Searches for new phenomena with the ATLAS detector

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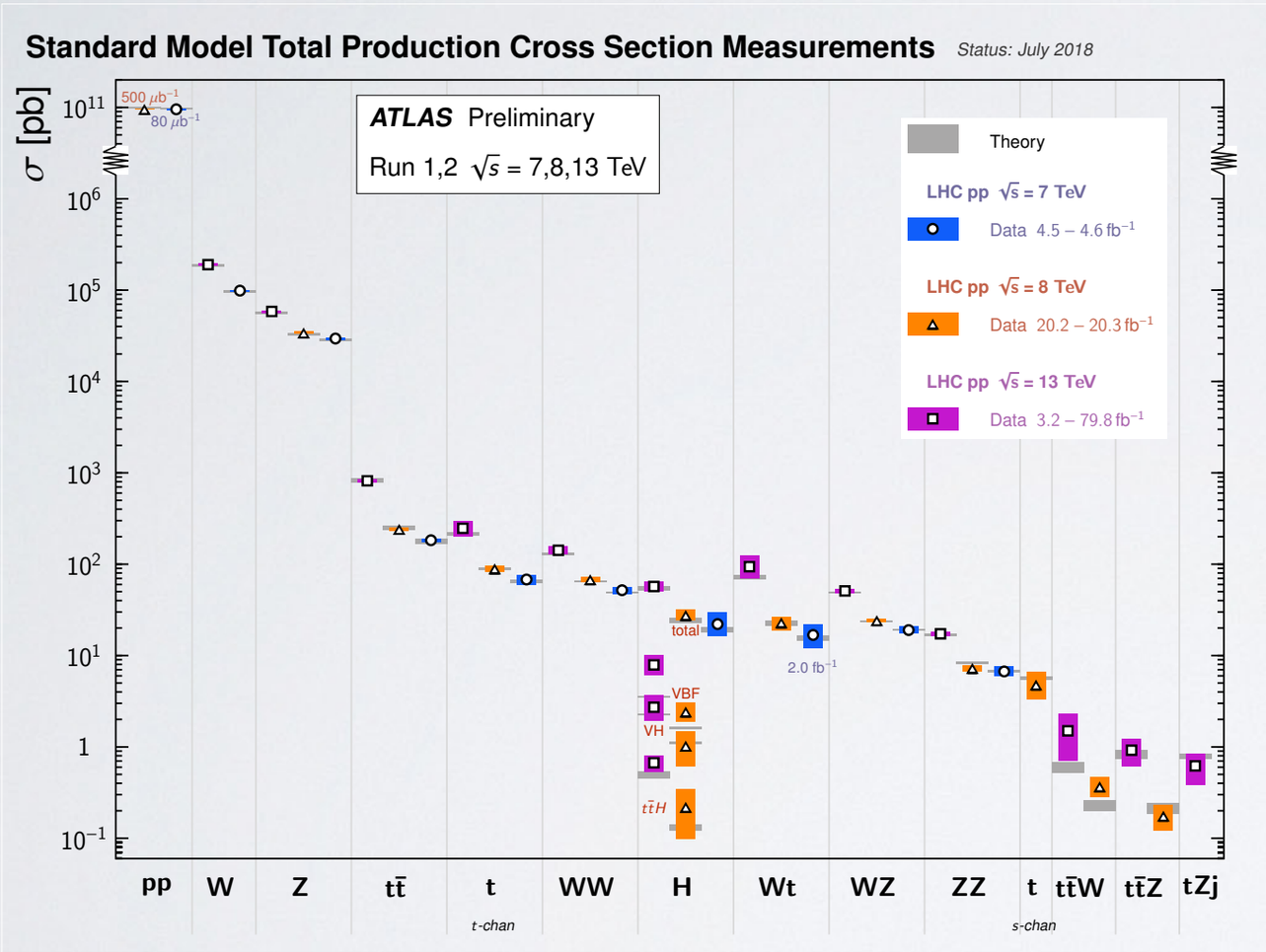
HEPMAD18 @Antananarivo — 7 September 2018

A Premise

After the observation of Higgs boson in 2012 at ATLAS and CMS experiments, all the elementary particles predicted by the Standard Model (SM) have been observed.



The SM total production cross-section measurements in the ATLAS experiment show high consistency with the theoretical expectations.

The SM works extremely well…but…

Phenomena not explained

- Gravity
- Dark Matter & Dark Energy
- Neutrino Mass
- …

Naturalness Questions

- The hierarchy problem
- The strong CP-problem
- …

Beyond the Standard Model Searches

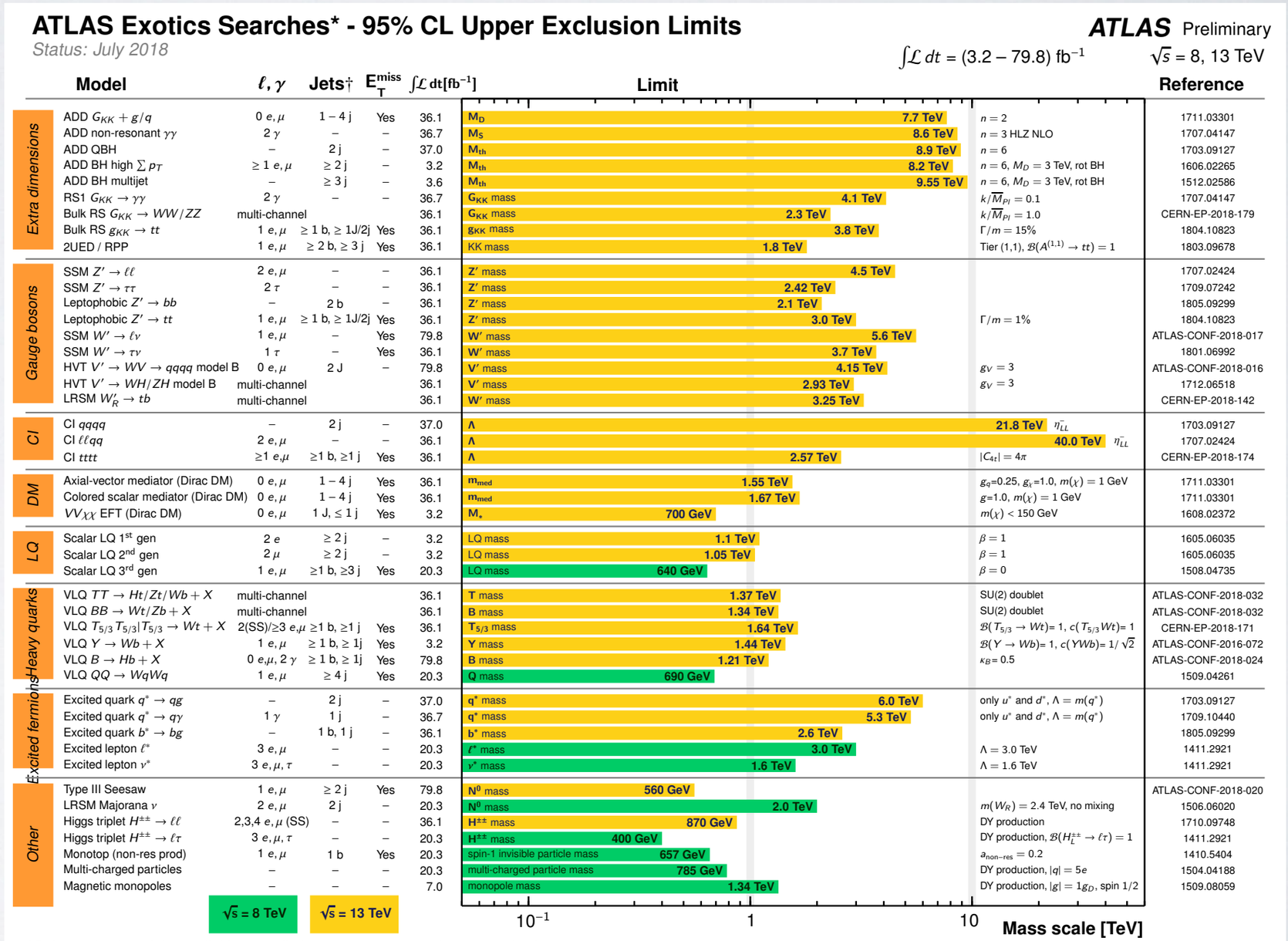
Many theories beyond the Standard Model (BSM), providing solutions to these problems, predict new phenomena accessible by the LHC

Exotic searches:

- Dark Matter
- Extended Gauge Groups
- Extra dimensions
- Vector like Quarks
- Contact Interaction
- Leptoquarks
- Excited fermions

…

* red: covered in this talk



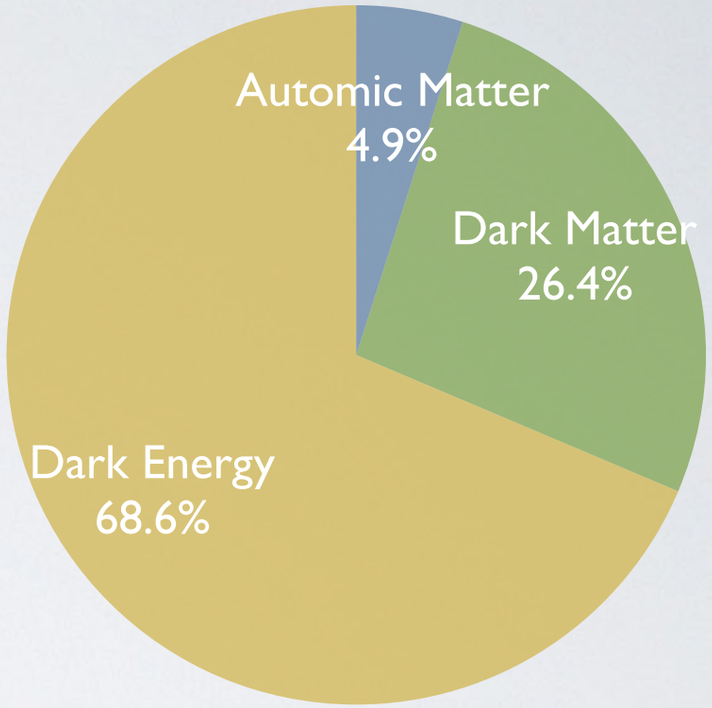
Dark Matter

A Mystery in the Universe

Dark Matter Searches

Evidences of Dark Matter (DM)

- galaxy rotation curves
- gravitational lensing
- cosmic microwave background
- …



The newest result (2018) from Plank gives out that 26.4% of our universe is dark matter arxiv:1807.06209

Searches

- Direct detection: the measurement of elastic scattering of DM with nuclei in a detector;
- Indirect detection: the detection of standard model (SM) particles produced in the annihilations or decays of DM in the universe;
- Searches in colliders: production of DM particles at colliders;

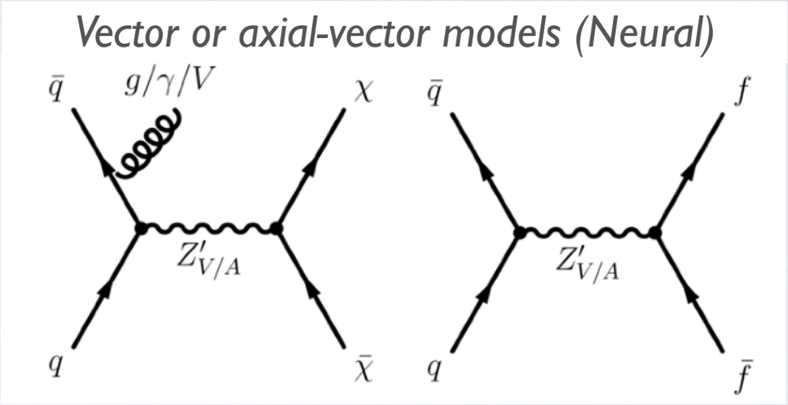
A weak-interaction massive particle (WIMP) is a compelling candidate of DM.

Signal Models Overview

ATLAS Paper EXOT 2017-032, DM & DE Summary

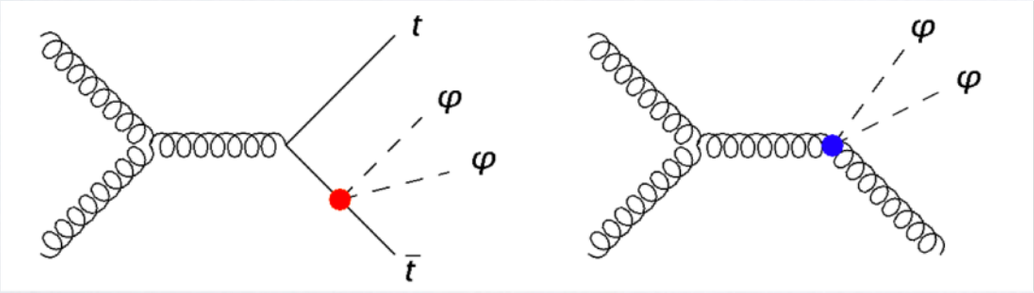
Simplified models — new particle(s) mediate(s) the interaction of DM with the SM particles

- dark sector is composed of a single particle
  - spin 1: vector or axial-vector DM models
  - spin 0: scalar or pseudo-scalar DM models

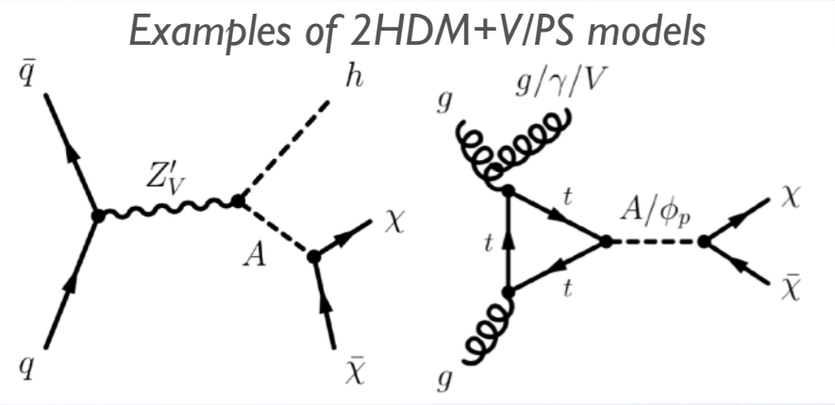


- dark sector is composed of an extended-Higgs sector plus an additional mediator
  - Two-Higgs-doublet models with a vector / pseudo-scalar mediator

- EFT models of scalar dark energy



Dark Energy diagrams in ttbar+MET and mono jet signatures

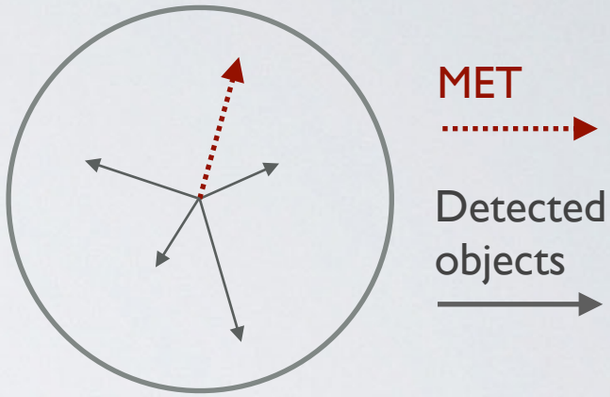


Other models like those can provide a viable WIMP DM candidate are not summarized here

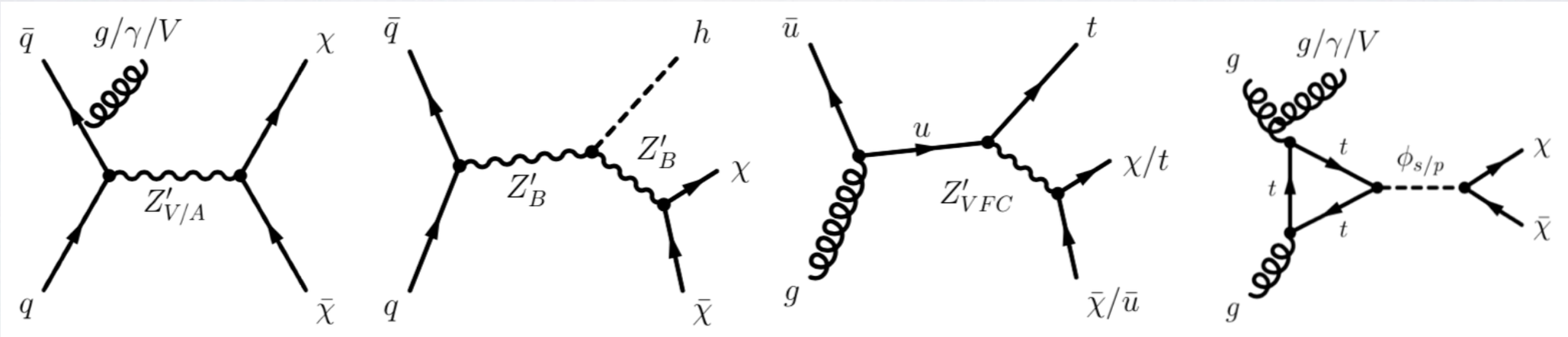
Searches for invisible final states

- If WIMPs are produced at the LHC, they are invisible to the detector.
  - Missing transfers momentum (MET)
- To tag the event and measure the recoiling MET
  - Additional particle(s) X produced in association with DM

➡ experimental final states: MET + X



ATLAS Paper EXOT 2017-032



Example diagrams for invisible final states

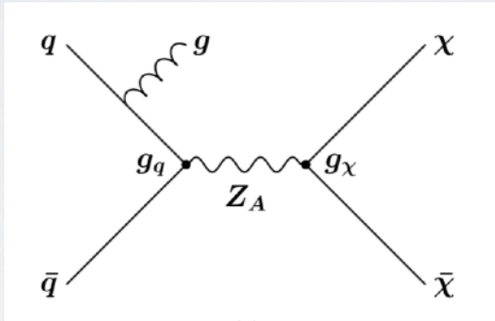
Analyses: MET + jet / γ / $V(qq)$ / $Z(ll)$ / $h(bb)$ / $h(\gamma\gamma)$ / top

mono jet + MET

arxiv:1711.03301

➡ Signal Model(s)

- 4 free parameters: WIMP mass; mediator mass; coupling of the mediator to quarks (g_q); coupling to WIMPs (g_x);



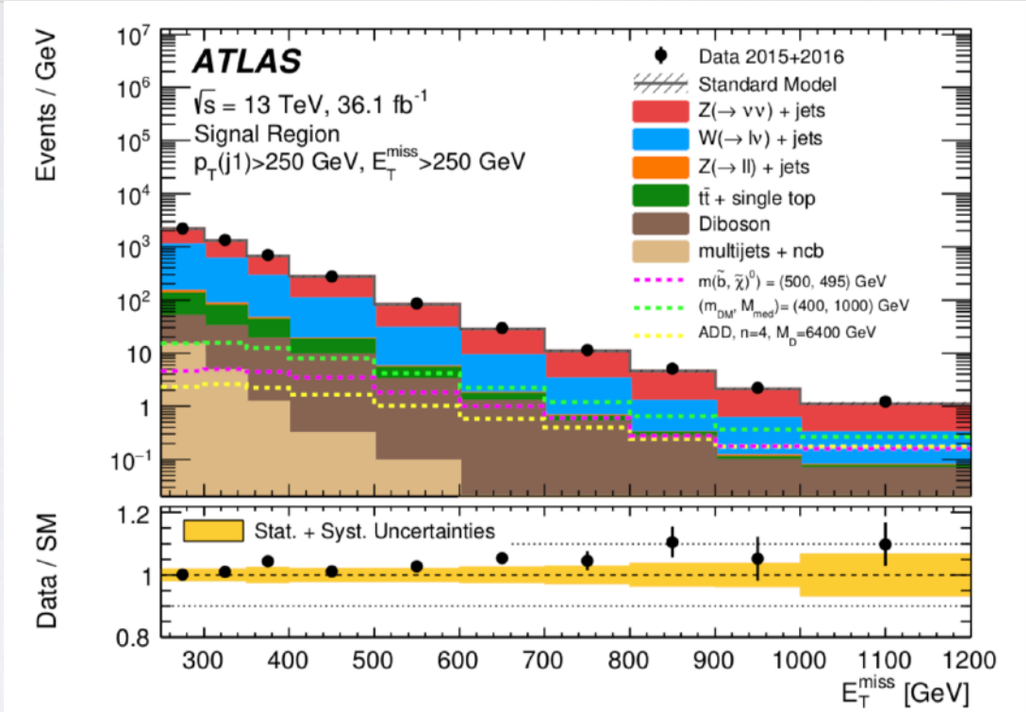
➡ Event Selection

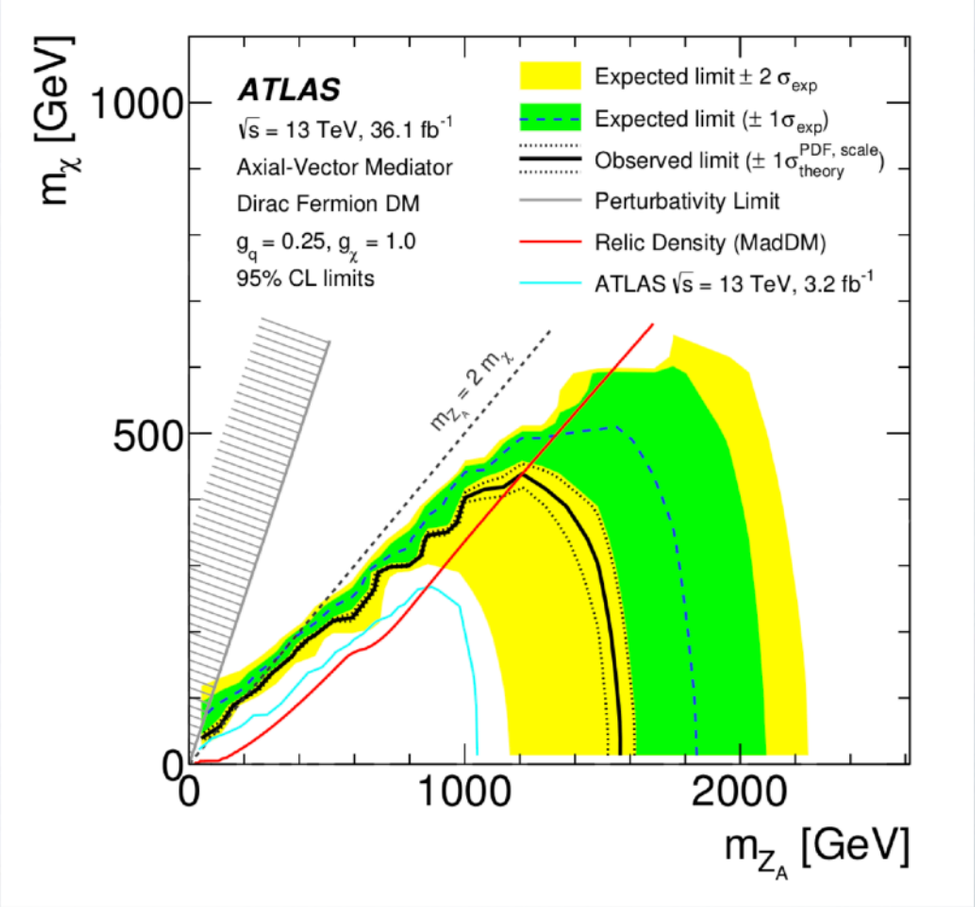
- a large MET (MET > 250 GeV)
- jets (leading jet pT > 250 GeV, …)
- separation between MET and jets (Δϕ(MET, jet) > 0.4), suppress multi-jet background

➡ Background estimation

- W+jets, Z+jets, top-quark-related background are constrained using MC samples in control regions
- multi-jet background , non-collision background are also estimated, small contribution / negligible
- background fit — constrain the normalization of dominant background, reduce the uncertainties

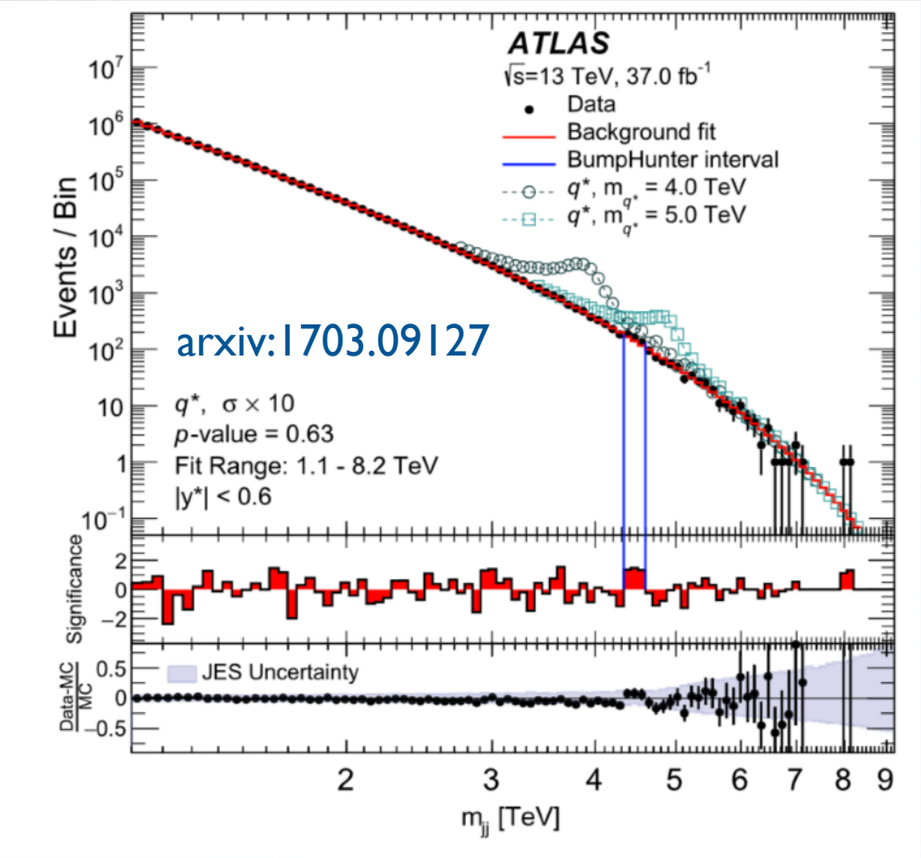
➡ Systematic Uncertainties …





Searches for visible final states

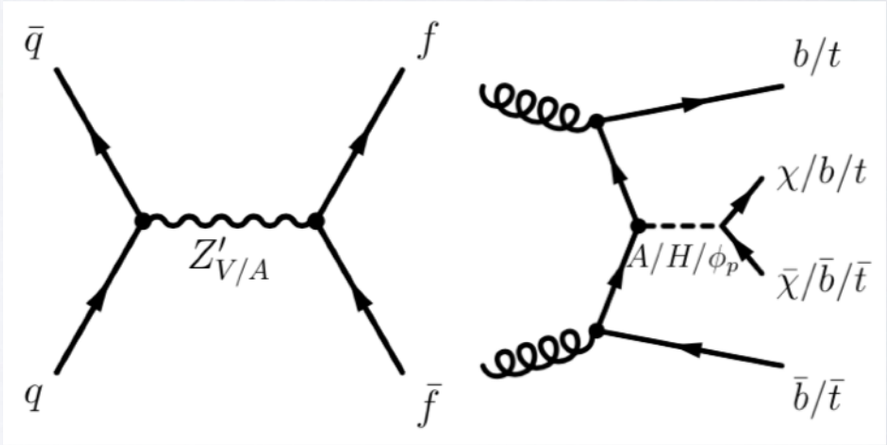
- The mediators couple to SM particles — interpreting the DM models in resonance searches is also interesting



Dijet background estimated by the falling m(jj) distribution. A sliding-window fitting technique is used.

The visible final states searches

- Dijet: high mass resonance search, m(jj) > 1.1 TeV
- Trigger-level dijet analysis (TLA): using only trigger level jets to reach lower mjj
- Boosted dijet + ISR analysis: light resonances boosted via recoil from high-pT ISR photon or jet
- Di-bjet
- Di-lepton
- ttbar resonance
- 4 top

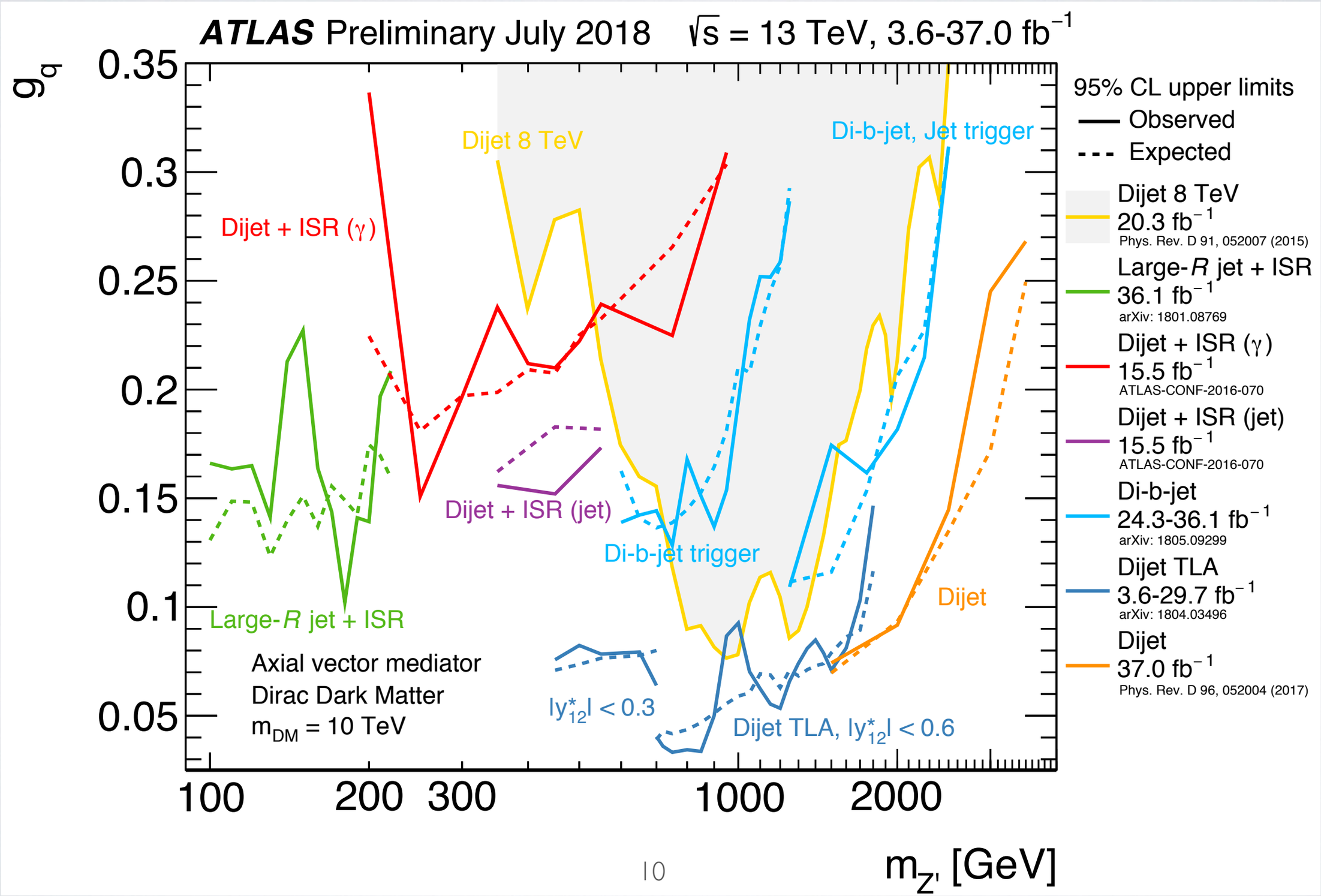


Example diagrams for visible final states

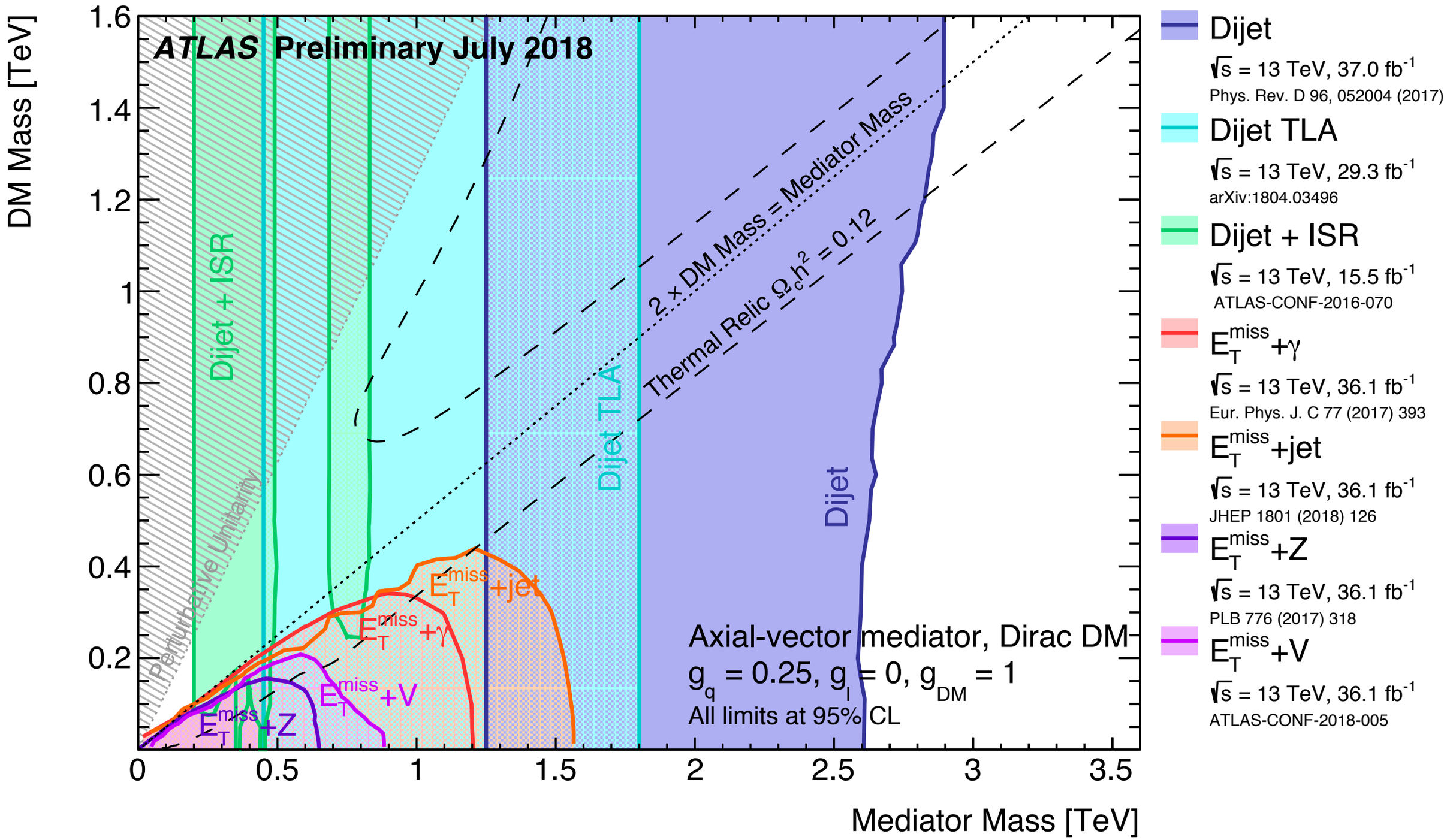
ATLAS Paper EXOT 2017-032

The Complementarity of Dijet Searches

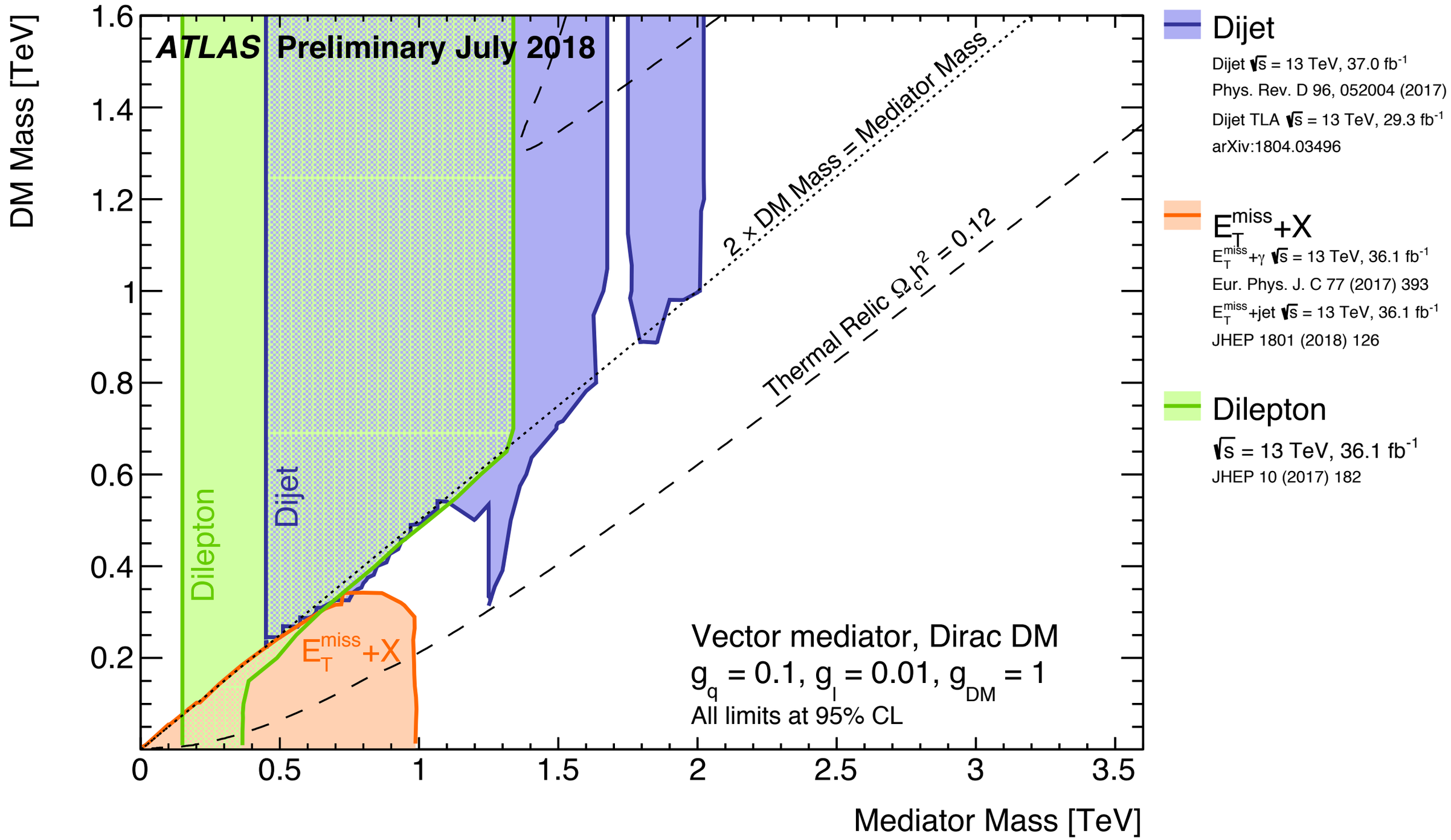
Bounds in the Coupling-Mediator plane



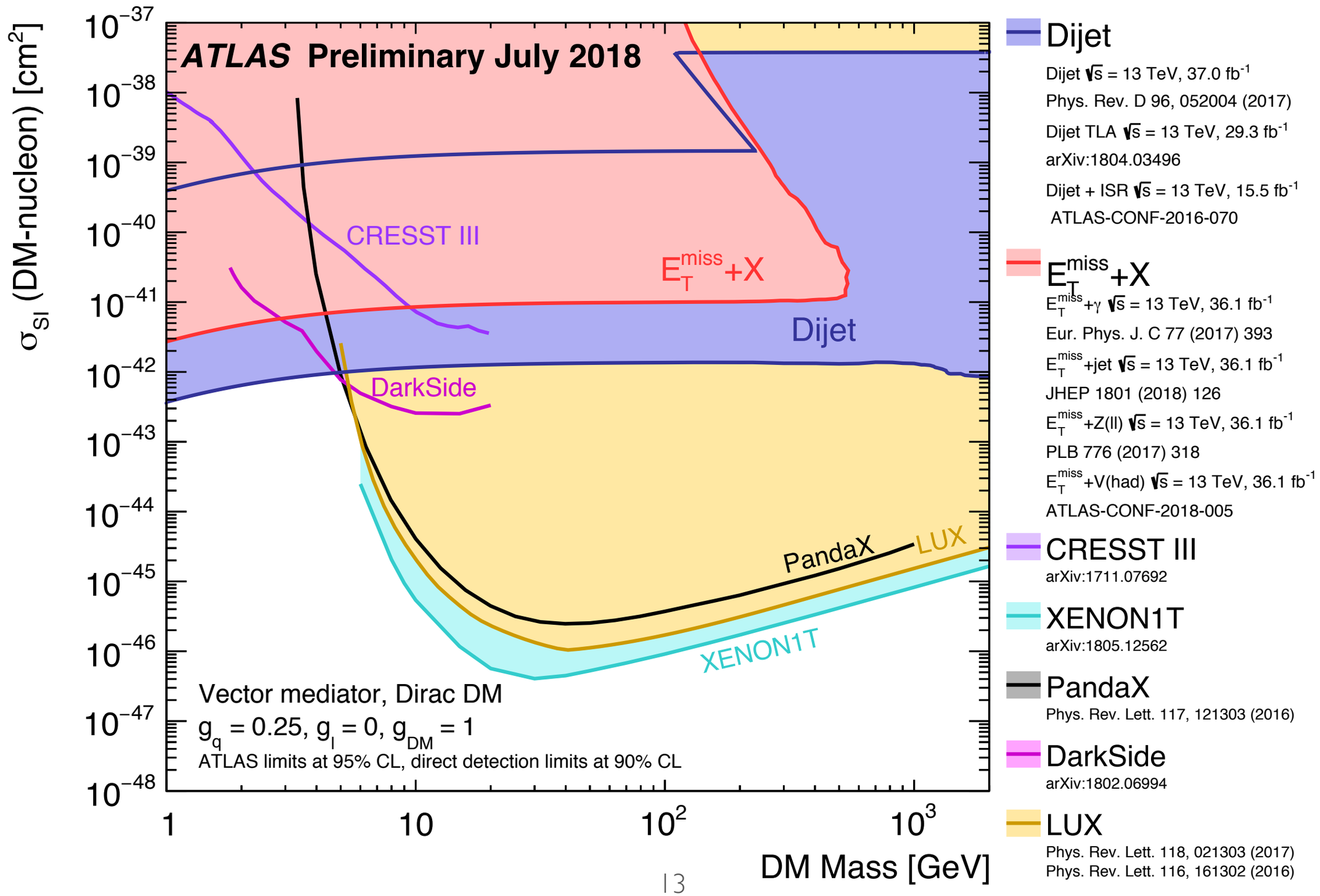
Axial-Vector Mediator g(q) = 0.25, g(l) = 0, g(DM) = 1



Vector Mediator g(q) = 0.1, g(l) = 0.01, g(DM) = 1



Compared with Direct Detection (Model Dependent)



Extended Gauge Groups

Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z′ mass	4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z′ mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z′ mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	$\geq$ 1 b, $\geq$ 1J/2j	Yes	36.1	Z′ mass	3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	W′ mass	5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W′ mass	3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	79.8	V′ mass	4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V′ mass	2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W′ mass	3.25 TeV		CERN-EP-2018-142

arxiv:1805.09299

$Z' \rightarrow$ bb in Di-bjets Searches

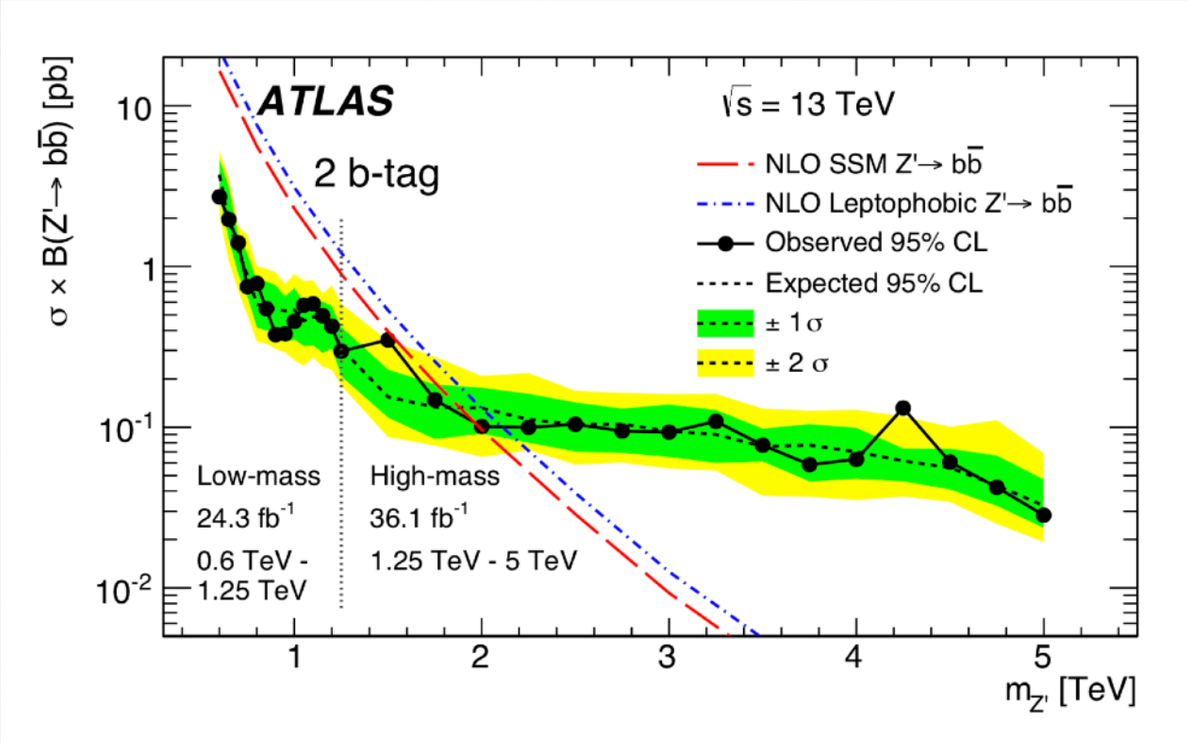
- The sequential standard model (SSM)

  the Z ′ boson has the same couplings to SM fermions as the SM Z boson

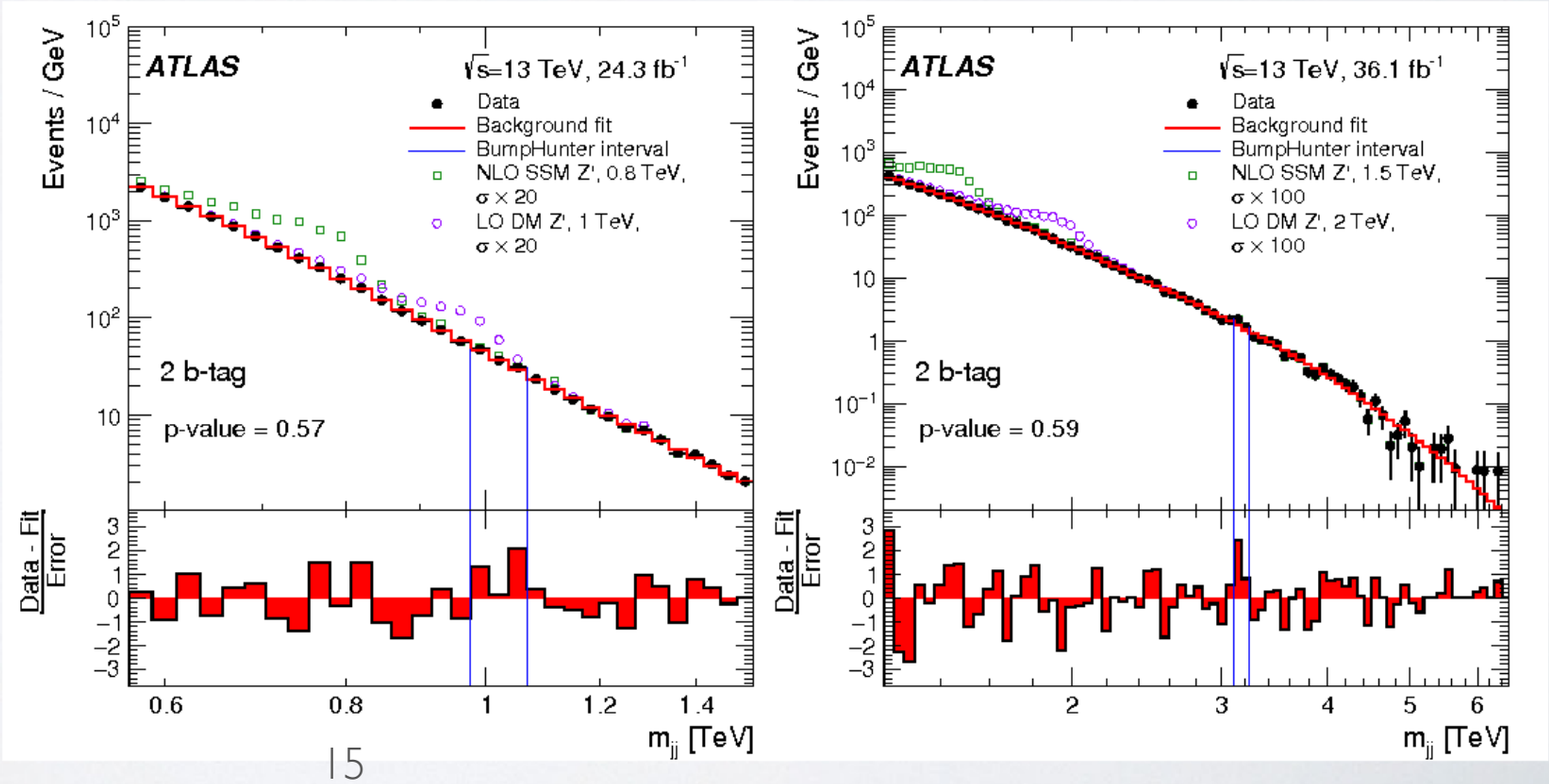
- The leptophobic Z′ model

  having vanishing couplings to leptons

- A simplified dark matter model with Z' axial-vector mediator



Di-bjet background estimated by the falling m(jj) distribution.
A sliding-window fitting technique is used.



arxiv:1804.10823

$Z' \rightarrow$ ttbar in Top Quark Pair Searches

- A leptophobic Z′ model

  Topcolor-assisted-technicolor (TC2)

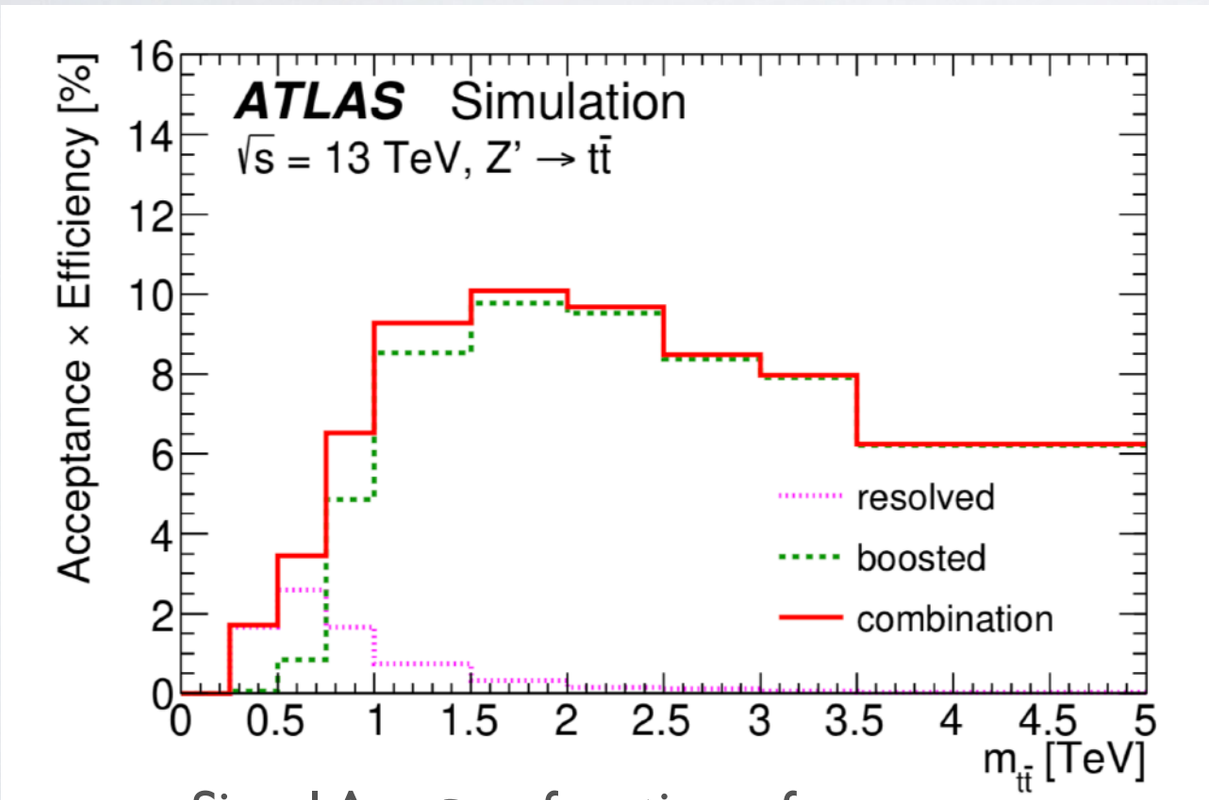
  only couples to first- and third-generation quarks

- Simplified dark matter models with Z' vector/axial-vector mediator

Considering the leptons-plus-jets topology

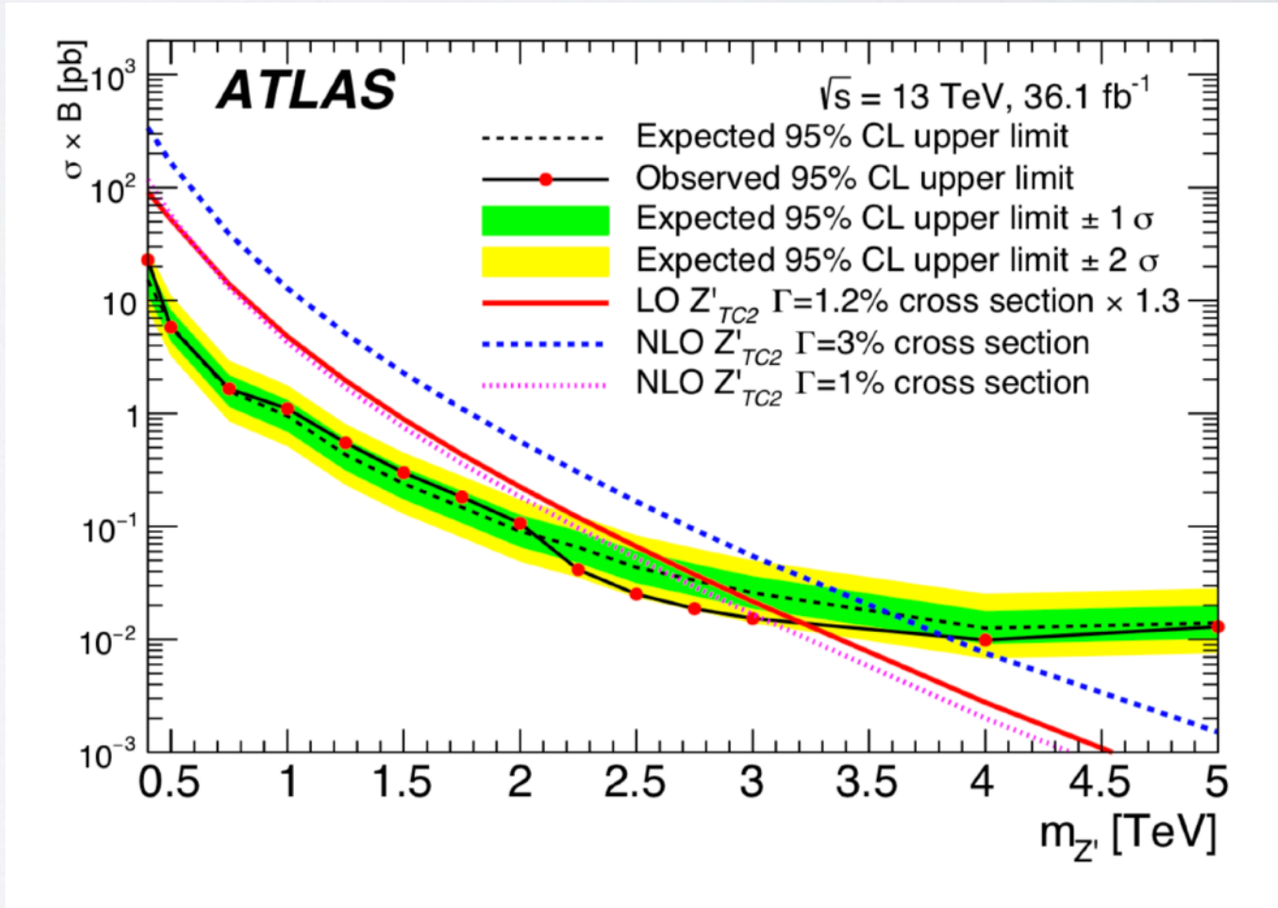
- $t \rightarrow Wb$
- $W \rightarrow e\nu/\mu\nu$ or $W \rightarrow \tau\nu$ if the τ decays leptonically

  the other W boson decays into quarks
- ~30% of ttbar events decays in this way

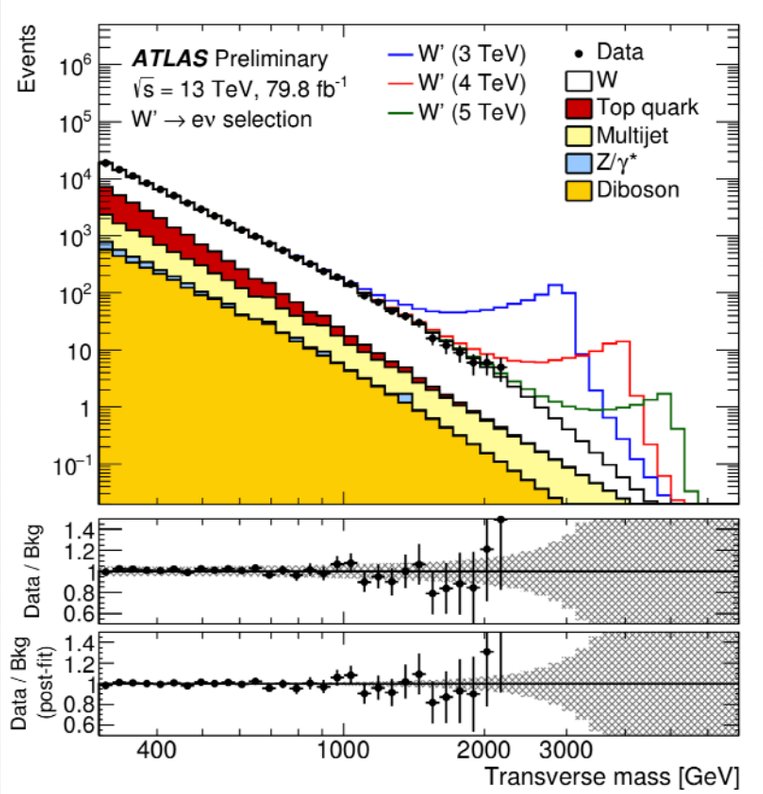


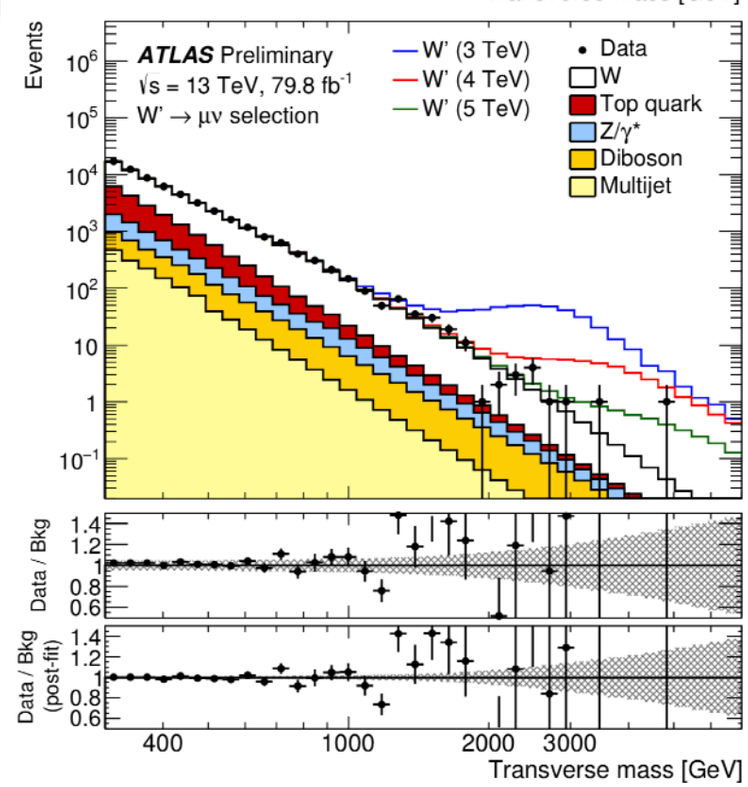
Signal A x ϵ as function of m_{ttbar}

(m_{ttbar} computed before parton radiation)

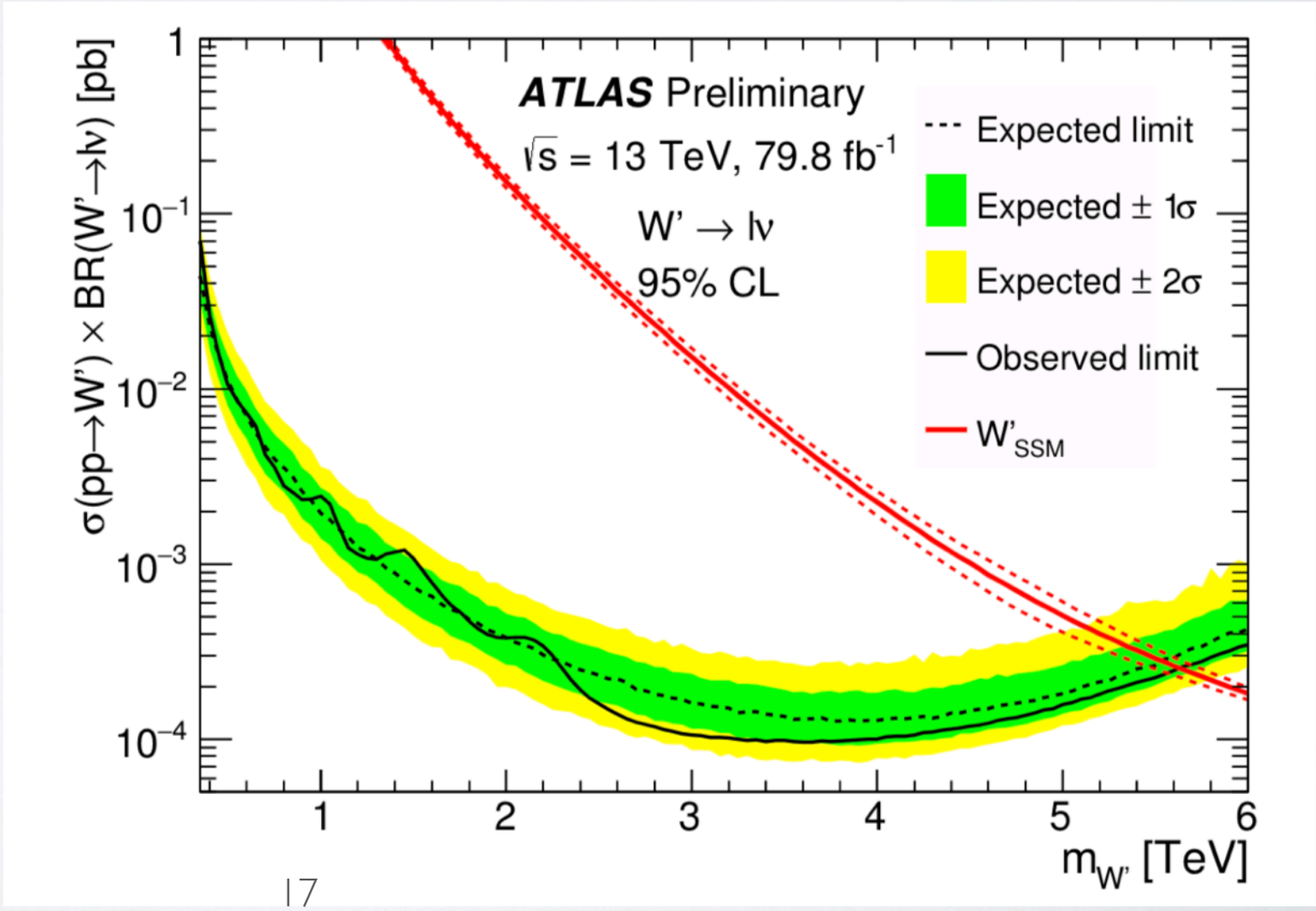


$W' \to \ell \nu$ ATLAS-CONF-2018-017





- Search for W ′ decaying into a lepton (electron /muon) and MET
- The sequential standard model (SSM)
  the W ′ boson has the same couplings to SM fermions as the SM W boson
- using 2015+2016+2017 data (79.8 fb^{-1} in total)



Extra Dimensions

Several models with extra-dimension(s) provide solutions to the hierarchy problem

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2\ \gamma$	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \rightarrow tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	1803.09678

Large Extra Dimension Model

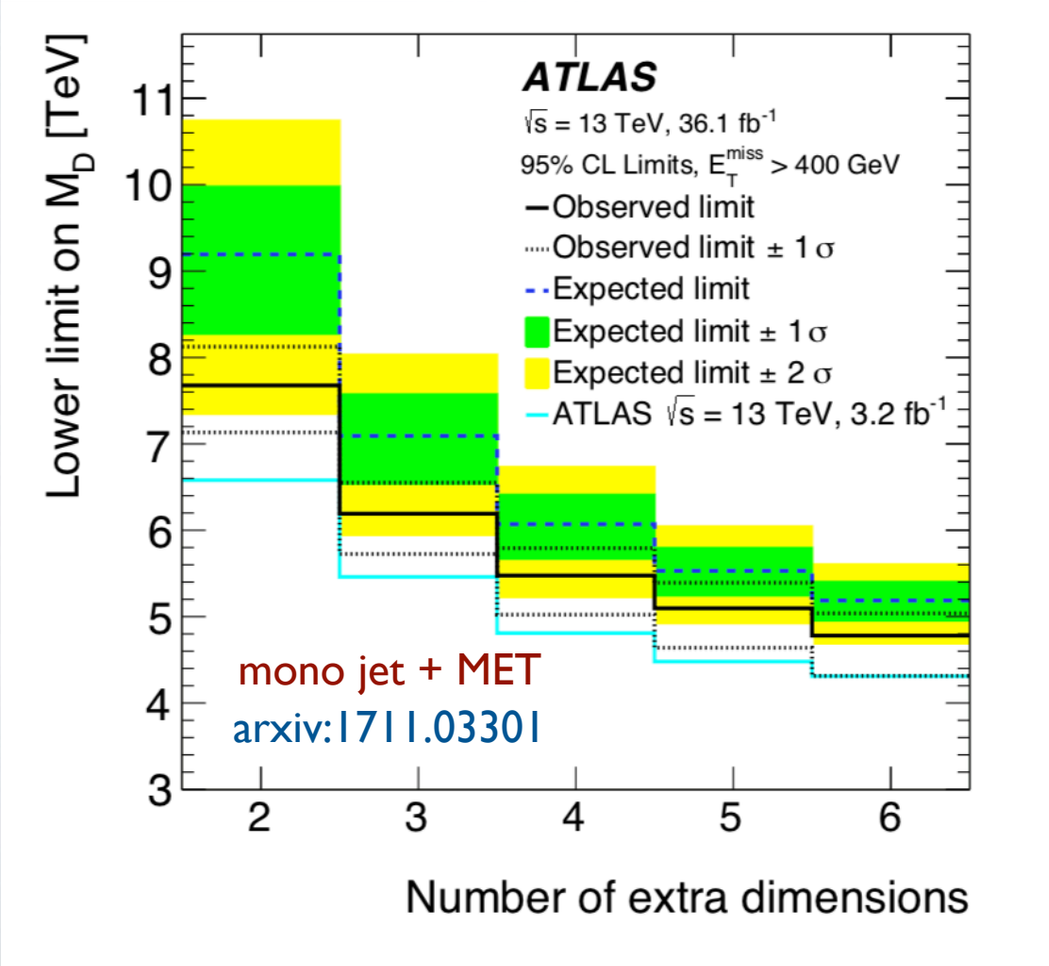
- Large extra dimension model (ADD model) — product spacetime

With n extra spatial dimensions of size R, the plank scale in 4+n dimensions given by,

$M_{Pl} \sim M_D^{2+n} R^n$ where M_D is the fundamental scale

e.g. with 2 extra dimensions whose size is 10^{16} TeV^{-1} (~1mm scale), M_D is at TeV scale

large compared with the Plank scale (10^{-35} m)



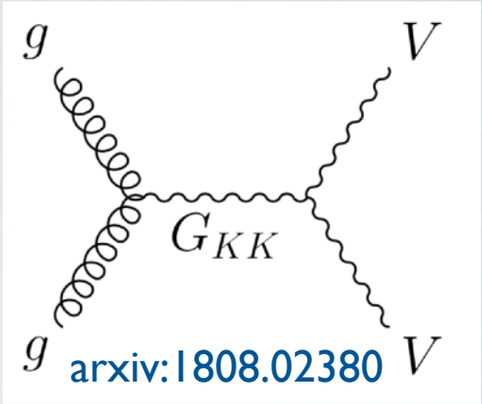
Lower Limits of M_D from mono jet + MET analysis

Randall-Sundrum Models

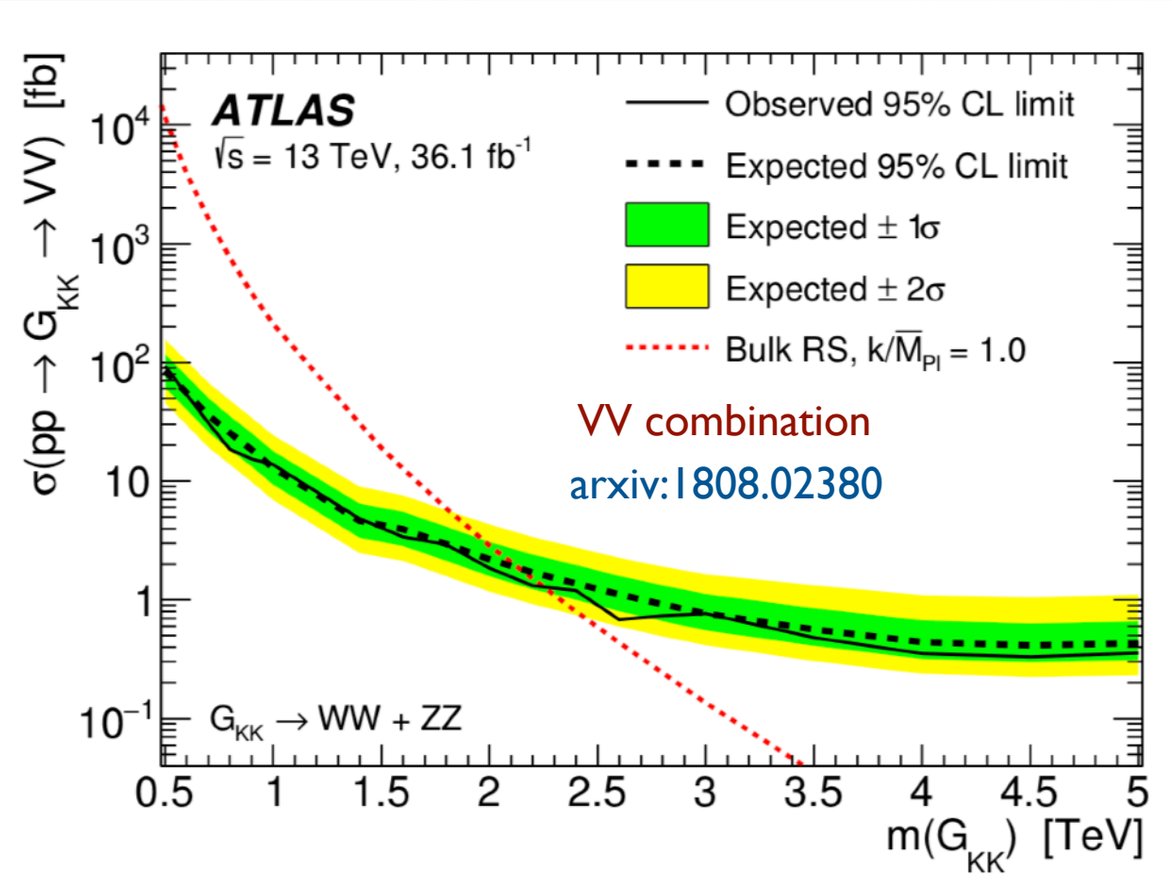
A warped external dimension in which

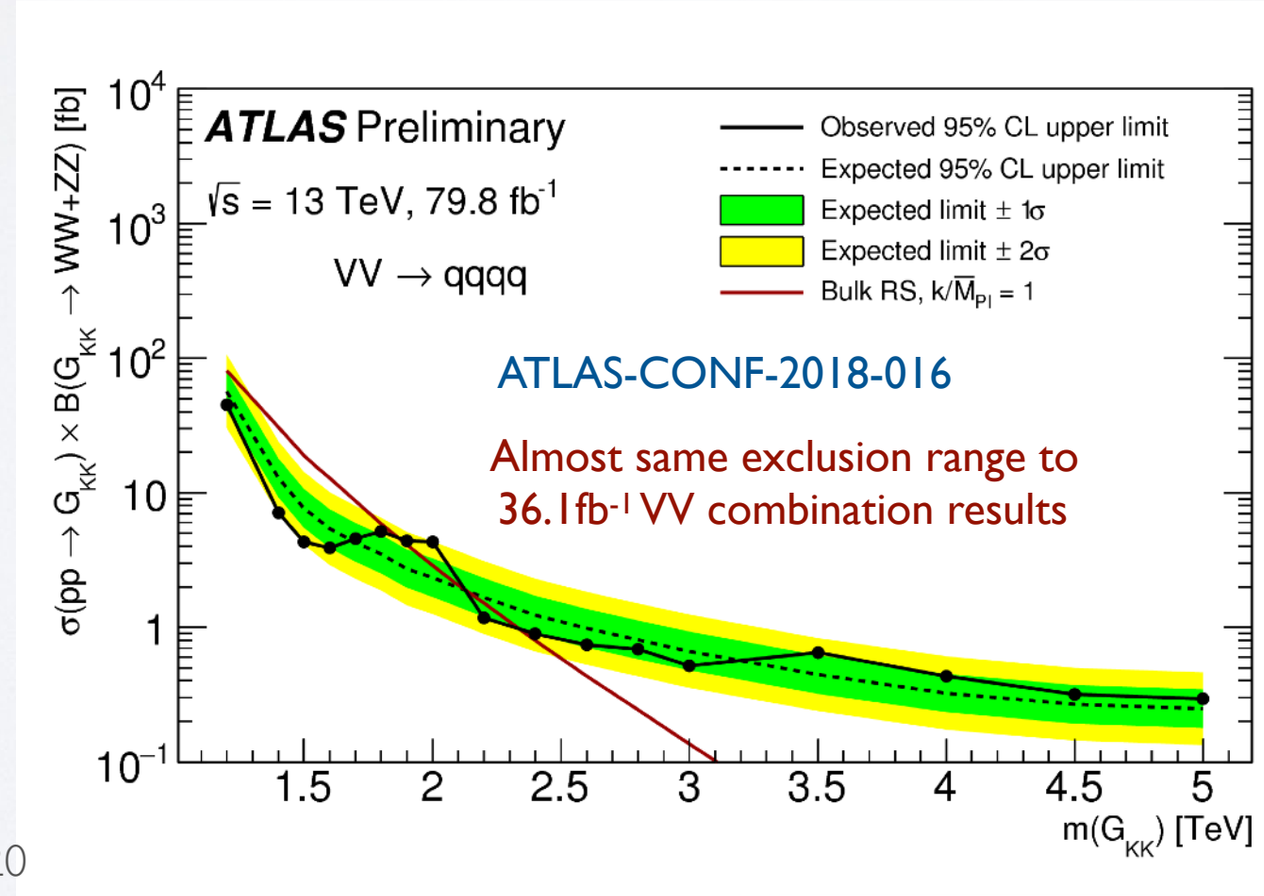
- only gravity propagates — RS1 scenario
- both gravity and all SM fields propagate — bulk RS scenario

Mass term suppressed exponentially, without introducing new hierarchy problem



❖ Limits on G_{kk} (Kaluza-Klein excitations of gravitons), from VV resonance searches where V is W/Z boson, VV combination includes 5 leptonic and hadronic final states from llll to qqqq





Vector Like Quarks

predicted by many BSM models aimed at solving the hierarchy problem

Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3}T_{5/3} \mid T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	1 e,μ	≥ 1 b, ≥ 1j	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e,μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261

Vector-like Quarks (VLQ)

Vector-like quarks are predicted by many BSM models aimed at solving the hierarchy problem, e.g. little Higgs, Composite Higgs

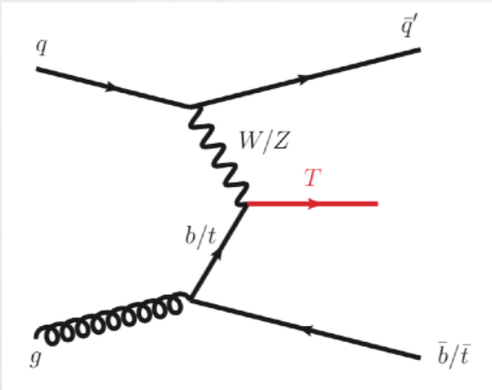
- color-triplet spin-1/2 fermions
- left- and right-hand particles have same quantum numbers
- could be singlet, doublet or triplet of T, B, X or Y
  - T (2/3e), B(-1/3e), X(5/3e), Y(-4/3e)
  - T, B, (X,T), (T, B), (B,Y), (X, T, B), (T, B, Y)
- couples to preferentially to third-generation quarks

  assuming: couples to SM particles only (No T→WB)

Decay

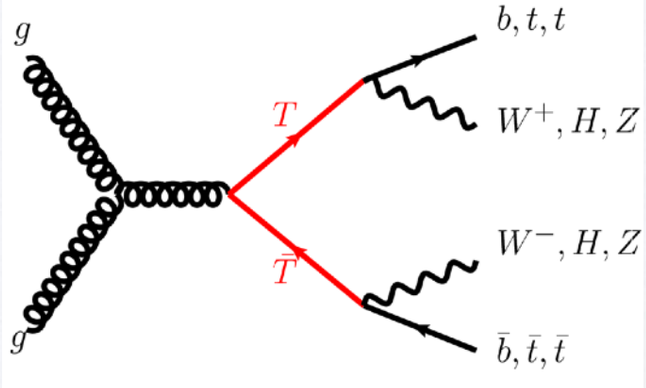
$$T \to Wb, Zt, Ht$$
$$B \to Wt, Zb, Hb$$

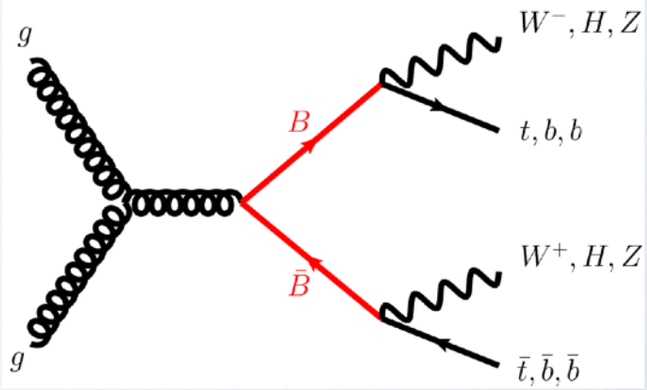
Single Production



CERN-EP-2018-171

Pair Production





arxiv:1808.02343

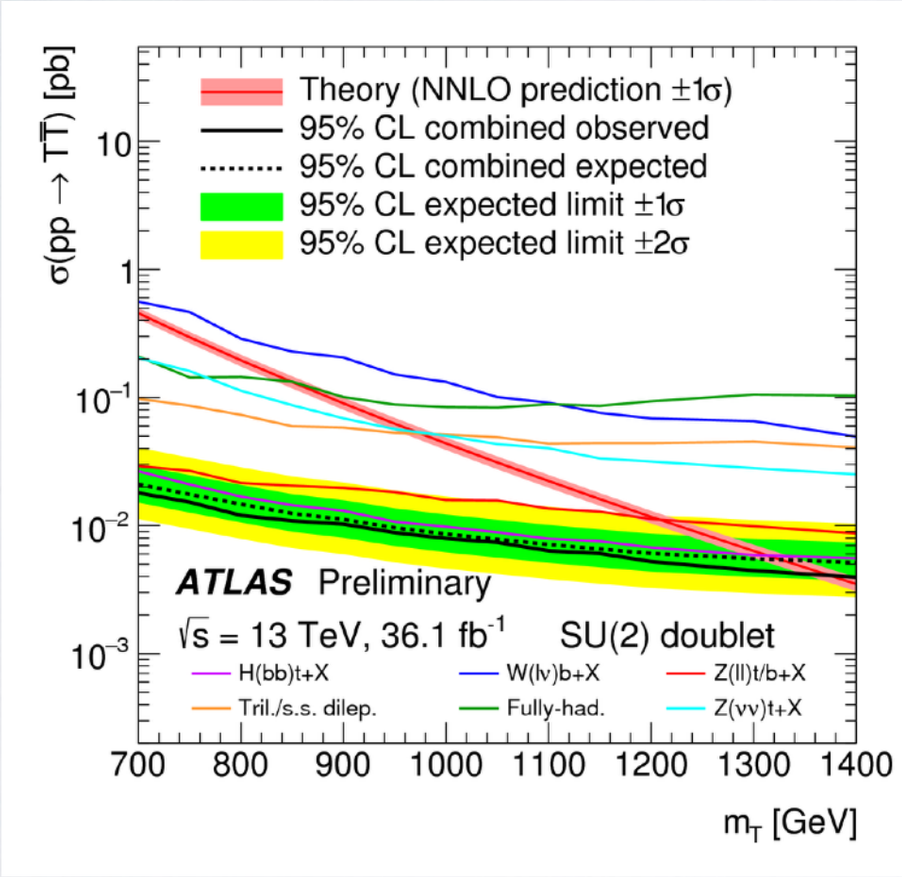
A Combination of ATLAS pair-product VLQ searches

arxiv:1808.02343

- The focus was on pair production in the past years
  - ✓ strong production (larger cross-section)
  - ✓ model independence

Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t + X$	$HtH\bar{t}$	-
$W(\ell\nu)b + X$	$WbW\bar{b}$	-
$W(\ell\nu)t + X$	-	$WtW\bar{t}$
$Z(\nu\nu)t + X$	$ZtZ\bar{t}$	-
$Z(\ell\ell)t/b + X$	$ZtZ\bar{t}$	$ZbZ\bar{b}$
tril./s.s. dilepton	$HtH\bar{t}$	$WtW\bar{t}$
fully-hadronic	$HtH\bar{t}$	$HbH\bar{b}$

Strategy for pair-production is to target different final states with optimized analyses



Lower Mass Limits (TeV)				
singlet T	doublet T	singlet B	B in (T, B)	B in (B,Y)
1.31	1.37	1.22	1.37	1.14

Mass limits of doublet T, where Ht+X limits are the strongest (situation would change with different branch ratio, 2D plots in next page)

**T Quark branching ratio is identical in (X,T) and (T, B), no discrimination made in results.*

Model Independent Lower Mass Limits

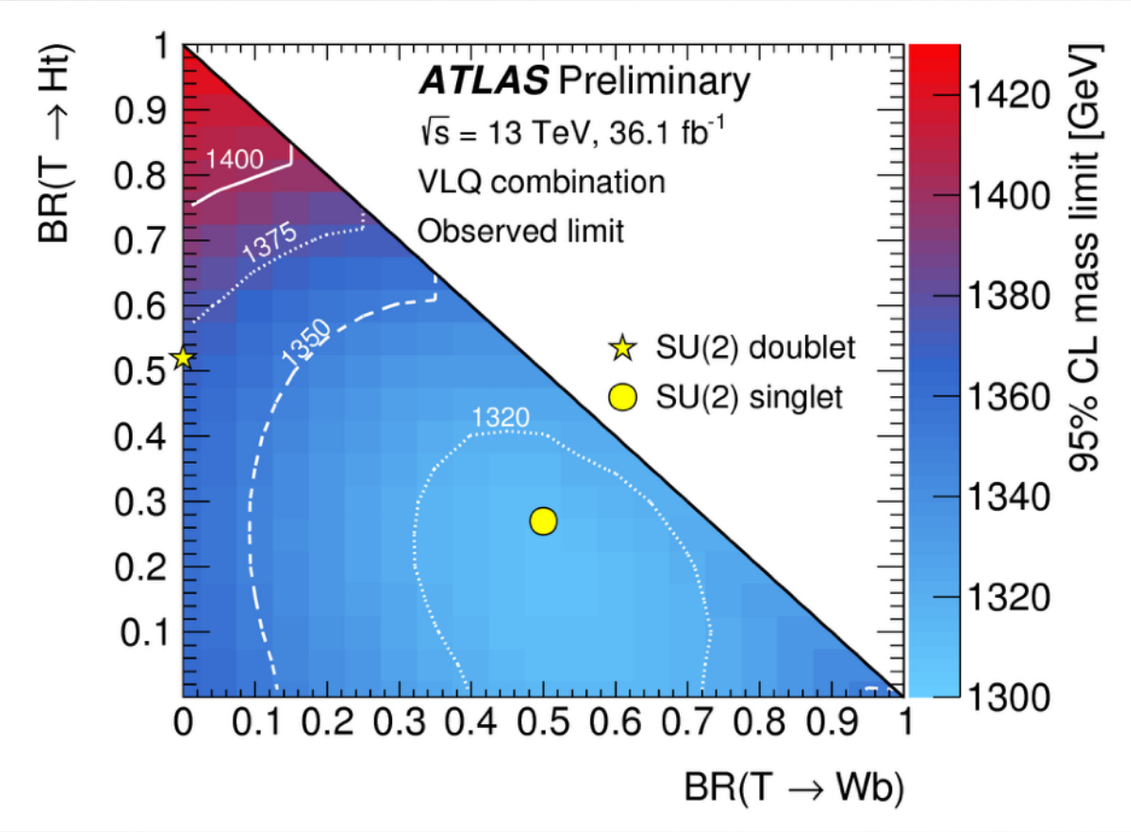
Assuming

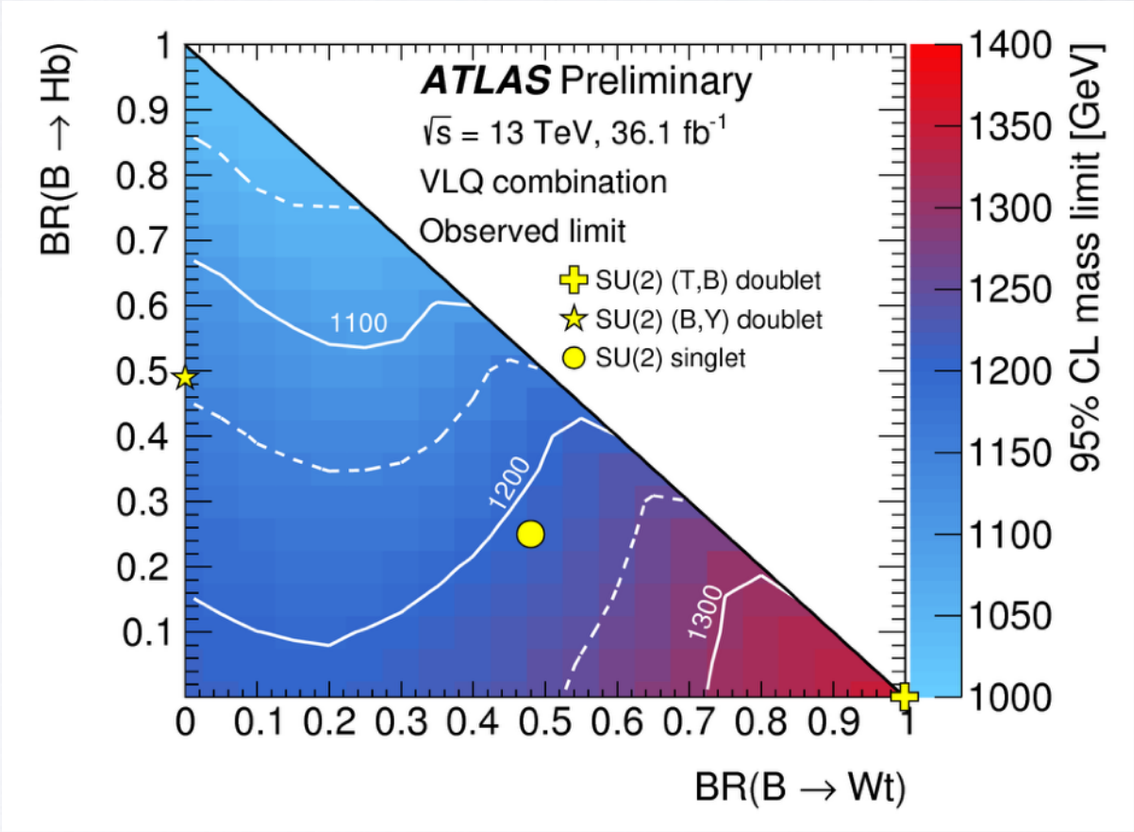
arxiv:1808.02343

$$\mathrm{Br}(T \to Ht) + \mathrm{Br}(T \to Zt) + \mathrm{Br}(T \to Wb) = 1$$

$$\mathrm{Br}(B \to Hb) + \mathrm{Br}(B \to Zb) + \mathrm{Br}(B \to Wt) = 1$$

★ Excluding T(B) mass below 1.31(1.03) TeV for ANY combination of branching ratio.





➡ With the limit above 1 TeV, the attention is recently shifting towards single production, which is dominant at higher VLQ masses (depending on the model parameters).

Summary

ATLAS is looking for BSM signals in a large variety of final states

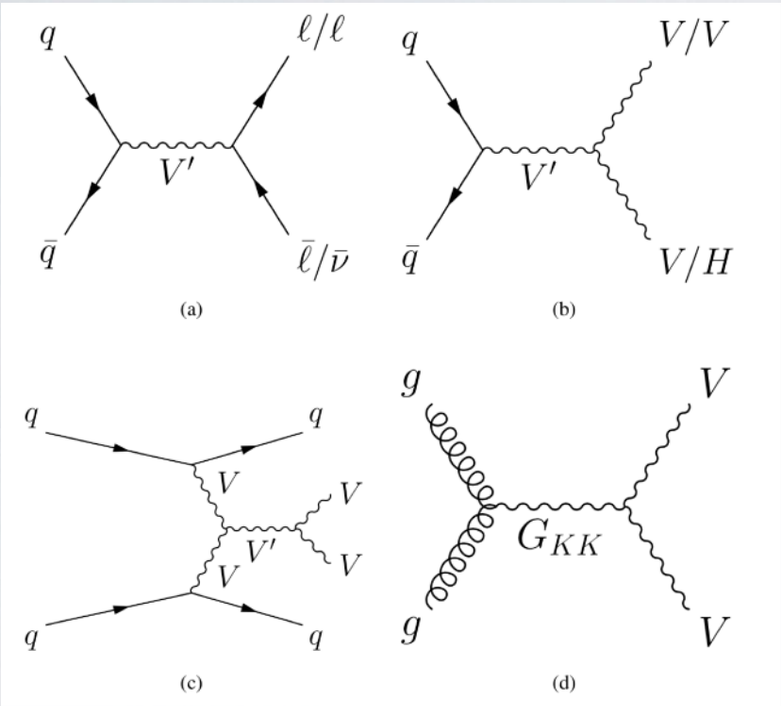
Though no new physics is find, limits are improved a lot (or set for the first time) in these analyses. The limits are guiding us for future analysis.

With new techniques and full Run-2 data been used in more and more analysis teams, we expect to have improved results in next years and are looking forward to see new signals.

Back Up

V' — Combination of searches for heavy resonance in bosonic and leptonic final states

arxiv:1808.02380



A combination of VV, VH, ll, lν searches for

- Heavy flavor triplet model (HVT)
  - model A: Drell-Yan, weak coupling
  - model B: Drell-Yan, strong coupling
  - model C:VBF (no exclusion region find)
- Randall-Sundrum model (Page 20)
- narrow heavy scalar resonance

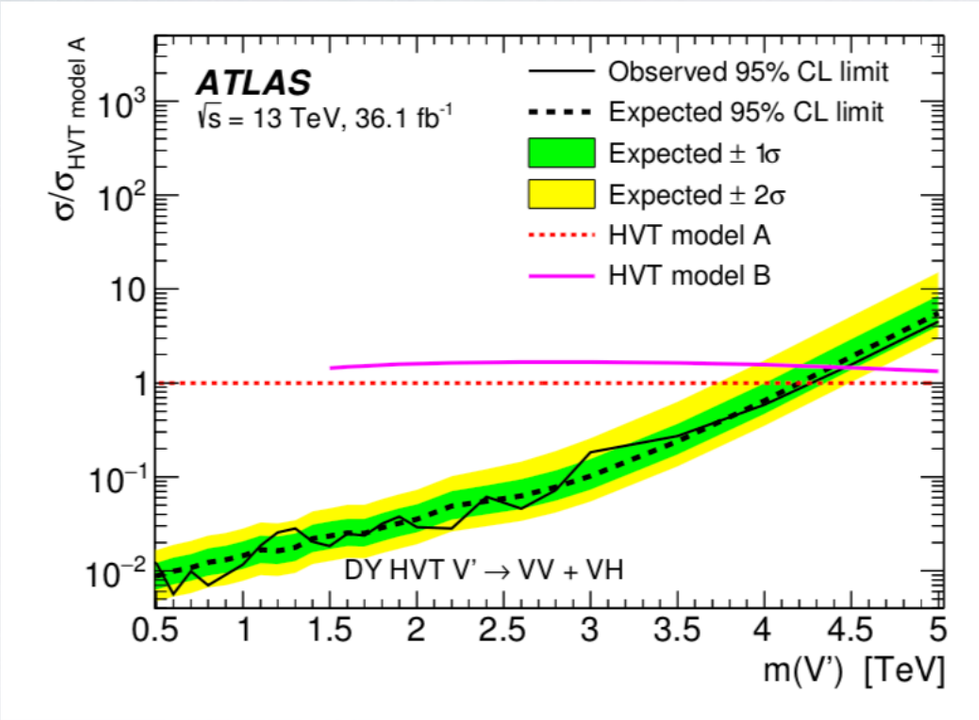
Table 2: Signal models, resonances, and decay modes considered in the combination.

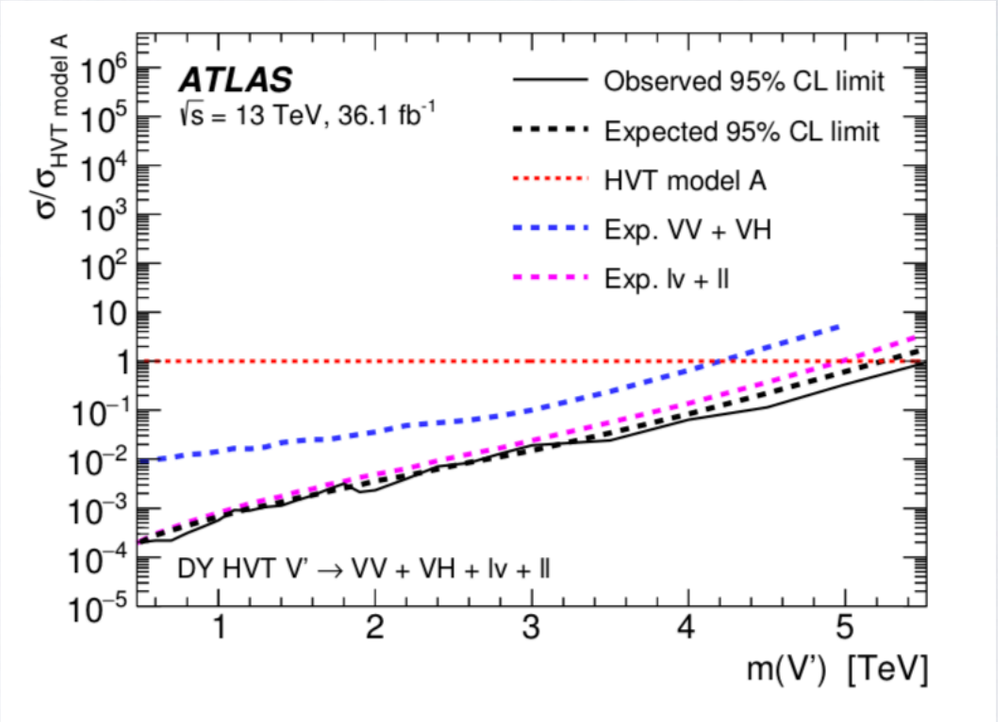
Model \ Decay mode	WW	WZ	ZZ	WH	ZH	$\ell\nu$	$\ell\ell$
HVT	Z'	W'		W'	Z'	W'	Z'
Bulk RS	G_{KK}		G_{KK}				
Scalar	Scalar		Scalar				

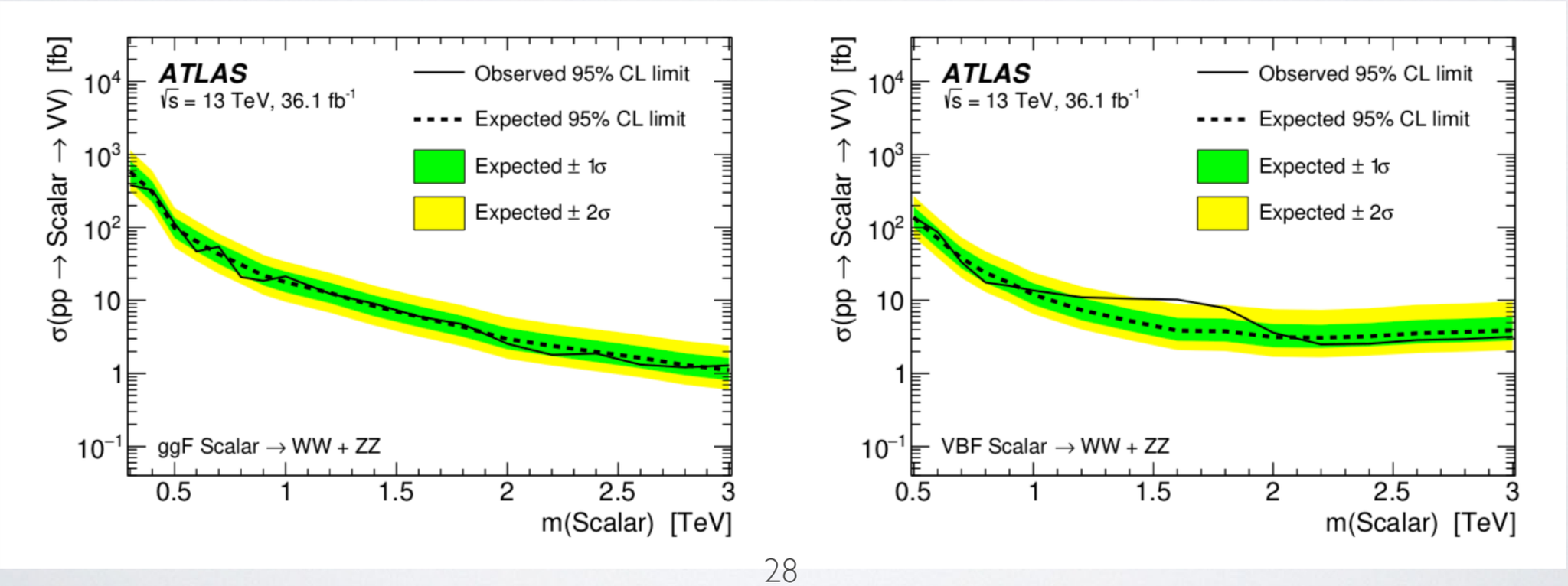
Models
&
Channels

V' — Combination of searches for heavy resonance in bosonic and leptonic final states

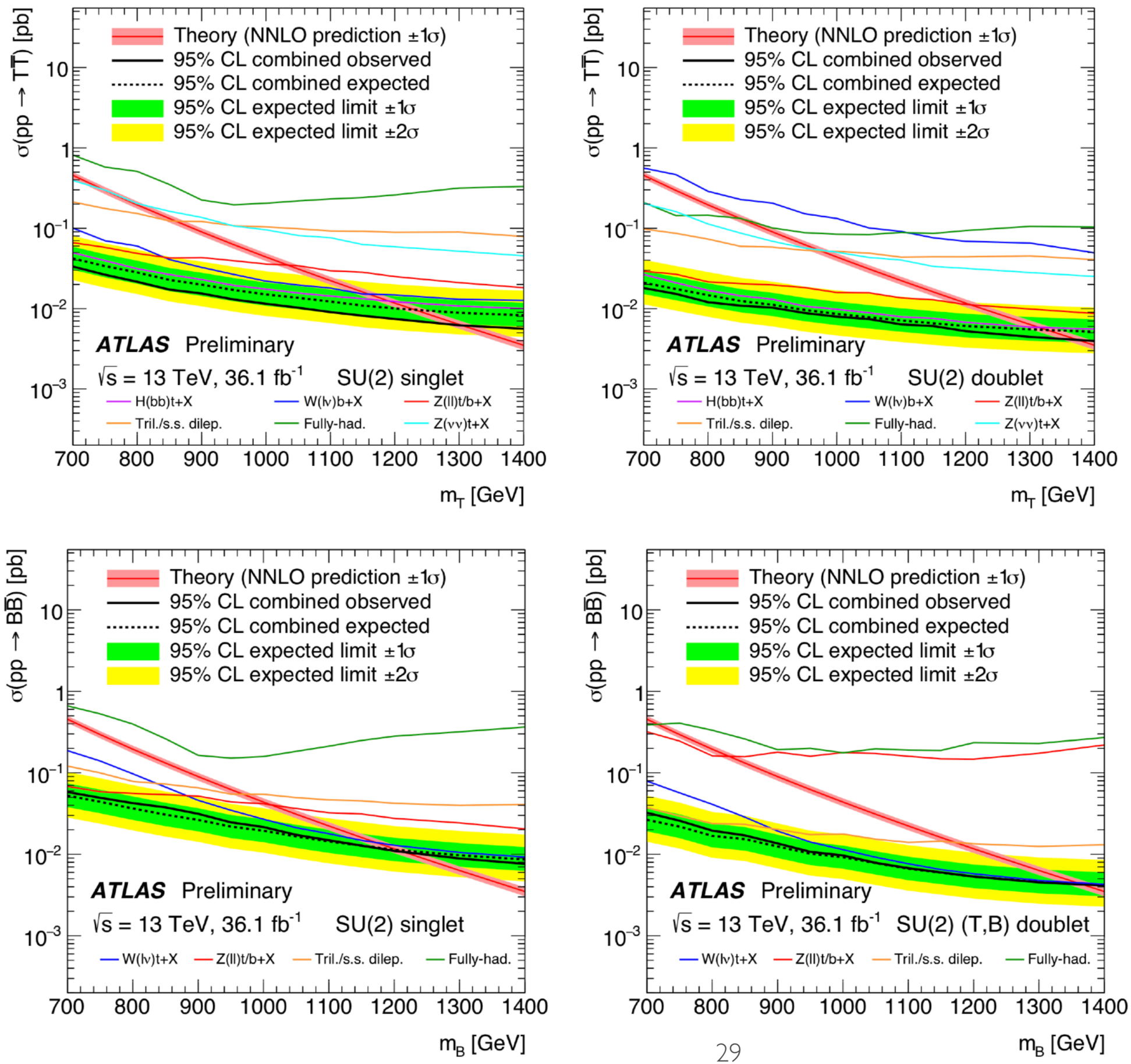
arxiv:1808.02380







VLQ Limits



Lower mass limit (TeV)	
singlet T	1.31
doublet T	1.37
singlet B	1.22
B in (T, B)	1.37
B in (B,Y)	1.14