

Searches for Vector-Like Quarks and Top-Pair Resonances with the ATLAS Detector

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on behalf of
The ATLAS Collaboration



Phenomenology 2013 Symposium

Introduction

Searches for new physics involving top quarks are well motivated by the peculiar position of the top quark in the Standard Model

This talk will present three searches for deviations in the Standard Model top pair prediction

- Two searches for **new top pair resonances**
Boosted Fully Hadronic Channel
Lepton + Jets Channel

Using **new jet substructure tagging** techniques to identify **boosted top-quarks**

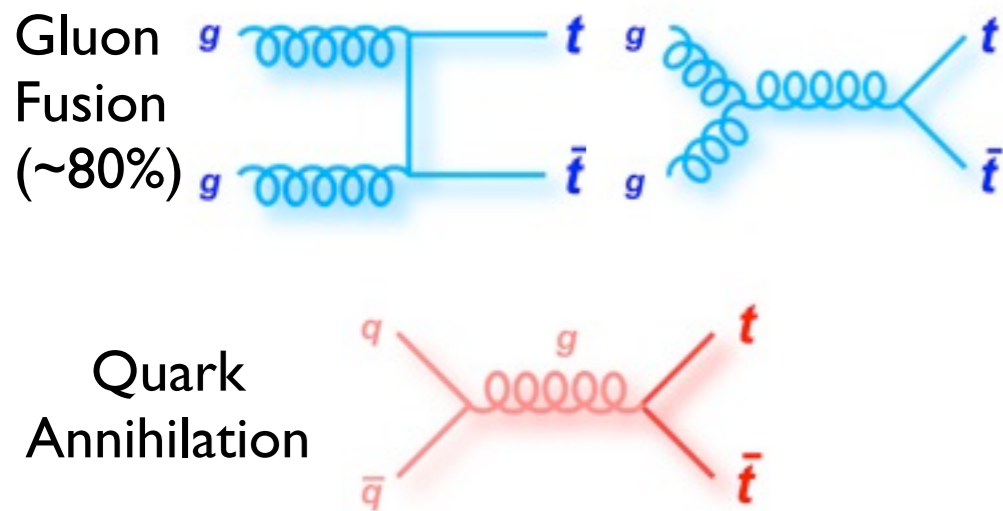
- One search for **t' pair production** as predicted by **Vector-Like-Quark models** in the lepton + jets channel

First ATLAS search **optimized** for $t' \rightarrow Ht$ decay

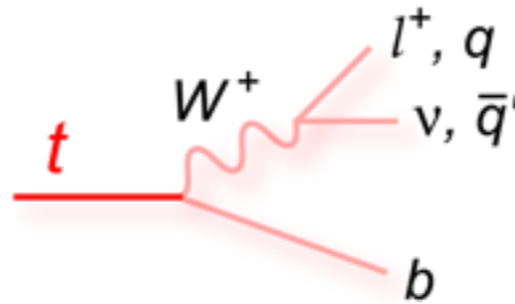
First ATLAS analysis setting **model independent limits** on VLQ t's

Top Pairs

Standard Model Top Pair Production



Search Channels



Top Pair Decay Channels

$c\bar{s}$	electron+jets	muon+jets	tau+jets	all-hadronic	
$u\bar{d}$	electron+jets	muon+jets	tau+jets		
τ^-	e τ	τ^-	$\tau^+\tau^-$		tau+jets
e^-	e e	e τ	τ^-		muon+jets
W^- decay	e^-	μ^-	τ^-	electron+jets	
	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$

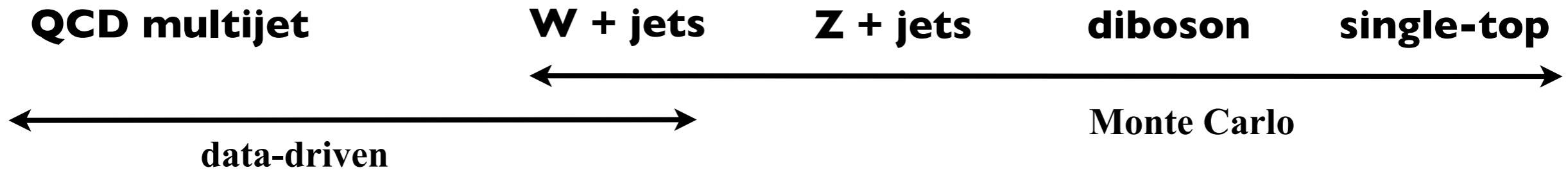
~ 46% all hadronic

2-bjets, 4-jets

~ 36% lepton + jets

2 b-jets, 2-jets
lepton, neutrino

Backgrounds



Standard Object Selections

Leptons:

$$p_T > 25 \text{ GeV} \quad \Delta R_{jets} > 0.4$$

$$|\eta| < 2.5 \quad \text{mini-isolation}$$

Jets:

$$p_T > 25 \text{ GeV}$$

$$|\eta| < 2.5$$

b-Jets:

- 70% eff.

Neutrino:

$$E_T^{miss} \geq 20(35) \text{ GeV}$$

Multijet Rejection:

$$e : m_T(W) \geq 35 \text{ GeV}$$

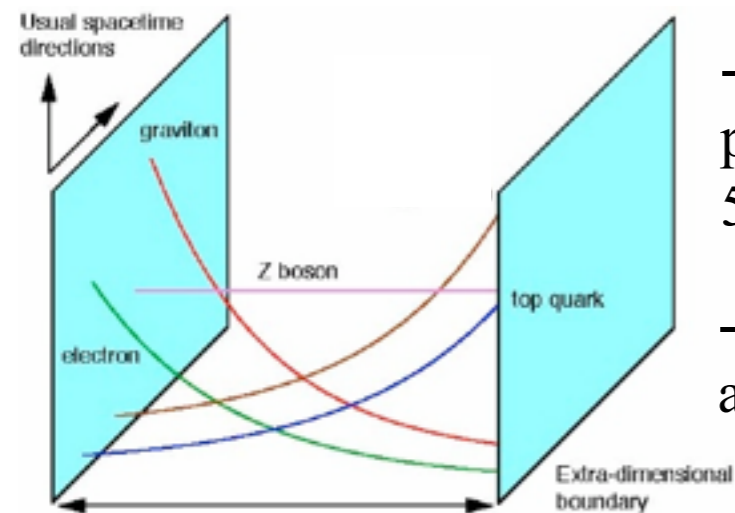
$$\mu : E_T^{miss} + m_T(W) \geq 60 \text{ GeV}$$

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

Top pair resonances

New resonant top-pair production: two benchmark models are searched for

Randall-Sundrum Warped Extra-dimensions



- Gravitons and SM propagate in warped 5D bulk
- Hierarchies explained as geometric effects

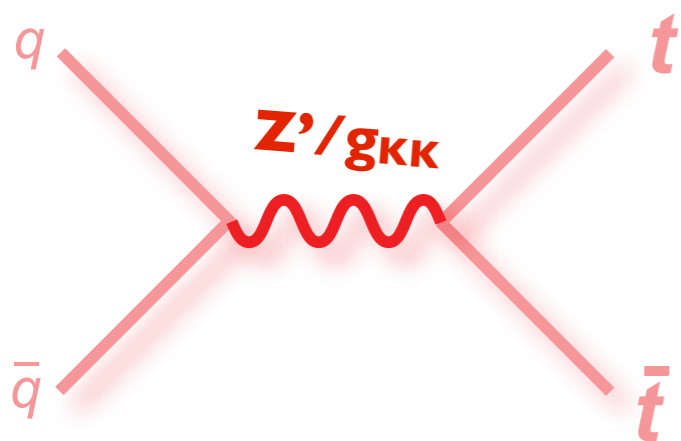
- **Kaluza-Klein gluon** couples strongly to top-quarks

TopColor

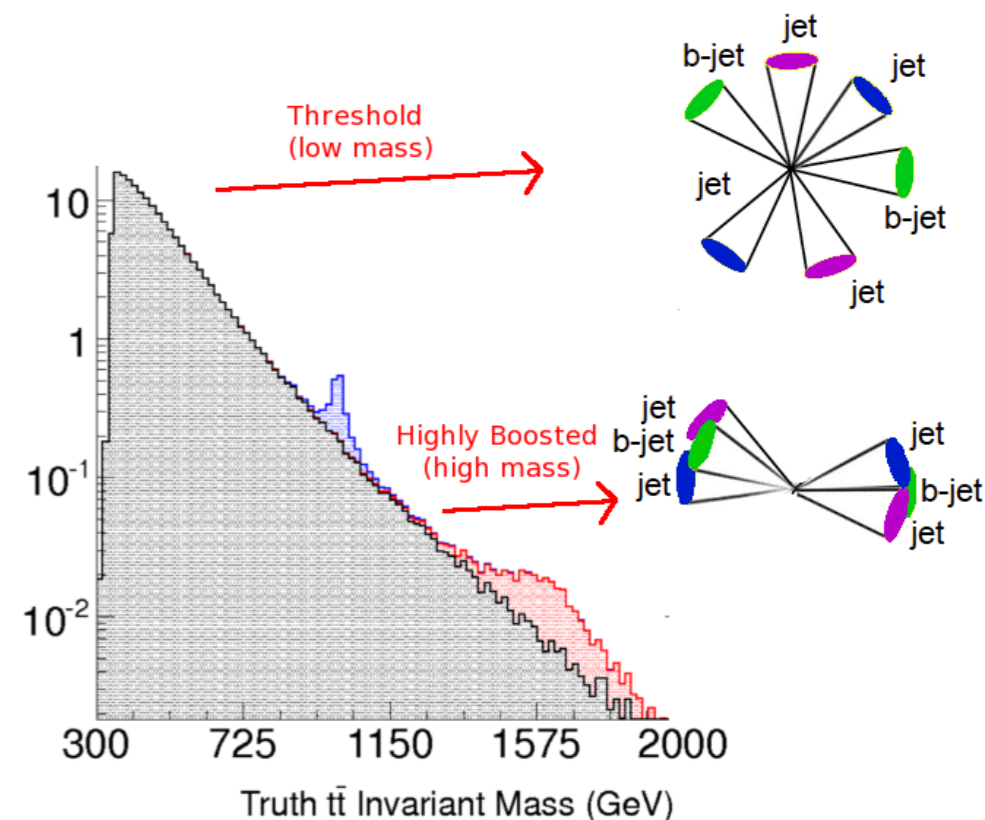
$$SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_C$$

- Compatible with various models
- Massive topgluons enhance third generation masses

- **leptophobic Z'** breaks 3rd generation mass degeneracy



	Z'	KK-gluon
Γ/M	1.2%	15%



top-pairs produced at **high invariant mass**

Reconstructing **boosted topologies** is important

Resonances: Top Decay Topologies

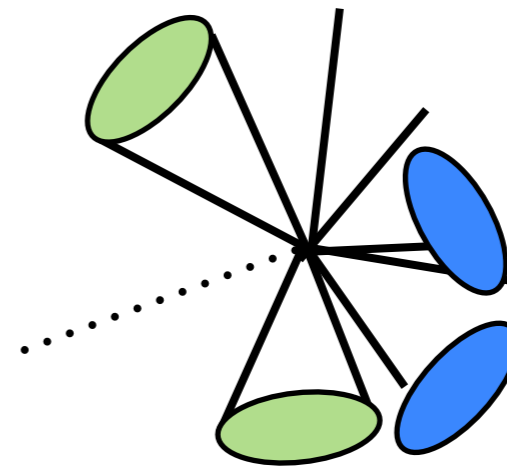
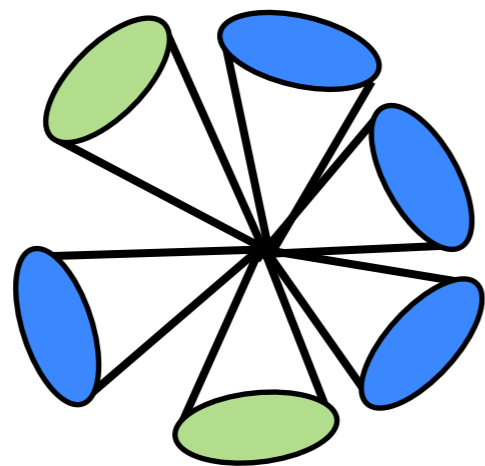
Resonant Search Strategy: Reconstruct each top-decay and the invariant mass of the ditop system

Methods depend on how boosted the top-quarks are

Resolved decays: the top-decays products are well separated

fully hadronic: 2 b-jets + 4 jets

lepton + jets: lepton + missing E_T + 2 b-jets + 2 jets

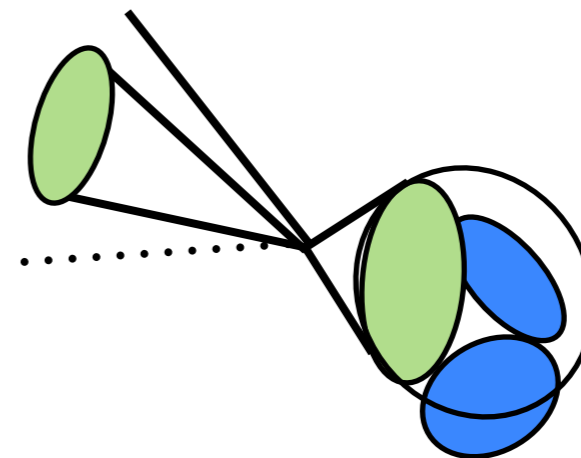
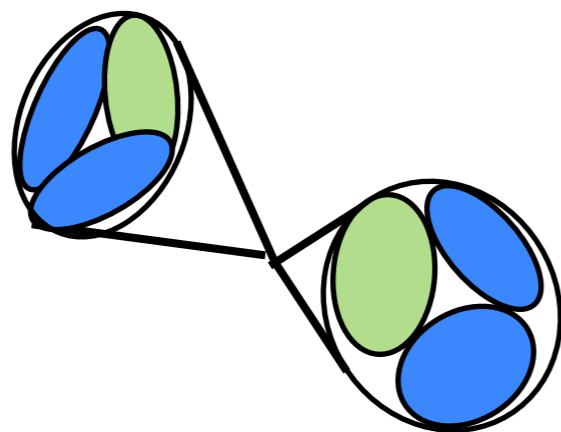


Associate final state objects to top/anti-top decays with a kinematic fitter

Boosted channels: top is sufficiently boosted such that its decay products are well collimated

fully hadronic: 2 large R-jets

lepton + jets: 1 large R-jet + jet + lepton + missing E_T



Distinguish hadronic top decay from QCD jets \rightarrow jet mass, associated b-jet, **jet substructure (*top-tagging*)**

Presence of unconventional jet helps reject backgrounds

Resonances: Fully Hadronic Search

- First ATLAS results in the boosted fully hadronic channel
- Two separate analyses each using a different substructure tagger

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Top Template Tagger

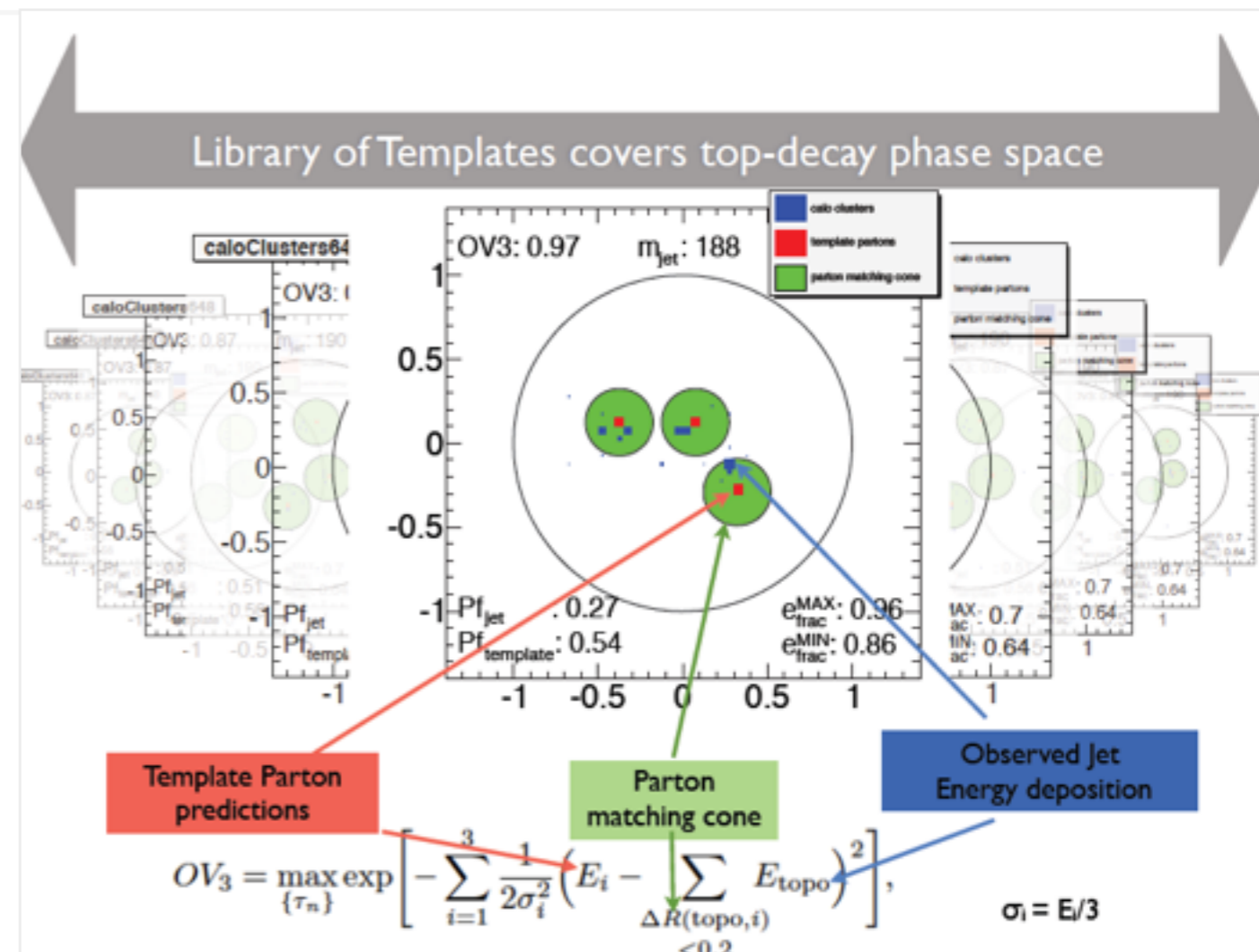
Targets high mass resonances $m > 1$ TeV

Event Selection:

- 2 fat jets** $R=1.0$ anti- k_T jets
- high p_T* $p_T > 500(450)$ GeV
- b-tagged* b-jet in $\Delta R < 1$.
- top mass* $122 < m_j < 222$

Top-Tagged:

Compare energy distribution inside jet to library of **parton-level top-decay predictions**



HepTopTagger

- Looser p_T selection gives greater sensitivity to lower invariant mass

Event Selection:

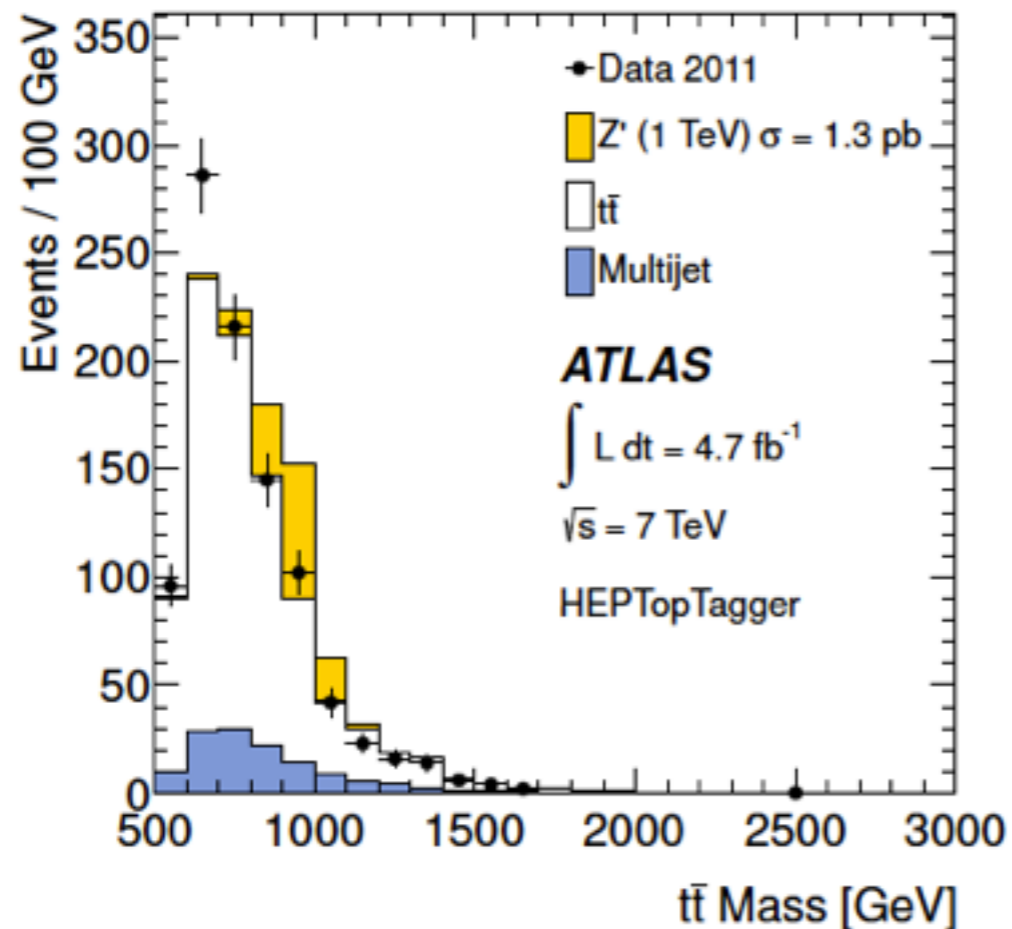
- 2 fat jets** $R=1.5$ C/A jets
- high p_T* $p_T > 200$ GeV
- b-tagged* b-jet in $\Delta R < 1.4$

Top-Tagged:

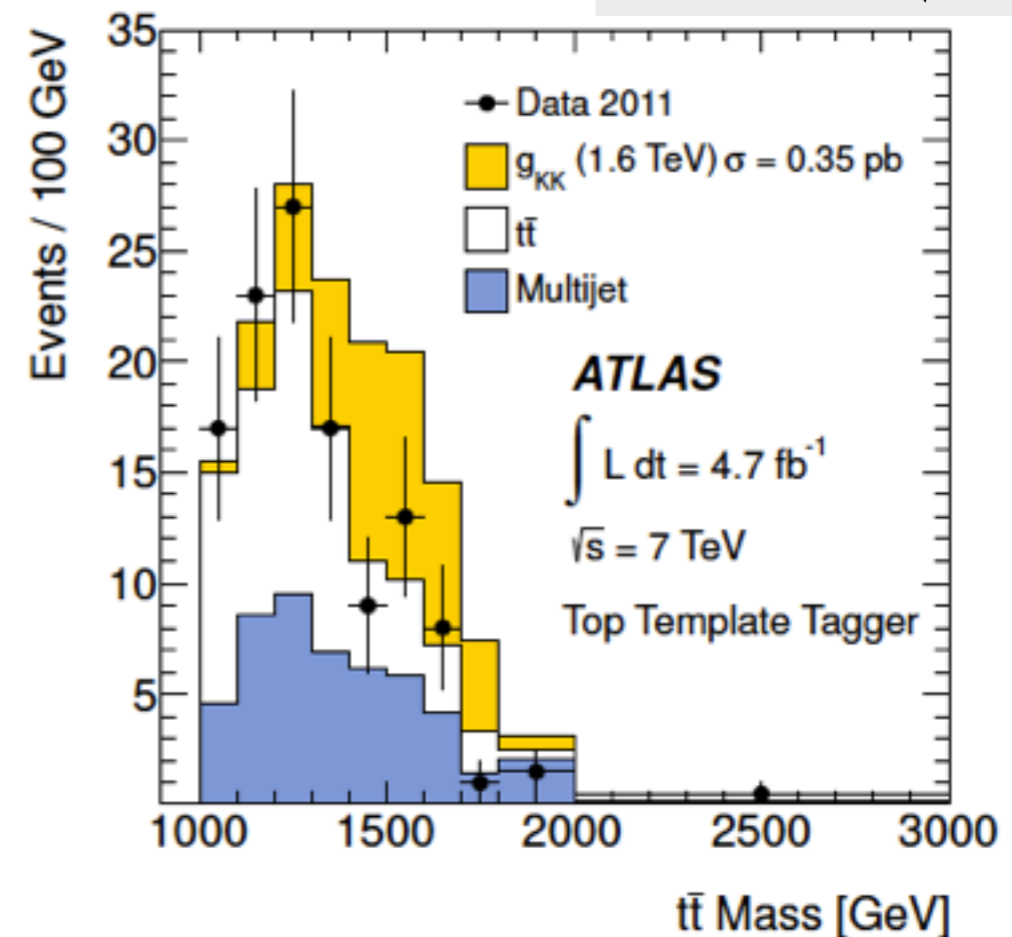
Identify best **three candidate subjects**
Require 3-subjet system has $144 < m_j < 210$

Resonances: Fully Hadronic Search

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SM tt	770^{+220}_{-180}
multijet	130 ± 70
data	953



SM tt	59^{+27}_{-26}
multijet	53 ± 6
data	123

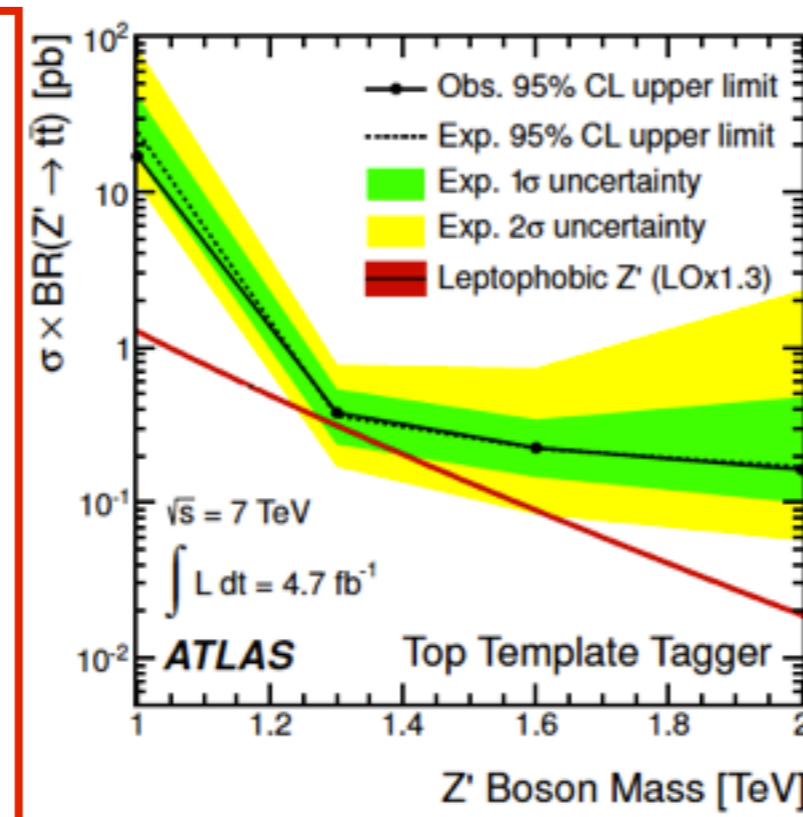
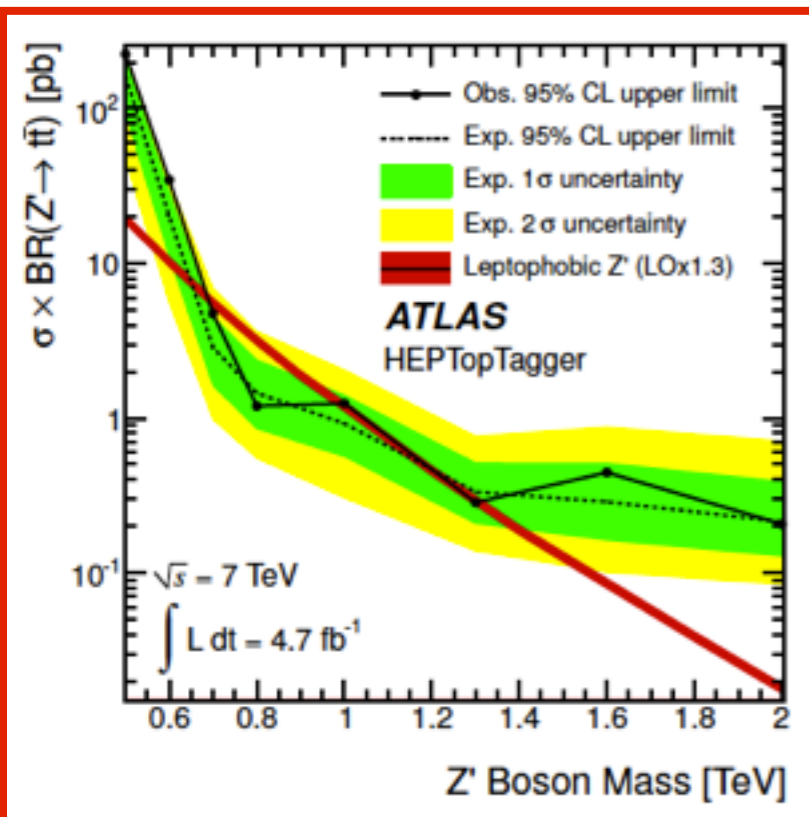
Backgrounds

- SM top-pair: Monte Carlo
- QCD Multijet: Data-Driven

Dominant Sources of Systematic Uncertainty

- b-tagging
- Jet Energy Calibration
- Initial/Final State Radiation
- Parton Distribution Function

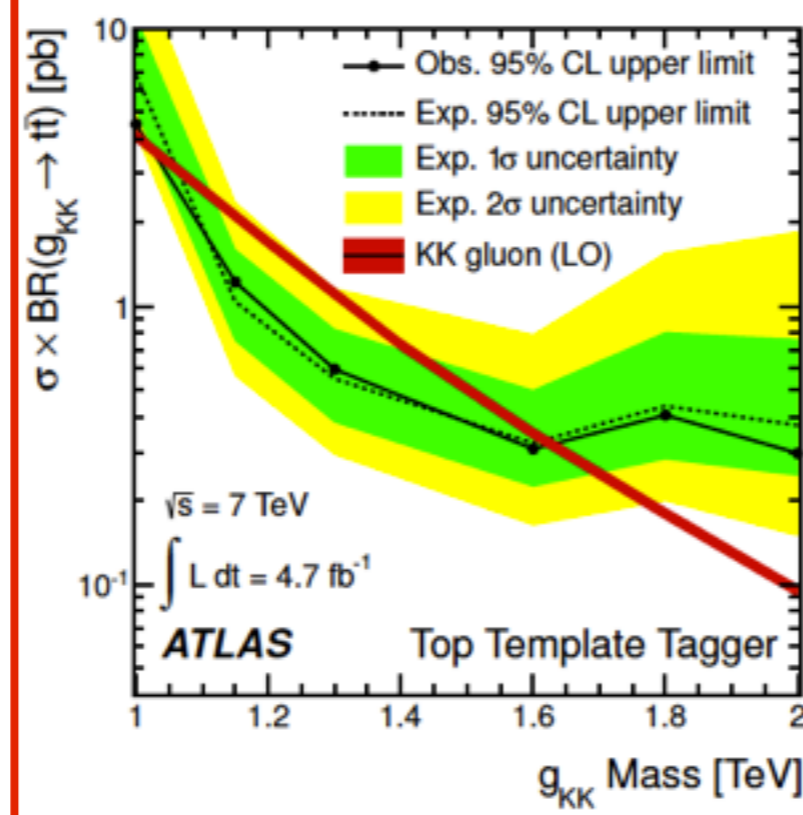
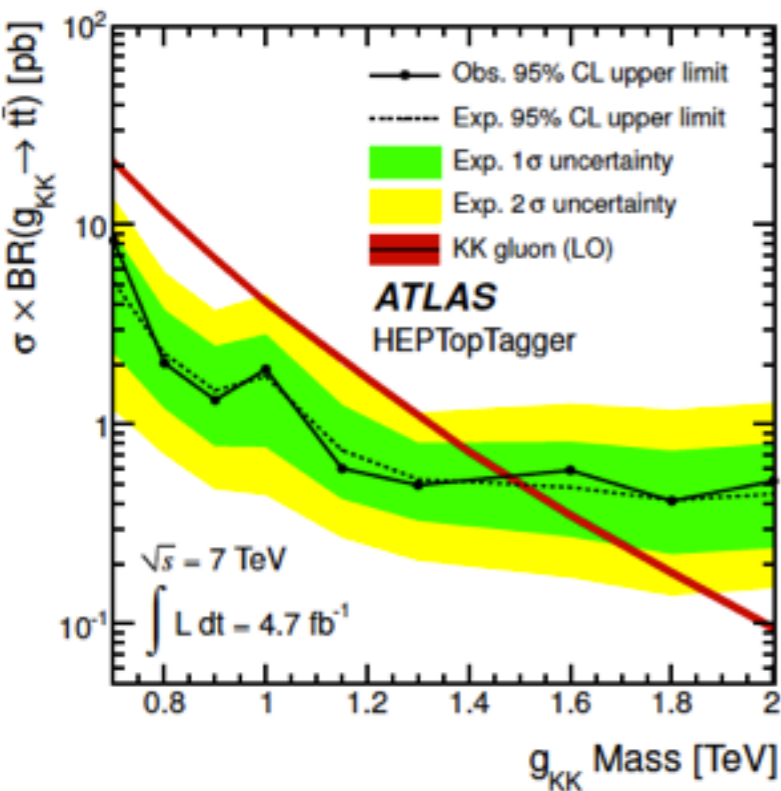
-No signal-like excess is observed



95% C.L. Bayesian upper limits are determined for benchmark KK gluon and Z' models

Best Z' limit set by HepTopTagger

Best KK-gluon limit set by Top Template Tagger



Model	Obs. Limit (TeV)	Exp. Limit (TeV)
HEPTopTagger		
Z'	0.70 < m _{Z'} < 1.00 1.28 < m _{Z'} < 1.32	0.68 < m _{Z'} < 1.16
KK gluon	0.70 < m _{g_{KK}} < 1.48	0.70 < m _{g_{KK}} < 1.52
Top Template Tagger		
KK gluon	1.02 < m _{g_{KK}} < 1.62	1.08 < m _{g_{KK}} < 1.62

First ATLAS search that **combines boosted and resolved** lepton+jets topologies to maximize sensitivity

Boosted Selection

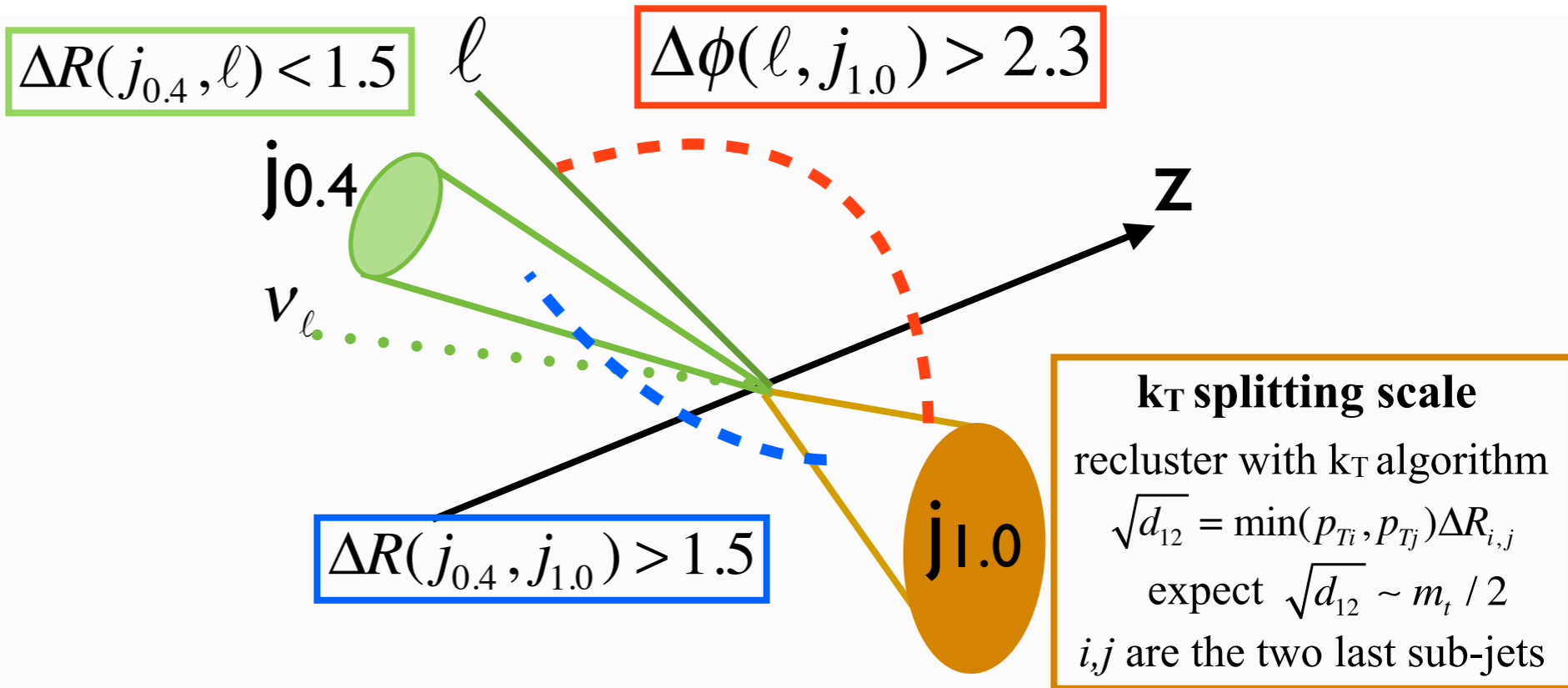
Hadronic Leg:

- one fat:** jet anti- k_T $R=1.0$
- high p_T :** $p_T > 350$ GeV
- top mass:** $m_j > 100$ GeV
- top tag:** k_T splitting scale:
 $\sqrt{d_{12}} > 40$ GeV

Semileptonic Leg:

- b-jet:** $R=0.4$ jet (not tagged)
- collimated lepton**
- missing E_T**

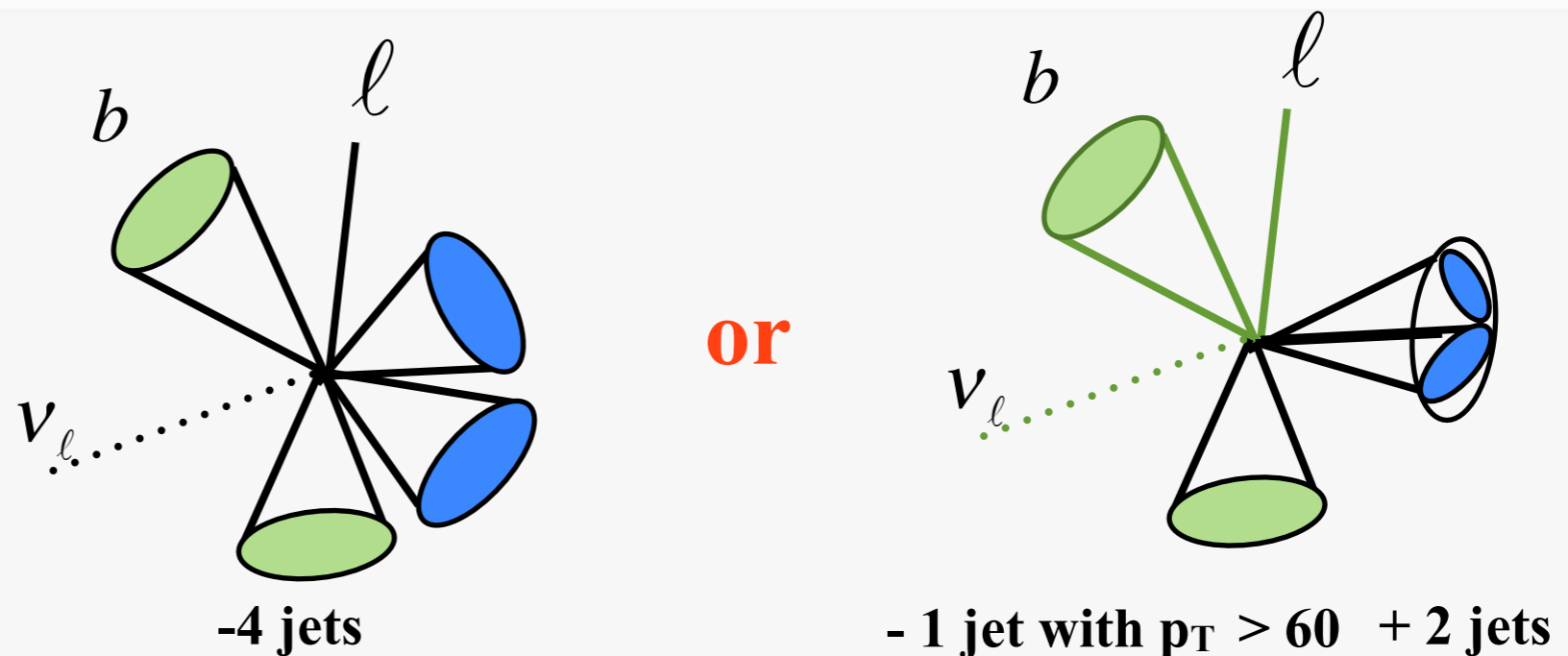
Legs must be separated

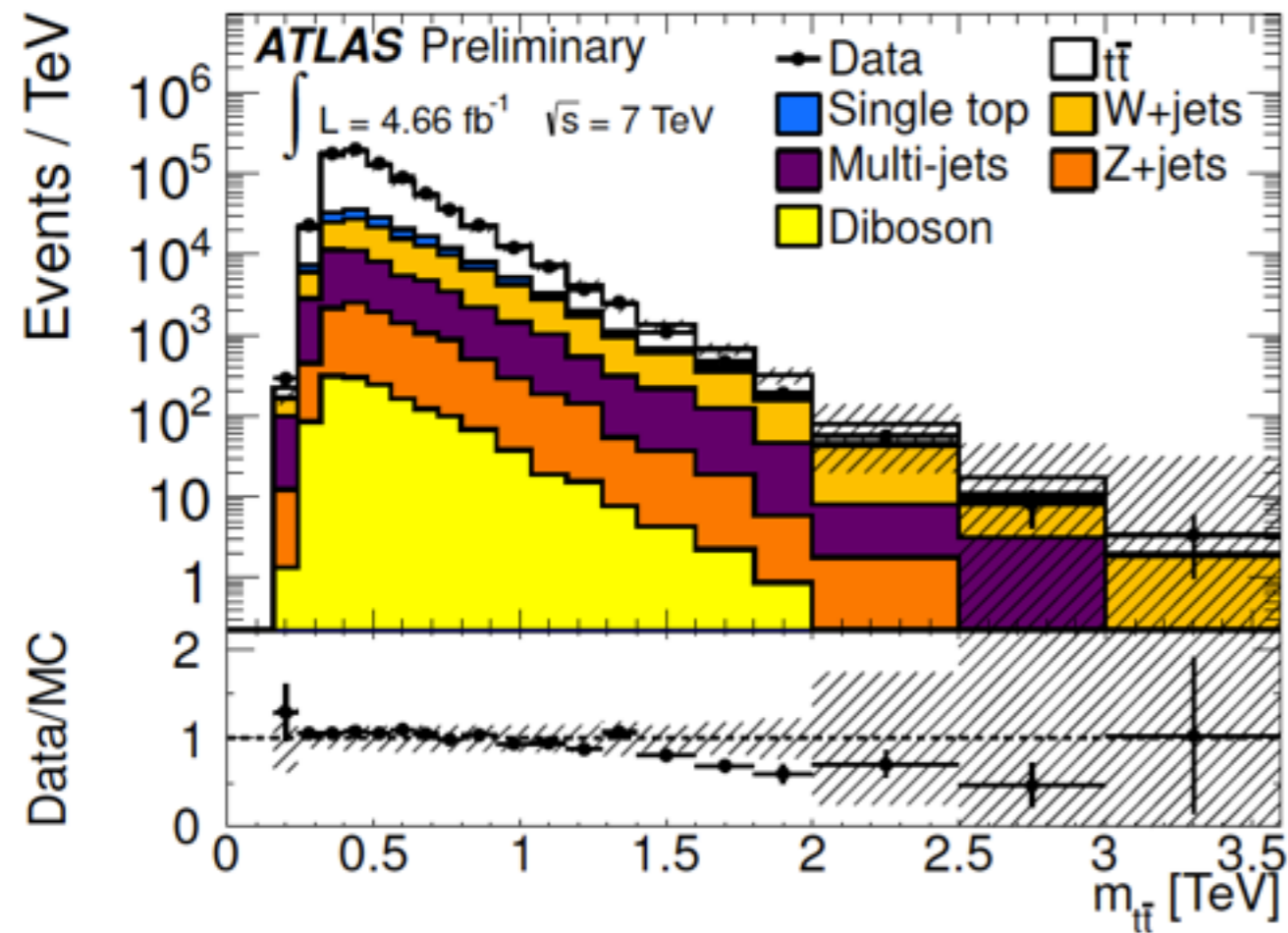


Resolved Selection

- Fails boosted selection
- one lepton
- missing E_T
- 3 or more jets

with at least **one b-tag**





Type	Resolved selection	Boosted selection
$t\bar{t}$	44 000 \pm 4 700	950 \pm 100
Single top	3 250 \pm 250	49 \pm 4
Multi-jets e +jets	2 500 \pm 1 500	12 \pm 7
Multi-jets μ +jet	1 010 \pm 610	20 \pm 12
W+jets	6 940 \pm 730	82 \pm 15
Z+jets	840 \pm 410	11 \pm 5
Di-bosons	124 \pm 43	0.88 \pm 0.30
Total	58 700 \pm 5 300	1 120 \pm 100
Data	61 954	1 079

backgrounds

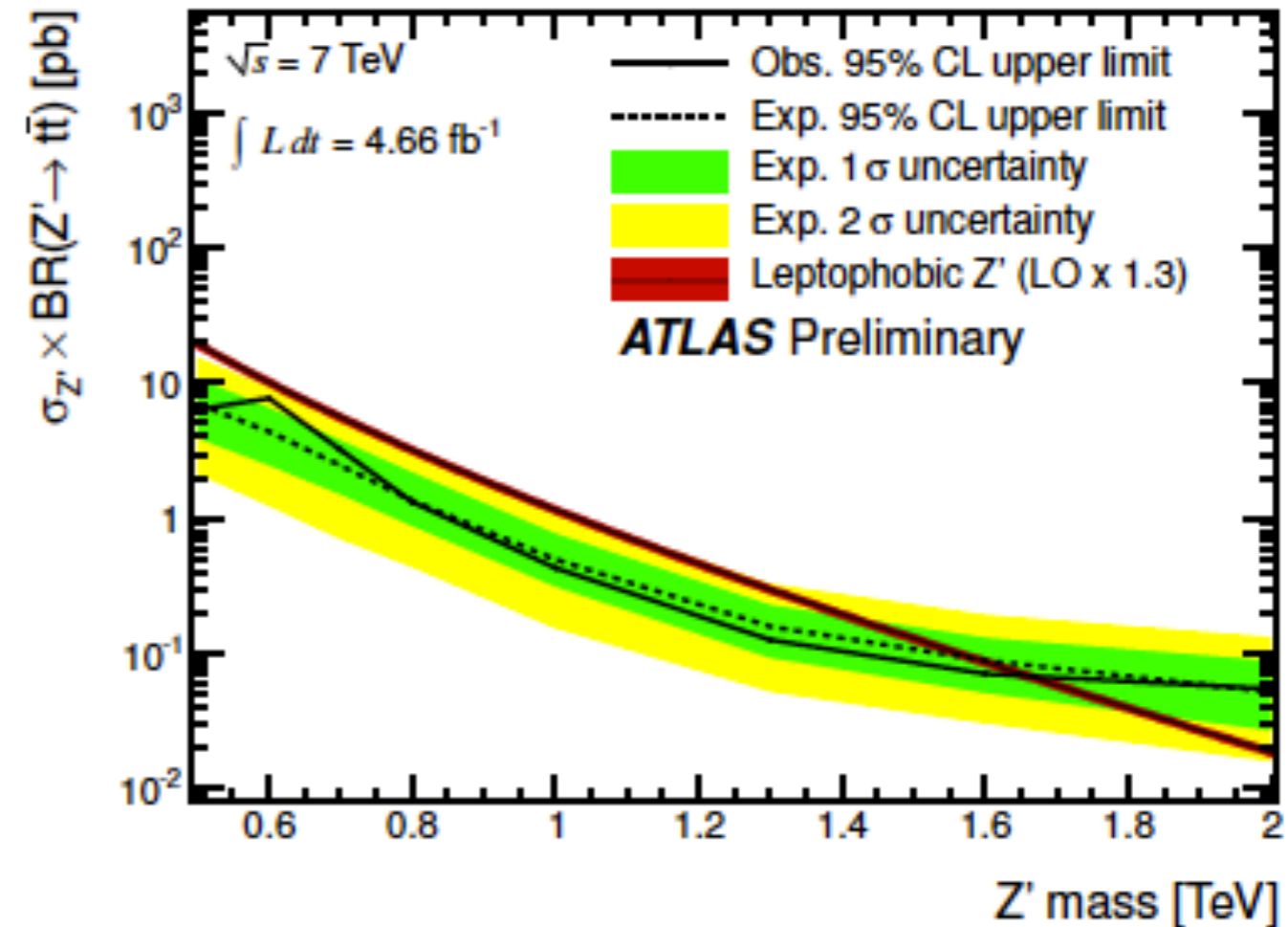
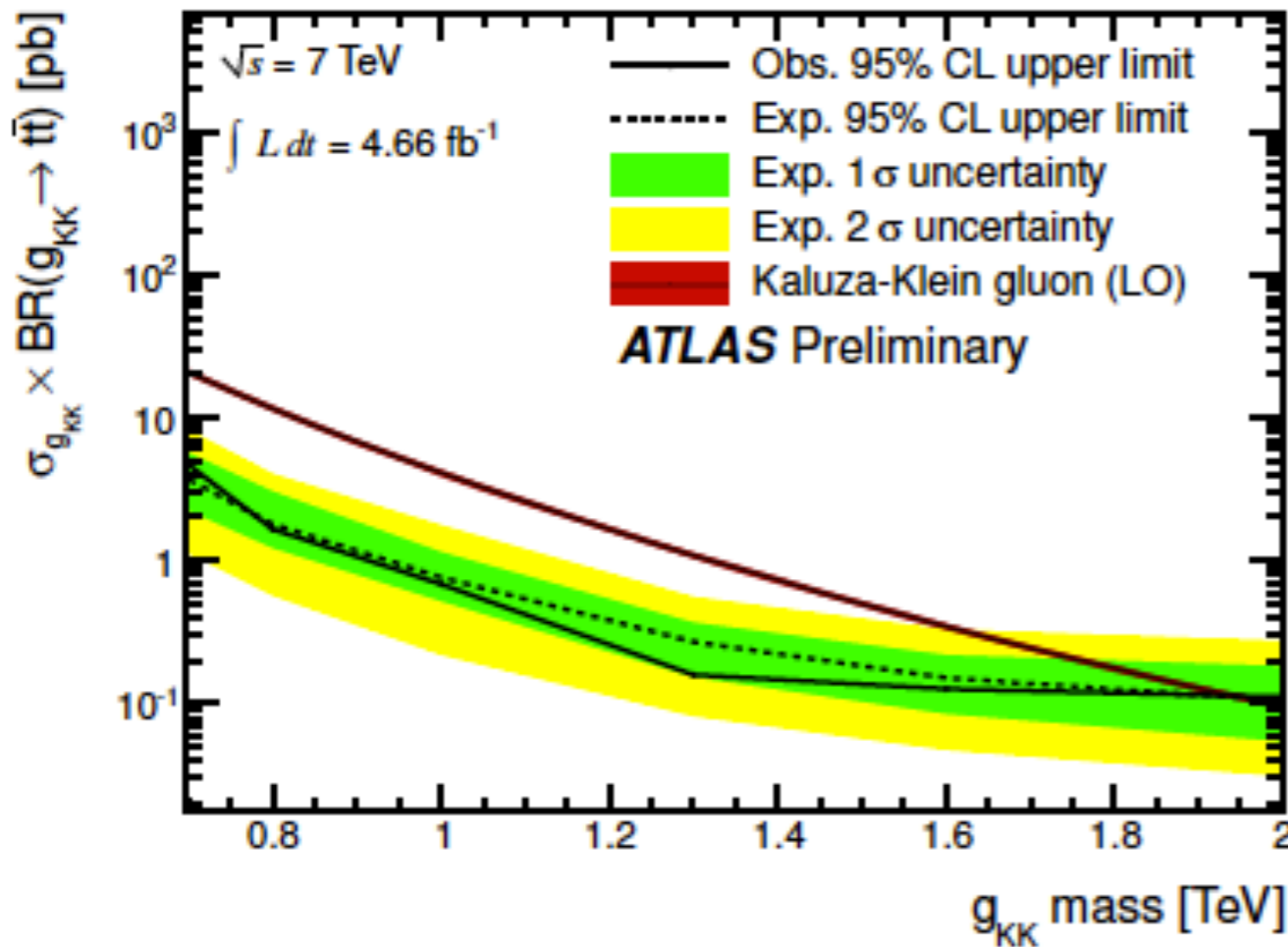
- SM top-pair: Monte Carlo
- W+jets: Data-Driven Rate
- QCD Multijet: Data-Driven
- Others: Monte Carlo

Dominant Sources of Systematic Uncertainty

- SM tt - cross-section
- Jet Energy Calibration
- b-tagging
- higher-order SM tt corrections
- parton shower
- Initial / Final State radiation

-No signal-like excess is observed

95% C.L. Bayesian upper limits are determined for benchmark KK gluon and Z' models



Best ATLAS limits from lepton+jets channel

Model	obs. limit (TeV)
Z'	$0.5 < m_{Z'} < 1.7$
KK gluon	$0.7 < m_{Z'} < 1.9$

Vector-Like Quarks

- New quark singlet, doublet, or triplets whose left- and right-handed representations transform identically under the electroweak gauge group

$$Q : (t') \quad (t', b') / (t', X) \quad (t', b', X) / (t', b', Y) \quad \sim W_\mu \bar{Q} \gamma^\mu Q$$

- Appear in various models: Extra-Dimensions, Little Higgs, Non-minimal SUSY...
- t' is a top-partner to cancel top quark contribution to Higgs self-coupling
- Can couple preferentially to 3rd generation Standard Model $\sim m_{3rd} / M_{t'}$
- **Non-resonant pair production** analogous to SM top-quarks \rightarrow Cross-section depends on $M_{t'}$

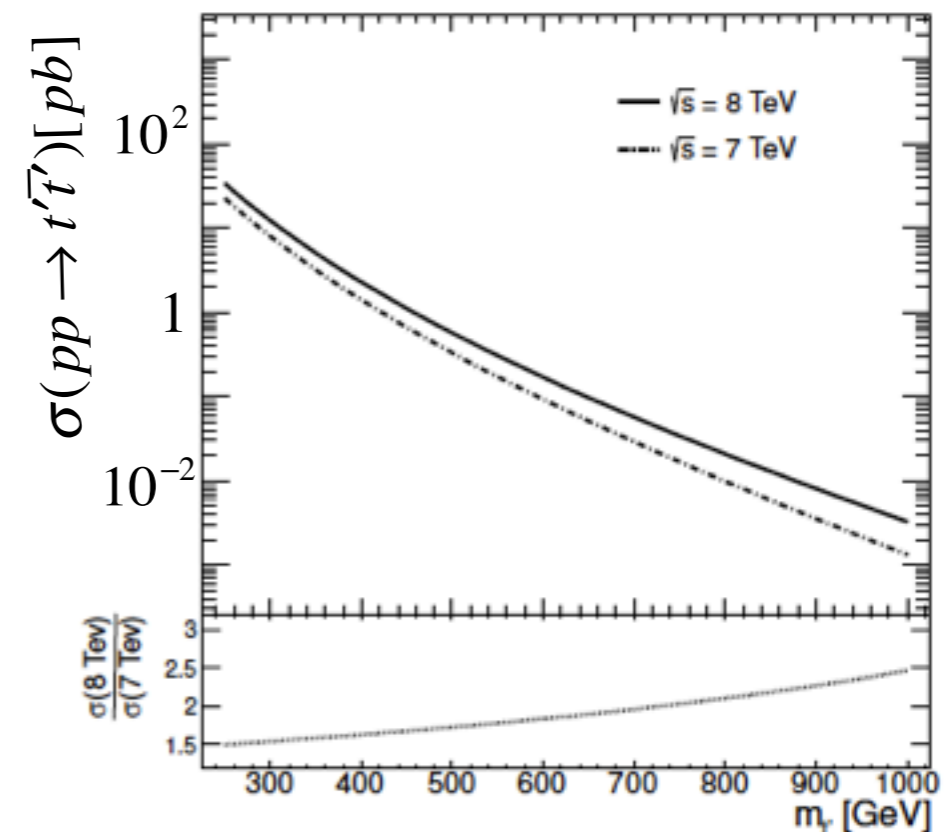
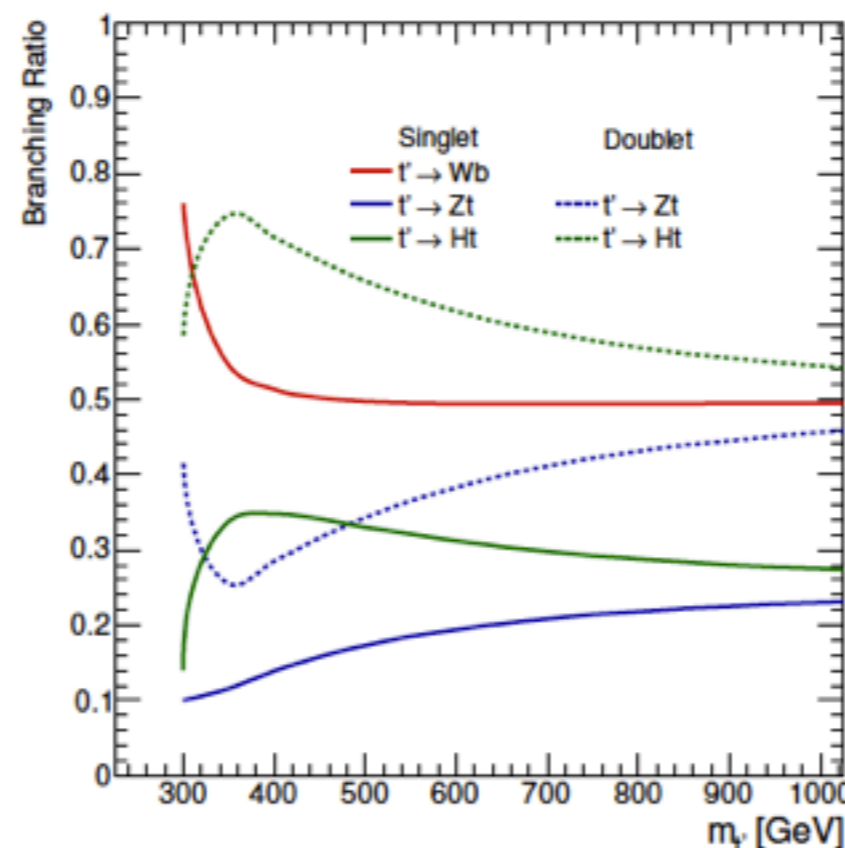
- t' has three decay modes

$$t' \rightarrow Wb$$

$$t' \rightarrow Zt$$

$$t' \rightarrow Ht$$

- Branching ratio depends on: $m_{t'}$, and multiplet

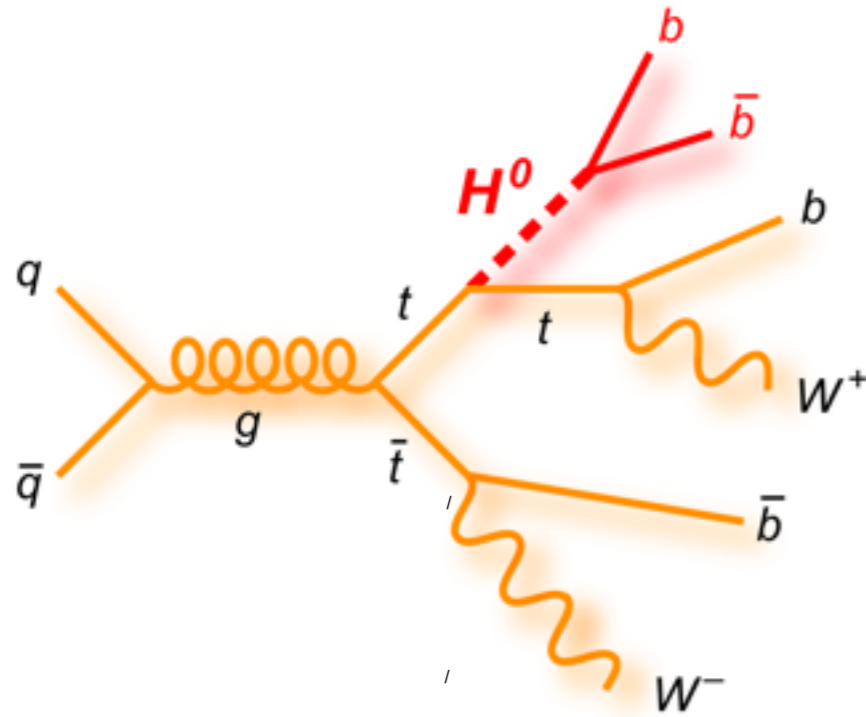


VLQ Search: lepton + jets + bb

ATLAS-CONF-2013-018

First analysis optimized for the $t' \rightarrow Ht$ decay, which is now fully specified ($m_H = 125$ GeV)

Distinguish $t'\bar{t}'$ events by searching for l+jets top-pairs events with additional b-jets



Event Selection:

one lepton
missing E_T
 ≥ 6 jets

Three $N_{b\text{-tag}}$ channels:

2 / 3 / ≥ 4 : Drives Sensitivity

(constrain SM $t\bar{t}$ + HF/LF)

Sensitive to three decay modes:

$t'\bar{t}' \rightarrow HtH\bar{t}, (HtZt), (HtWb)$

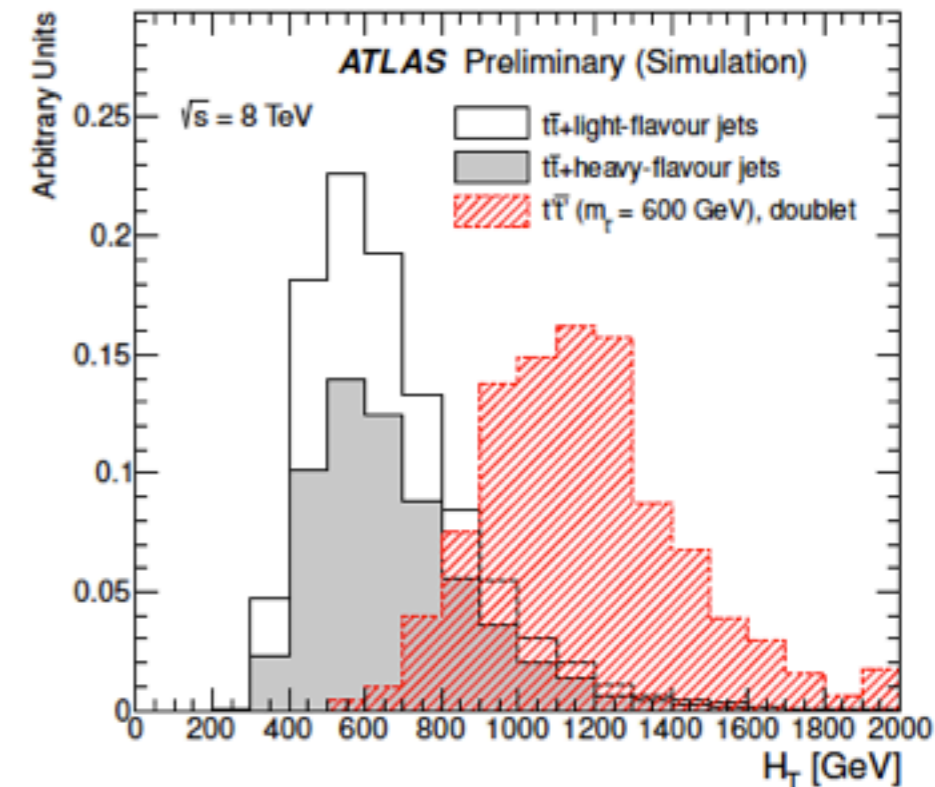
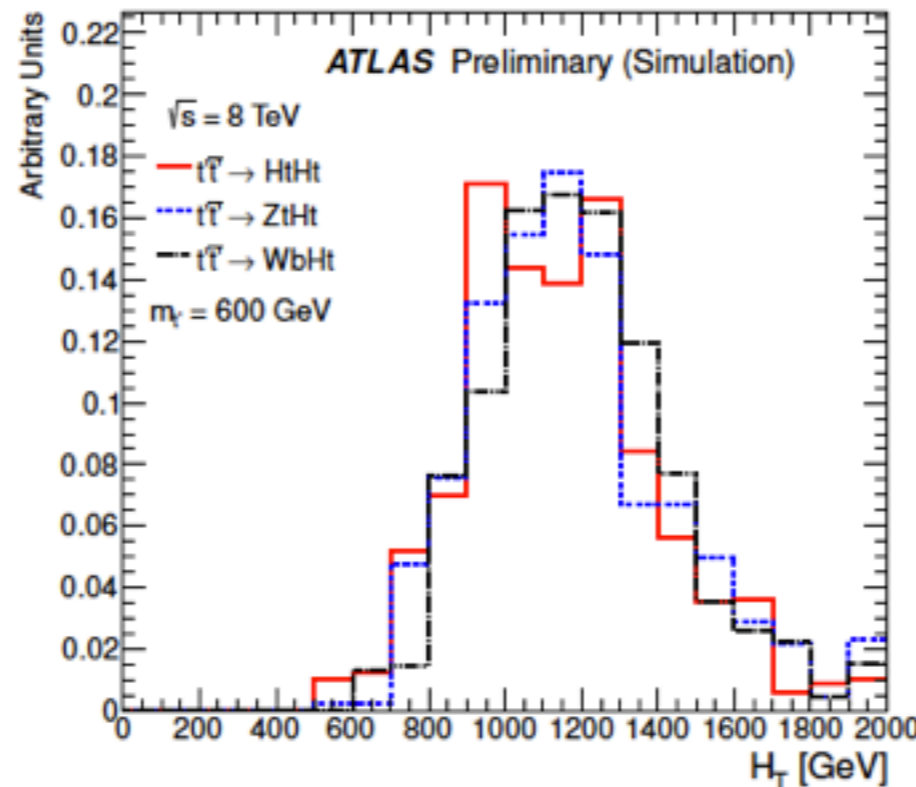
$BR(H \rightarrow b\bar{b}) \sim 60\%$

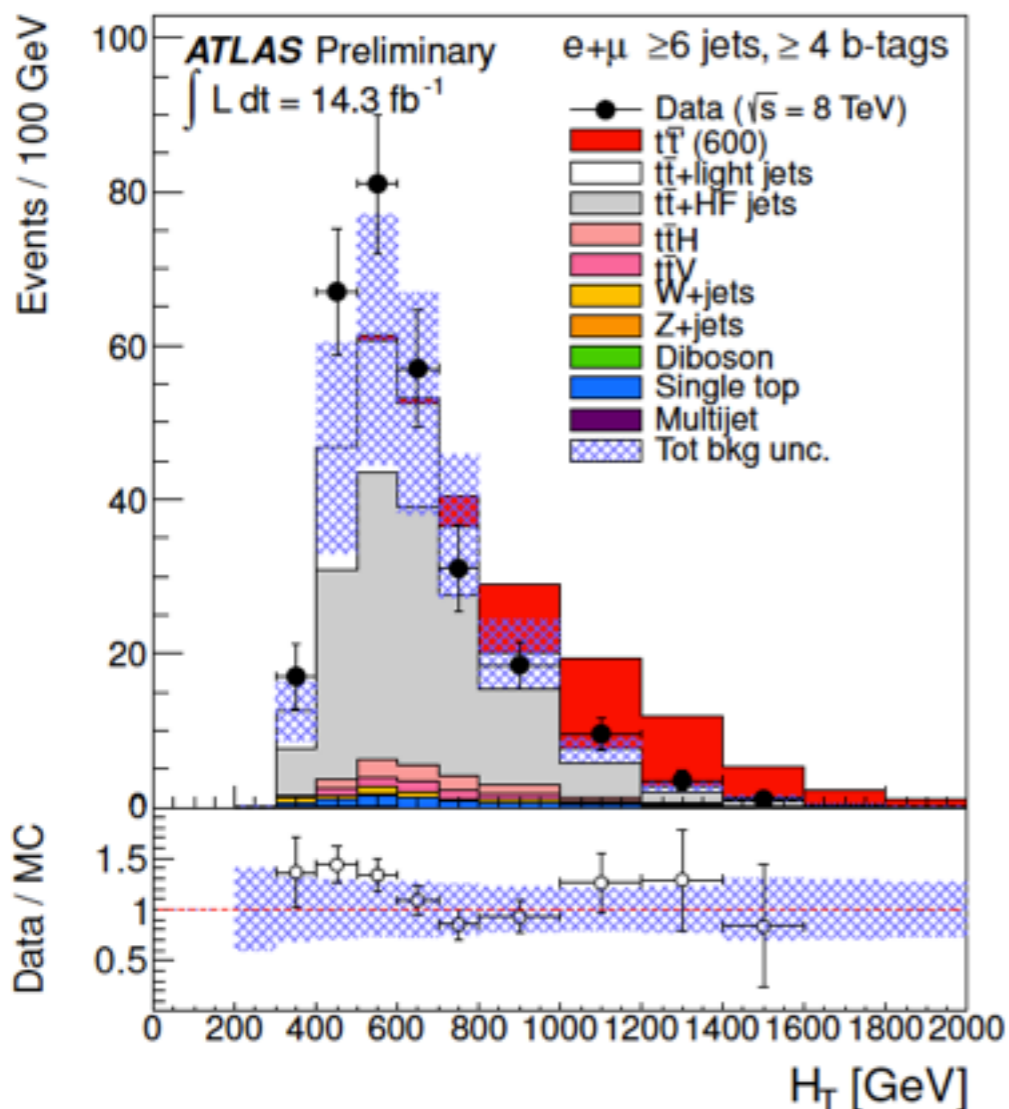
$BR(Z \rightarrow b\bar{b}) \sim 15\%$

Discriminating Variable

is chosen to be insensitive to decay mode:

$$H_T = p_{T,\ell} + E_T^{miss} + \sum_{jets} p_T$$





3 parameter likelihood fit in each b-jet bin for: signal, and tt+HF/LF rate

backgrounds

- W+jets rate: Data-Driven
- QCD Multijet: Data-Driven
- Others: Monte Carlo

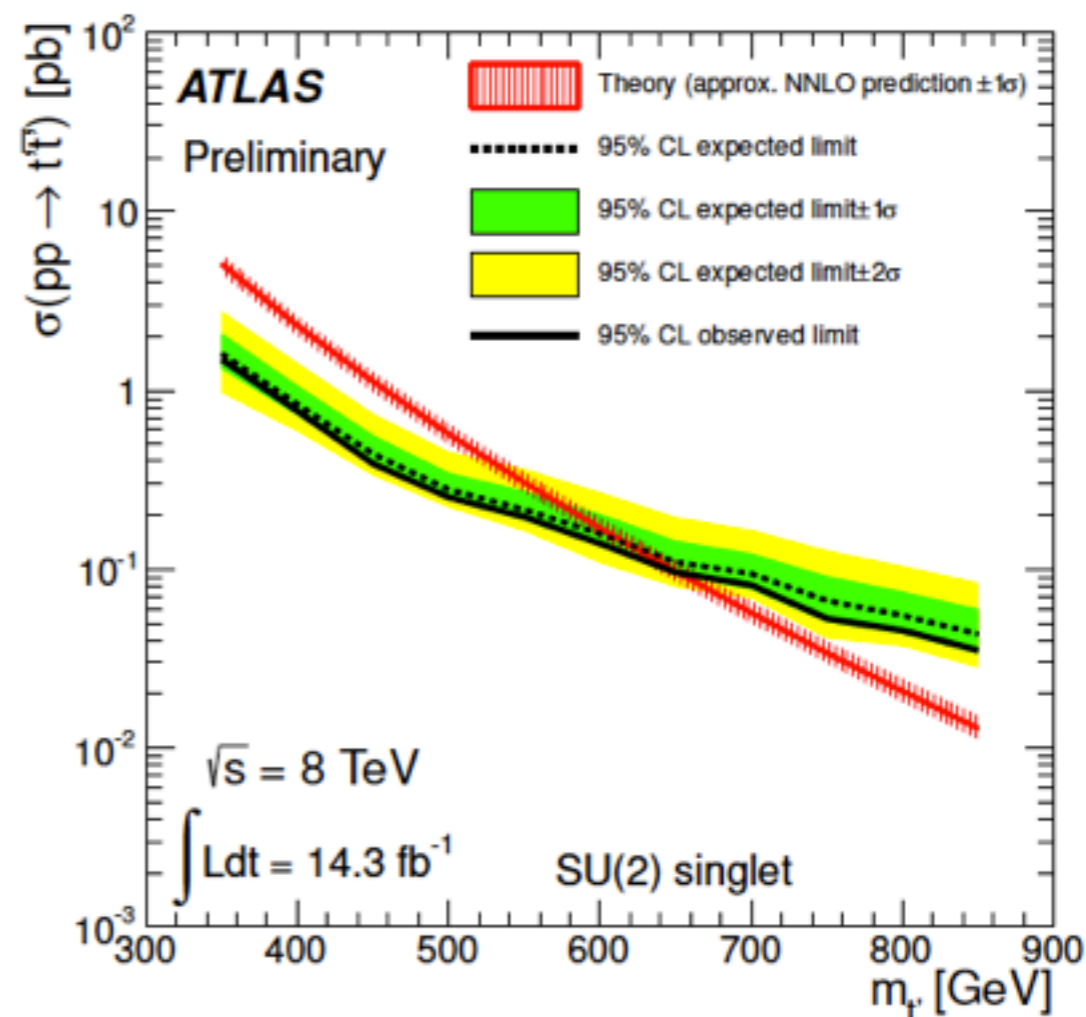
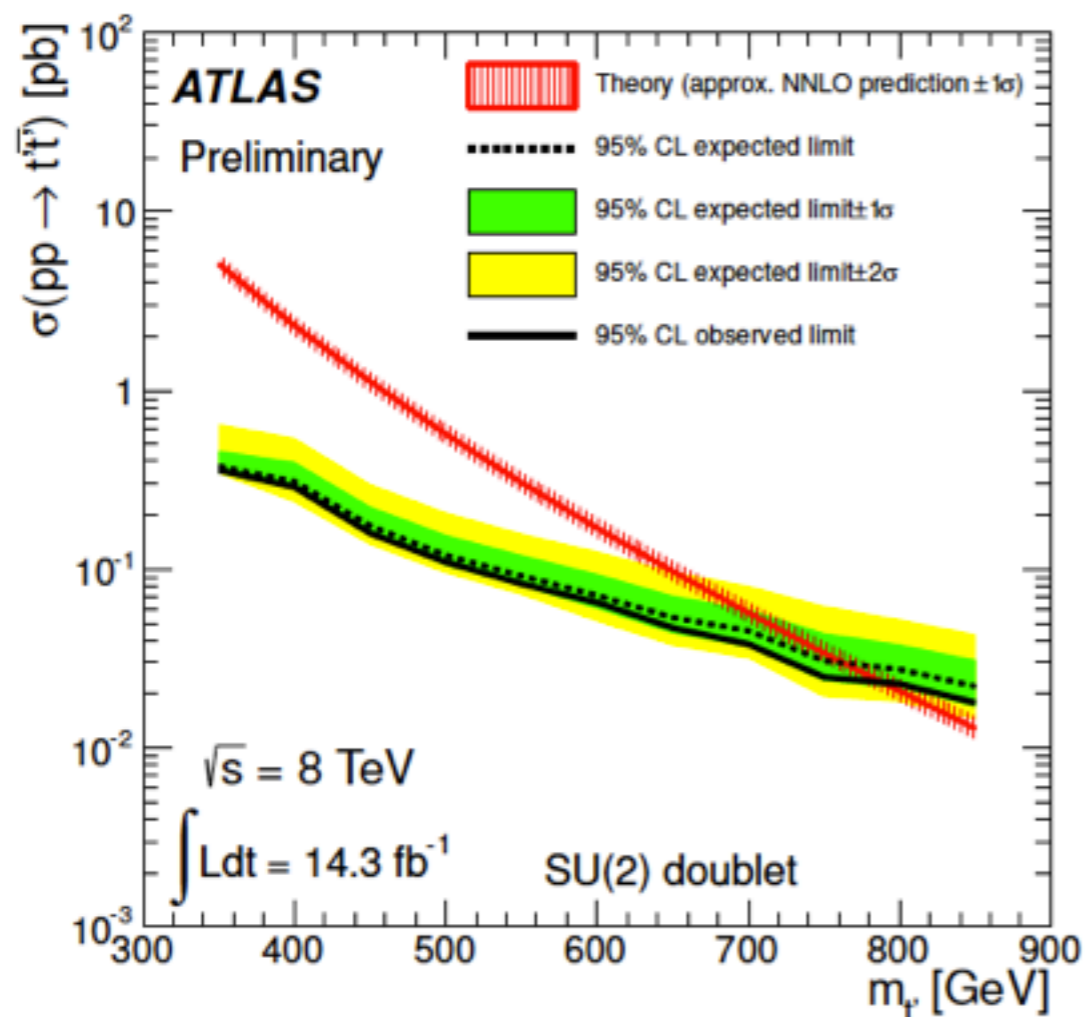
	≥ 6 jets, 2 b -tags	≥ 6 jets, 3 b -tags	≥ 6 jets, ≥ 4 b -tags
$t\bar{t}$ +heavy-flavour jets	1500 ± 900	900 ± 400	170 ± 70
$t\bar{t}$ +light-flavour jets	9600 ± 1000	1900 ± 350	75 ± 22
W+jets	250 ± 130	50 ± 30	5 ± 3
Z+jets	50 ± 40	9 ± 6	0.5 ± 0.9
Single top	300 ± 70	75 ± 18	7 ± 3
Diboson	1.7 ± 0.6	0.3 ± 0.1	0.03 ± 0.03
$t\bar{t}V$	70 ± 20	36 ± 12	7 ± 3
$t\bar{t}H$	28 ± 4	31 ± 6	12 ± 3
Multijet	49 ± 23	1.7 ± 0.8	0.15 ± 0.06
Total background	11860 ± 260	2990 ± 210	270 ± 60
Data	11885	2922	318
Doublet			
$t'\bar{t}'(400)$	550 ± 70	1100 ± 100	790 ± 160
$t'\bar{t}'(600)$	4.3 ± 1.2	94 ± 7	79 ± 18
$t'\bar{t}'(800)$	0.12 ± 0.05	10.7 ± 0.8	9.1 ± 2.1
Singlet			
$t'\bar{t}'(400)$	290 ± 30	650 ± 80	330 ± 70
$t'\bar{t}'(600)$	2.3 ± 0.4	61 ± 7	36 ± 9
$t'\bar{t}'(800)$	0.06 ± 0.01	6.9 ± 0.7	4.2 ± 1.1

Dominant Sources of Systematic Uncertainty

- b-tagging
- Jet Energy Calibration
- SM top pair modelling

-No signal-like excess is observed

95% C.L. CL_s upper limits are determined for two benchmark models



	doublet	singlet
Observed	$m_{t'} > 790 \text{ GeV}$	$m_{t'} > 640 \text{ GeV}$
Expected	$m_{t'} > 745 \text{ GeV}$	$m_{t'} > 615 \text{ GeV}$

Model independent exclusion obtained for the first time by reweighting the BRs in signal Monte Carlo

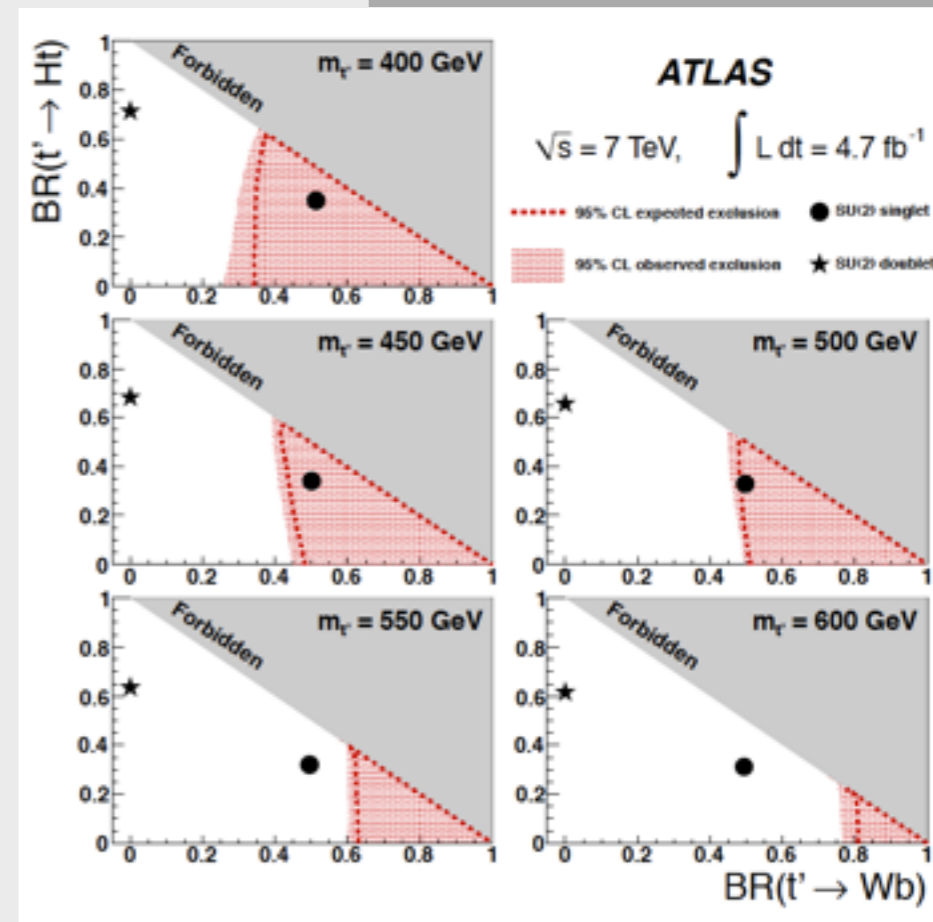
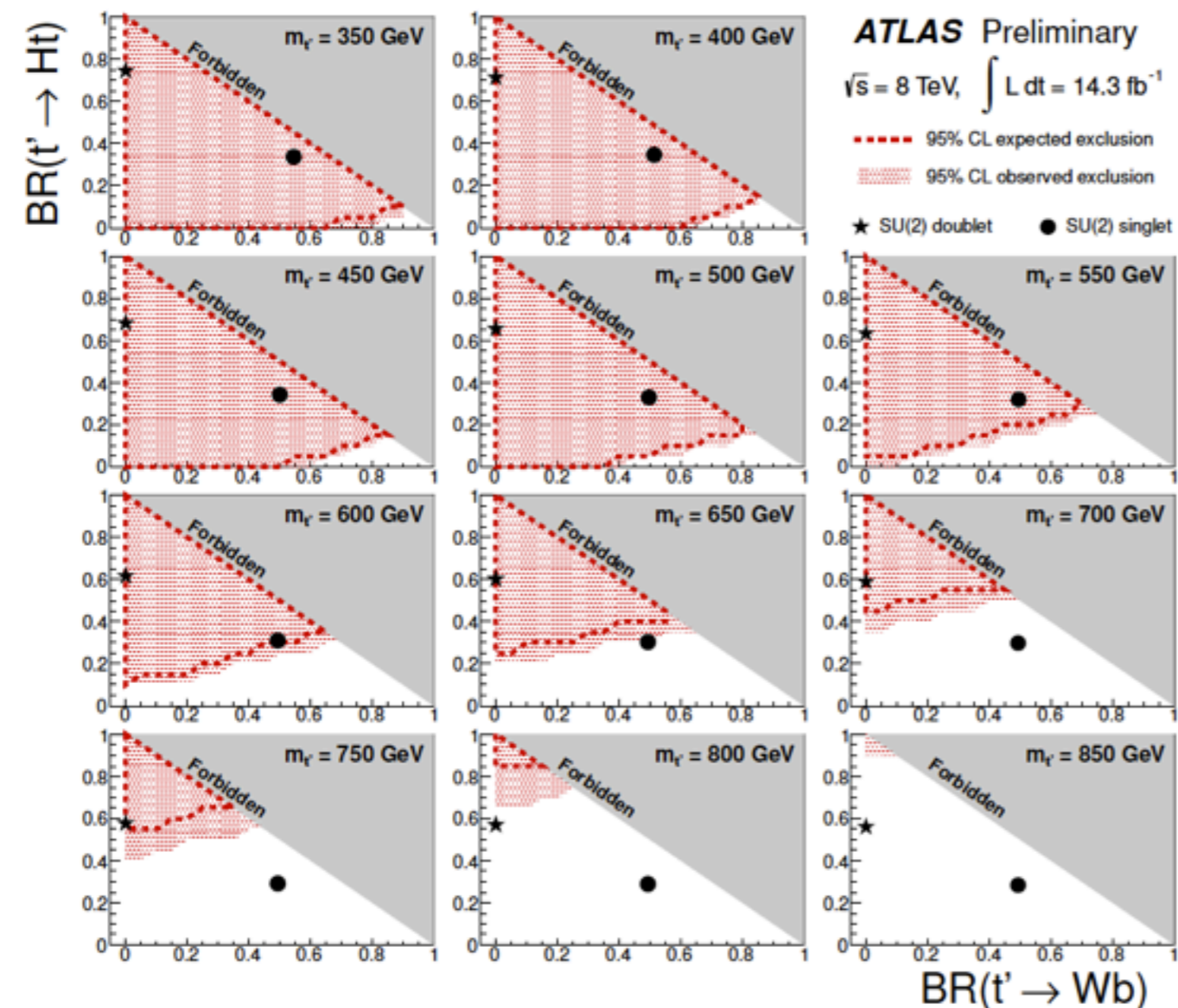
Model points are fully specified by $BR(t' \rightarrow Wb)$, $BR(t' \rightarrow Ht)$ and $m_{t'}$

8 TeV

7 TeV

Complementary $t' \rightarrow Wb$ Optimized search
 t' decay: collimated W + separated b-jet

PLB 718, 1284 (2013)



$$BR(t' \rightarrow Zt) = 1 - BR(t' \rightarrow Ht) - BR(t' \rightarrow Wb)$$

Conclusion

ATLAS is setting stringent model independent limits on the vector-like t' s using two complementary analyses

With the $t' \rightarrow Ht$ process fully specified, very effective $t' \rightarrow Ht$ optimized searches can be carried out

Complimentary $t' \rightarrow Wb$ searches provide extend sensitivity over large parameter space

ATLAS has conducted various searches for new top-pair resonances that rely on selecting collimated hadronic top decays

ATLAS has developed novel and specialized top tagging tools to distinguish boosted hadronic decays from the QCD background

These methods continue to be optimized and are becoming increasingly important as searches push limits to higher masses

The 7 TeV analyses presented here are being updated with 8 TeV data

Luminosity: $4.7 \text{ fb}^{-1} \rightarrow 20 \text{ fb}^{-1}$

SM $t\bar{t}$ σ : $165 \text{ pb} \rightarrow 238 \text{ pb}$

$$\text{gKK} \frac{\sigma_{8\text{TeV}}}{\sigma_{7\text{TeV}}} \sim 2$$