Searches for Physics Beyond the Standard Model with Third-Generation Quarks

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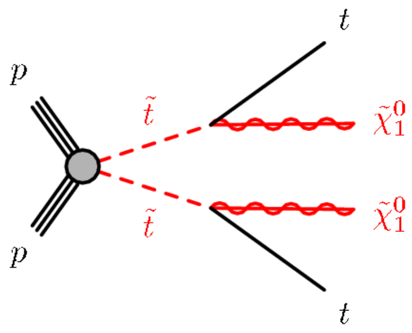
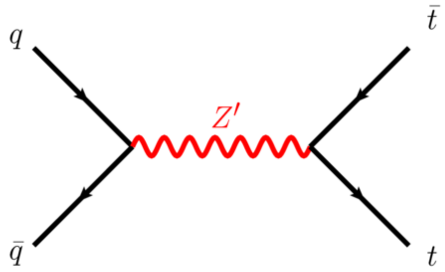
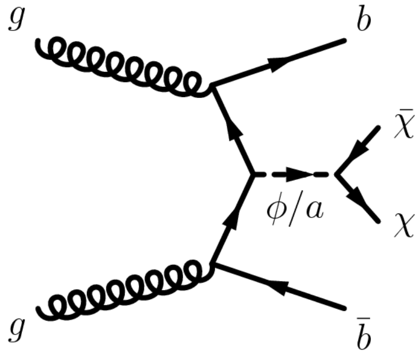
Presented at CIPANP 2018
On Behalf of the ATLAS Collaboration

Searching for BSM Physics

- BSM physics at the TeV scale is a major goal for the LHC
- Example of unanswered questions include:
  - The hierarchy problem of the Higgs
  - What is dark matter?
  - Do other Gauge groups exist outside the SM U(1)xSU(2)xSU(3)
- Many of the proposed theories involve new particles that interact with b's and tops

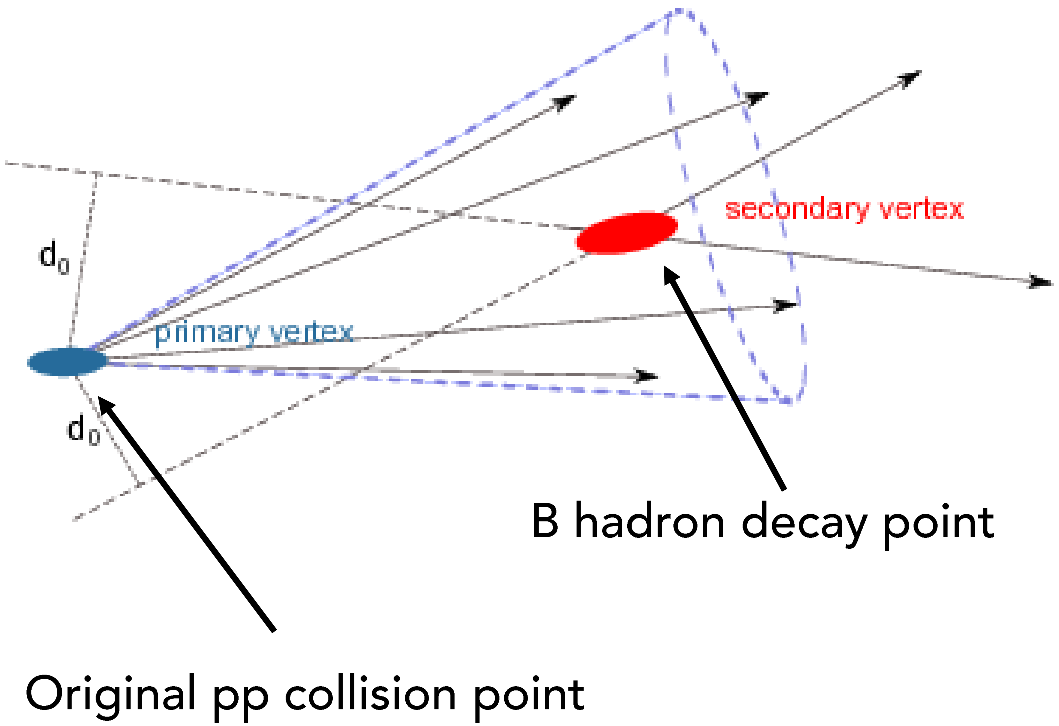






Identifying B Hadrons

- Like all hadrons b hadrons fragments into a jet of particles in the detector
- Hadrons containing b-quarks have long half-lives
- Typical lifetime of ~1.5 ps or a cτ ~450 μm (depends on hadron momentum)
- Can reconstruct the "secondary vertex" of the b hadron decay

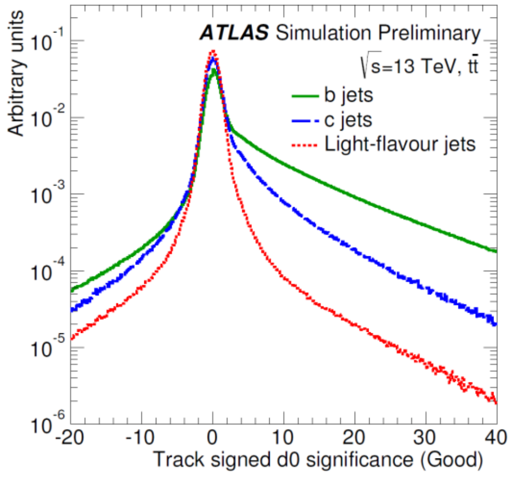


Tagging B Jets

- Exploit differences between b and light hadrons including long lifetime, high mass, and decay multiplicity

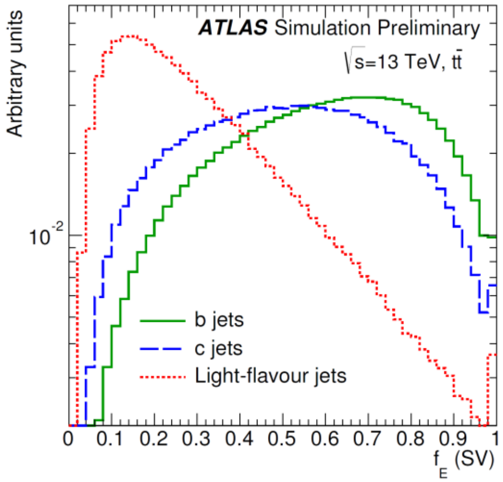
- Use a boosted decision tree (BDT) to distinguish between b hadrons and light/c hadrons

Track d0 significance



+

Fraction of Energy in Secondary Vertex

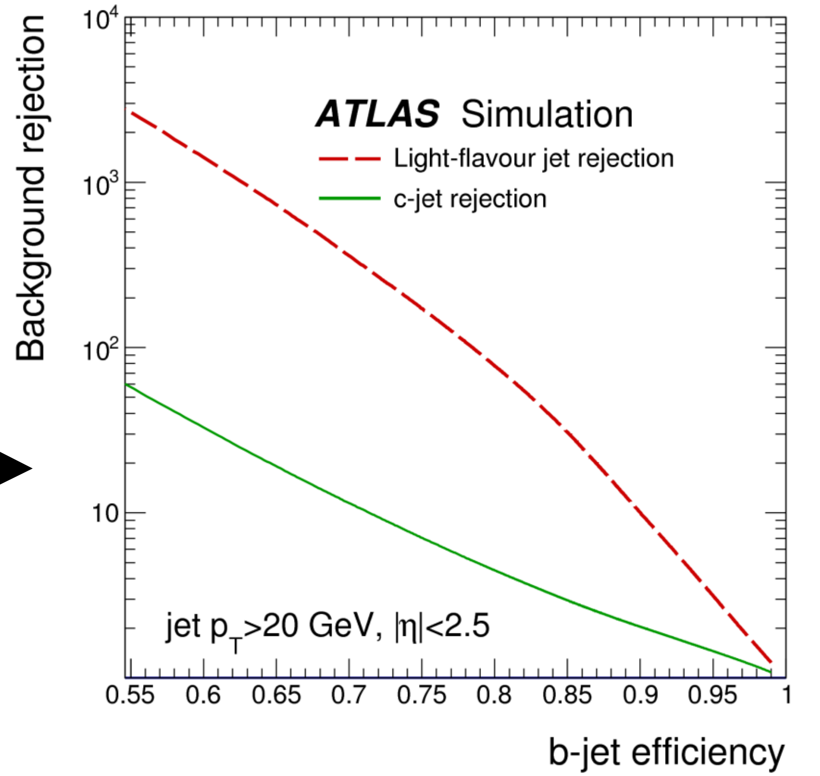


+ Other Variables →

Background rejection

vs

b jet identification efficiency



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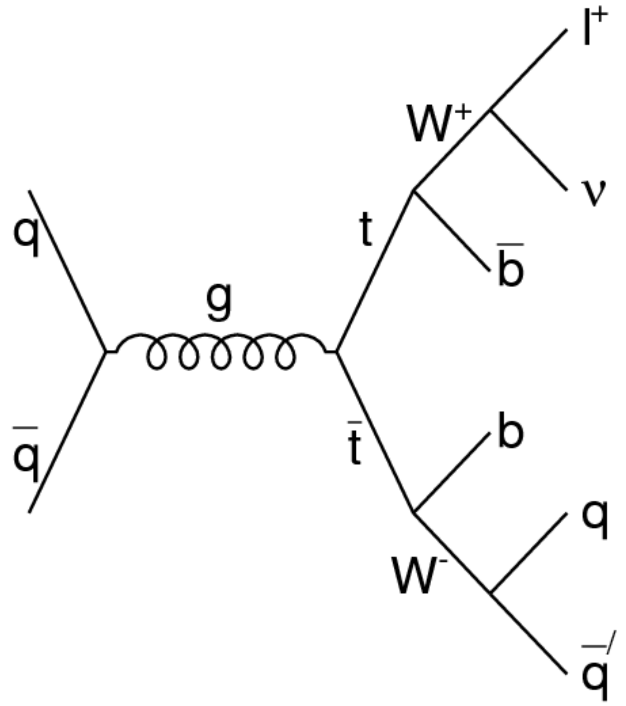
Identifying Top Quarks

- Top quarks decay almost exclusively to bW
- If top decays to blν
  - Electrons and muons can be cleanly identified
  - Looses information on invisible system p_z and mass
- If top decays to bqq'
  - B jet can be distinguished from light quark jets
  - Kinematics depends on top p_T

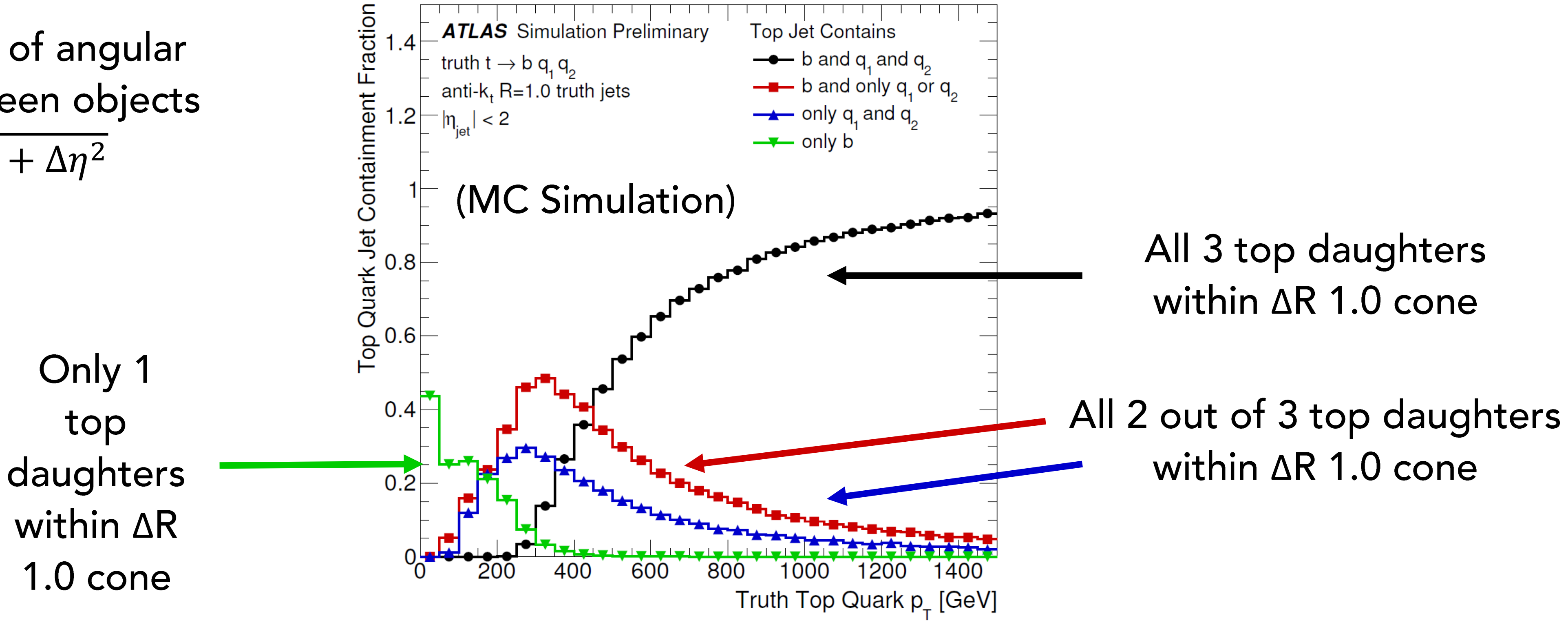


Hadronic Top Kinematics Depends on P_T

Fraction of top decay products contained within a ΔR cone of 1.0

ΔR is a measure of angular separation between objects

$$\Delta R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$$



https://cds.cern.ch/record/2281054/files/ATLAS-CONF-2017-064.pdf

Observed Top Kinematics in Data

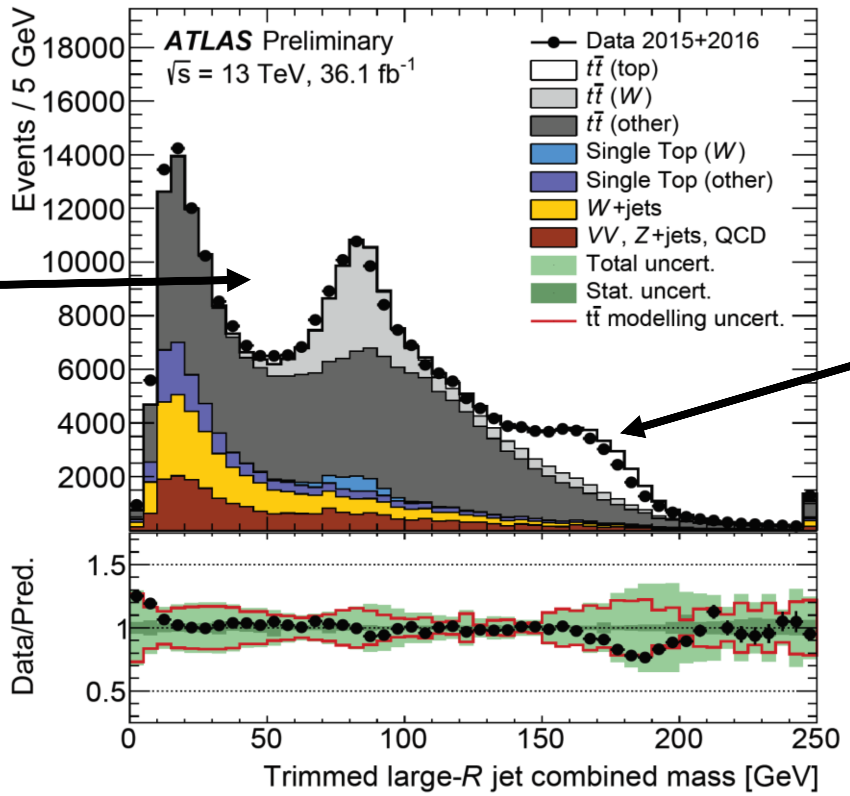
Reconstructed Mass of Jets with ΔR cone of 1.0 in Data
($t\bar{t}$ enriched sample)

Low pT Tops

The W from a top decay within

ΔR=1.0 jet

Reconstructs W mass



High pT Tops

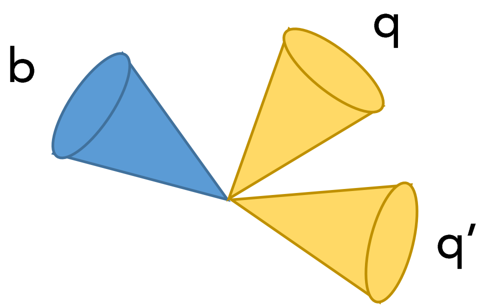
All 3 top daughters within
ΔR=1.0 jet

Reconstructs top mass

https://cds.cern.ch/record/2281054/files/ATLAS-CONF-2017-064.pdf

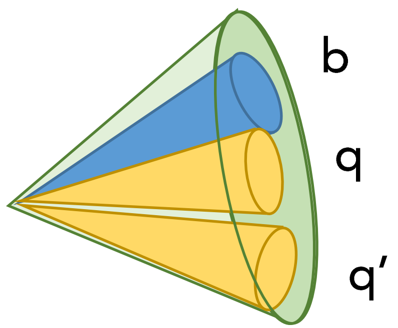
Boosted and Resolved Top Reconstruction

Resolved Tops



- Separate reconstructed jets for top daughters
- Minimize the χ^2 between the reconstructed mass and true top mass
- $\chi^2 = (m_{reco} - m_t)/\sigma$ or $(m_{reco} - m_w)/\sigma$ where σ is the uncertainty of mass
- In events with 2 tops can also use balance in pT between the two tops

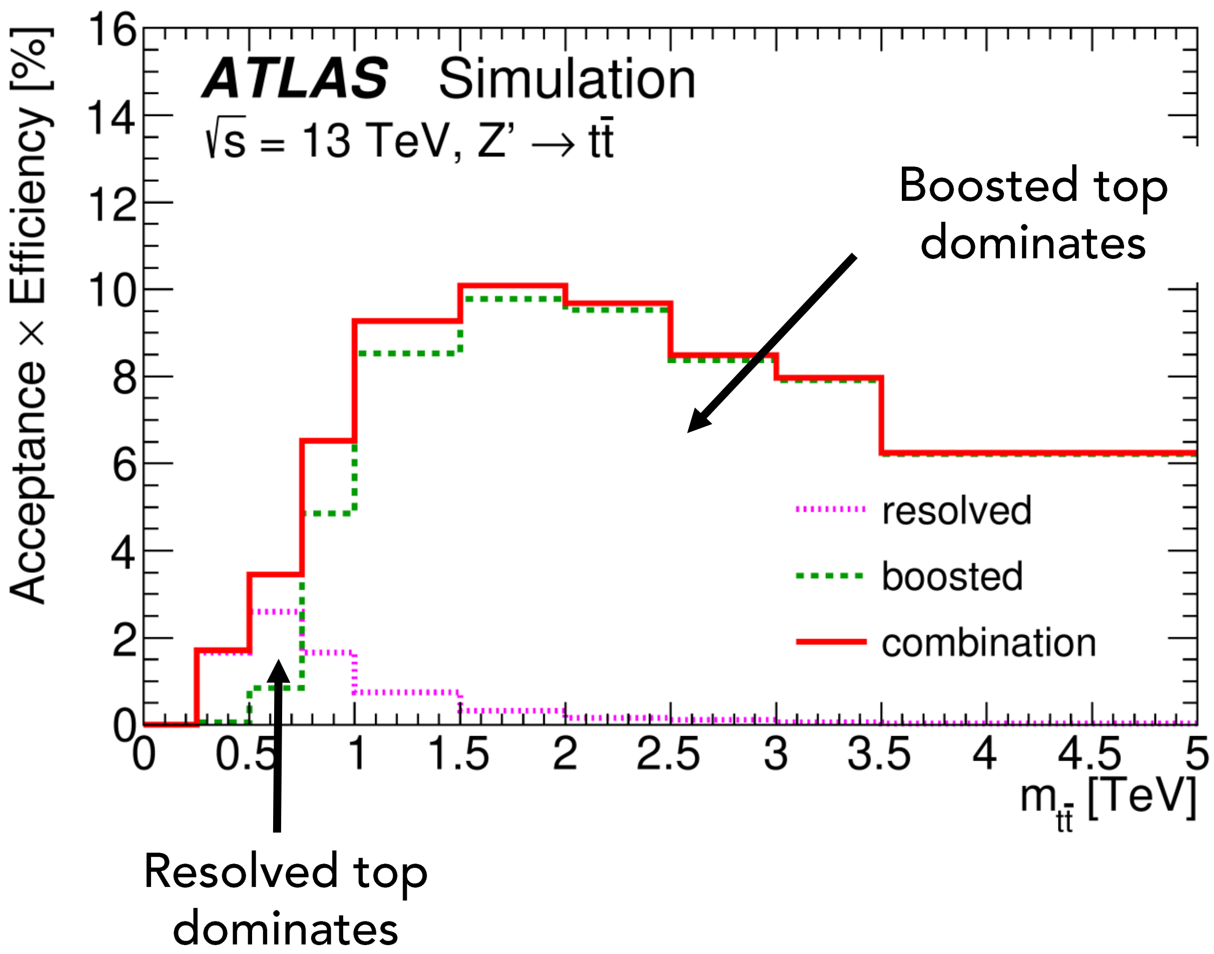
Boosted Collimated Tops



- Top daughters contained within a single large jet
- Quantify if distribution of energy is uniform or clustered along several axis
- Quantify angular correlation of energy within the jet
- Use multivariate and machine learning techniques to maximize separation power

Top Tagging in Practice: Search for Z′ → tt

- Searches for heavy Z′ (~a few TeV)
- High mass Z′ thought to give large boost to tops
- Low mass Z′ decays to low p_T tops
- A combination of resolved top and boosted top reconstruction used to gain reconstruction efficiency for all Z′ masses



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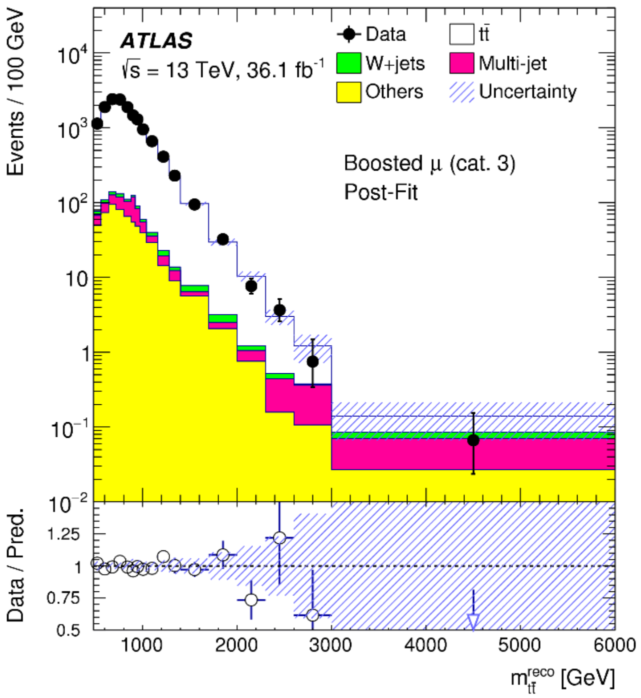
Searches for Heavy Resonances and Z′ > tt and Z′ > bb

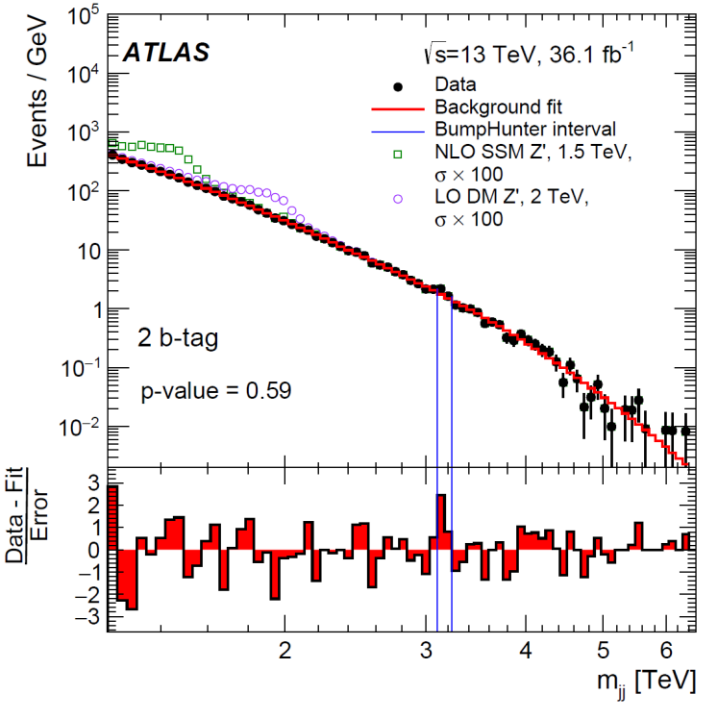
Mass of tt system in search for Z′ > tt



Search for resonance bump on top of exponentially falling distribution

No excess observed

Mass of bb system in search for Z′ > bb



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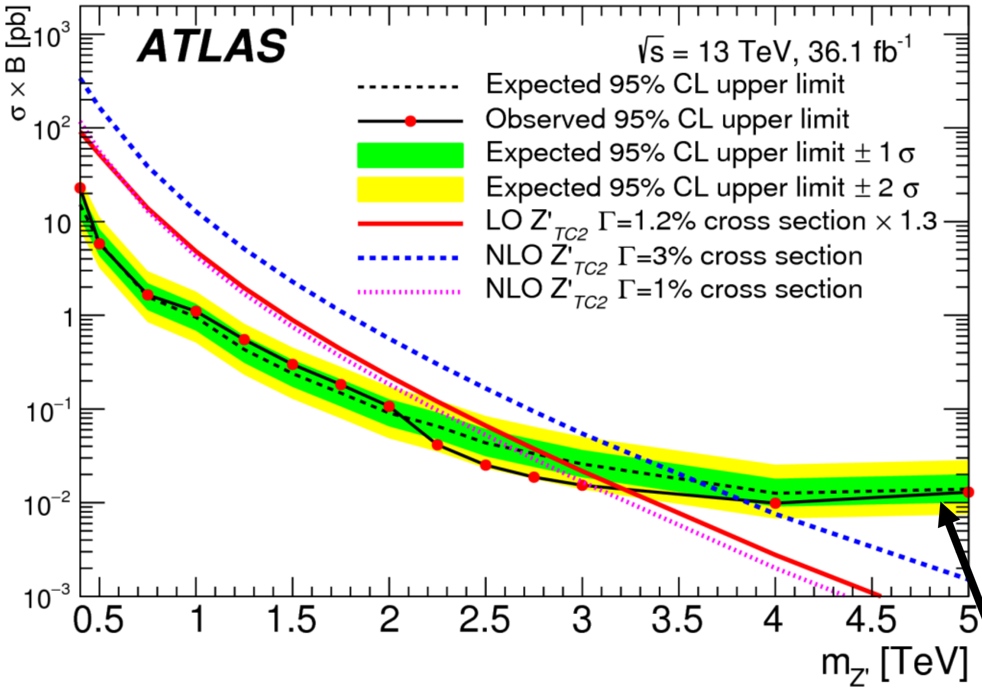
Searches for Heavy Resonances Z′ > bb and Z′ > tt Results

95% Confidence Limit on Z′ > tt production cross section * branching ratio



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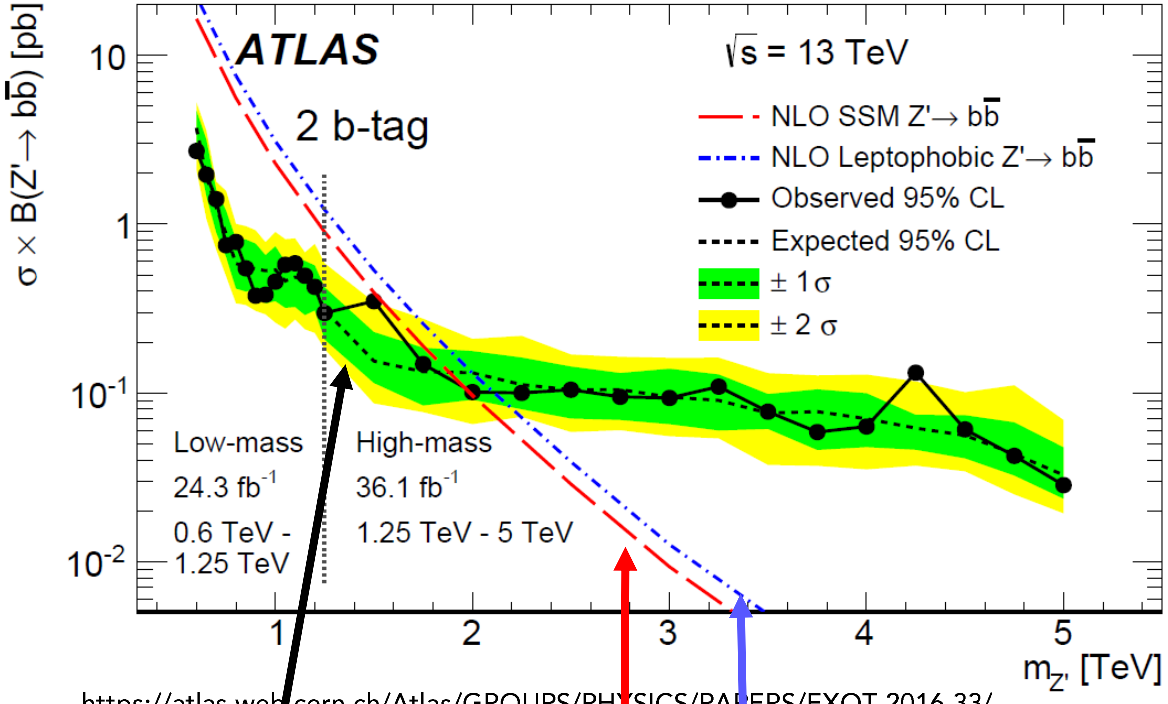
95% Confidence Limit on Z′ > bb production cross section * branching ratio



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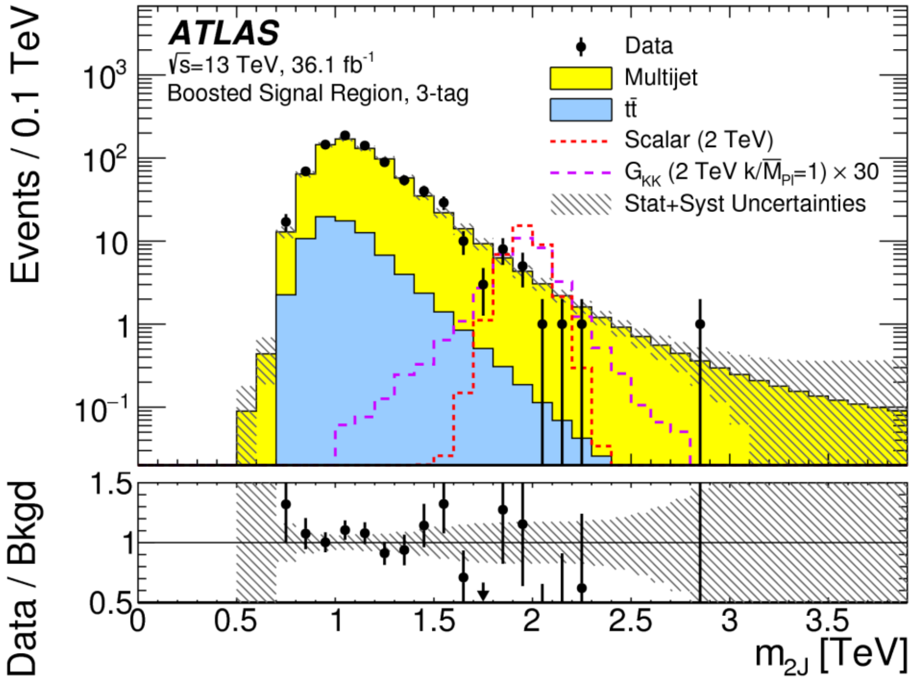
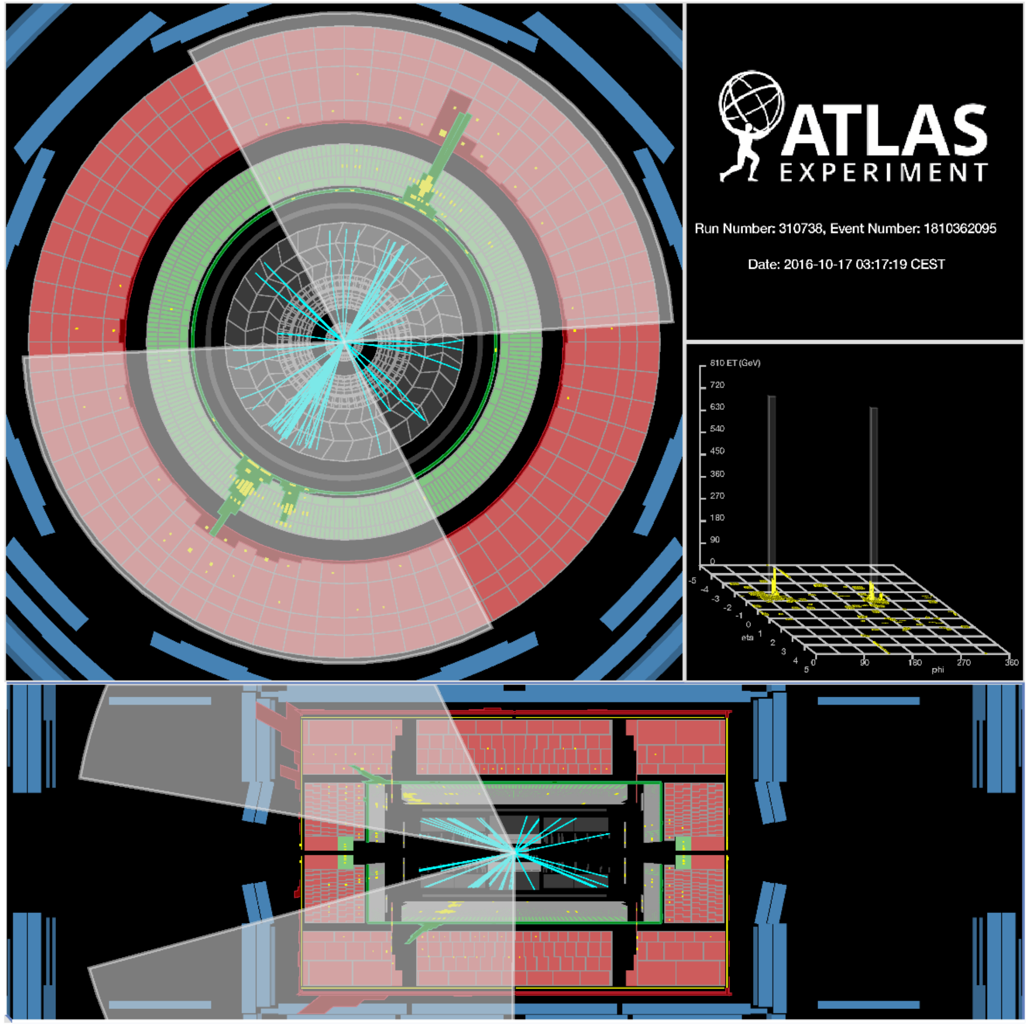
Measured cross section limit (solid black line)

Predicted cross section for different theory models

Search for X > HH > bbbb





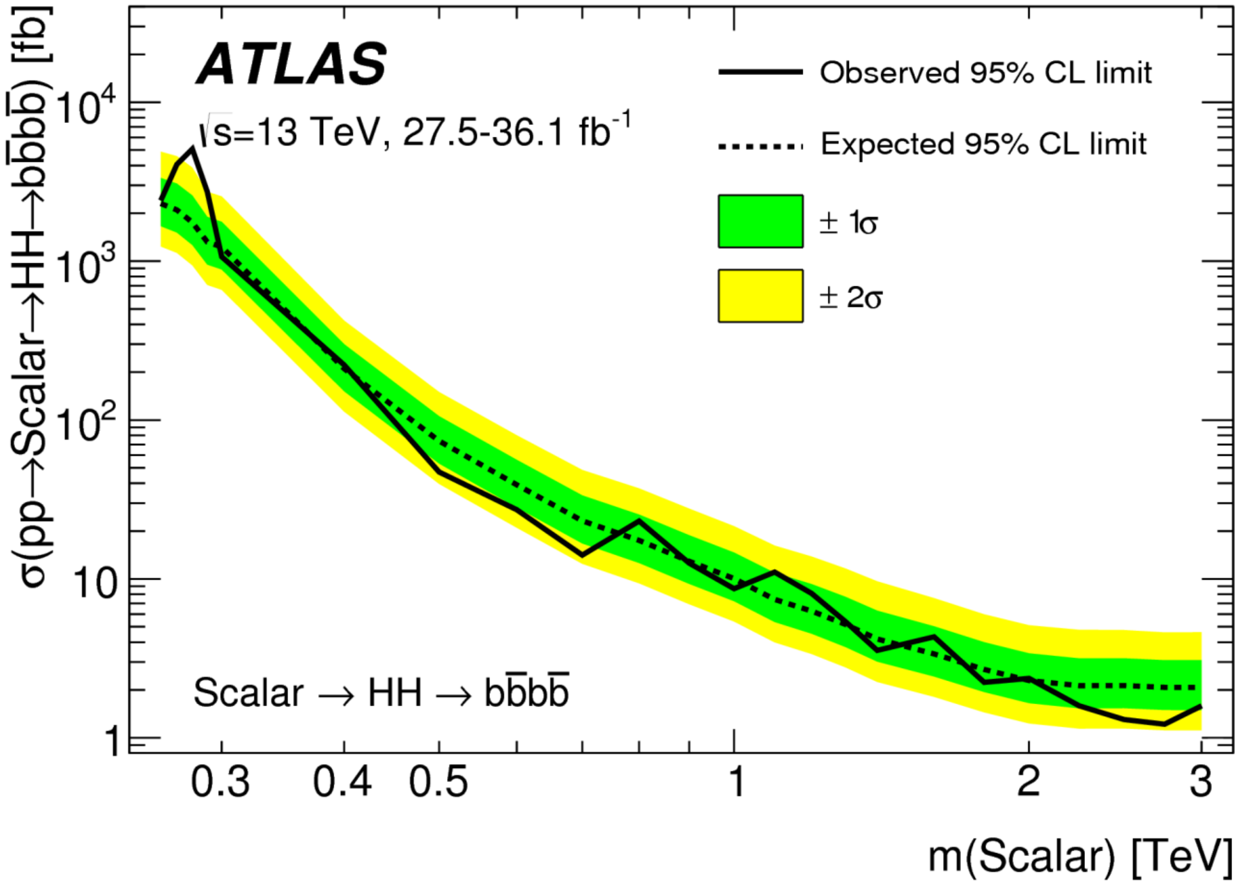
- Kinematics depends strongly on particle X's mass

- Low X mass > low H boost, separated bs
- High X mass > high H boost, collimated bb

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-31/

Results of the X > HH > bbbb Search

- Set limit on heavy scalar particle that is coupled to two Higgs.
- Can result from a heavy BSM Higgs that has some mixing with SM Higgs
- Limit at ~13*SM pp > HH cross-section



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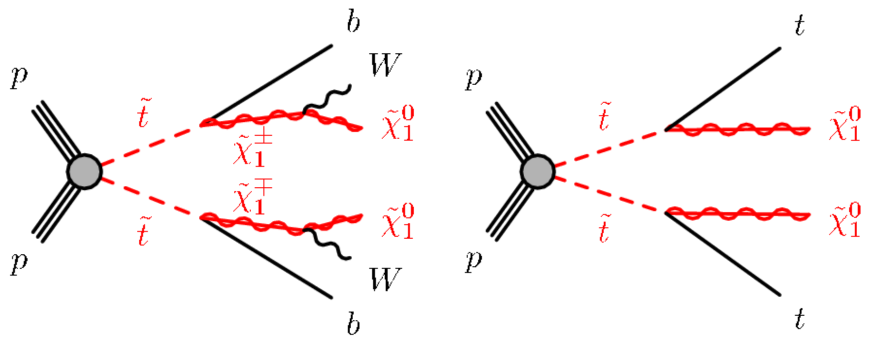
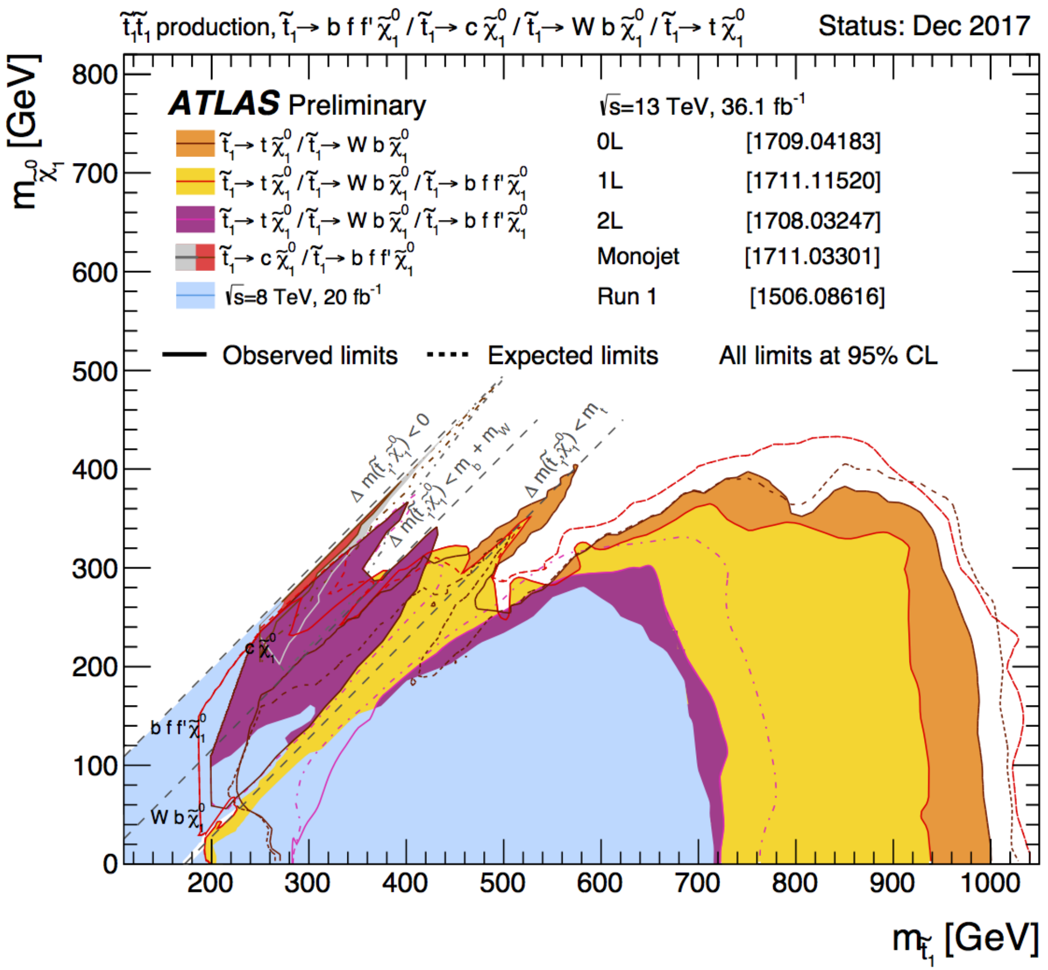
Direct Search for R-Parity Respecting Top Squark





Stop decay kinematics depends strongly on the stop and neutralino mass split

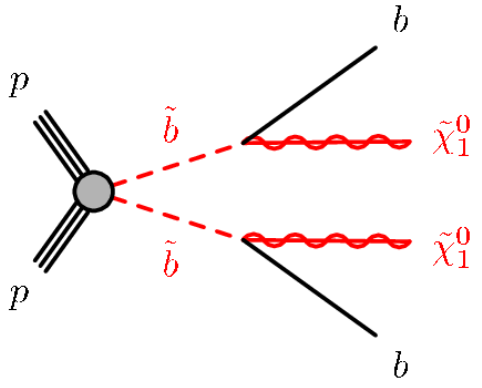
Large mass split > Large p_T tops and neutralinos

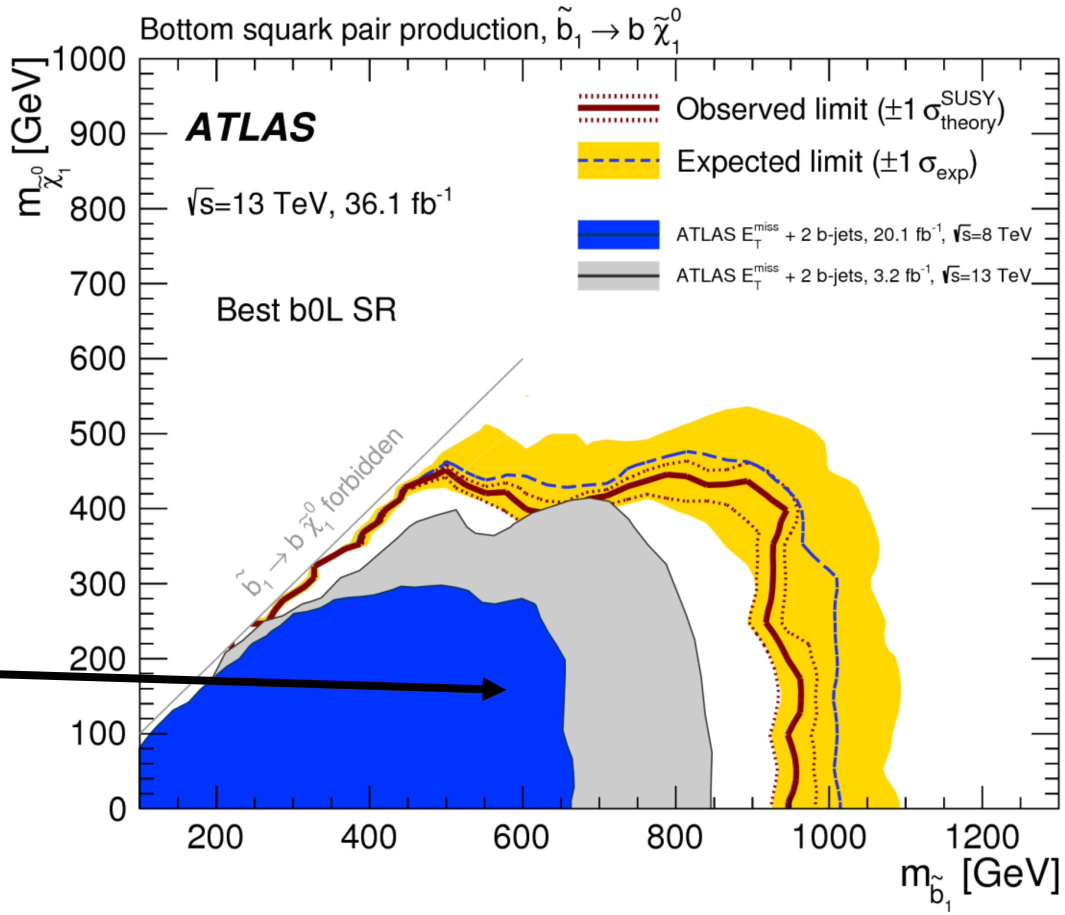
Small mass split > low pT tops and neutralinos

Very small mass split > not enough mass for on shell tops

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY

Direct Search for Bottom Squarks





Search for bottom quarks and MET

Phase space below limit curve excluded assuming sbottom decays directly to neutralino LSP

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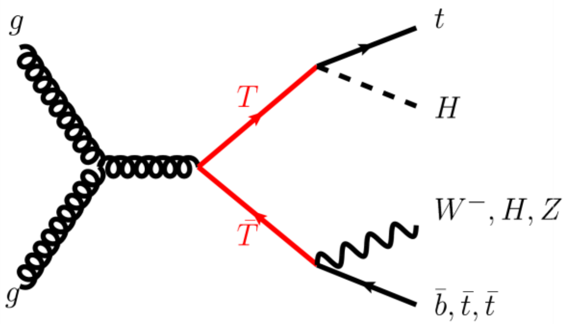
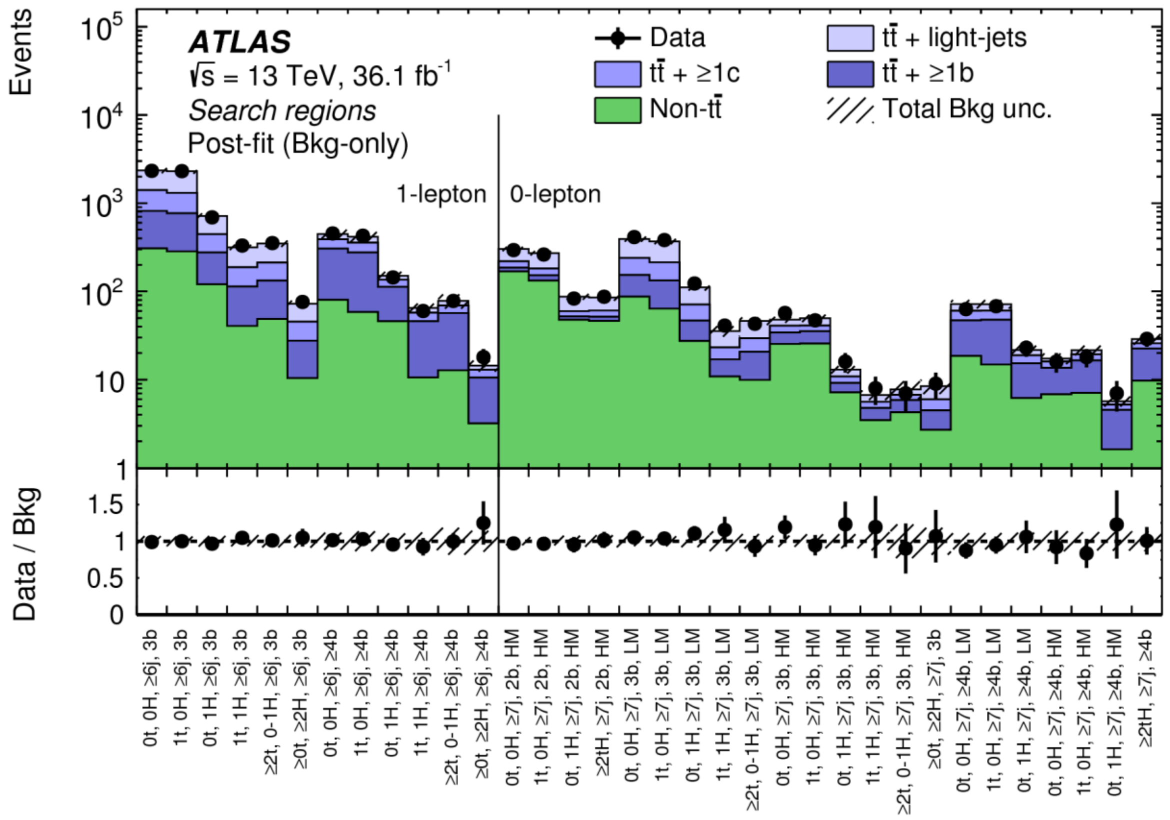
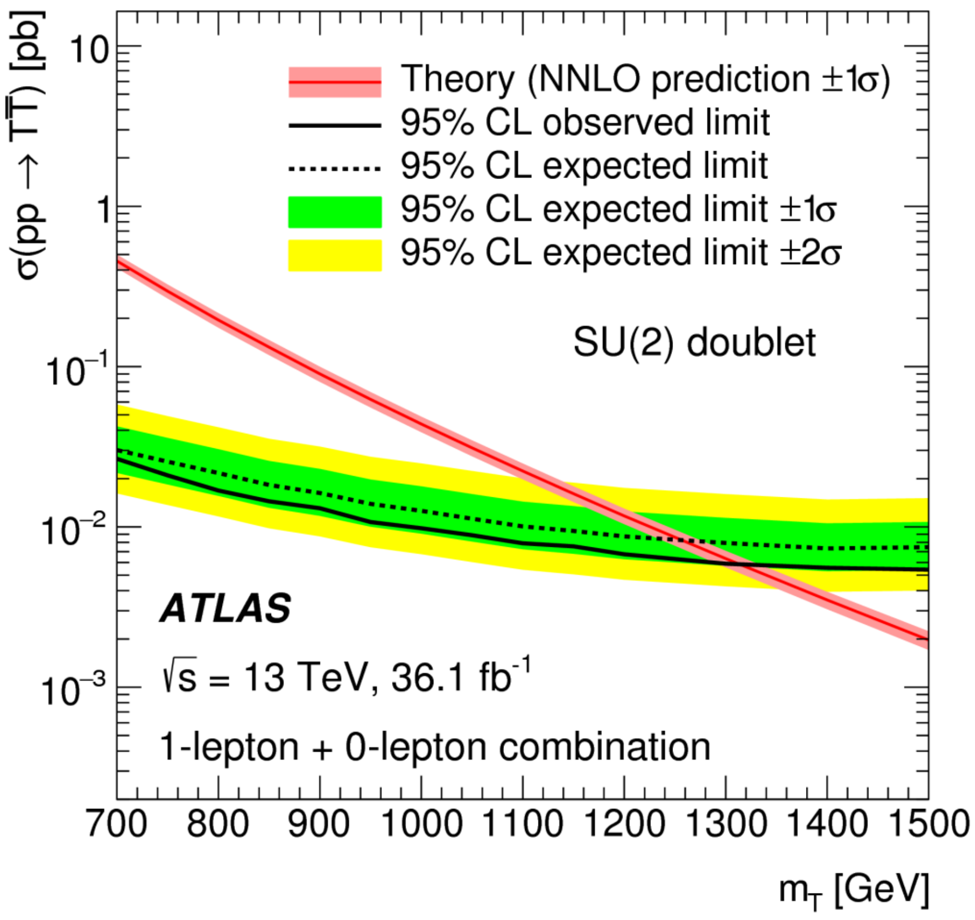
Vector Like Quarks T > Ht+X



- Search for tHtH, tHbW, tHtZ
- Signature high b multiplicity and high jet multiplicity
- 0 lepton + 6-7 jets or 1 lepton + 5-6 jets with more than 2 b-tagged jets
- Tag boosted hadronic tops and H > bb



T > Ht+X, Limit on TT cross-section



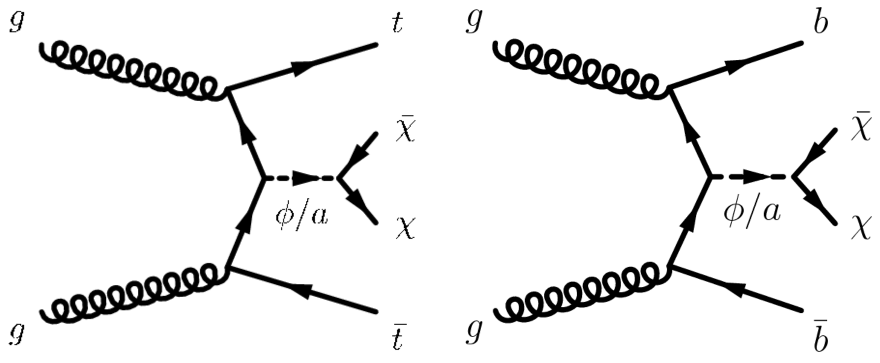
Conclusion

- ATLAS has collected 80 fb^{-1} of 13 TeV pp collision data in 2015 – 2017 and we continue to collect data this year.
- ATLAS uses advanced techniques to identify and separate b hadrons and top quarks from hadrons with only light quarks
- Many BSM physics searches need to identify b's and tops because they are one of the expected decay products
- The kinematics of the decay products vary significantly depending on the particle boost.
  - A more boosted particle's decay products tend to be more collimated
  - Different strategies are employed for boosted an not boosted particle identification
- Covered a few select results here but many more can be found on the ATLAS publication page
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic

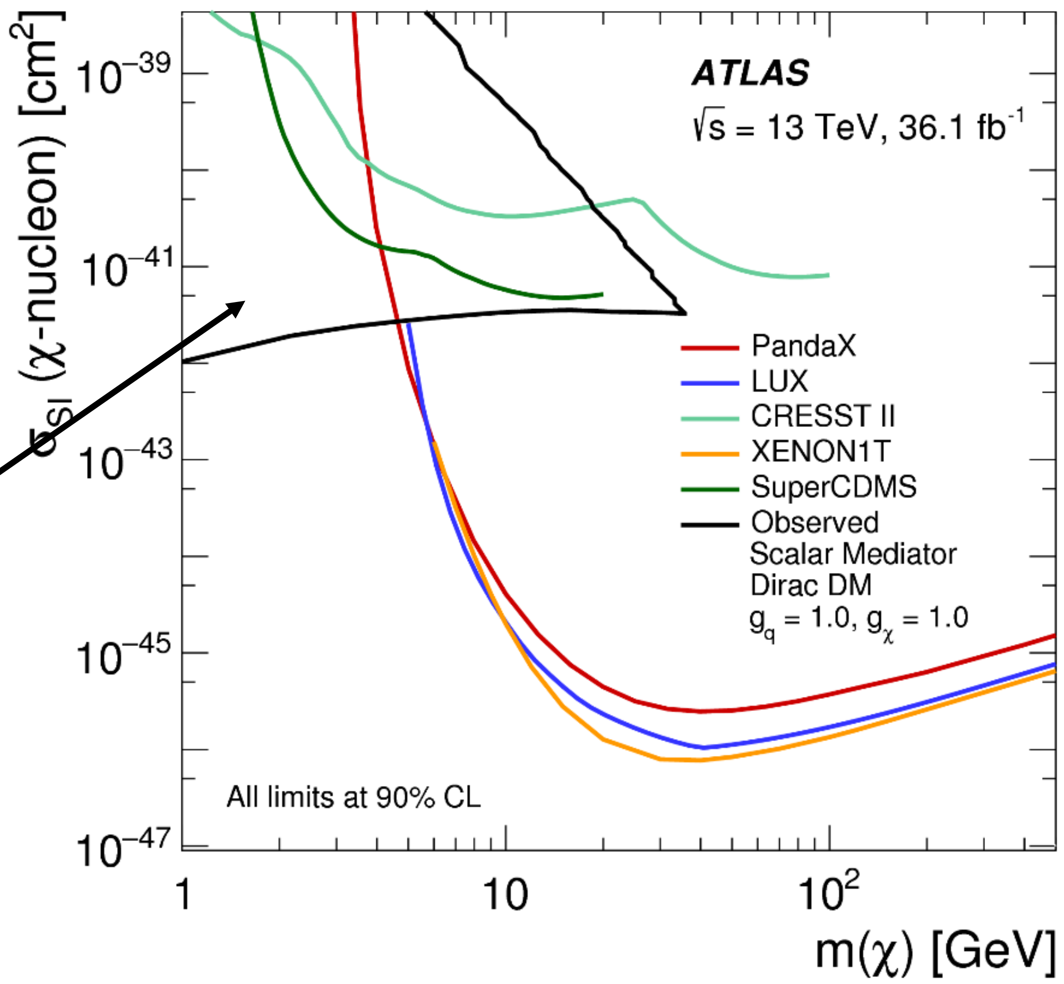
0-lepton channel					
Search regions (≥7 jets)					
N_t	N_H	b-tag multiplicity	$m_{T, min}^{b}$	m_{eff}	Channel name
0	0	2	>160 GeV	>1 TeV	0t, 0H, ≥7j, 2b, HM
0	0	3	<160 GeV	>1 TeV	0t, 0H, ≥7j, 3b, LM
0	0	3	>160 GeV	>1 TeV	0t, 0H, ≥7j, 3b, HM
0	0	≥4	<160 GeV	>1 TeV	0t, 0H, ≥7j, ≥4b, LM
0	0	≥4	>160 GeV	>1 TeV	0t, 0H, ≥7j, ≥4b, HM
1	0	2	>160 GeV	>1 TeV	1t, 0H, ≥7j, 2b, HM
1	0	3	<160 GeV	>1 TeV	1t, 0H, ≥7j, 3b, LM
1	0	3	>160 GeV	>1 TeV	1t, 0H, ≥7j, 3b, HM
1	0	≥4	<160 GeV	>1 TeV	1t, 0H, ≥7j, ≥4b, LM
1	0	≥4	>160 GeV	>1 TeV	1t, 0H, ≥7j, ≥4b, HM
0	1	2	>160 GeV	>1 TeV	0t, 1H, ≥7j, 2b, HM
0	1	3	<160 GeV	>1 TeV	0t, 1H, ≥7j, 3b, LM
0	1	3	>160 GeV	>1 TeV	0t, 1H, ≥7j, 3b, HM
0	1	≥4	<160 GeV	>1 TeV	0t, 1H, ≥7j, ≥4b, LM
0	1	≥4	>160 GeV	>1 TeV	0t, 1H, ≥7j, ≥4b, HM
1	1	3	<160 GeV	>1 TeV	1t, 1H, ≥7j, 3b, LM
1	1	3	>160 GeV	>1 TeV	1t, 1H, ≥7j, 3b, HM
≥2	0 or 1	3	<160 GeV	>1 TeV	≥2t, 0–1H, ≥7j, 3b, LM
≥2	0 or 1	3	>160 GeV	>1 TeV	≥2t, 0–1H, ≥7j, 3b, HM
≥0	≥2	3	–	>1 TeV	≥0t, ≥2H, ≥7j, 3b
$N_t + N_H \geq 2$		2	>160 GeV	>1 TeV	≥2tH, ≥7j, 2b, HM
$N_t + N_H \geq 2$		≥4	–	>1 TeV	≥2tH, ≥7j, ≥4b
Validation regions (6 jets)					
N_t	N_H	b-tag multiplicity	$m_{T, min}^{b}$	m_{eff}	Channel name
0	0	2	>160 GeV	>1 TeV	0t, 0H, 6j, 2b, HM
0	0	3	<160 GeV	>1 TeV	0t, 0H, 6j, 3b, LM
0	0	3	>160 GeV	>1 TeV	0t, 0H, 6j, 3b, HM
0	0	≥4	<160 GeV	>1 TeV	0t, 0H, 6j, ≥4b, LM
0	0	≥4	>160 GeV	>1 TeV	0t, 0H, 6j, ≥4b, HM
1	0	2	>160 GeV	>1 TeV	1t, 0H, 6j, 2b, HM
1	0	3	<160 GeV	>1 TeV	1t, 0H, 6j, 3b, LM
1	0	3	>160 GeV	>1 TeV	1t, 0H, 6j, 3b, HM
1	0	≥4	–	>1 TeV	1t, 0H, 6j, ≥4b
0	1	2	>160 GeV	>1 TeV	0t, 1H, 6j, 2b, HM
0	1	3	<160 GeV	>1 TeV	0t, 1H, 6j, 3b, LM
0	1	3	>160 GeV	>1 TeV	0t, 1H, 6j, 3b, HM
0	1	≥4	–	>1 TeV	0t, 1H, 6j, ≥4b
$N_t + N_H \geq 2$		2	>160 GeV	>1 TeV	≥2tH, 6j, 2b, HM
$N_t + N_H \geq 2$		3	–	>1 TeV	≥2tH, 6j, 3b
$N_t + N_H \geq 2$		≥4	–	>1 TeV	≥2tH, 6j, ≥4b

1-lepton channel				
Search regions (≥6 jets)				
N_t	N_H	b-tag multiplicity	m_{eff}	Channel name
0	0	3	>1 TeV	0t, 0H, ≥6j, 3b
0	0	≥4	>1 TeV	0t, 0H, ≥6j, ≥4b
1	0	3	>1 TeV	1t, 0H, ≥6j, 3b
1	0	≥4	>1 TeV	1t, 0H, ≥6j, ≥4b
0	1	3	>1 TeV	0t, 1H, ≥6j, 3b
0	1	≥4	>1 TeV	0t, 1H, ≥6j, ≥4b
1	1	3	–	1t, 1H, ≥6j, 3b
1	1	≥4	–	1t, 1H, ≥6j, ≥4b
≥2	0 or 1	3	–	≥2t, 0–1H, ≥6j, 3b
≥2	0 or 1	≥4	–	≥2t, 0–1H, ≥6j, ≥4b
≥0	≥2	3	–	≥0t, ≥2H, ≥6j, 3b
≥0	≥2	≥4	–	≥0t, ≥2H, ≥6j, ≥4b
Validation regions (5 jets)				
N_t	N_H	b-tag multiplicity	m_{eff}	Channel name
0	0	3	>1 TeV	0t, 0H, 5j, 3b
0	0	≥4	>1 TeV	0t, 0H, 5j, ≥4b
1	0	3	>1 TeV	1t, 0H, 5j, 3b
1	0	≥4	>1 TeV	1t, 0H, 5j, ≥4b
0	1	3	>1 TeV	0t, 1H, 5j, 3b
0	1	≥4	>1 TeV	0t, 1H, 5j, ≥4b
1	1	3	–	1t, 1H, 5j, 3b
≥2	0 or 1	3	–	≥2t, 0–1H, 5j, 3b
≥0	≥2	3	–	≥0t, ≥2H, 5j, 3b
$N_t + N_H \geq 2$		≥4	–	≥2tH, 5j, ≥4b

Example of Dark Matter Searches



- The same signature as SUSY searches tt+MET or bb+MET
- Observed limits on effective interaction cross section between dark matter and nucleon
- Just two simplified models. Many others exist and covered more in the dark matter talk



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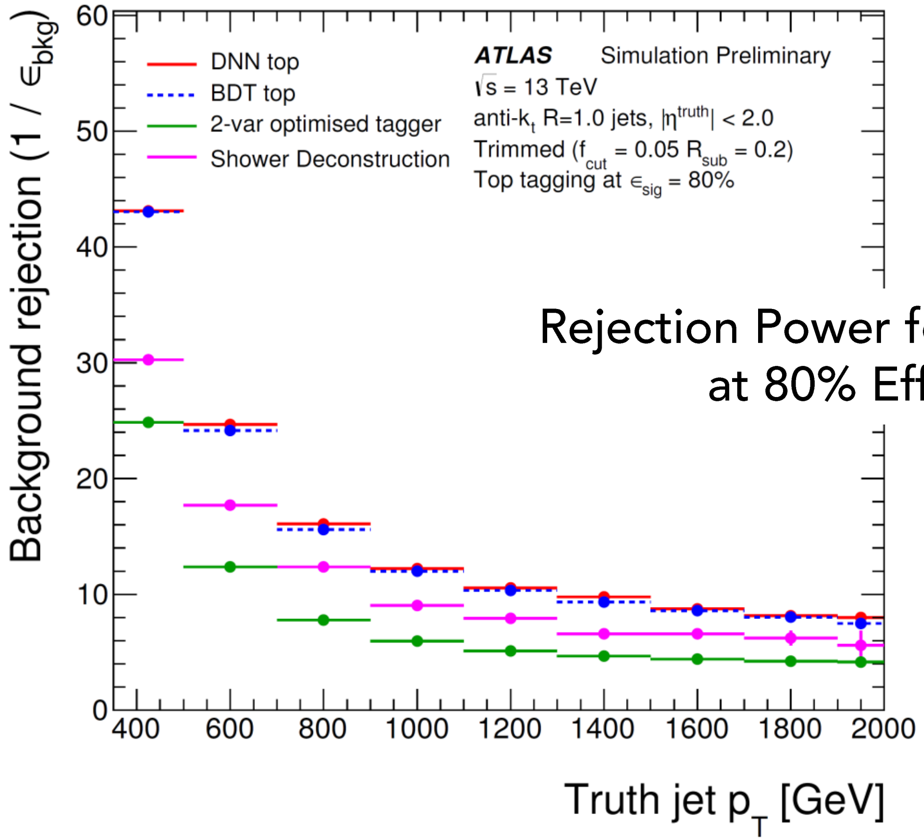
Bkg Rejection Power vs Top p_T



Rejection Power for Tagging Top at 80% Efficiency

https://cds.cern.ch/record/2281054/files/ATLAS-CONF-2017-064.pdf