Peaky blinders: searches for $t\bar{t}$ resonances

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Elementary Particle Physics Group Seminar
University of Birmingham
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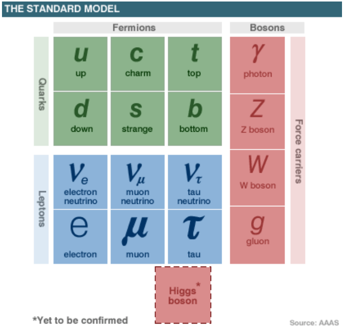
Outline

- Why search for $t\bar{t}$ resonances?
- Review of $t\bar{t}$ resonance searches
- Looking towards the future

Will focus on the details of ATLAS searches but also show the best results from the competition

The Standard Model (SM) of particle physics:

- Fermionic matter:
  - Three generations of **quarks**
  - Three generations of **leptons**
- Gauge Bosons:
  - Four Force carriers : γ(EM), $W^{\pm}$, Z (Weak), g (strong)
  - The Higgs Boson to give mass



"Was she pretty?" asked the bigger of the small girls. "Not as pretty as any of you," said the bachelor, "but she was horribly good."
The storyteller - H. H. Munro (Saki)

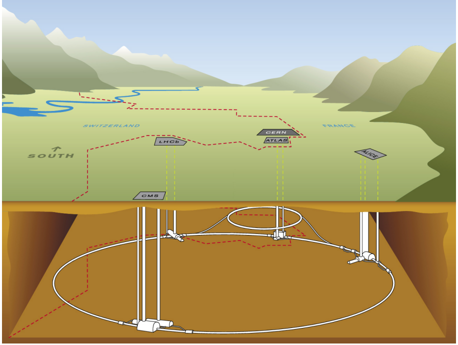
So what's wrong with the Standard Model?

- No Dark Matter candidates
- Not enough CP violation to explain the observed matter-antimatter imbalance
- ~~The Higgs boson has still not been observed~~
- No gravity
- Particle masses are not understood

Is there physics beyond the Standard Model?

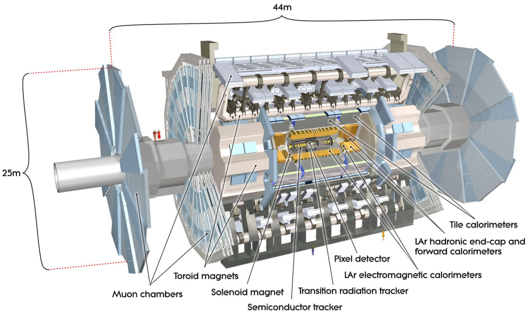
Where to look for answers? The Large Hadron Collider at CERN

- 27 km circumference ring
- Currently collides protons at centre-of-mass energy 8 TeV
- Four detectors installed around the ring
- An excellent environment to test the Standard Model and search for new Physics
- Triviality/Unitarity constraints on some SM cross sections imply a Higgs Boson or something else at an energy scale $< 800\,\mathrm{GeV}$



What equipment to use? A Toroidal Large ApparatuS (ATLAS)

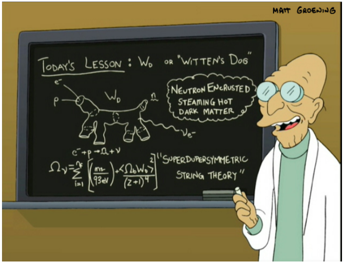
- 4 Detectors:
  - 2 General Purpose
    - **ATLAS**
    - CMS
  - Two Specialised
    - ALICE - Heavy ion
    - LHCb - CP violation



ATLAS with full solid angle coverage, excellent charged particle tracking, particle ID and energy measurement is well-suited for TeV-Scale physics (and so is CMS of course)

- The top quark was discovered at TeVatron in 1995
- Extremely heavy for a fundamental particle:
  - Similar mass to a gold atom
  - $\sim$ 35 times heavier than the next heaviest quark (the bottom quark)
- Usually produced in a $t\bar{t}$ pair with its partner the anti-top
- Could it provide a gateway to new physics?

- Many BSM scenarios on the market
- Large top mass ($m_t \approx 173\,\mathrm{GeV}$) $\rightarrow$ top often plays a special role in BSM theories
- BSM physics often has consequences for the third generation quarks



Some examples:

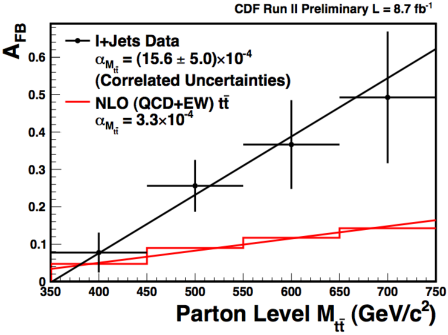
- **Add new heavy quarks:** Often decay to tops or look like heavy tops
- **Incorporate Gravity using Extra Dimensions:** Many models predict new states with strong coupling to the top
- **Exotic Higgs Bosons:** large coupling to the top
- **SUSY:** naturalness prefers top-partners not too far from m_t

Extra motivation: TeVatron $p\bar{p}$ data

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

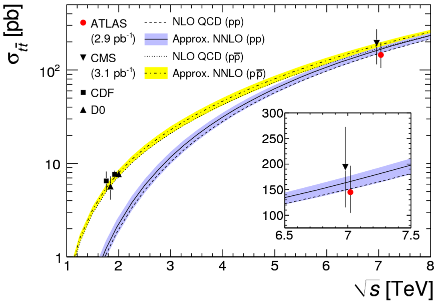
- Tevatron collides p and $\bar{p}$ producing $t\bar{t}$
- $A_{t\bar{t}}$ a measure of how much the t prefers the p direction
- p-value of such a large slope 0.00646 (CDF)

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

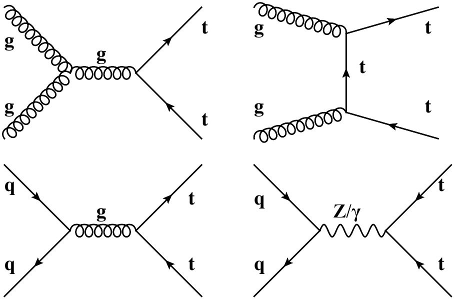


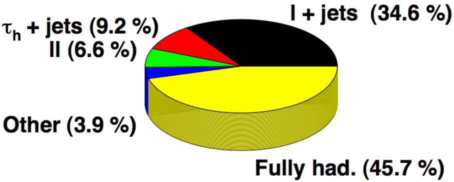
Measurements of top properties at TeVatron statistically limited

- The LHC $t\bar{t}$ production cross-section is much larger
- In effect the LHC is a **top quark factory**
- TeVatron: $< 8 \times 10^4$ ($10\,\mathrm{fb}^{-1}$) top pairs per experiment ∼10 years running
- LHC: $> 6 \times 10^6$ top pairs per experiment in 2011-12



At the LHC many top quark studies are possible that were not feasible at TeVatron





- In the SM, top decays approximately 100% $t \rightarrow Wb$
- Classified according to the W decays

Broadly speaking can study new physics in $t\bar{t}$ in three different ways

- Look for anomalous production of tops
- Look for unexpected behaviour in top quark decays
- Directly search for new particles decaying to tops (and possibly something else)

This talk focuses on the latter, searching for a peak in the $m_{t\bar{t}}$ distribution from production of new particles that decay to $t\bar{t}$ pairs

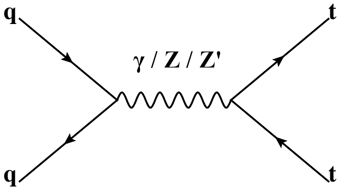
A wealth of peaky new physics signals from different scenarios:

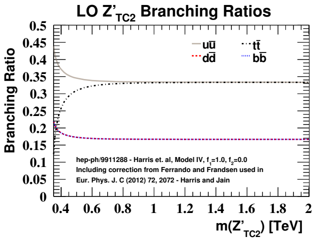
- **Extra dimensions (Bulk RS)**: Excitations of gluon (g_{KK})/ graviton (G_{KK}) preferentially decay to $t\bar{t}$
- **Topcolor-assisted Technicolor**: Strong EWSB model via a top condensate - expect top-π (H-like) and top-ρ (Z'-like) the latter heavy enough to decay to $t\bar{t}$

  - **Composite Higgs scenarios**: Usually require (naturalness) extra heavy-fermions, and commonly heavy "gluons" that decay to t_R or new heavy fermions depending on the masses
  - **BSM Higgs**: New heavy pseudoscalar Higgs-like particles in, e.g. the MSSM, would also have a large $t\bar{t}$ branching ratio

Searches so far have focused on two benchmark scenarios:

- Topcolor-assisted technicolor (TC2) $Z'_{\mathrm{TC2}} \to t\bar{t}$
  - Spin-1
  - Color singlet
  - Narrow width (1.2%) modelled with SSM Z' (3%) width
  - hep-ph/9911288, Eur. Phys. J. C (2012) 72 2072
- RS Kaluza-Klein Gluon $g_{\mathrm{KK}} \to t\bar{t}$
  - Spin-1
  - color octet
  - wide (10-15%)
  - $\mathcal{BR}(g_{\mathrm{KK}} \to t\bar{t}) \sim 92.5\%$
  - JHEP 0709 (2007) 074





First $t\bar{t}$ resonance search at the LHC selected tops in a familar way (ATLAS - Eur.Phys.J. C72 (2012) 2083)

dilepton channel

- 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

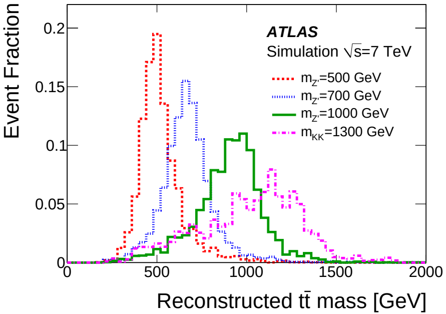
l+jets channel

- Isolated electron or muon
- Missing Transverse momentum (E_T^{miss})
- 4 or more jets (inclusive Anti-K_T, $R = 0.4$) or, 3 jets and one jet has mass > 60 GeV
- At least 1 b-tagged jet

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

Use kinematic distributions to search for background

- l+jets reconstruct $m_{t\bar{t}}$
  - Solve quadratic for E_T^{miss} to reconstruct neutrino using $m_{l\nu} = m_W$ constraint
  - exclude jets if $\Delta R > 2.5 - 0.0015 \times m_j$ iteratively until none fail, or there are only three jets
  - take 4 (or 3) highest p_T remaining jets
  - reconstruct the mass of the 4 jet, lepton + neutrino system
- dilepton: use H_T

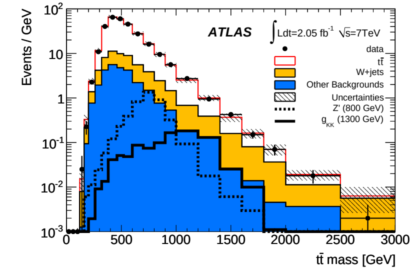


Estimation of backgrounds:

- **top-pair**: (irreducible) taken from Monte Carlo (MC)
- **W+jets**: taken from MC and then normalised using data control regions (l+jet channel)
- **Z+jets**: taken from MC and then normalised using data control regions (dilepton channel)
- **single-top**: taken from MC
- **Massive di-boson**: taken from MC
- **non-top multijet**: estimated directly from data

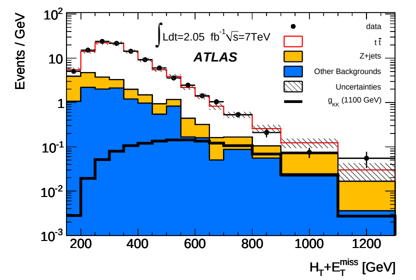
l+jets

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



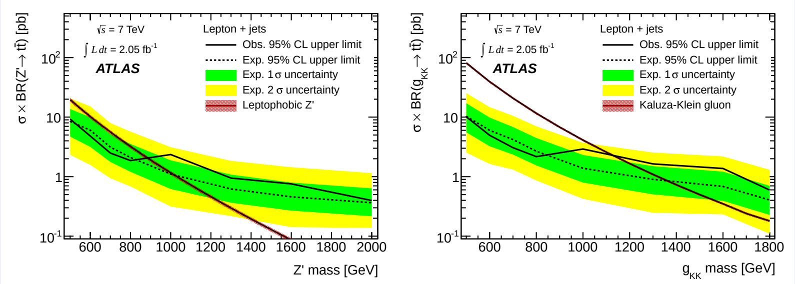
dileptons

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



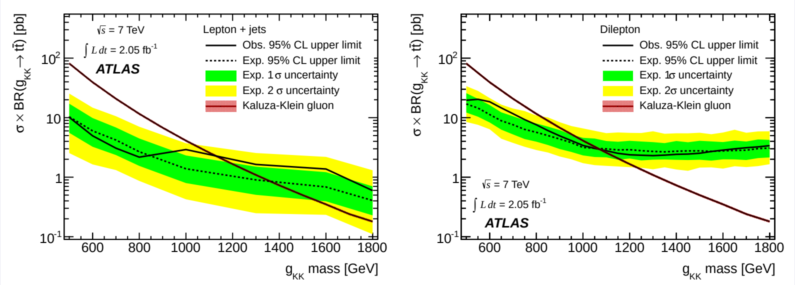
No evidence for new physics signals

l+jets



- **l+jets:** Limits set on narrow Z'-like resonances: Exclude $500 < M_{Z'} < 880\,\text{GeV}$ for benchmark (Topcolor-assisted technicolor) Z' model.

dileptons



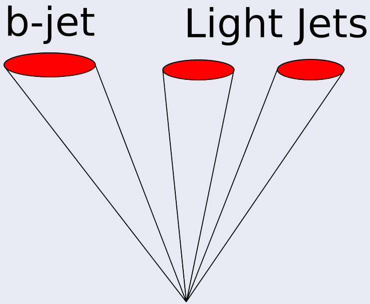
- **dileptons:** Limits set on broader g_{KK}-like resonances. Benchmark scenario: $M_{g_{KK}} < 1025$ TeV excluded. (l+jets excludes $500 < M_{g_{KK}} < 1130$ for the main benchmark scenario)

On the previous slides, expected limits flatten at higher $m_{t\bar{t}}$

When pushing to higher energies, new factors come into play:

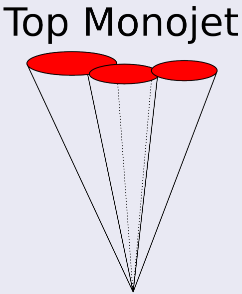
Low-energy tops

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



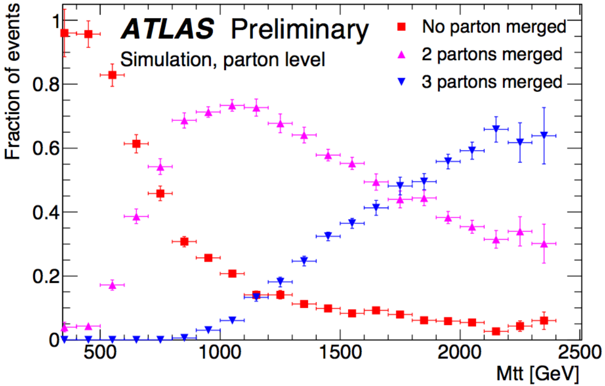
High-energy tops

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



Need new techniques to identify these boosted objects

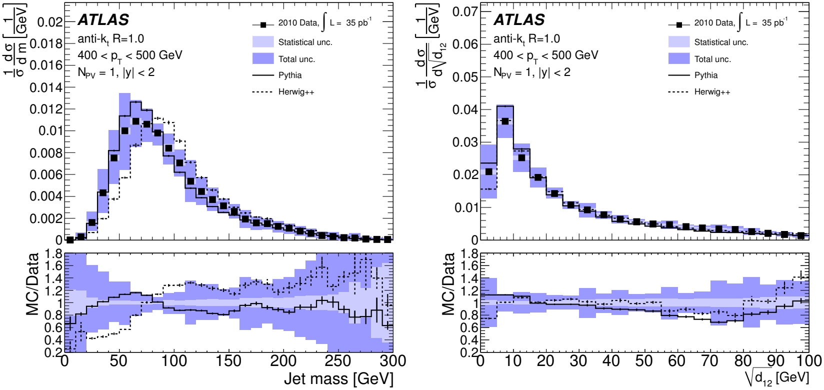
Merging of some description occurs for SM $t\bar{t}$ production:



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

Hadronic top decays give the simplest case:

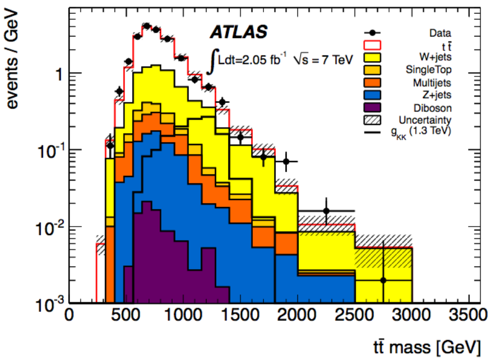
- Use the mass of the jet and exploit features of the K_T algorithm:
  - Start with standard Anti-K_T jets and run exclusive K_T algorithm on the constituents.
  - K_T effectively undoes the QCD showering
  - Objects merged at each step have smallest $d_{ij} = \min(k_{T,i}^2, k_{T,j}^2)\frac{(\Delta R)^2}{R}$
  - 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**



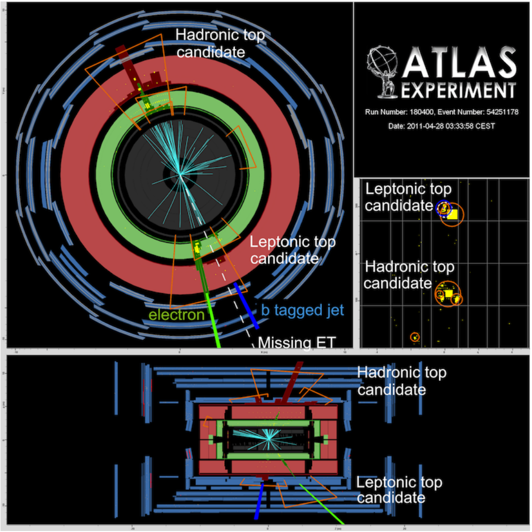
- Jet substructure (including mass and splitting scales) was measured in ATLAS - JHEP 1205 (2012) 128
- Calibration and uncertainties of simple splitting variables and jet mass already understood at ATLAS

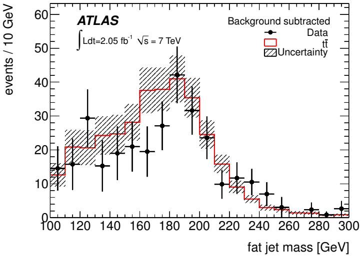
Put into practice in: ATLAS - JHEP 1209 (2012) 041

- Same lepton selection as previous analysis (l+jets)
- No b-tag
- Look for boosted $t \to bqq$:
  - Large-R (1.0) anti-k_T jet
  - Require large jet mass and first k_T splitting scale (d_{12})
- Reconstruct $m_{t\bar{t}}$ from hadronic top cand +lepton, E_T^{miss} and nearest anti-k_T (R=0.4) jet

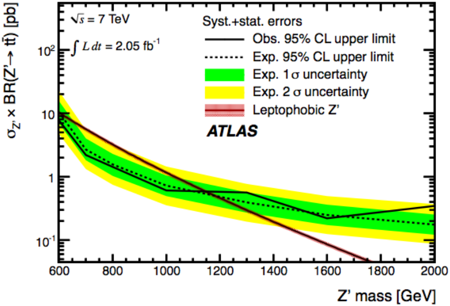


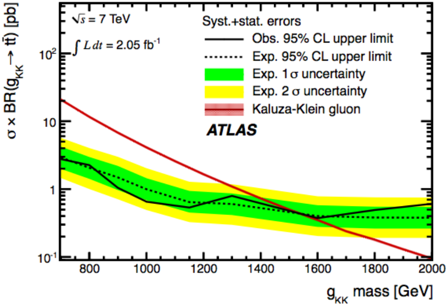
Candidate


Hadronic top candidate
ATLAS EXPERIMENT
Run Number: 180400, Event Number: 54251178
Date: 2011-04-28 03:33:58 CEST
Leptonic top candidate
Hadronic top candidate
Leptonic top candidate
electron
b tagged jet
Missing ET
Hadronic top candidate
Leptonic top candidate


ATLAS
∫Ldt=2.05 fb⁻¹ √s = 7 TeV
Background subtracted
Data
tt̄
Uncertainty
events / 10 GeV
fat jet mass [GeV]
0
10
20
30
40
50
60
100
120
140
160
180
200
220
240
260
280
300

Extract limits on narrow (<3%) or Wide (∼10%) resonance → $t\bar{t}$:





comfortably outperforming the conventional analysis at high $m_{t\bar{t}}$

The first search to fully combine boosted and resolved approaches:
Phys. Rev. D 88, 012004 (2013)

- **Boosted:**
  - lepton
  - E_T^{miss}
  - ≥ 1 large-R jet with $p_T > 350$ GeV and large jet-mass
  - ≥ 1 b-jet
- **Resolved**
  - Fails boosted selection
  - lepton
  - E_T^{miss}
  - ≥ 4 jets or ≥ 3 jets and one jet has a mass > 60 GeV
  - ≥ 1 b-jet

included also several improvements compared to previous iterations

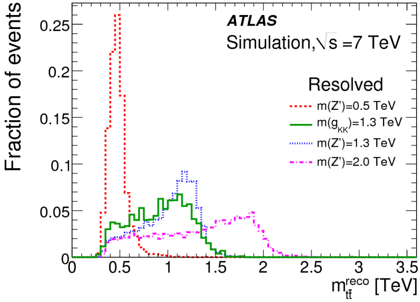
We can make it better

Building a better search:

- **Resolved:** Improve $t\bar{t}$ reconstruction
- **Boosted:** Add b-tagging (reduce large W+jets background),
- **Both:** Improve isolation definition,

Adopted a χ^2 method for choosing jets to use in calculation of the $t\bar{t}$ mass:

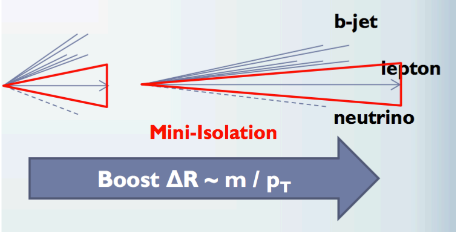
$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{t_h - W}}{\sigma_{t_h - W}}\right]^2 + \left[\frac{m_{j\ell\nu} - m_{t_\ell}}{\sigma_{t_\ell}}\right]^2 + \left[\frac{(p_{\mathrm{T},jjb} - p_{\mathrm{T},j\ell\nu}) - (p_{\mathrm{T},t_h} - p_{\mathrm{T},t_\ell})}{\sigma_{\mathrm{diff}\,p_\mathrm{T}}}\right]^2$$



Conventional lepton isolation is also a problem for boosted tops:

Standard isolation requirements:

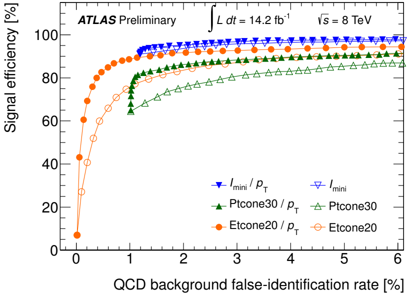
- Require lepton and nearest jet well separated ($\Delta R(l, j) > 0.4$)
- require p_T within a small cone around the lepton track is less than some value

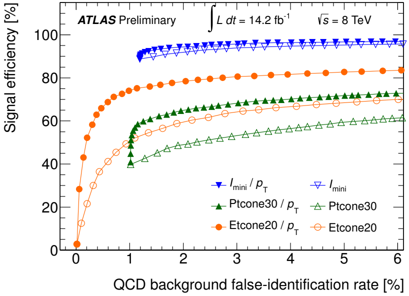


Solution: Adopt mini-isolation (JHEP 1103 (2011) 059)

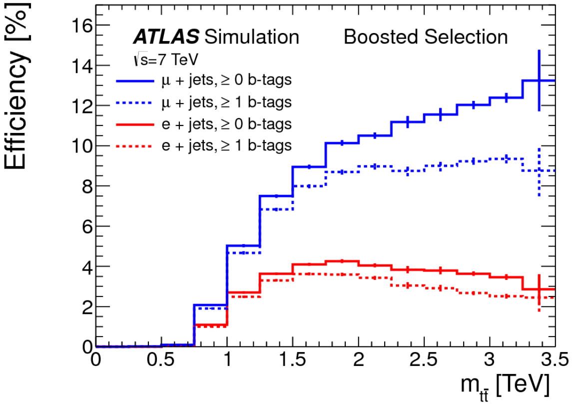
- Size of isolation cone shrinks with p_T , $\Delta R = k/p_T^l$ (in the case of ATLAS $k = 10\,\text{GeV}$ is used)
- Require p_T is less than some value (in the case of ATLAS $< p_T^l/20.0$)

... and relax requirement on $\Delta R(l, j)$ in the μ channel.



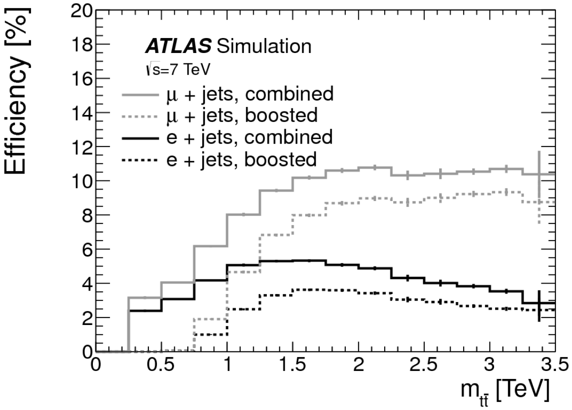


Performance of mini-isolation is very good and stable for different Z' masses (1.0 TeV (left) and 2 TeV (right))

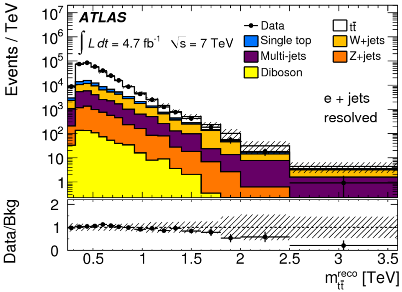


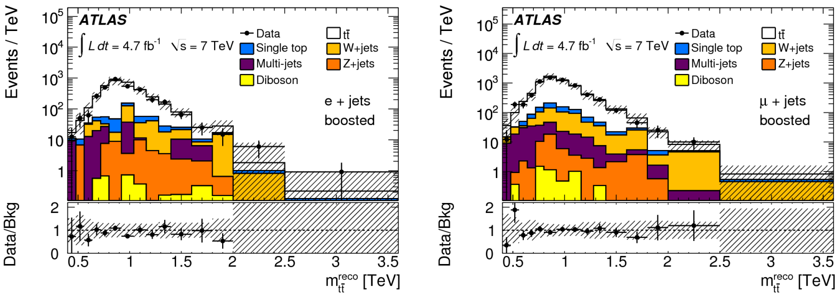
- Muon channel efficiency now rises with $m_{t\bar{t}}$
- Fall-off at high masses for electrons because $\Delta R(l, j)$ cut could not be relaxed

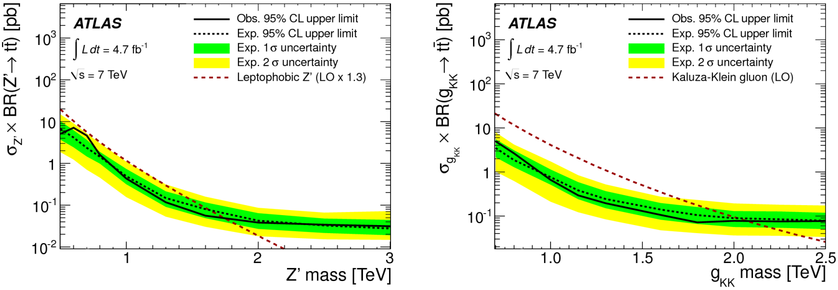
Selection efficiency



Overall signal efficiency is high (this value is relative to all $t\bar{t}$)


ATLAS
∫ L dt = 4.7 fb-1 √s = 7 TeV
Data
tt̄
Single top
W+jets
Multi-jets
Z+jets
Diboson
e + jets
resolved
Events / TeV
Data/Bkg
m_tt̄^reco [TeV]
ATLAS
∫ L dt = 4.7 fb-1 √s = 7 TeV
Data
tt̄
Single top
W+jets
Multi-jets
Z+jets
Diboson
μ + jets
resolved
Events / TeV
Data/Bkg
m_tt̄^reco [TeV]


ATLAS
∫ L dt = 4.7 fb-1 √s = 7 TeV
Data
Single top
Multi-jets
Diboson
tt̄
W+jets
Z+jets
e + jets
boosted
Events / TeV
Data/Bkg
m_tt̄^reco [TeV]
ATLAS
∫ L dt = 4.7 fb-1 √s = 7 TeV
Data
Single top
Multi-jets
Diboson
tt̄
W+jets
Z+jets
μ + jets
boosted
Events / TeV
Data/Bkg
m_tt̄^reco [TeV]

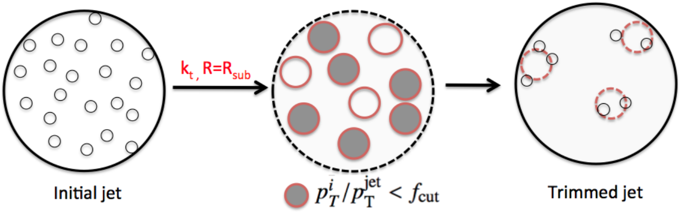


benchmark models excluded up to 1.75 TeV (Z') and 2.1 TeV (g_{KK})

First ATLAS search using partial 8 TeV dataset:

- **Improvements:**
  - Introduced Trimming of large-R jet to mitigate pile-up
- **Disadvantages:**
  - large-R jet triggers not available at this time (large hit im muon channel efficiency)

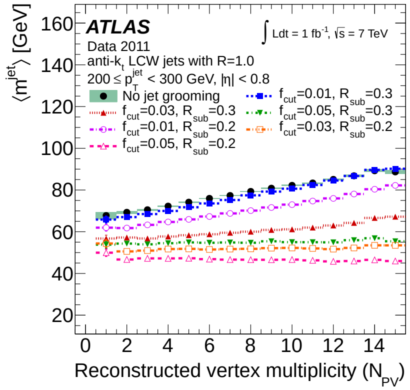
Performance of Trimming discussed in detail in:
ATLAS - JHEP 1309 (2013) 076

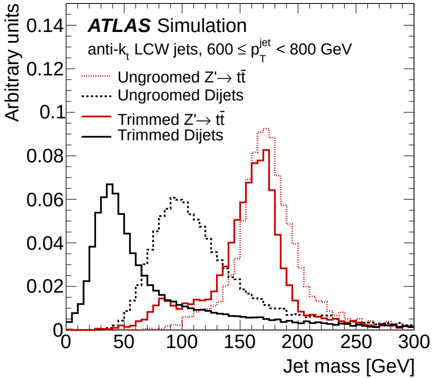


Works by:

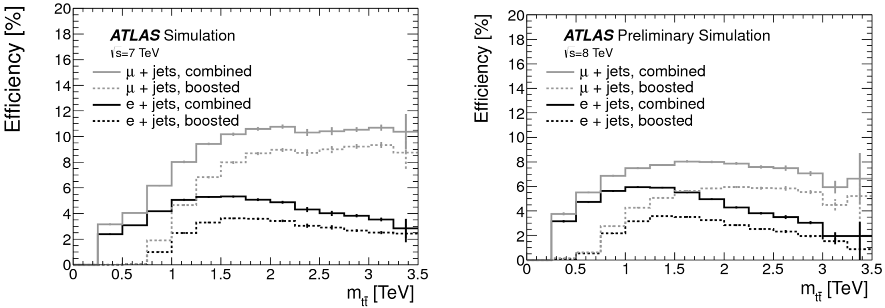
- running a small-R (0.3) k_T algorithm on large-R jet constituents to make subjets
- keeping only subjets with p_T greater than a certain fraction (0.05) of the large-R-jet
- This "trims" away soft activity in the jet

Trimming: Performance

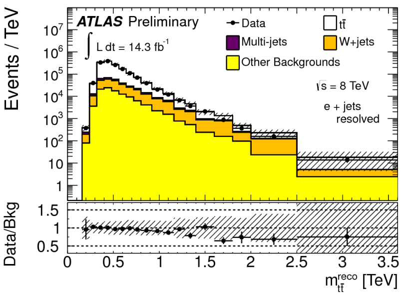


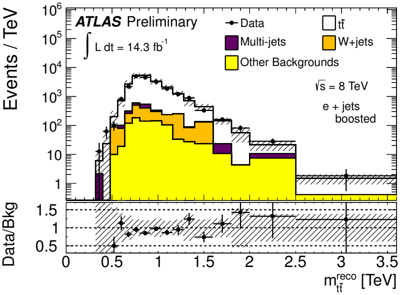


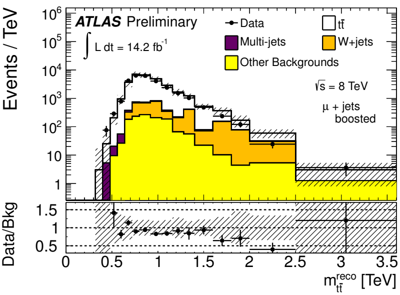
Trimming makes jet substructure quantities robust against pile-up



- Electron channel loss - due to trimming
- Muon channel loss - trimming and trigger
- Partly mitigated by some other gains in reconstruction


ATLAS Preliminary
∫ L dt = 14.3 fb-1
Data
tt̄
Multi-jets
W+jets
Other Backgrounds
√s = 8 TeV
e + jets
resolved
Events / TeV
Data/Bkg
m reco tt̄ [TeV]
ATLAS Preliminary
∫ L dt = 14.2 fb-1
μ + jets
resolved


ATLAS Preliminary
$\int$ L dt = 14.3 fb^{-1}
Data
$t\bar{t}$
Multi-jets
W+jets
Other Backgrounds
$\sqrt{s}$ = 8 TeV
e + jets
boosted
Events / TeV
Data/Bkg
$m_{t\bar{t}}^{reco}$ [TeV]


ATLAS Preliminary
$\int$ L dt = 14.2 fb^{-1}
Data
$t\bar{t}$
Multi-jets
W+jets
Other Backgrounds
$\sqrt{s}$ = 8 TeV
μ + jets
boosted
Events / TeV
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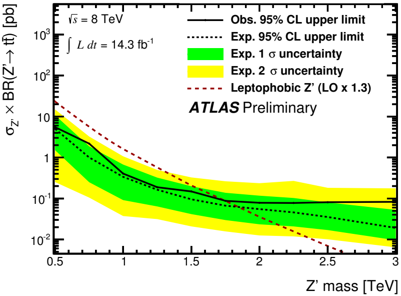
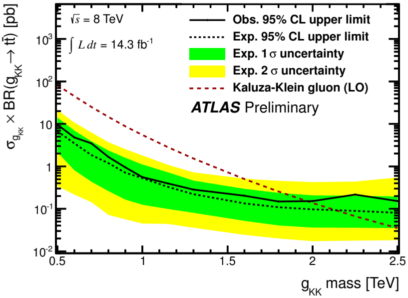
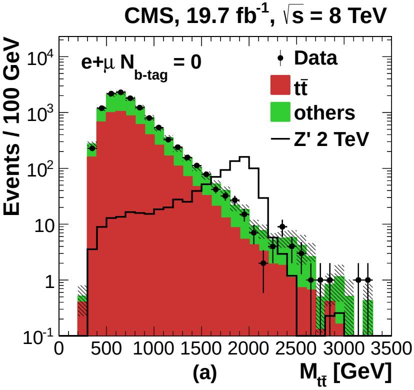




benchmark models excluded up to 1.8 TeV (Z') and 2.0 TeV ($g_{\rm KK}$)

New CMS search CMS - Phys. Rev. Lett. 111 (2013) 211804

- Combines all-hadronic (boosted) and l+jets (resolved and boosted), channels
- Boosted l+jets:
  - Separated into separate channels by b-tag
  - no isolation required for leptons
  - require at least two jets
  - Build $t\bar{t}$ combination via a chi^2, cut on the chi^2 to reduce backgrounds



New CMS search CMS - Phys. Rev. Lett. 111 (2013) 211804

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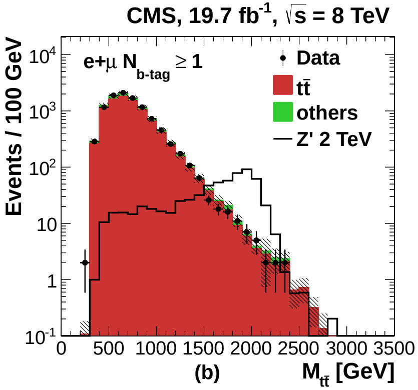
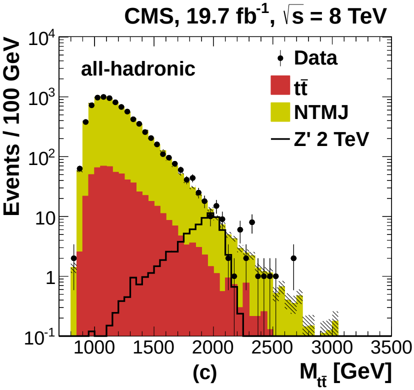


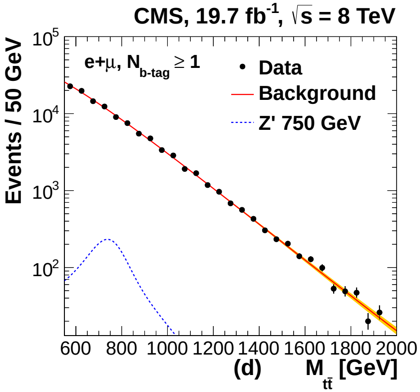
New CMS search CMS - Phys. Rev. Lett. 111 (2013) 211804

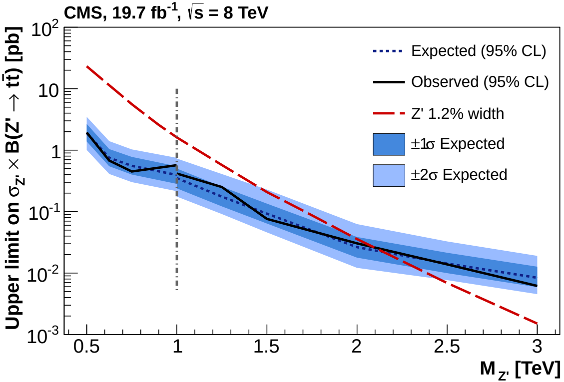
- Combines all-hadronic (boosted) and l+jets (resolved and boosted), channels
- All-hadronic:
  - Requires two high-p_T large-R jets - that are "top-tagged" with a sophsiticated tagger
  - two leading back-to-back b-tagged small-R jets



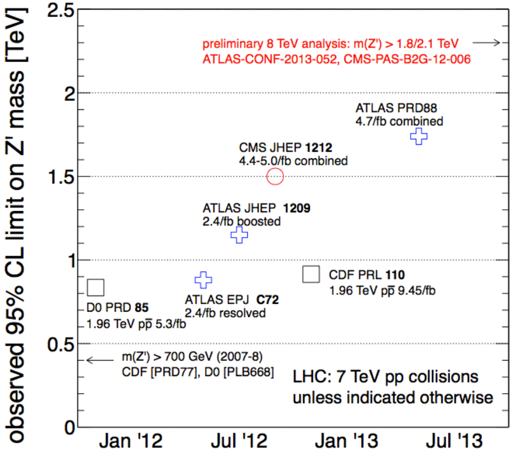
New CMS search CMS - Phys. Rev. Lett. 111 (2013) 211804

- Combines all-hadronic (boosted) and l+jets (resolved and boosted), channels
- Resolved $l + jets$:
  - require at least four jets
  - separate into b-tag categories
  - build a χ^2 and cut on it
  - Fit a smoothyl falling pdf to the SM background





All-hadronic combined with the separate resolved and boosted l+jets results in different kinematc regimes.

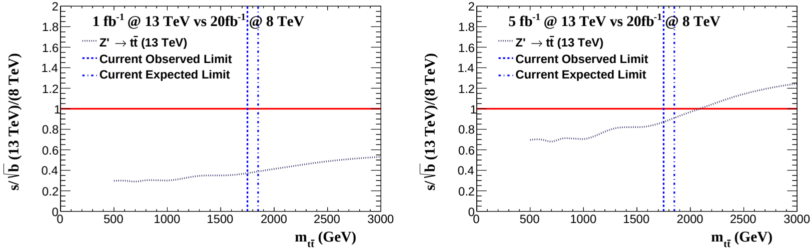


Boost 2012 report - arXiv:1311.2708

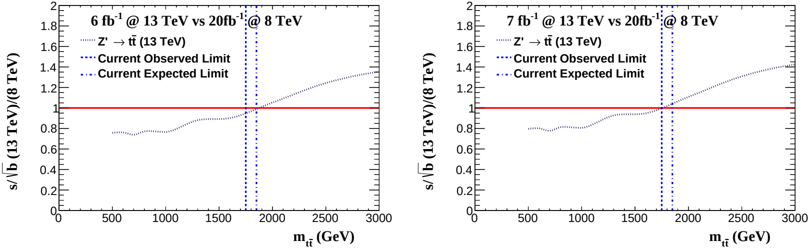
What's next?

- Towards LHC run-II
- Prospects with the upgraded LHC

How much luminosity is neeed at 13 TeV to be competitive with current data?

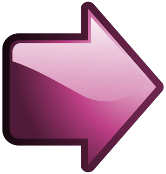


(simple extrapolation using cross sections for Z' and NLO $t\bar{t}$ in appropriate $m_{t\bar{t}}$ range)



Reach should start to increase as we approach 6-7 fb^{-1}

Upgrades



Example, ATLAS upgrade schedule:

Phase I

- **Installation Date:** 2018-19
- **Detector upgrades:** μ-trigger, L1 Calo-trigger, FTK, new Small wheel for muons , new forward detectors . Various readout improvements. (Maintain performance at higher luminosity)
- **Lumi** $2.2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, 300-400 fb^{-1} by 2022, $\mu =$ 55-80

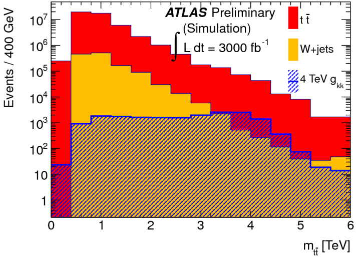
Phase II

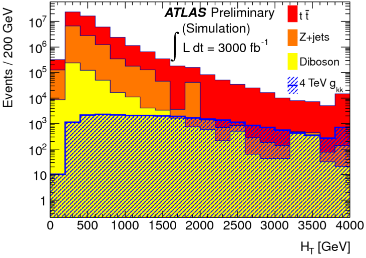
- **Installation Date:** 2022-24
- **Detector upgrades:** Split L0/L1 trigger, numerous trigger and readout upgrades, improved HLT, RPC precision upgrade, complete tracker replacement. (Maintain/improve performance at higher μ, improve resistance to radiation damage)
- **Lumi** $5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, up to 3000 fb^{-1}, $\mu =$ 140-200

ATLAS upgrade performance and physics prospects have been studied in:

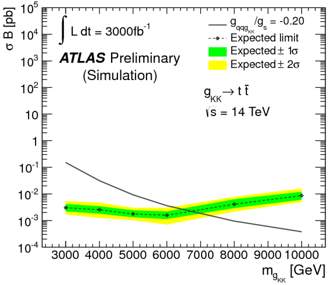
- Phase-I LOI: CERN-LHCC-2011-012
- Phase-II LOI: CERN-LHCC-2012-022
- $t\bar{t}$ resonance search: ATL-PHYS-PUB-2013-003

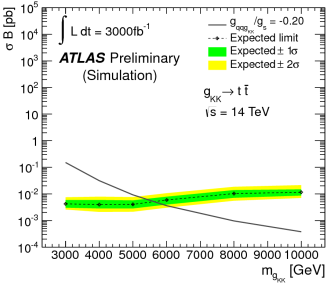
Studies of $t\bar{t}$ resonance searches done with a parametrisation of detector response, not at the full-simulation level.



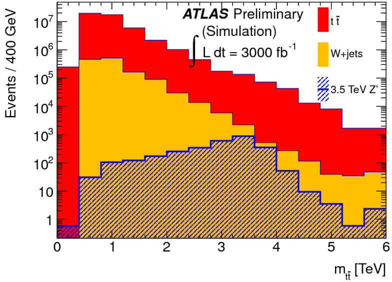


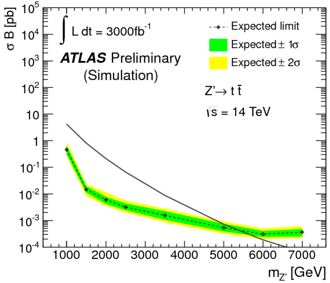
- $t\bar{t}$ in simplified l+jets (boosted) and dilepton selections





- $t\bar{t}$ in simplified l+jets (boosted) and dilepton selections





- $t\bar{t}$ in simplified l+jets (*boosted*) and dilepton selections

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
Z'_{topcolor}	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)

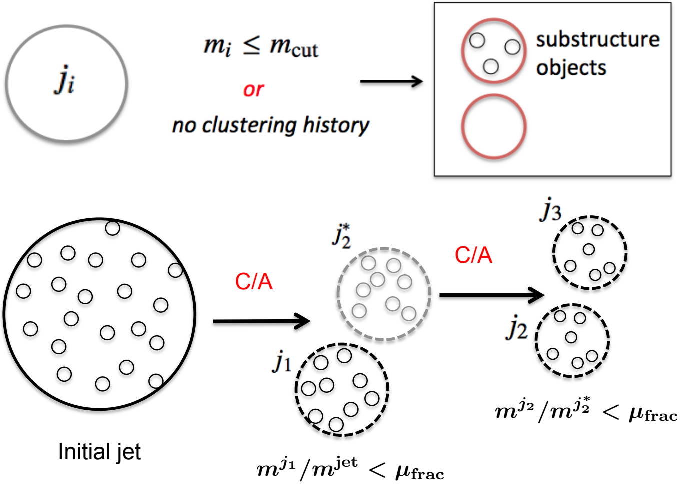
- $t\bar{t}$ in simplified l+jets (*boosted*) and dilepton selections
- Exclusion reach for benchmarks could extend as far as 5-6 TeV after the phase=II upgrade
- Of course we hope for a discovery before then

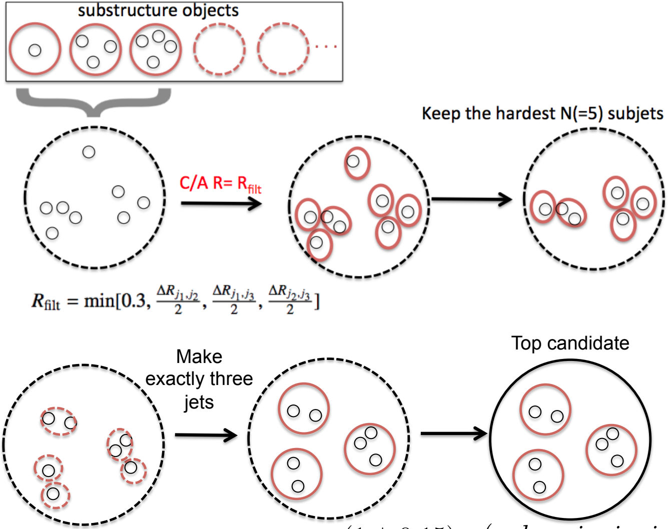
Summary

- ATLAS + CMS have performed several searches for new particles decaying to $t\bar{t}$
- Deployed new techniques for the identification of heavy boosted objects
- No evidence for new particles $\rightarrow t\bar{t}$ yet
- Need to look carefully at the data for all kinds of new physics, it may not contain what we expect...


Allison Pearson
Talking offence is the new national sport
Peter Oborne
Tony Blair has failed in the Middle East and should quit
Pep Guardiola
Why he turned his back on England
The Daily Telegraph
Thursday, January 17, 2013
telegraph.co.uk
Horse meat in burgers for years
Crash helicopter 'was out of control'
Briton dies, many held, in al-Qaeda revenge raid

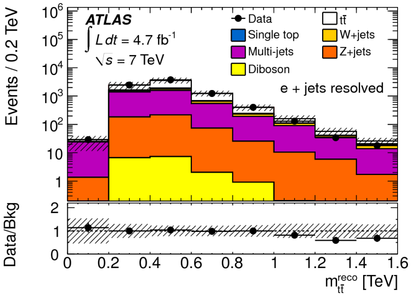
Back-up

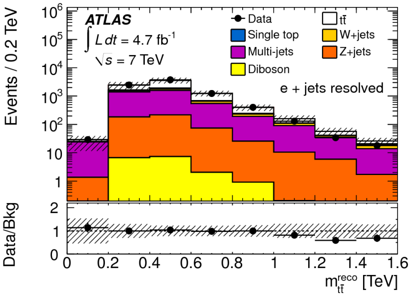

j_i
$m_i \le m_{cut}$
or
no clustering history
substructure objects
Initial jet
C/A
j_2^*
j_1
C/A
j_3
j_2
$m^{j_1}/m^{jet} < \mu_{frac}$
$m^{j_2}/m^{j_2^*} < \mu_{frac}$



$$R_{\rm filt} = \min[0.3, \frac{\Delta R_{j_1,j_2}}{2}, \frac{\Delta R_{j_1,j_3}}{2}, \frac{\Delta R_{j_2,j_3}}{2}]$$

$$m_{ab} = m_W(1 \pm 0.15) \quad (a, b = j_1, j_2, j_3)$$


ATLAS
$\int L\,dt$ = 4.7 fb^{-1}
$\sqrt{s}$ = 7 TeV
Data
$t\bar{t}$
Single top
W+jets
Multi-jets
Z+jets
Diboson
e + jets resolved
Events / 0.2 TeV
Data/Bkg
$m_{t\bar{t}}^{reco}$ [TeV]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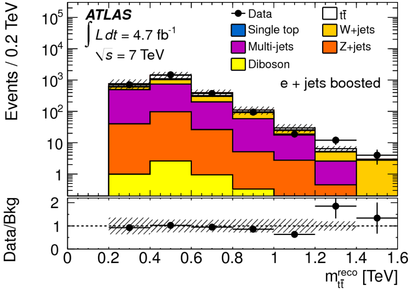
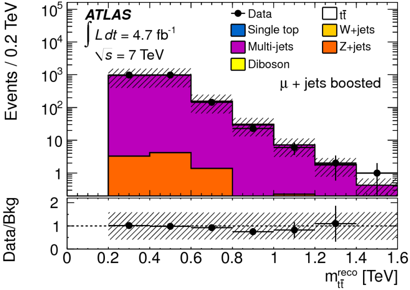
Data
$t\bar{t}$
Single top
W+jets
Multi-jets
Z+jets
Diboson
e + jets resolved
Events / 0.2 TeV
Data/Bkg
$m_{t\bar{t}}^{reco}$ [TeV]

l+jets
Backgrounds





Progress in top tagging: ATLAS-CONF-2013-084