Top, Top-like BSM Models And Boosted Objects At ATLAS - Status And Plans

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On behalf of the ATLAS collaboration

Implications of LHC results for TeV-scale physics
CERN
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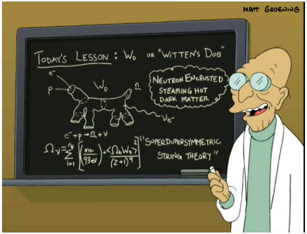
Outline

- Motivation
- New physics in top production and decay
- Searches for top-Like BSM signatures
- Boosted objects

- Many BSM scenarios are on the market
- Large top mass ($m_t \approx 172.5\,\mathrm{GeV}$) $\rightarrow$ top often plays a special role in BSM theories
- BSM physics often has consequences for the third generation quarks



Some examples:

- **Add 4$^{\text{th}}$ generation quarks:** Often decay to tops or look like heavy tops
- **Incorporate Gravity using Extra Dimensions:** Many models predict new states with strong coupling to the top
- **Exotic Higgs Bosons:** large coupling to the top

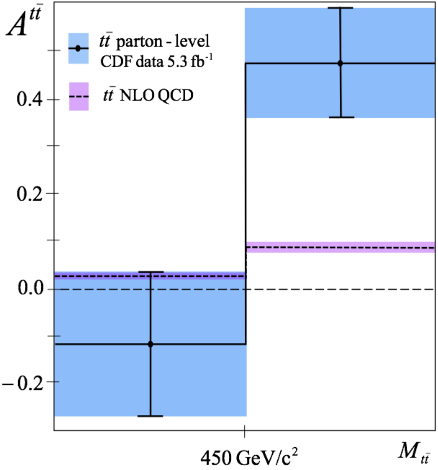
New High-Scale physics scenarios often produce Ws or tops at high-energy (boosted)

Extra motivation: Tevatron data:

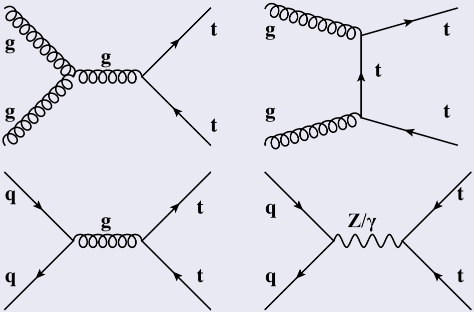
$$A_{t\bar{t}} = \frac{N(y_t^{t\bar{t}} > 0) - N(y_t^{t\bar{t}} < 0)}{N(y_t^{t\bar{t}} > 0) + N(y_t^{t\bar{t}} < 0)}$$

- Tevatron collides p and $\bar{p}$ producing $t\bar{t}$
- $A_{t\bar{t}}$ a measure of how much the t prefers the p direction
- 3.4 Standard deviations away from the Standard Model at high $M_{t\bar{t}}$

"Strengthens the case that new physics plays a role in $t\bar{t}$ production"



$t\bar{t}$ Production



Can look for new physics in $t\bar{t}$ production such as:

- **New bosons e.g. Z', g_{KK}, G_{KK}, in resonant production**
- Flavour Changing Z' → Same-sign tops
- **Asymmetry in t vs $\bar{t}$ production**

Search for $t\bar{t}$ resonances, use a standard $t\bar{t}$ selection:

dilepton channel

ATLAS-CONF-2011-123

- Two isolated leptons $ll = ee, e\mu, \mu\mu$
- ee or $\mu\mu$: M_{ll} outside M_Z window
- $e\mu$: Require large H_T
- $M_{ll} > 10$ GeV
- E_T^{miss}
- 2 or more jets

l+jets channel

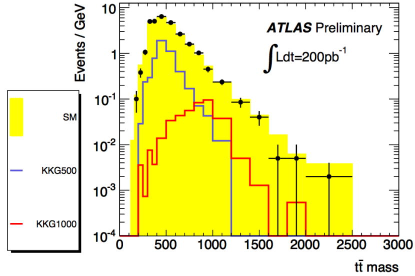
ATLAS-CONF-2011-087

- Isolated electron or muon
- Missing Transverse momentum (E_T^{miss})
- 4 or more jets (inclusive Anti-K_T, $R = 0.4$)
- At least 1 b-tagged jet

H_T is the scalar sum of P_T of all hard objects in event.

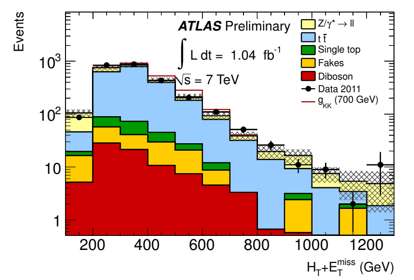
l+jets

search for bumps in $M_{t\bar{t}}$:



dileptons

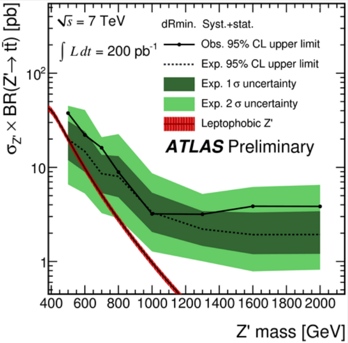
Use $H_T + E_T^{\text{miss}}$:



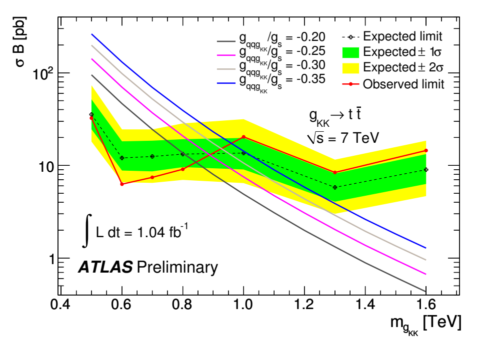
No evidence for new physics signals

$t\bar{t}$ resonances

l+jets



dileptons



- **l+jets:** Limits set on narrow Z'-like resonances: No exclusion for benchmark (Topcolor-assisted technicolor) Z' model.
- **dileptons:** Limits set on broader g_{KK}-like resonances. Benchmark scenario: $M_{g_{KK}} < 0.84$ TeV excluded.

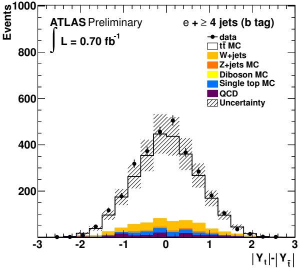
$t\bar{t}$ Charge Asymmetry:
ATLAS-CONF-2011-106

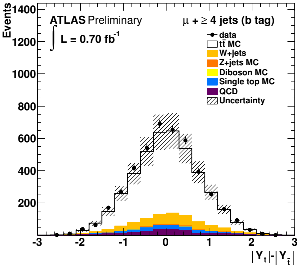
- Can't use Tevatron $A_{t\bar{t}}$
- An $A_{t\bar{t}}$ alternative for pp:

$$A_C = \frac{N(\Delta|Y| > 0) - N(\Delta|Y| < 0)}{N(\Delta|Y| > 0) + N(\Delta|Y| < 0)}$$

where $\Delta|Y| = |Y_t| - |Y_{\bar{t}}|$

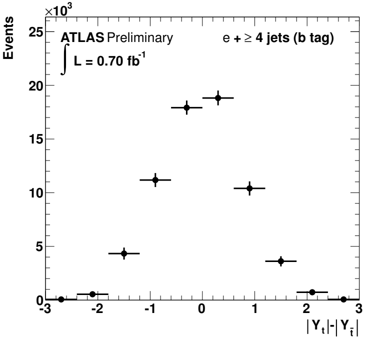
- Use l+jets selection
- Kinematic Likelihood fit to reconstruct $t\bar{t}$





Distributions are unfolded to the level of undecayed tops.

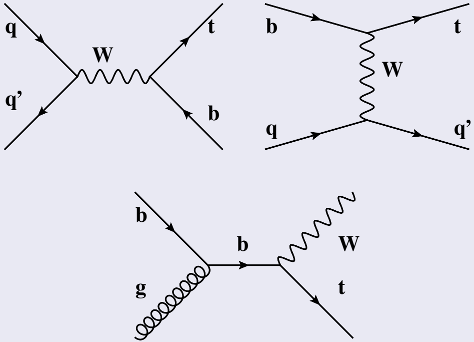
$$A_C = -0.009 \pm 0.023(\text{stat.}) \pm 0.032(\text{syst.}) \quad (e\text{+jets})$$
$$A_C = -0.028 \pm 0.019(\text{stat.}) \pm 0.022(\text{syst.}) \quad (\mu\text{+jets})$$
$$A_C = -0.024 \pm 0.016(\text{stat.}) \pm 0.023(\text{syst.}) \quad (\text{combined})$$



SM expectation (MC@NLO): $A_C = 0.006$

No evidence for BSM physics

Single Top Production



Can look for new physics in single top such as:

- Anomalous FCNC $tug, tuZ, tu\gamma$
- W' (esp. top-philic) $\rightarrow$ resonant production
- Anomalous Wtb couplings

None shown today, Single top measurements (consistent with SM):

t-channel measurement: ATLAS-CONF-2011-101

Wt-channel search : ATLAS-CONF-2011-104

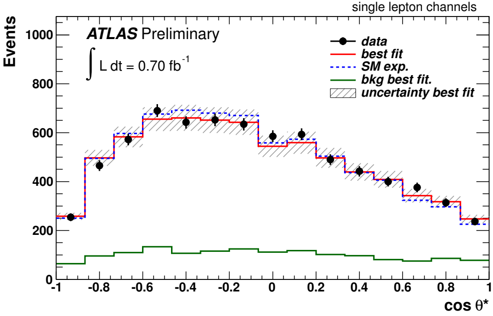
s-channel search : ATLAS-CONF-2011-118

We can also look for new physics in top decays:

- In SM $t \to Wb \sim 100\%$ of the time:
  - **Can look for anomalous tWb couplings via W polarisation**
  - Significant deviation of $R = BR(t \to Wb)/BR(t \to Wq)$ from 1 would indicate new physics
- Can look for FCNC decays $(t \to Zq, gq, \gamma q)$ (ATLAS-CONF-2011-061)
- Decays involving charged Higgs bosons (not shown today, see ATLAS-CONF-2011-094)
- In SM top decays before hadronising
  - **t$\bar{\text{t}}$ spin correlations are directly transferred to decay products and can be measured directly from their angular distributions**

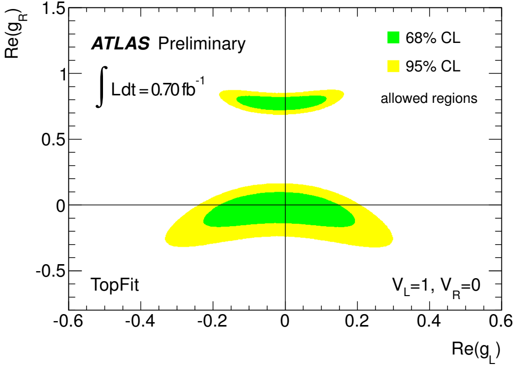
W polarisation in t decays: ATLAS-CONF-2011-122

- l + jets and dilepton channel selections
- Reconstruct top quarks:
  - **l+jets:** use a χ^2 from mass differences for reconstructed, true m_t and m_W masses, and kinematic likelihood
  - **dileptons:** solve six independent equations with m_W, m_t and E_T^{miss} constraints
- Reconstruct θ^*: angle between $-\mathbf{p_b}$ and $\mathbf{p_l}$ in W rest frame



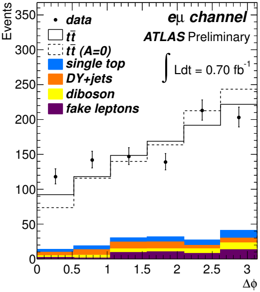
W Polarisation

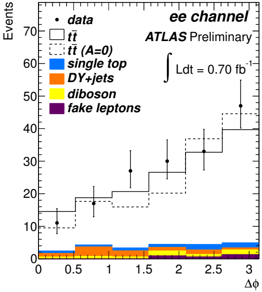
- Data consistent with SM
- Can set limits on anomalous couplings that would alter polarisation
- Choose g_R, g_L from an effective operator approach to top decays
  - g_R, g_L are 0 in SM
  - values $! = 0$ could come from BSM physics at a higher energy scale
- Upper region not compatible with measured single top cross sections

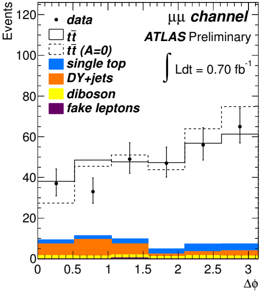


$t\bar{t}$ spin correlations: ATLAS-CONF-2011-117

- Use dilepton channel
- $\Delta\phi_{ll}$ in lab frame sufficient to distinguish SM expectation from no-correlation scenario







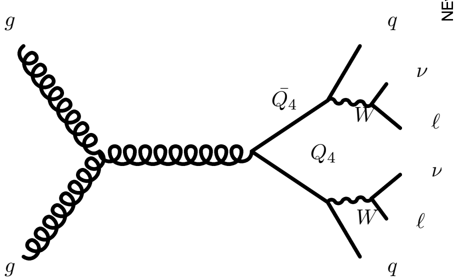
channel	f^{SM}
e^+e^-	0.89 ± 0.40
$\mu^+\mu^-$	0.67 ± 0.37
$e^\pm\mu^\mp$	1.46 ± 0.33
combination	1.06 ± 0.21

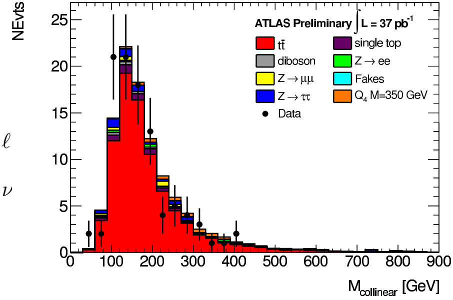
Fourth generation quarks are an attractive topic for BSM searches at the LHC:

- Aysmptotic freedom allows up to 9 generations
- Mass **must** be less than 3 TeV, diffculties already in accomodating them at $\mathcal{O}(1\,\mathrm{TeV})$
- A well-understood strong (QCD) production cross section
- Relatively small parameter space $\rightarrow$ a falsifiable theory at the LHC

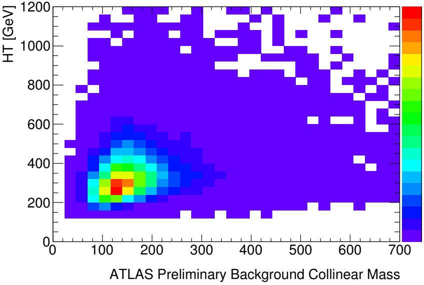
Also: Tevatron searches generally have poorer observed limits compared to expectations

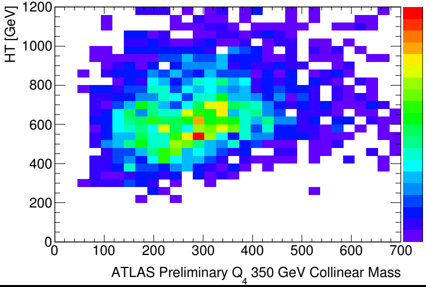
$Q_4 \bar{Q}_4 \rightarrow q\bar{q}l^- l^+ \nu\bar{\nu}$ search , $q \neq t$ (ATLAS-CONF-2011-022)



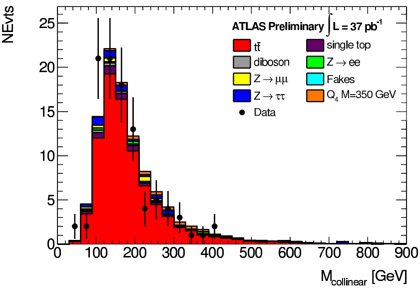


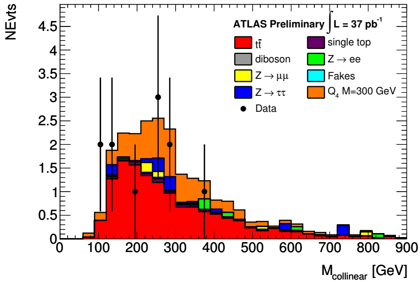
- Use $t\bar{t}$, dilepton channel selection
- Reconstruct a "collinear" mass, by scanning allowed neutrino momenta and looking for consistent Q_4 mass





- Define triangular cut in H_T and collinear mass to enhance signal-backround ratio
- No evidence for signal seen
- Fit Collinear mass distribution to set limits





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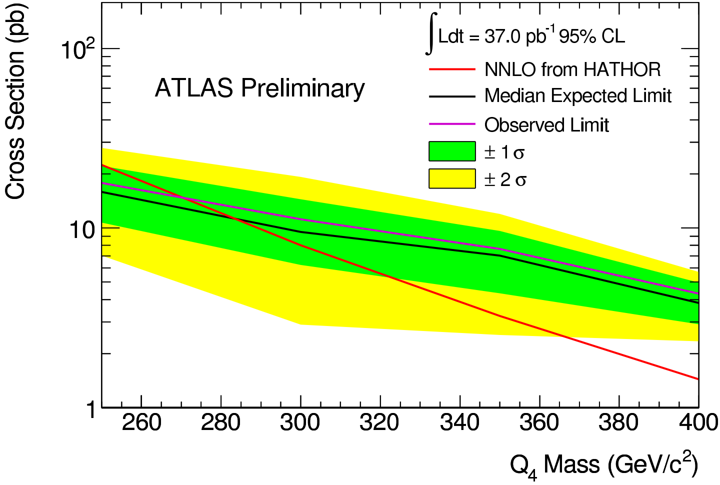
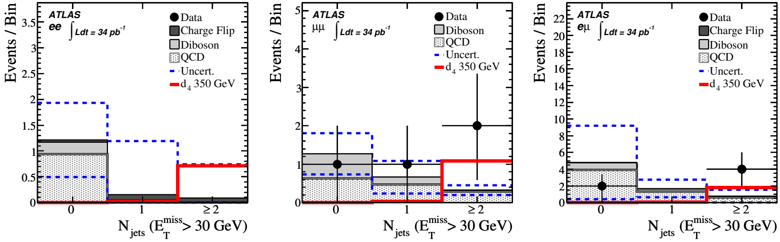
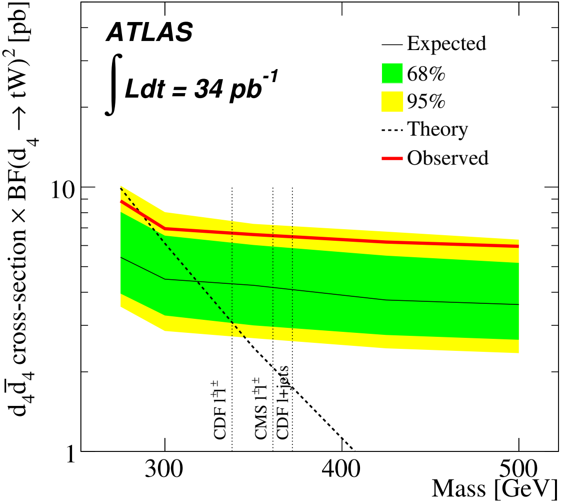
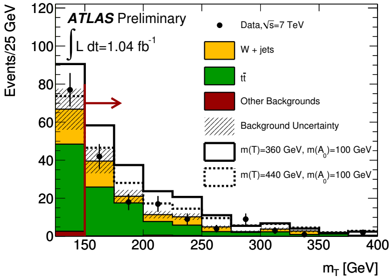

Cross Section (pb)
10^2
10
1
ATLAS Preliminary
$\int Ldt = 37.0\ pb^{-1}$ 95% CL
NNLO from HATHOR
Median Expected Limit
Observed Limit
$\pm 1\sigma$
$\pm 2\sigma$
260
280
300
320
340
360
380
400
Q_4 Mass (GeV/c^2)

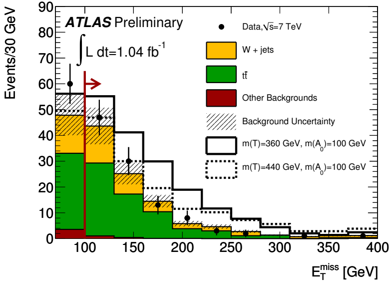
Inclusive same-sign lepton search: arXiv:1108.0366

- Select same sign leptons (e, μ)
- Sensitive to $d_4 d_4 \to ttWW \to bbjjjj\nu\nu l^{\pm} l^{\pm}$
- Set limits on $d_4\bar{d}_4$ production by:
  - Cutting on E_T^{miss}
  - Template fit to jet multiplicity distribution



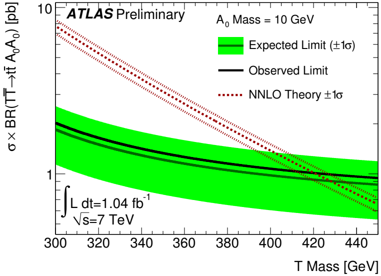

ATLAS
∫Ldt = 34 pb⁻¹
Expected
68%
95%
Theory
Observed
CDF l±l±
CMS l±l±
CDF l+jets
d4d̄4 cross-section × BF(d4 → tW)² [pb]
10
1
300
400
500
Mass [GeV]

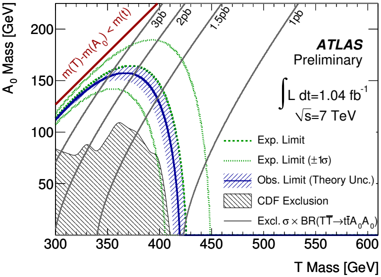




Consider pair production of 4^{th} generation quark T which decays $T \to tA_0$, where A_0 is a scalar dark matter candidate:

- Signal is $t\bar{t}$ + missing transverse momentum
- Use $t\bar{t}$ l+jets channel selection (no b-tag)
- Stronger cuts on transverse mass of $l\nu$ and E_T^{miss}
- Strict dilepton veto.



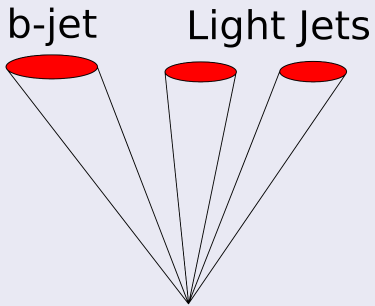


- Cut and count analysis
- Limits set on $\sigma \times \mathcal{BR}$ for different m_T, m_{A_0}
- Converted to mass exclusion in model of Phys.Rev.D81:114027,(2010)

Top quarks as an example of boosted objects:

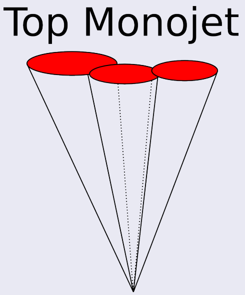
Low Energy tops

$t \rightarrow bW, W \rightarrow qq'$ gives three distinct "jets":



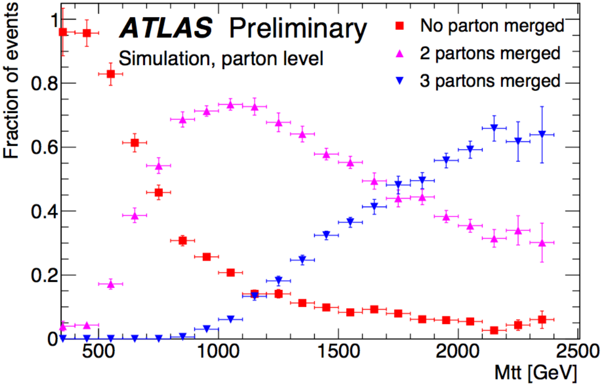
High Energy tops

top decay system is highly boosted and reconstructed as only one jet:



Need new techniques to identify these boosted objects

Merging of some description occurs for SM $t\bar{t}$ production:



Effect must be taken into account for SM measurements at higher P_T^t or $M_{t\bar{t}}$

In addition,there are many potential sources of boosted tops/Ws/Zs/Hs including:

- Heavy particles decaying to $t\bar{t}$ or WW, WZ, ZZ
- Enhancement of the high tail of $M_{t\bar{t}}$ for models that explain the TeVatron foward-backward asymmetry (J.A. Aguilar-Saavedra talk)
- Light Higgs in Association with $t\bar{t}$, Z or W
- Heavy 4^{th} generation quarks
- WW scattering

Understanding boosted objects is therefore very important for top physics and searches for the Higgs or Exotica.

The standard $t\bar{t}$ requirements of ≥ 4 jets, missing transverse momentum and an isolated lepton are not suitable for identification of boosted tops.

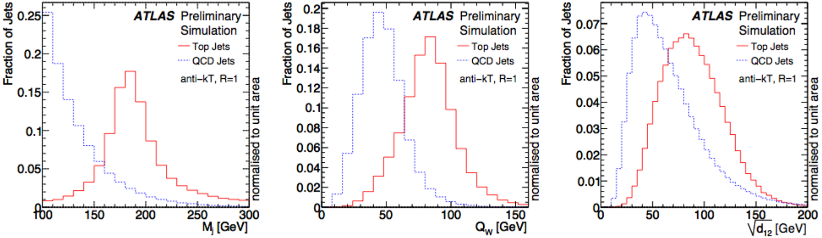
- Hadronic top decays:
  - Choose a large R jet algorithm to maximise merging probability
  - For merged jets use jet substructure techniques to identify jets containing all decay products of a top (or of a W)
  - ATLAS studies[1] look for fully-merged top jets
- Leptonic top decays:
  - Look for jet + lepton combination
  - Leptons are not necessarily isolated from the jet
  - kinematics of the decay are exploited to separate from backgrounds

In effect, the jets are 'Top-tagged'

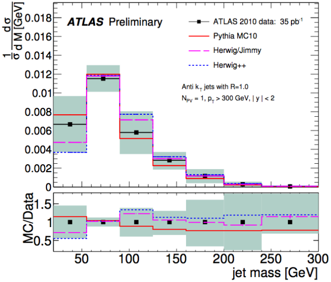
[1] (ATL-PHYS-PUB-2010-008)

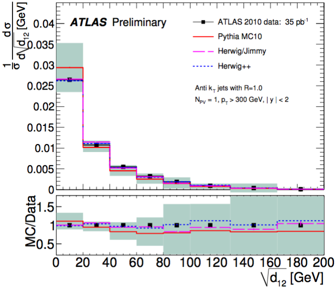
Hadronic top decays give the simplest case:

- Use the mass of the jet and Exploit features of the K_T algorithm:
  - Start with standard Anti-K_T jets and run exclusive K_T algorithm on the constituents.
  - K_T effectively undoes the QCD showering
  - Objects merged at each step have smallest $d_{ij} = \min(k_{T,i}^2, k_{T,j}^2)\frac{(\Delta R)^2}{R}$
  - So the last objects merged have the largest d_{ij} (e.g. come from the highest scale splitting)
  - **We force K_T to give us n jets and ask what the last d_{ij} was**

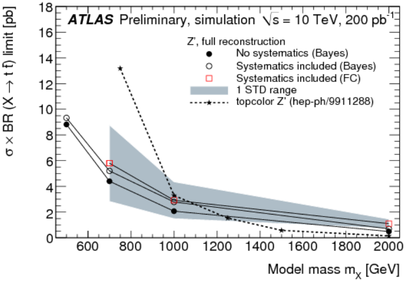


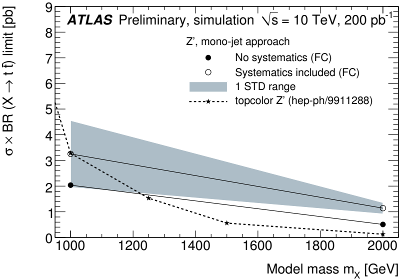
Jet substructure variables can separate top jets from QCD background



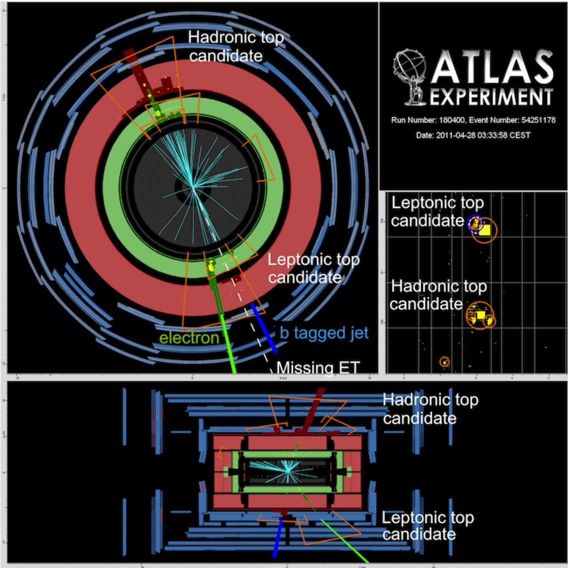


- Jet substructure (including mass and splitting scales) was measured in ATLAS-CONF-2011-073
- Calibration and uncertainties of simple splitting variables and jet mass already understood at ATLAS
- See Jon Butterworth's talk yesterday for more details





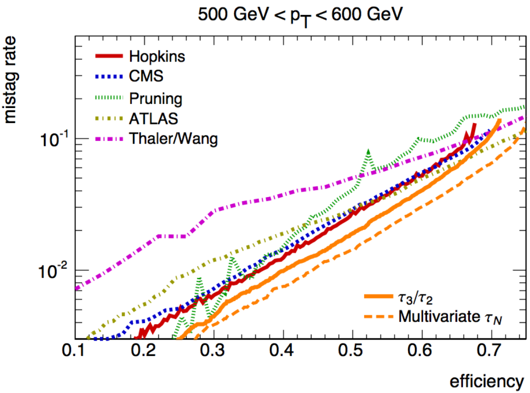
- MC study showed comparable performance of boosted (monojet) approach vs more standard approaches for $M_{t\bar{t}} > 1000\,\text{GeV}$.



- We can already see events that pass resolved citeria but have very collimated decay products.
- This example from the l+jets $t\bar{t}$ resonance search discussed earlier
- $M_{t\bar{t}} = 1602\,\mathrm{GeV}$
- Samples are now large enough to begin evaluating the performance of boosted top ID

A variety of top-tagging algorithms on the market:

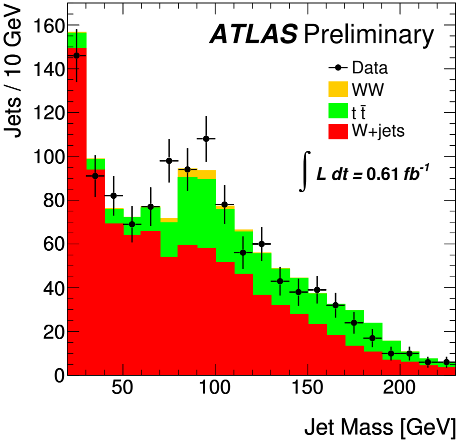
- BOOST 2010 established a level playing field for comparisons[a]
- ATLAS-style tagging competitive with more sophisticated approaches for high efficiency ($> 50\%$) working points
- Other taggers remain under consideration at ATLAS for future work



[a] Eur.Phys.J.C71:1661,2011, arXiv:1108.2701

Deployment of a mass-drop-filter approach to jet substructure[a]

- $WH,\ H \to b\bar{b}$
- "Butterworth Style":
  - Use C/A 1.2 jets
  - filter out soft recombinations
- No use of b-tagging here
- A reasonably described distribution
- A pleasing W peak from boosted W's in $t\bar{t}$
- An encouraging first look



[a] ATLAS-CONF-2011-103

- A variety of top and top-like final states are being explored in ATLAS
- No evidence for new physics (yet) seen
- Still a large landscape to explore
- We are beginning to need boosted object reconstruction for our searches:
  - Many options available
  - Most well-studied techniques already being commisioned
  - Initial studies look very promising

Back-up

(ATLAS-CONF-2011-061)

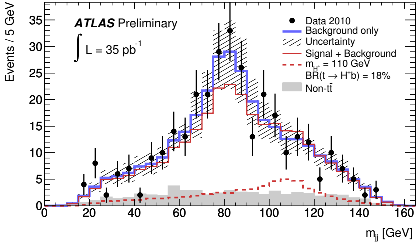
	ATLAS	LEP	HERA	Tevatron
$t \rightarrow q\gamma$		2.4%	**0.64%**	3.2%
$t \rightarrow qZ$	17%	7.8%	49%	**3.2%**
$t \rightarrow qg$		17%	13%	**2.0×10^{-4}(tug)** **$3.8 \times 10^{-}4$(tcg)**

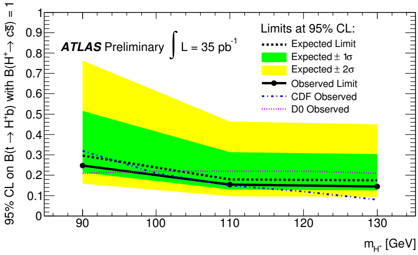
Single top results:

Channel	SM	Measured
s	4.6 ± 0.3 pb	< 26.5 pb
t	$64.6^{+3.3}_{-2.6}$ pb	90^{+32}_{-22} pb
Wt	$15.7^{+1.3}_{-1.4}$ pb	< 39 pb

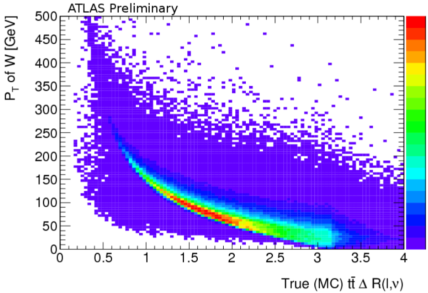
$H^\pm$

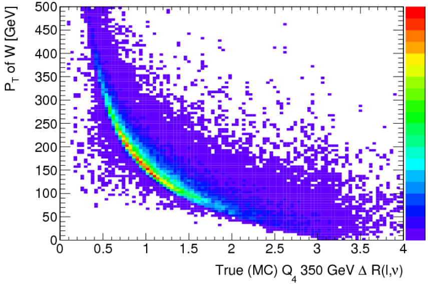
Search for charged Higgs $H+ \rightarrow c\bar{s}$ in top decays
ATLAS-CONF-2011-094)





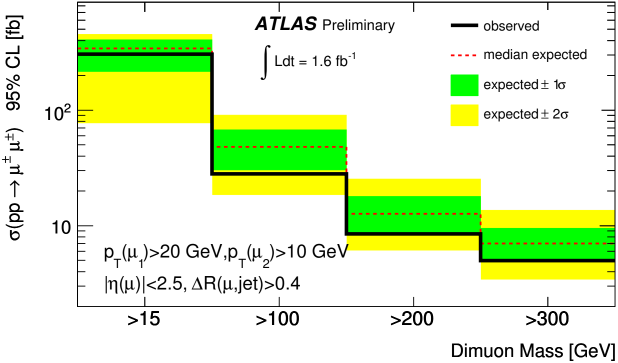
$u_4 \bar{u}_4$': Boosted Ws





SS μ

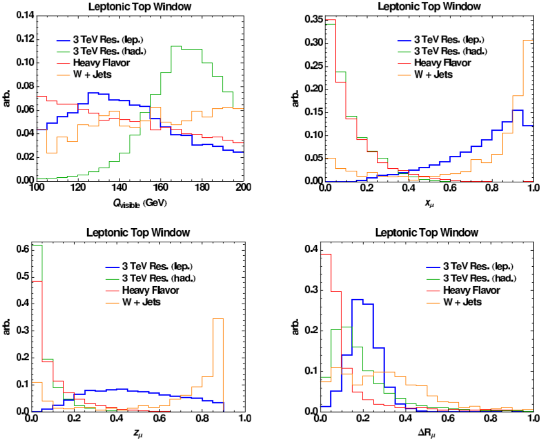
Fiducial limits on Same sign μ production:



applicable to same-sign tops (ATLAS-CONF-2011-126)

Leptonic Tops

Several variables for leptonic t-tagging from JHEP0807:092,2008:

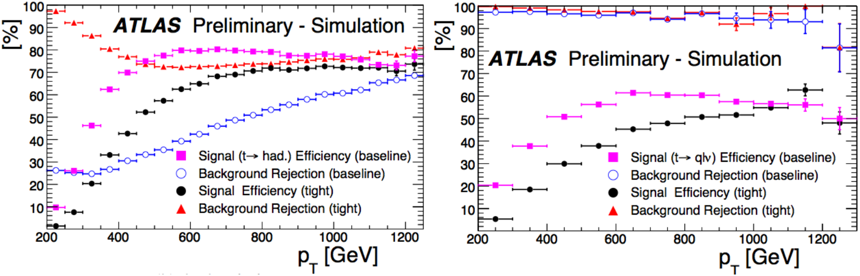


- $Q_{\rm vis}$ - The visible invariant mass of the jet + muon
- $x_\mu = \frac{2p_\mu \cdot p_b}{(p_\mu + p_b)^2} \to 1 - \frac{m_b^2}{Q_{\rm vis}^2}$
- $z_\mu = \frac{E_\mu}{E_\mu + E_b}$
- $\Delta R = \Delta R(p_\mu, p_b)$

Further variables from: ATL-PHYS-PUB-2010-008

- $y_l = p_{l \perp b} \times \Delta R(l, b)$
- $y'_e = p_{e \perp j} \times \Delta R(l, j)$

j is a jet constructed without removing the e candidate.



- In a boosted semi-leptonic $t\bar{t}$ event the main background discrimination comes from the leptonic leg
- Good efficiency for $P_T > 500\,\text{GeV}$