

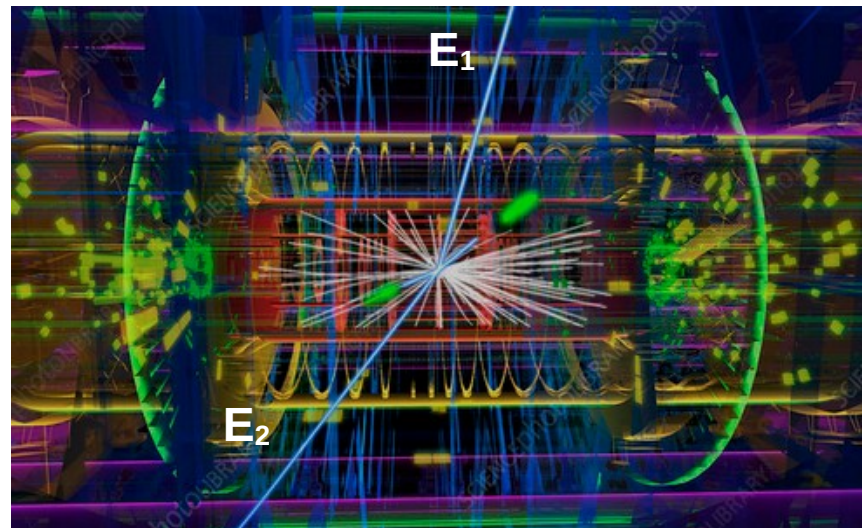
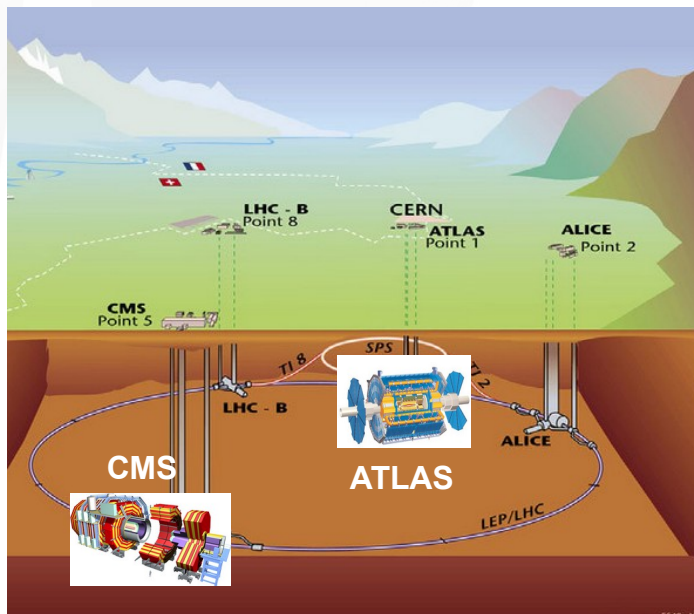
Highlights of Search for New Particles at the LHC

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on behalf of the ATLAS and CMS collaborations

LHC experiments

Mitchell 2022, Texas A&M University, USA
May 24-27 2022



New particles at collider experiments

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

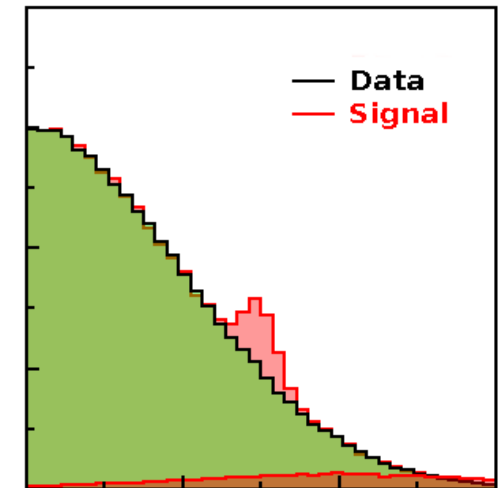
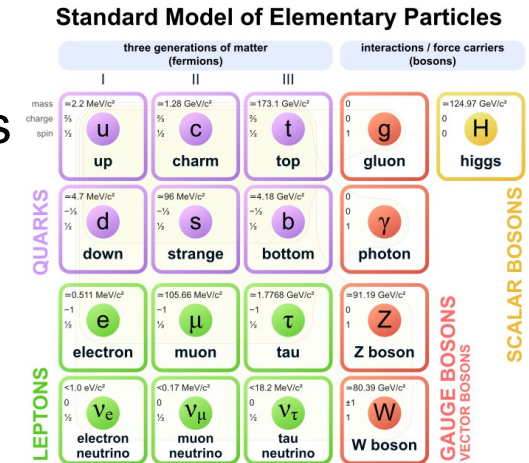
Direct observations of new particles

- Combine known particles to create “invariant masses” & search for “resonance” enhancements above background
- or observe through unusual signatures in detectors (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 particles with energy E and 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

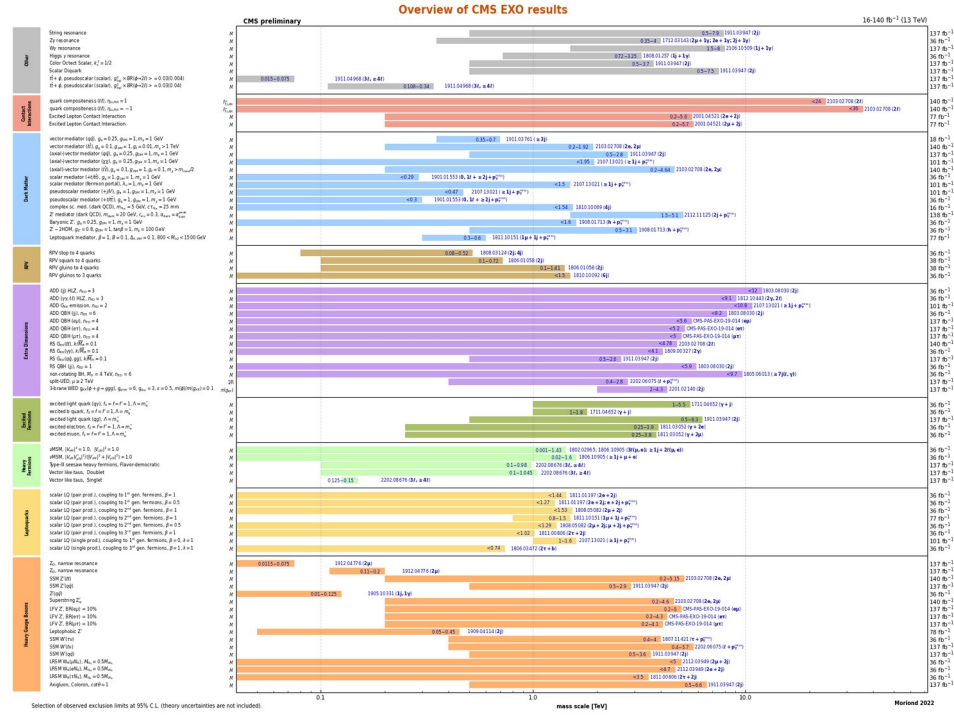
Status: March 2022

Model	ℓ, γ	Jets [†]	E_{miss}^T	$[\int \mathcal{L} dt] [fb^{-1}]$	Limit	Reference
Extra dimensions						
ADD $G_{KK} + g/\alpha$	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	M_{KK} 11.2 TeV $n=2$	2102.10874
ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_{KK} 8.6 TeV $n=3$ HLZ NLO	1707.04147
ADD OH	-	2	-	37.0	M_{KK} 8.9 TeV	1703.09127
ADD BH multijet	-	≥ 3	-	3.6	M_{KK} $n=6, M_{\text{pl}} = 3 \text{ TeV, rot BH}$	1512.02566
RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	G_{KK} mass 4.5 TeV $k/\overline{M}_{\text{pl}} = 0.1$	2102.13405
Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	139	G_{KK} mass 36.1 $k/\overline{M}_{\text{pl}} = 1.0$	1808.02280
Bulk RS $G_{KK} \rightarrow W\gamma$	$1, e, \mu$	2/1/1	Yes	139	G_{KK} mass 2.0 TeV $k/\overline{M}_{\text{pl}} = 1.0$	2004.14636
Bulk RS $G_{KK} \rightarrow t\bar{t}$	$1, e, \mu$	$\geq 1, b, \geq 1, \tau$	Yes	36.1	G_{KK} mass 2.0 TeV $f/m = 15\%$	1904.10823
2UED / RPP	$1, e, \mu$	$\geq 2, b, \geq 3$	Yes	36.1	H_{KK} mass 1.8 TeV $\text{Tier } (1, 1), \mathcal{R}(\mathcal{A}^{(1)} \rightarrow t\bar{t}) = 1$	1803.09678
Gauge bosons						
SSM $Z' \rightarrow \ell\ell$	$2, e, \mu, \tau$	-	-	139	Z' mass 2.42 TeV 5.1 TeV	1903.06248
SSM $Z' \rightarrow \nu\nu$	$2, \tau$	-	-	36.1	Z' mass 2.1 TeV	1709.07242
Leptophobic $Z' \rightarrow b\bar{b}$	-	$2, b$	-	36.1	Z' mass 2.1 TeV	1806.00999
Leptophobic $Z' \rightarrow t\bar{t}$	$0, e, \mu, \tau$	$\geq 1, b, \geq 2, \gamma$	Yes	139	Z' mass 4.1 TeV	2005.05138
SSM $W' \rightarrow \nu\nu$	$1, e, \mu, \tau$	-	-	139	W' mass 5.0 TeV 6.0 TeV	1906.05509
SSM $W' \rightarrow \nu\tau$	$1, \tau$	-	-	139	W' mass 5.0 TeV	1906.05509
SSM $W' \rightarrow t\bar{b}$	-	$\geq 1, b, \geq 1, \gamma$	-	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	Yes	139	W' mass 340 GeV	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	$2, \mu$	$\geq 1, b, \geq 2, \gamma$	Yes	139	W' mass 3.2 TeV	2007.05293
LFSM $W_R \rightarrow \mu N_R$	$2, \mu$	1	-	80	W_R mass 5.0 TeV	1904.12679
CI						
CI $qqqq$	-	2	-	37.0	A 21.8 TeV η_{CI}	1703.09127
CI $lqqq$	$2, e, \mu, \tau$	-	-	139	A 2006.12946	2006.12946
CI $qqbb$	$2, e, \mu, \tau$	-	-	139	A 2106.13847	2106.13847
CI $qqtt$	$2, \mu$	1	-	139	A 2105.13847	2105.13847
CI $tttt$	$\geq 1, e, \mu, \tau$	$\geq 1, b, \geq 1, \gamma$	Yes	36.1	A 2.57 TeV $ k_{CI} = 4\text{t}$	1811.02005
DM						
Axial-vector med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	M_{DM} 376 GeV 2.1 TeV	2102.10874
Pseudo-scalar med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	M_{DM} 376 GeV 2.1 TeV	2102.10874
Vector med. Z' -2HDM (Dirac DM)	$0, e, \mu, \tau$	2	Yes	139	M_{DM} 376 GeV 3.1 TeV	2108.13091
Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	M_{DM} 560 GeV	ATLAS-CONF-2021-036
LO						
Scalar LQ 1 st gen	$2, e$	≥ 2	Yes	139	LQ mass 1.8 TeV	2006.05872
Scalar LQ 2 nd gen	$2, \mu$	≥ 2	Yes	139	LQ mass 1.7 TeV	2006.05872
Scalar LQ 3 rd gen	$1, \tau$	$2, b$	Yes	139	LQ mass 1.24 TeV	2108.07665
Scalar LQ 3 rd gen	$0, e, \mu, \tau$	$\geq 2, \geq 2, b$	Yes	139	LQ mass 1.24 TeV	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	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	2101.12527
Vector LQ 3 rd gen	$1, \tau$	$2, b$	Yes	139	LQ mass 1.77 TeV	2108.07665
Heavy quarks						
VLQ $TT \rightarrow Z + X$	$2e/2\mu/3e, \mu$	$\geq 1, b, \geq 1, \gamma$	-	139	V mass 1.4 TeV	SU(2) doublet ATLAS-CONF-2021-024
VLQ $BB \rightarrow W + Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	1808.02243
VLQ $T_{1/3} T_{2/3} W_{1/3} \rightarrow W + X$	$2(S)/3, 3, e, \mu, \tau$	$\geq 1, b, \geq 1, \gamma$	Yes	36.1	$T_{1/3}$ mass 1.64 TeV	1807.11983
VLQ $T \rightarrow H, Z, \gamma$	$1, e, \mu, \tau$	$\geq 1, b, \geq 1, \gamma$	Yes	139	T mass 1.8 TeV	ATLAS-CONF-2021-040
VLQ $Y \rightarrow Wb$	$1, e, \mu, \tau$	$\geq 1, b, \geq 1, \gamma$	Yes	36.1	Y mass 1.85 TeV	1812.07343
VLQ $B \rightarrow Hb$	$0, e, \mu, \tau$	$\geq 2, b, \geq 1, \gamma$	-	139	B mass 2.0 TeV	ATLAS-CONF-2021-018
Excited fermions						
Excited quark $q^* \rightarrow qg$	-	2	-	139	q^* mass 6.7 TeV	1910.08447
Excited quark $q^* \rightarrow q\gamma$	-	1	-	36.7	q^* mass 3.2 TeV	1709.10440
Excited quark $b^* \rightarrow b\gamma$	-	1, b	-	36.1	b^* mass 2.6 TeV	1905.09999
Excited lepton e^*	$3, e, \mu, \tau$	-	-	20.3	e^* mass 3.0 TeV	1411.2921
Excited lepton ν^*	$3, e, \mu, \tau$	-	-	20.3	ν^* mass 1.6 TeV	1411.2921
Other						
Type II Seesaw	$2, 3, 4, e, \mu, \tau$	≥ 2	Yes	139	M_{Higgs} mass 910 GeV	2202.00039
LFSM Majorana ν	$2, \mu, \tau$	2	Yes	36.1	M_{Higgs} mass 350 GeV	1808.11105
Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$	$2, 3, 4, e, \mu, \tau$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 1.08 TeV	2101.11961
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4, e, \mu, \tau$ (SS)	-	-	139	$H^{\pm\pm}$ mass 400 GeV	ATLAS-CONF-2022-010
Higgs triplet $H^{\pm\pm} \rightarrow \nu\nu$	$3, e, \mu, \tau$ (SS)	-	-	20.3	$H^{\pm\pm}$ mass 1.22 TeV	1411.2921
Multi-charged particles	-	-	-	36.1	multi-charged particle mass	1812.03673
Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	1905.10130

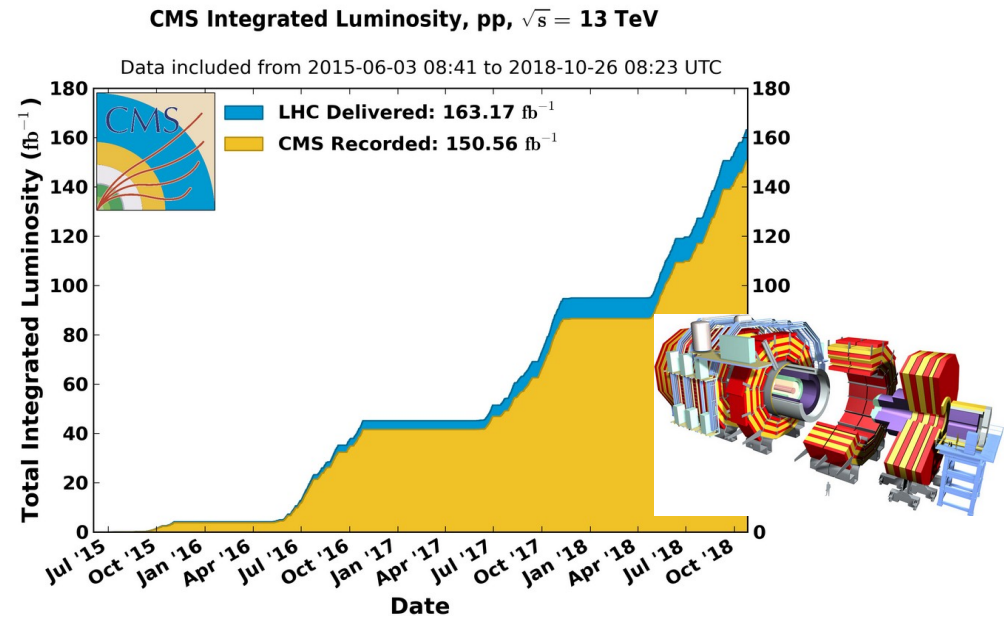
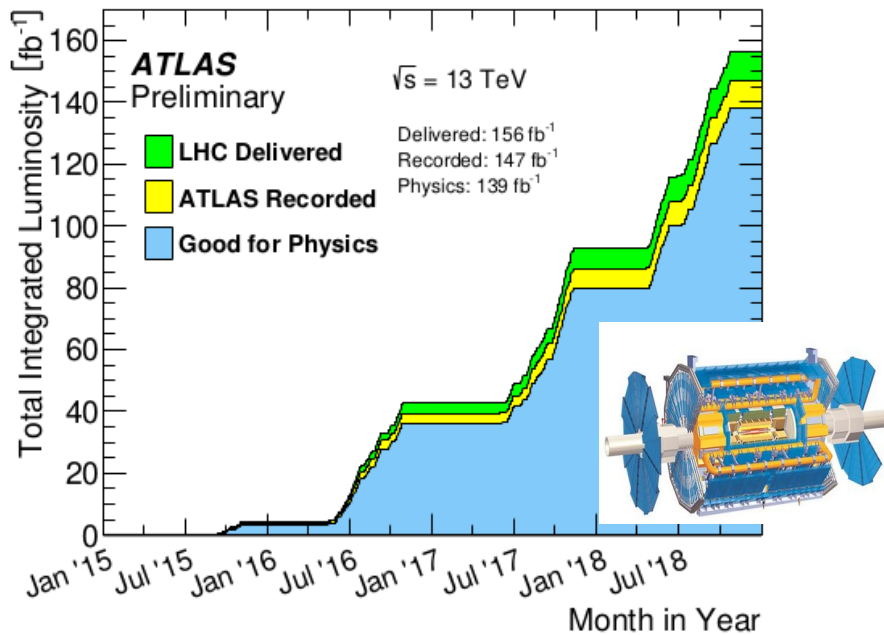
*Only a selection of the available mass limits on new states or phenomena is shown.

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

- ~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!



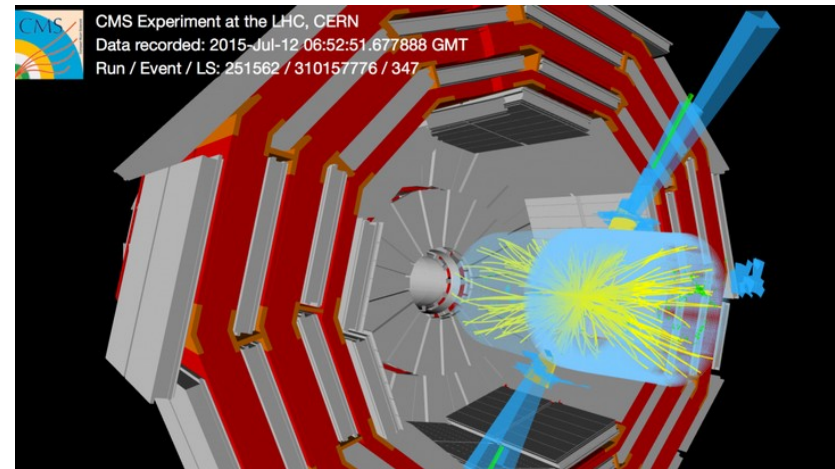
LHC operation



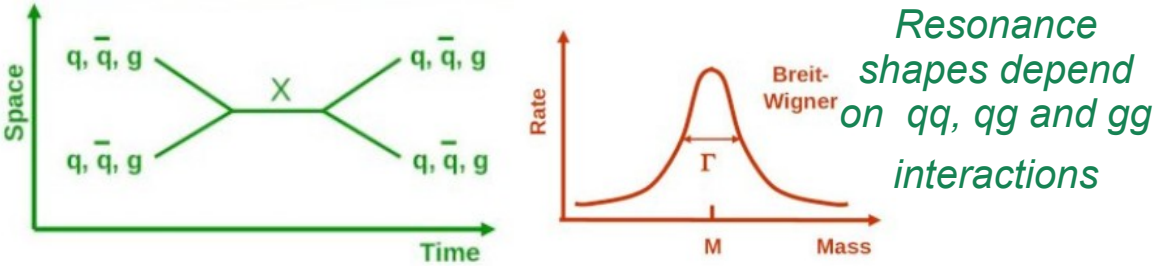
- Run2 pp collision data-set, $\sqrt{s} = 13$ TeV.
- Both experiments collected ~ 150 fb⁻¹.

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



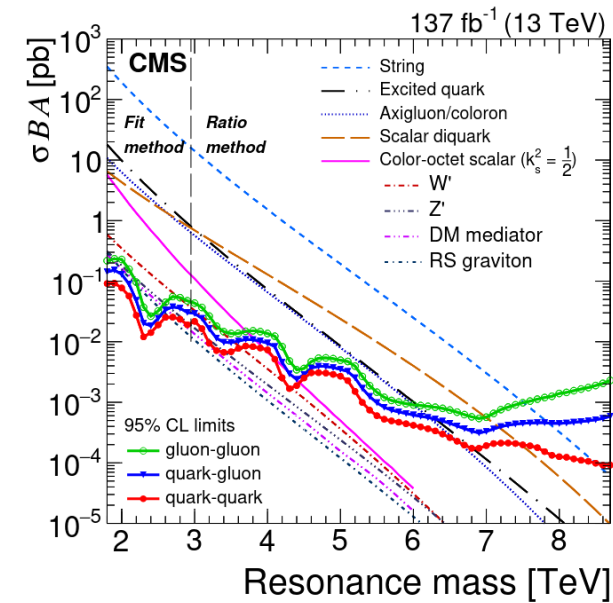
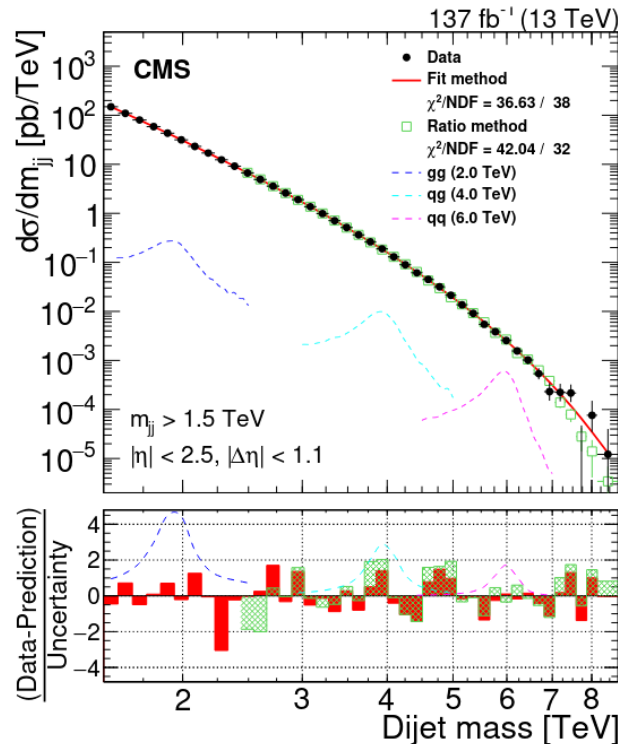
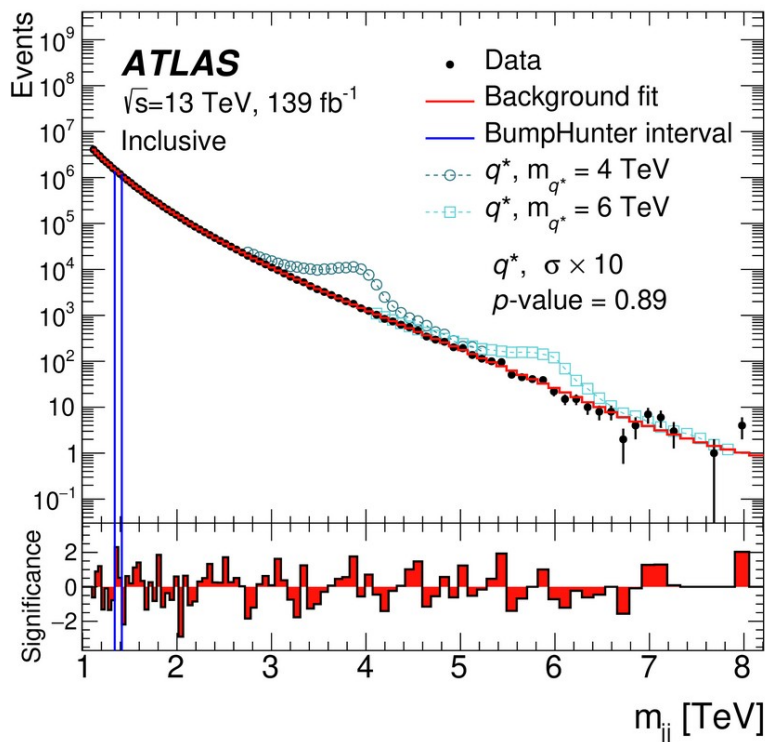
Search for high mass dijet resonances



Physics of additional 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.

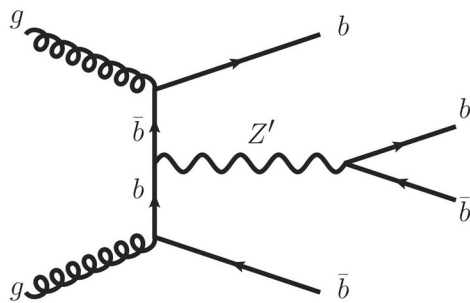
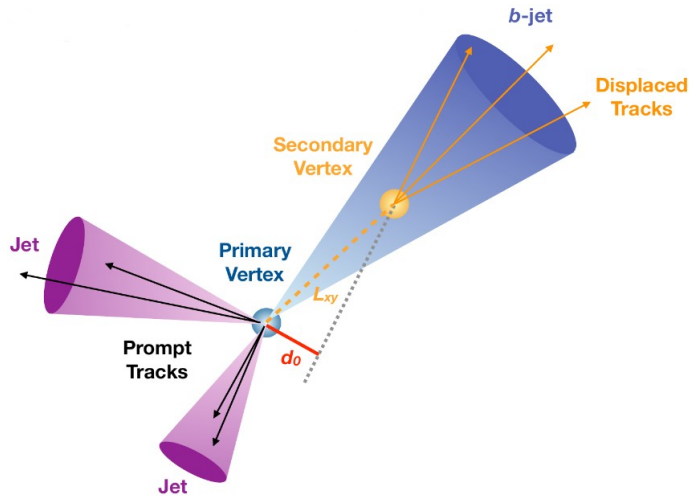
- ▶ Calculate invariant mass from 2 hadronic jets
- ▶ Fit with smooth analytic functions (red lines)
- ▶ Competitive limits for masses from 1 to 8 TeV



Observed and expected mass limits at 95% CL

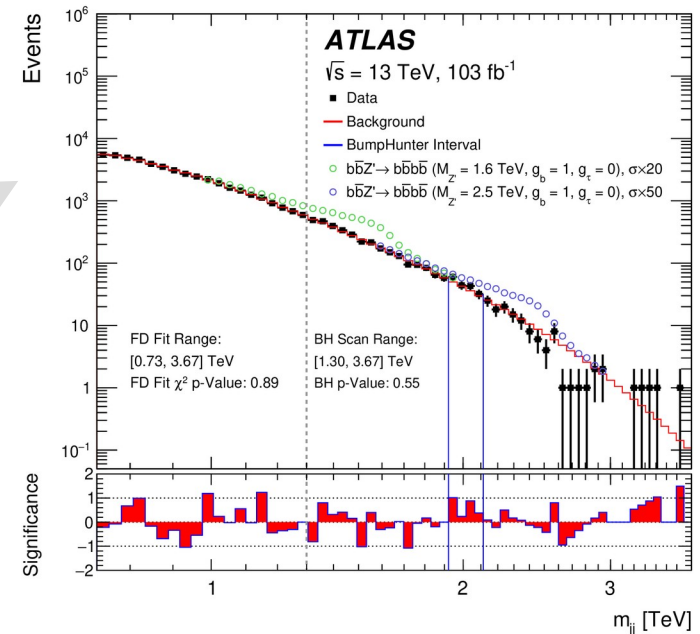
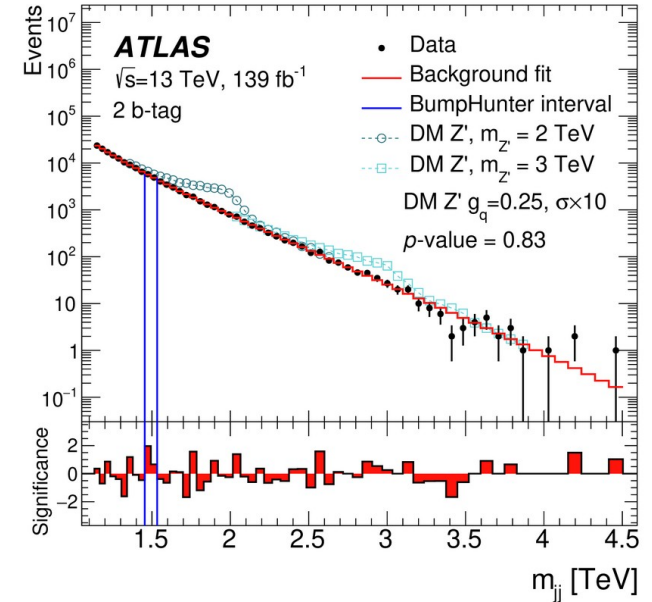
Jets originating from b-quark

- 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
- Search for $Z' \rightarrow b\bar{b}$ by combining jets from b-quarks



2-b jet mass in all events

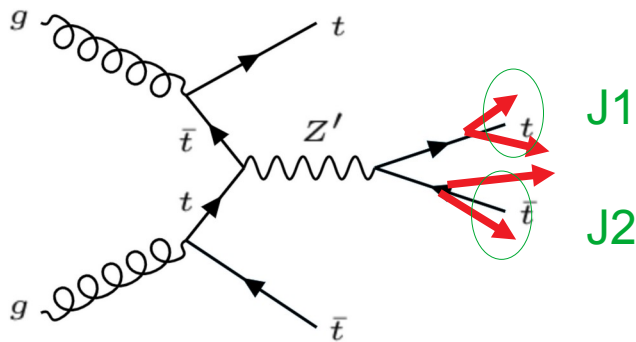
2-b jet mass in events with multiple b-quarks



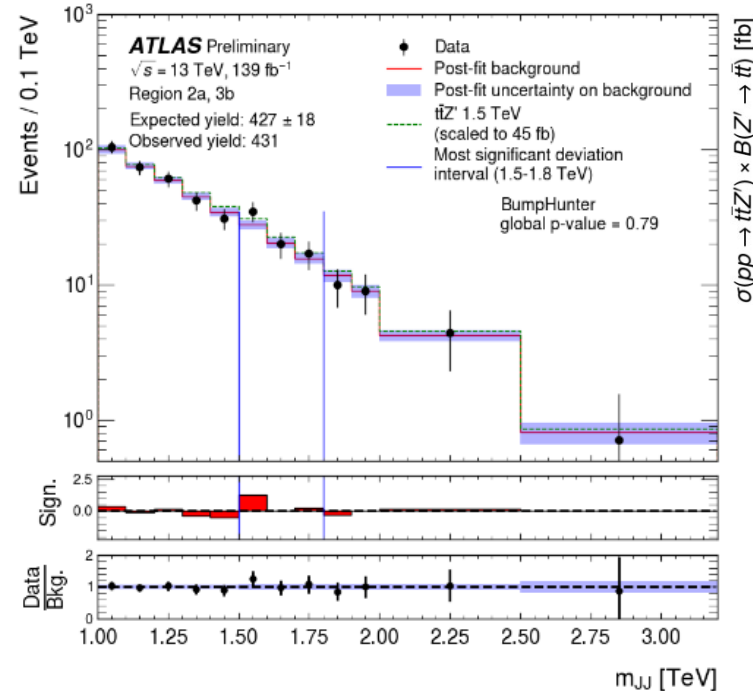
- No signals. Competitive limits for $Z' \rightarrow b\bar{b}$ processes

- 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)

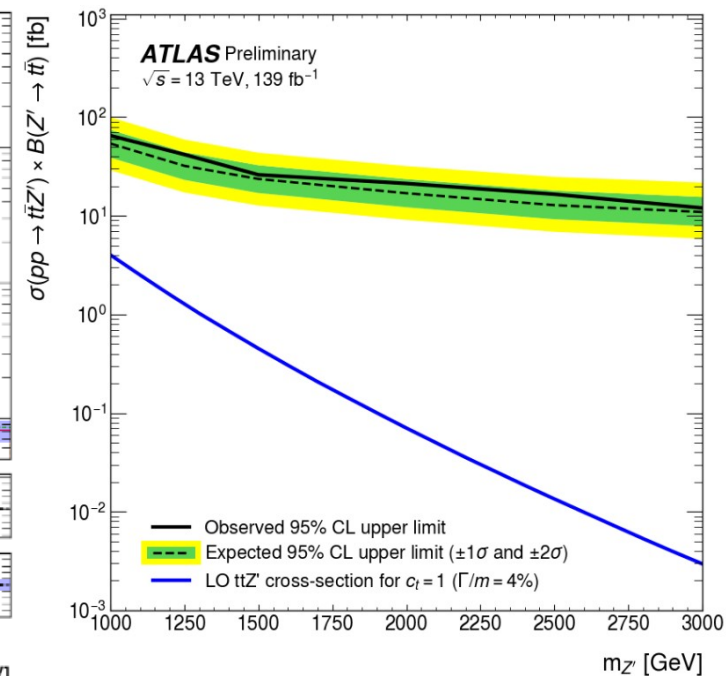
> 1 boosted jets
> 2 b-tagged jets
at least 1 lepton



Representative invariant mass of two large-radius jets



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

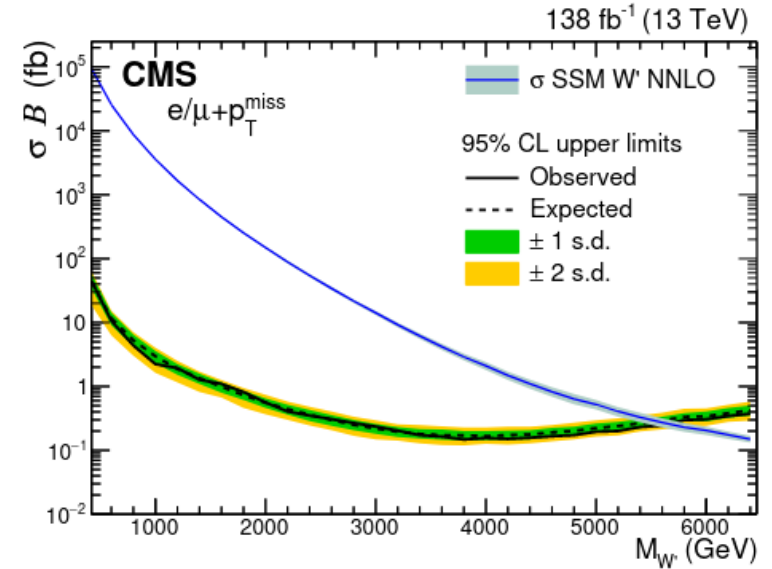
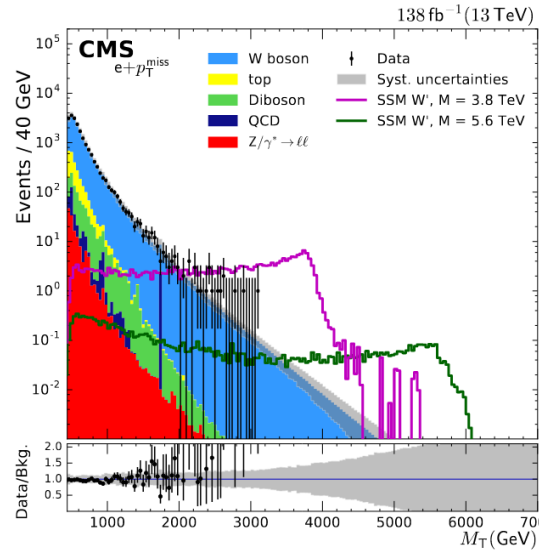
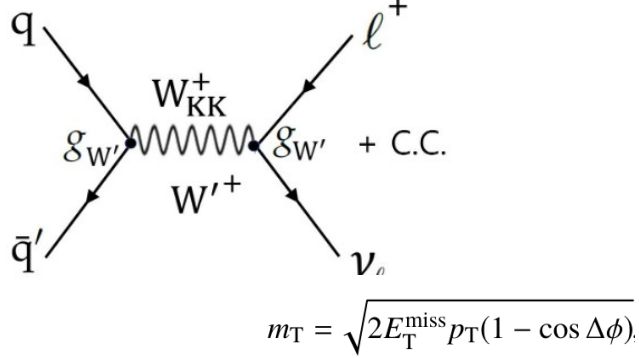


- No excess above the expected SM background
- Competitive Run II limits. Require more data to exclude $t\bar{t}Z'$ production

Searches for W' heavy bosons - I

W' is analog of W bosons in several BSM scenarios

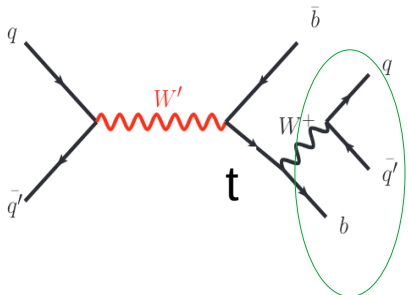
All leptonic W' (W_{KK}')



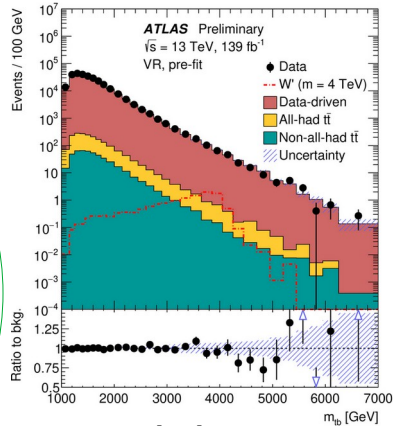
CMS: use transverse mass (m_T) calculated from charged lepton and the missing transverse momenta

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

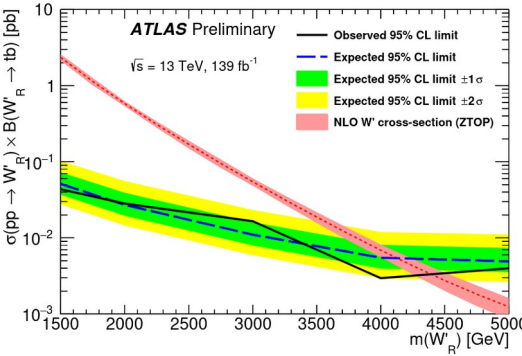
All-hadronic W'



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)

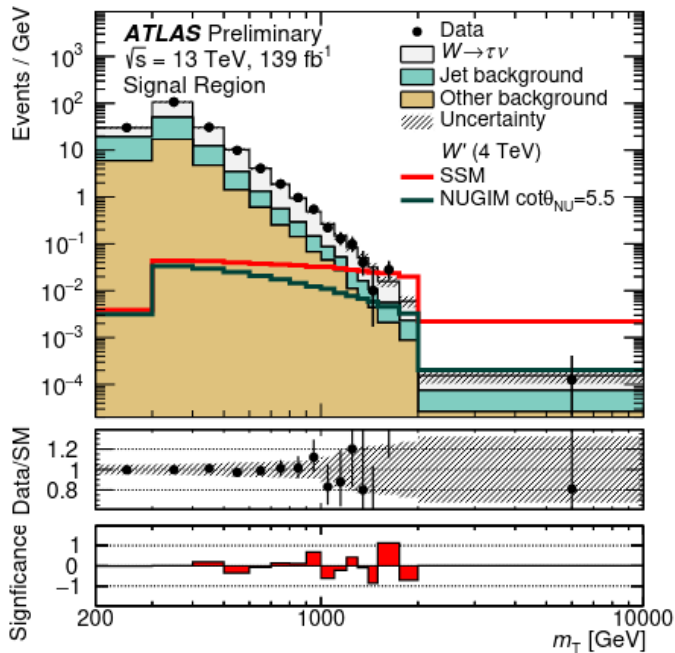
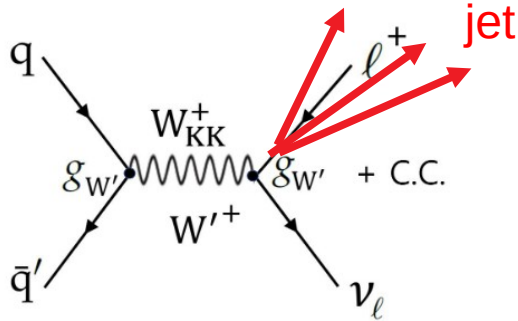
Exclude BSM models:

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

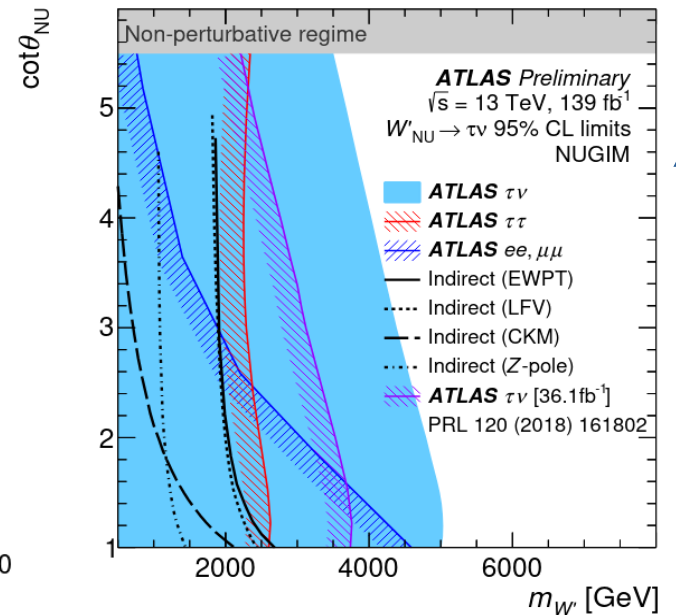
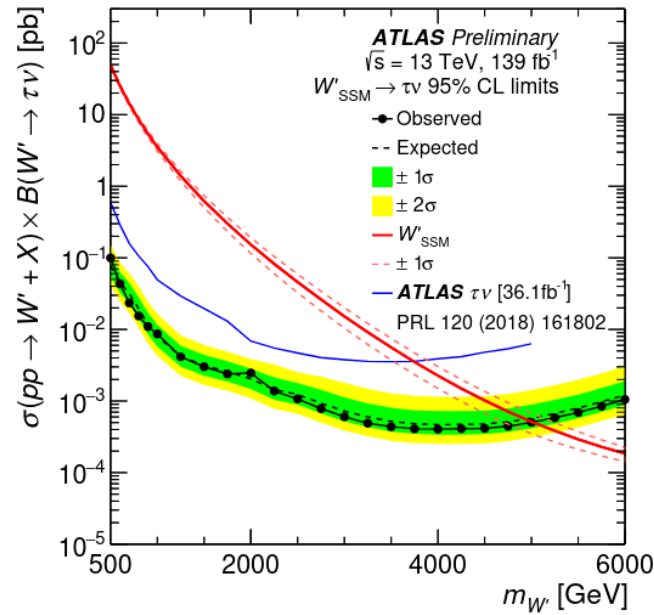
Hadronic decays of tau-leptons

Challenging background!

→ use machine learning (ML)



$$m_T = \sqrt{2E_T^{\text{miss}} p_T (1 - \cos \Delta\phi)}$$



Increase coupling to 3rd generation

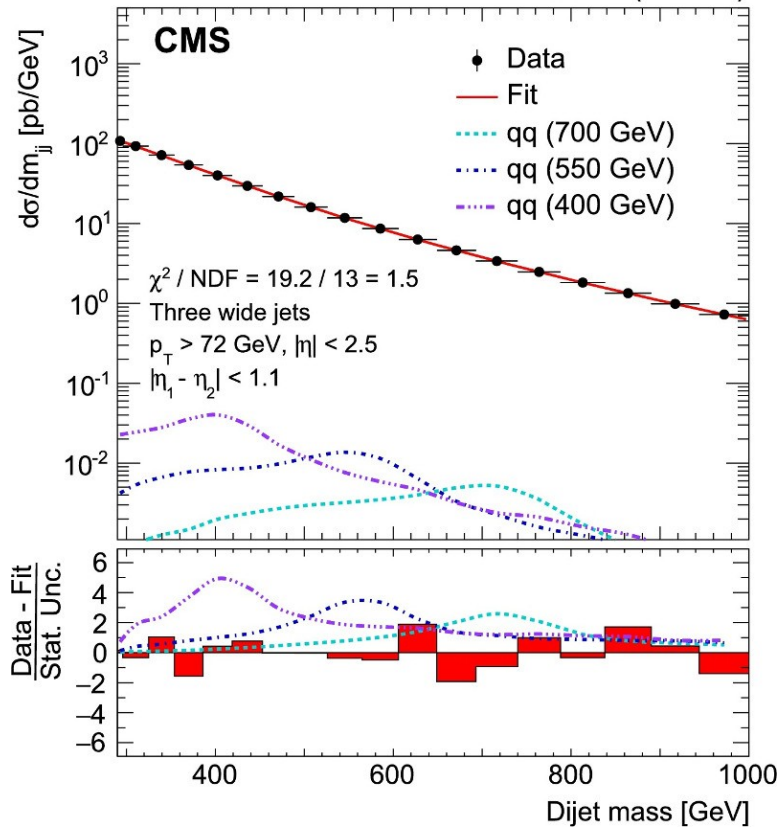
- Model independent limits
- <5 TeV 95% CL for SSM scenario
- Limits for Non-Universal Gauge Interaction Models (NUGIM) with additional parameter $\cot \theta_{\text{NU}}$ used to scale the couplings to the first and second generations of fermions

Searches using di-jets + X

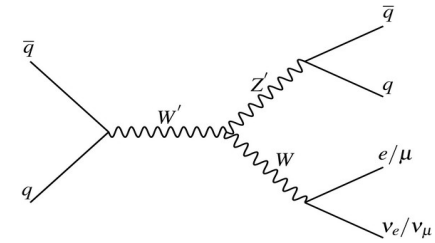
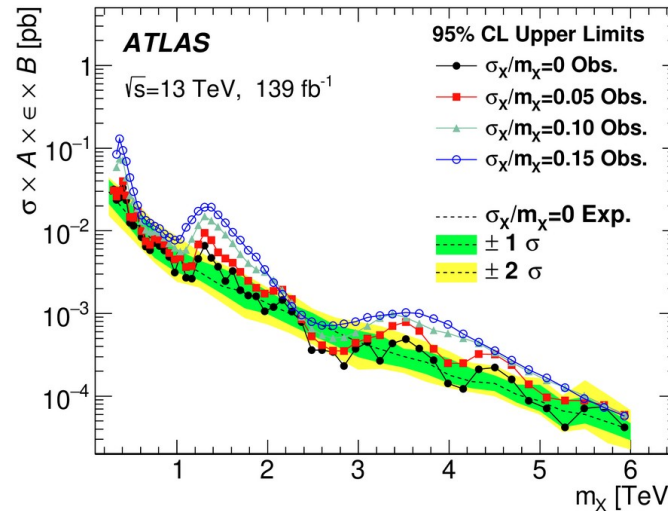
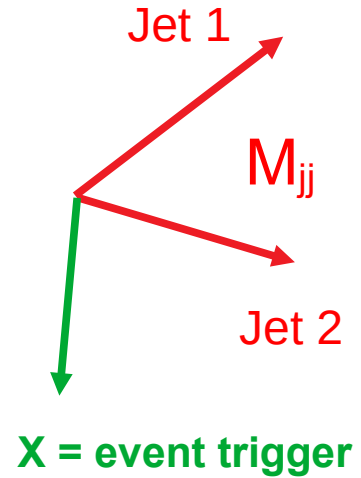
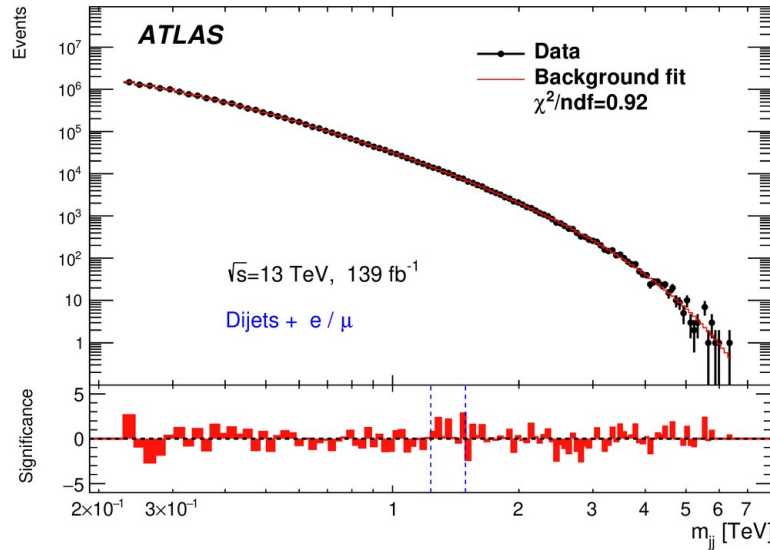
- Additional object X (lepton, jet, photon) helps triggering events with smaller masses (~ 300 GeV – 1 TeV)

X = 3rd jet

18.3 fb⁻¹ (13 TeV)



X = e, μ

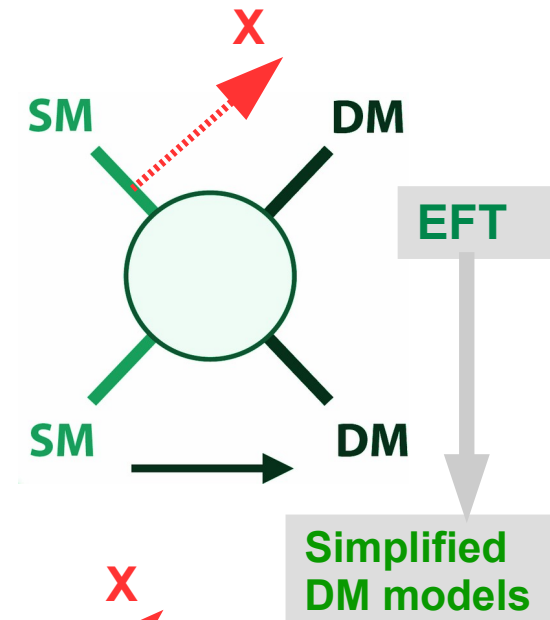


Limits on Sequential Standard model at 1.5 TeV

- 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

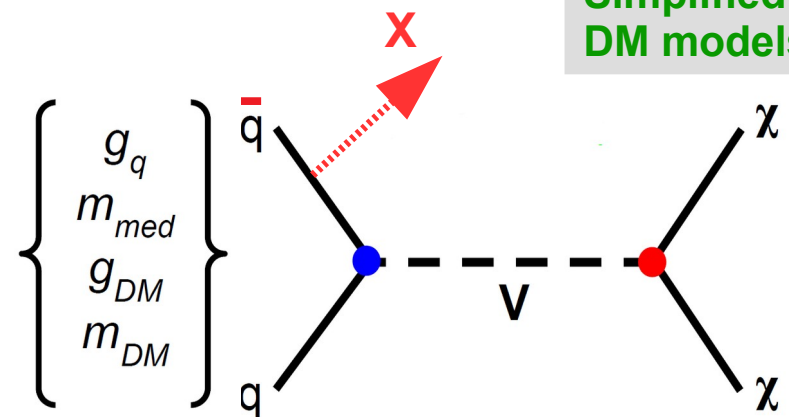


Adopt simplified DM model with a “mediator” V

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

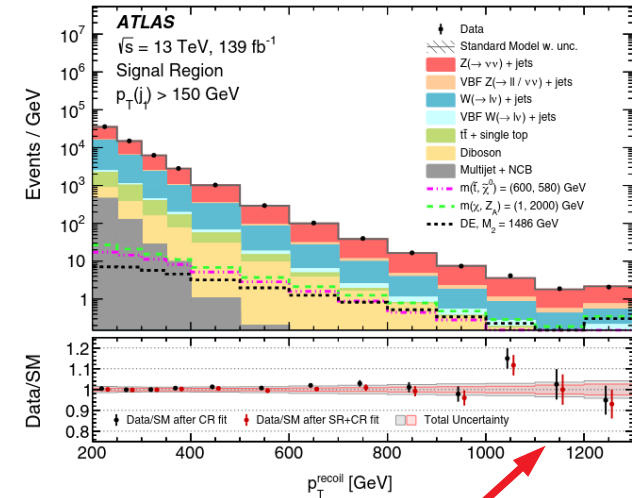
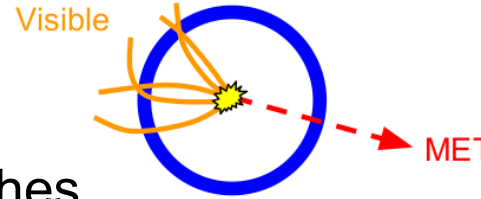
ATLAS & CMS: $g_q=0.25$ (S=1), $g_q=1$ (S=0), $g_{DM}=1$

Γ =minimum width formula



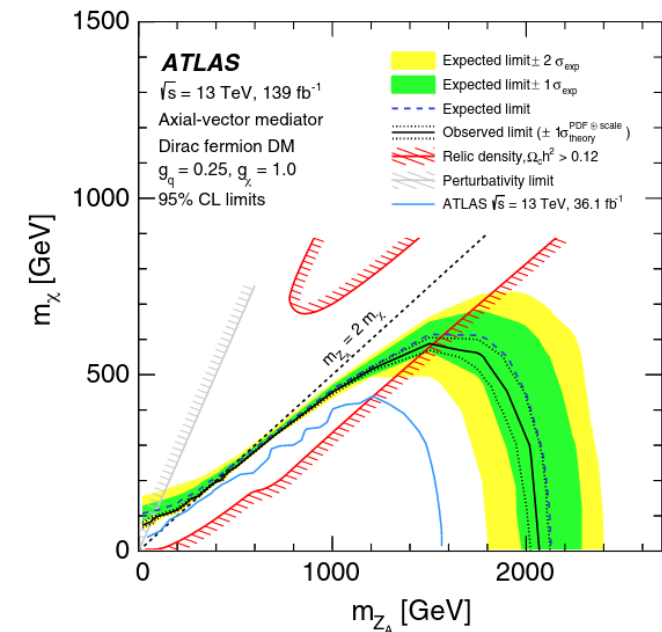
Mono jet searches

- ▼ 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

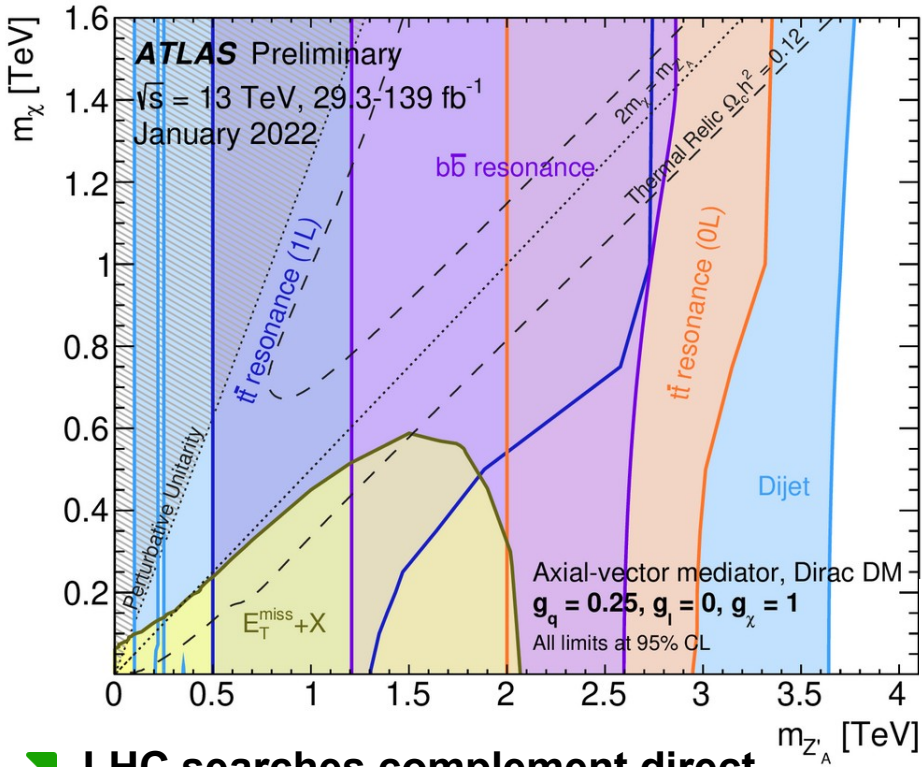


Typical precision for SM description

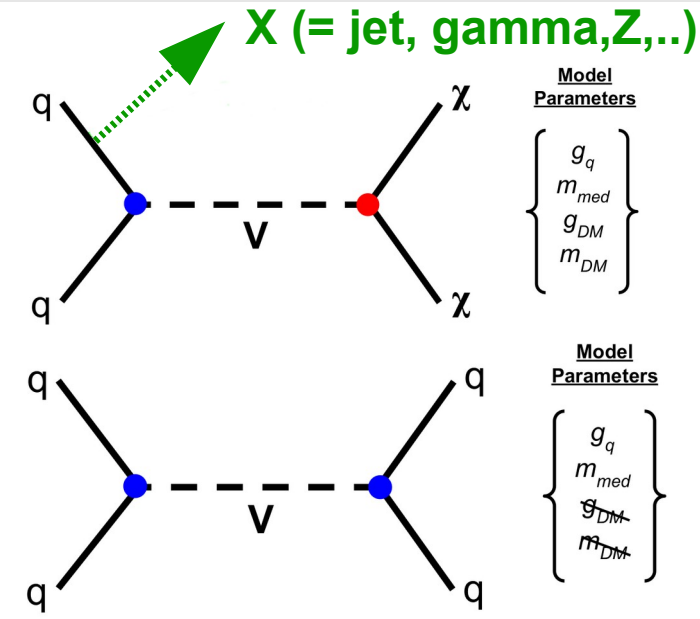
- ▼ Required high-precision SM measurements
- ▼ Examples:
 - ▼ $jet+\gamma$ – missing NNLO effects for $Z(\nu\nu)$ (CMS)
 - ▼ $W+jet$ control region also for $Z(\nu\nu)$ (ATLAS)



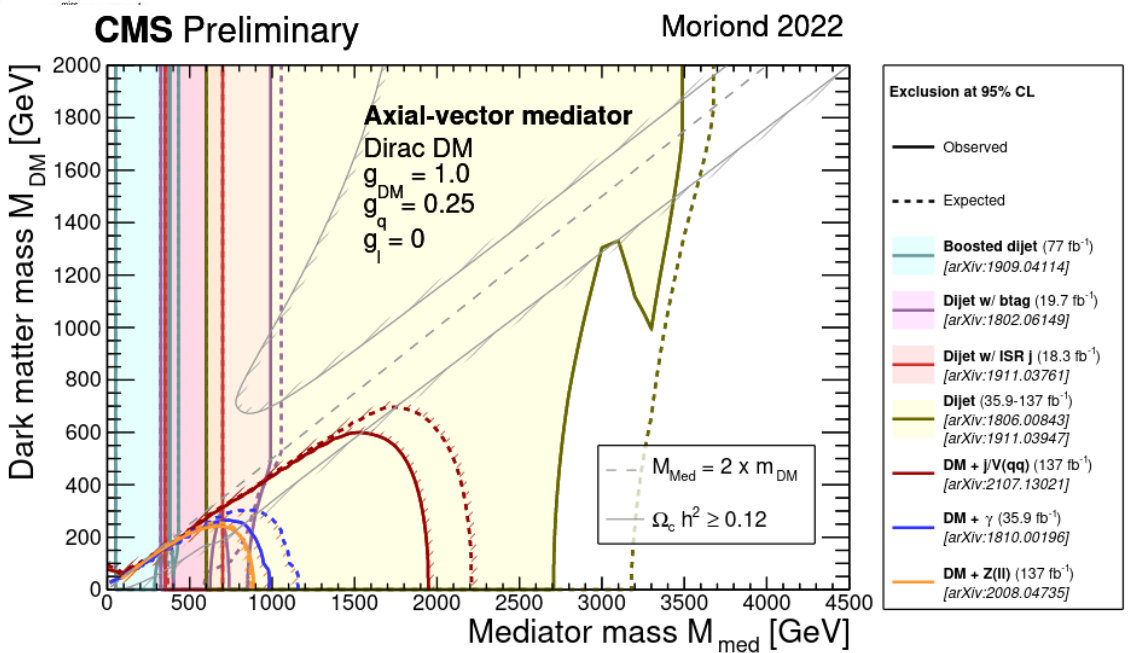
Dark Matter summary plots



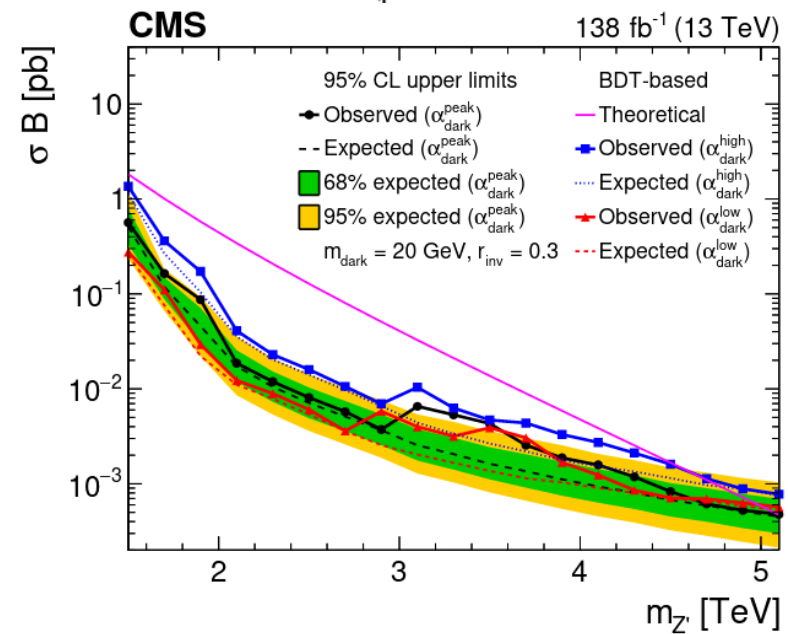
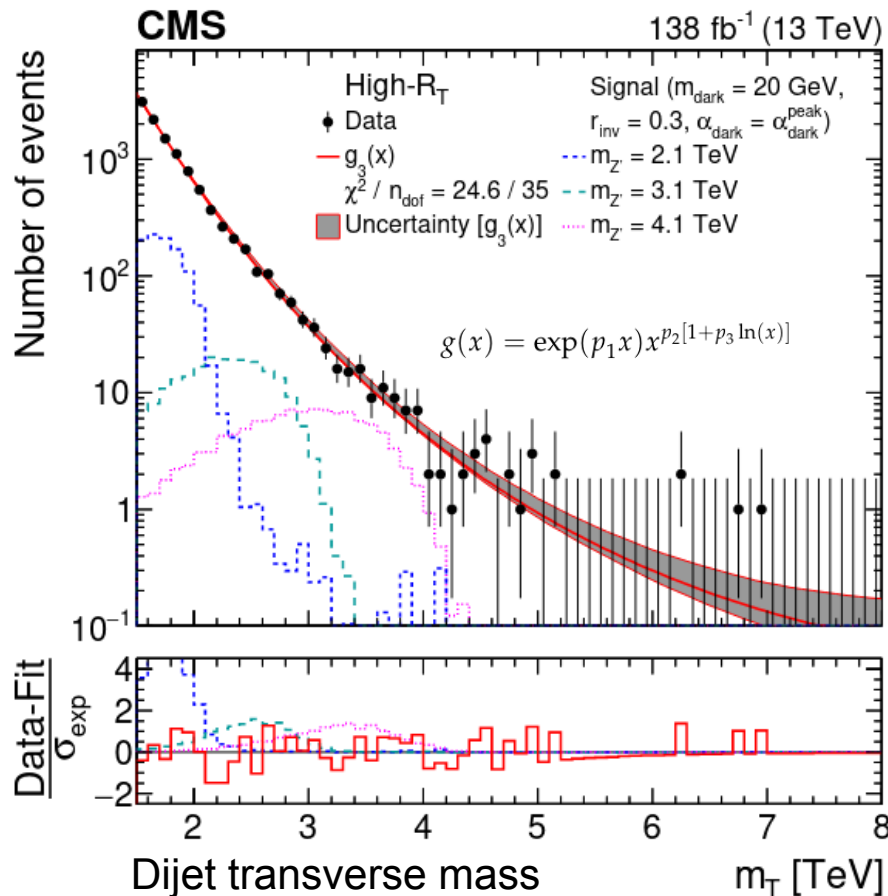
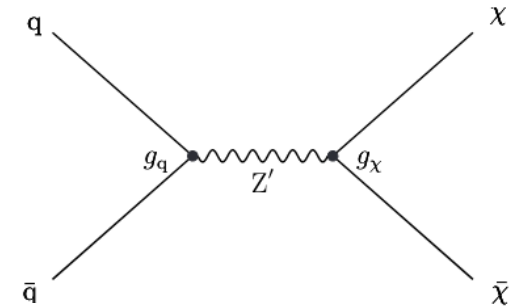
- Dijet**
Dijet, 139 fb⁻¹
JHEP 03 (2020) 145
Dijet TLA, 29.3 fb⁻¹
PRL 121 (2018) 081801
Dijet+ISR, 79.8 fb⁻¹
PLB 795 (2019) 56
Boosted dijet+ISR, 36.1 fb⁻¹
PLB 788 (2019) 316
Boosted di-b+ISR, 80.5 fb⁻¹
ATLAS-CONF-2018-052
- t t-bar resonance (1L)**
36.1 fb⁻¹
EPJC 78 (2018) 565
- t t-bar resonance (0L)**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



- ▶ **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



- Heavy leptophobic Z' mediator can decay to two "semi-visible" jets, containing both visible matter and invisible dark matter ("dark hadrons" from "dark quarks")
- Train BDT to separate SM and wider "semi-visible" jets

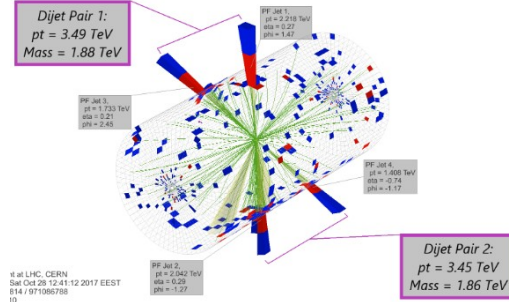
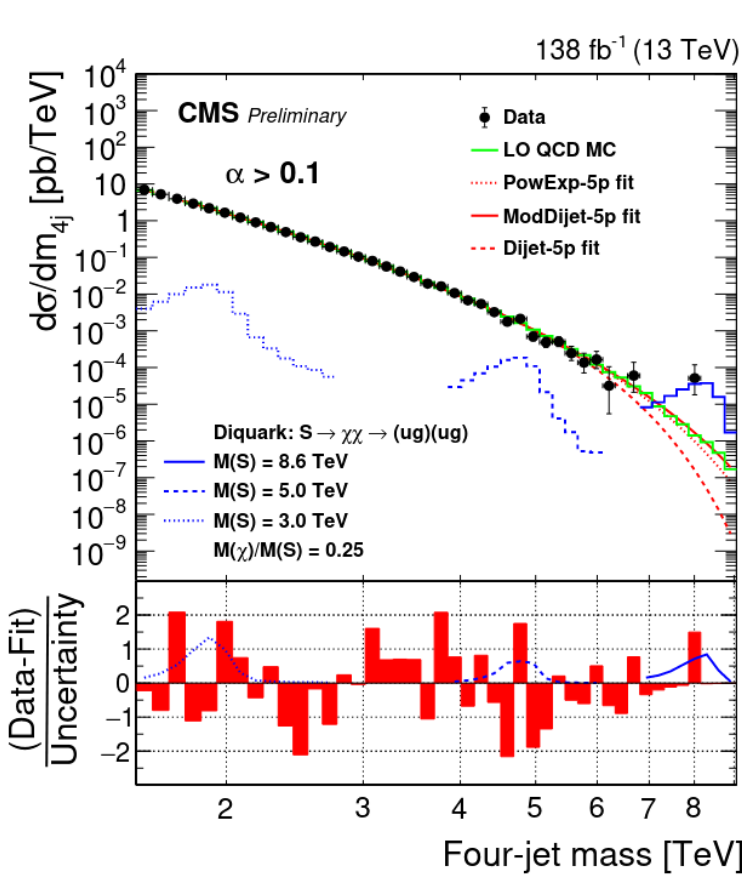


Limits for Z' mass for $m_{\text{dark}}=20$ GeV and fraction of stable invisible dark hadrons

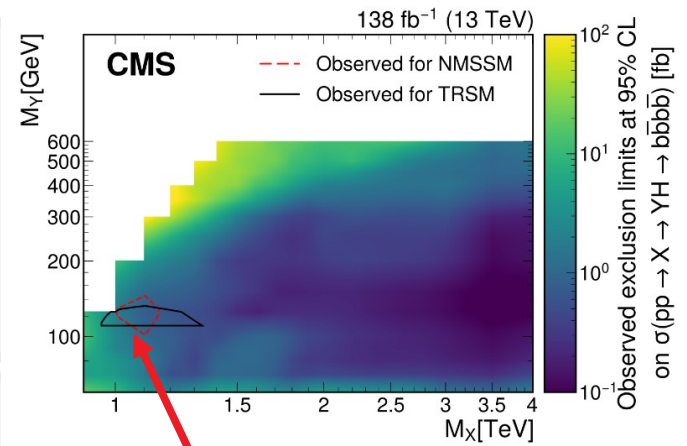
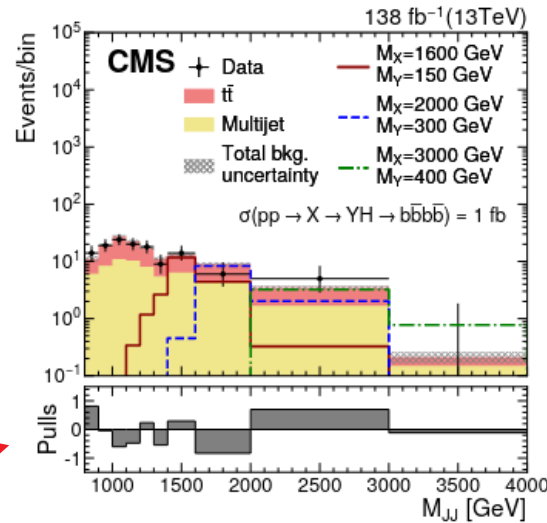
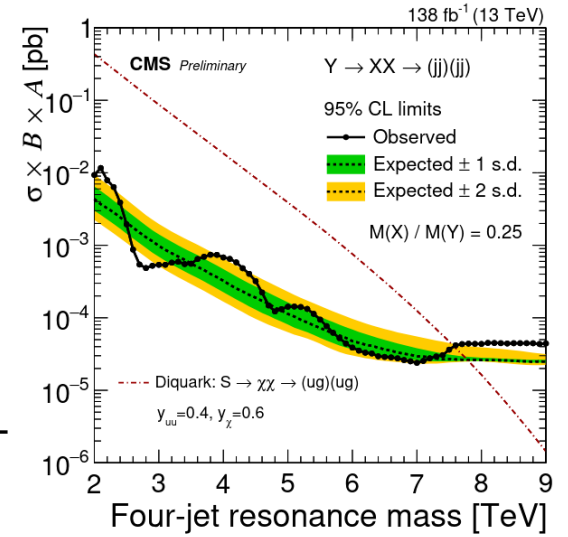
Complement DM searches using missing momentum and initial-state radiation

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 α values (average mass of the two dijets divided by the four-jet mass)



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

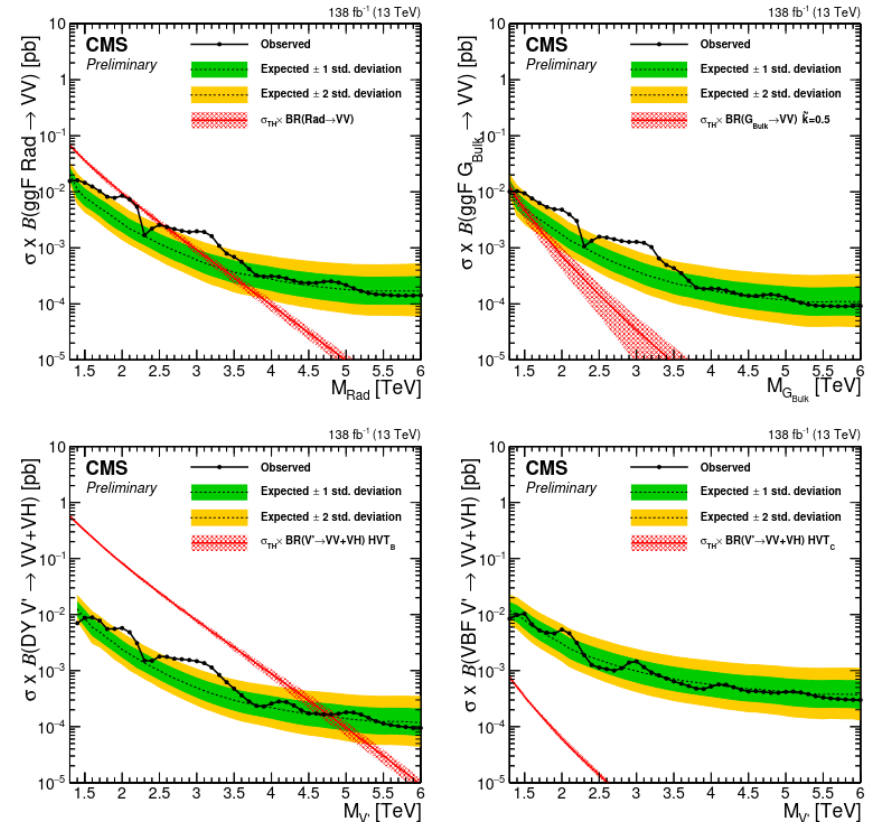
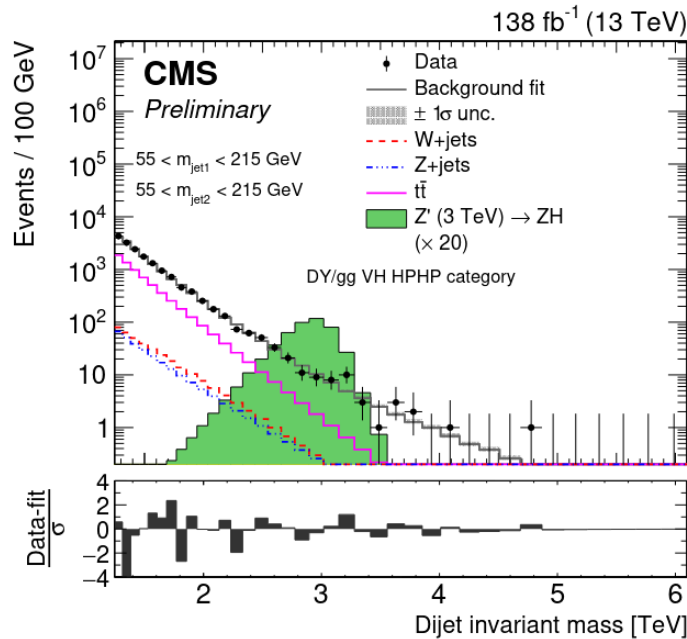
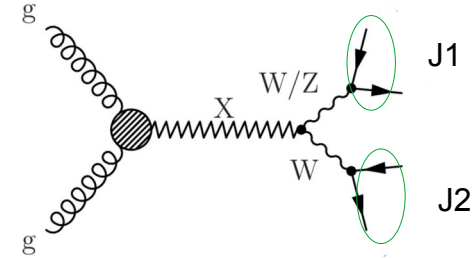


95% CL exclusions for M_X and M_Y

- $pp \rightarrow X$ (scalar) $\rightarrow YH \rightarrow bbb\bar{b}$

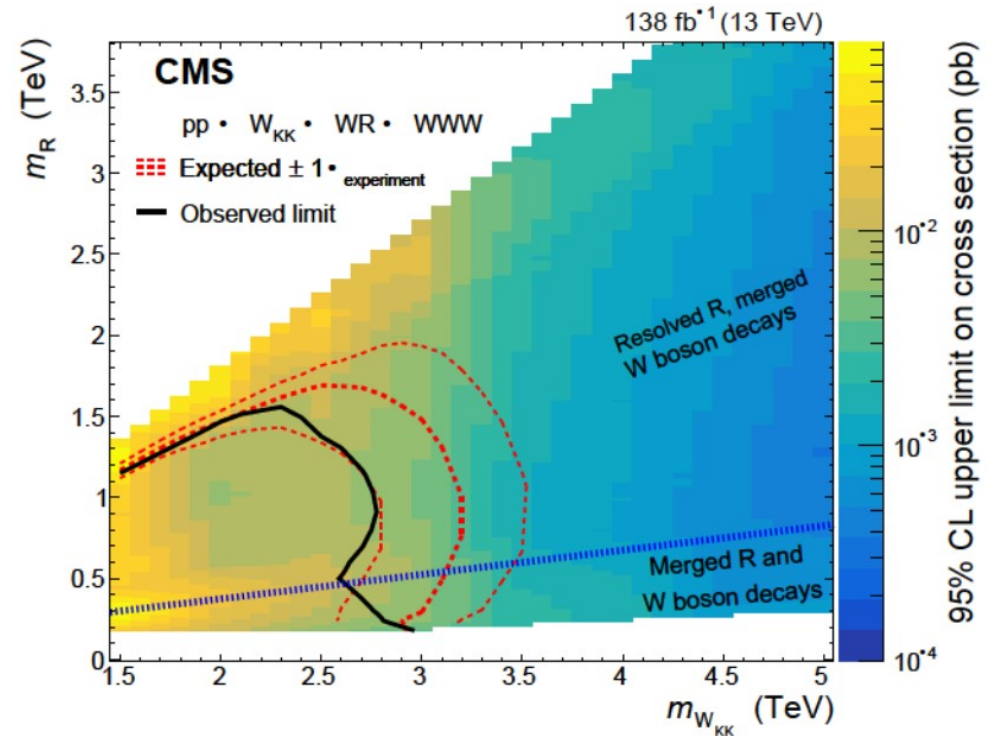
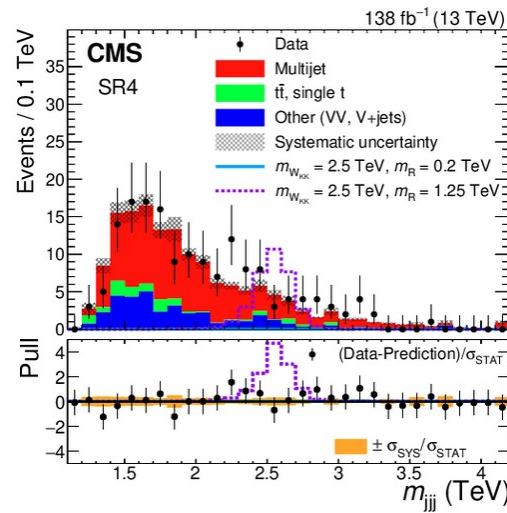
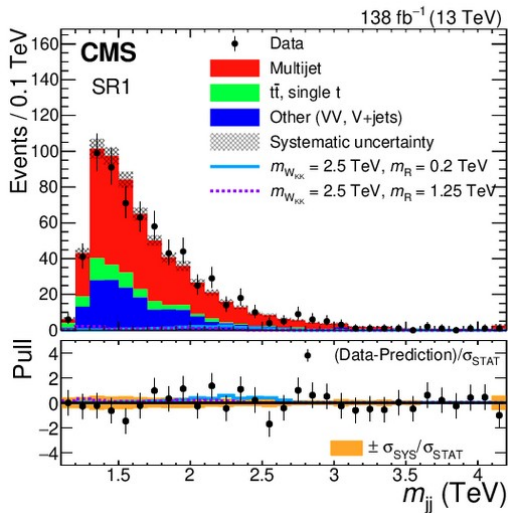
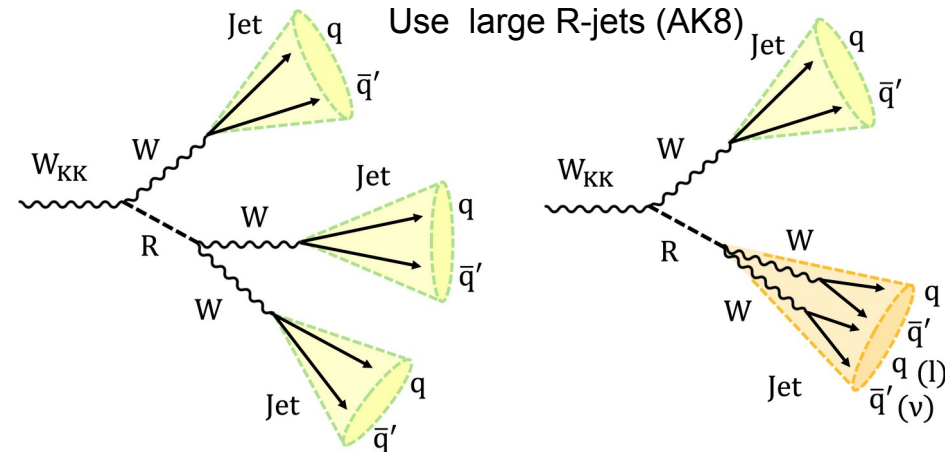
- Boosted regime: 2 large R-jets

- For heavy resonances, each W/Z/H decays to large R-jet (AK8)
- 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 deviation at $\sim 2\text{-}3 \text{ TeV}$ has $\sim 2.3 \sigma$ (global)
- Competitive limits for several BSM signals (including VBF mode)

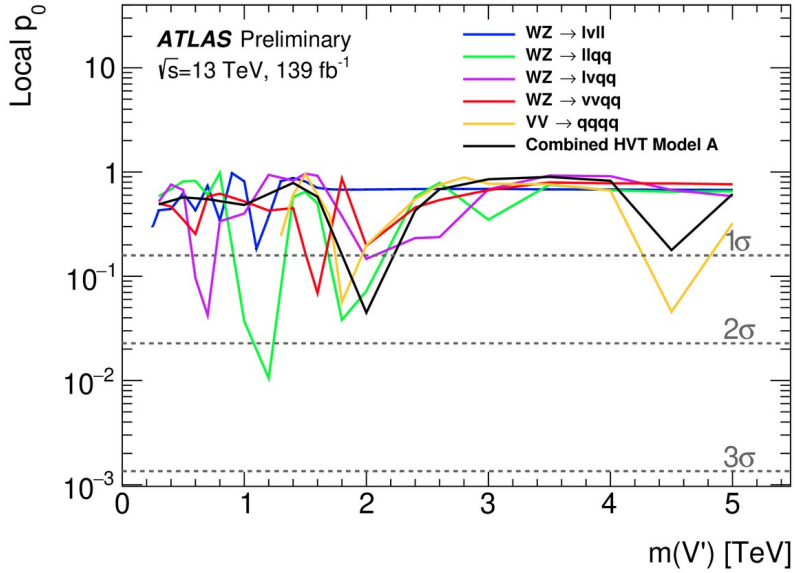
- Search for Kaluza–Klein excited vector boson resonances, $W_{KK} \rightarrow R W \rightarrow WWW$ (R is a scalar radion)
- No signal-like excess over the background



- 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'

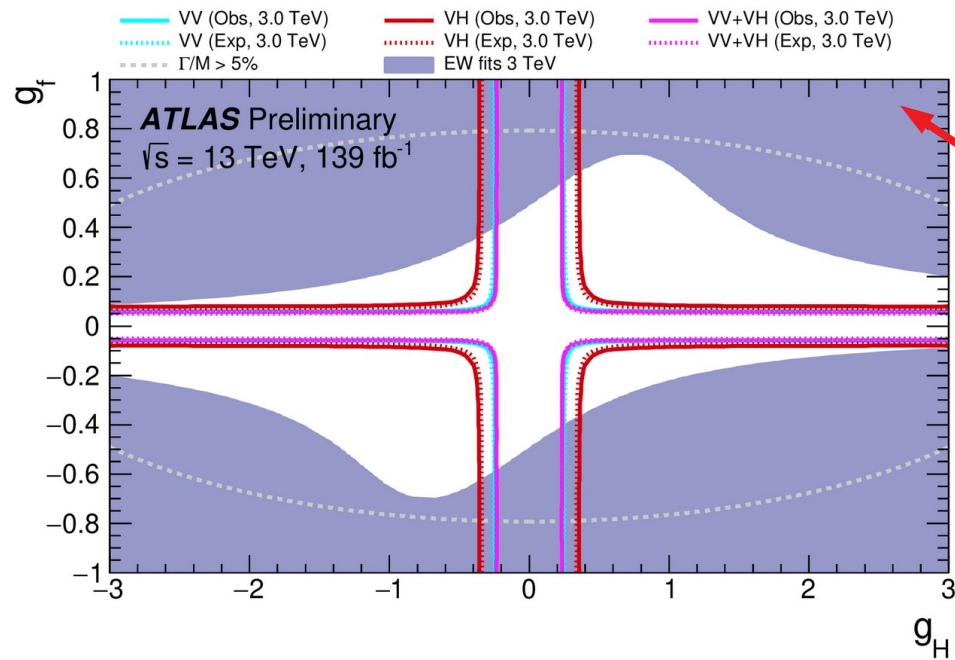
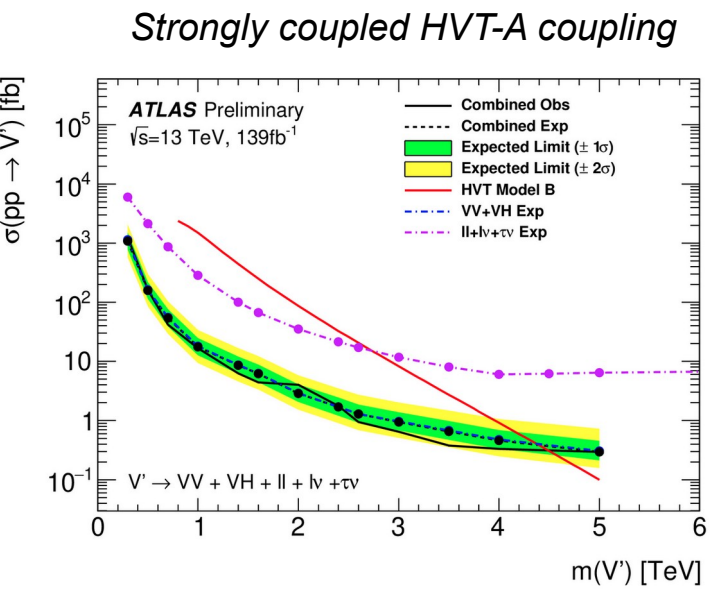
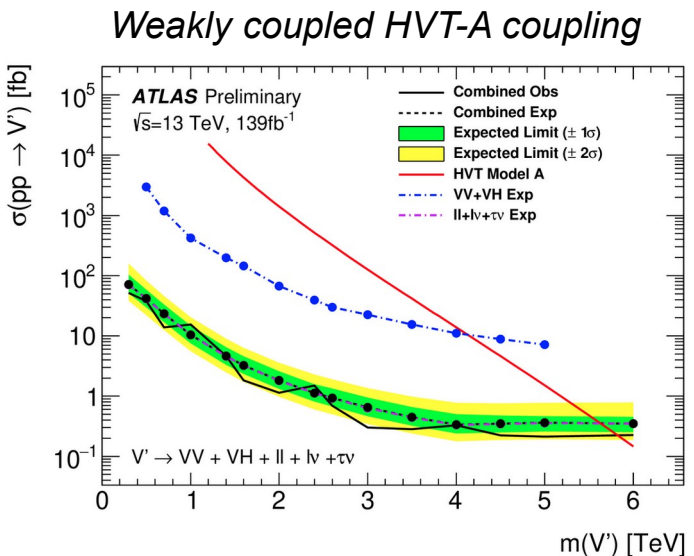
Analysis	leptons	$E_{T_{miss}}$	jets	b-tags	Discr.
$WW/WZ/ZZ \rightarrow qqqq$	0	Veto	$\geq 2J$	-	m_{VV}
$WZ/ZZ \rightarrow \nu\nu qq$	0	Yes	$\geq 1J$	0	m_{VV}
$WW/WZ \rightarrow \ell\nu qq$	1e, 1 μ	Yes	$\geq 2j, \geq 1J$	0, 1, 2	m_{VV}
$WZ/ZZ \rightarrow \ell\ell qq$	2e, 2 μ	-	$\geq 2j, \geq 1J$	0	m_{VV}
$WZ \rightarrow \ell\nu\ell\ell$	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



Constraints from EWK measurements

See other channels & masses in the original CONF note

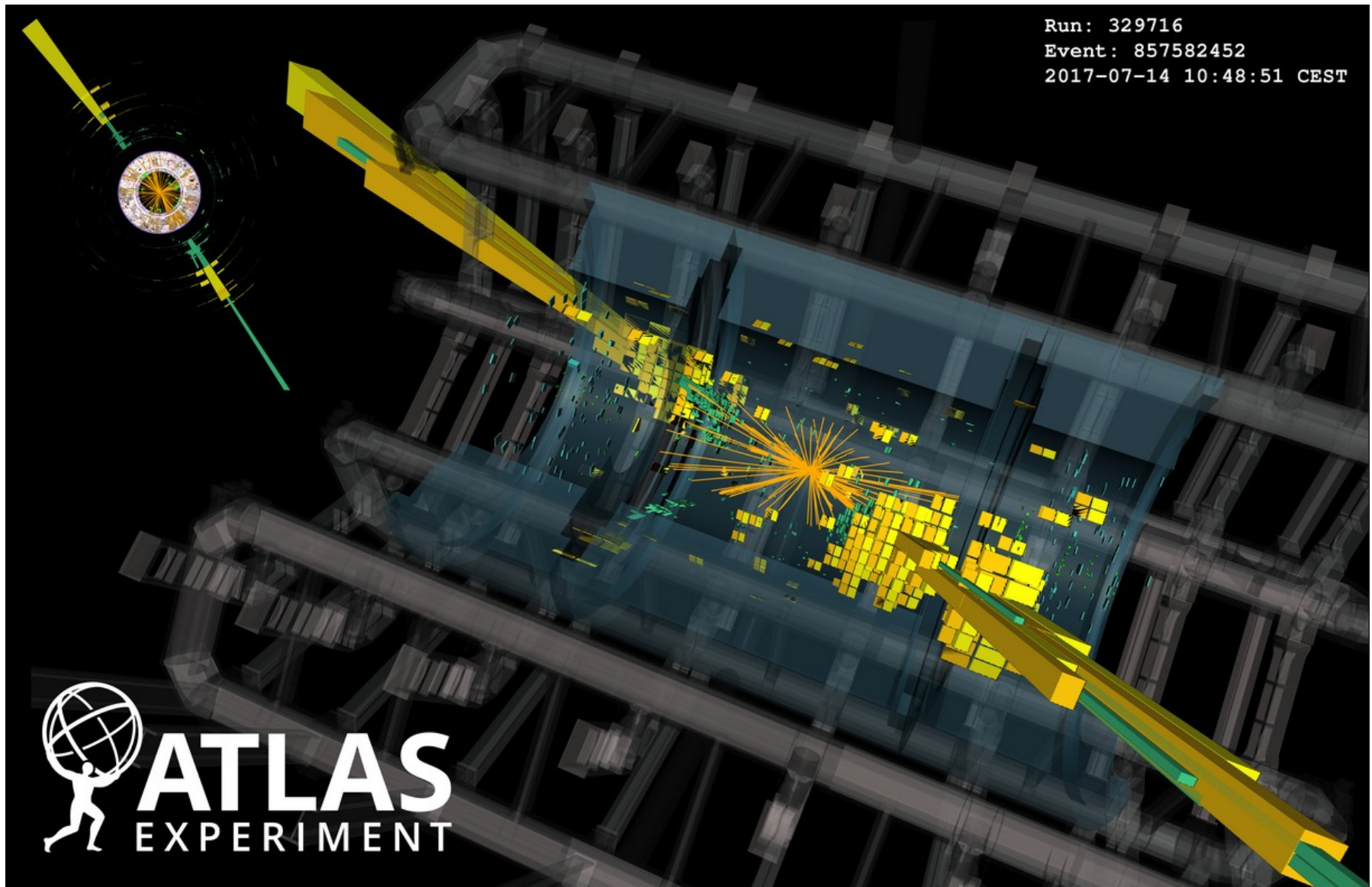
Typical exclusions for 3 TeV for $\{g_H, g_f\}$ for qq production mode

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

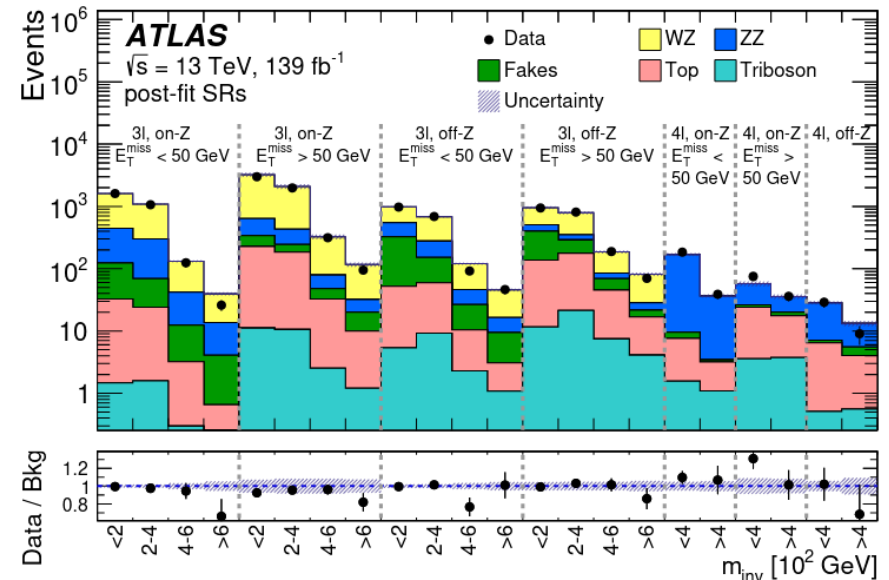
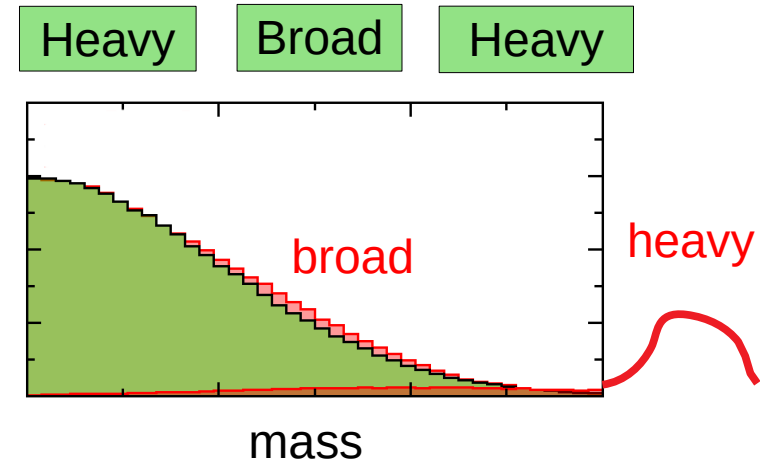
\rightarrow Can translate to ~ 1 TeV in mass reach for some channels

Backup



Non-resonant production

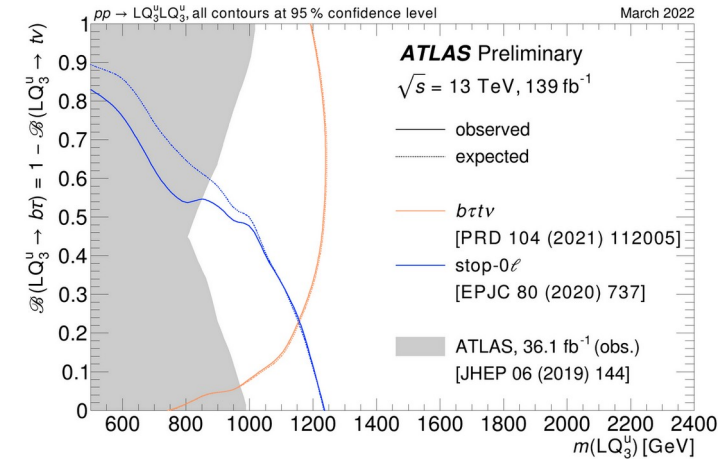
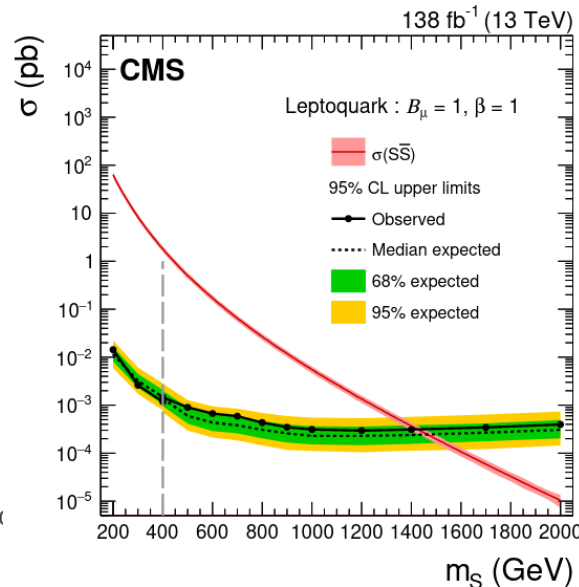
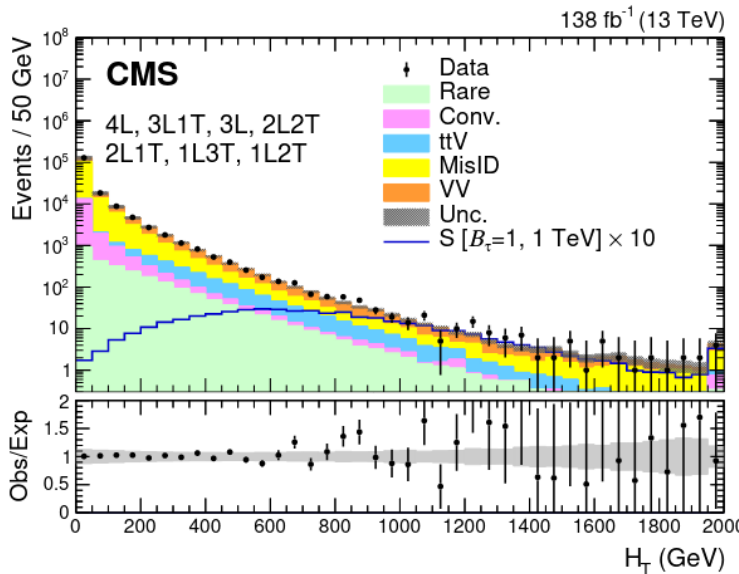
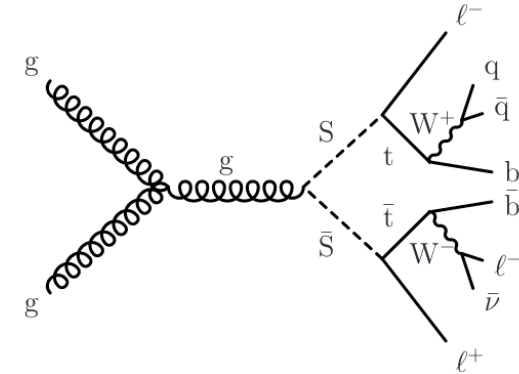
See M.Folgado & V.Sanz, Advances in High Energy Physics, Volume 2021, Article ID 2573471,



- ▶ 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