Search for new resonances in hadronic final states with the ATLAS and CMS detectors

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on behalf of the ATLAS and CMS Collaborations

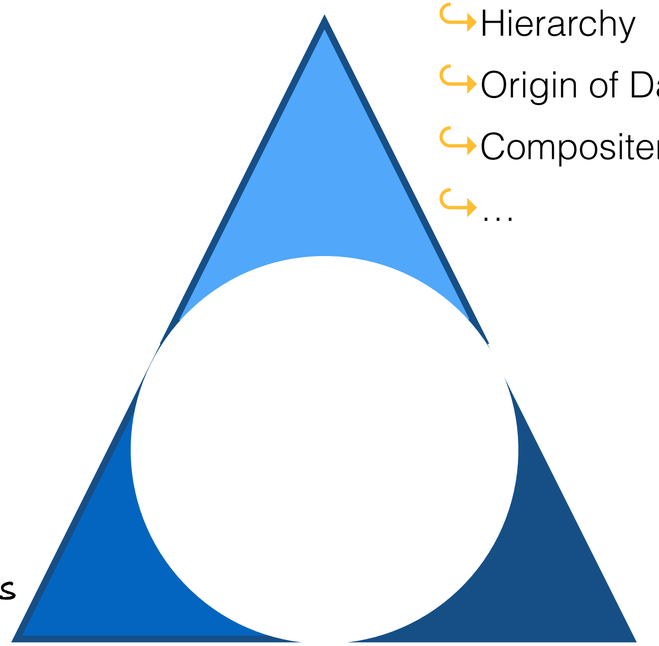
SUSY 2019

Probing new resonances

Beyond Standard Model (BSM) physics predicts new resonances decay to a pair of objects

The Problems

- Hierarchy
- Origin of Dark Matter
- Compositeness
- …



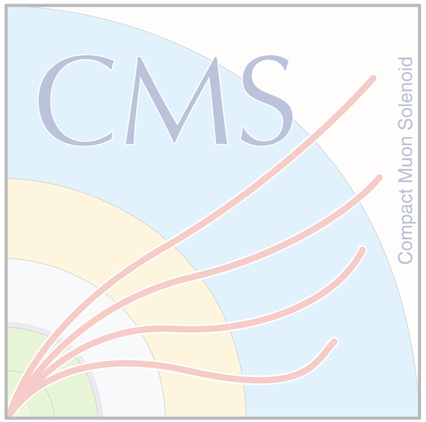
The Standard Model extensions

- New heavy gauge bosons
- New resonances
- Simplified models of WIMP dark matter
- Extra-dimensions
- Excited fermions
- …

The (partial) Searches

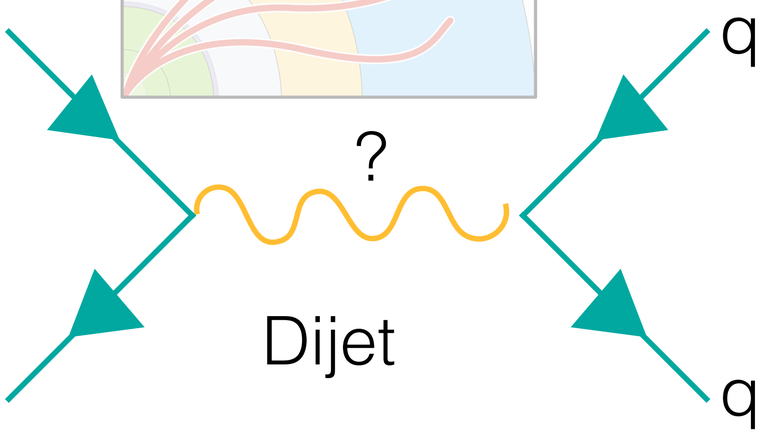
- Full hadronic final states (In this talk) with ATLAS and CMS

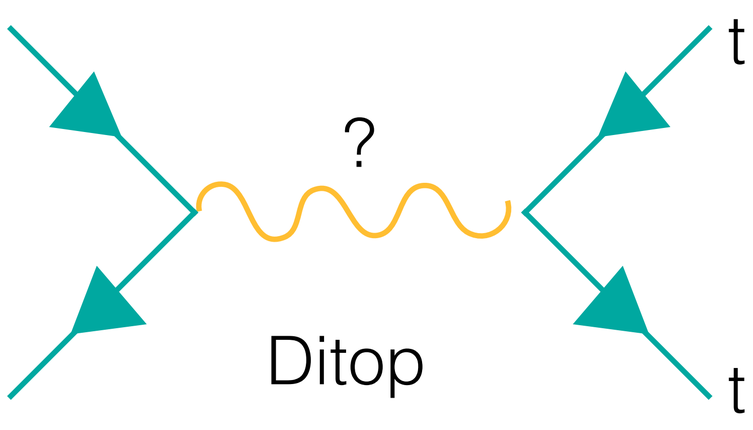
Status of the analyses

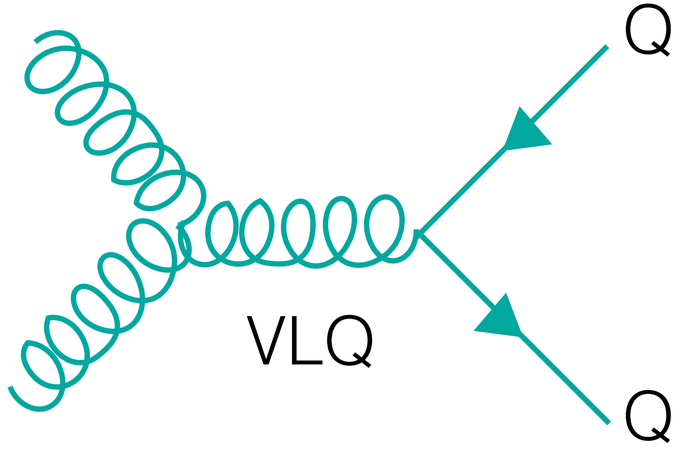


36 fb^{-1}
boosted dibjet
boosted dijet + ISR (jet, photon)
top - anti top
VLQ

80 fb^{-1}
dijet







36 fb^{-1}
boosted dijet + ISR (jet, photon)
top - anti top
VLQ

80 fb^{-1}
dijet + ISR (photon, lepton)
dibjet + ISR

140 fb^{-1}
dijet

Dijet searches

Dijet analysis strategy

①Definition of a set of **signal region**(s) **(SR)**

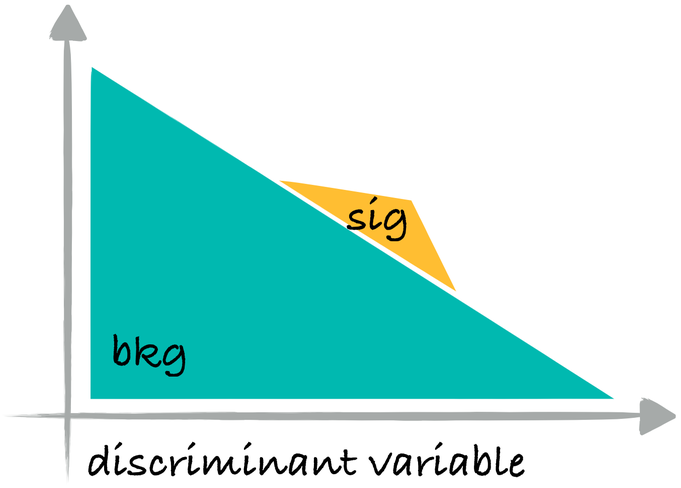
↪Find the best cuts to optimize signal over background

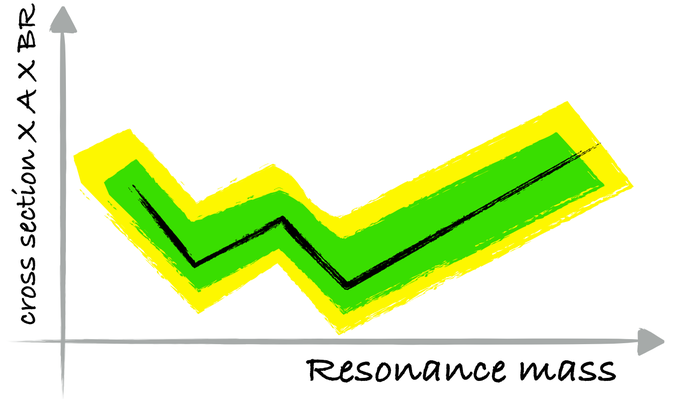
②Model background with parametric function or use side band method

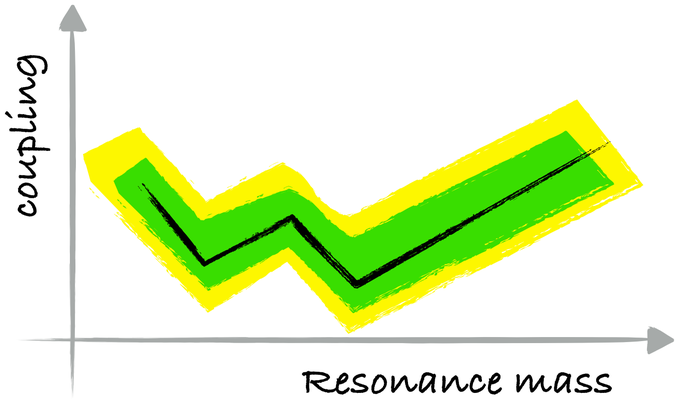
③Unblinding ➜ Is there an **excess**?

↪Look for a narrow peak

④If no excess is found the results are interpreted in terms of **limits on models** under study







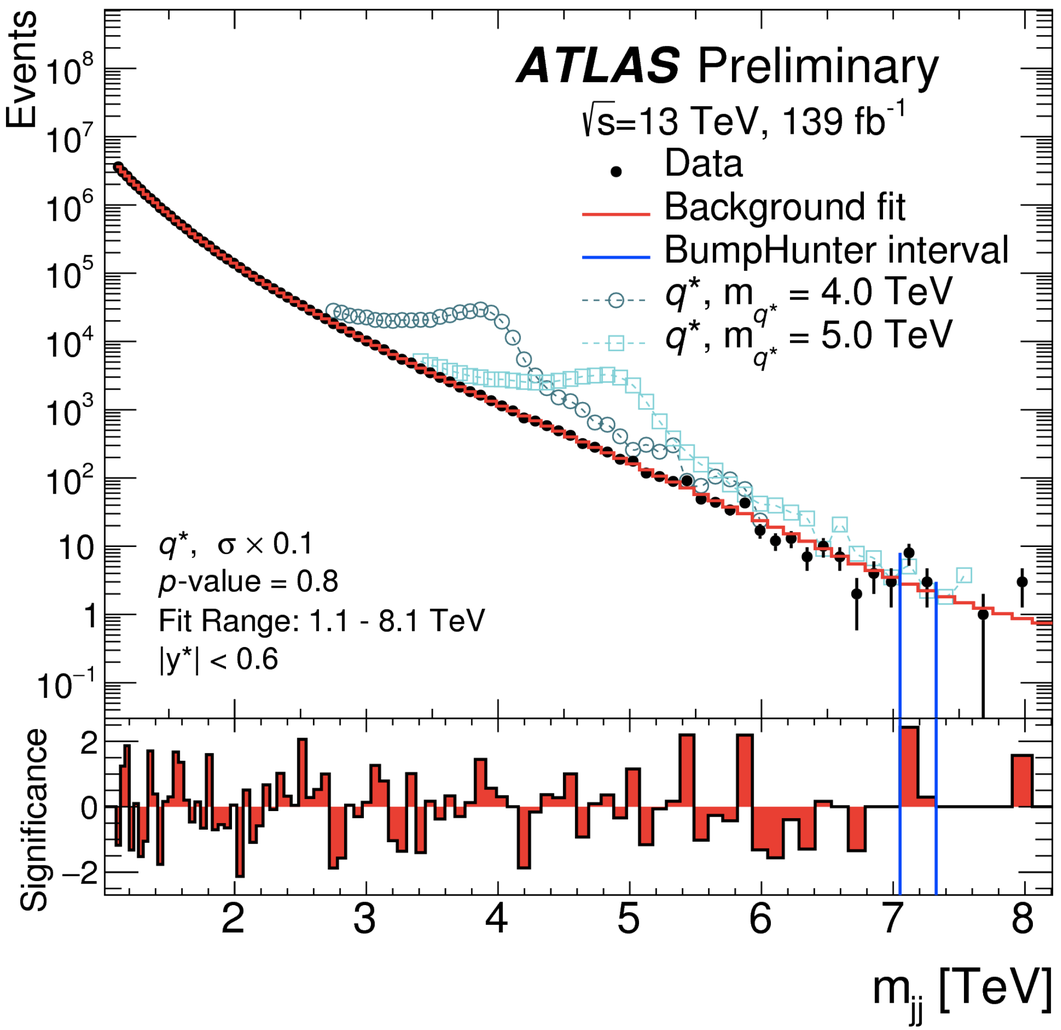
Dijet searches

139 fb^{-1}

ATLAS EXPERIMENT

- Full Run 2 datasets: 2015-2018, corresponding to 139 fb^{-1}
- Collecting data with single jet trigger (p_T threshold: 420 GeV)
- Probe high mass region
- Variable binning to reflect varying resolution
- Background estimate with sliding windows method
- Data fitted with a 5 parameter function
  - ↪ No significant excesses found

$$f(x) = p_1 (1-x)^{p_2} x^{p_3 + p_4 \ln x + p_5 (\ln x)^2}$$



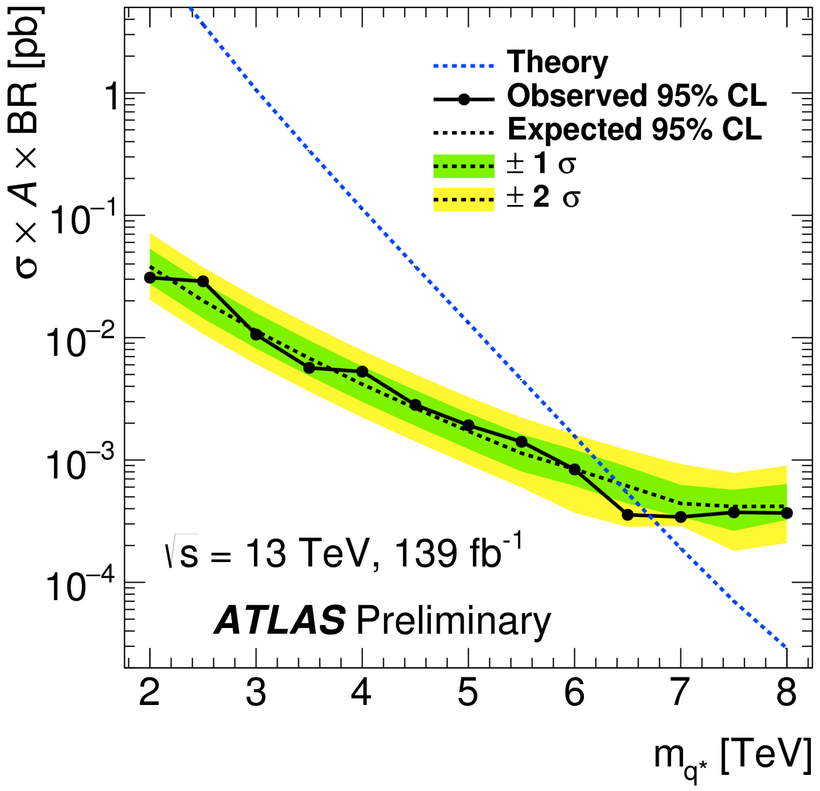
ATLAS-CONF-2019-007

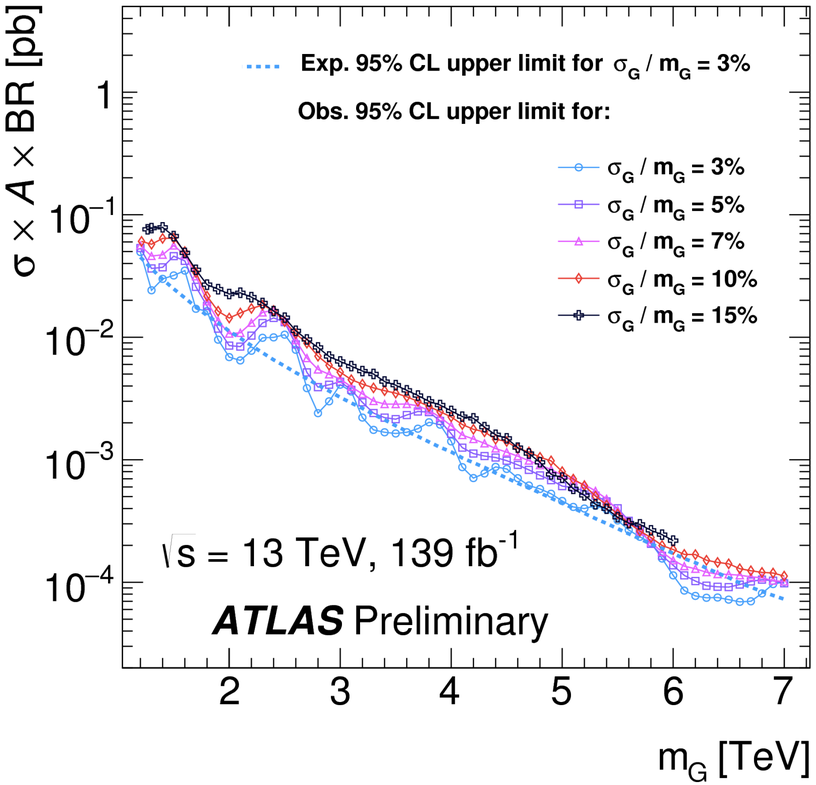
Dijet searches

139 fb^{-1}

ATLAS EXPERIMENT

- Improved sensitivity with respect 2015/2016 analysis
- Benchmark: q* model
- Limits on Gaussian signal models





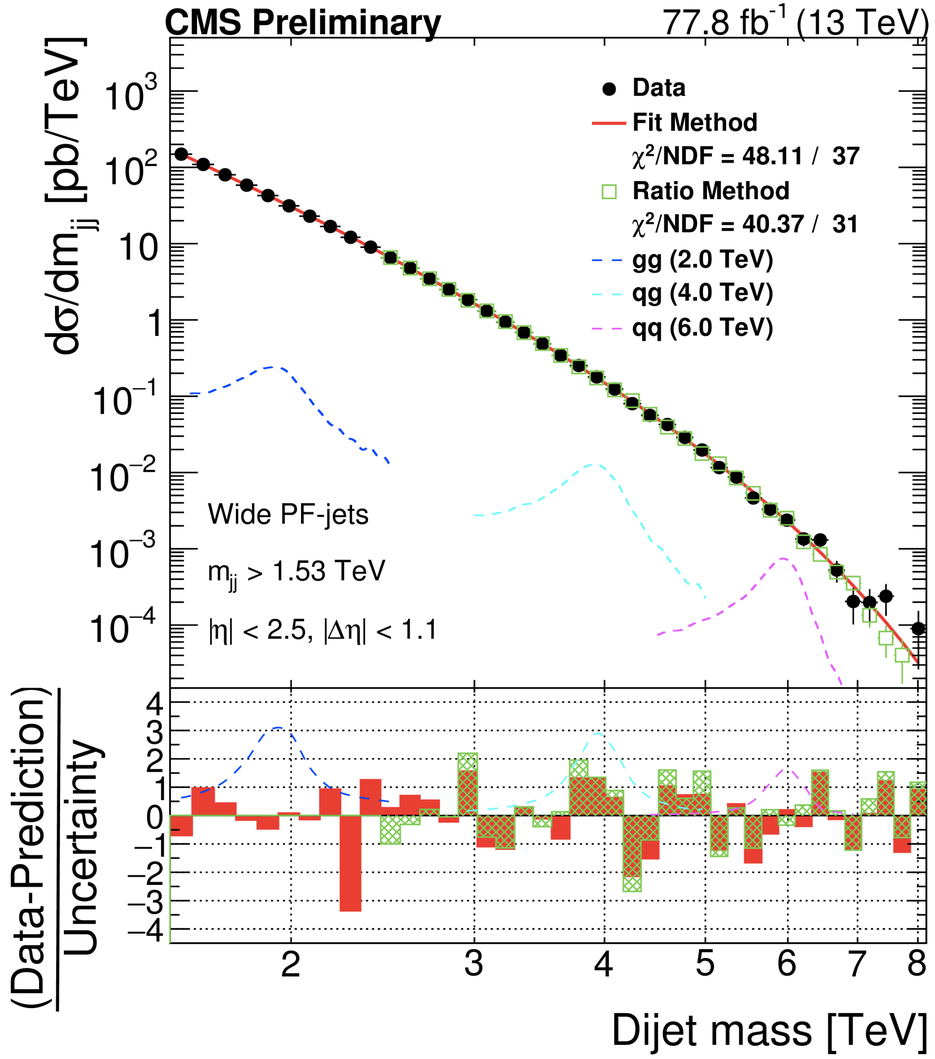
ATLAS-CONF-2019-007

Dijet searches

77.8 fb^{-1}

- 2016 and 2017 datasets: corresponding to 77.8 fb^{-1}
- Invariant mass of two “wide” jets
  - Add jets with $\Delta R < 1.1$
- QCD background predicted both by fitting data and with new ratio method
  - Ratio method: estimate background using m_{jj} distribution in CR defined by a $|\Delta\eta|$ sideband between two leading jets
    - Valid from 2.5 TeV
    - If a signal is observed the method leads to smaller uncertainties on the background prediction and to increased sensitivity
  - QCD suppression in SR by applying $|\Delta\eta|<1.1$ cut

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

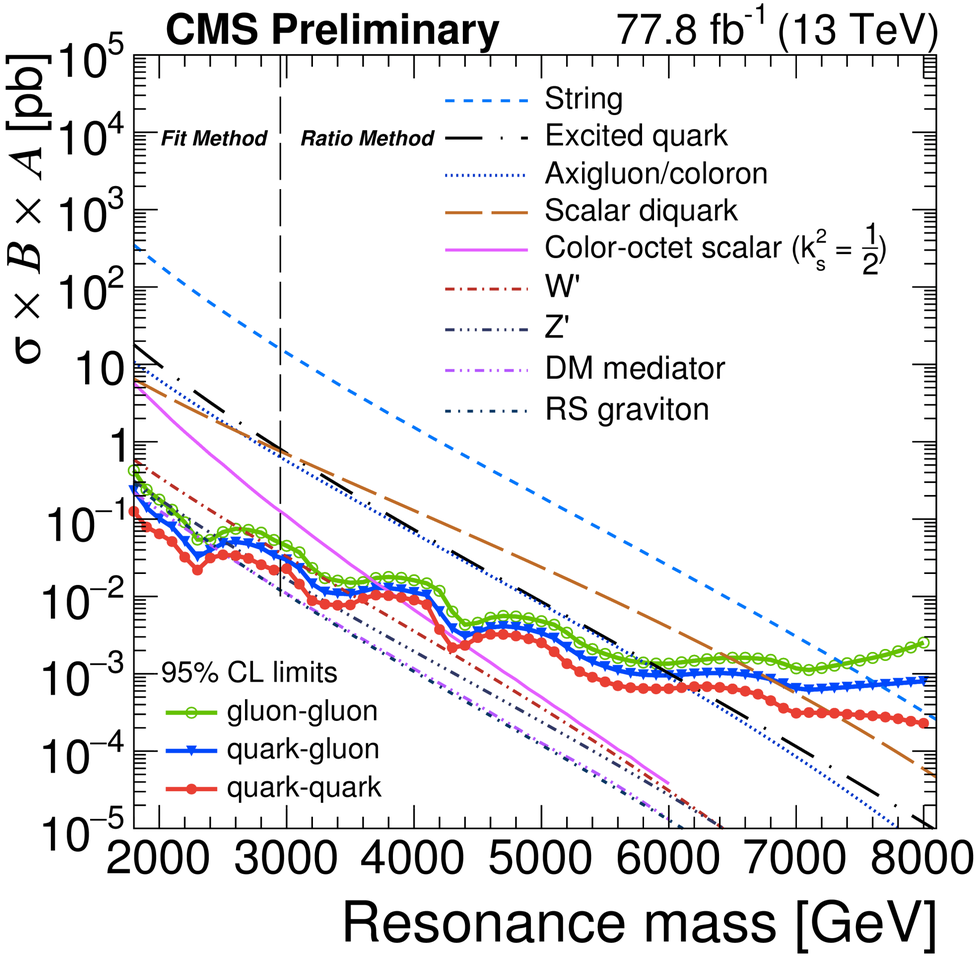


CMS-PAS EXO-17-026

Dijet searches

77.8 fb^{-1}

- Separate limits for different final states: qq, gg, qg
  - ↳ Dijet resonances shapes depending on the final state

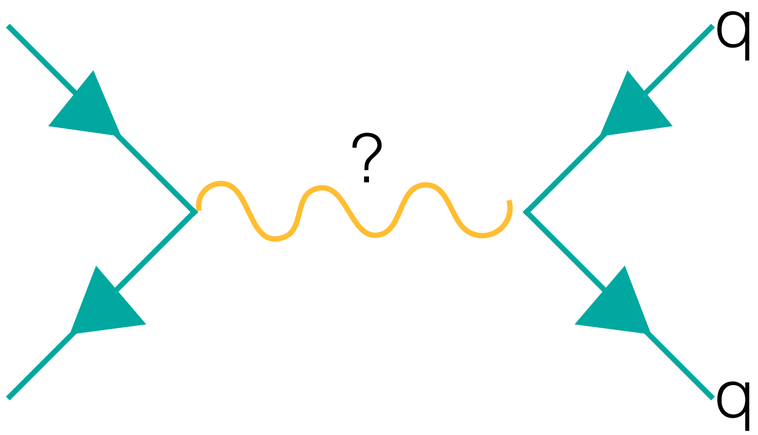


CMS-PAS EXO-17-026

Dijet searches limitation

- Dijet searches are limited at lower masses by a large multi-jet background
  - Trigger saturation
  - Minimum trigger thresholds ~$2p_T$, with p_T typically of several hundreds GeV ➜ Poor sensitivity below 1 TeV

- Several strategies:
  - ATLAS “Trigger level analyses”, CMS “data scouting” ➜ NOT covered in this talk
  - Triggering on Initial State Radiation: photon, lepton, jet



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  - ↪ ATLAS “Trigger level analyses”, CMS “data scouting” ➜ NOT covered in this talk
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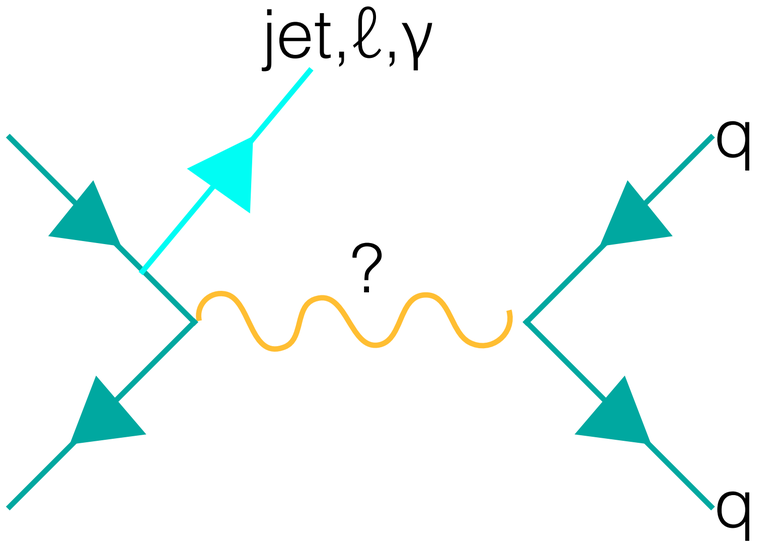
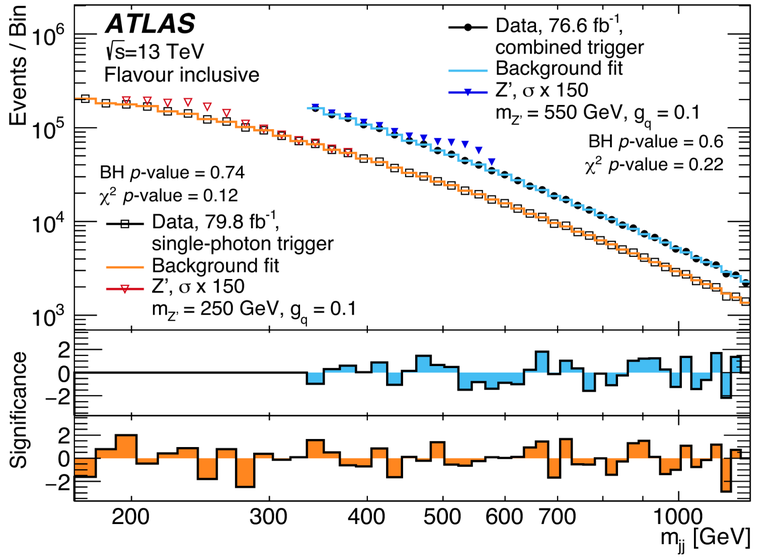
- Requesting an ISR:
  - ↪ Reduces signal acceptance but allows efficient triggering at lower masses
  - ↪ At even lower masses the decay products of the resonance will merge into a single large-radius jet

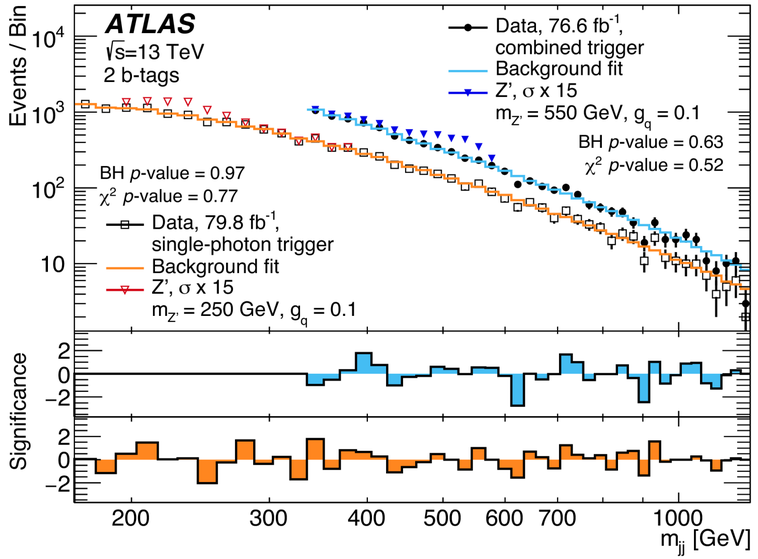


Dijet + photon

80 fb^{-1}

- Single photon or photon + jet trigger (better at high mass)
  - Combined trigger not active during 2015 data ➜ ~3.2 fb^{-1} less than single photon trigger
- QCD suppressed with y*<0.75 (cut on rapidity difference)
- Sliding windows estimate
- 4 region defined:
  - Combined photon trigger (m_{jj} > 335 GeV)
  - Single photon trigger (m_{jj} > 169 GeV)
  - Flavor inclusive and 2 b-tag selection
- No deviations observed





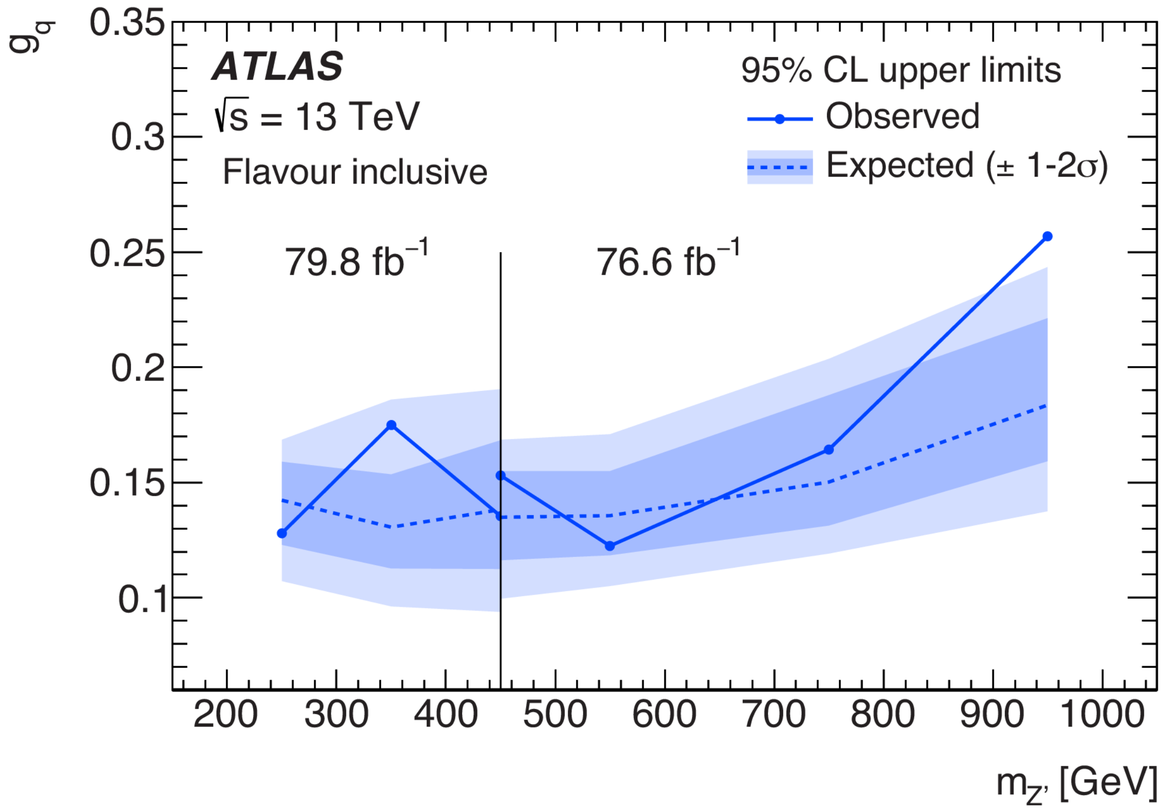
arXiv:1901.10917

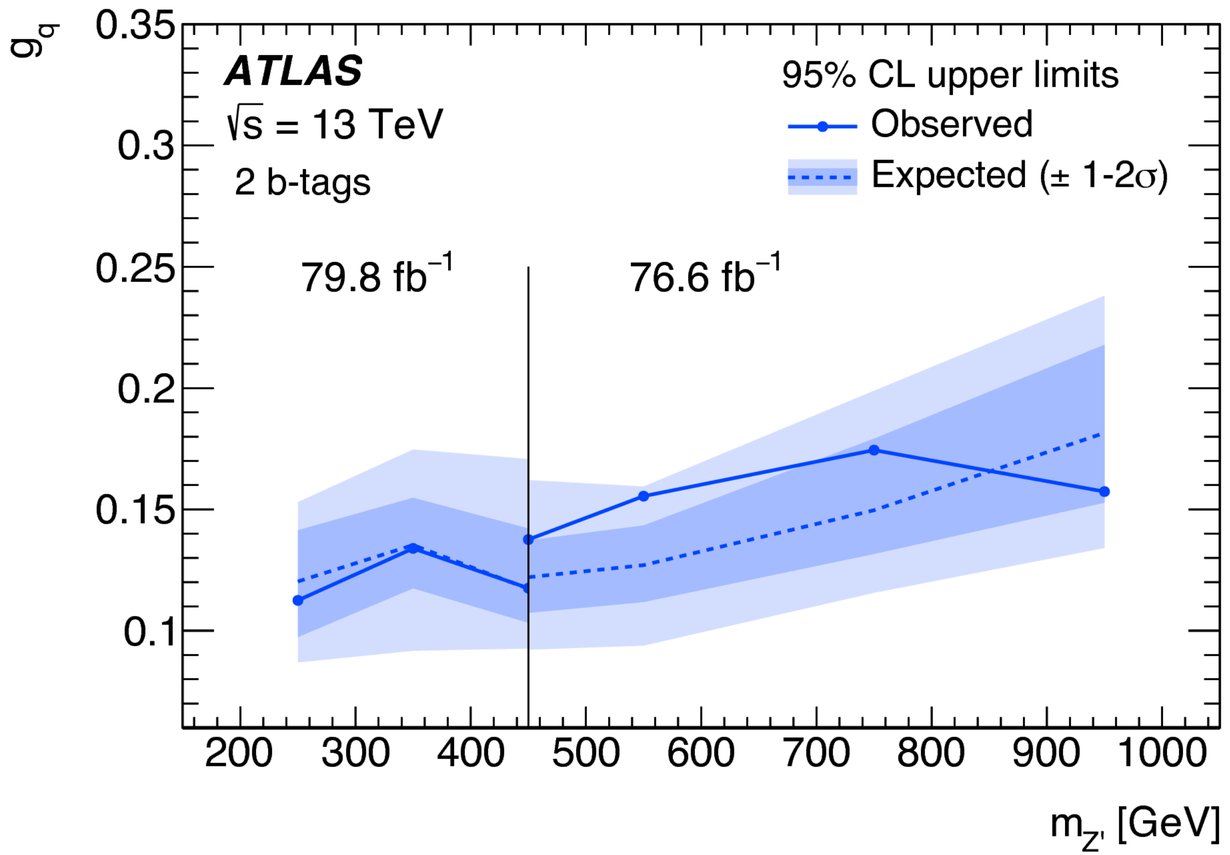
Dijet + photon

80 fb^{-1}

ATLAS EXPERIMENT

- Limits on Z' axial-vector-dark-matter mediators as function of coupling





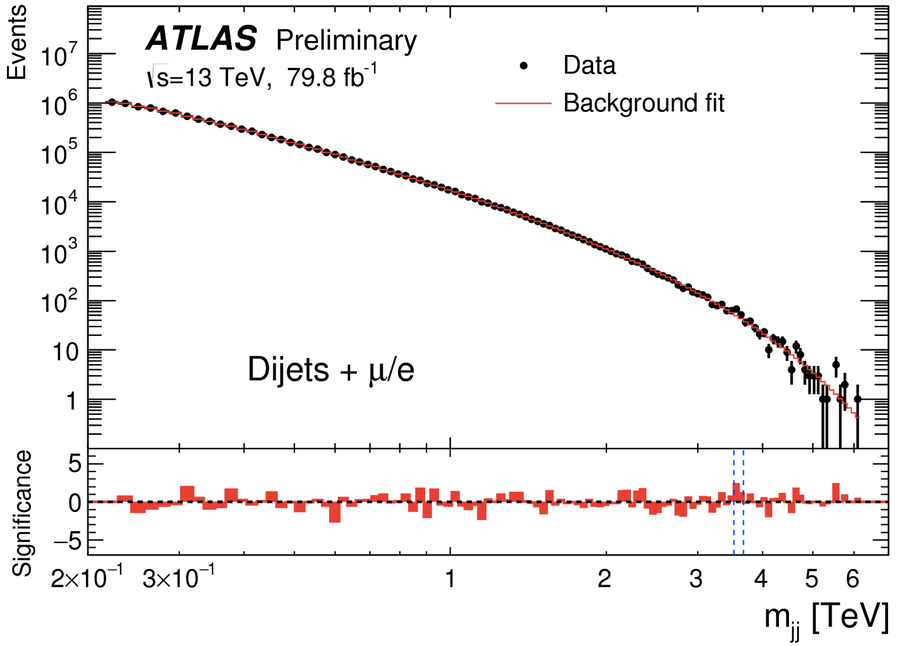
arXiv:1901.10917

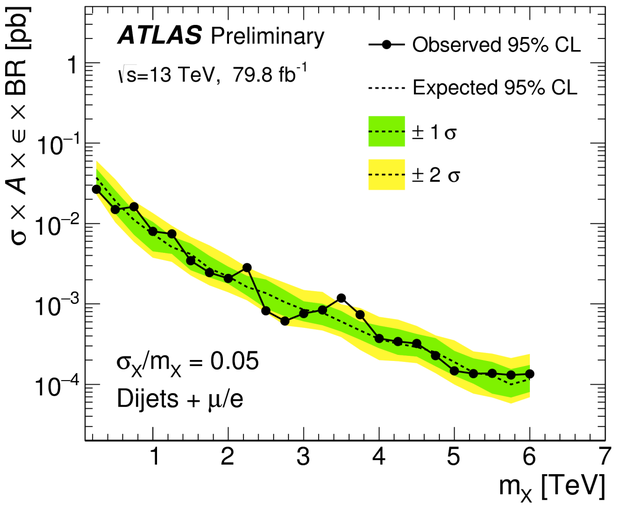
Dijet + lepton

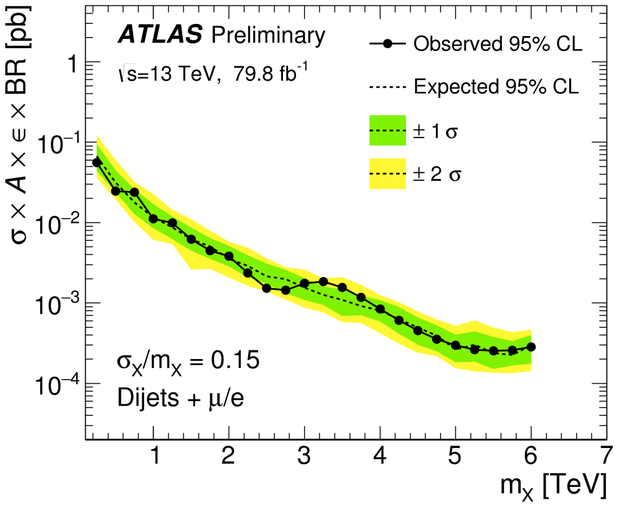
80 fb^{-1}

ATLAS EXPERIMENT

- Single lepton (electron or muon) trigger
  - ↪ Extend m_{jj} sensitivity below 1 TeV
- Background modeled with a five parameter function and by using sliding window fit
- Sliding windows estimate
- Limits on new resonances described by Gaussian signals

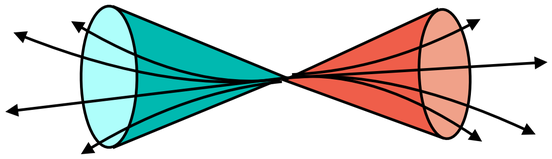






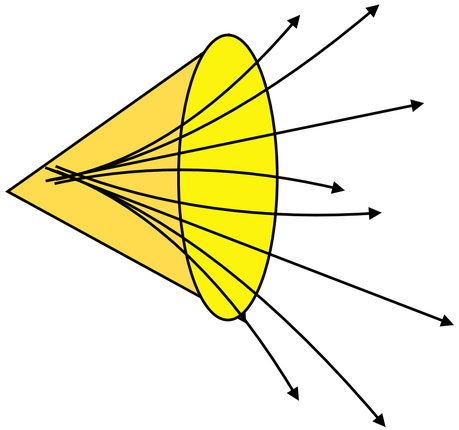
ATLAS-CONF-2018-015

Searches with boosted objects



Resolving individual decay products become more difficult at high mass (boosted objects)

Reconstruct a single large-R jet and investigate its substructure



- Recover signal efficiency for merged decays
- Grooming: remove pile-up and soft radiation
  - ↪ Improve mass resolution
- Use tracking information

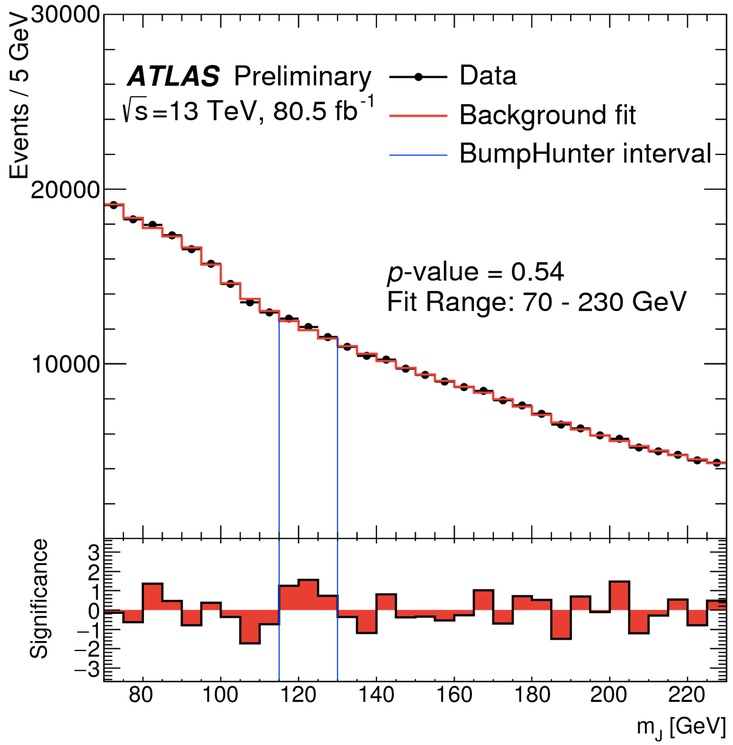
	ATLAS	CMS
anti-k_t R	1.0	0.8
grooming algorithm	trimming	soft drop mass

Dibjets + ISR

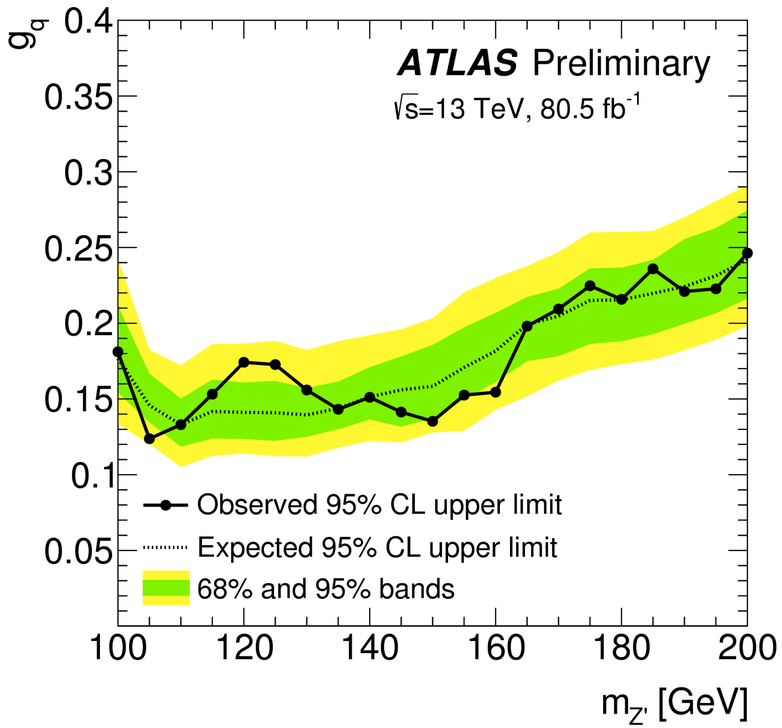
80 fb^{-1}

ATLAS EXPERIMENT

- Search range in 70 < m_{jj} < 230 GeV
  - Complementarity to dijet + photon search (2 b-tag region)
- QCD estimation:
  - Fit to data
  - Validation in CR with 0 b-tagged jets



$$f_n\left(x\middle|\vec{\theta}\right) = \theta_0 \exp\left(\sum_{i=1}^{n} \theta_i x^i\right)$$

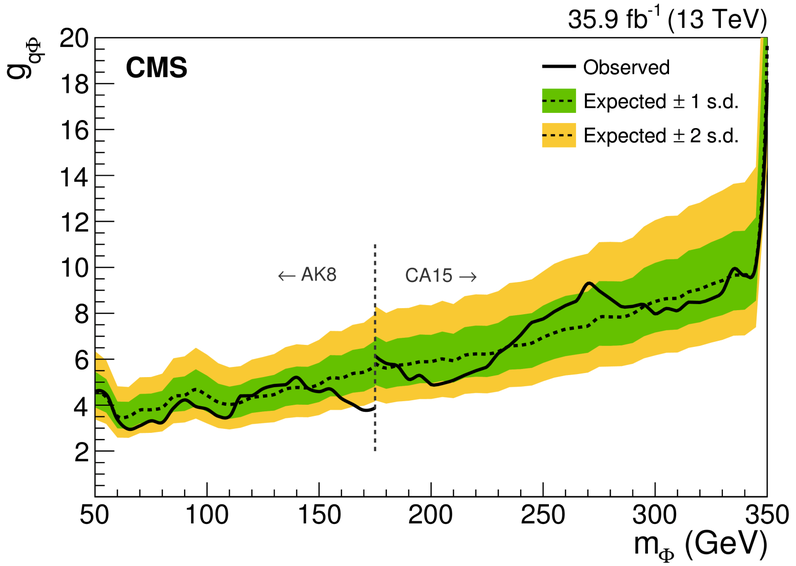


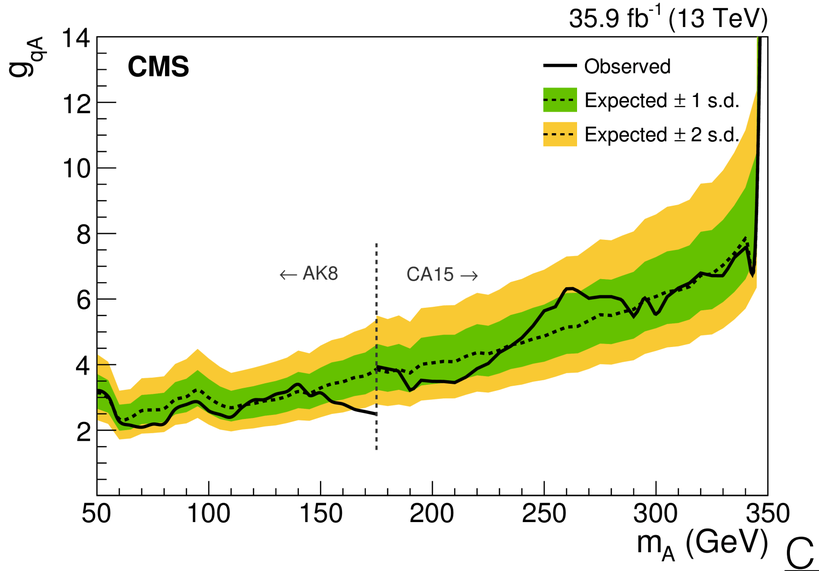
ATLAS-CONF-2018-052

Dibjets + ISR

36 fb^{-1}

- Sensitivity between 50 and 300 GeV
- Two wide-jet algorithm considered
  - anti-k_t R=0.8, better sensitivity at signal masses below 175 GeV
  - Cambridge-Aachen R=1.5, better sensitivity at higher masses
- Dedicated double b-tagger
  - Events failing the selection are used for the QCD estimation
- 11 p_T categories (six for anti-k_t, five for CA) X failing/passing b-tagger
- Soft drop jet mass as discriminating variable





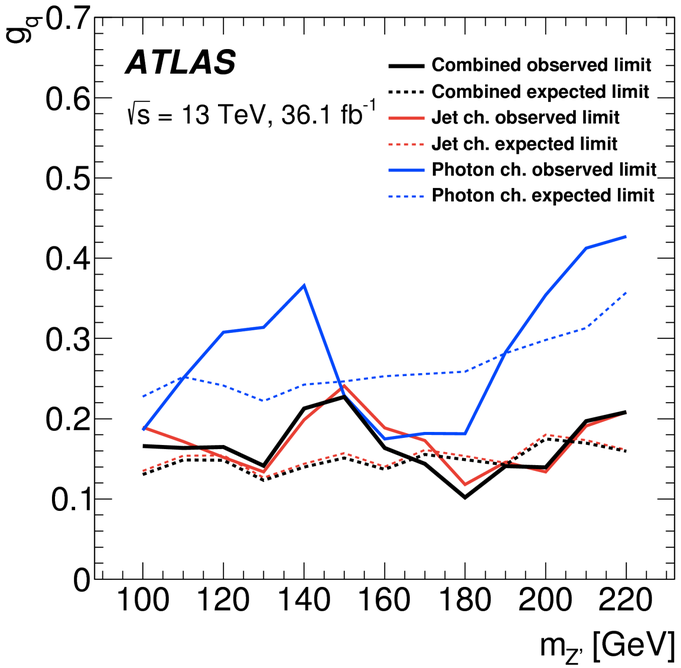
CMS-EXO-17-024

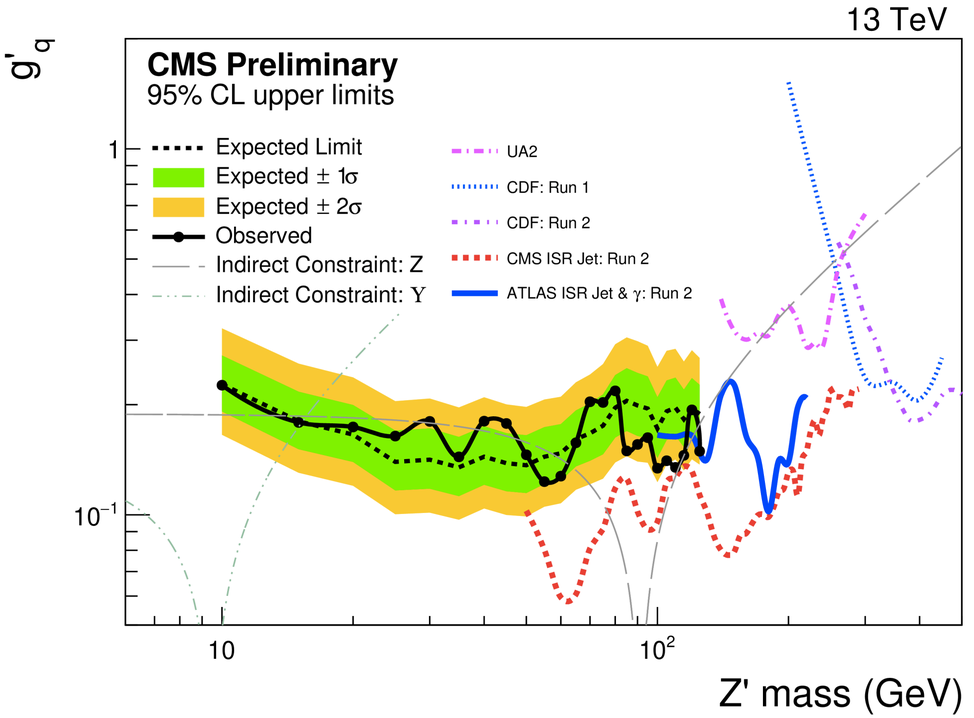
Dijet + ISR(photon/jets)

36 fb^{-1}

Very similar techniques in all analyses

- Search for an excess in m_{jj}
- ATLAS: γ E_T > 155 GeV, p_T (anti-k_t = 0.4) > 420 GeV
- CMS: γ E_T > 200 GeV, p_T (anti-k_t = 0.8) > 500 GeV
- Limits on DM mediators
  - ↪ CMS results below 50 GeV are the first to be published in this mass range





ATLAS-EXOT-2017-01

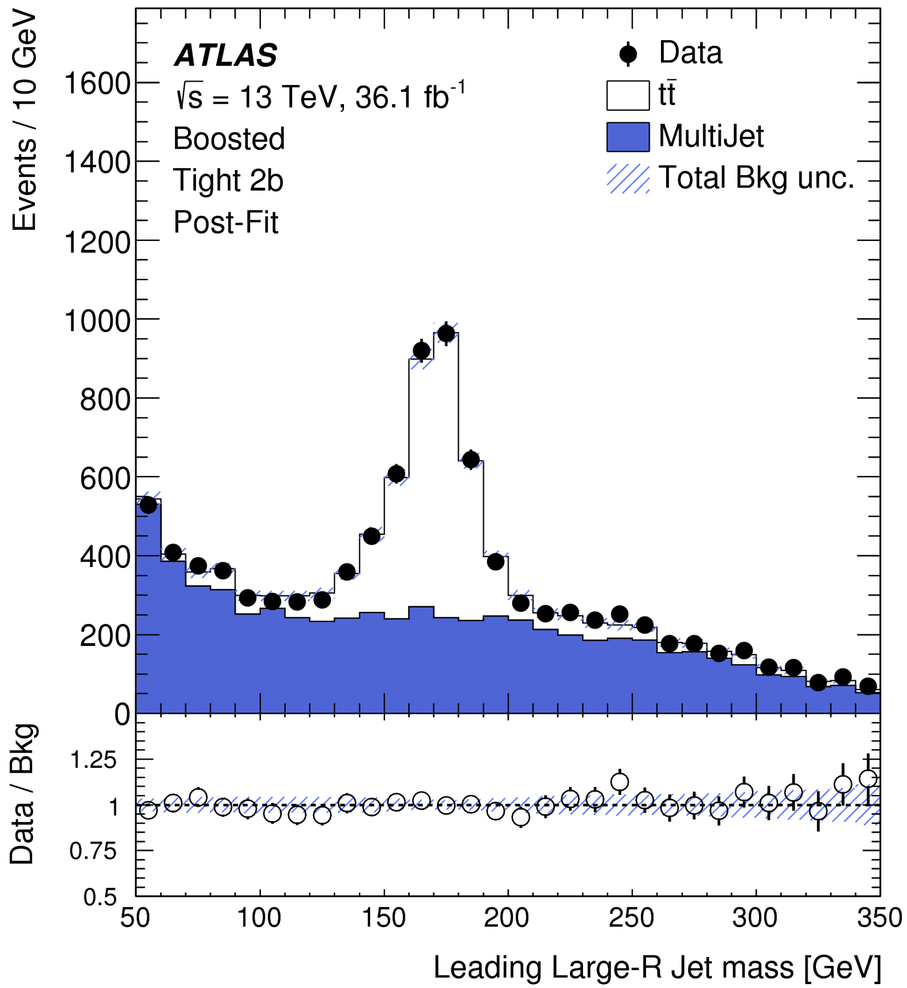
CMS-PAS-EXO-17-027

Top-antitop resonances

36 fb^{-1}

ATLAS EXPERIMENT

- Mass categorization:
  - Low mass: multijet final state (“resolved”)
  - High mass: large-R jets (“boosted”)
- Pair reconstruction:
  - Resolved analysis: buckets of tops algorithm, based on m_{top} and m_W
  - Boosted: top-tagging based on jet mass and substructure
- Background estimation:
  - QCD from enriched regions (data-driven)
  - Resolved: different quality criteria on top and b jets
  - Boosted: invert b-tag and jet mass



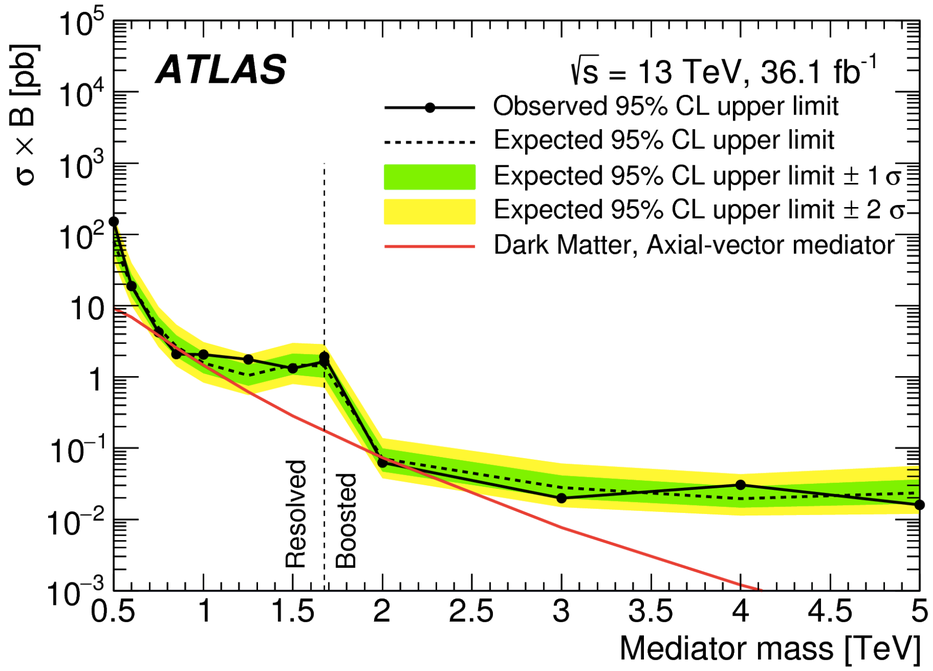
ATLAS-EXOT-2016-24

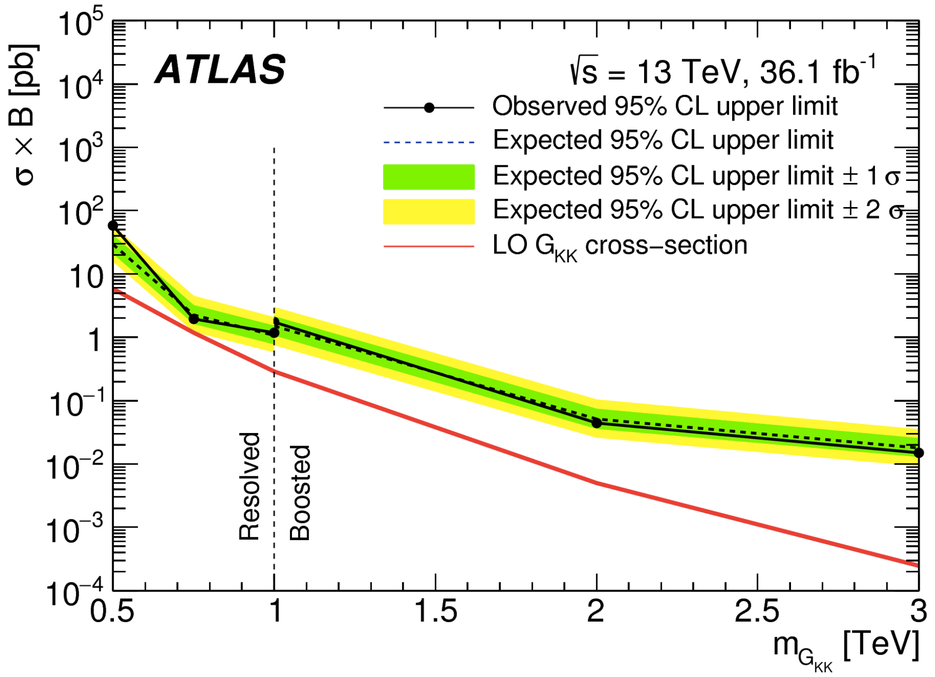
Top-antitop resonances

36 fb^{-1}

ATLAS EXPERIMENT

- Fit Results:
  - Fit on m_{tt}
  - Resolved: 3CRs + 1 SR
  - Boosted: 8 SRs
- Tested many models:
  - top color-assisted-technicolor model
  - vector and axial-vector mediators Z' in the dark-matter simplified model
  - KK excitations of the graviton G_{KK} and gluon g_{KK} in RS extra-dimension scenario





ATLAS-EXOT-2016-24

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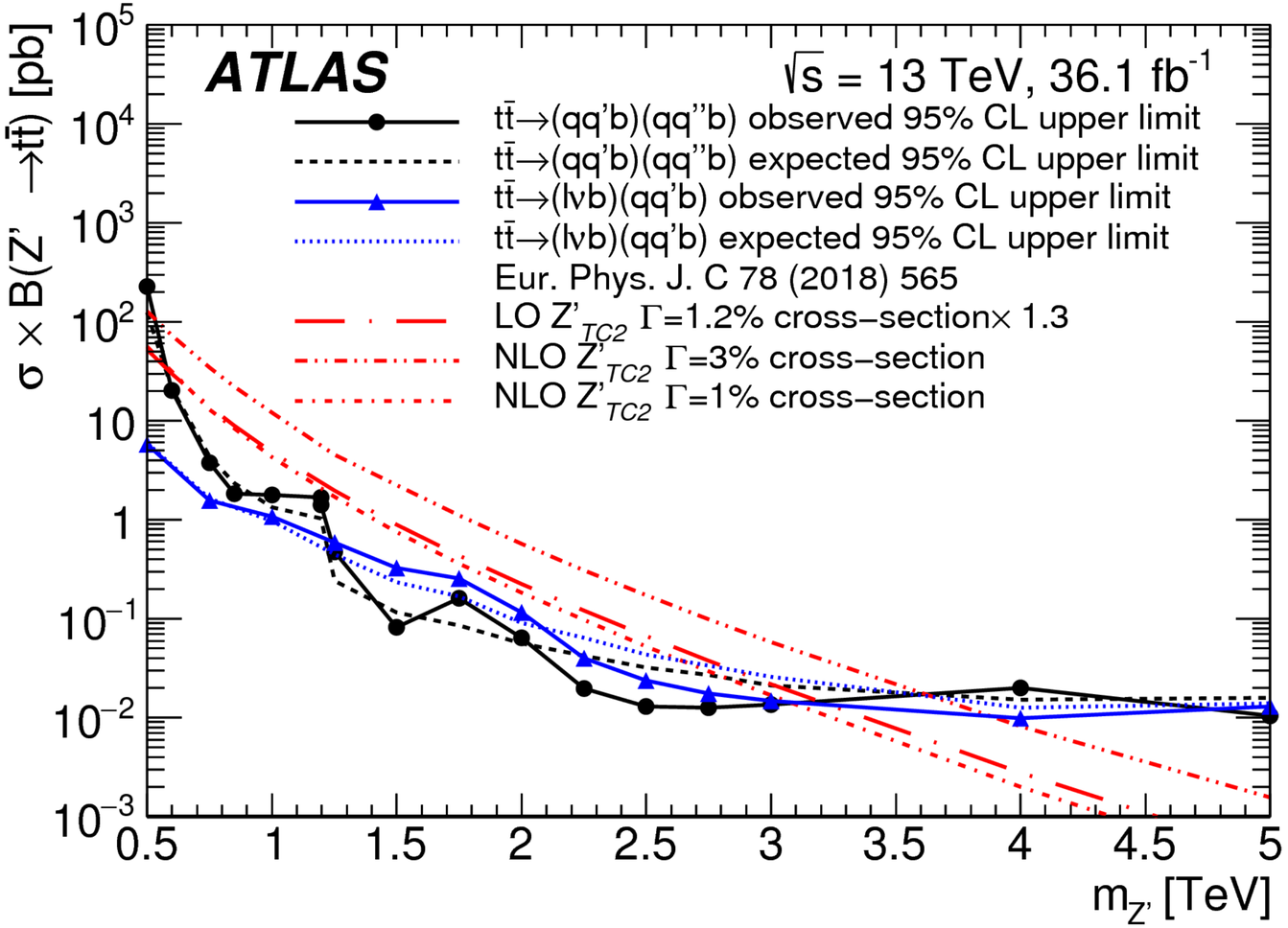
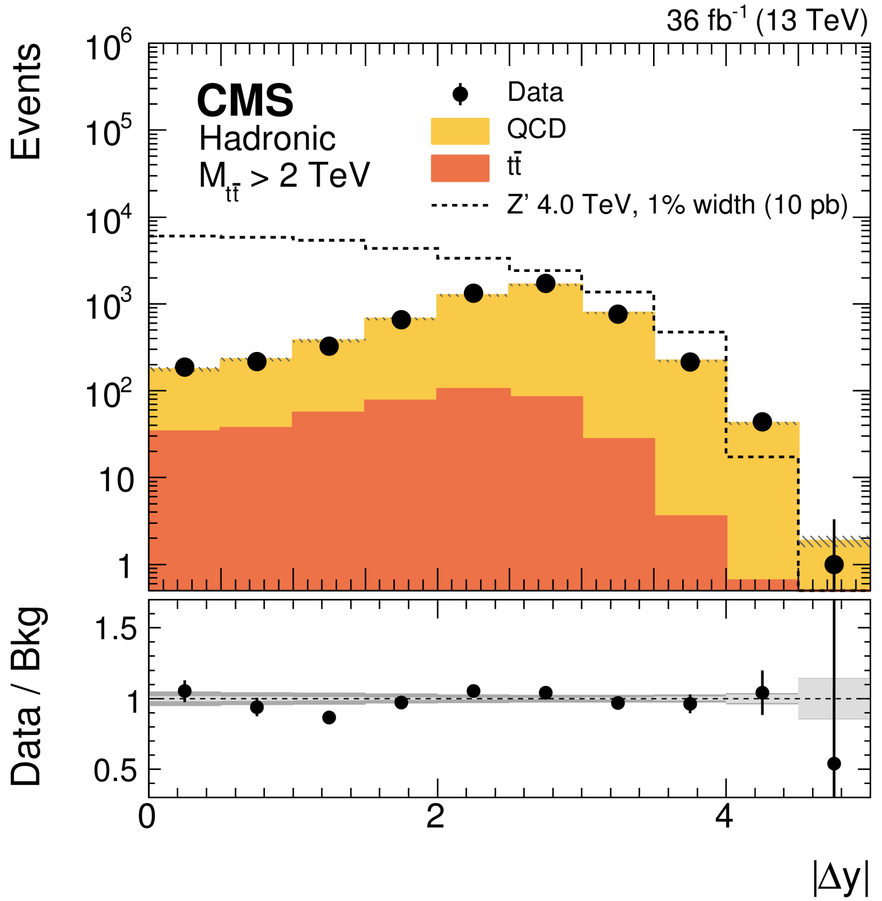


ATLAS-EXOT-2016-24

Top-antitop resonances

36 fb^{-1}

- Require large-R jet topology
- Reconstruction techniques optimized for top quarks with high Lorentz boosts
  - PUPPI algorithm: use pileup information to separate hadronically decaying top quarks from light quark or gluon jets
  - Soft Drop algorithm: criteria applied on sub-jets p_T and their relative distances
- Six SRs based on two criteria
  - Rapidity difference between the two jets
  - Number of jets with a b-tagged subject (0,1,2)
- Background estimation
  - QCD from data

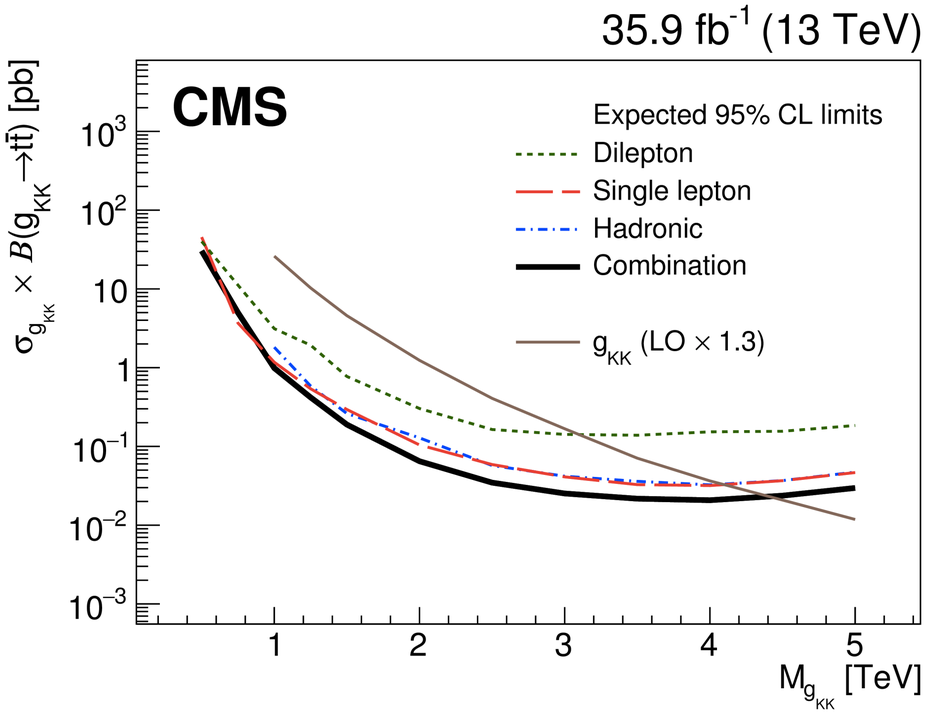


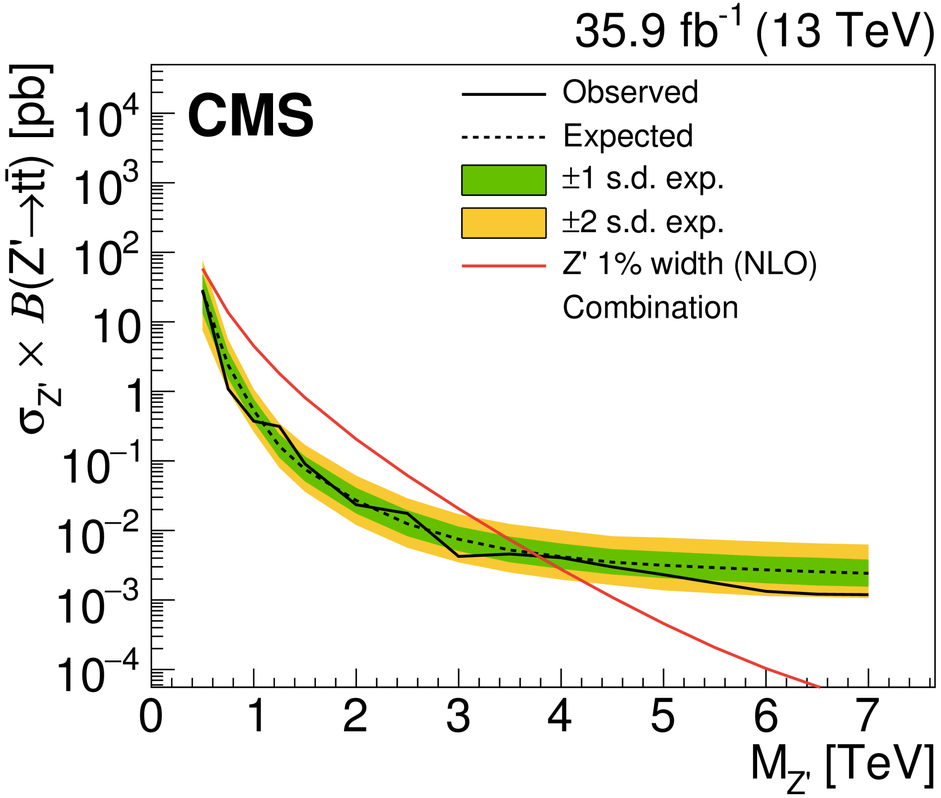
CMS-B2G-17-017

Top-antitop resonances

36 fb^{-1}

- Full Hadronic channel provides the best sensitivity along with single lepton



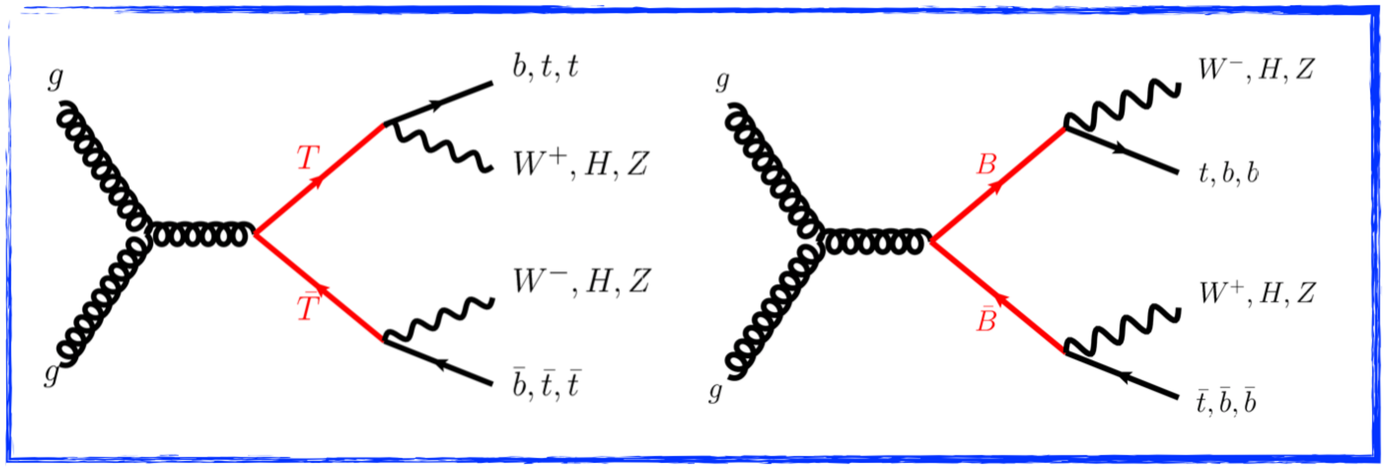


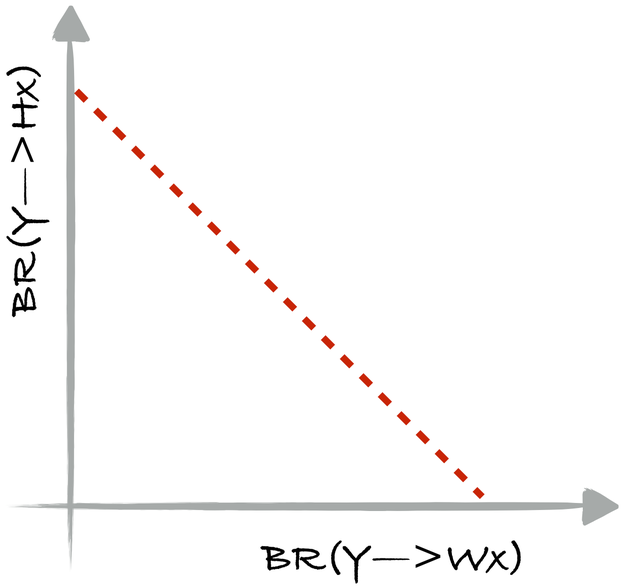
CMS-B2G-17-017

VLQ searches

Vector-like quarks

- Fermions predicted in many theories addressing naturalness
- Spin-1/2 fermions having ψ_L and ψ_R in the same SU(2) representation
- Most searches assume that the VLQs couple/decay to SM particles (a boson and a 3rd generation quark)
- Rich phenomenology at the LHC — lots of top quarks, bottom quarks, leptons, and jets in the final state!





$T \to bW$ $B \to tW$

$T \to tZ$ $B \to bZ$

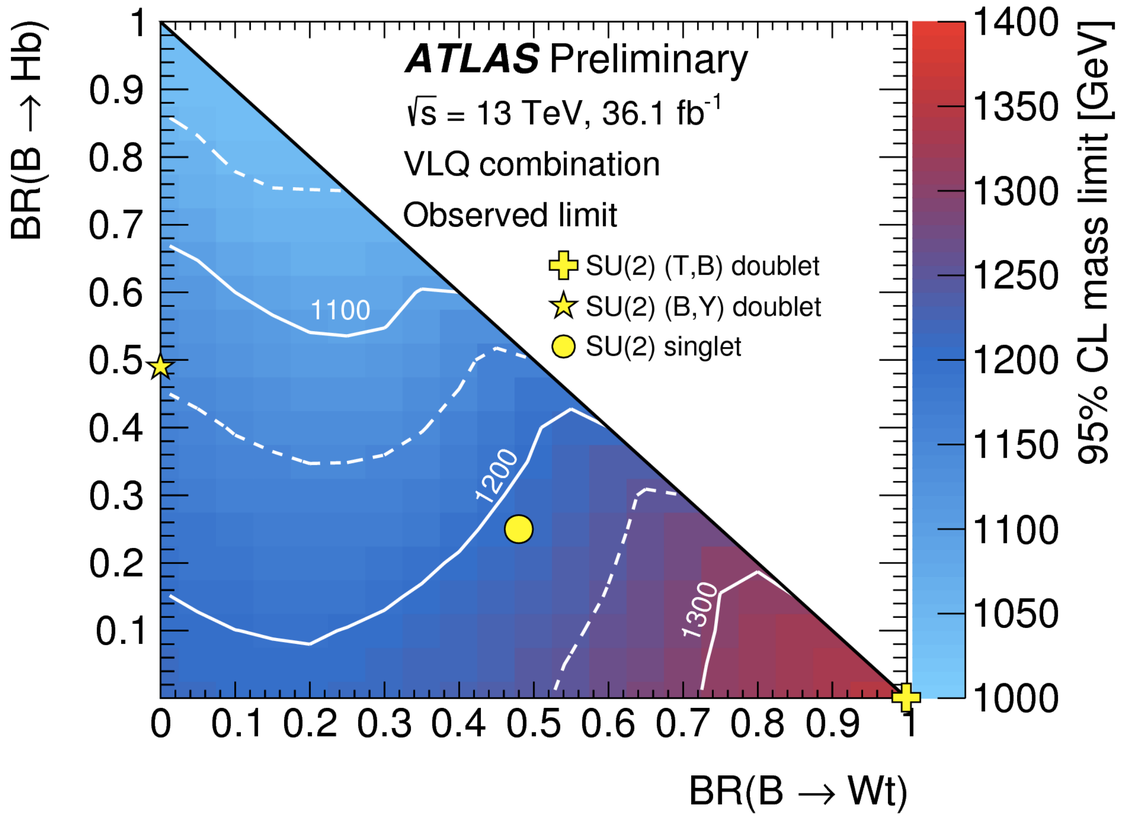
$T \to tH$ $B \to bH$

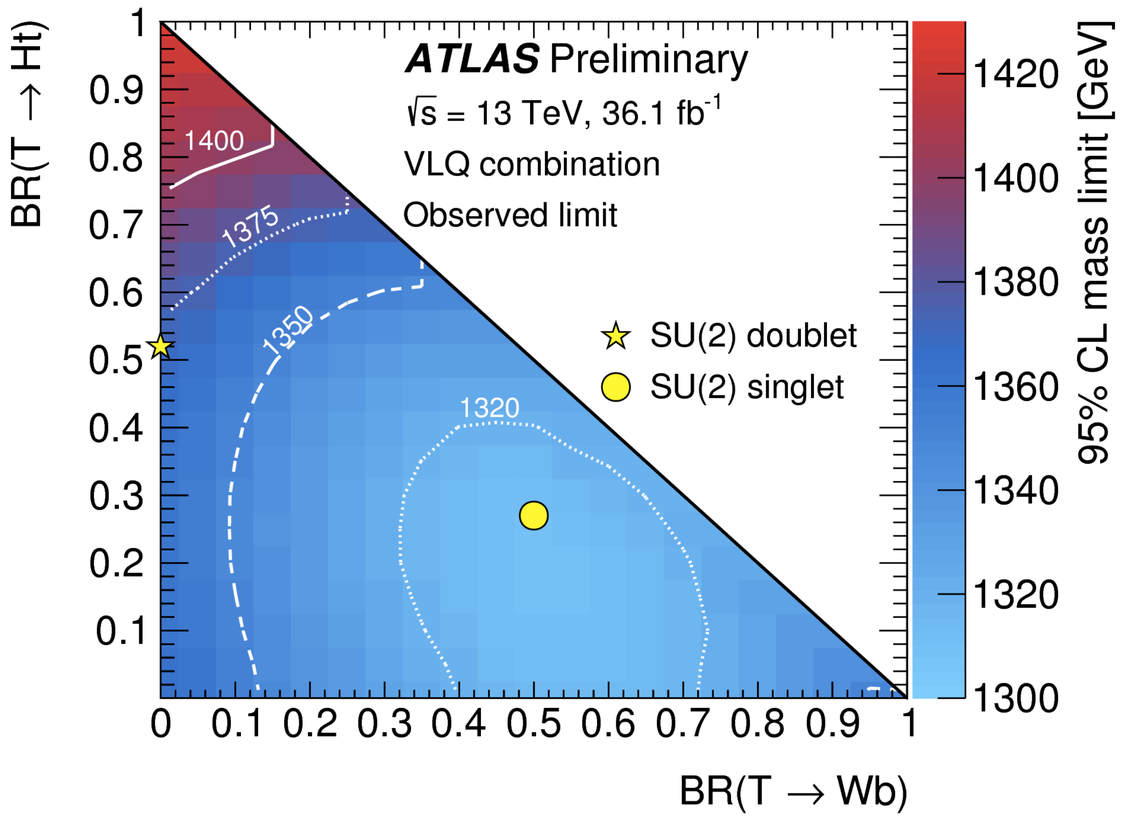
Vector-Like Quarks - Combination

36 fb^{-1}

ATLAS EXPERIMENT

- 6 published analyses for vector-like T
- 4 published analyses for vector-like B



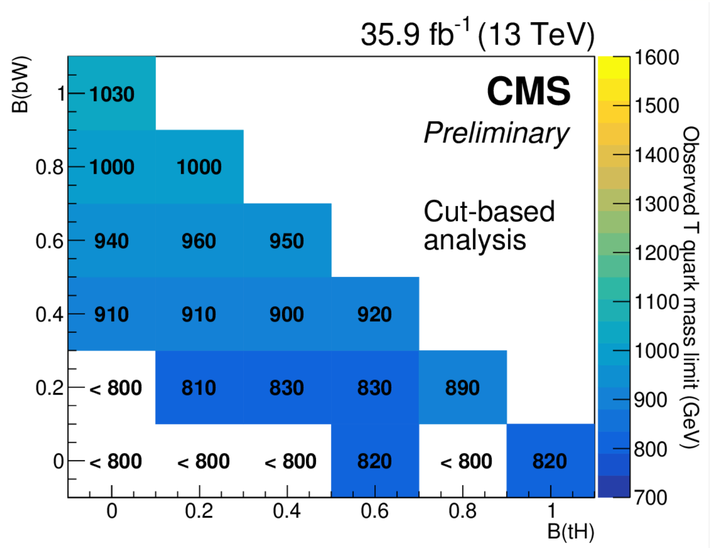


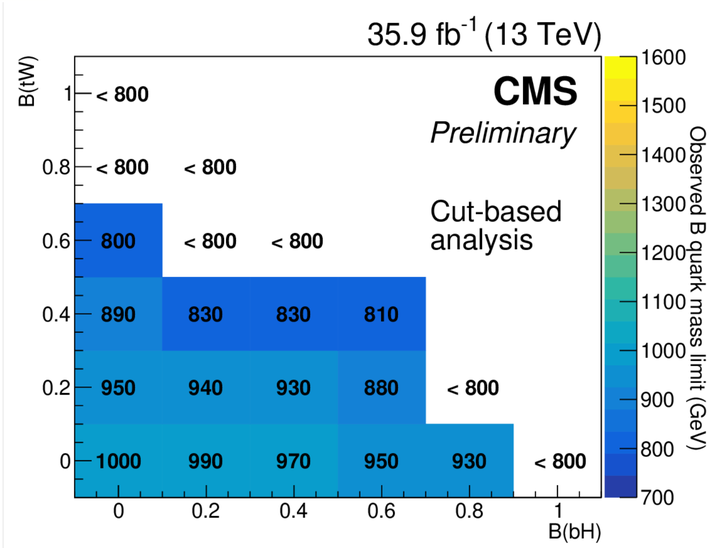
ATLAS-CONF-2018-032

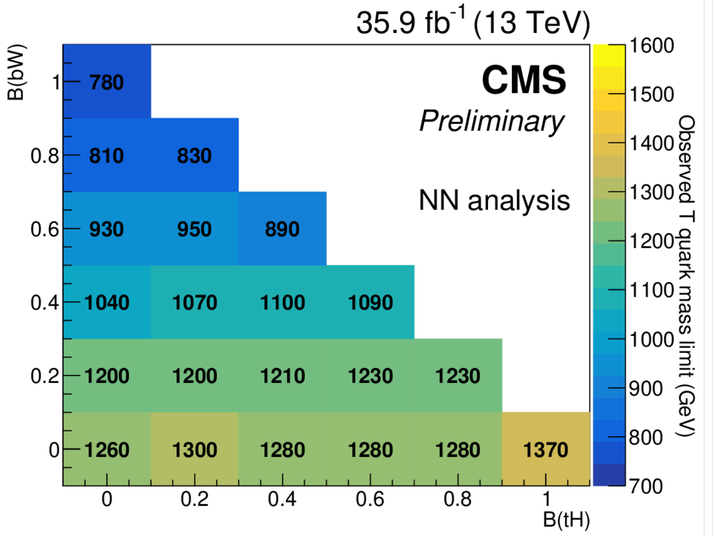
Vector-Like Quarks - Combination

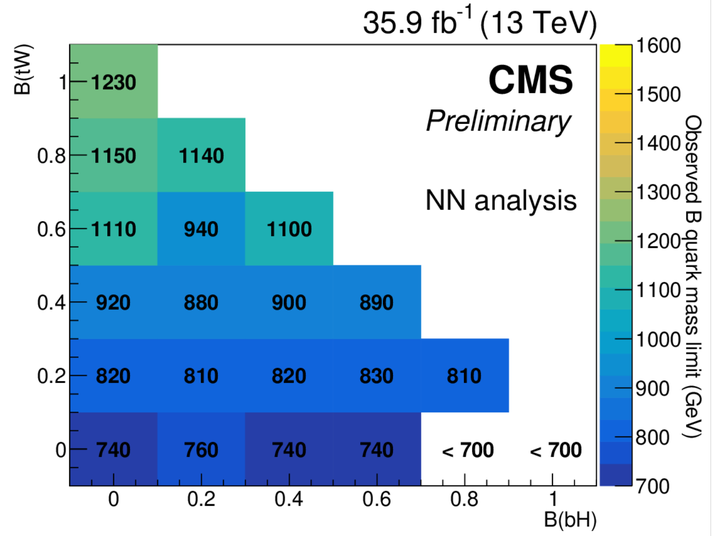
36 fb^{-1}

- Cut based analysis
- NN analysis









CMS-PAS-B2G-18-005

Conclusions

- The ATLAS and CMS collaborations have investigated invariant mass spectra of jets for BSM resonances with Run 2 LHC data.

- ATLAS and CMS have common signatures
  - ↳ New ATLAS results: dijet search with full Run-2 dataset
  - ↳ New CMS results: lowering sensitivity below 50 GeV

- No evidence for new physics, 95% CL limits are set

- Exploits full Run-2 statistics
  - ↳ Most signatures only use 1/3 of the available dataset
  - ↳ Continuous improvements to substructure tools
  - ↳ Upgrade detectors

Backup

Dijet searches

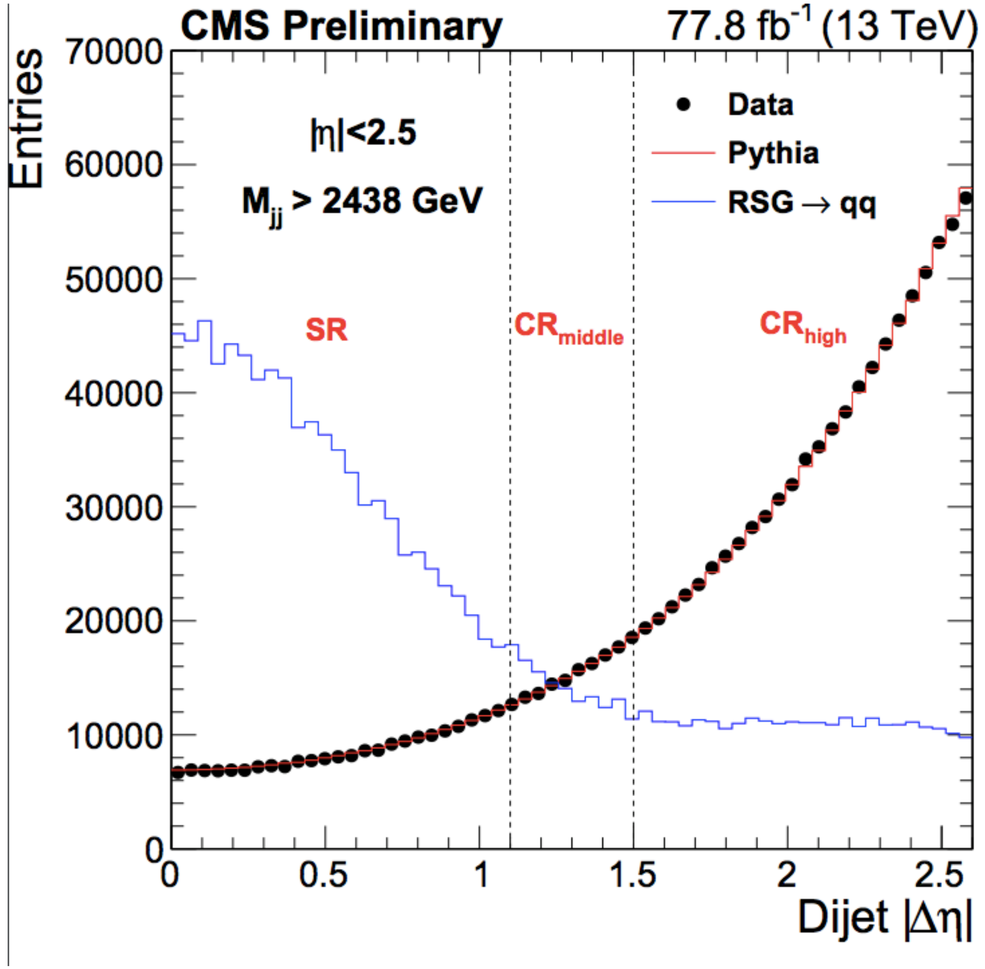
$$N(m_{jj})^{\text{Prediction}}_{\text{SR}} = R_{\text{ext.}} \times N(m_{jj})^{\text{Data}}_{\text{CR}_{\text{high}}}$$

$$R_{\text{ext.}} = \text{Corr}(m_{jj}) \times N(m_{jj})^{\text{Simulation}}_{\text{SR}} / N(m_{jj})^{\text{Simulation}}_{\text{CR}_{\text{high}}}$$

$$R^{\text{aux.}}_{\text{ext.}} = N(m_{jj})_{\text{CR}_{\text{middle}}} / N(m_{jj})_{\text{CR}_{\text{high}}}$$

$$\text{Corr}(m_{jj}) = \frac{R^{\text{aux.Data}}_{\text{ext.}}}{R^{\text{aux.Simulation}}_{\text{ext.}}} = P_0 + P_1 \times (m_{jj}/\sqrt{s})^4$$

Model	Final State	Observed (expected) mass limit [TeV] 36 fb^{-1} 13 TeV	77.8 fb^{-1} 13 TeV
String	qg	7.7 (7.7)	7.6 (7.9)
Scalar diquark	qq	7.2 (7.4)	7.3 (7.5)
Axigluon/coloron	$q\bar{q}$	6.1 (6.0)	6.2 (6.3)
Excited quark	qg	6.0 (5.8)	6.0 (6.0)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)	3.7 (3.8)
W′	$q\bar{q}$	3.3 (3.6)	3.6 (3.8)
Z′	$q\bar{q}$	2.7 (2.9)	2.9 (3.1)
RS graviton ($k/M_{\text{PL}} = 0.1$)	$q\bar{q}$, gg	1.8 (2.3)	2.4 (2.4)
DM mediator ($m_{\text{DM}} = 1$ GeV)	$q\bar{q}$	2.6 (2.5)	2.5 (2.8)



CMS-PAS EXO-17-026

Dijet + photon

80 fb^{-1}

ATLAS EXPERIMENT

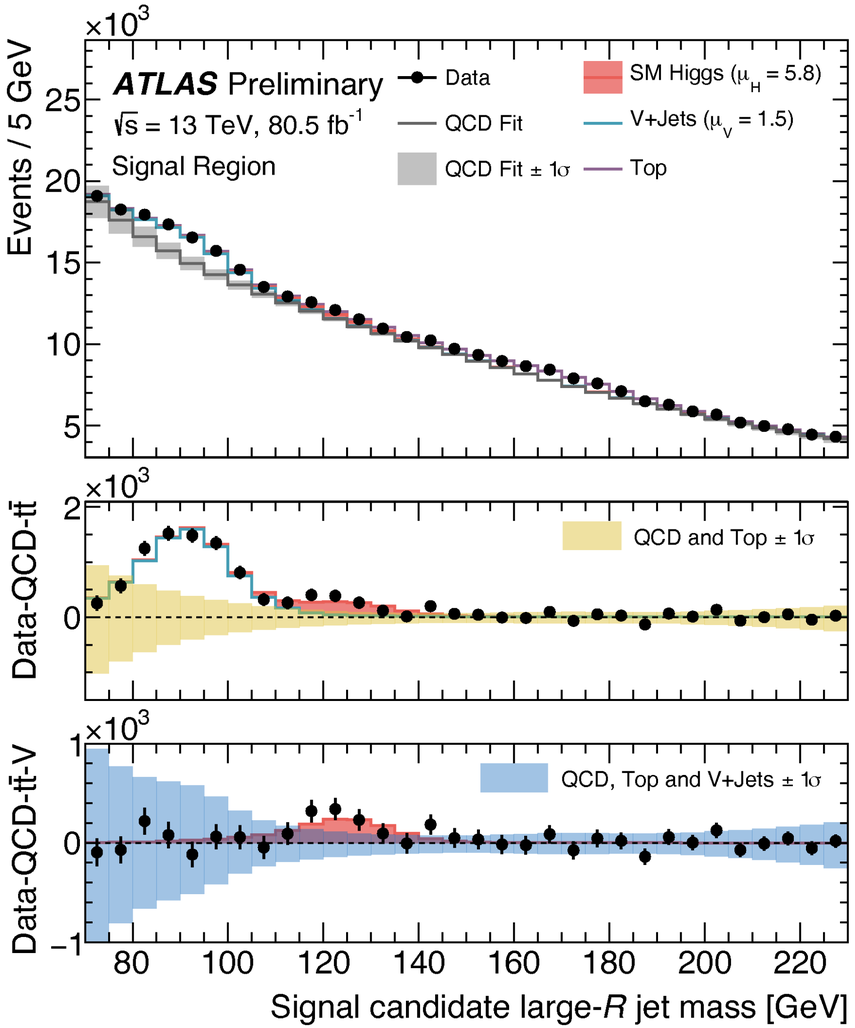
Criterion	Single-photon trigger	Combined trigger
Number of jets	$n_{\text{jets}} \geq 2$	
Number of photons	$n_\gamma \geq 1$	
Leading photon	$E_{\text{T}}^{\gamma} > 150$ GeV	$E_{\text{T}}^{\gamma} > 95$ GeV
Leading, subleading jet	$p_{\text{T}}^{\text{jet}} > 25$ GeV	$p_{\text{T}}^{\text{jet}} > 65$ GeV
Centrality	$\lvert y^* \rvert = \lvert y_1 - y_2 \rvert / 2 < 0.75$	
Invariant mass	$m_{\text{jj}} > 169$ GeV	$m_{\text{jj}} > 335$ GeV

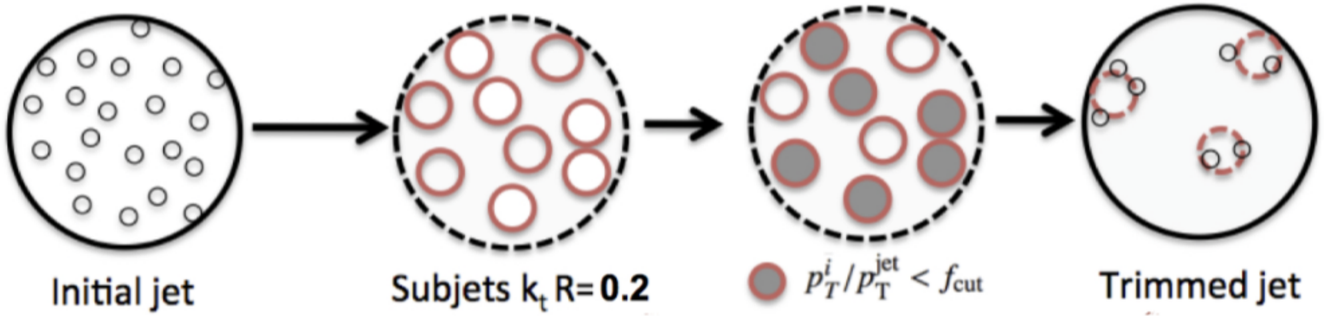
Criterion (applied to each trigger selection)	Inclusive	b-tagged
Jet $\lvert\eta\rvert$	$\lvert\eta^{\text{jet}}\rvert < 2.8$	$\lvert\eta^{\text{jet}}\rvert < 2.5$
b-tagging	–	$n_{b\text{-tag}} \geq 2$

$$y = \frac{1}{2} \ln \left[(E + p_z)/(E - p_z) \right]$$

arXiv:1901.10917

Dibjets + ISR

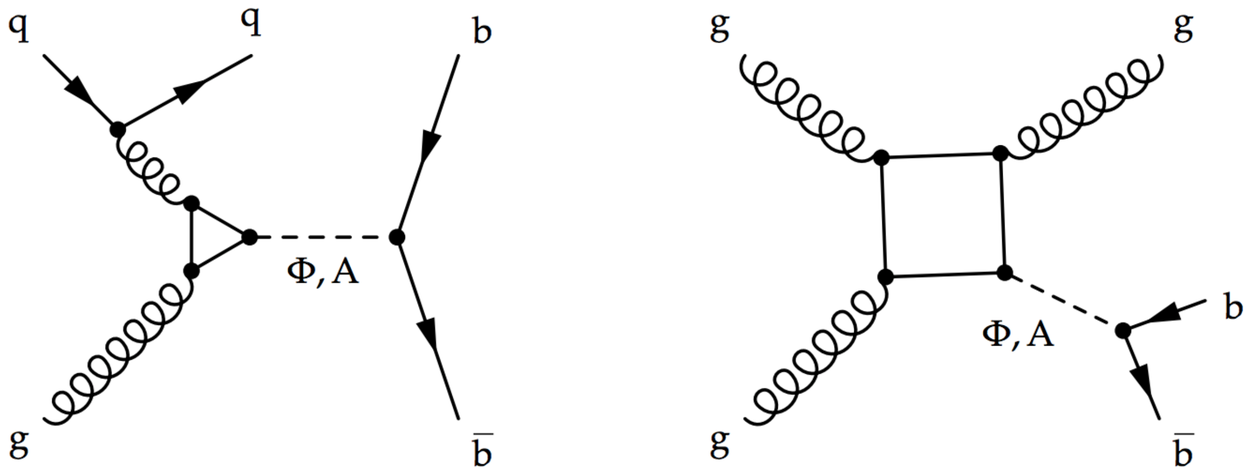




		Impact on Signals ($\sqrt{\Delta\sigma^2}/\mu$)			
Source	Type	V+jets	Higgs	Z' (100 GeV)	Z' (175 GeV)
Jet energy and mass scale	Norm. & Shape	15%	14%	23%	18%
Jet mass resolution	Norm. & Shape	20%	17%	30%	20%
V + jets modeling	Shape	9%	4%	4%	< 1%
$t\bar{t}$ modeling	Shape	< 1%	1%	< 1%	11%
b-tagging (b)	Normalisation	11%	12%	11%	15%
b-tagging (c)	Normalisation	3%	1%	3%	5%
b-tagging (l)	Normalisation	4%	1%	4%	7%
$t\bar{t}$ scale factor	Normalisation	2%	3%	2%	58%
Luminosity	Normalisation	2%	2%	2%	3%
Alternative QCD function	Norm. & Shape	4%	4%	3%	17%
W/Z and QCD (Theory)	Normalisation	14%	–	–	–
Higgs (Theory)	Normalisation	–	30%	–	–

ATLAS-CONF-2018-052

Dibjets + ISR



Uncertainty source	Process			
	W or Z (AK8)	W or Z (CA15)	Φ or A (AK8)	Φ or A (CA15)
Integrated luminosity	2.5%	2.5%	2.5%	2.5%
Trigger efficiency	2%	2%	2%	2%
Pileup	<1%	<1%	<1%	<1%
$N_2^{1,DDT}$ selection efficiency	4.3%	6%	4.3%	6%
Double-b tag	4% (Z)	8% (Z)	4%	8%
Jet energy scale / resolution	5–15%	5–15%	5–15%	5–15%
Jet mass resolution	8%	8%	8%	8%
Jet mass scale (% / (p_T [GeV] / 100))	0.4%	1%	0.4%	1%
Simulation sample size	2–25%	2–25%	4–20%	4–20%
NLO QCD corrections	10%	10%	—	—
NLO EW corrections	15–35%	15–35%	—	—
NLO EW W/Z decorrelation	5–15%	5–15%	—	—

CMS-EXO-17-024

Dijet + ISR(photon/jets)

	$m_{Z'}$ = 160 GeV		$m_{Z'}$ = 220 GeV	
ISR jet (ISR γ) selection criterion	ISR jet ϵ [%]	ISR γ ϵ [%]	ISR jet ϵ [%]	ISR γ ϵ [%]
p_{T}^{J} > 450 (200) GeV	0.22	5.8	0.17	1.1
ρ^{DDT} > 1.5	0.11	2.4	0.07	0.4
$p_{\mathrm{T}}^{\mathrm{ISR}}$ > 420 (155) GeV	0.09	2.4	0.06	0.4
τ_{21}^{DDT} < 0.5	0.07	1.3	0.04	0.3

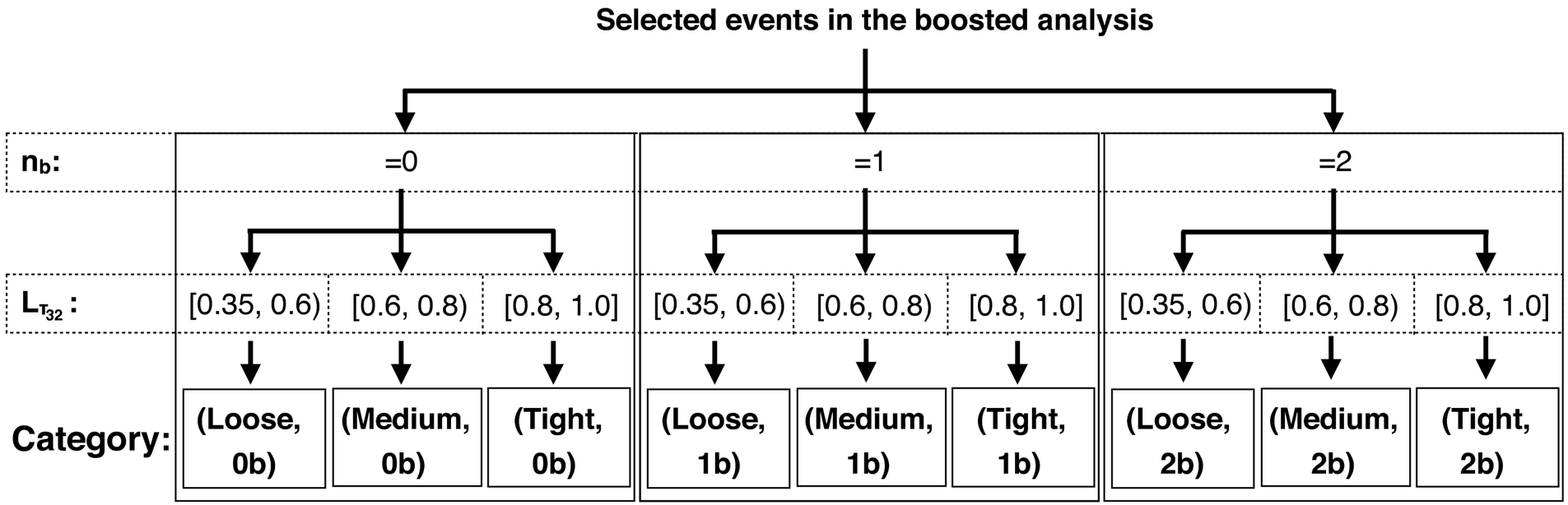
Uncertainty source	$\Delta\mu/\mu$ [%]		
	$m_{Z'}$ = 100 GeV	$m_{Z'}$ = 160 GeV	$m_{Z'}$ = 220 GeV
Transfer factor	86	90	88
Large-R jet calib. and modelling	19	25	17
W/Z normalisation	43	0	0
Signal PDF	0	0	1
Luminosity	2	0	0
Total systematic uncertainty	91	93	91
Statistical uncertainty	9	10	11

Uncertainty	Affected Distributions	Effect
Polynomial fit†*	Non-resonant	$1-5\%$
Electron veto	$t\bar{t}$, W, Z, Z'	0.5%
Muon veto	$t\bar{t}$, W, Z, Z'	0.5%
Jet mass smear†*	$t\bar{t}$, W, Z, Z'	0.7%
Jet energy corrections	$t\bar{t}$, W, Z, Z'	2%
Luminosity	$t\bar{t}$, W, Z, Z'	2.5%
Trigger*	$t\bar{t}$, W, Z, Z'	3%
N_2^{DDT} efficiency	$t\bar{t}$, W, Z, Z'	5%
Photon ID	$t\bar{t}$, W, Z, Z'	6%
Jet Mass Scale†*	$t\bar{t}$, W, Z, Z'	6%
$W+\gamma$ normalization†	W	11%
$Z+\gamma$ normalization†	Z	45%
$t\bar{t}$ normalization†	$t\bar{t}$	54%

ATLAS-EXOT-2017-01

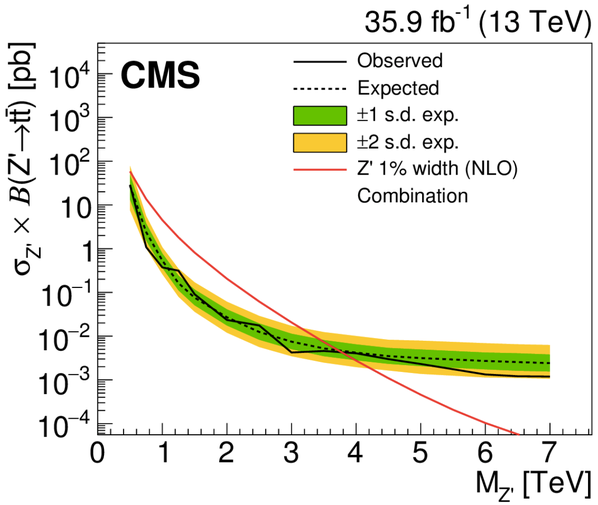
CMS-PAS-EXO-17-027

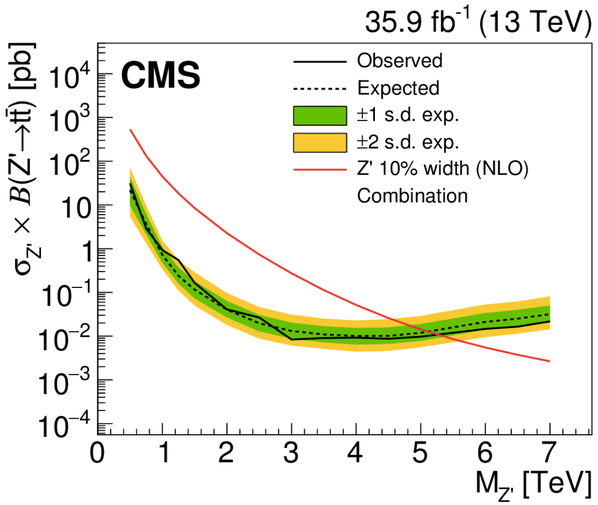
Top-antitop resonances

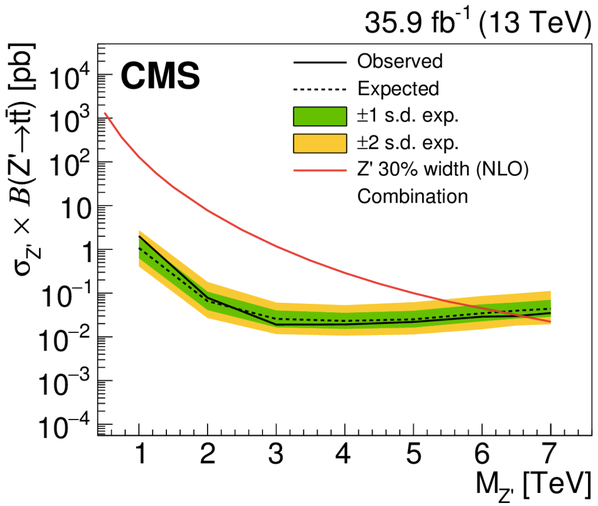


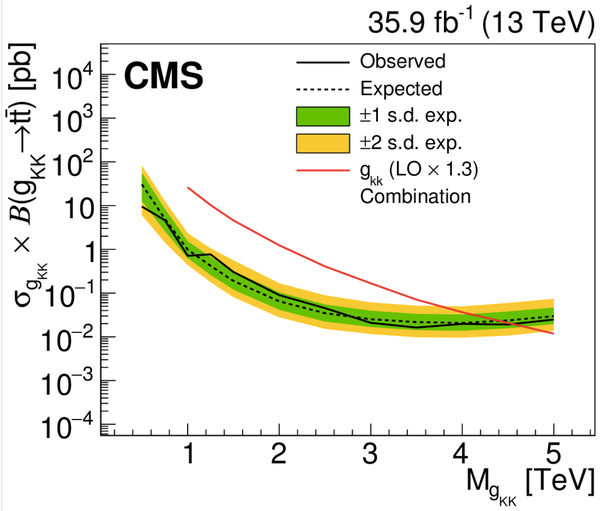
ATLAS-EXOT-2016-24

Top-antitop resonances



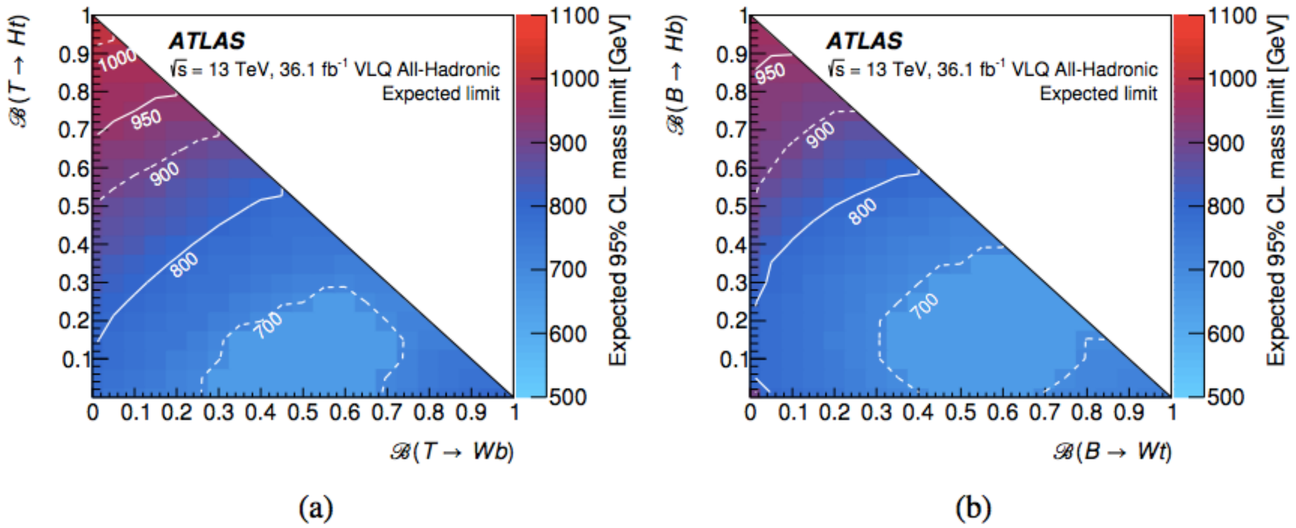






CMS-B2G-17-017

Vector-Like Quarks - All hadronic



ATLAS-EXOT-2017-14