Review of physics results using jet substructure techniques in LHC Run1

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on behalf of the ATLAS and CMS collaborations

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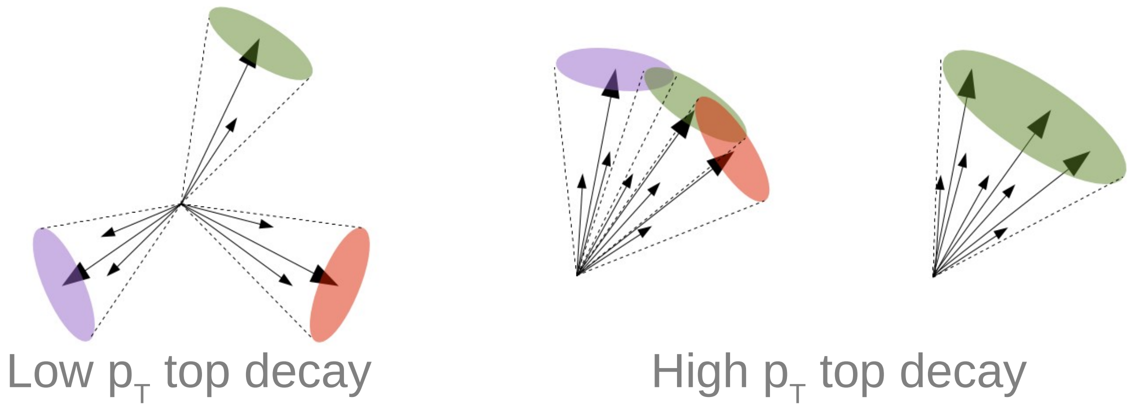
Motivation

- Search for new physics at the TeV scale
- Decay products of massive objects (W,Z,t,H) with large Lorentz boost (p_T>>m) tend to be collimated and can partially overlap in the reconstruction
- Standard reconstruction techniques employing resolved objects become inefficient
- Decay products of boosted massive objects can be contained in a single large-R jet

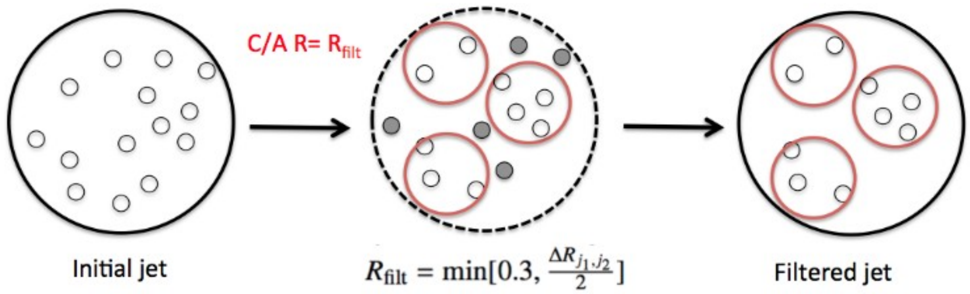


- Jets with large R receive significant contribution from pile-up
- Event reconstruction and selection based on jet substructure analysis
  - jet grooming - jet substructure observables - taggers

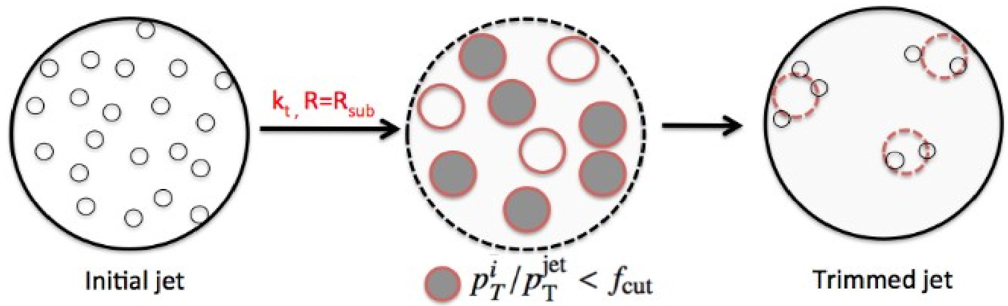
Jet grooming

Techniques used to mitigate the effect of pile-up (typically soft radiation spatially separated from the main energy deposits)

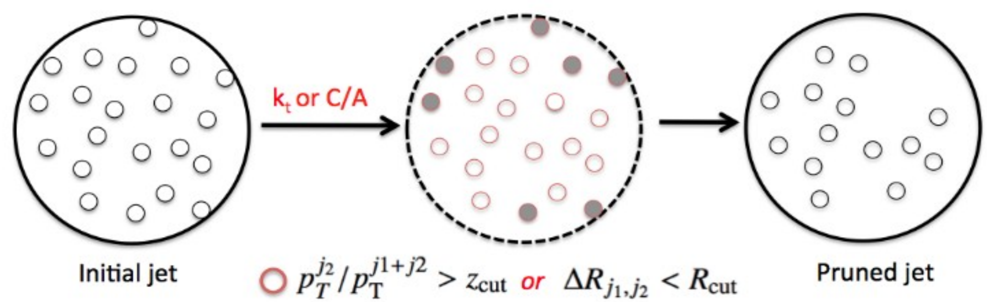
Mass-drop filtering: sub-jets with reduced R and significantly smaller mass are constructed. Residual energy deposits are rejected.



Trimming: sub-jets of smaller R are constructed. Sub-jets with p_T smaller than a fixed fraction of the p_T of the original jet are removed.



Pruning: jet reconstruction re-applied to all jet constituents. At each step of the reconstruction the constituents of small p_T and spatially separated are removed.



Jet substructure observables

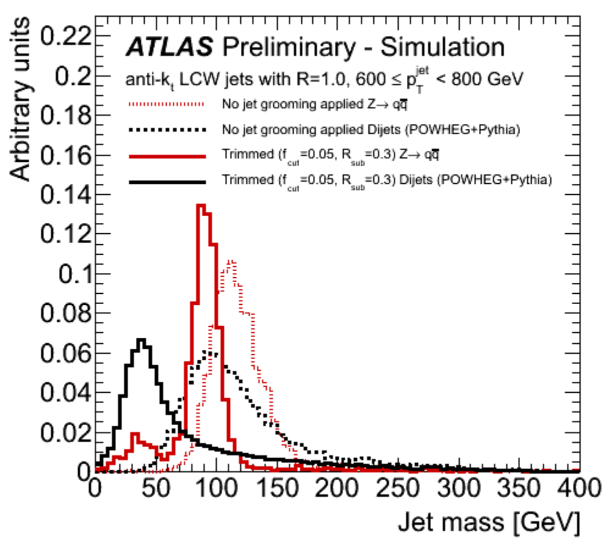
Examples of observables applied in the analysis:

- **Mass:** invariant mass computed from jet constituents
- **Splitting scales ($\sqrt{d_{ij}}$):** k_T distance between the two proto-jets in the last step of the jet clustering
- **Momentum balance ($\sqrt{y_f}$):** ratio between the splitting scale and the jet mass
- **Mass-drop (μ_{12}):** fraction of mass of the most massive proto-jets
- **N-subjettiness (τ_N):** quantifies to what degree the substructure resembles the one of a jet with N or less sub-jets. Ratios ($\tau_{ij}=\tau_i/\tau_j$) are commonly used
- **Taggers:** techniques testing specific scenarios of interest

$$\sqrt{d_{12}} = min(p_{T1}, p_{T2}) \cdot \Delta R_{12}$$

$$\sqrt{y_f} = \frac{min(p_{T1}, p_{T2})}{m_{12}} \cdot \Delta R_{12}$$

$$\mu_{12} = \frac{max(m_1, m_2)}{m_{jet}}$$



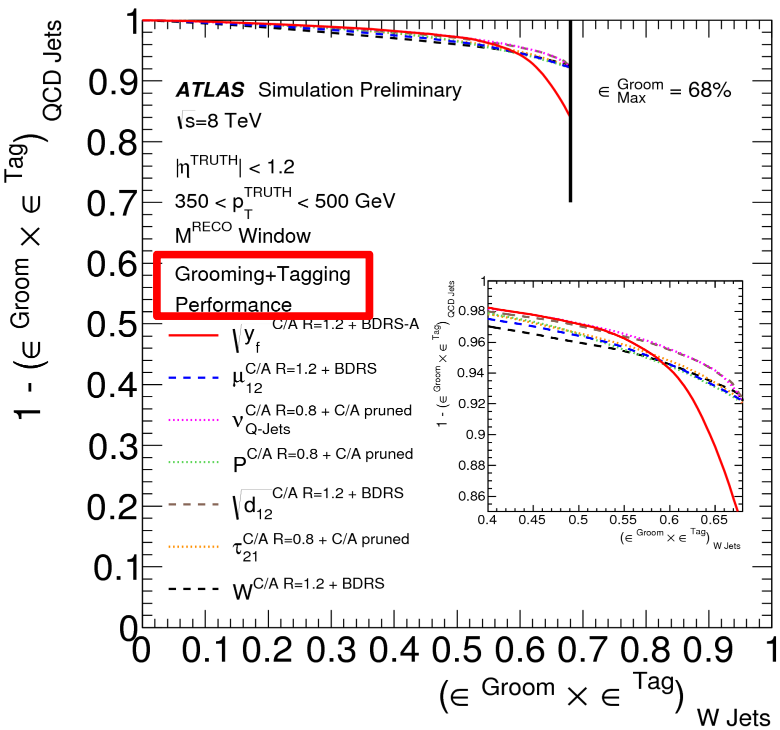
Improvement in jet mass resolution after grooming (trimming, R_{sub}=0.3, f_{cut}=5%)

Jet mass distribution shown for **di-jet** and **Z→$q\bar{q}$** events

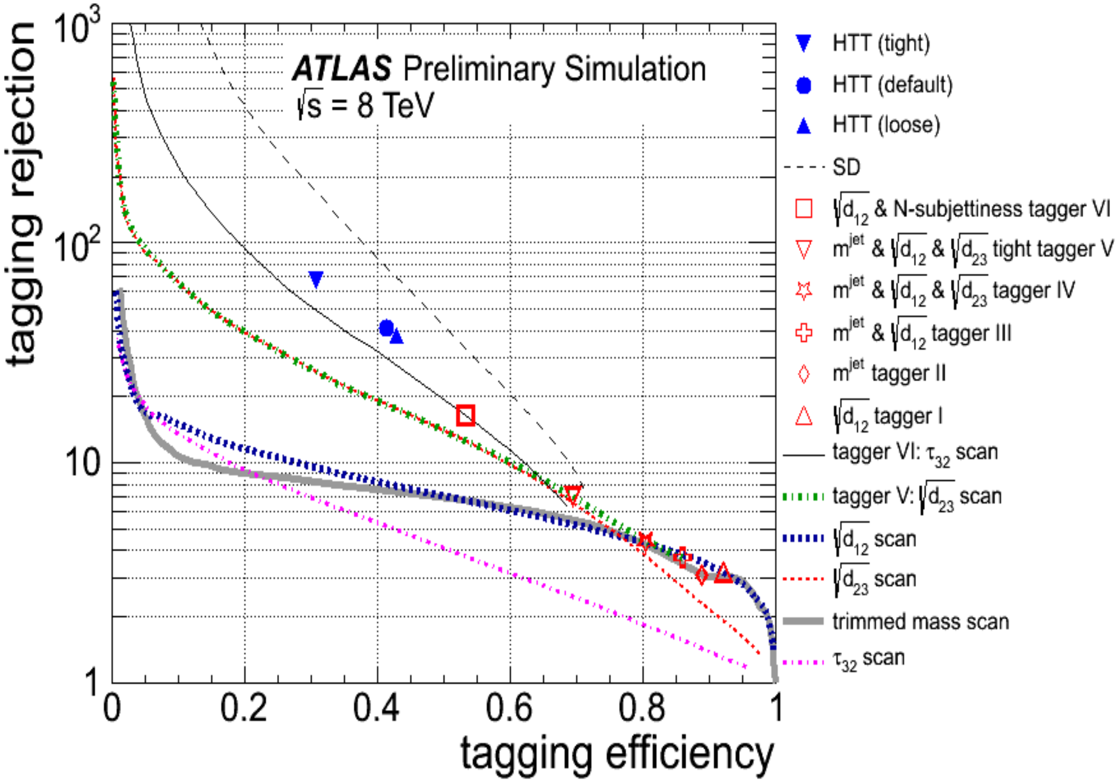
Boosted boson and top taggers

- Several tagging techniques have been developed for the discrimination of boosted massive objects jets from q/g jets
- Taggers check the compatibility with an assumed scenario
- Different performance (especially in different p_T regimes)

Bosons taggers
ATL-PHYS-PUB-2014-004



Top taggers
ATLAS-CONF-2014-003



Selection of results

- High-p_T $V \rightarrow q\bar{q}$ (ATLAS)
- VV resonance search → di-jets (CMS)
- VV resonance search → lepton + jets (ATLAS & CMS)
- W' → tb (ATLAS & CMS)
- $t\bar{t}$ resonance search → lepton + jets (ATLAS)
- $t\bar{t}$ resonance search → full hadronic (CMS)
- tH resonance search (CMS)

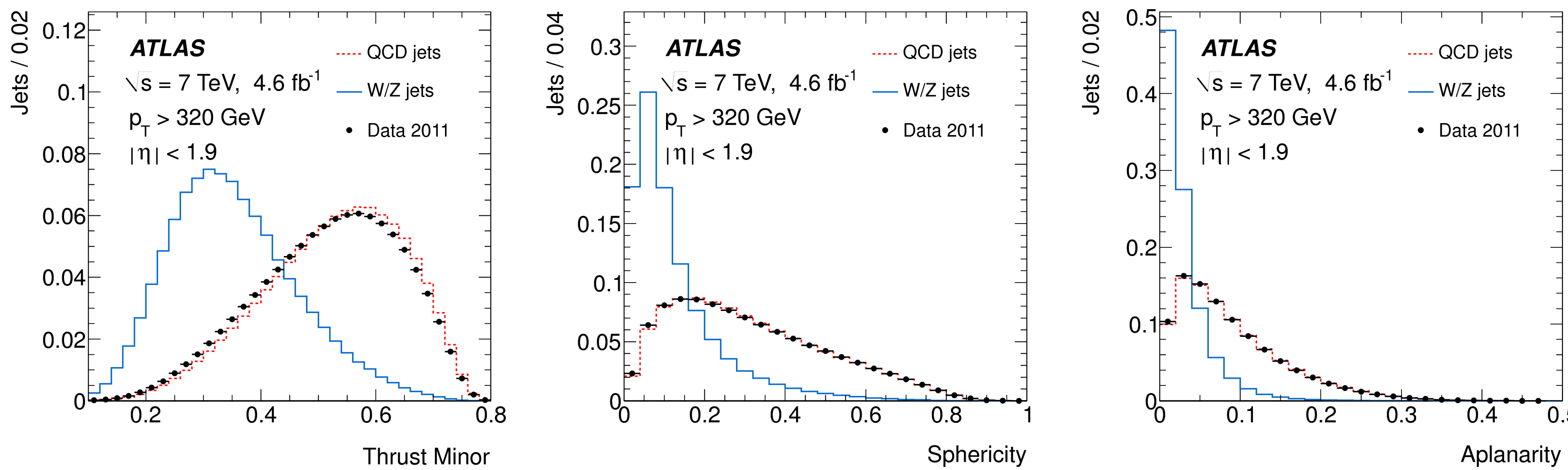
High-p_T $V \to q\bar{q}$ - I

arXiv:1407.0800

- Reconstruct $W,Z \to q\bar{q}$ in a single R=0.6 anti-k_T jet
- Measure the cross section in the fiducial region: p_T>320 GeV, |η|<1.9
- W/Z MC (signal): HERWIG+JIMMY
- Multi-jet QCD MC (background): PYTHIA
- $t\bar{t}$ MC (background): MC@NLO+HERWIG

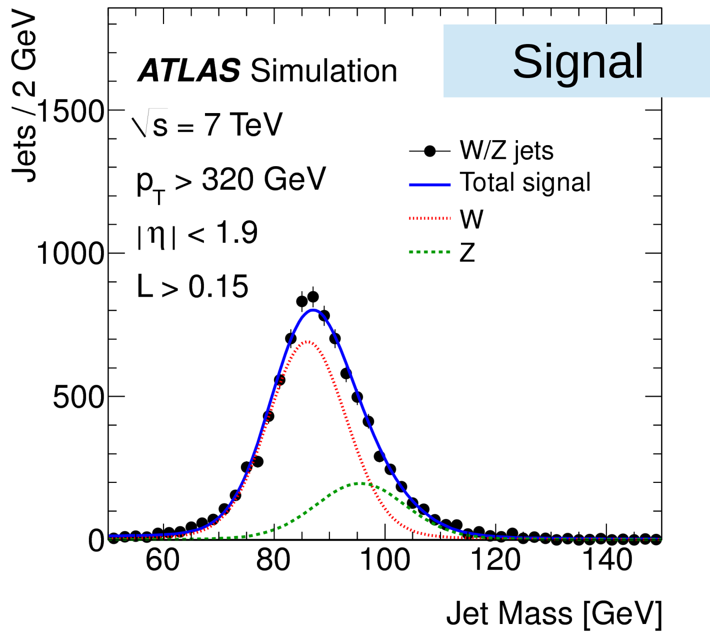
Alternative generators used for systematics evaluations

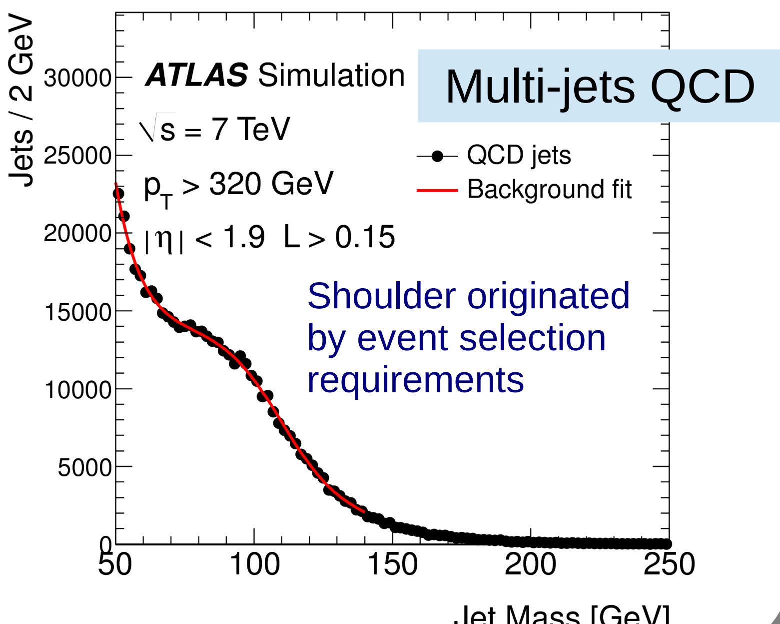
- W/Z jets selection based on jet mass (50<m_{jet}<140 GeV) and on topological variables evaluated in the jet centre-of-mass frame, combined in a likelihood discriminant
  - W/Z jets: back-to-back topology
  - QCD jets: isotropic topology

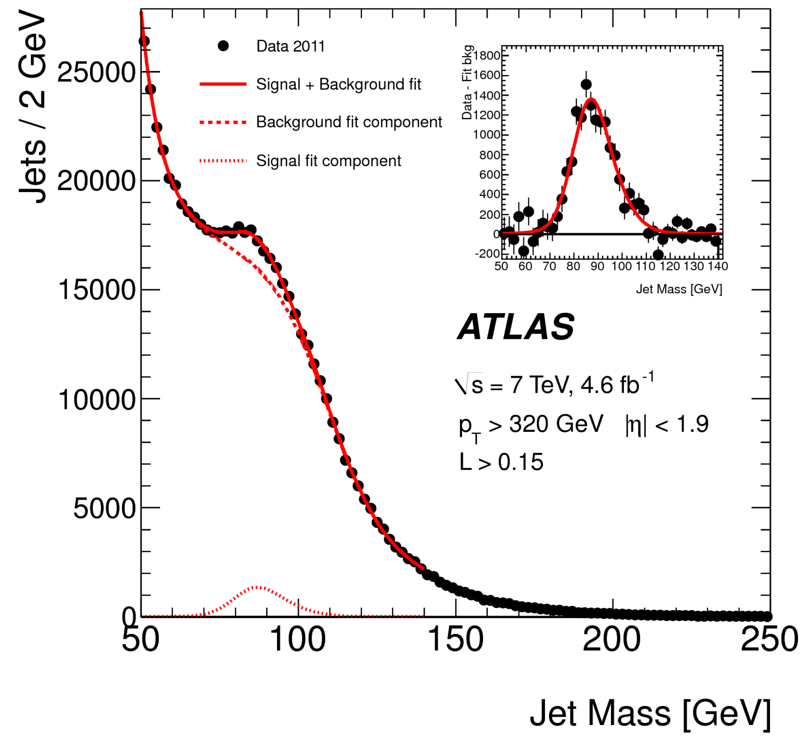


High-p_T $V \to q\bar{q}$ - II

arXiv:1407.0800







Fiducial cross section measurement:
$\sigma_{W+Z} = 8.5 \pm 0.8\,(stat) \pm 1.5\,(syst)\; pb$

MCFM (NLO) calculation for W/Z+jets production: $\sigma_{W+Z} = 5.1 \pm 0.5\; pb$
Agreement within 2σ

Excellent agreement with MC also observed in the measurement of boosted $\sigma(Z \to b\bar{b})$
arXiv:1404.7042

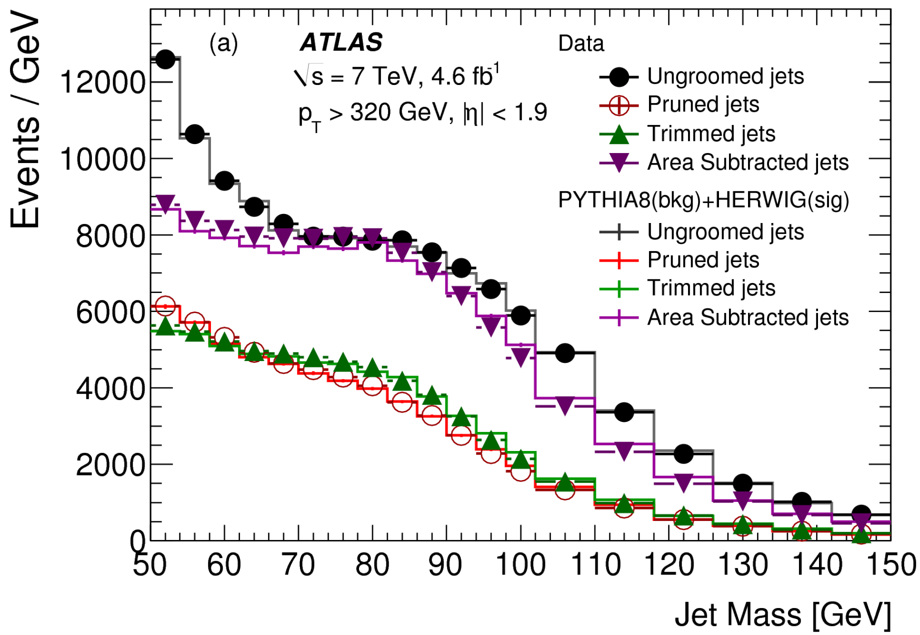
High-p_T $V \rightarrow q\bar{q}$ – III

Effect of grooming

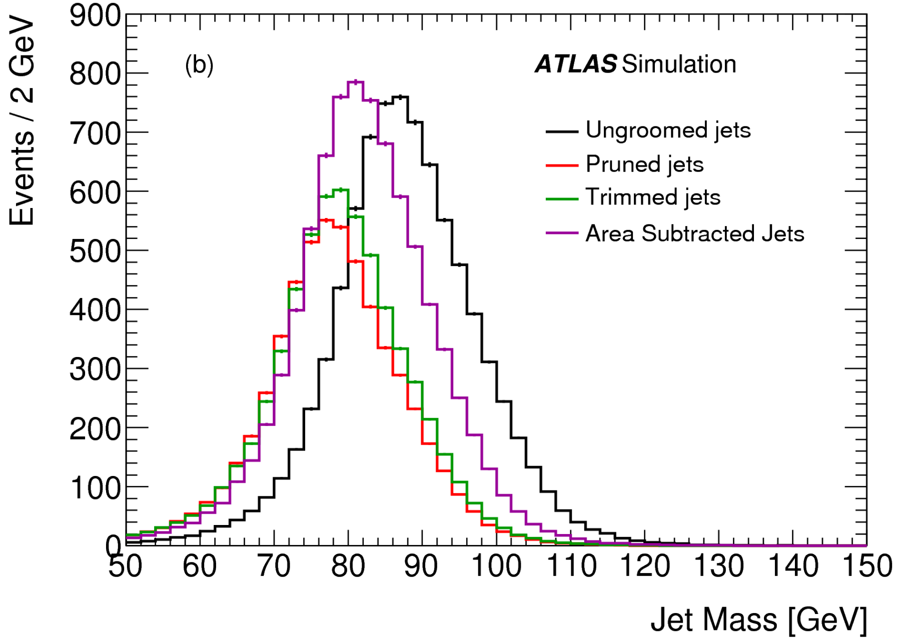
arXiv:1407.0800

Use the selected W/Z event sample to study the effect of trimming, pruning and area subtraction (without specific optimization)

Signal+background



Signal only



- Grooming techniques reduce the impact of pile-up on the measurement
- Shoulder structure in the background still present after grooming
- Number of selected jets reduced by ~30% after grooming
- Similar statistical significance of W+Z signal

VV, $t\bar{t}$ resonance searches

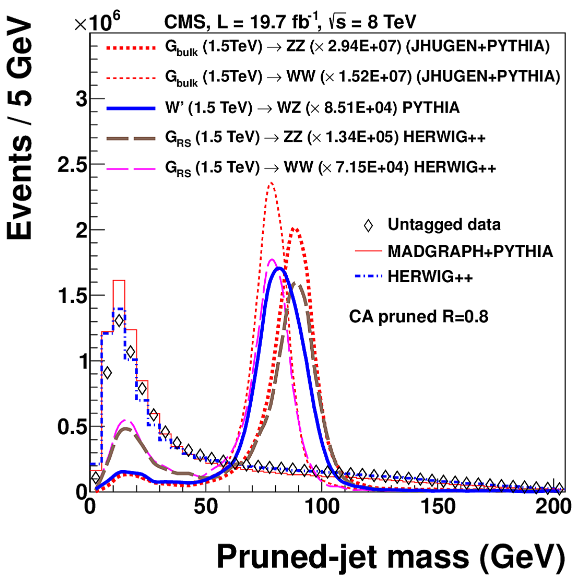
- Predicted by several BSM theories
  - VV: Randall-Sundrum / Bulk gravitons, extended gauge models ($W' \rightarrow WZ$)
  - $t\bar{t}$: KK gluons, Z'
- Look for high-p_T large-R jet associated with the hadronic decays $V \rightarrow q\bar{q}$ and $t \rightarrow bW \rightarrow bq\bar{q}$
- Background rejection based on large-R jet substructure and event topology
  - Full-hadronic or lepton+jets
  - b-tagging
- Strategy: bump search

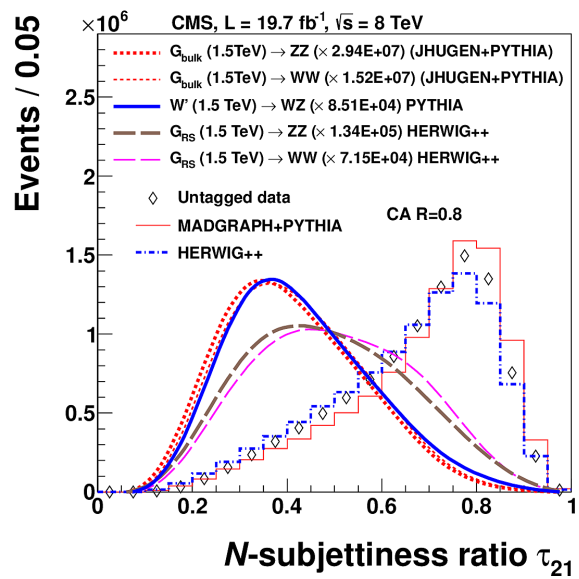
VV, qV resonance search - I
di-jet channel

arXiv:1405.1994

- Events with at least two R=0.8 Cambridge-Aachen jets
- W,Z → $q\bar{q}$ tagging algorithm based on pruning
- Separate sample in one- or two-tagged jets:
  - two tags: G_{RS}, G_{bulk} → WW/ZZ (HERWIG++, JHUGEN), W' → WZ (PYTHIA)
  - one tag: test excited quark resonances q* → qZ, qW (PYTHIA)
- Multi-jet QCD MC (background): HERWIG++ and MADGRAPH

- W/Z jets selection based on pruned jet mass ($70<m_{jet}<100$ GeV) and on the N-subjettiness ratio τ_{21} (high purity: $\tau_{21}<0.5$, low purity: $0.5<\tau_{21}<0.75$)

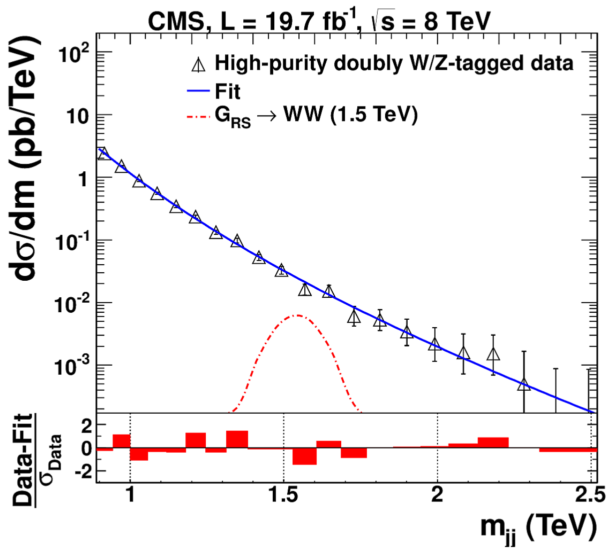


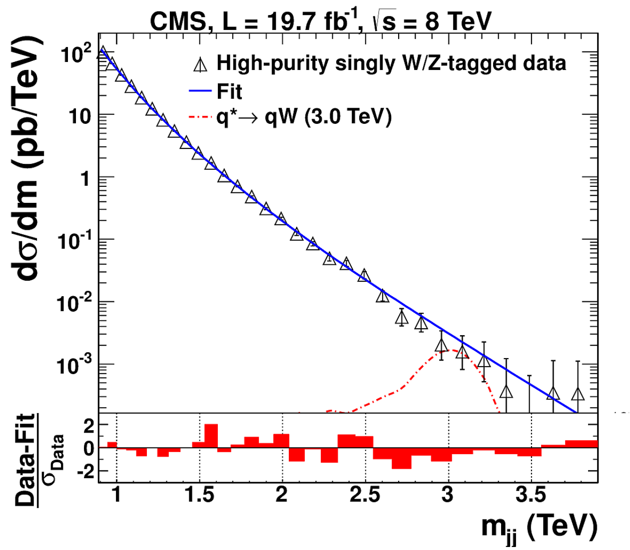


VV, qV resonance search - II
di-jet channel

arXiv:1405.1994

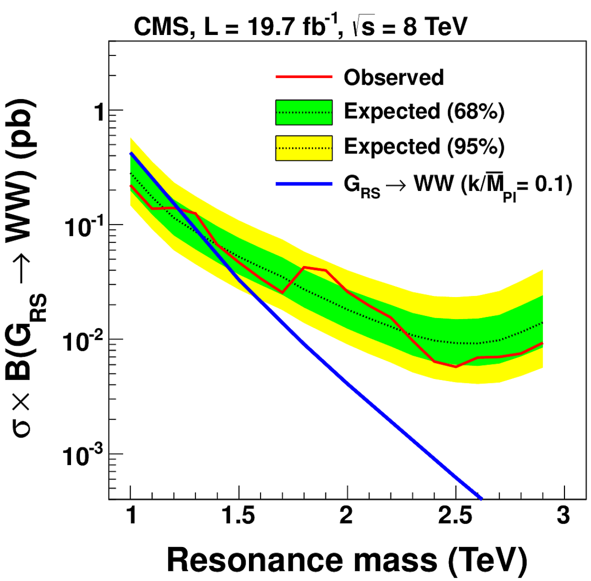
No excess visible on background (smooth function fitted on data)

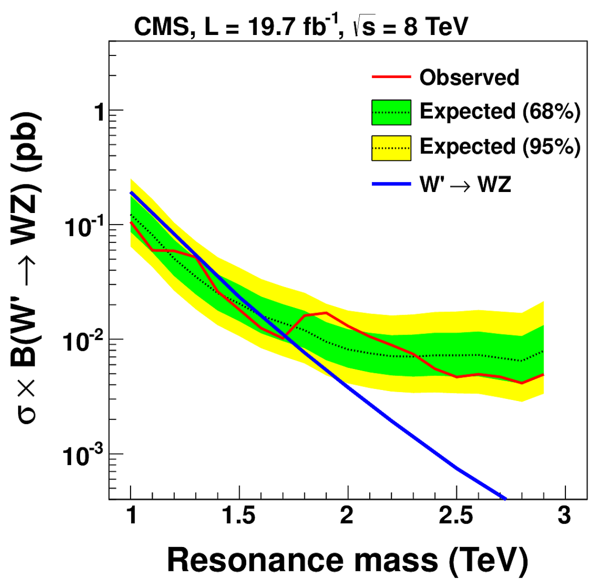


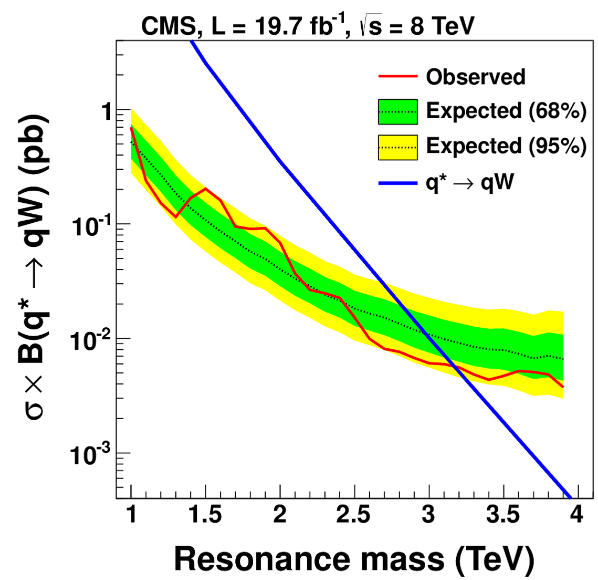


95% CL exclusion limits

Process	Mass (TeV)
$q^* \to qW$	3.2
$q^* \to qZ$	2.9
$W' \to WZ$	1.7
$G_{RS} \to WW$	1.2





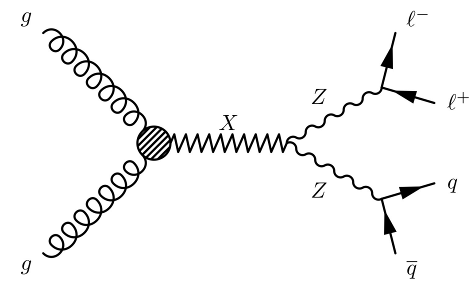


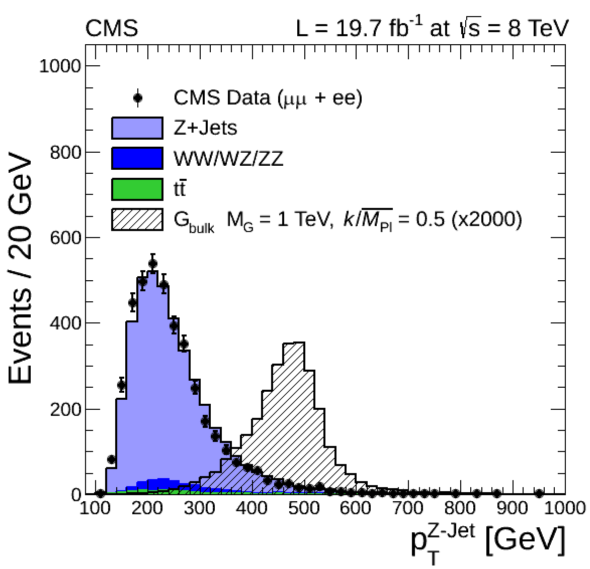
VV resonance search - I

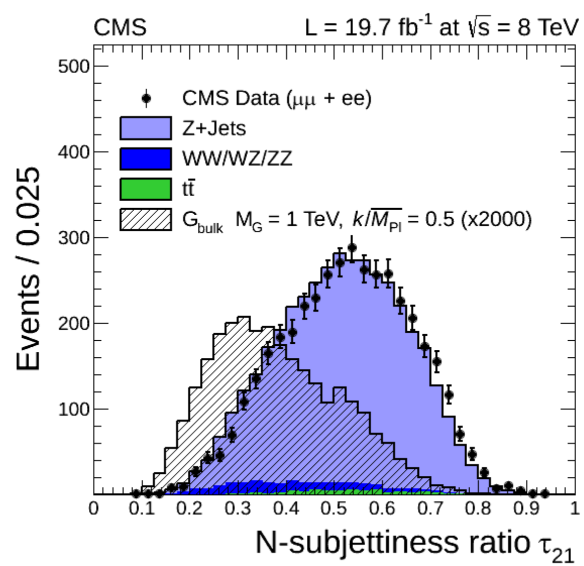
lepton+jet channel

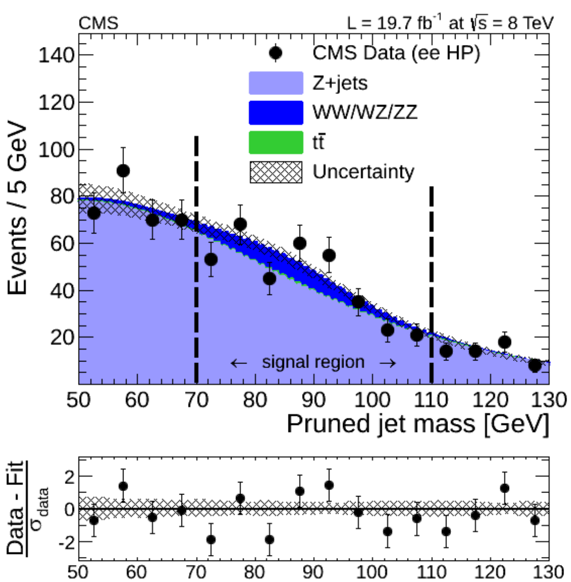
arXiv:1405.3447

- Events with one R=0.8 Cambridge-Aachen jet tagged as W,Z → $q\bar{q}$
- Same tagging algorithm used for the di-jet channel
- Presence of leptons / E_T^{miss} in the final state
- Signal MC: G_{bulk} → WW/ZZ (JHUGEN)
- Background MC: W/Z+jets MC (MADGRAPH), $t\bar{t}$ (POWHEG), diboson (PYTHIA)
- Selection: p_T(W,Z), τ_{21} and VV spatial separation provide good background discrimination









VV resonance search - II

lepton+jet channel

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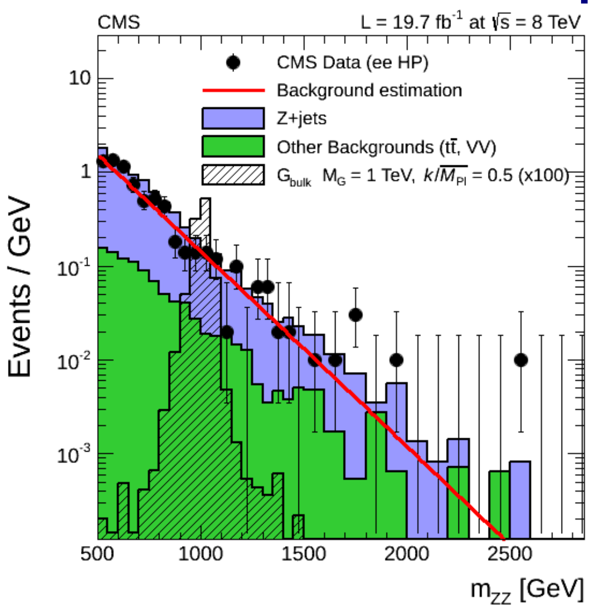
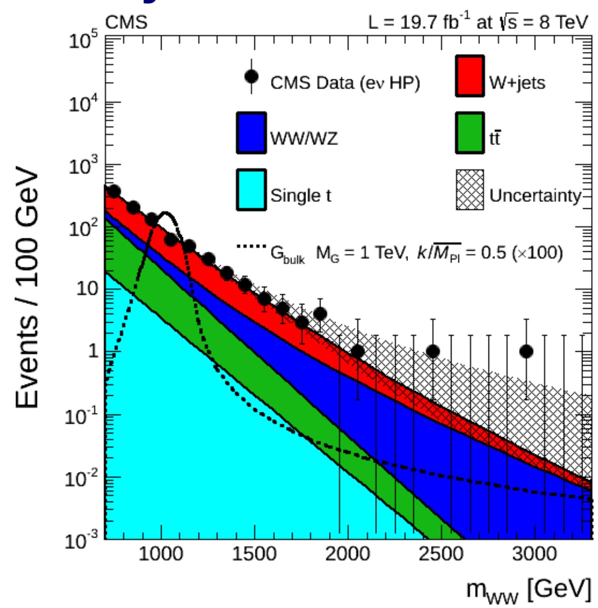
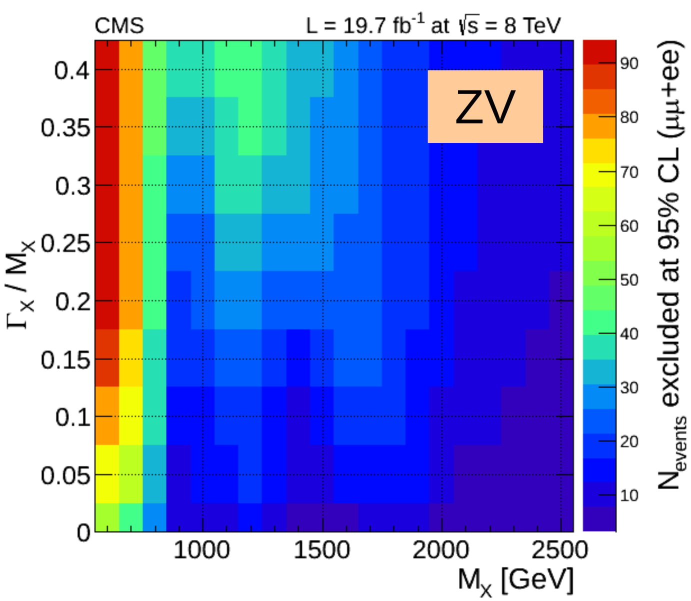
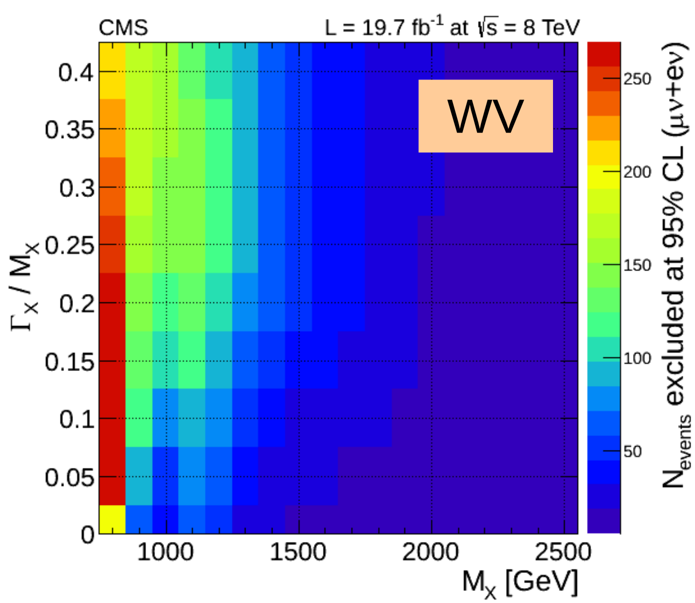




No excess visible on SM background

Sensitivity of lepton+jet channel to G_{bulk} still limited





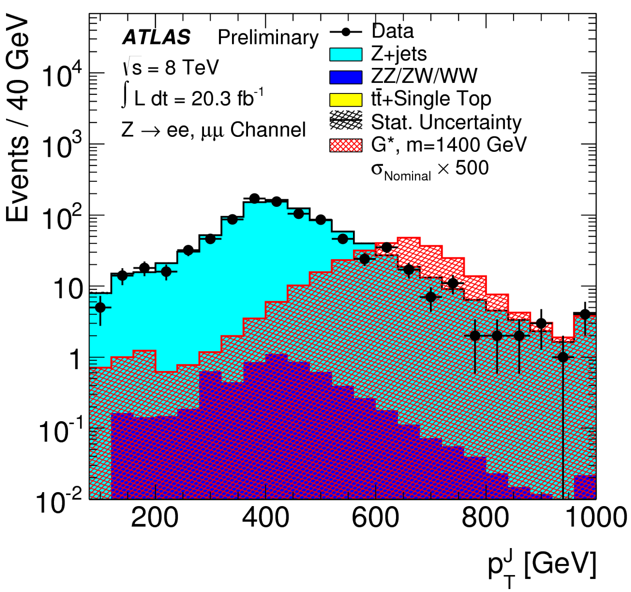
Model-independent interpretation of the result: exclusion limit for generic resonance $X \rightarrow WV,ZV$ with mass M_X and width Γ_X

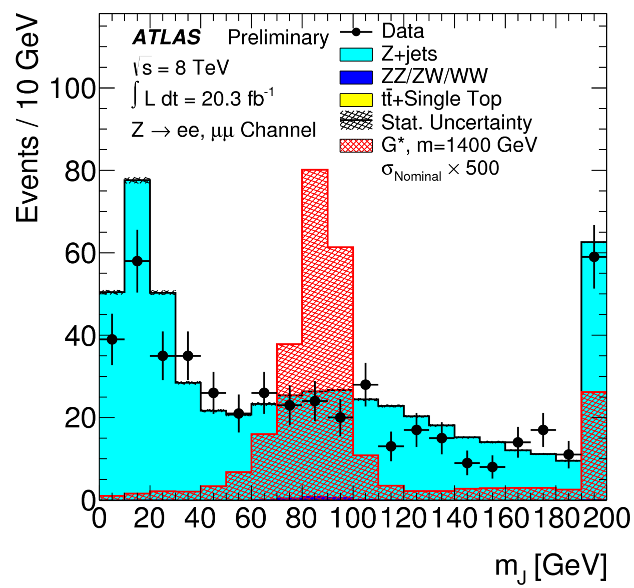
ZV resonance search - I

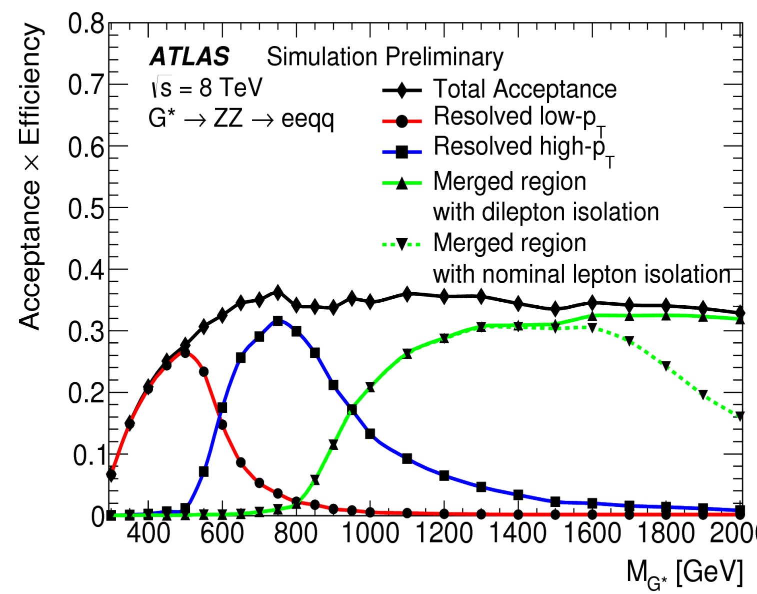
di-lepton+jet channel

ATLAS-CONF-2014-039

- Event selection optimized in three different kinematical regimes: low-pT resolved, high-pT resolved, merged (W,Z → $q\bar{q}$ in C/A R=1.2 jet)
- W,Z → $q\bar{q}$ tagging in the merged regime based on jet splitting/filtering
- Tested models: G* → ZZ (CALCHEP), W' → ZW (PYTHIA)
  (Note: Kaluza-Klein graviton G* was G_{bulk} in CMS notation)
- Background MC: W/Z+jets (SHERPA), $t\bar{t}$ (MC@NLO), diboson (HERWIG)



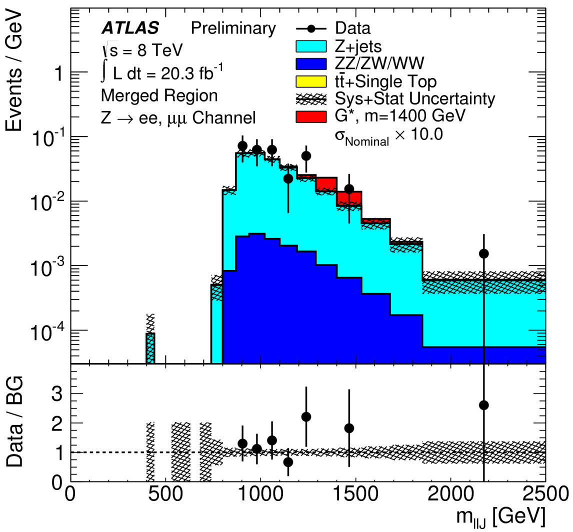




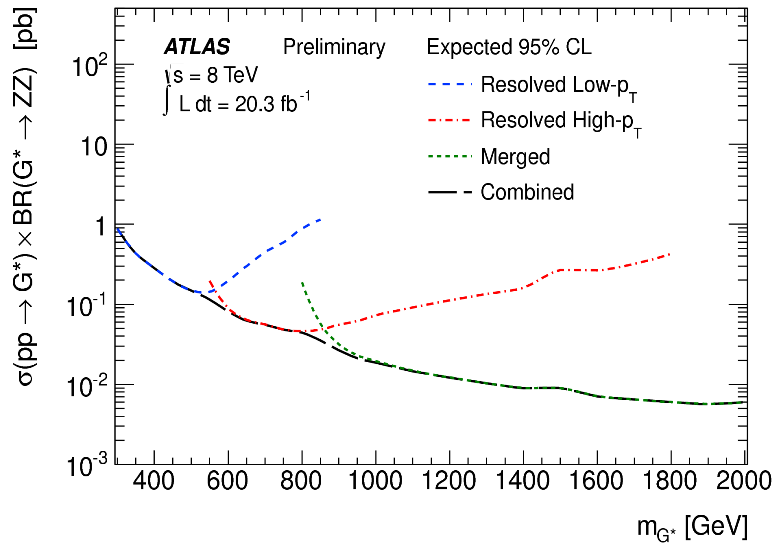
ZV resonance search - II

di-lepton+jet channel

ATLAS-CONF-2014-039



Expected limits for the 3 selections

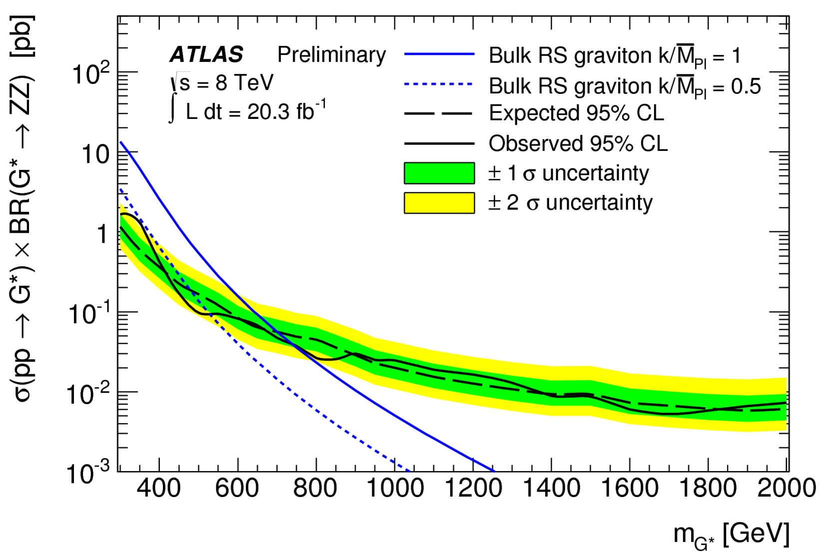


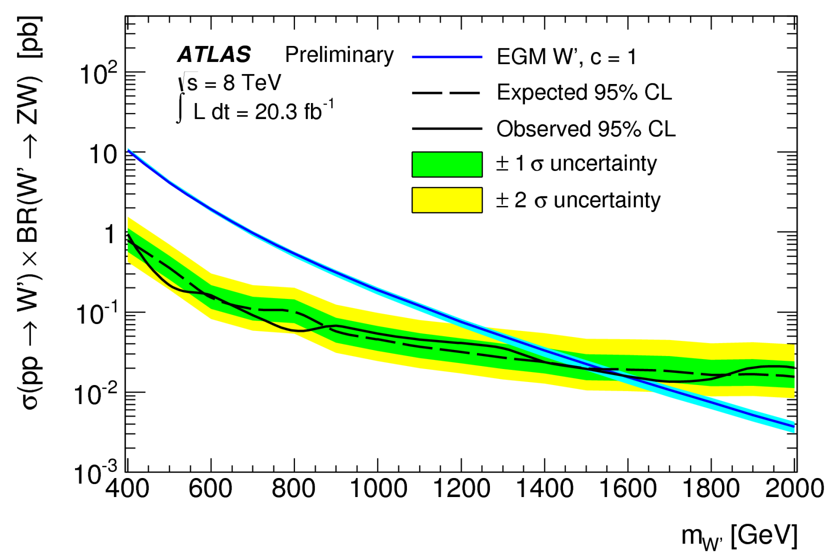
No excess over SM observed

The merged selection drives the limit in the high-mass region

95% CL limits

	Mass (GeV)
G*	740
W'	1590

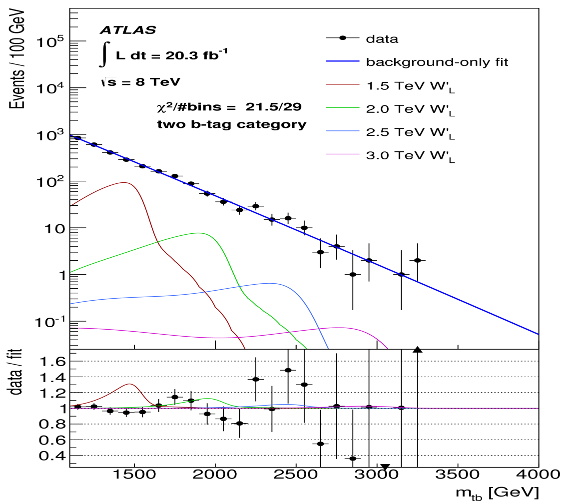


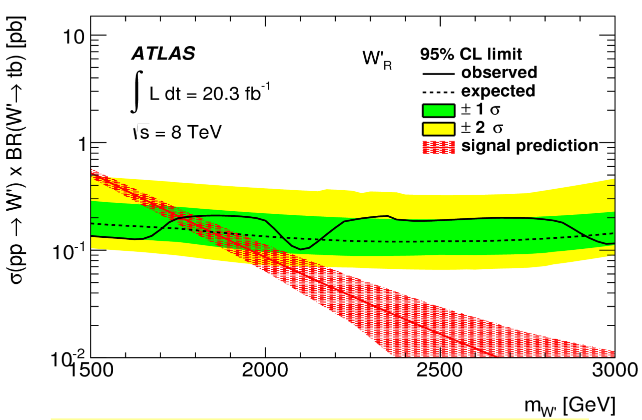


W'→tb (qqbb) search

- Top candidate reconstructed in a single large-R jet
- Tagging based on jet substructure (splitting scales and N-subjettiness)
- b-tagging
- Main backgrounds: QCD and $t\bar{t}$

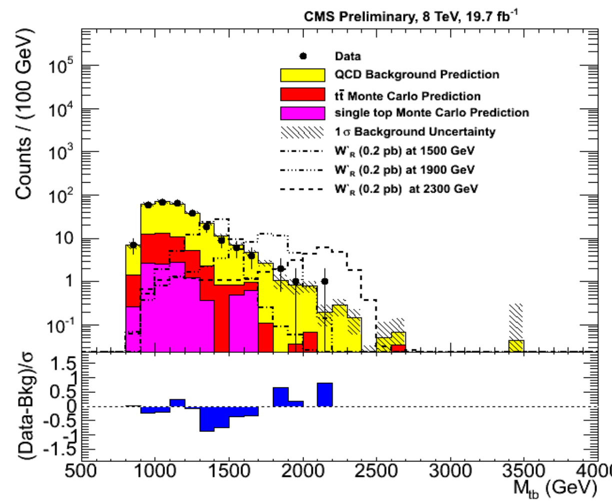
arXiv:1408.0886 (ATLAS)

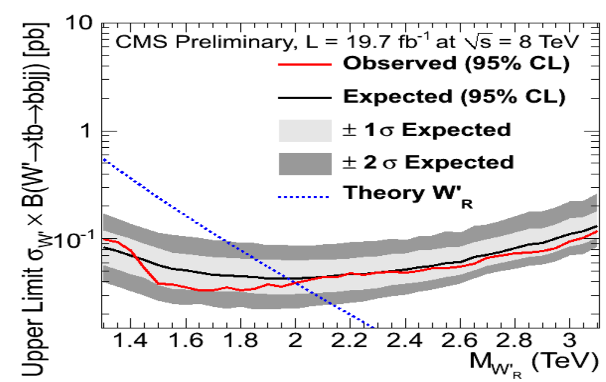




$m_{W'}$>1.76 TeV
(95% CL for right-handed W')

B2G-12-009 (CMS)





$m_{W'}$>2.15 TeV
(95% CL for right-handed W')

$t\bar{t}$ resonance search - I

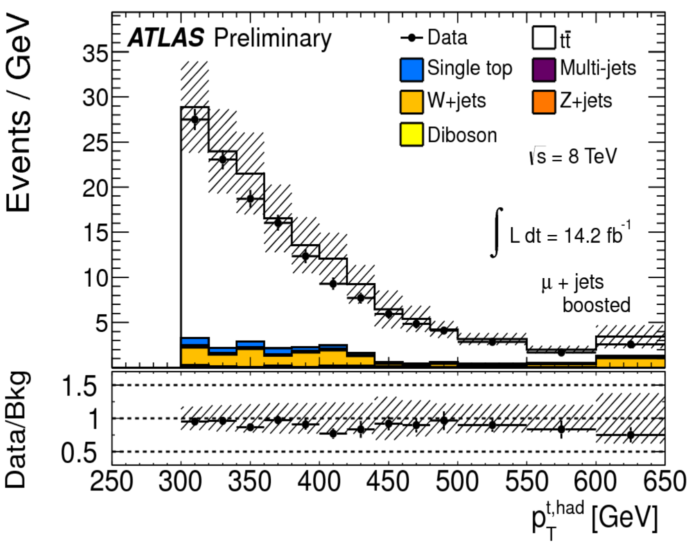
lepton+jet channel

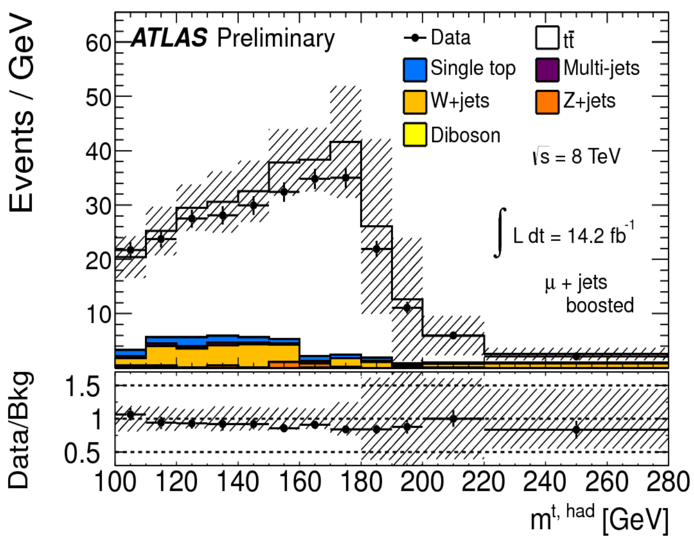
ATLAS-CONF-2013-052

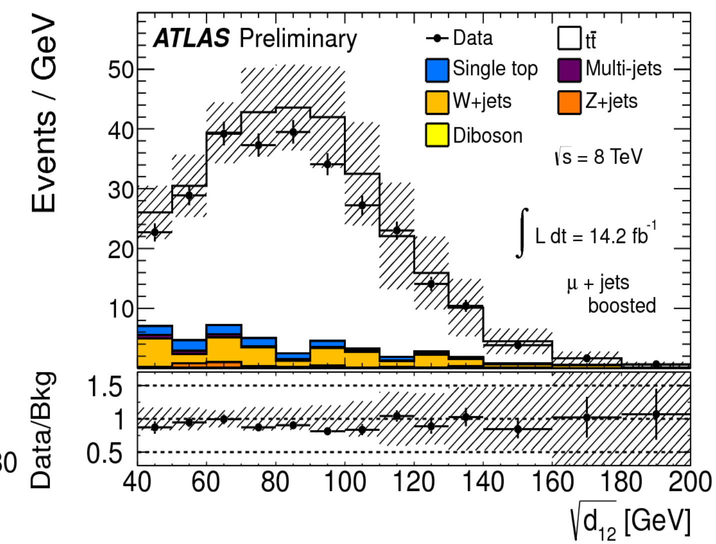
CMS analysis:
CMS-PAS-B2G-12-006

- Resolved and boosted event selection
- Hadronic top candidate reconstructed in a anti-k_T R=1.0 jet
- Tagging based on large-R jet mass and splitting scale
- b-tagging

- Models: Kaluza-Klein gluon, leptophobic Z'
- Main background: SM $t\bar{t}$ – Other: W+jets, single top, QCD



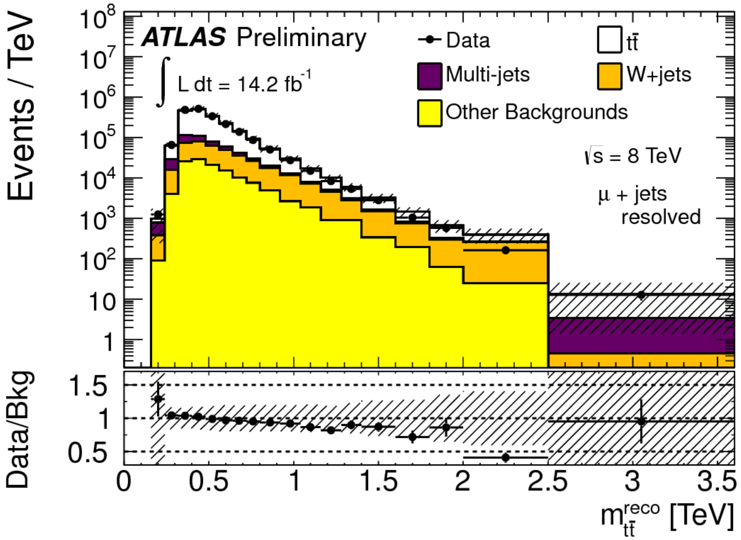


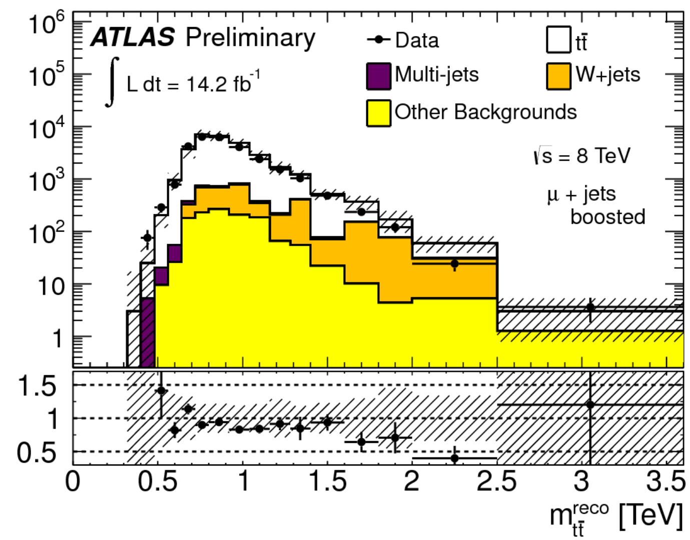


$t\bar{t}$ resonance search - II

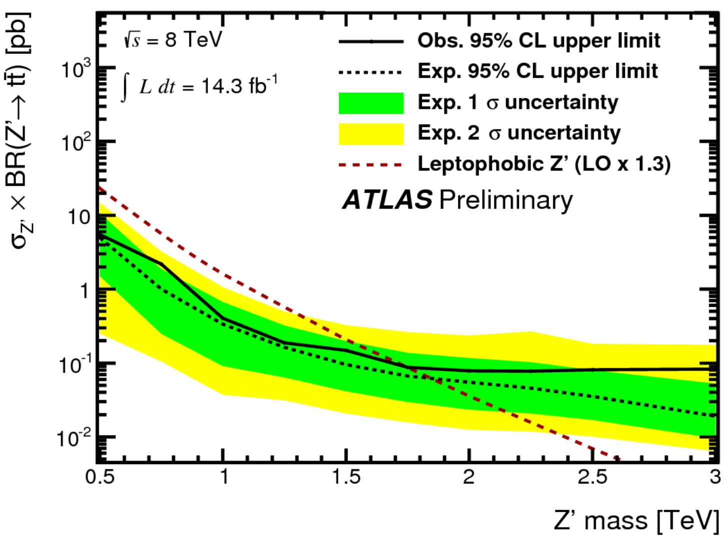
lepton+jet channel

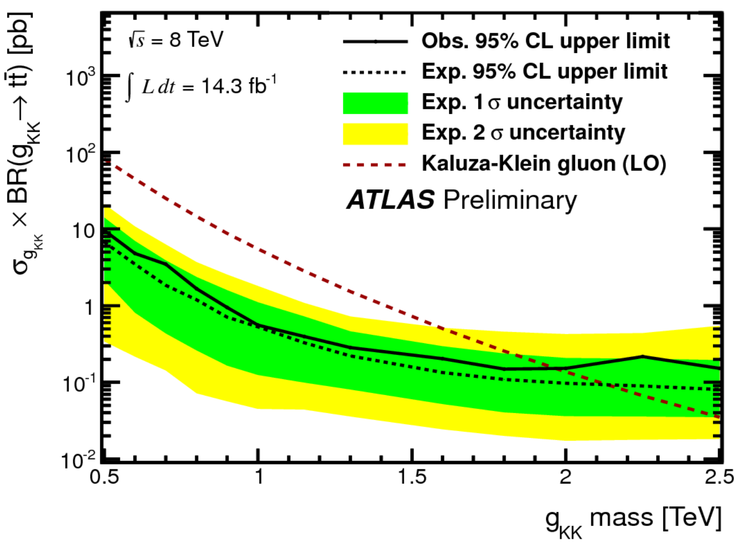
ATLAS-CONF-2013-052





No excess over SM observed





The boosted selection drives the limit in the high-mass region

95% CL limits

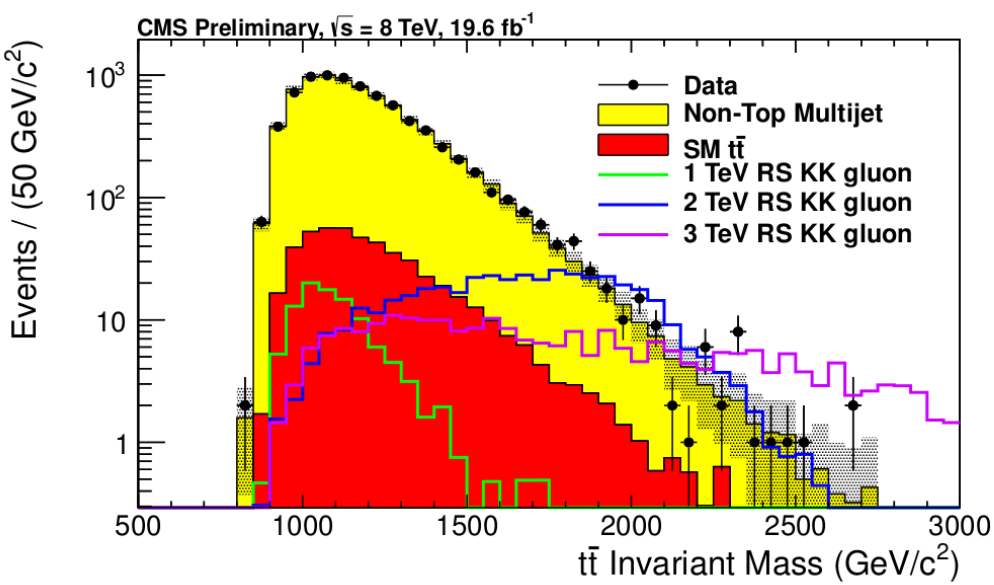
	Mass (TeV)
Z'	1.8
g_{KK}	2.0

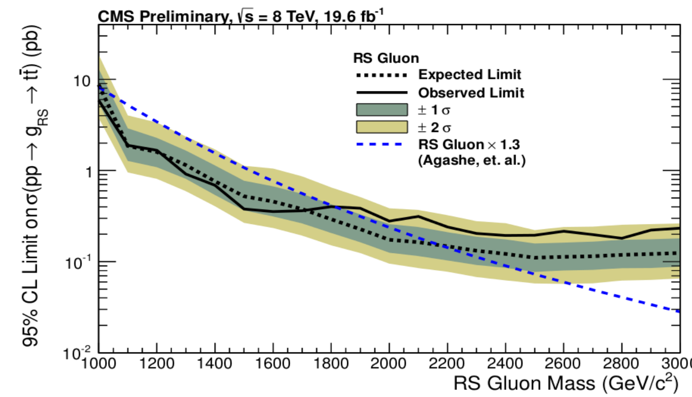
$t\bar{t}$ resonance search
full-hadronic channel

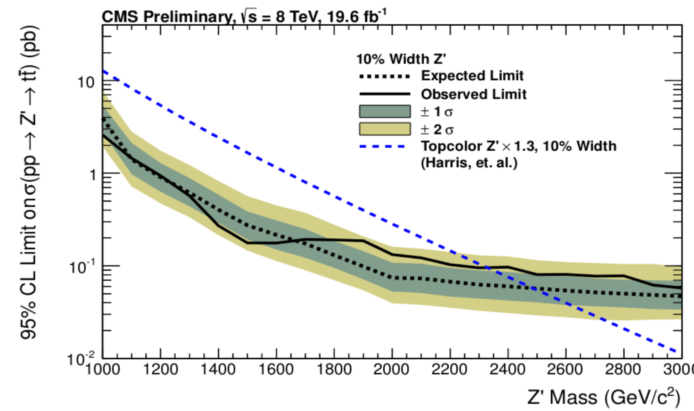
CMS-PAS-B2G-12-005

- Two top candidate reconstructed in C/A R=0.8 jets
- Both jets tagged as top candidates (CMS top tagger: 140<m_{jet}<250 GeV, at least 3 sub-jets, min mass of subjet pairs > 50 GeV)
- b-tagging

- Models: Kaluza-Klein gluon, leptophobic Z'
- Main backgrounds: multi-jet QCD, SM $t\bar{t}$







95% CL limits

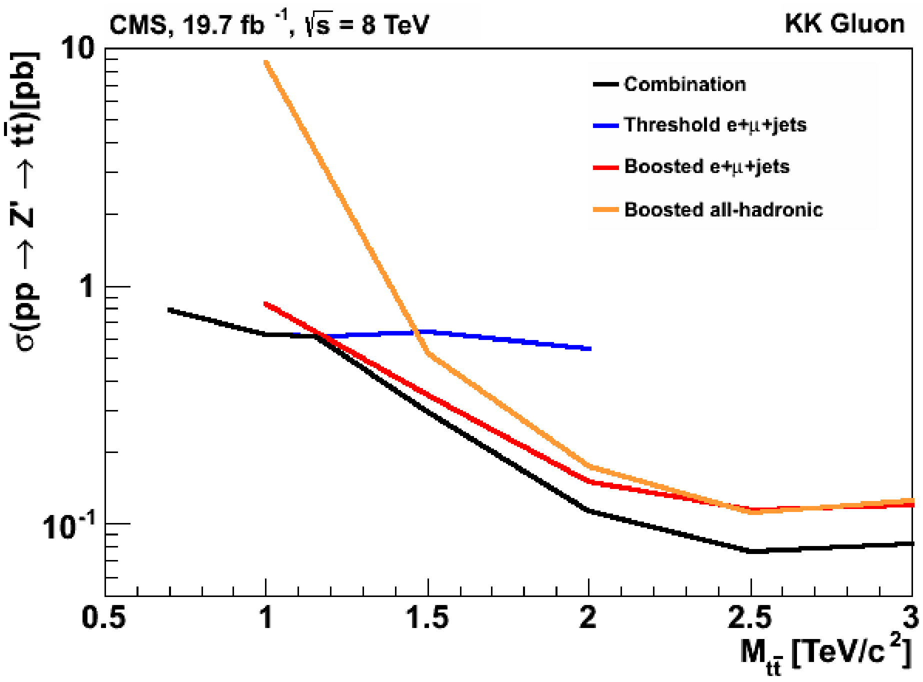
	Mass (TeV)
Wide Z'	2.35
Narrow Z'	1.7
g_{KK}	1.8

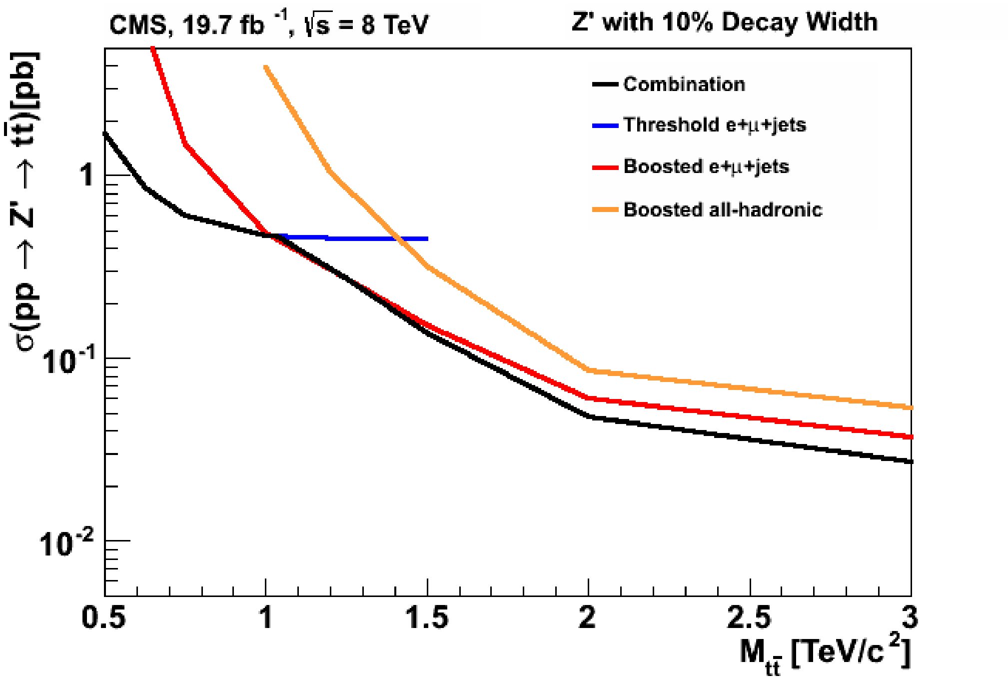
ATLAS analysis:
JHEP 01, 116 (2013)

$t\bar{t}$ resonance search

Phys. Rev. Lett. 111, 211804 (2013)

The boosted selection plays the leading role in pushing the $t\bar{t}$ resonances mass limit to higher values





tH resonance search - I

CMS-PAS-B2G-14-002

- Search for tH resonances in full-hadronic final state
- Top-tagging (HEPTopTagger) and Higgs-tagging (sub-jets b-tagging) algorithms applied to C/A R=1.5 jets
- Likelihood discriminator built from scalar sum of transverse momenta of selected objects (H_T) and mass of the two b-tagged sub-jets (m_H)

- Model: pair of vector-like T quarks (MADGRAPH)
- Main background: multi-jet QCD (extracted from data), $t\bar{t}$ (MADGRAPH)

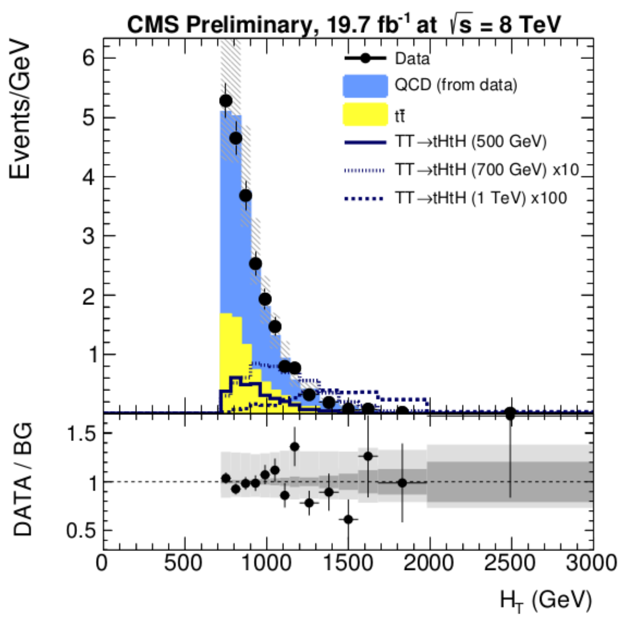
- QCD background estimated using matrix metod
- Sidebands region obtained inverting the top and Higgs tagging selections
- The two taggers are uncorrelated:

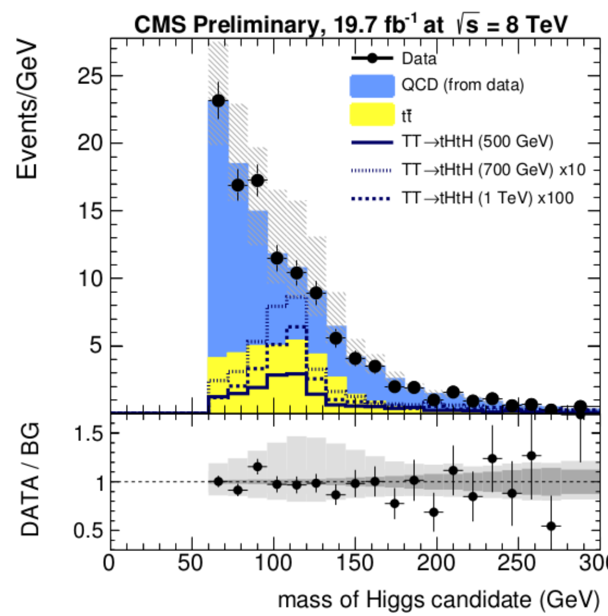
$$\frac{N_D}{N_C}=\frac{N_B}{N_A}$$

	$\overline{\text{H-tag}}$	H-tag
$\overline{\text{t-tag}}$	A	B
t-tag	C	D

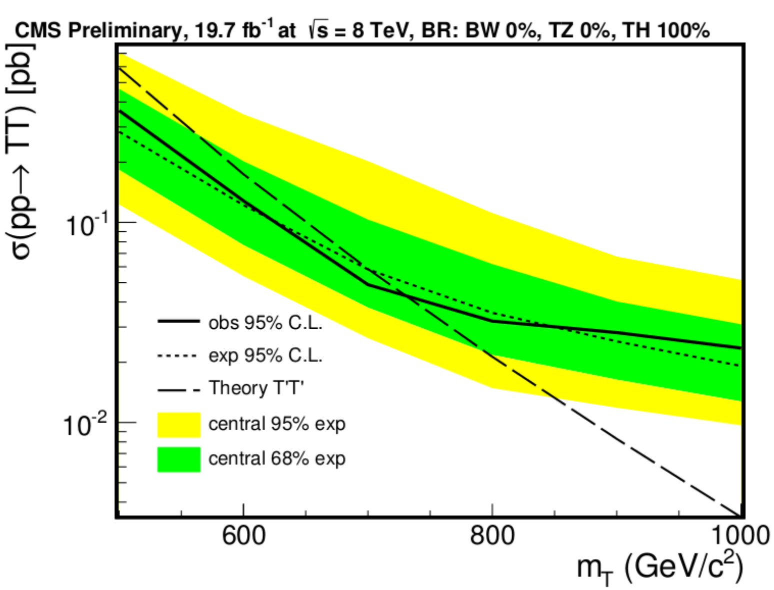
tH resonance search - II

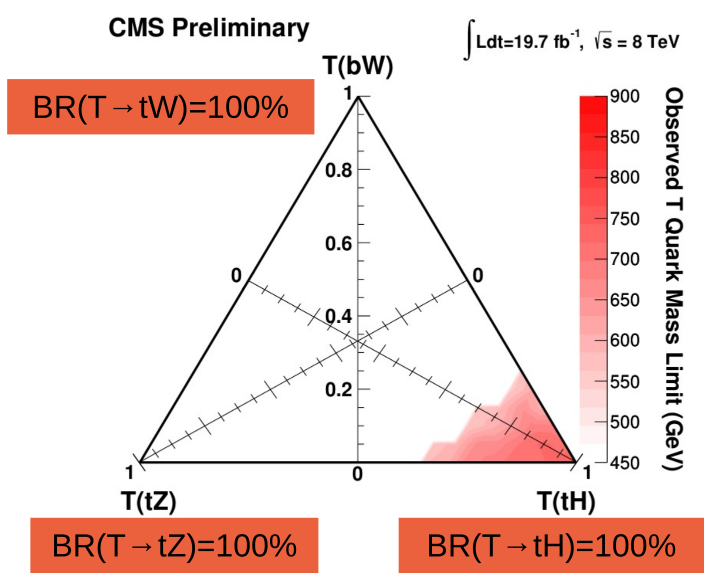
CMS-PAS-B2G-14-002





H_T and m_H combined in a likelihood discriminator





Assuming BR(T→tH)=100% exclude m_T<747 GeV (95% CL)

Derive mass limits also as a function of the T branching ratios

Summary

- Techniques for jet substructure analysis developed by ATLAS and CMS allow to reconstruct hadronic decay of massive objects in the boosted regime
- Successfully applied in several measurements and BSM physics searches
  - Physics results complementary to the ones obtained using resolved reconstruction techniques
  - Boosted analysis push farther the mass limits
- These techniques (and future extensions) are crucial for LHC Run2 physics program
  - Energy and pile-up will increase
  - Techniques still under active developments
  - Fruitful interplay between theorists and experimentalists

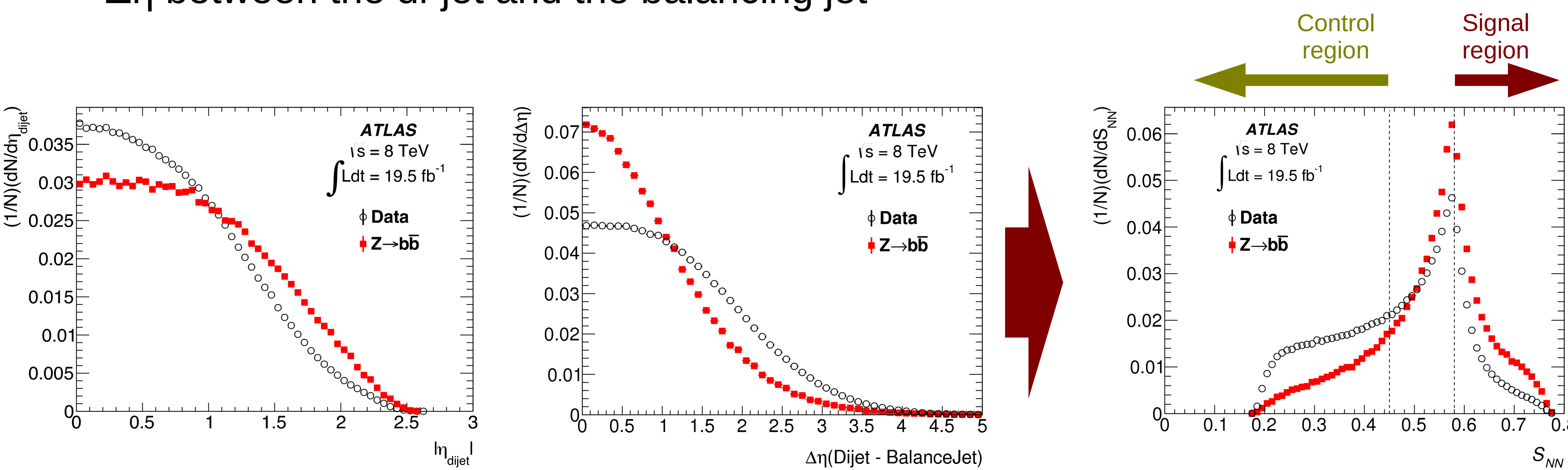
BACKUP

High-pT $Z\rightarrow b\bar{b}$ - I

arXiv:1404.7042

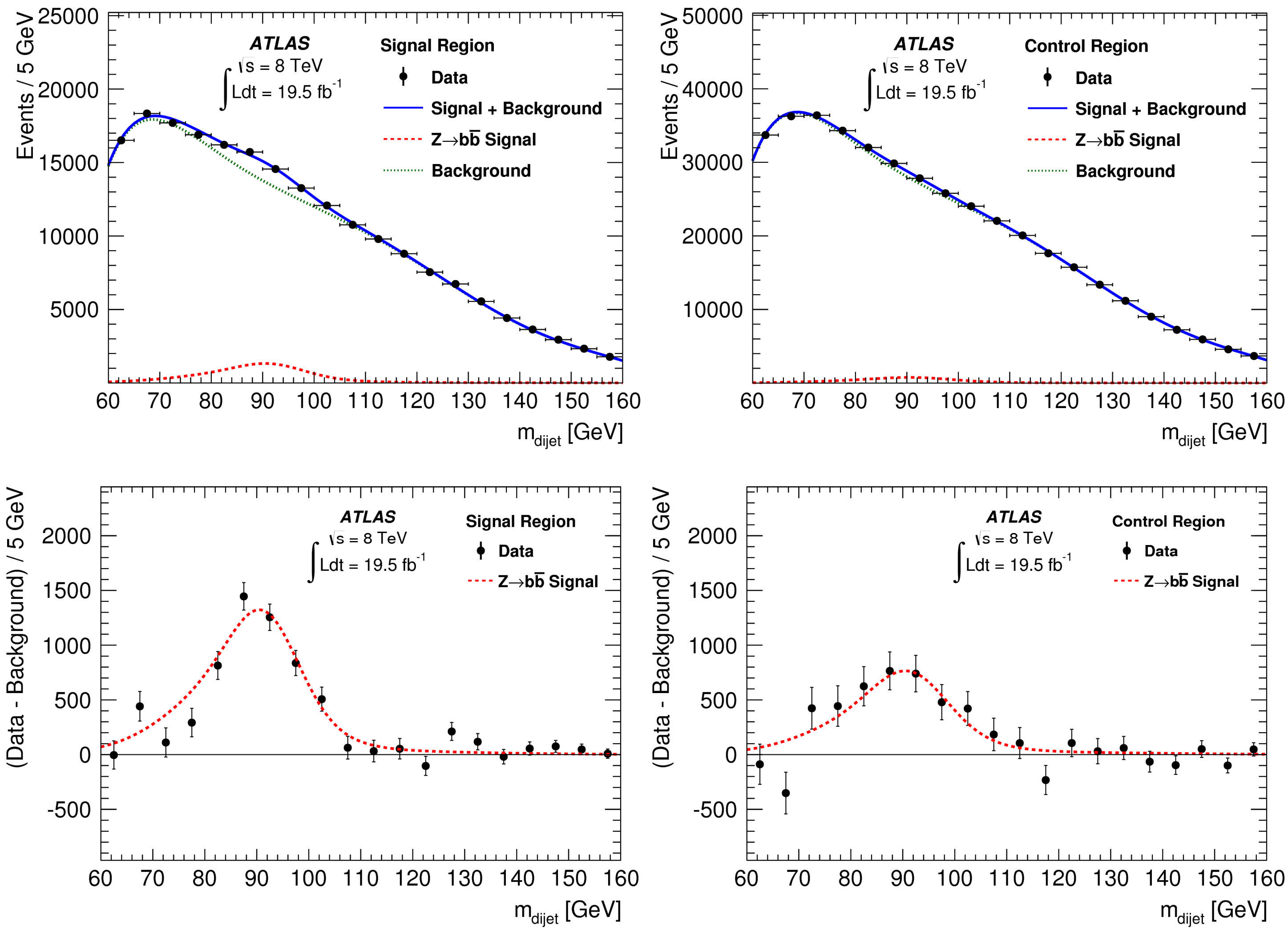
- Reconstruct $Z\rightarrow b\bar{b}$ using pair of b-tagged R=0.4 anti-k_T jet ($\Delta R<1.2$, $p_T>200$ GeV)
- Measure the cross section in a fiducial region
- Z MC (signal): SHERPA
- Multi-jet QCD MC (main background): from data

- W/Z jets selection based on artificial neural network discriminator (S_{NN}) based on topological variables:
  - ➔ η of di-jet system
  - ➔ Δη between the di-jet and the balancing jet



High-pT $Z \to b\bar{b}$ - II

arXiv:1404.7042



Simultaneous fit in signal and control regions

Measured fiducial cross section:

$$\sigma^{fid}_{Z \to b\bar{b}} = 2.02 \pm 0.20\,(stat) \pm 0.26\,(syst)\ pb$$

Excellent agreement with NLO+PS MC calculations (CT10 PDF):

- POWHEG:

$$\sigma^{fid}_{Z \to b\bar{b}} = 2.02^{+0.25}_{0.19}\,(scales)^{+0.03}_{0.04}\,(PDF)\ pb$$

- aMC@NLO:

$$\sigma^{fid}_{Z \to b\bar{b}} = 1.98^{+0.16}_{0.08}\,(scales) \pm 0.03\,(PDF)\ pb$$