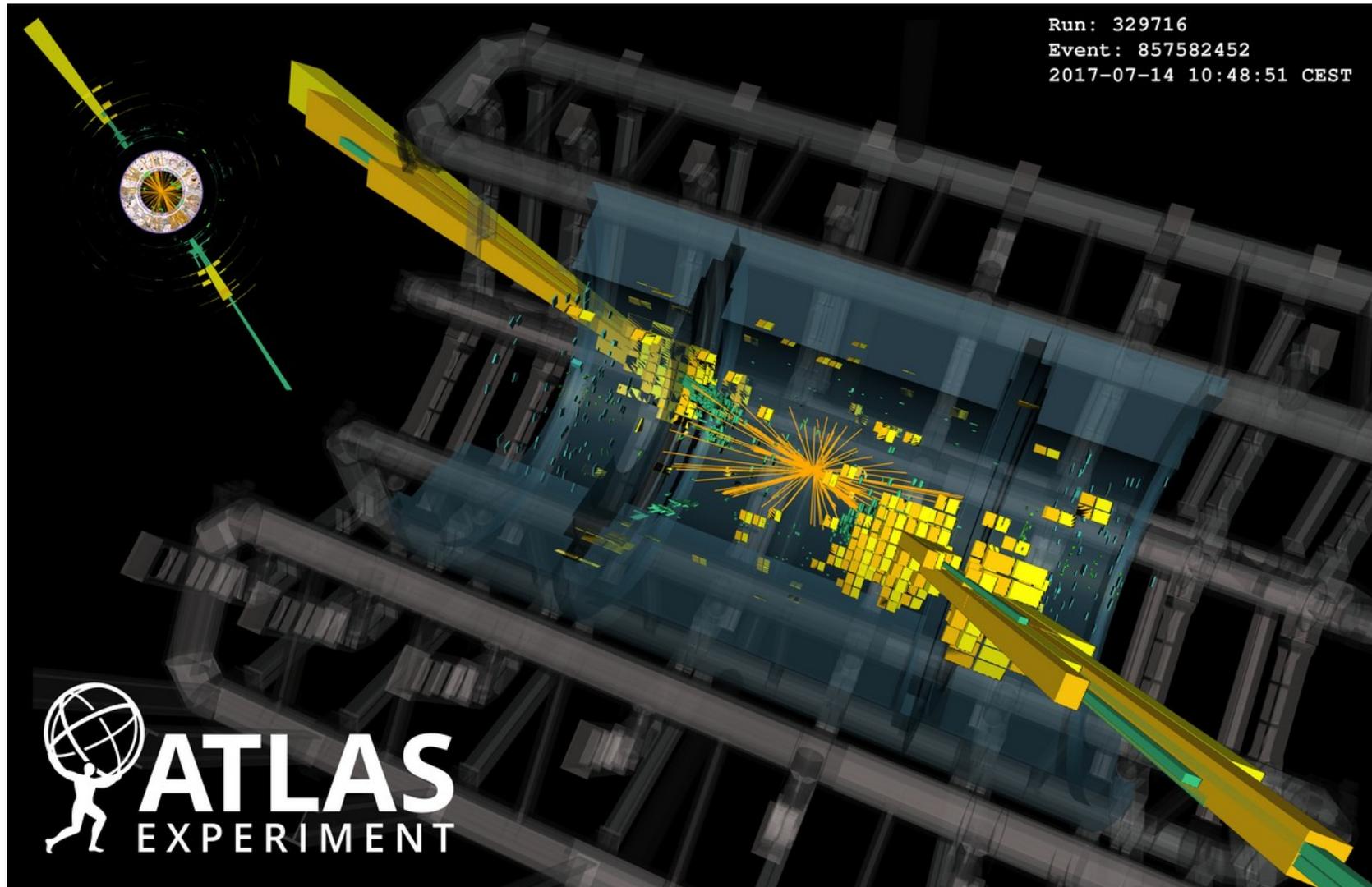
Typical exclusions for 3 TeV for $\{g_V, g_H\}$ for $q\bar{q}$ production mode

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, γ , $t\bar{t}$, 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_{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

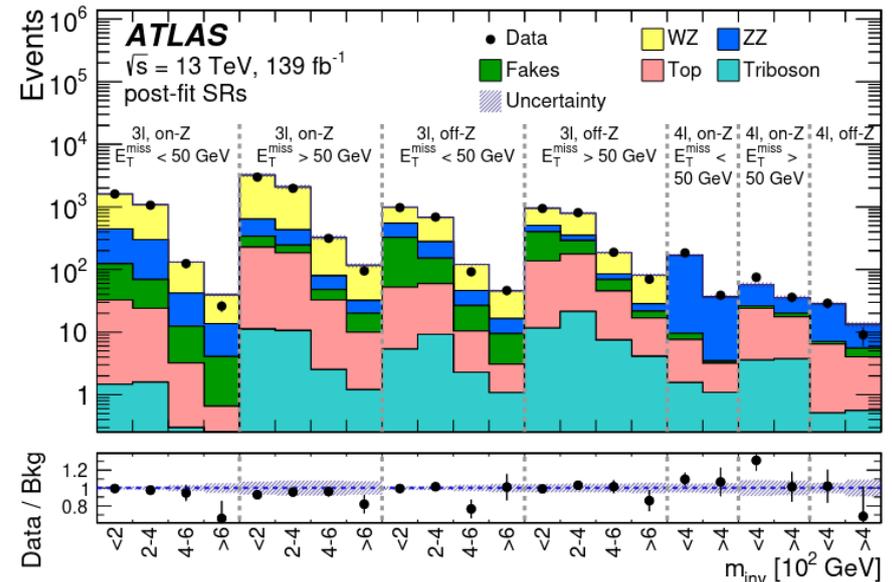
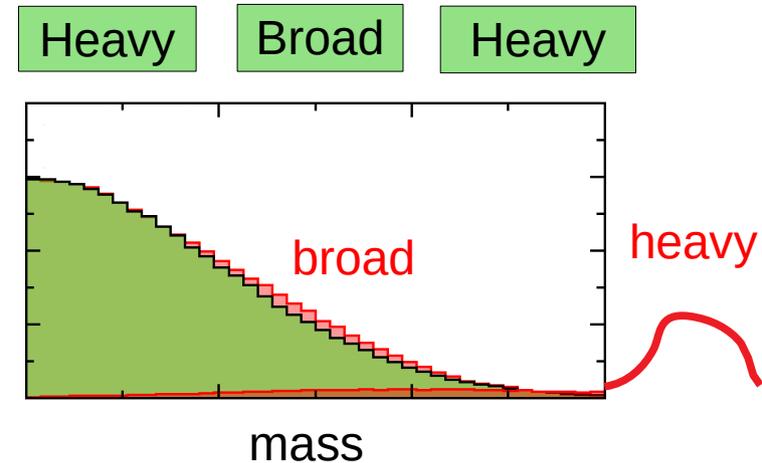
\rightarrow Can translate to ~ 1 TeV in mass reach for some channels

Backup



Non-resonant production

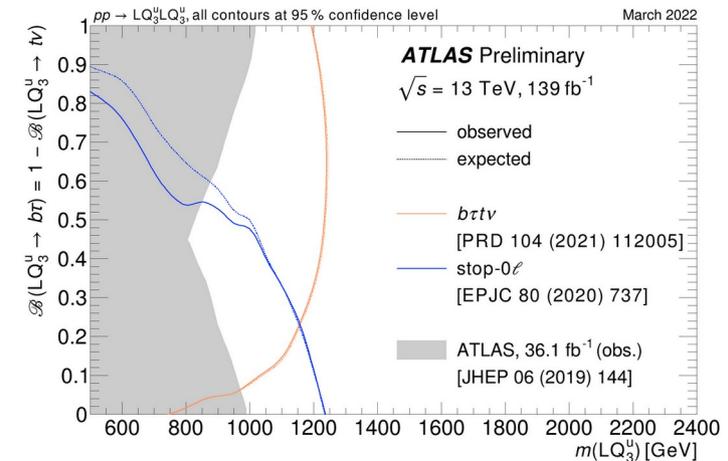
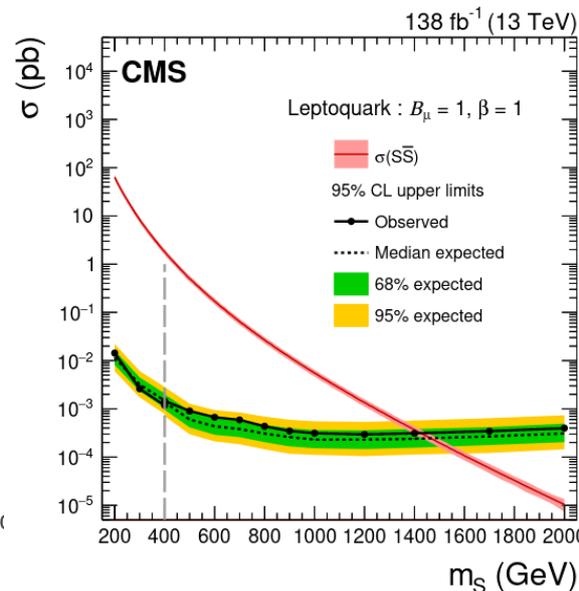
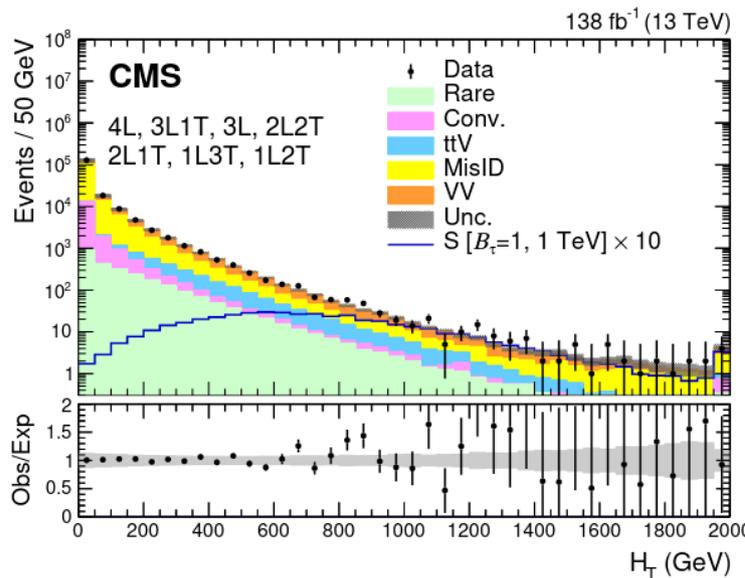
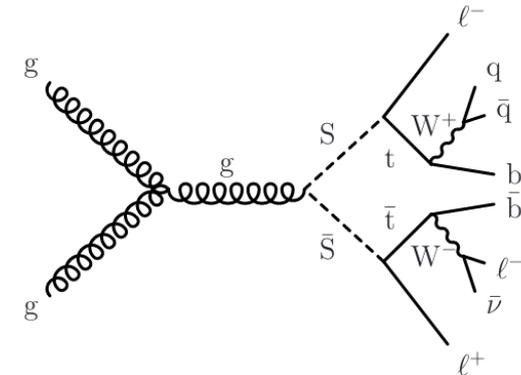
See M.Folgado & V.Sanz, Advances in High Energy Physics, Volume 2021, Article ID 2573471,



- ▶ 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