Search for resonances in hadronic final states with the ATLAS detector

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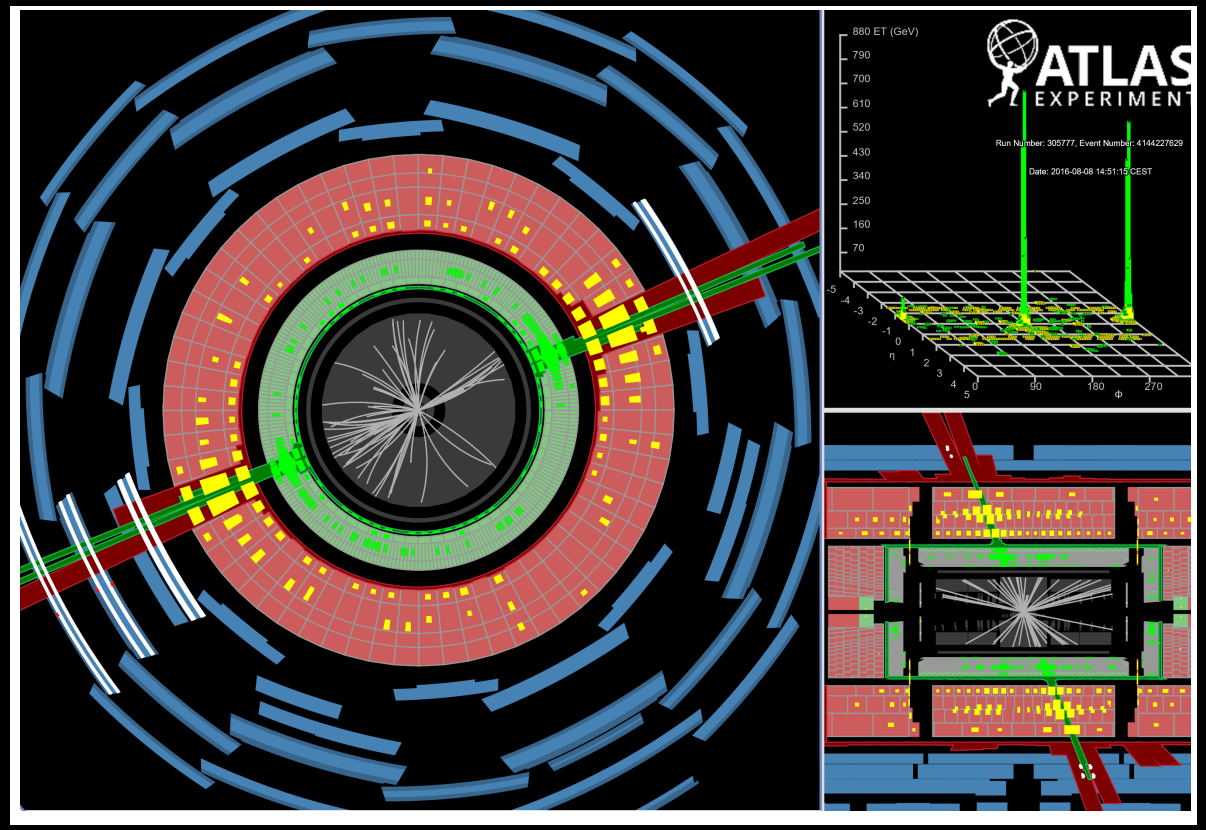
Signal models considered in the searches

1. Search for new phenomena in dijet events:
   - Excited quark signal processes: Assuming spin-1⁄2 excited quarks with the same coupling constants as SM quarks.
   - General Gaussian-shaped signals.

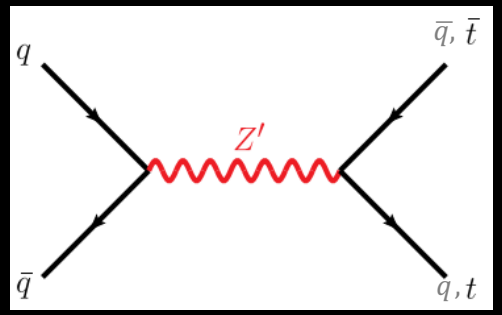
visualization of the highest-mass dijet event,
(Event 4144227629, Run 305777) recorded in 2016,
both central jets have :
pT = 3.74 TeV,
y* of 0.38 and
mjj = 8.02 TeV.

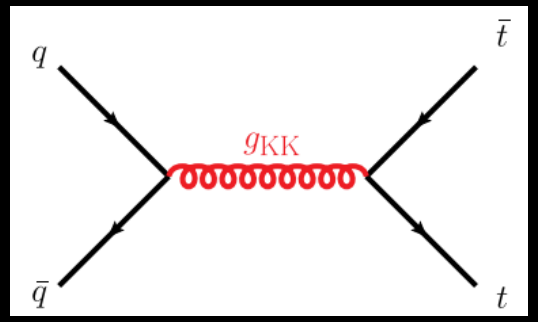


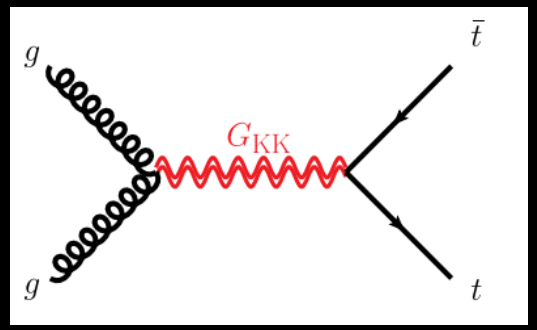
2. Search for low-mass resonances decaying into 2 jets and produced in association with a photon:
   - Z ′ axial-vector dark-matter mediators.
   - Gaussian-shape signal processes.

Signal models considered in the searches

3. Boosted resonances decaying to 2 b-quarks in association with a jet:
   - Standard Model Higgs boson —> 2 b-quarks & a leptophobic Z' —> two quarks and produced in association with a jet, generated using a Simplified Dark Matter (DM) model.
   - This Z' has democratic axial coupling (g_q) to all quark generations.







4. Search for heavy particles decaying into a top-quark pair in the fully hadronic final state:
   - Leptophobic Z' boson in the top-color assisted technicolor model.
   - Z' axial-vector or vector mediators in a framework of simplified models for DM.
   - Kaluza-Klein (KK) excitation of the gluon, gKK, and graviton, Gkk, in Randall-Sundrum (RS) extra-dimension scenario.

ATLAS-CONF-2019-007 139 fb-1, √s=13 TeV

Search for new phenomena in dijet events

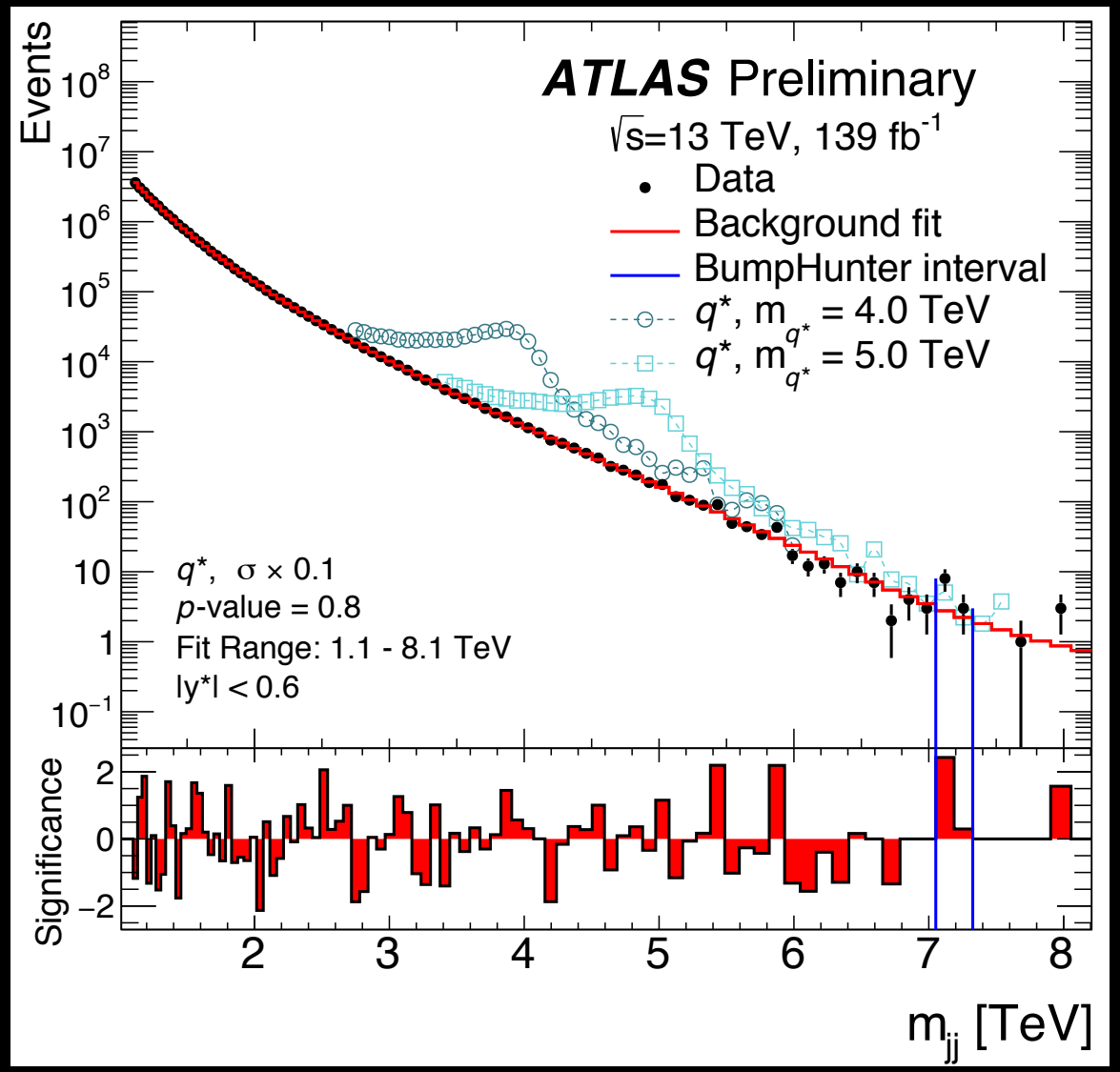
Search for new phenomena in dijet events (1)

ATLAS-CONF-2019-007 139 fb-1, √s=13 TeV

- Trigger requires 1 jet with pT >= 440 GeV.
- Events containing at least two jets considered in this analysis, pT of the two leading ones greater than 150 GeV.
- Selection on rapidity difference between the two leading jets, $|y^*| = \frac{1}{2}|y_1 - y_2| < 0.6$: reduces the contribution from QCD t-channel processes.
- Search starts at a dijet invariant mass (mjj) > 1.1 TeV for which the trigger requirement is fully efficient within the detector acceptance.

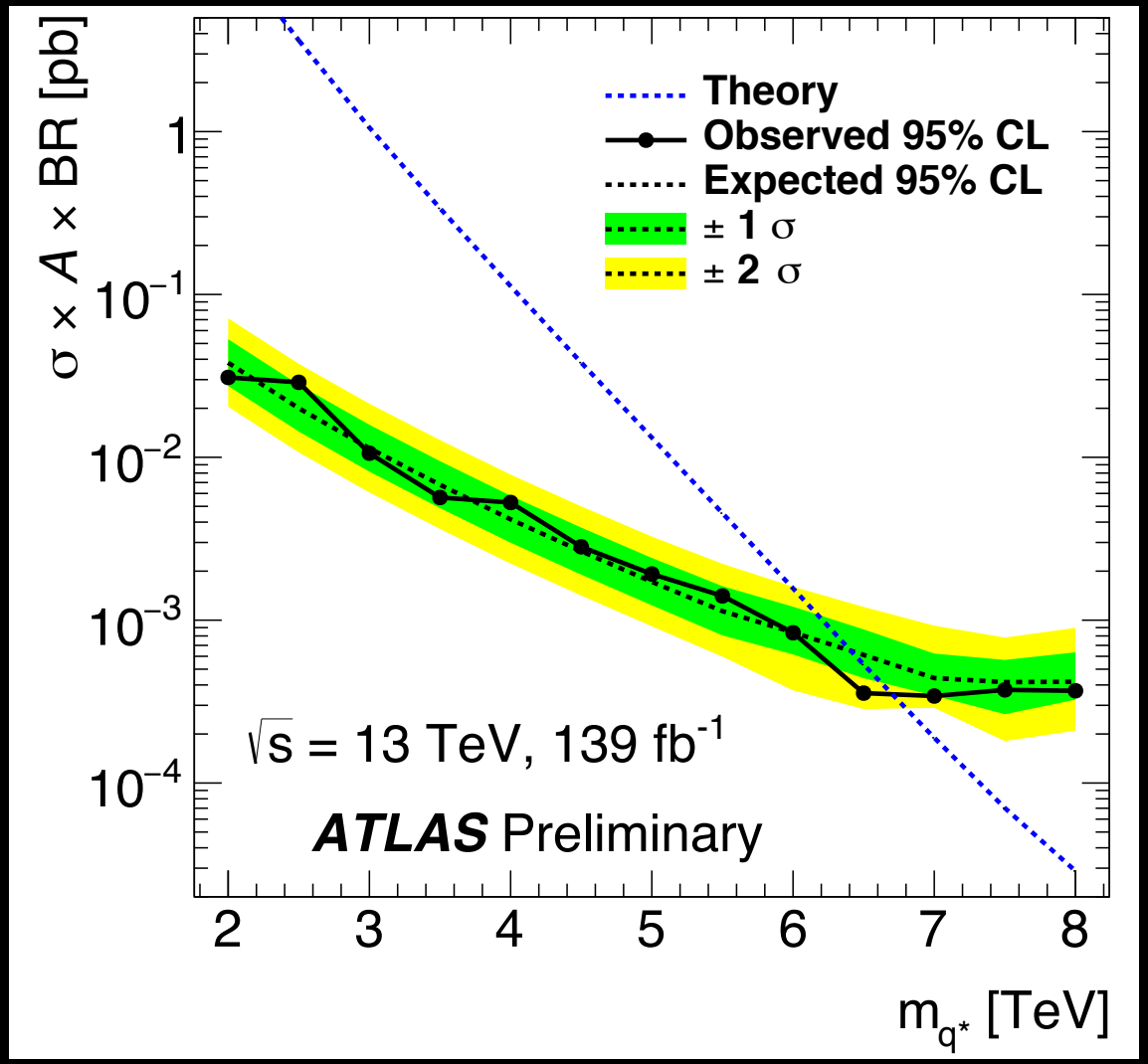
background estimate from data using the sliding-window method [Ref] using a background parametrization of the form:

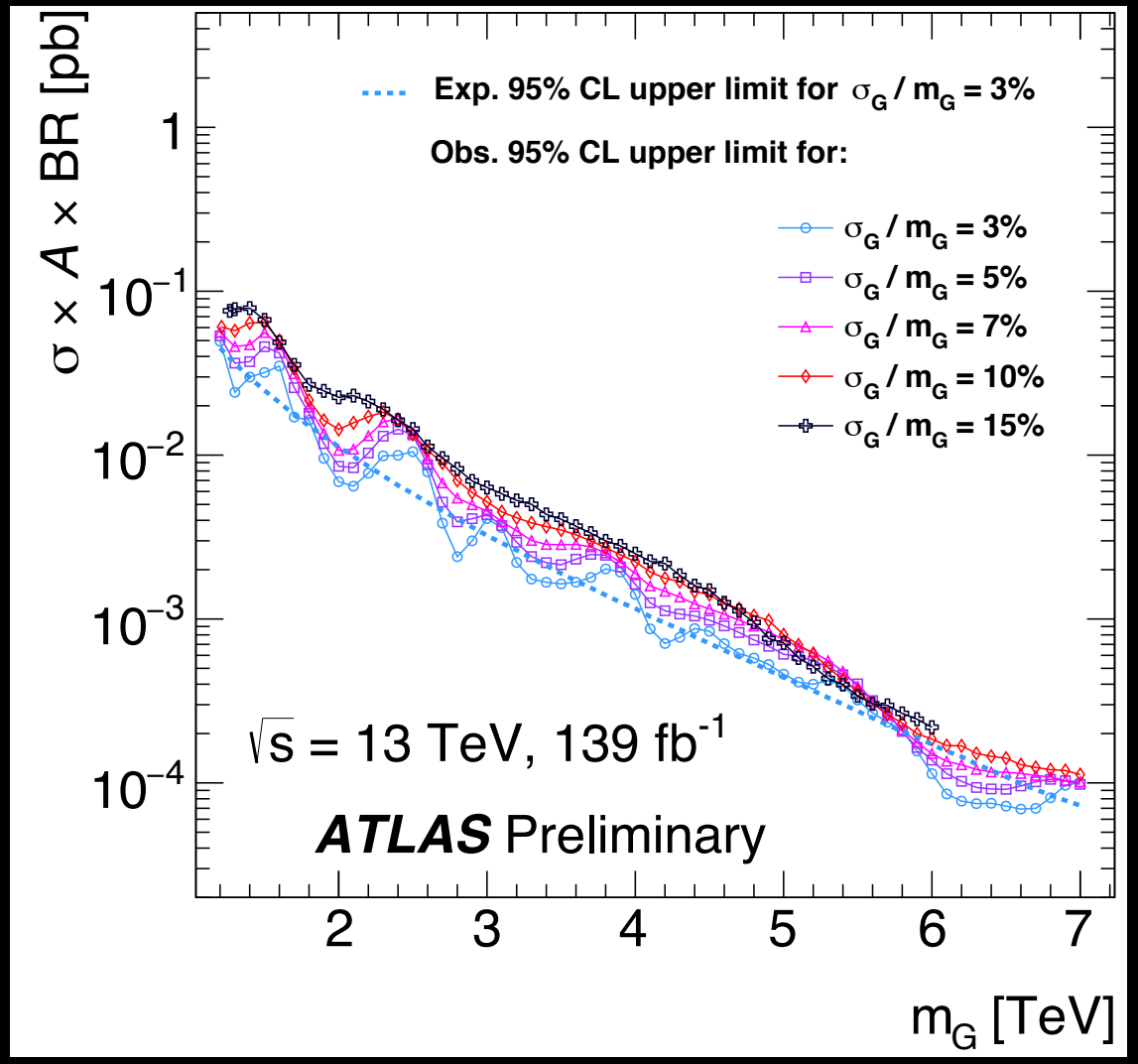
$$f(x) = p_1 (1-x)^{p_2} x^{p_3 + p_4 \ln x + p_5 (\ln x)^2}$$



Search for new phenomena in dijet events (2)

ATLAS-CONF-2019-007 139 fb-1, √s=13 TeV





95% CL upper limit obtained from the mjj distribution on σ * A * BR (cross-section*acceptance*branching ratio) to two jets as a function of (left) mass of a q* signal (mq*) and (right) the mass of a hypothetical signal that produces a Gaussian-shaped contribution to the mjj distribution.

arXiv:1901.10917 79.8 fb-1, $\sqrt{s}$=13 TeV

Search for low-mass resonances decaying into 2 jets and produced in association with a photon

Search for low-mass resonances decaying into 2 jets and produced in association with a photon (1)

arXiv:1901.10917

79.8 fb-1, √s=13 TeV

Event selection

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	–	$n_{b\text{-tag}} \geq 2$

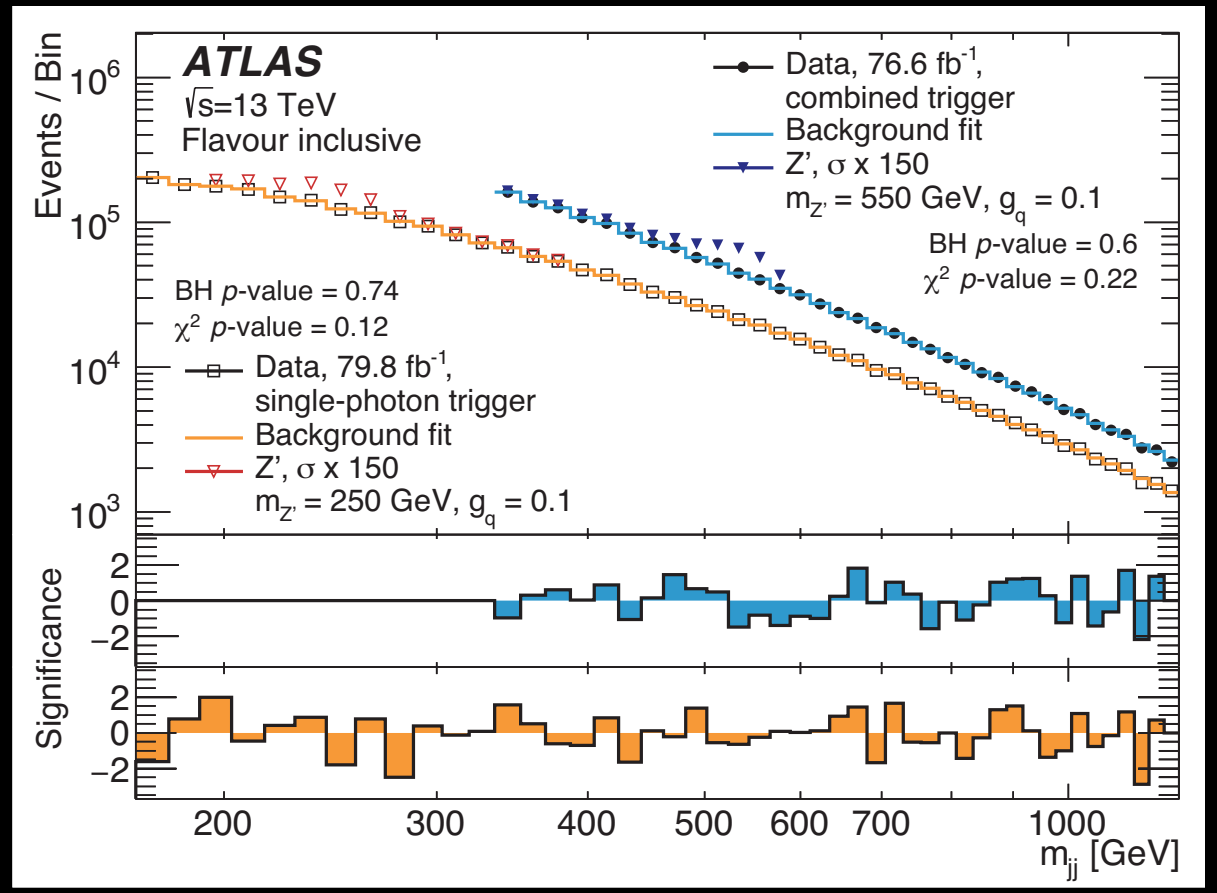
Background estimation done using a similar data driven approach as discussed for the dijet search on slide 4.

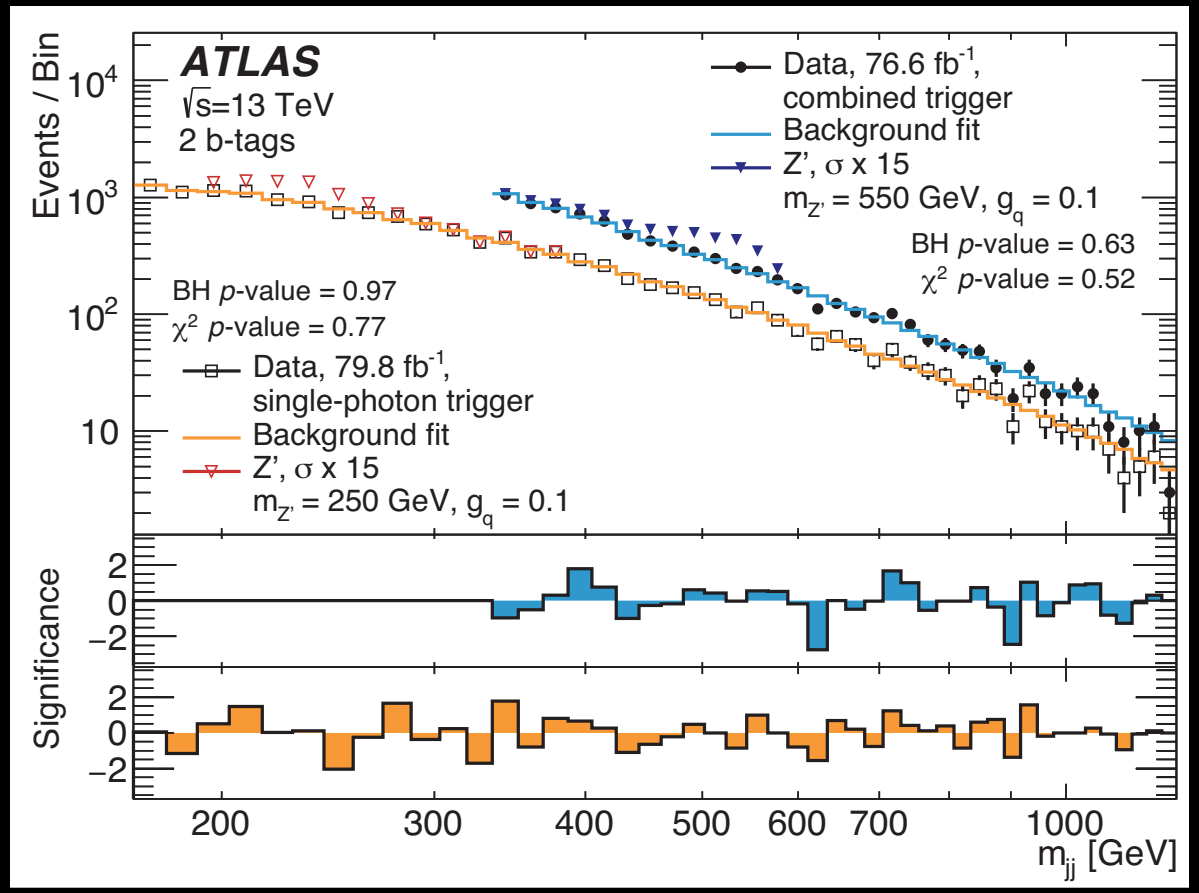
Search for low-mass resonances decaying into 2 jets and produced in association with a photon (2)

arXiv:1901.10917

Mjj distributions for the inclusive flavor (left) and b-tagged (right) categories

79.8 fb-1, √s=13 TeV

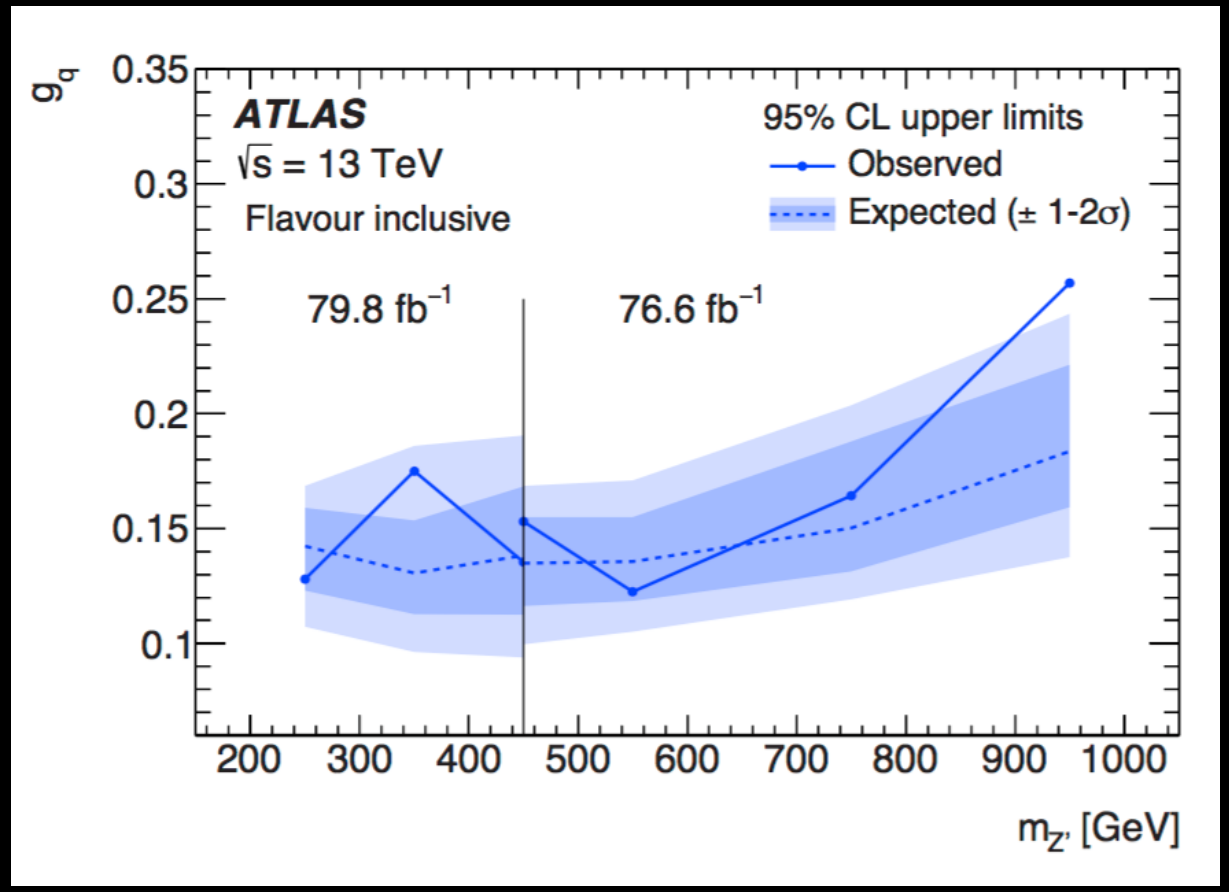




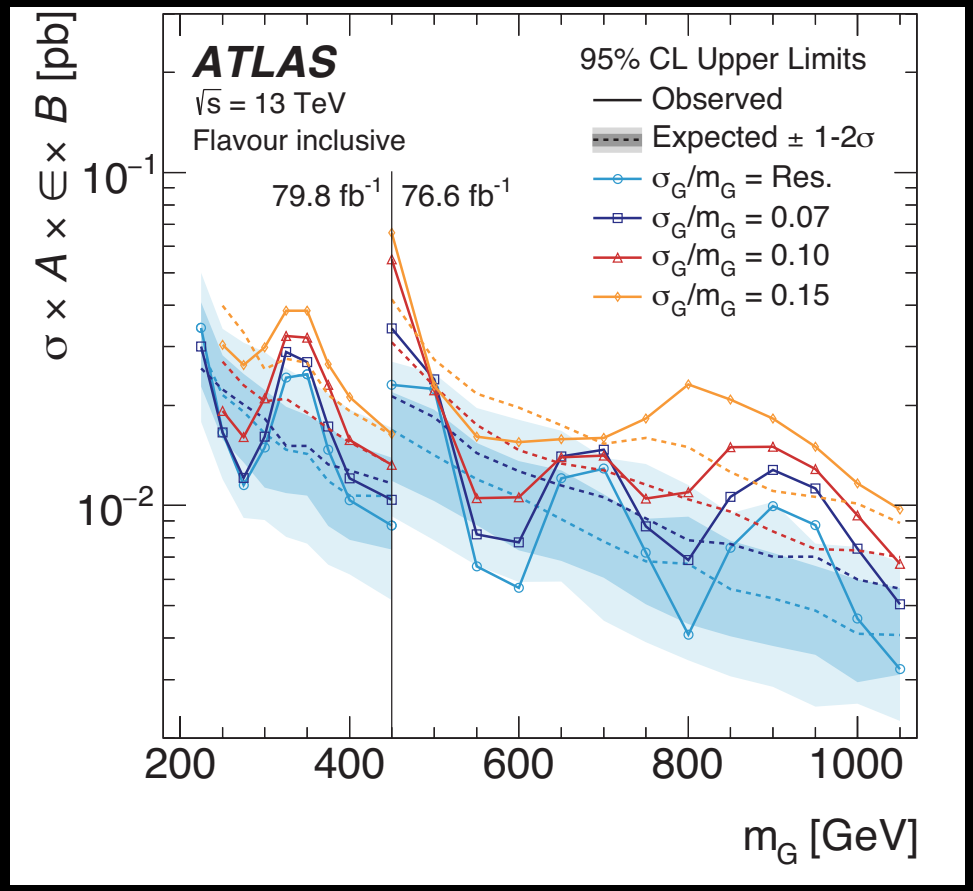
Search for low-mass resonances decaying into 2 jets and produced in association with a photon (3)

arXiv:1901.10917

Excluded values of the coupling between a Z' and quarks, as a function of $m_{Z'}$, from the flavor-inclusive category.



79.8 fb-1, √s=13 TeV



Upper limits on σ * A * BR for Gaussian-shape contributions to the dijet mass distributions from the flavor-inclusive category

ATLAS-CONF-2018-052 80 fb-1, √s=13 TeV

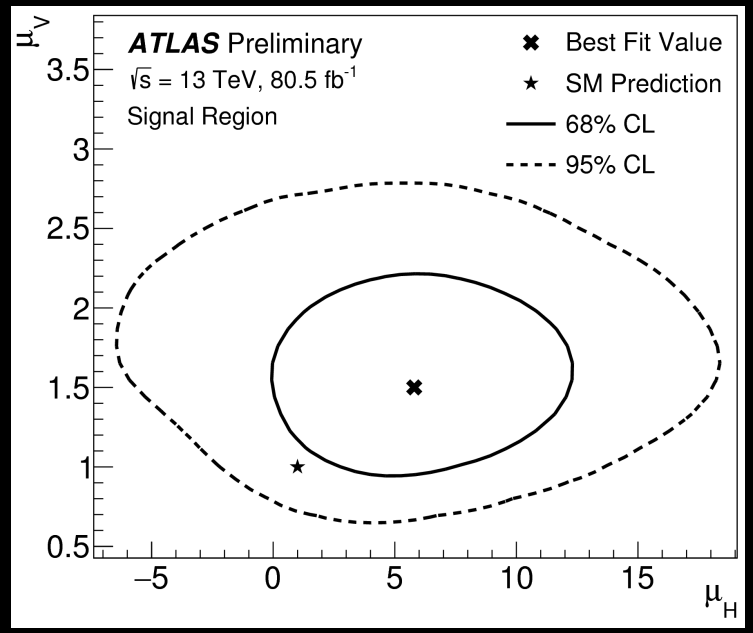
Boosted resonances decaying to 2 b-quarks in association with a jet

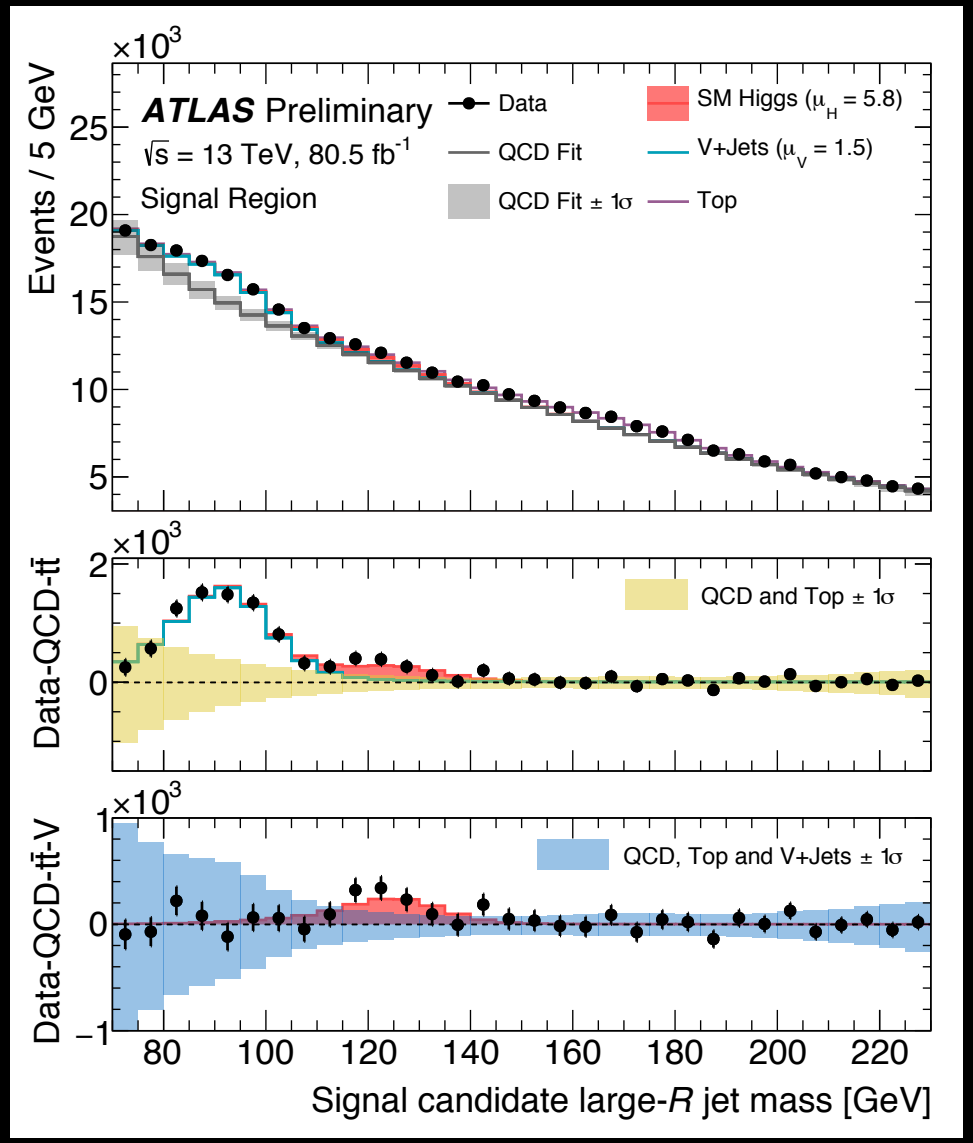
Boosted resonances decaying to 2 b-quarks in association with a jet (1)

ATLAS-CONF-2018-052
80 fb-1, √s=13 TeV

- Search for new resonances decaying into a pair of bottom (b) quarks in the mass range : 70 to 230 GeV.
- Final state consists of a signal large-R jet (to reconstruct particle decaying to bb) plus an additional jet.
- Requirement of an additional jet with high transverse momentum (pT) ensures a boosted regime.
- b-hadrons are identified using the multivariate b-tagging algorithm MV2c10 [Ref] on track-jets.

Observed signal strength for a SM higgs boson
μH = 5.8±3.1(stat.)±1.9(syst.) ±1.7(th.) consistent with the background-only hypothesis at 1.6 sigma.

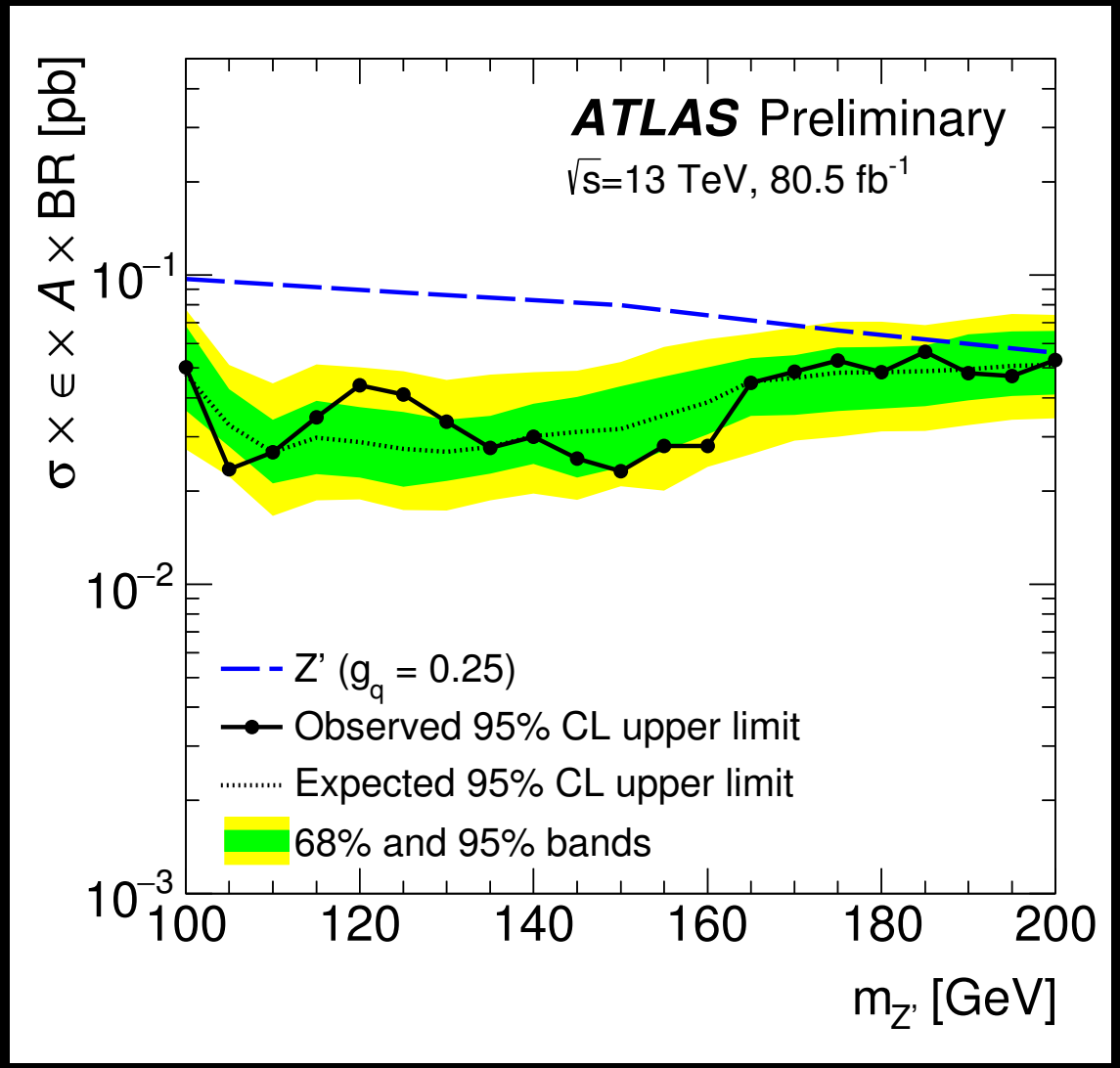


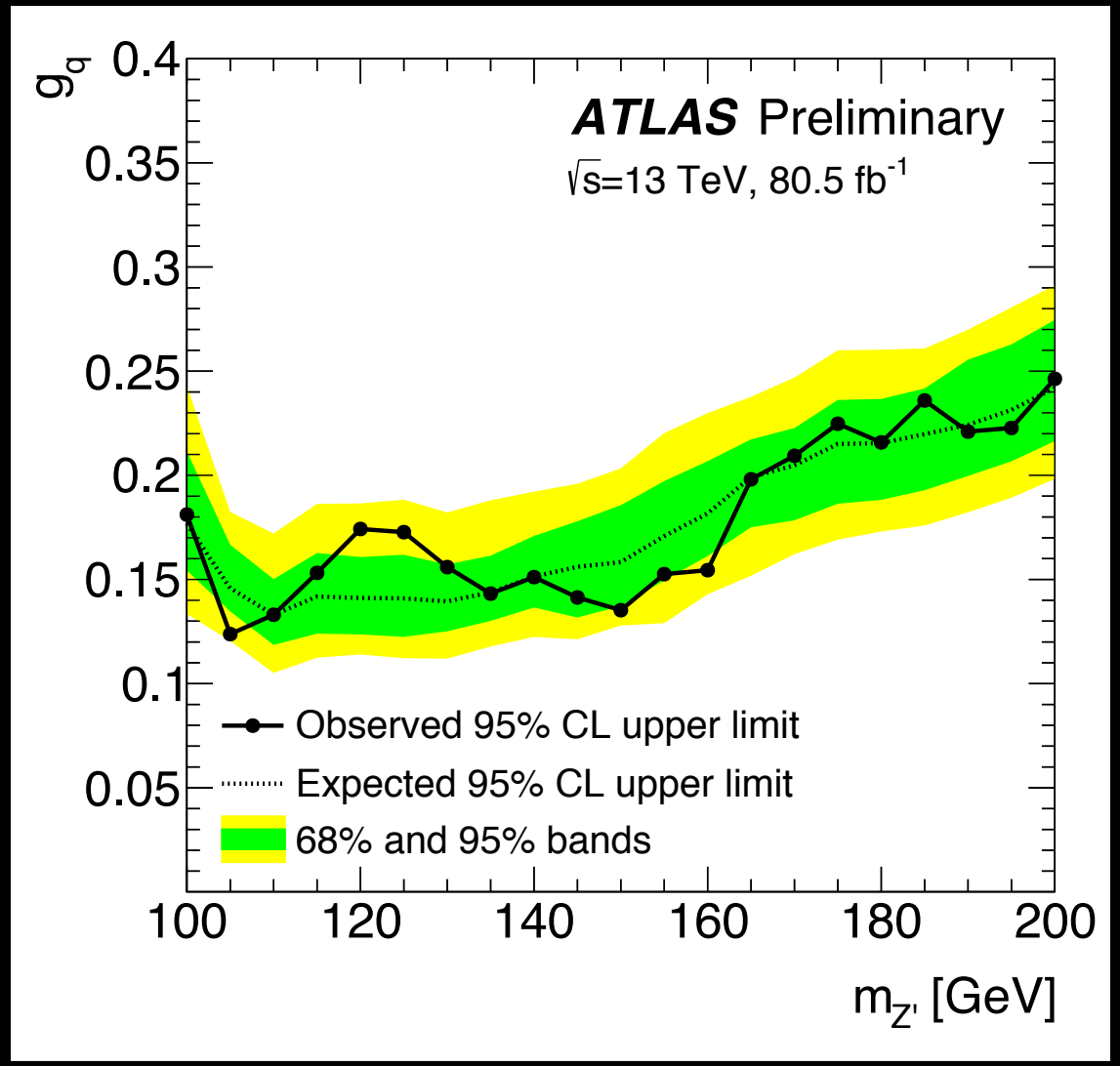


Large-R jet mass: SM Higgs boson, V+jets, tt̄ and QCD fit comparison to data, postfit.

Boosted resonances decaying to 2 b-quarks in association with a jet (2) ATLAS-CONF-2018-052

- Limits set on σ*efficiency*A*BR (left) and g_q parameter that controls the decay width of the DM mediator into SM particles (right) for a leptophobic Z' with democratic axial couplings.





PhysRevD.99.092004 36.1 fb-1, √s=13 TeV

Search for heavy particles decaying into a top-quark pair in the fully hadronic final state

Search for heavy particles decaying into a top-quark pair in the fully hadronic final state

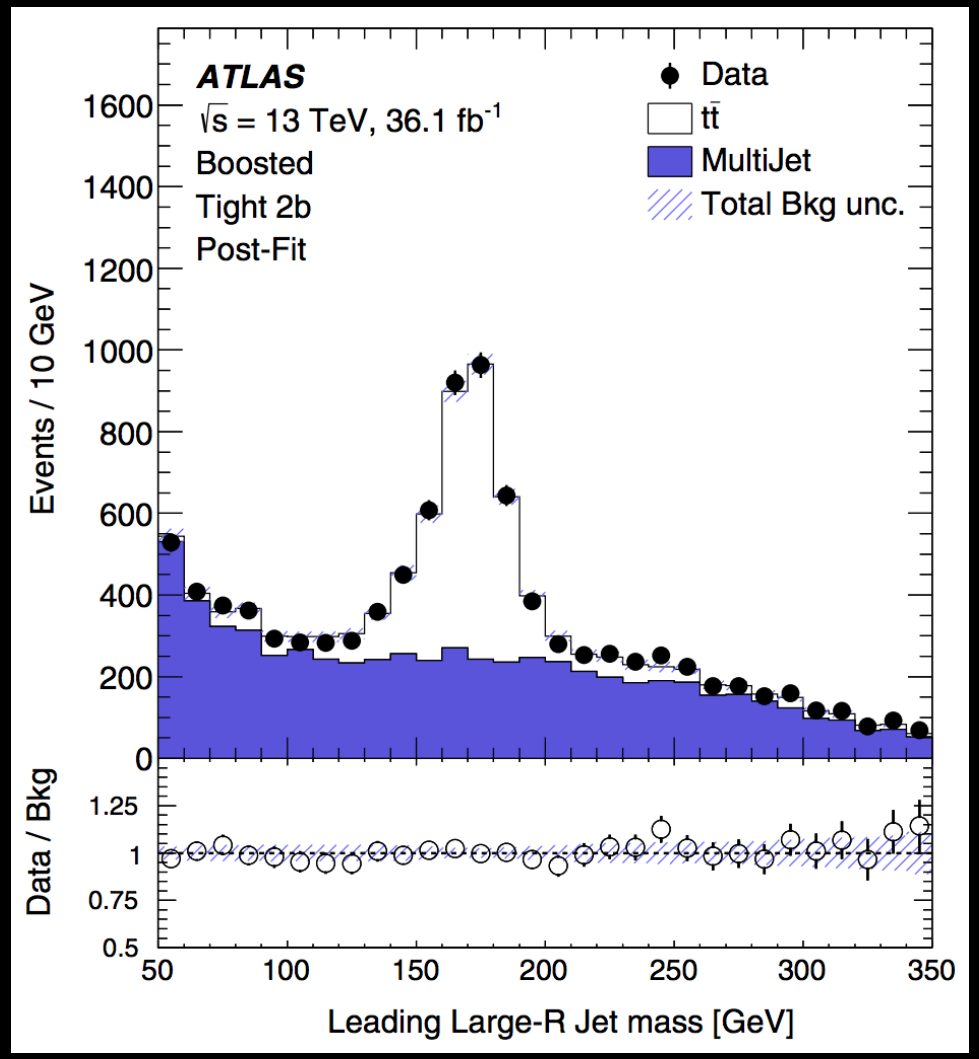
PhysRevD.99.092004 36.1 fb-1, √s=13 TeV

- Exploits two analysis techniques optimized for the reconstruction of a top-quark pair and background suppression
  - Resolved analysis: buckets of top method [Ref].
  - Boosted analysis: top-quark tagging requirements based on jet mass and a jet substructure variable called nsubjettiness τ_N :

$$\tau_n = \frac{1}{d_0} \sum_i p_{\mathrm{T}}^i \times \min(\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{n,i})$$

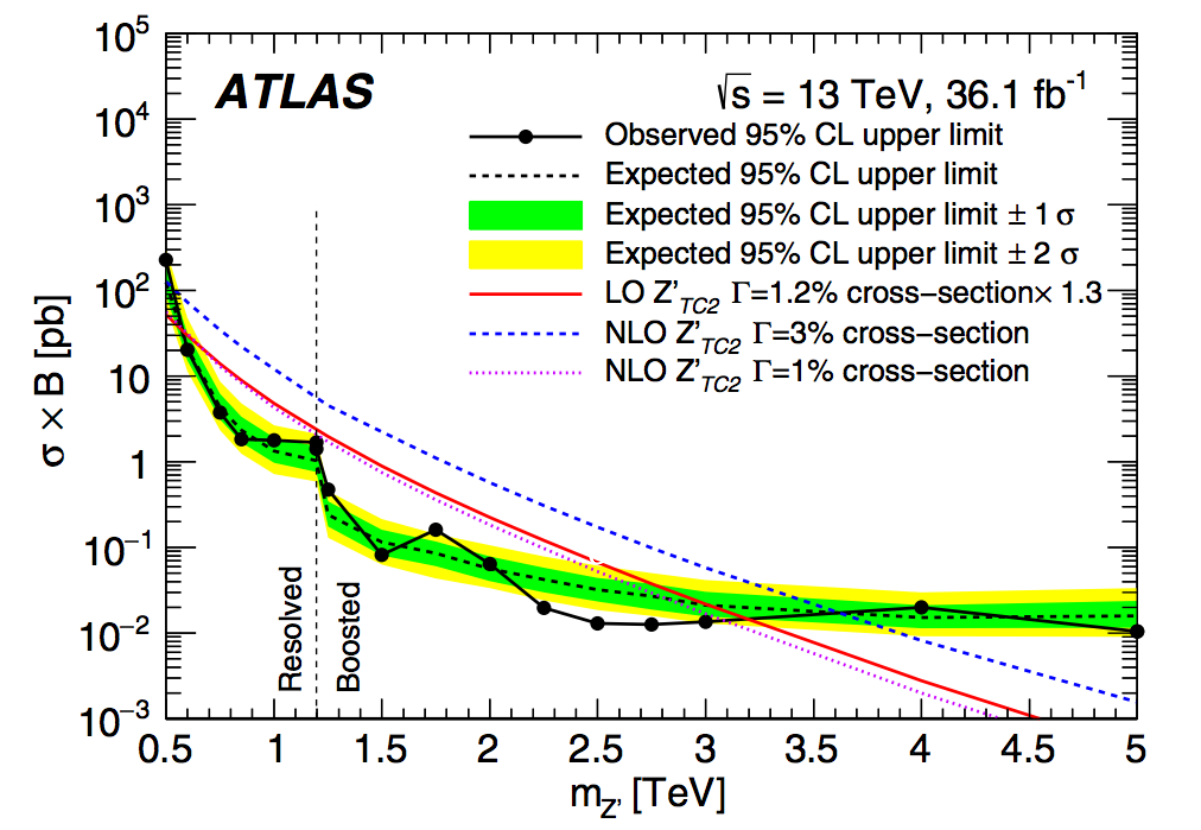
Fit on mtt (invariant mass of top anti-top system)

- Resolved: 3 control region (CRs) enriched in events from background processes + 1 signal region (SR). Categorization based on reconstructed top buckets and number of b-tagged jets in the events.
- Boosted: 8 SRs, categorized by the number of tight b-tagged track-jets and requirements on a n-subjettiness ratio observable.



Search for heavy particles decaying into a top-quark pair in the fully hadronic final state (2)

upper limits on σ* BR of Z'_{TC2} decaying into $t\bar{t}$ as a function of the Z'_{TC2} mass



PhysRevD.99.092004

36.1 fb-1, √s=13 TeV

Signal		Expected excluded mass [TeV]	Observed excluded mass [TeV]
Z'_{TC2}	($\Gamma = 1\%$)	[0.57, 2.8]	[0.58, 3.1]
	($\Gamma = 3\%$)	[0.51, 3.6]	[0.53, 3.6]
Z'_{med}	(vector)	$[0.75, 1.07] \cup [2.0, 2.1]$	$[0.74, 0.97] \cup [2.0, 2.2]$
	(axial-vector)	[1.99, 2.04]	$[0.80, 0.92] \cup [2.0, 2.2]$
g_{KK}	($\Gamma = 10\%$)	<3.5	<3.4
	($\Gamma = 20\%$)	<3.4	<3.4
	($\Gamma = 30\%$)	<3.3	<3.4
	($\Gamma = 40\%$)	<3.2	<3.4

Summary

- Final states with jets are investigated for BSM resonances in ATLAS with Run 2 LHC data

- Four searches discussed:
  - Dijet resonance search.
  - Resolved low mass dijet resonance search with ISR.
  - Low mass boosted di-b-jet resonances with an extra jet.
  - tt high-mass resonance search in all-hadronic final states.

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

- Continued Improvements to substructure tools and expected reduction in large-R jet uncertainties for future analyses.

- Studies of future prospects for Z' and W' searches at HL-LHC show that the mass search range for these particles can be extended by ~2 TeV (HL-LHCProspectsZ'_W').
  - Does not consider improvements in boosted jet reconstruction and top taggers.

Backup

Search for new phenomena in dijet events

139 fb-1, √s=13 TeV

events are selected from pp collisions using a trigger that requires at least one jet reconstructed with a pT greater than 420 GeV. This is the lowest-pT single-jet trigger for which all selected events are recorded.

The dijet pair with highest invariant mass in the dataset has mj j = 8.02 TeV and was collected in 2016.

Bin widths for mjj are chosen to reflect the evolution of the mj j resolution and therefore widen as the mass increases, from about 30 GeV at the lowest mj j values (1.1 TeV) to about 140 GeV at the highest values (8 TeV).

Search for low-mass resonances decaying into 2 jets and produced in association with a photon (1)

arXiv:1901.10917

Sliding window background fitting procedure

79.8 fb-1, √s=13 TeV

- single fit using a given function over the entire mass distribution is replaced by many successive fits.
- For each bin, same function is fit to a broad mass range centred on the bin, background prediction for that bin is the value of the fitted function in the centre of the range.
- process repeated for each bin and results are combined to form a background prediction covering the entire distribution.

$$f(x) = p_1 x^{-p_2} e^{-p_3 x - p_4 x^2}$$

set of parametric functions considered

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

In addition a 4 and 3 parameter variant are also considered with p5=0 and p4,p5=0

Width of mass range considered: broadest possible while maintaining a a chi-square p value of > 0.05 in regions where narrow excesses are not found. Excesses identified using the BH algorithm.

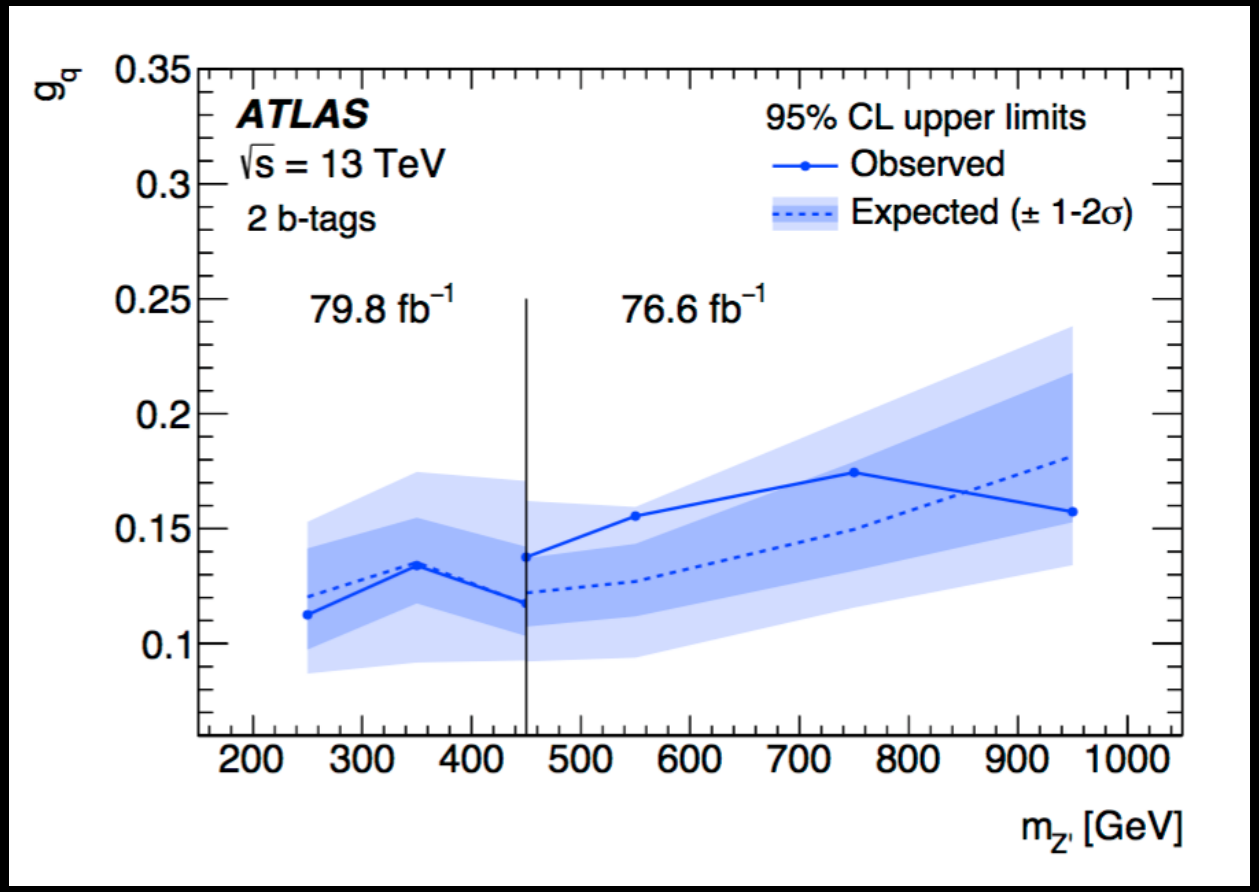
MC samples of background containing a photon with associated jets using Sherpa 2.1.1 in several bins of photon transverse momentum at the particle level. from 35 GeV to 4 TeV were used to validate the background fitting procedure. Also used to verify that fitting procedure is robust against false signals. MC also used to calculate the fractional dijet resolution: 8-3% for masses of 225 GeV to 1.1 TeV.

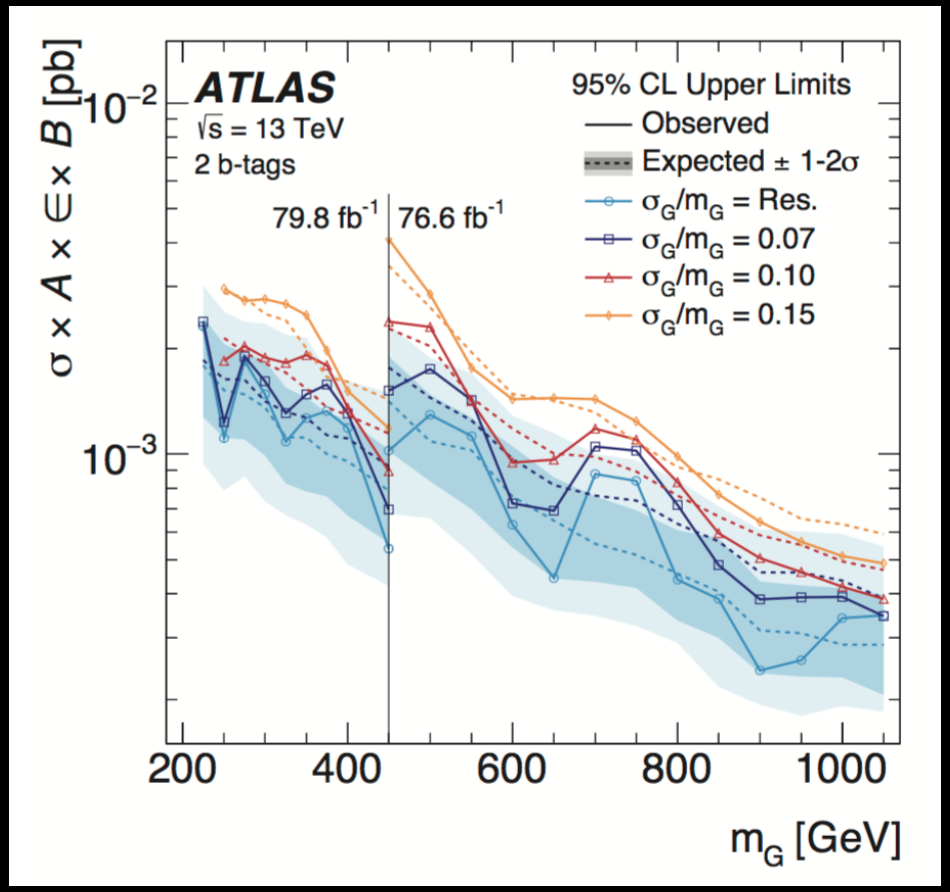
Search for low-mass resonances decaying into 2 jets and produced in association with a photon (2)

arXiv:1901.10917

b-tagged category, DI1 b-tagger

79.8 fb-1, √s=13 TeV

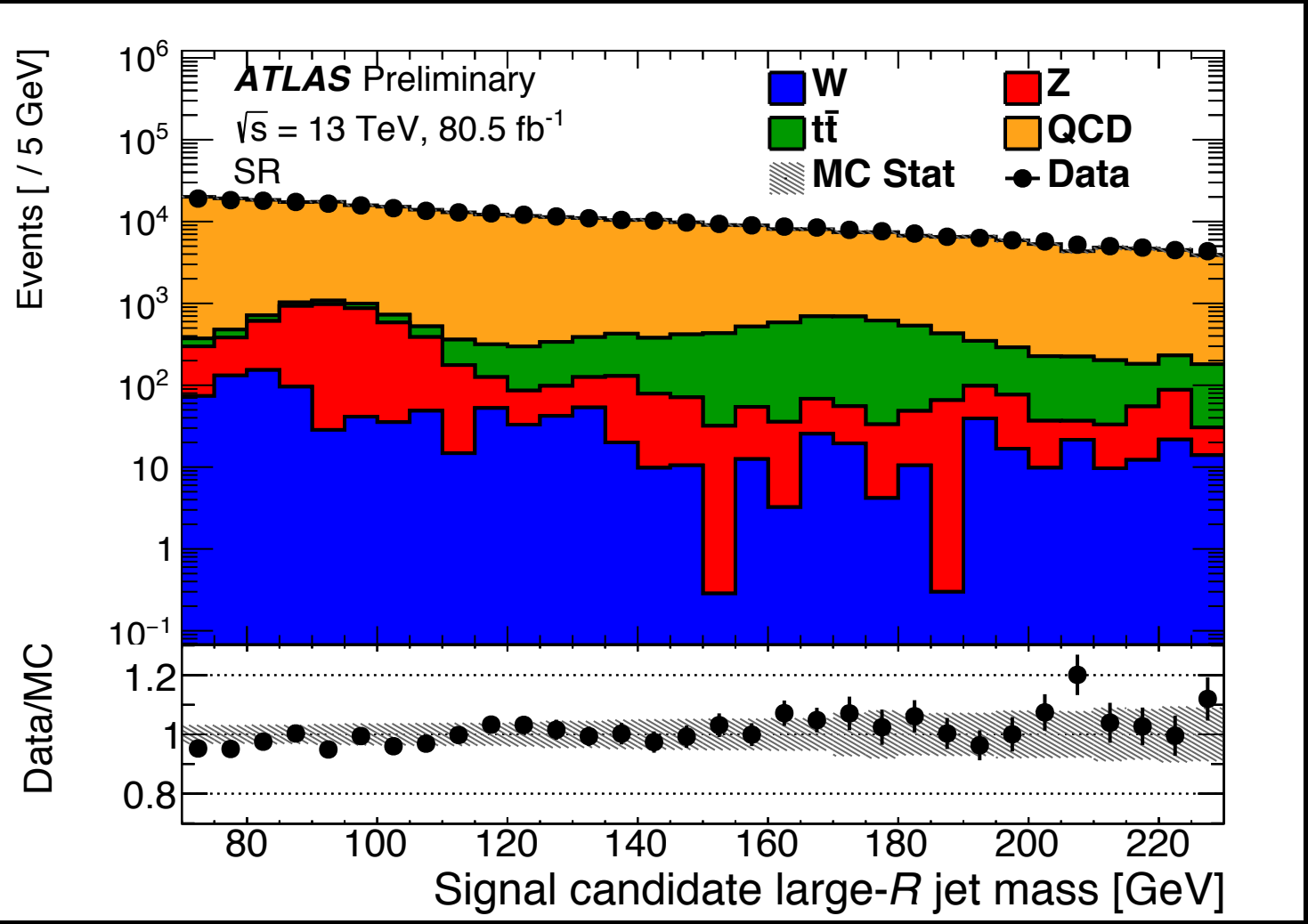


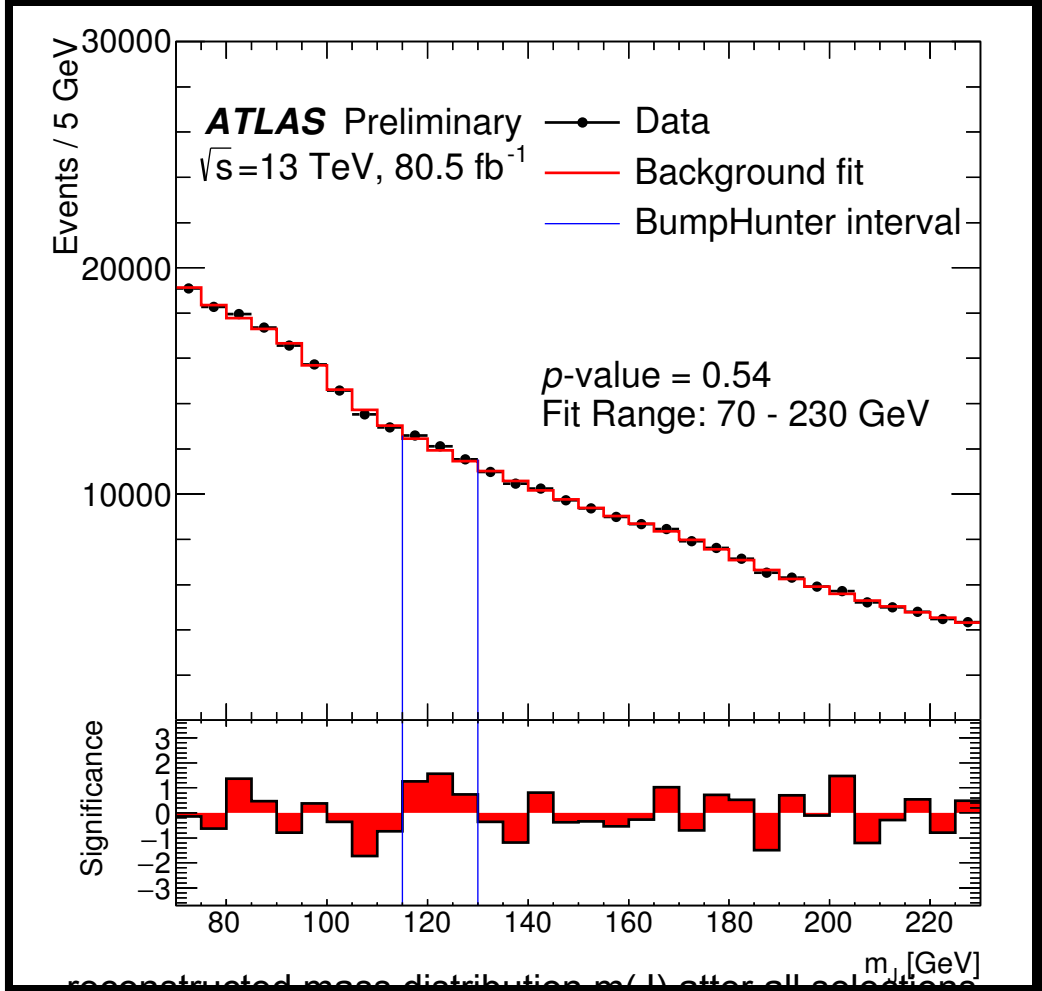


Boosted resonances decaying to 2 b-quarks in association with a jet (1) ATLAS-CONF-2018-052

MV2c10 b-tagger

80 fb-1, √s=13 TeV





Boosted resonances decaying to 2 b-quarks in association with a jet (2) ATLAS-CONF-2018-052

80 fb-1, √s=13 TeV

		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%	–	–

Boosted resonances decaying to 2 b-quarks in association with a jet (3) ATLAS-CONF-2018-052

80 fb-1, √s=13 TeV

		CR_{QCD}	SR
$V+$ jets	$Z+$ jets	0.28	0.80
	$W+$ jets	0.72	0.20
$t\bar{t}$	All hadronic	0.58	0.63
	Semi-leptonic	0.38	0.34
	Dileptonic	0.04	0.03
$H \to b\bar{b}$	ggF	0.49	0.53
	VBF	0.17	0.25
	WH	0.21	0.12
	ZH	0.12	0.10

fractional composition of the different resonant contributions in the defined regions

Search for heavy particles decaying into a top-quark pair in the fully hadronic final state: signal model details (1)

PhysRevD.99.092004 36.1 fb-1, √s=13 TeV

- Top-color assisted technicolor model
  - predicts Z'TC2
  - Spin 1 color singlet boson.
  - Leptophobic Z' couples only to 1st and 3rd generation quarks and produced mainly by qqbar annihilation.
  - Model parameters chosen to maximize branching fraction for Z' to ttbar decay, reaches of 33%
  - Width is set to 1-3 %

- Framework of simplified dark matter (DM) interactions
  - Uses Z' axial-vector or vector mediators, following recommendations of LHC DM working group.
  - 5 parameters of interest in the model: mediator mass m(med), dark matter mass m(DM), mediator couplings to quarks g(q), leptons g(l) and to dark matter g(DM).
  - Considers coupling parameters in the A1 (V1) scenario of Ref for the axial-vector (vector) mdeiator.
  - Branching fraction of the mediators into ttbar is 8.8 % and the width is approximately 5.6 % in the search range considered.
  - Dark matter mass m(DM) is fixed to 10 GeV.

Search for heavy particles decaying into a top-quark pair in the fully hadronic final state: signal model details (2)

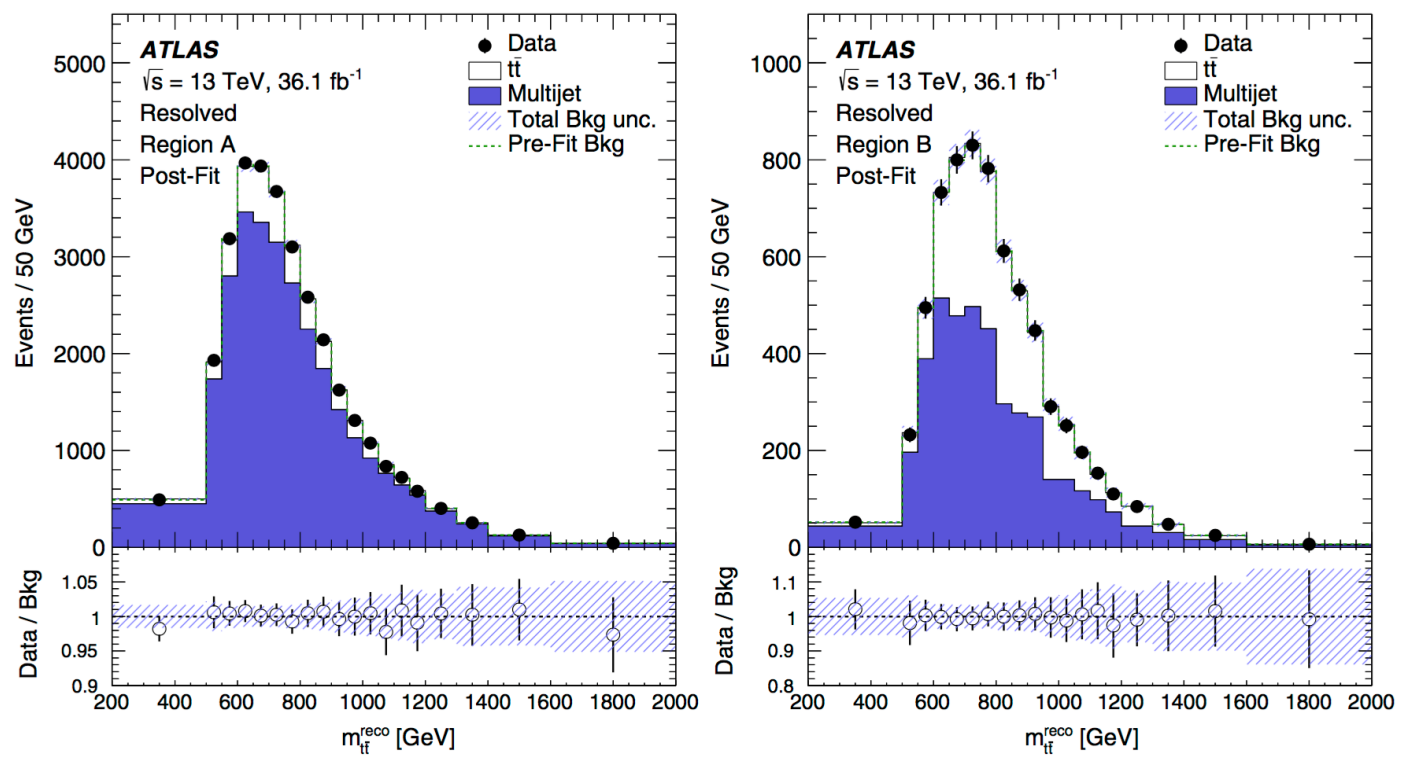
PhysRevD.99.092004 36.1 fb-1, √s=13 TeV

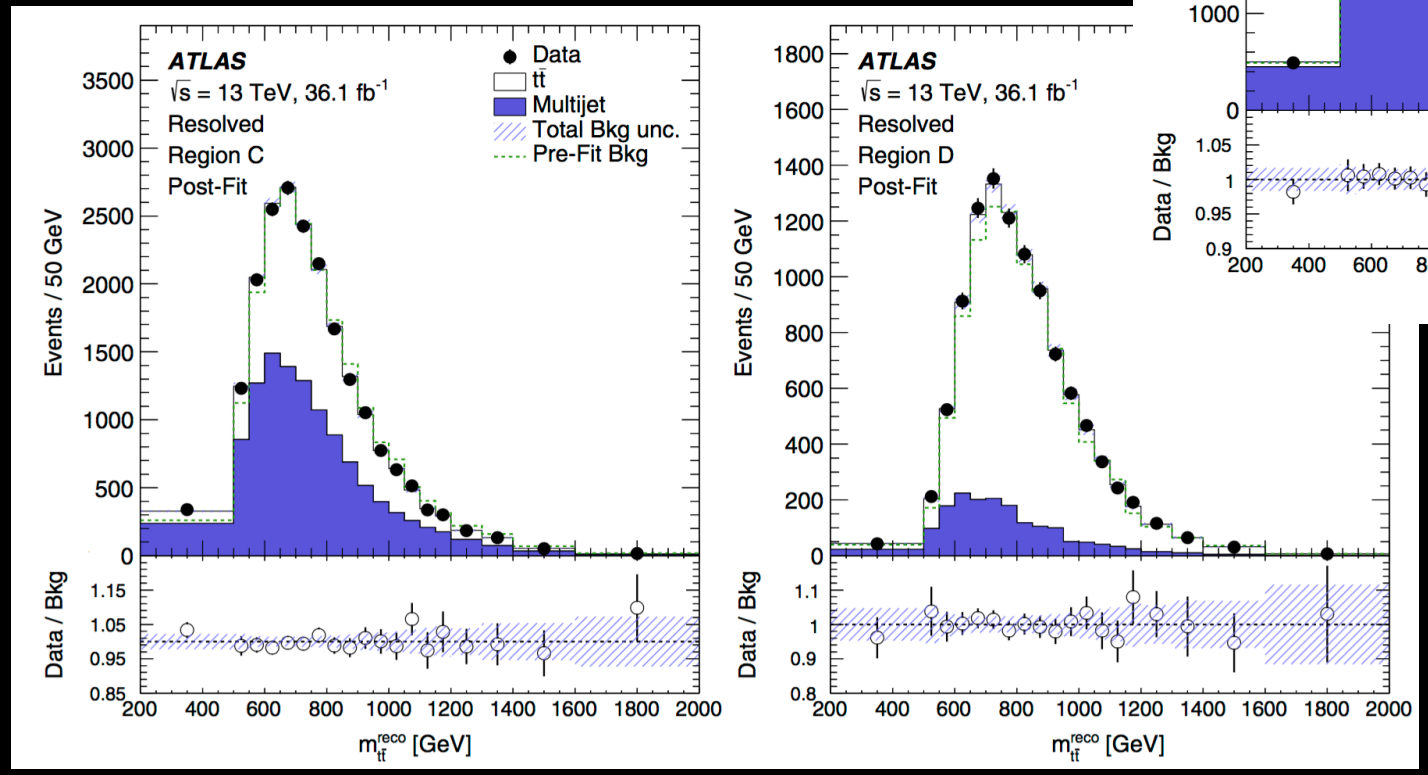
- A Randall-Sundrum model in which the SM fields propagate in the bulk of a single warped extra dimension.
  - Predicts a spin 1 color octet boson, Kaluza-Klein excitation of the gluon, gKK
  - This is primarily produced in qqbar annihilation and predominantly decays to ttbar with a branching fraction of 92.5%
  - The coupling of the gKK to quarks is set to -0.2gs, where gs is the strong coupling constant in the SM.
  - The left handed coupling to the top quark is fixed to gs while the right handed coupling is varied to change the intrinsic width.

- A “Bulk” RS model where the SM fields propagate in the bulk inherits from the original RS model
  - Predicts a spin 2 color singlet boson, Kaluza Klein excitation of the Graviton, GKK.
  - This is produced primarily in the gluon-gluon fusion
  - Production rate and branching fraction is controlled by a dimensionless constant k/M_Pl.
  - k/M_Pl is set to 1, resulting in the GKK width varying from 3-6 % in the mass range 0.5-3 TeV.
  - Branching fraction to ttbar increases from 18-50% between 400-600 GeV and stays constant at 68% above 1 Tev.
  - In addition, the GKK can decay to a pair of W, Z or Higgs bosons, and with negligible branching fraction to light fermions or photons.

Search for heavy particles decaying into a top-quark pair in the fully hadronic final state: mtt (3)

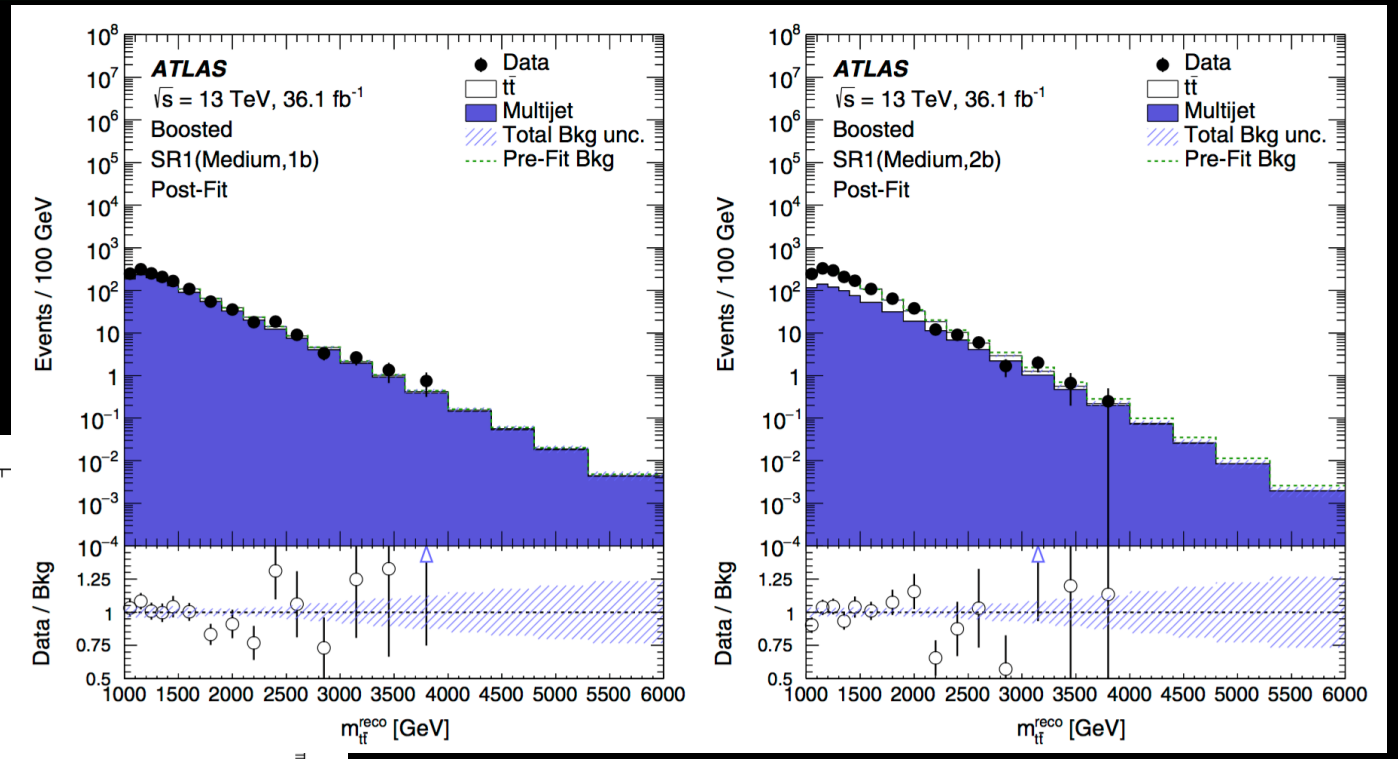
PhysRevD.99.092004 36.1 fb-1, √s=13 TeV

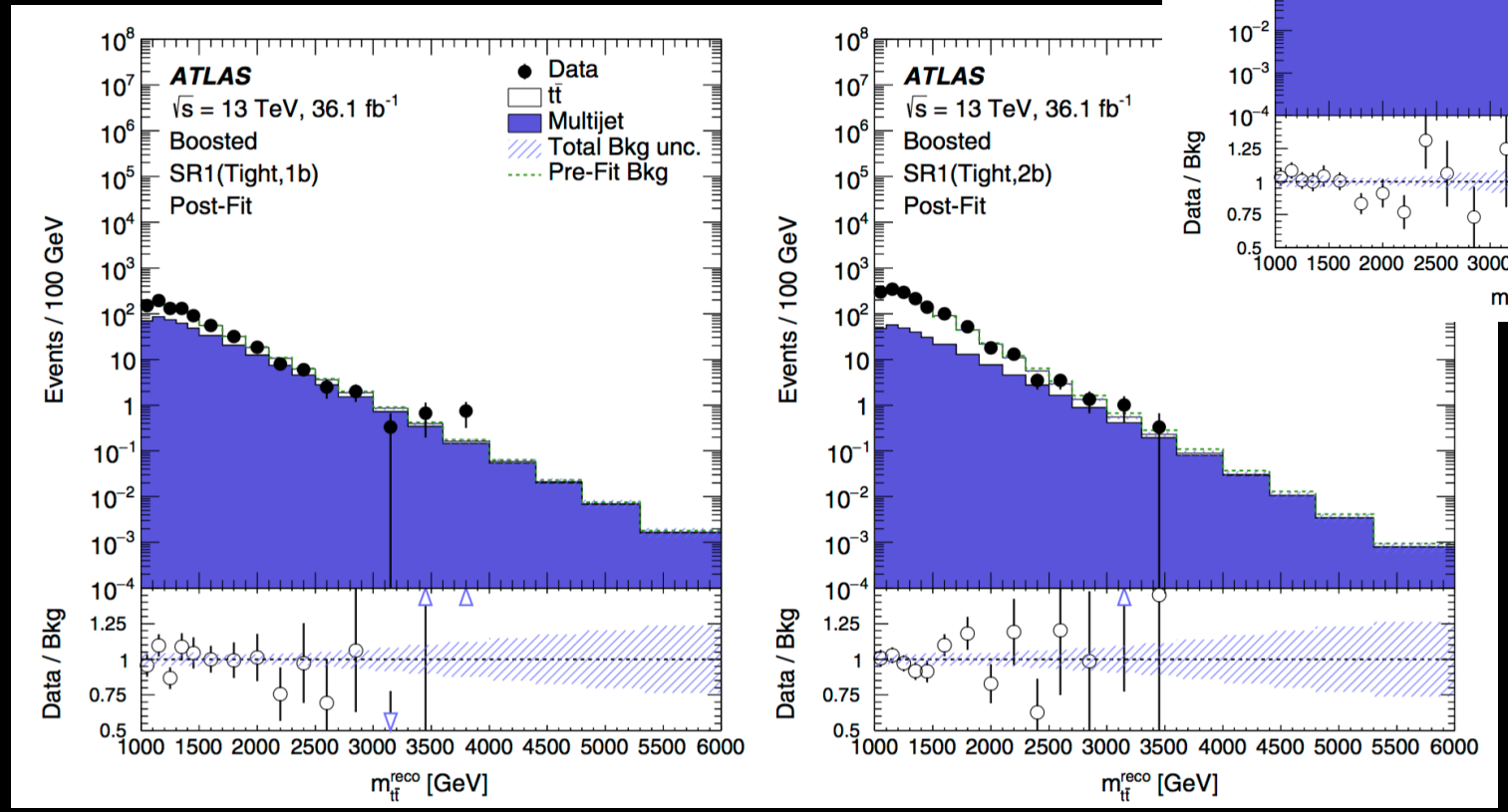




Search for heavy particles decaying into a top-quark pair in the fully hadronic final state: mtt (4)

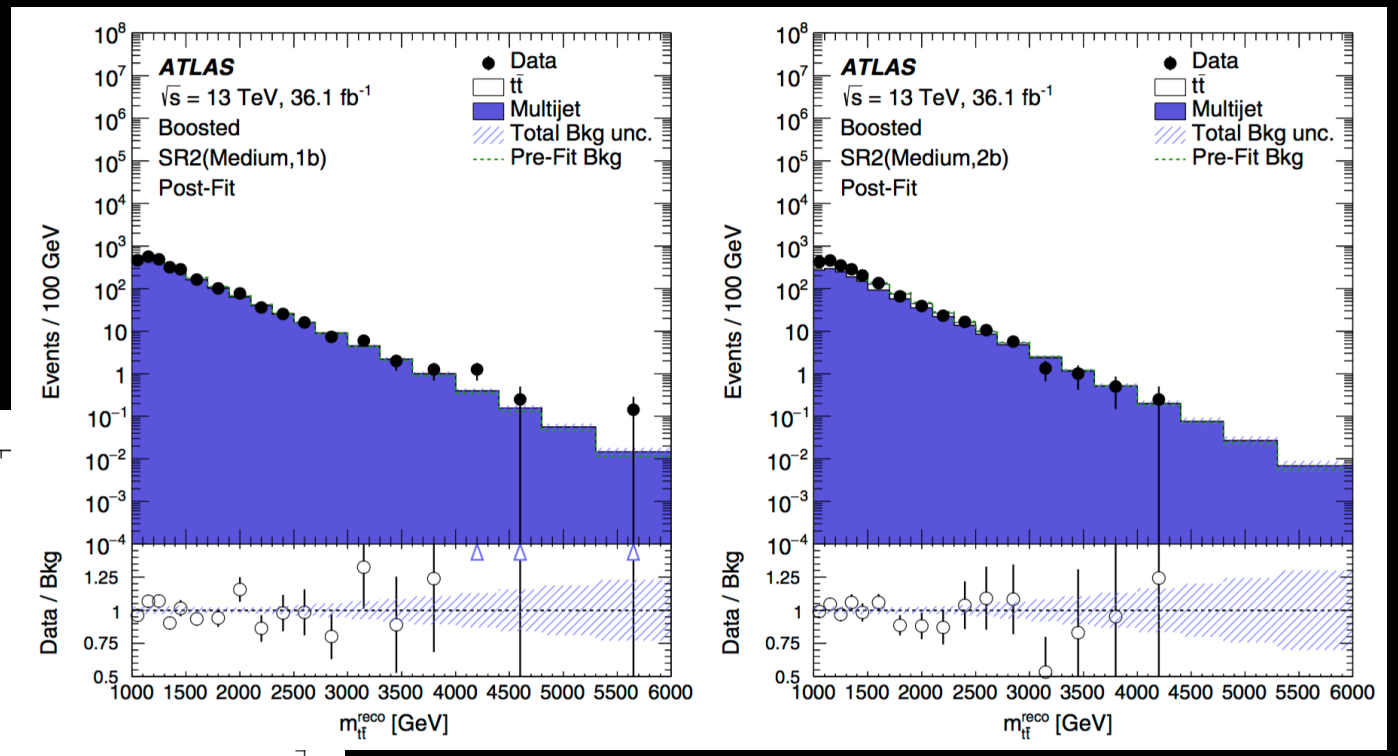
PhysRevD.99.092004 36.1 fb-1, √s=13 TeV

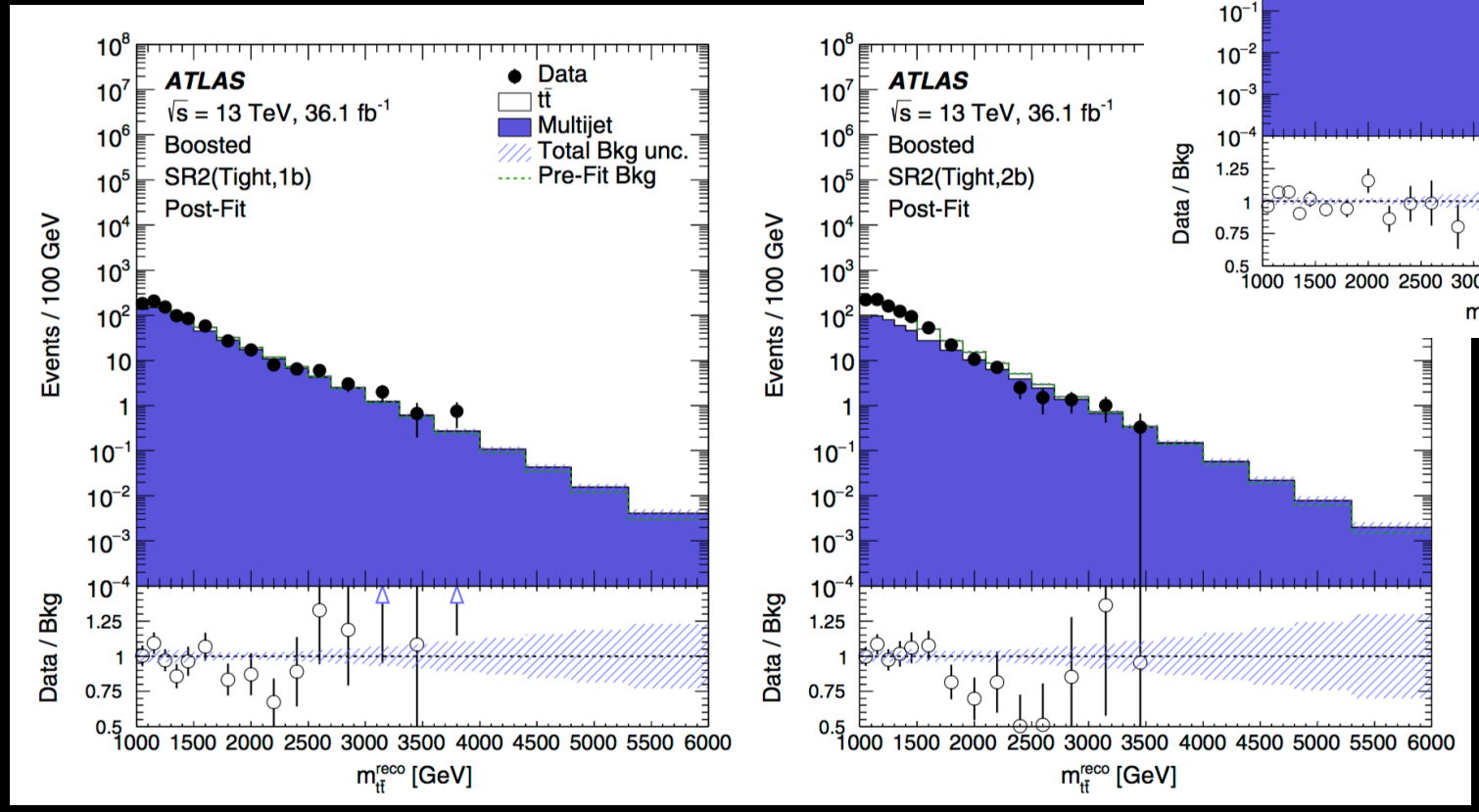




Search for heavy particles decaying into a top-quark pair in the fully hadronic final state: mtt (5)

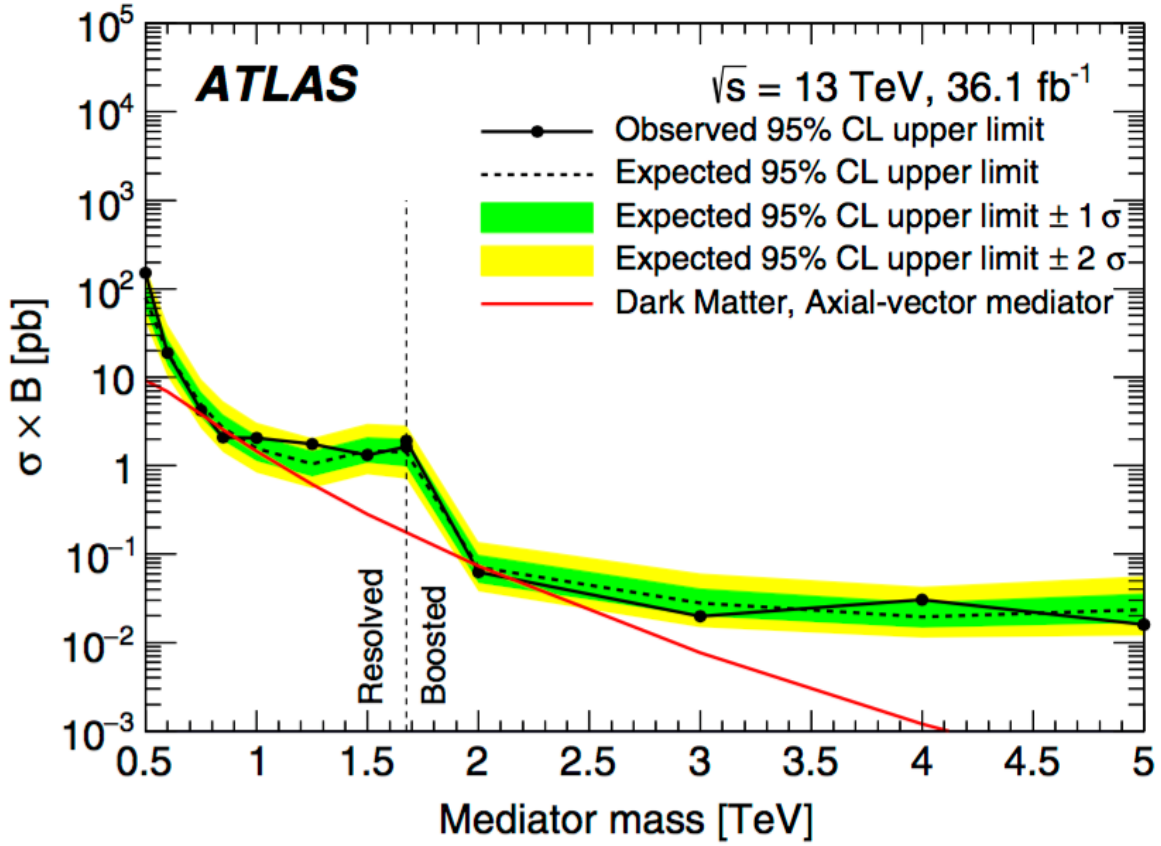
PhysRevD.99.092004 36.1 fb-1, √s=13 TeV

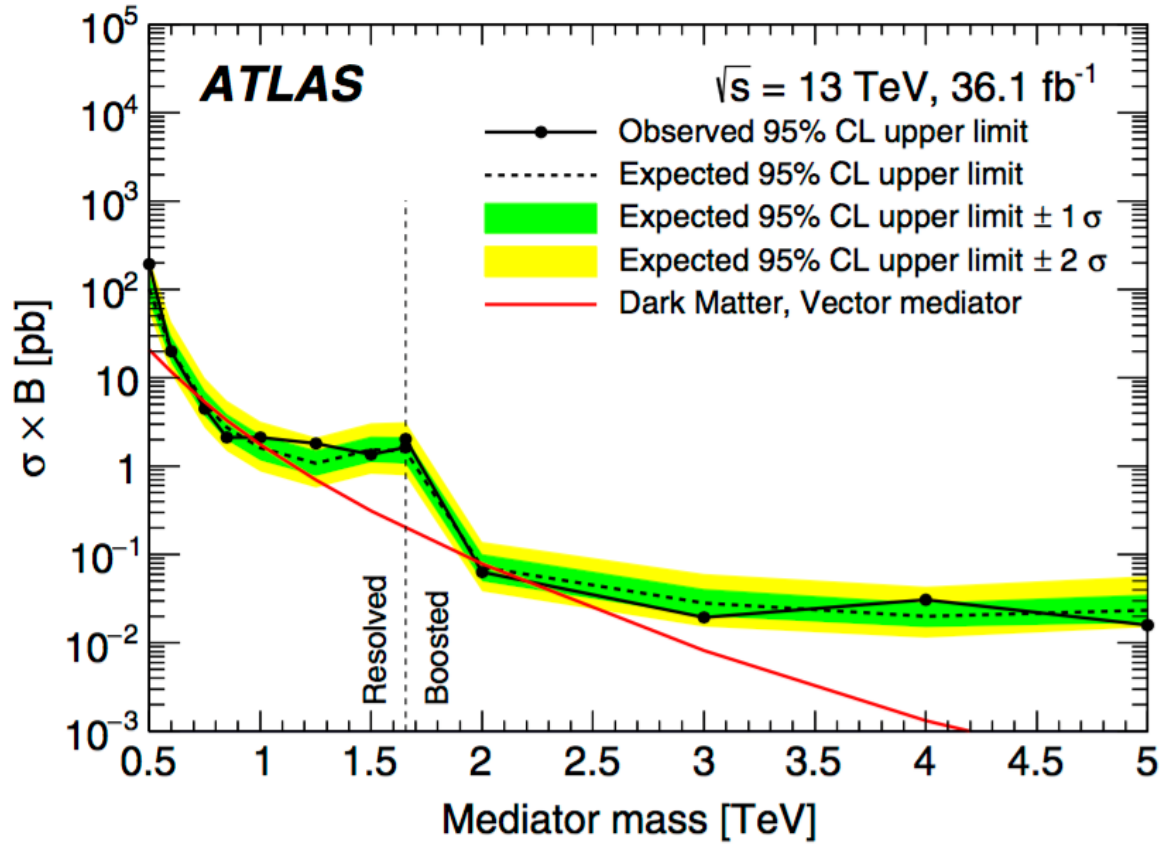




Search for heavy particles decaying into a top-quark pair in the fully hadronic final state: limits (6)

PhysRevD.99.092004 36.1 fb-1, √s=13 TeV





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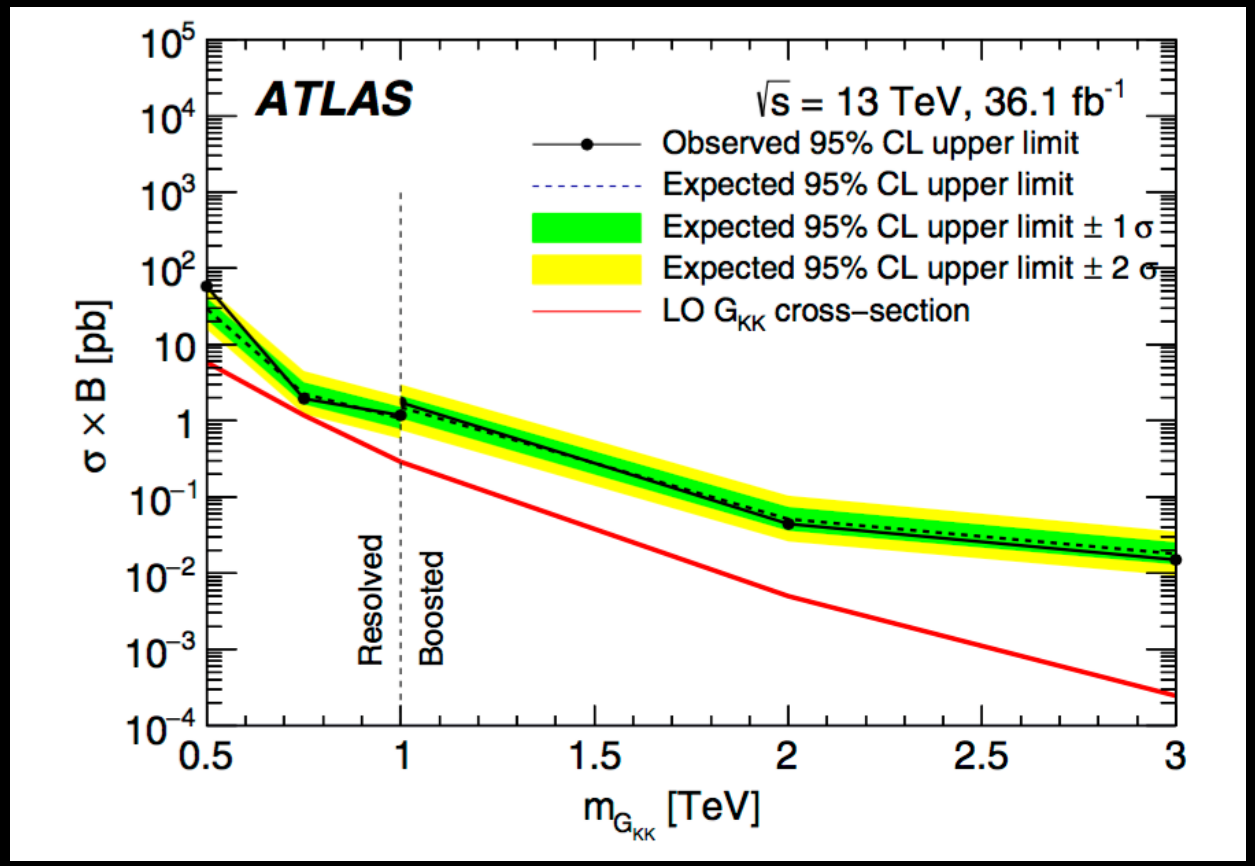

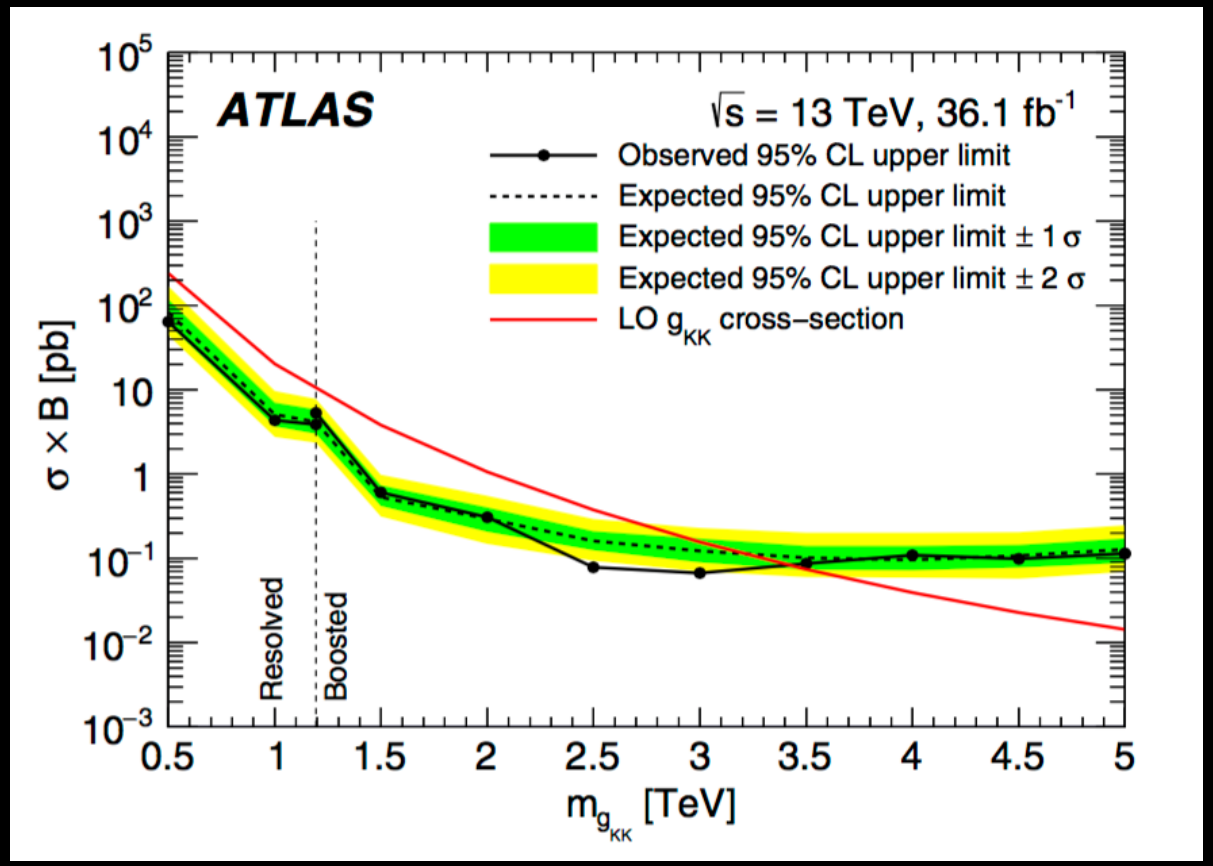

The XS times BF for GKK production with the model parameters is too low to be excluded with the sensitivity of this measurement, hence the limit is presented only up to 3 TeV.