ATLAS Progress in Boosted Top Quark Physics:
A first look at 13 TeV pp Colisions

Pekka K. Sinervo, FRSC
Department of Physics
University of Toronto

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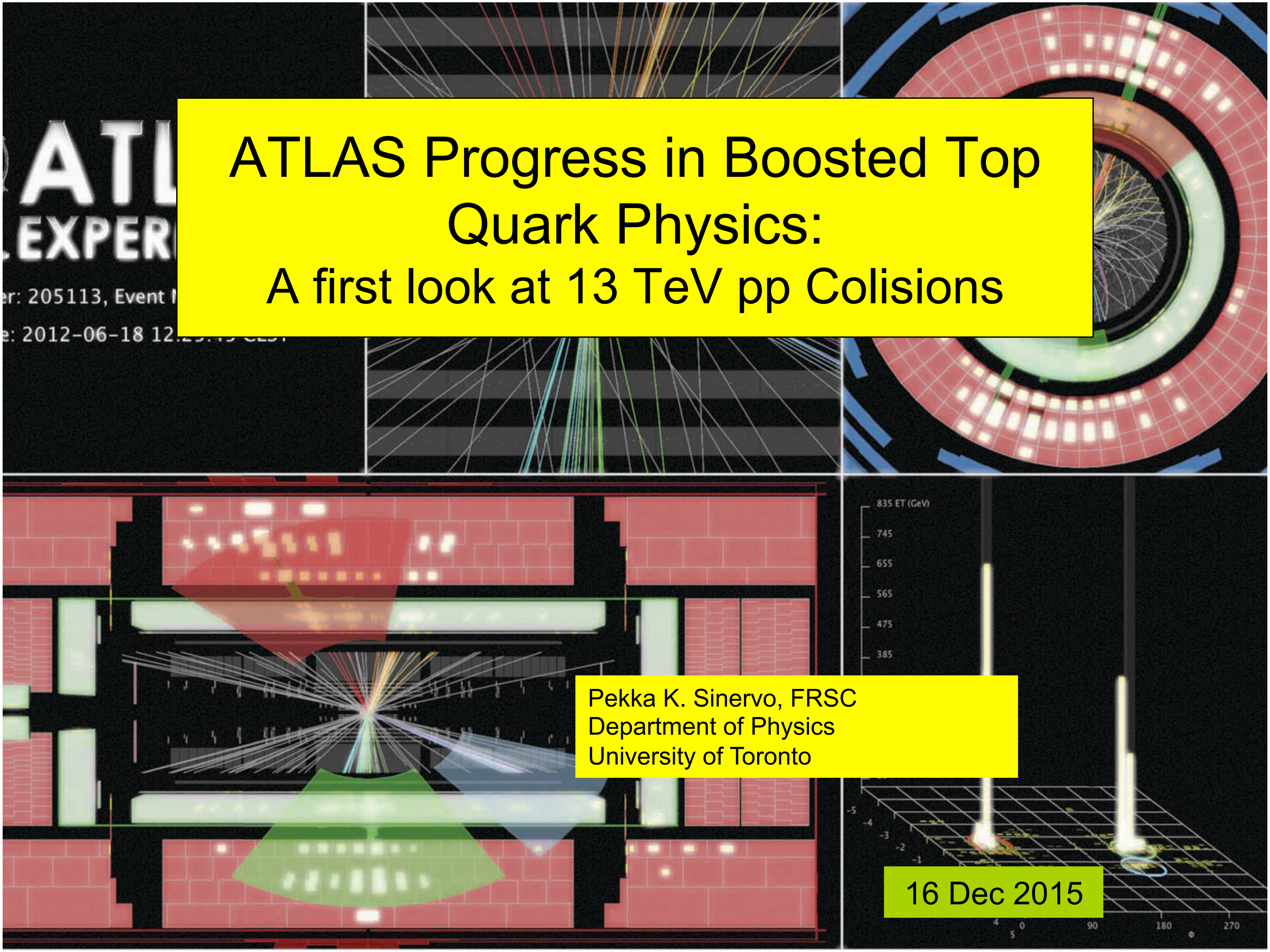
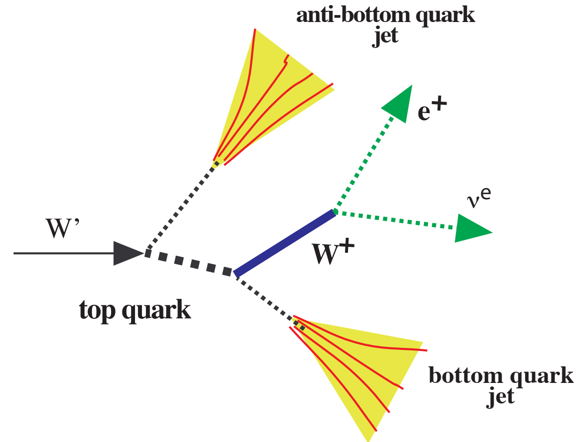


Outline

1. **Introduction to Boosted Top Quarks**
2. **Early Work**
3. **QCD and Top Jets**
4. **Top and Bottom Tagging Algorithms**
5. **Performance**
6. **Searches**
7. **Summary & Conclusions**



What Are Boosted Top Quarks?

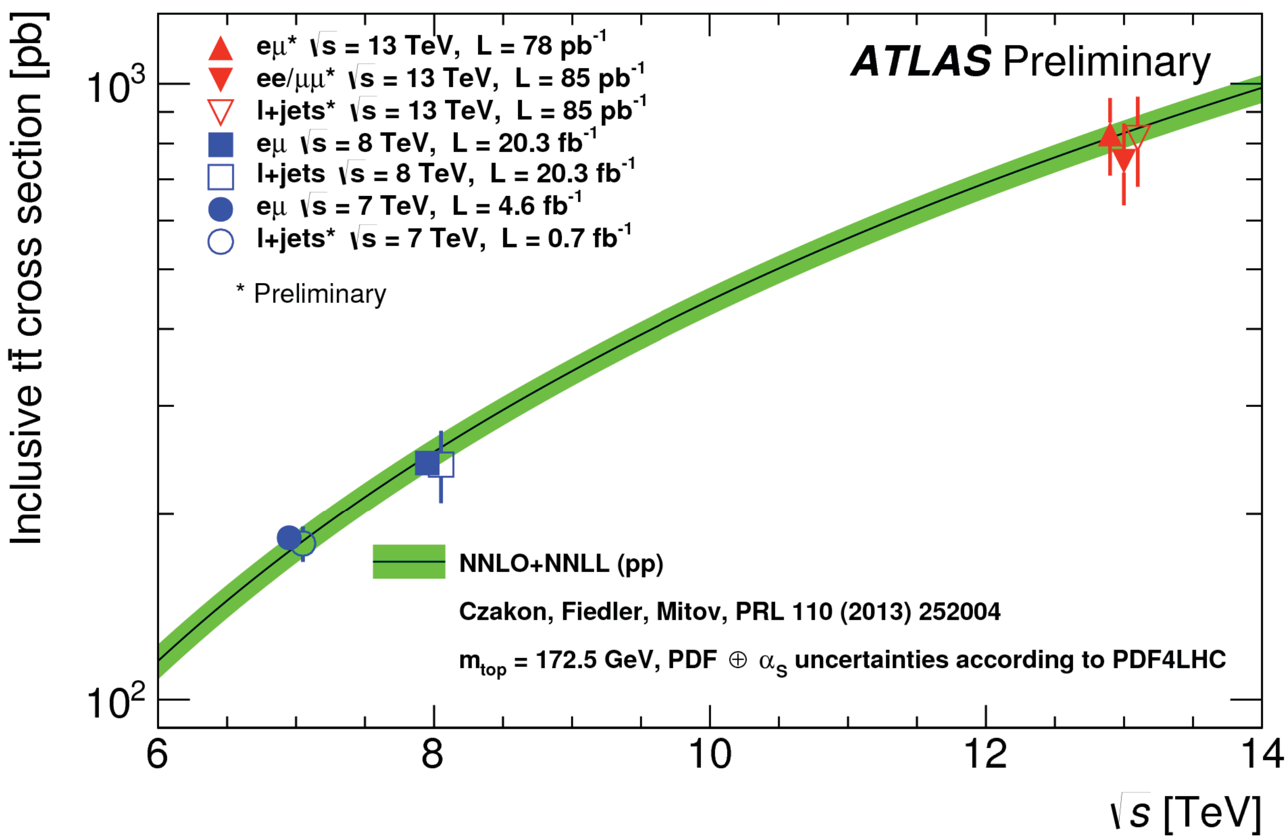
Top quark production is ubiquitous at LHC

- $\sigma = 749 \pm 57$ (stat) ± 79 (syst) ± 74 (lumi) pb

ATLAS-CONF-2015-049

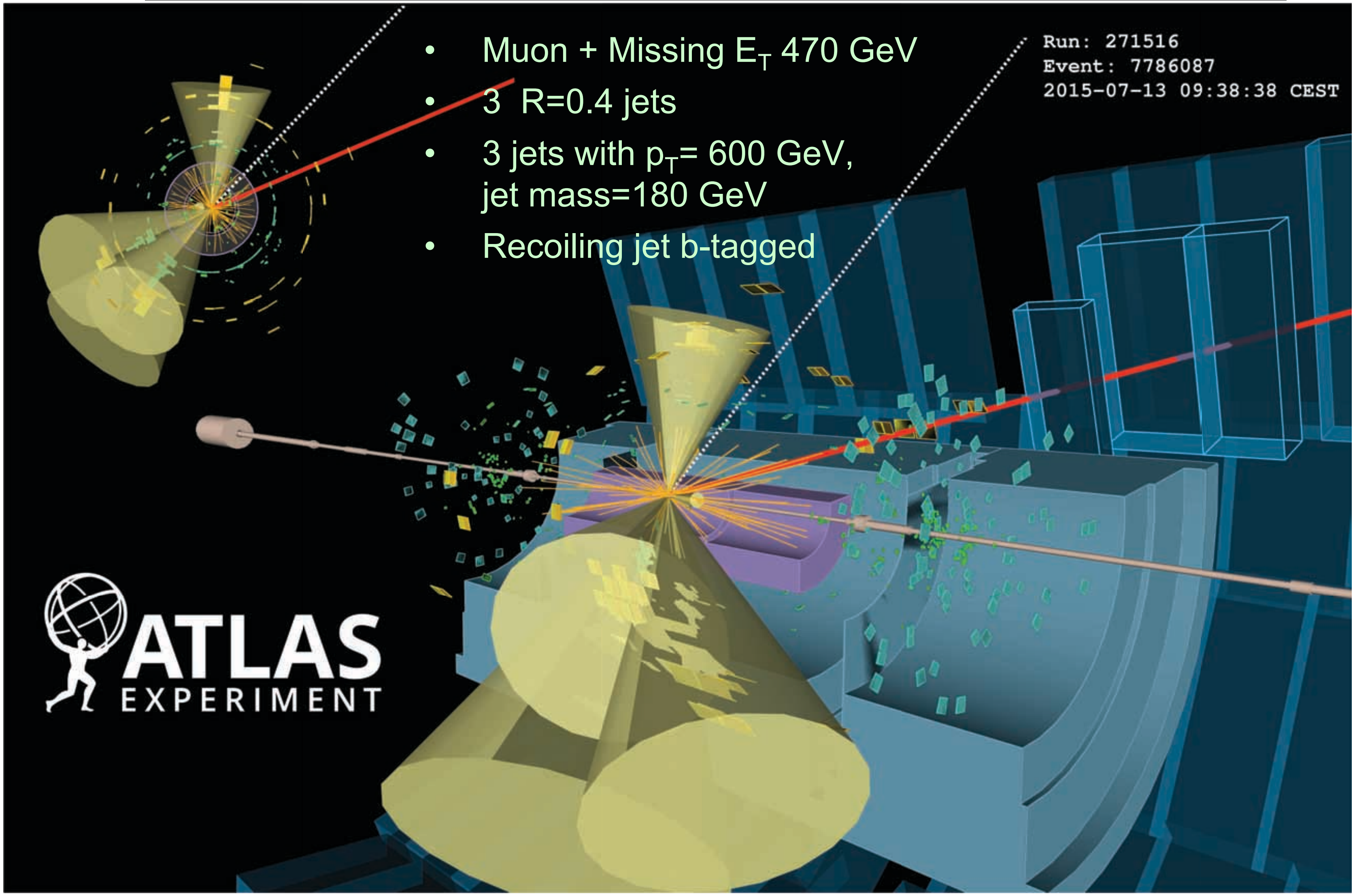
At 10^{34} cm^{-2} s^{-1}, this gives a top quark every few seconds

- But this is inclusive production
- All decay modes



Very high-P_T Tops are Rarer

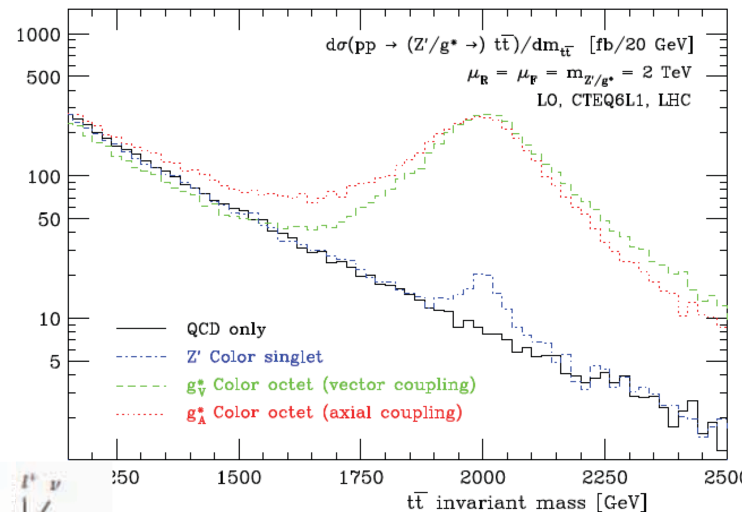
- Muon + Missing E_T 470 GeV
- 3 R=0.4 jets
- 3 jets with p_T= 600 GeV, jet mass=180 GeV
- Recoiling jet b-tagged



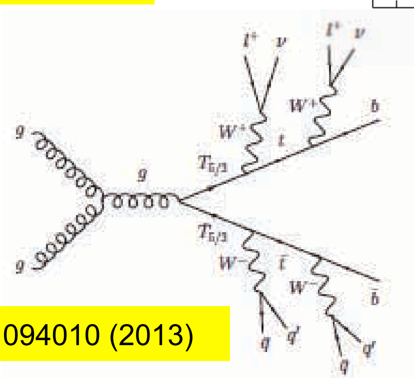
Why the Interest in Boosted Tops?

Top quarks play a special role in many models for new physics, eg.

- Couple to new force carriers
  - Leptophobic Z' preferentially decays to top quark pairs
    Rosner, PLB **387** (1996) 113
  - W' bosons could decay to t-b pair
- String-inspired resonances
  - Randall-Sundrum KK gluons/gravitons (g_{KK}, G_{KK}) favourite "wide" resonance
    Agashe et al., PRD **77**, 015003 (2008) ; Lillie et al., JHEP **09** (2007) 074
- New phenomena
  - Vector-like top quark partners
  - Supersymmetric top partners



Fredrerix & Maltonii, JHEP **01** (2009) 047



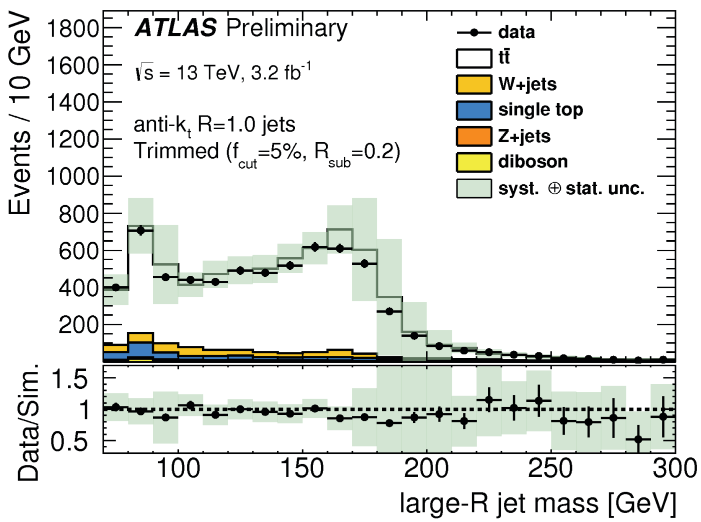
Agular-Saavedra et al, PRD **88**, 094010 (2013)

Strategies for Detection

Two strategies for detecting boosted tops

Top p_T > 300 GeV

1. Use semi-leptonic top quark decays and b-tagging
   - Branching ratios are small
   - Lepton ID is a limiting factor
2. Use fully-hadronic decays
   - Detect top quarks through jet substructure
   - Use b-tagging for additional rejection
   - Background calculations are difficult



ATLAS-JETM-2015-004

I'll focus on the second

- In practice, largest BR (2/3)
- Provides avenue to better understand QCD jet physics
- Not a new idea!

Long list of references….

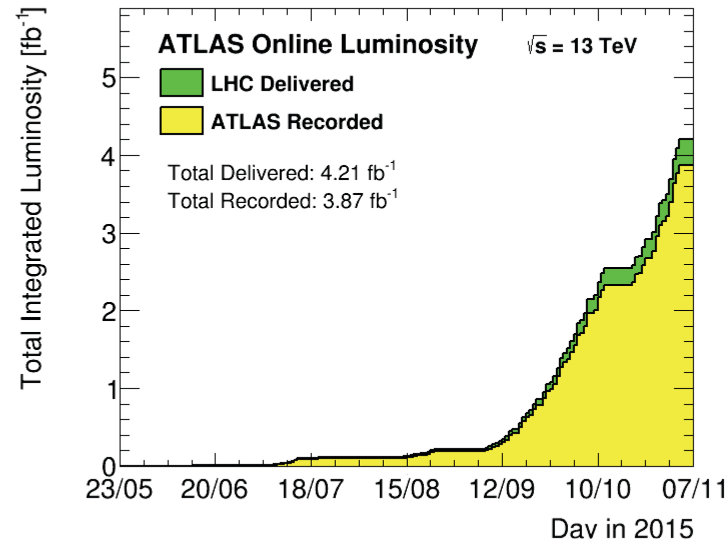
LHC Data Samples

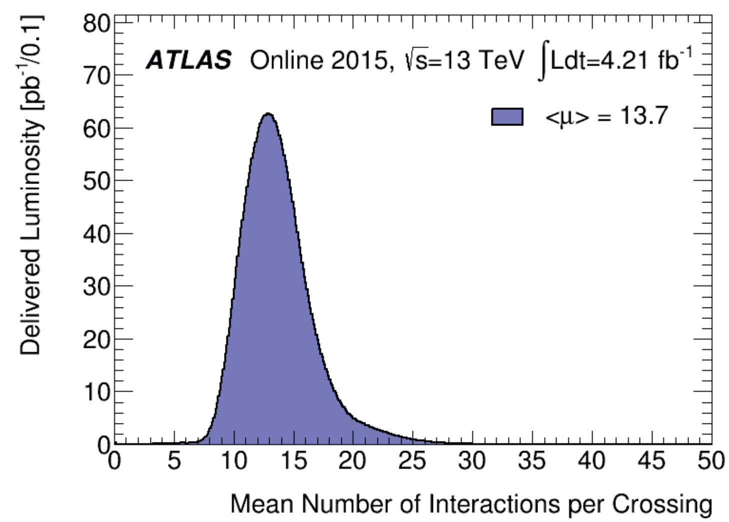
LHC has run very well

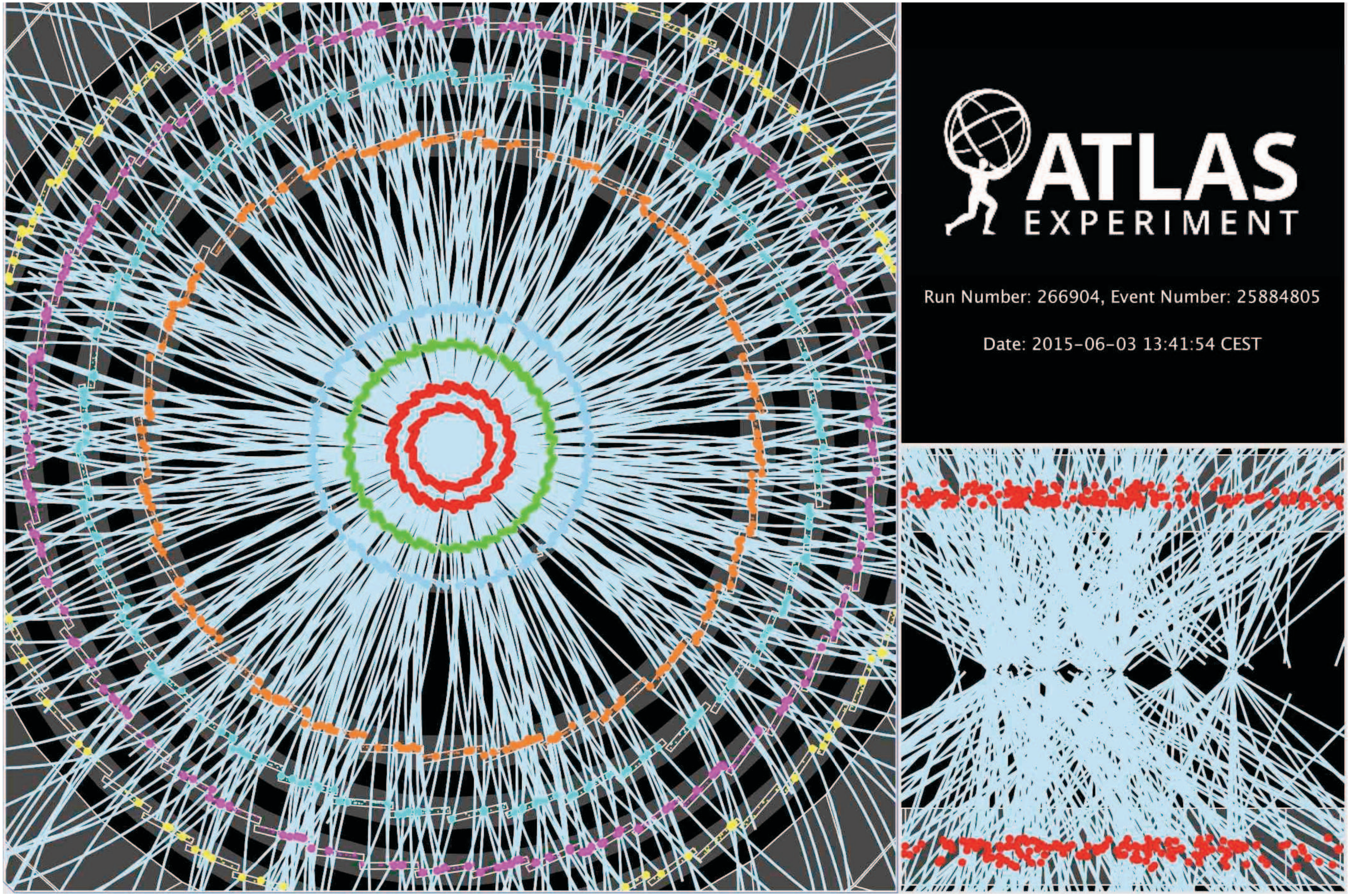
- Have ~5 fb^{-1} sample at 7 TeV (2011)
- Have ~20 fb^{-1} sample at 8 TeV (2012)
- Have 3.9 fb^{-1} sample at 13 TeV (2015)

These data samples have enabled detailed jet and E_T^{miss} reconstruction

- Pileup conditions similar to 2012

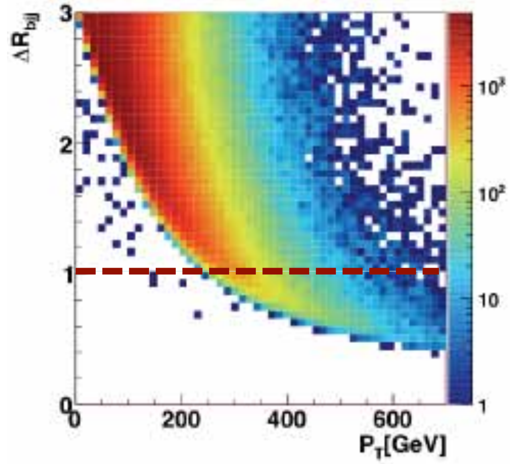






We believe there were 17 collisions…

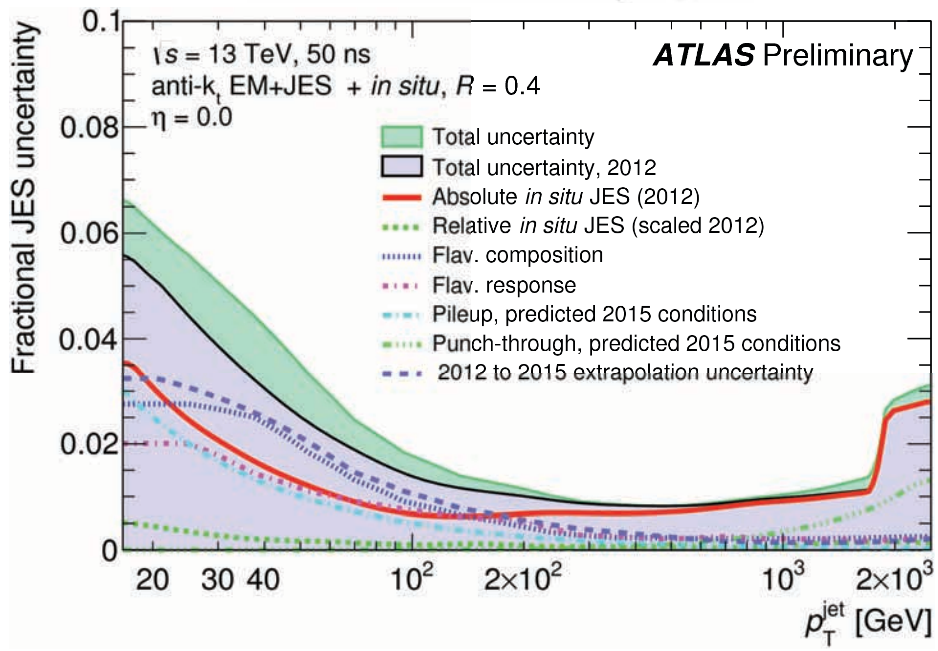
LHC “Fat Jets”



Jet reconstruction

- Use Anti-kt jet algorithm
  - For these studies, using R=1.0 to capture top decay products
- Employ some form of jet “grooming” to address pile-up
- Calibrate energy and mass scales using standard tools

ATLAS-PUB-2015-015



Addressing Pile-Up

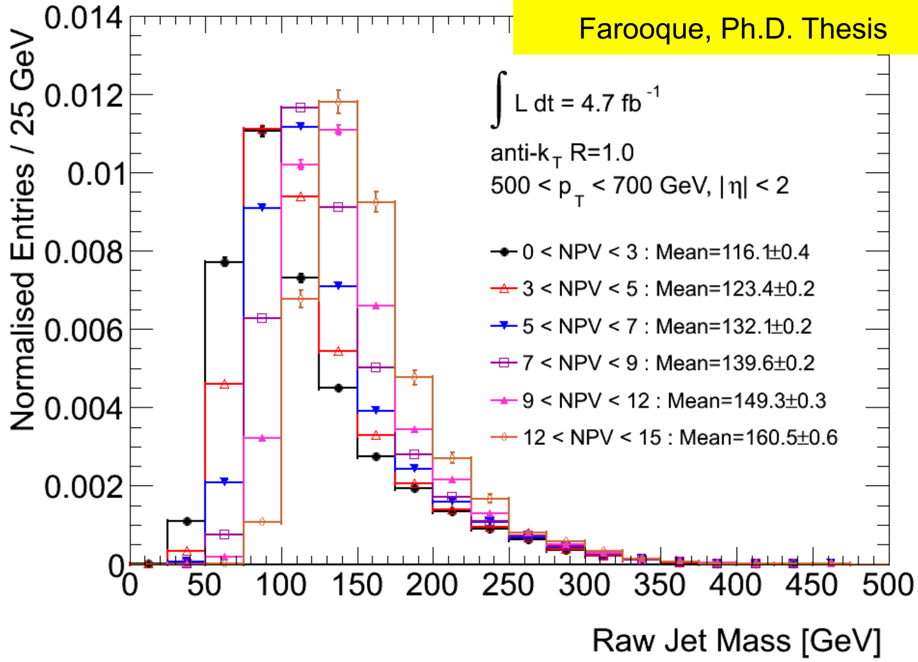
Jets are extended objects

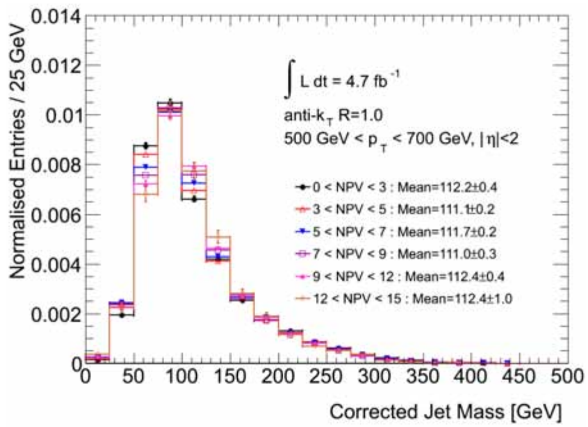
- Contributions from additional interactions have significant effect on observed properties

Various strategies to address

- Correct with average calibration
  - Only used at Tevatron, and never on jet substructure
- Correct event-by-event
  - Works OK but cumbersome
- Can "cut-out" pile-up contributions
  - This is method of choice
  - Requires careful calibration

Farooque, Ph.D. Thesis

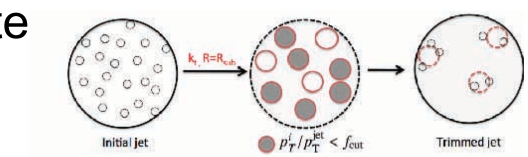




Jet Trimming

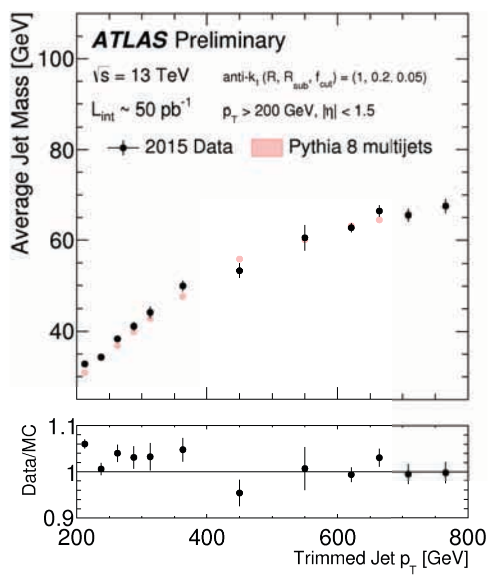
Approach is jet “trimming”

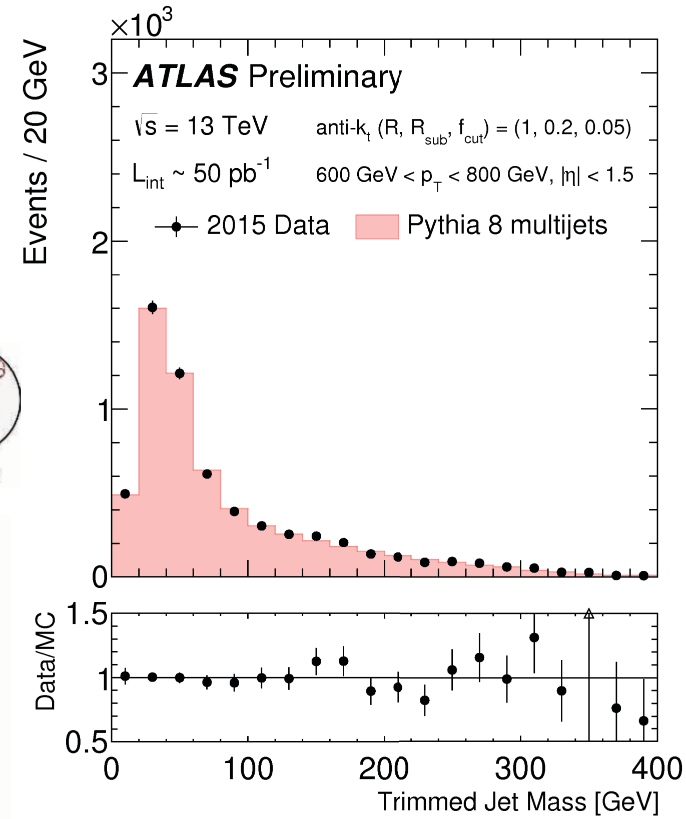
- Anti-kT cluster with R=1.0 – $p_T^{R1.0}$
- Anti-kT cluster constituents into R=0.2 “subjets”
- Keep subjets with pT > 0.05 $p_T^{R1.0}$
- Recombine and re-calibrate



Takes care of pile-up

- But also “suppresses” Sudakov peak
- Rises slowly with jet p_T
- Implications for very high pT jets





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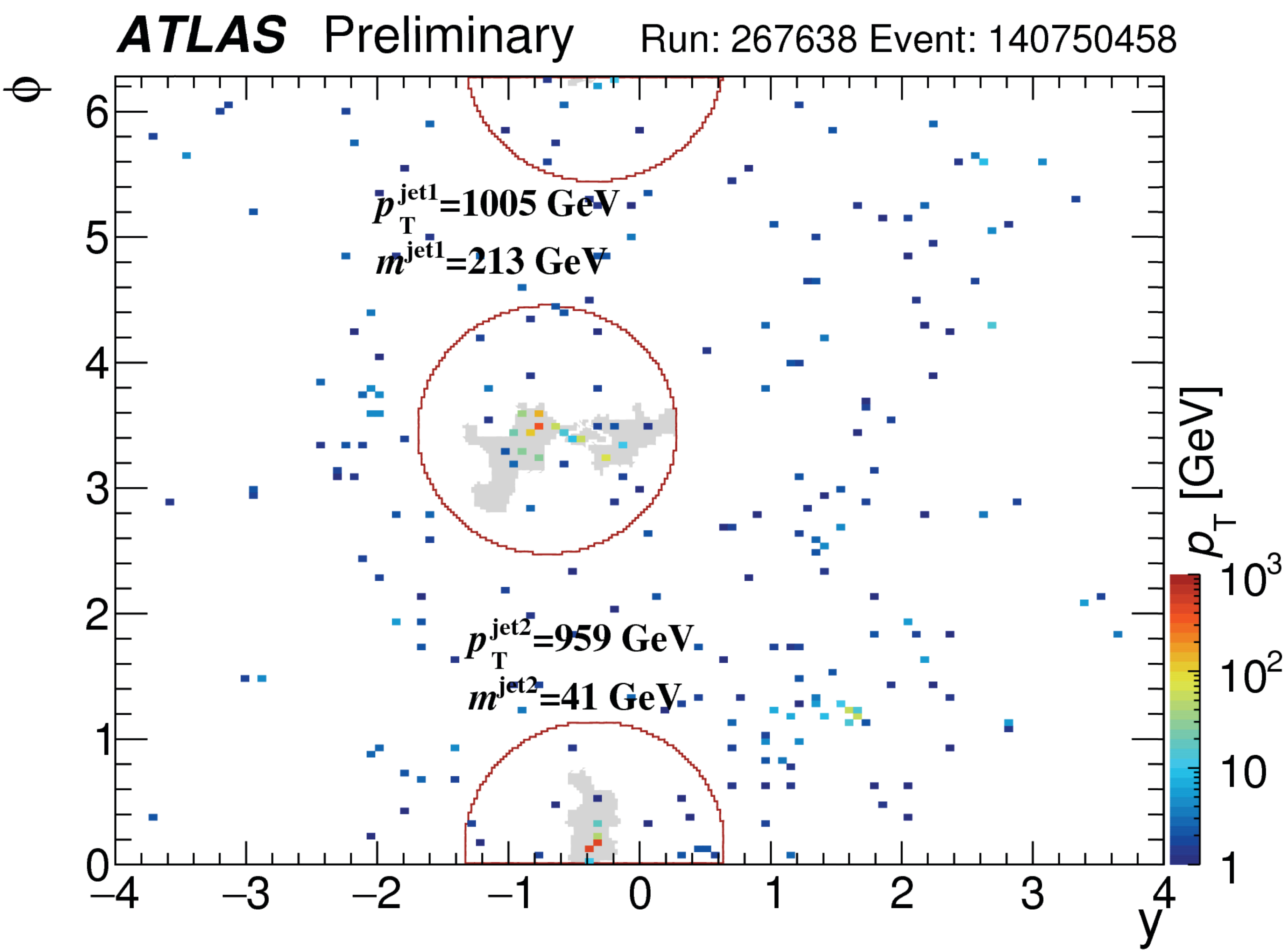

ATLAS Preliminary
Run: 267638 Event: 140750458
p_T^{jet1}=1005 GeV
m^{jet1}=213 GeV
p_T^{jet2}=959 GeV
m^{jet2}=41 GeV
φ
y
p_T [GeV]

Jet Mass Isn't Everything

Top decays have 3-prong kinematics

- Light quark and gluon jets with high mass largely result from single gluon emission

$$\tau_3 = \frac{1}{d_0}\sum_{k=1}^{3} p_{Tk} \times \min(\delta_{1k},\delta_{2k},\delta_{3k})$$

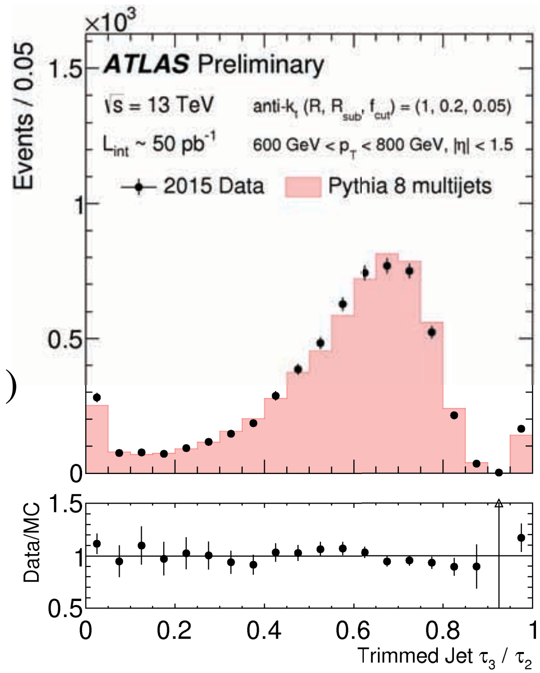
$$\tau_2 = \frac{1}{d_0}\sum_{k=1}^{2} p_{Tk} \times \min(\delta_{1k},\delta_{2k})$$

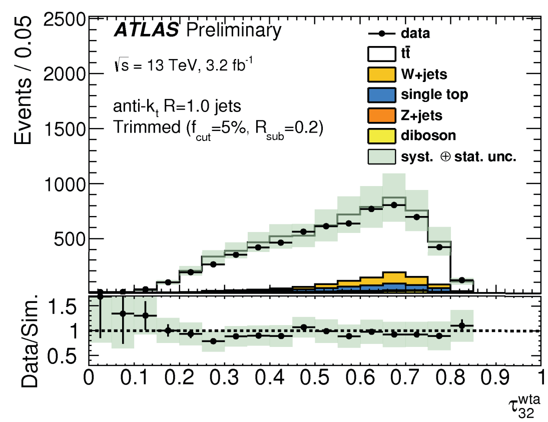
$$d_0 = \sum_{k=1}^{3} p_{Tk} \times R$$

Many strategies have been considered

- Eight algorithms compared in ATLAS-CONF-2015-036
  - HEPTopTagger was considered superior
  - But has large systematic uncertainties
- Taken a simpler approach for "top-tagger"
  - N-subjettiness measure

Thaler & van Tilburg, JHEP 03 (2011) 015; JHEP 02 (2012) 093

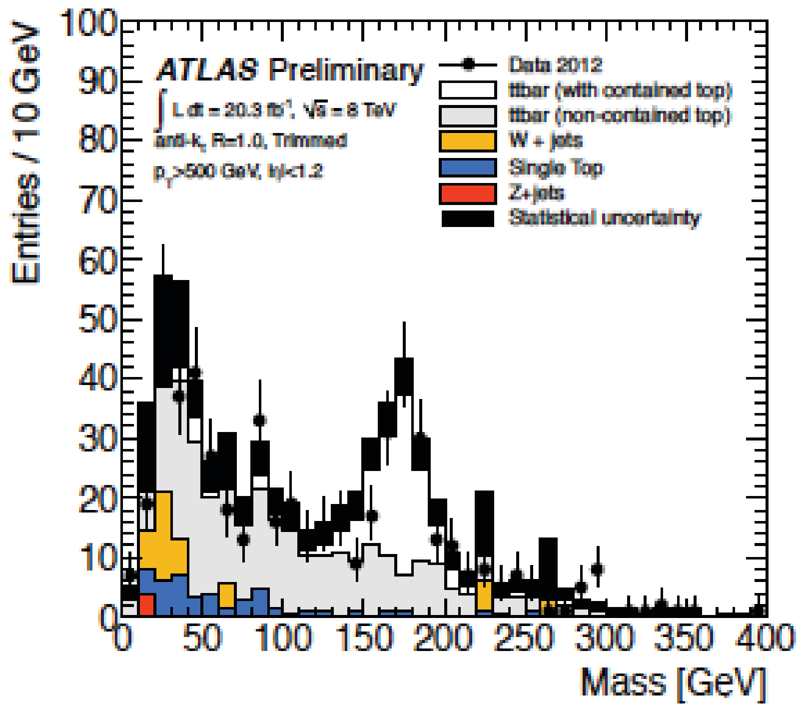




Aside: Trimming Cuts Out QCD Too

Trimming removes part of the QCD jet as well

- Current parameters f_{cut}=0.05 and R_{sub}=0.2 remove 100 GeV subjet for a 1 TeV object!
  - What are the “correct” parameters?
- Requires that we believe in our fragmentation models in order to calibrate correctly
- Also are competing schemes for this
  - Mass-drop
  - C/A clustering

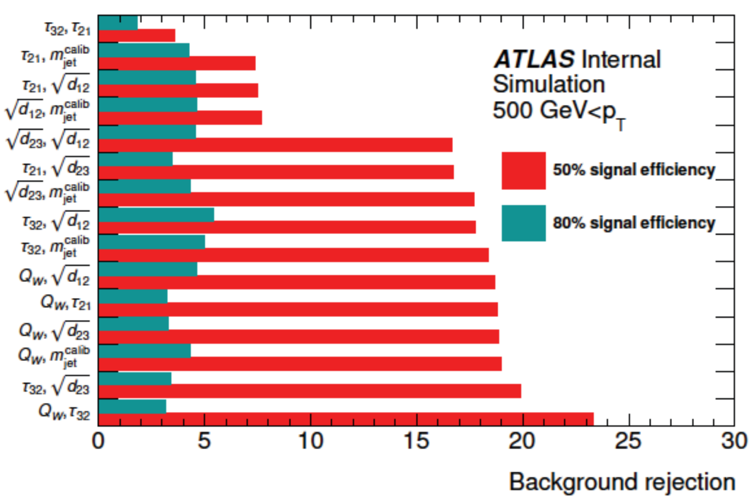


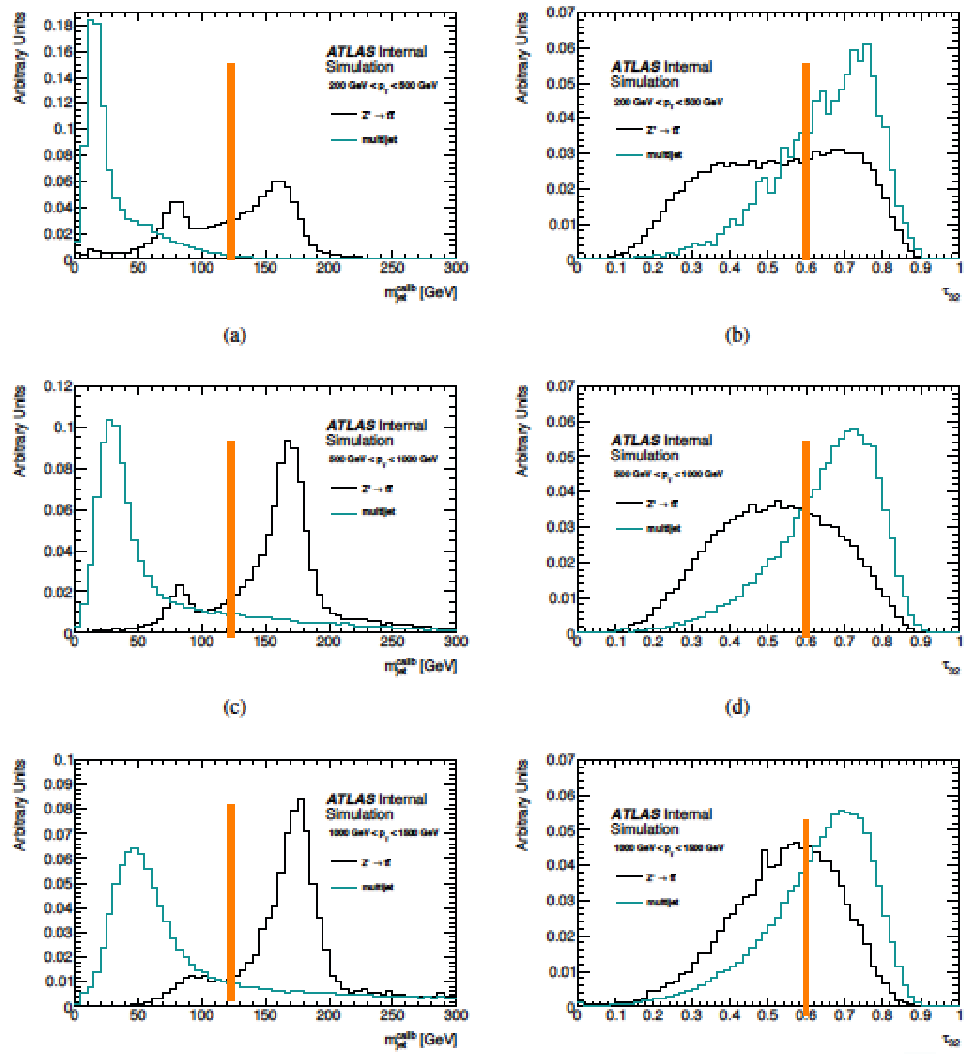
Current Choice of Algorithms

Looked at algorithm with 2 variables:

Optimitized for jets with p_T > 500 GeV,

- M_{jet} > 125 GeV
- τ_{32} > 0.58





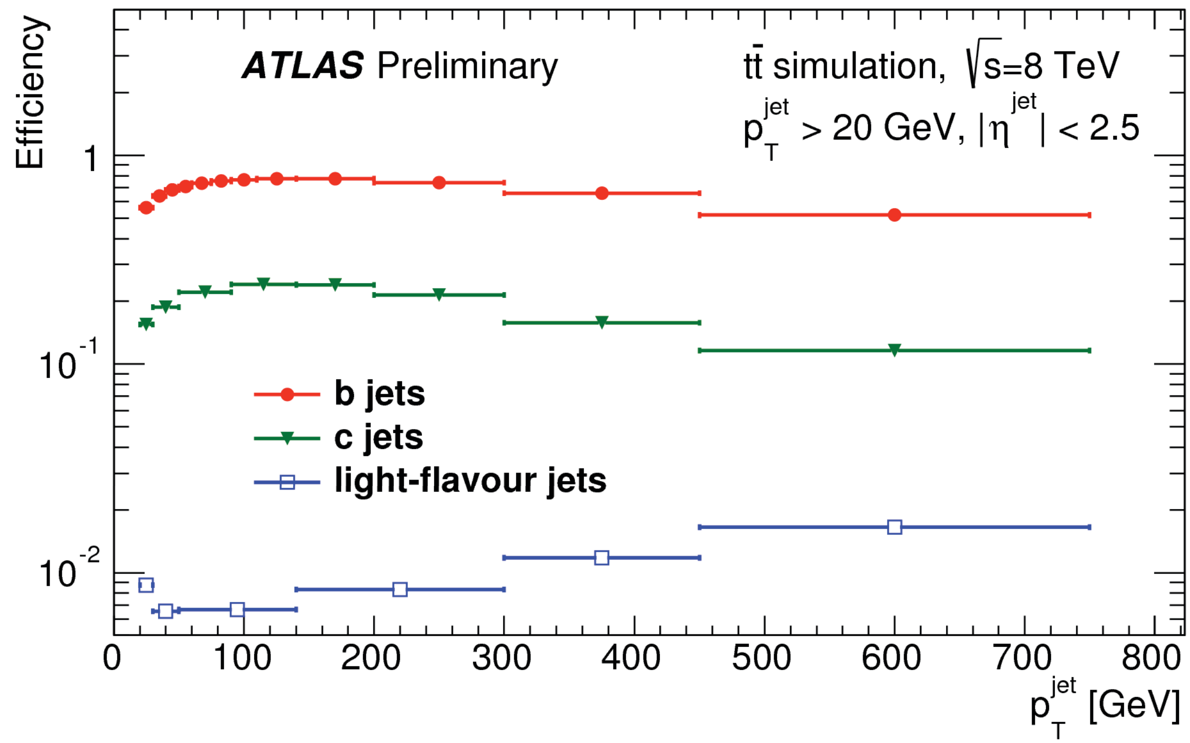
B Tagging Algorithms

ATLAS uses a multivariate algorithm to tag "b-jets"

- Combination of tracking, vertex and kinematic information
- Usual operating point of 70% efficiency, <1 % mistag rate

- Require that R=0.4 b-tagged jet be associated with top quark jet

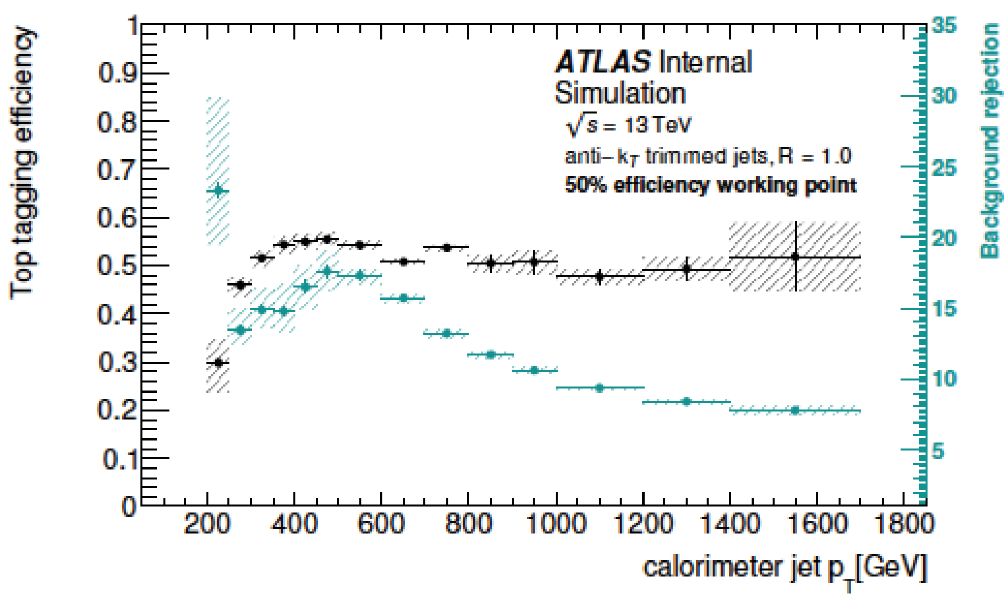
Essential element of tagging strategy



A 13 TeV Top Tagger

Put together top-tagging and b-tagging

- Require two R=1.0 jets
  - p_{T1} > 500 GeV and p_{T2} > 450 GeV
  - Require both are top-tagged
  - Require both have R=0.4 subjet that is b-tagged



Three 13 TeV analyses underway

- Two searches for resonance structure in m_{tt}
- Measure differential cross section for boosted top quarks

Results not yet public

- Expect to be dominated by SM top quark production
- Forms the irreducible bkgd

Searches for X->ttbar or VV

Various theories beyond the SM predict resonance states

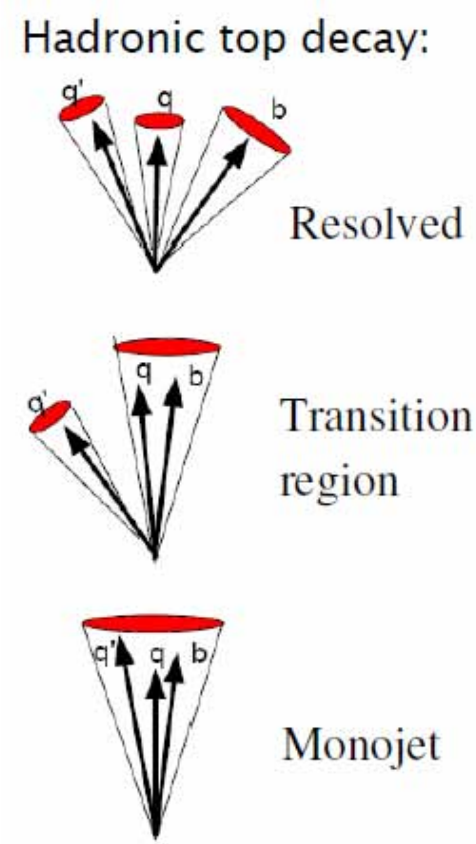
- Masses > 0.5 TeV with widths ranging from 1-2% to 10-20%
- Decay preferentially to ttbar or VV final states

Two “benchmark” scenarios have been used

- A narrow Top Colour Z’ boson (Γ/m = 1.2%)
- A broader Kaluza-Klein excitation of gluon (Γ/m = 17%)
- Experimental mass resolution is about 10%

Lead to top-quark pair final states characterized by high-p_T, “boosted” top quarks or vector bosons

- p_T of daughter determines signature for hadronic top decays
- Searches have used “lepton+jets” with boosted topologies and fully hadronic boosted searches

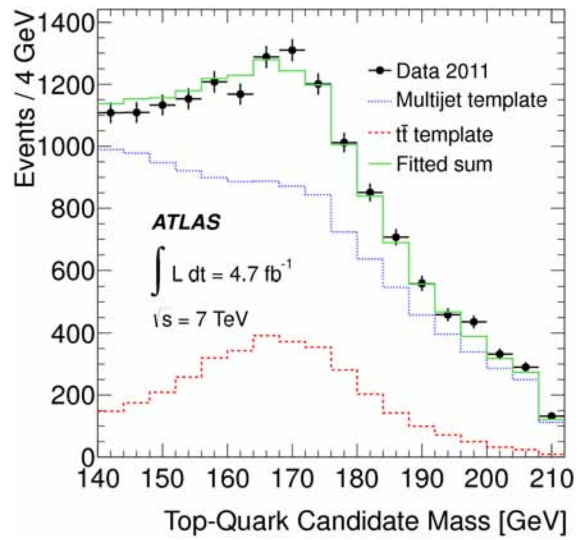


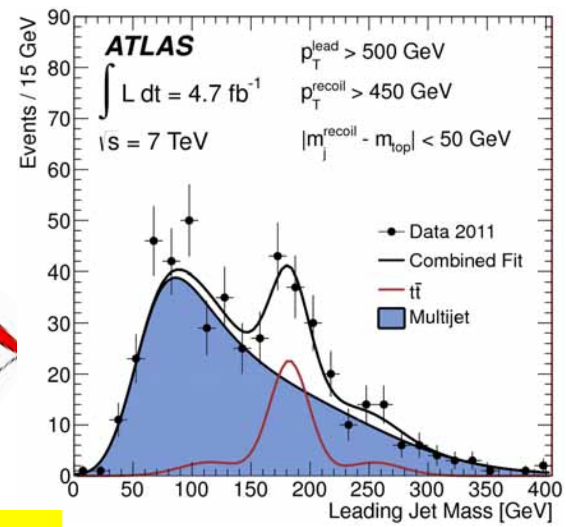
ATLAS Boosted Hadronic Search (I)

ATLAS implemented several top-tagging techniques in 7 TeV pp data

ATLAS, JHEP 01 (2013) 116

1. HEPTopTagger
   - Two CA jets with D=1.5, p_T>200 GeV and |η|<2.5, split into sub-jets (up to five retained)
   - Reclustered into three sub-jets required to be consistent with top quark (140 < m_{jet} < 210 GeV)
   - Require a D=0.4 anti-k_T cluster to be b-tagged
2. Top Template Tagger
   - Two anti-k_T jets with D=1.0, p_T>450 GeV and |η|<2.0, leading jet p_T>500 GeV
   - Require jet to be consistent with top quark through "template overlap" technique
   - Require a D=0.4 anti-k_T cluster to be b-tagged





Multijet backgrounds estimated from data

- Limited by SM ttbar background

Almeida, Lee, Perez, Sterman, Sung, PRD 82, 054034 (2010)

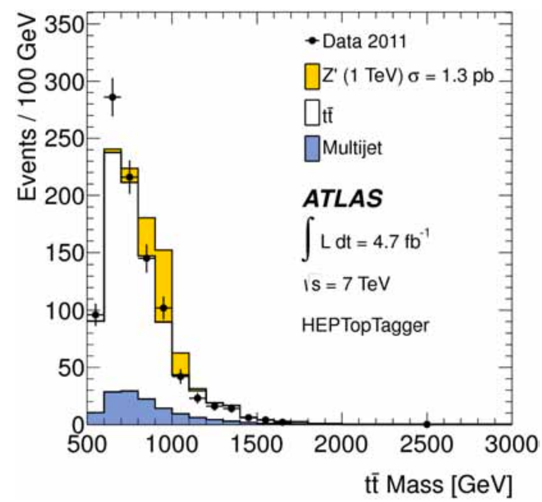
ATLAS Boosted Hadronic Search (II)

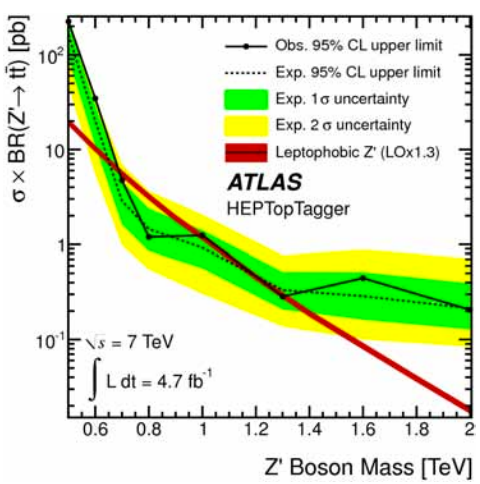
Backgrounds estimated using data-driven and MC calculations

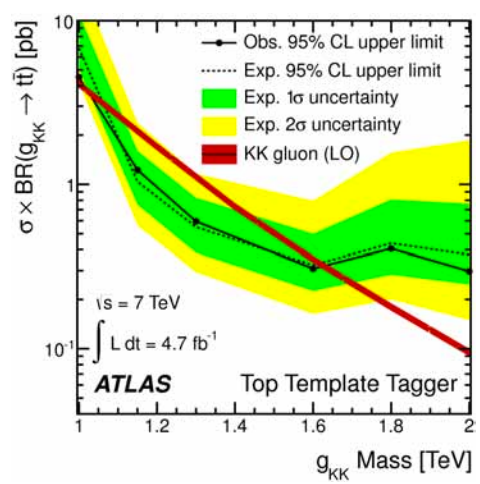
- Multijet backgrounds estimated by mistag rates
- SM ttbar estimated with MC@NLO+HERWIG showers

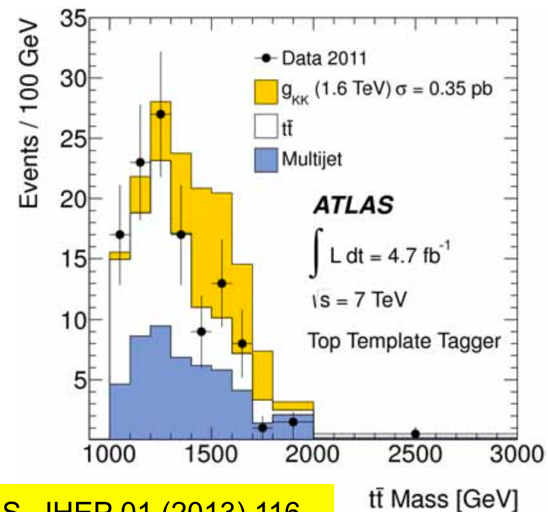
Estimate systematic uncertainties

- Set 95% CL limits using Bayesian calculation









$$M_{Z'} > 1.32 \text{ TeV for } \Gamma / M = 1.2\%$$
$$M_{gKK} > 1.62 \text{ TeV}$$

ATLAS, JHEP 01 (2013) 116

ATLAS Boosted l+jets Search (I)

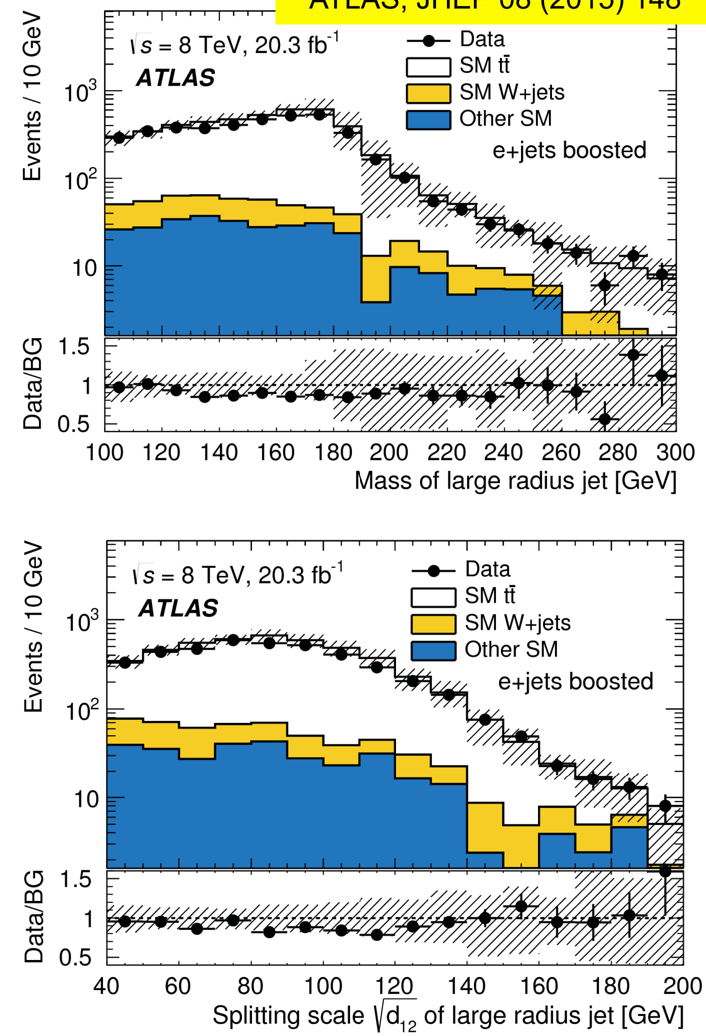
Searched in 20.3 fb^{-1} of 8 TeV data using lepton+jets channel with 2 analyses

1. Boosted analysis:
   - Isolated e candidate with p_T>25 GeV and $|\eta|$<2.47 with E_T^{miss}>30 GeV and m_T>30 GeV
   - Isolated μ candidate p_T>25 GeV and $|\eta|$<2.5, with E_T^{miss}>20 GeV and $E_T^{miss}+m_T$>60 GeV
   - ≥ 1 R=0.4 jet with p_T>25 GeV and $|\eta|$<2.5
   - 1 R=1.0 jet with p_T>300 GeV and $|\eta|$<2.0
     - Must also have 1st k_T splitting scale $(d_{12})^{0.5}$ > 40 GeV and m_{jet} > 100 GeV
2. Resolved analysis:
   - Same lepton requirements
   - 3 or 4 R=0.4 jets with p_T>25 GeV and $|\eta|$<2.5
     - If only 3 jets, one must have m_{jet}>60 GeV

Require at least one b-tagged jet

- Limited by SM ttbar background

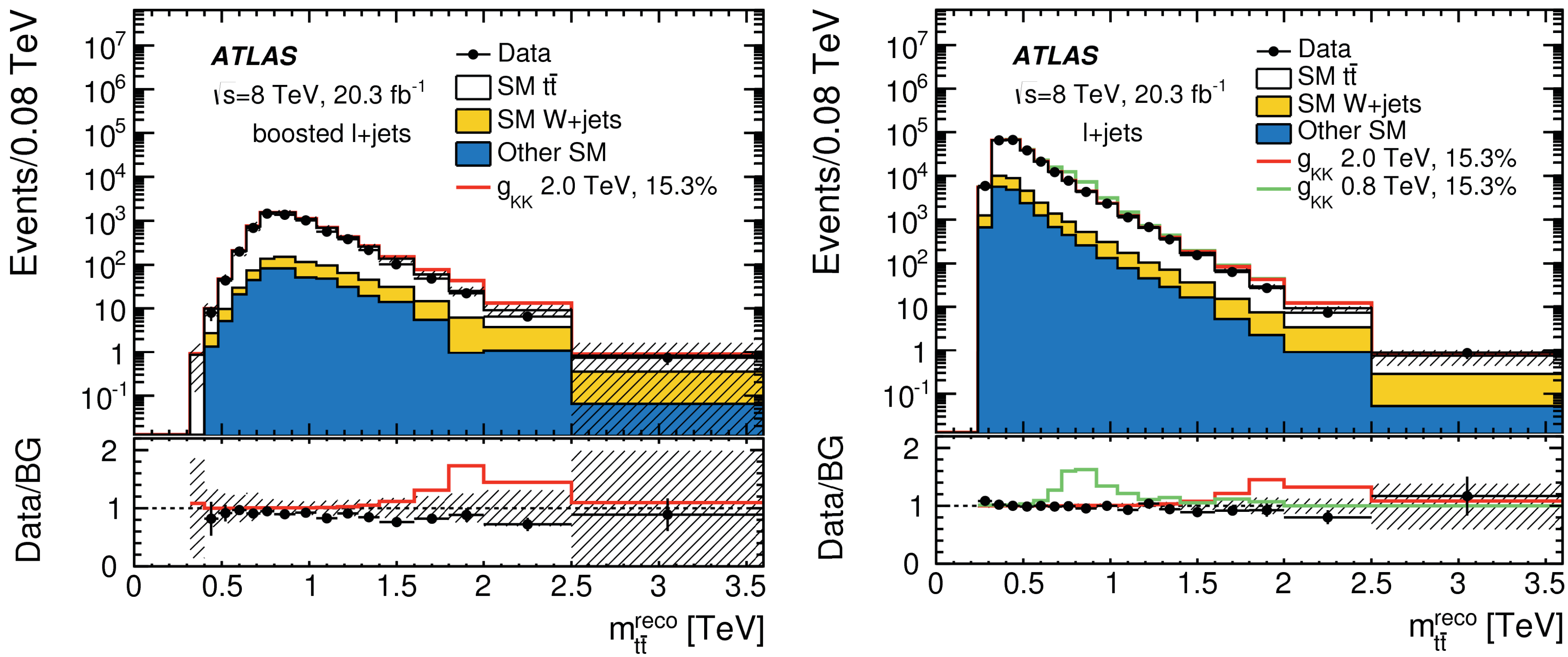
ATLAS, JHEP 08 (2015) 148



ATLAS Boosted l+jets Search (II)

Backgrounds estimated from MC

- Show both the boosted analysis, and all summed together



ATLAS, JHEP 08 (2015) 148

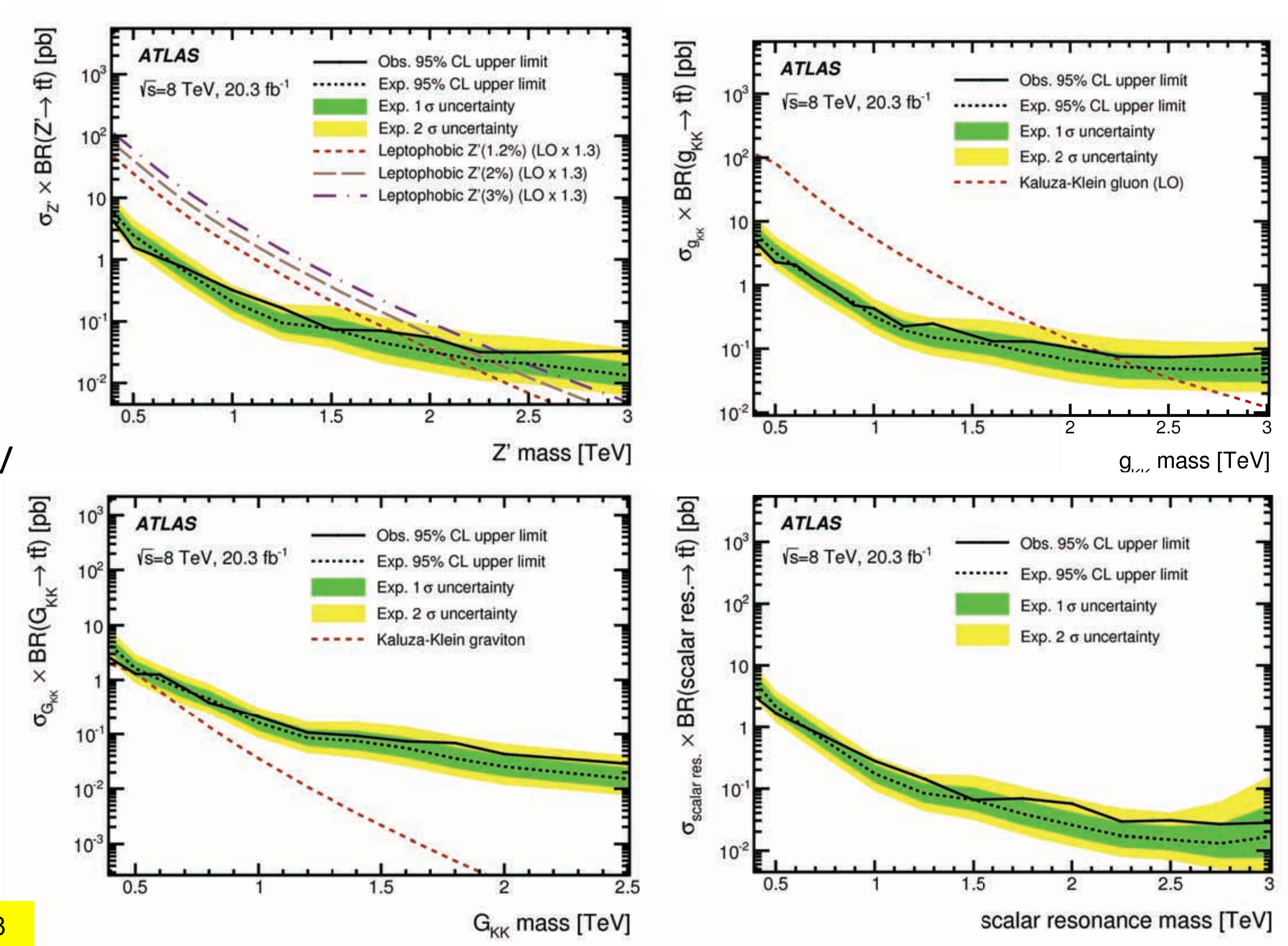
ATLAS Boosted l+jets Search (III)

95% CL limits:

Exclude

$0.4 < M_{Z'} < 1.8$ TeV

$0.4 < M_{gKK} < 2.2$ TeV

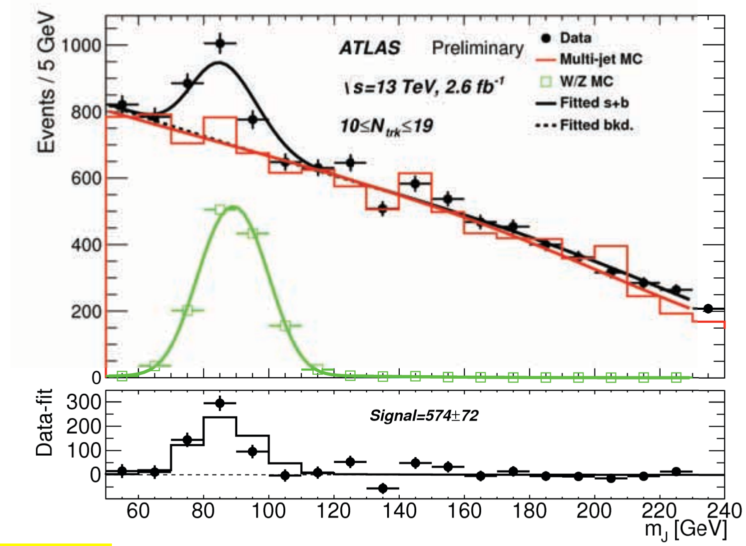


ATLAS, JHEP 08 (2015) 148

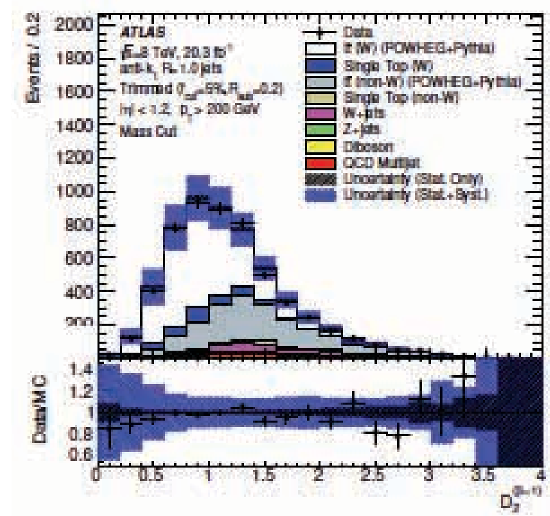
Boosted WW/WZ/ZZ Search

New analysis searching for boosted W/Z's

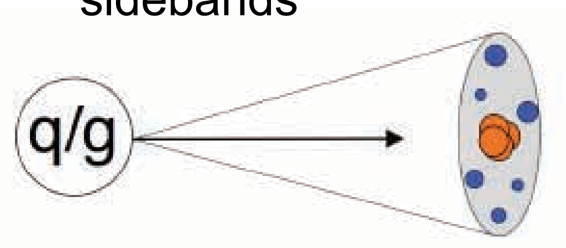
- Search for heavy object decaying to vector boson pair
- Look for pairs of fully hadronically-decaying Ws and Zs
- Differences with top-tagging:
  - Use energy-correlation variable D_2
  - Mass window ±15 GeV around M_W and M_Z
  - Require Ntrk < 30
  - Set D_2 cut so that tag is 50% efficient

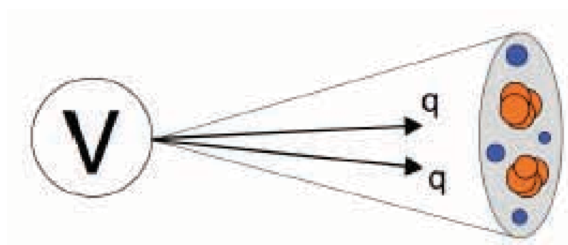


ATLAS-CONF-2015-073



Measure backgrounds using jet mass "sidebands"

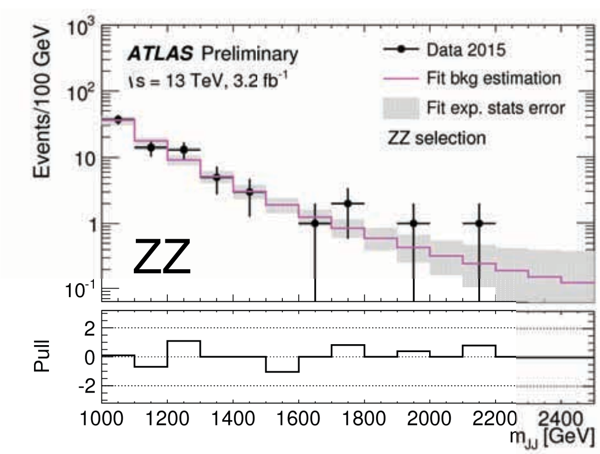


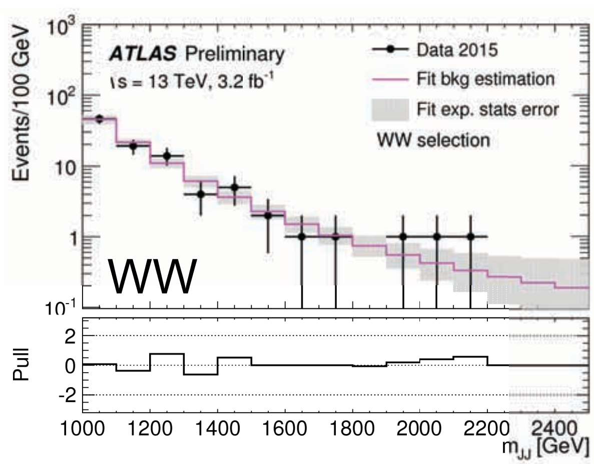


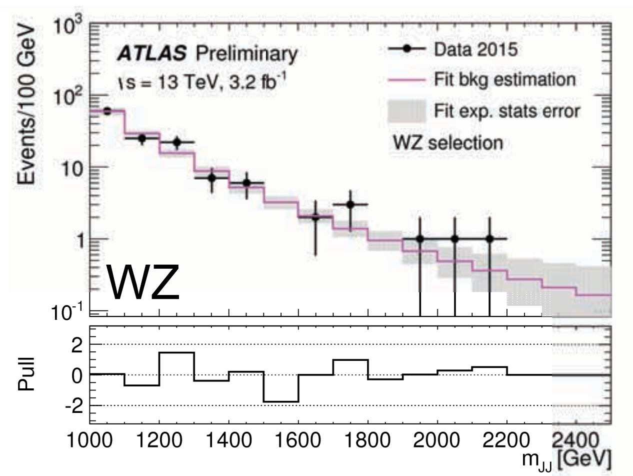
WW/WZ/ZZ Search Results (I)

Di-boson mass distributions show no evidence of resonance signal

- Use the data to set 95% CL limits
- Incorporate systematic uncertainties as Bayesian priors
- Compare with various models



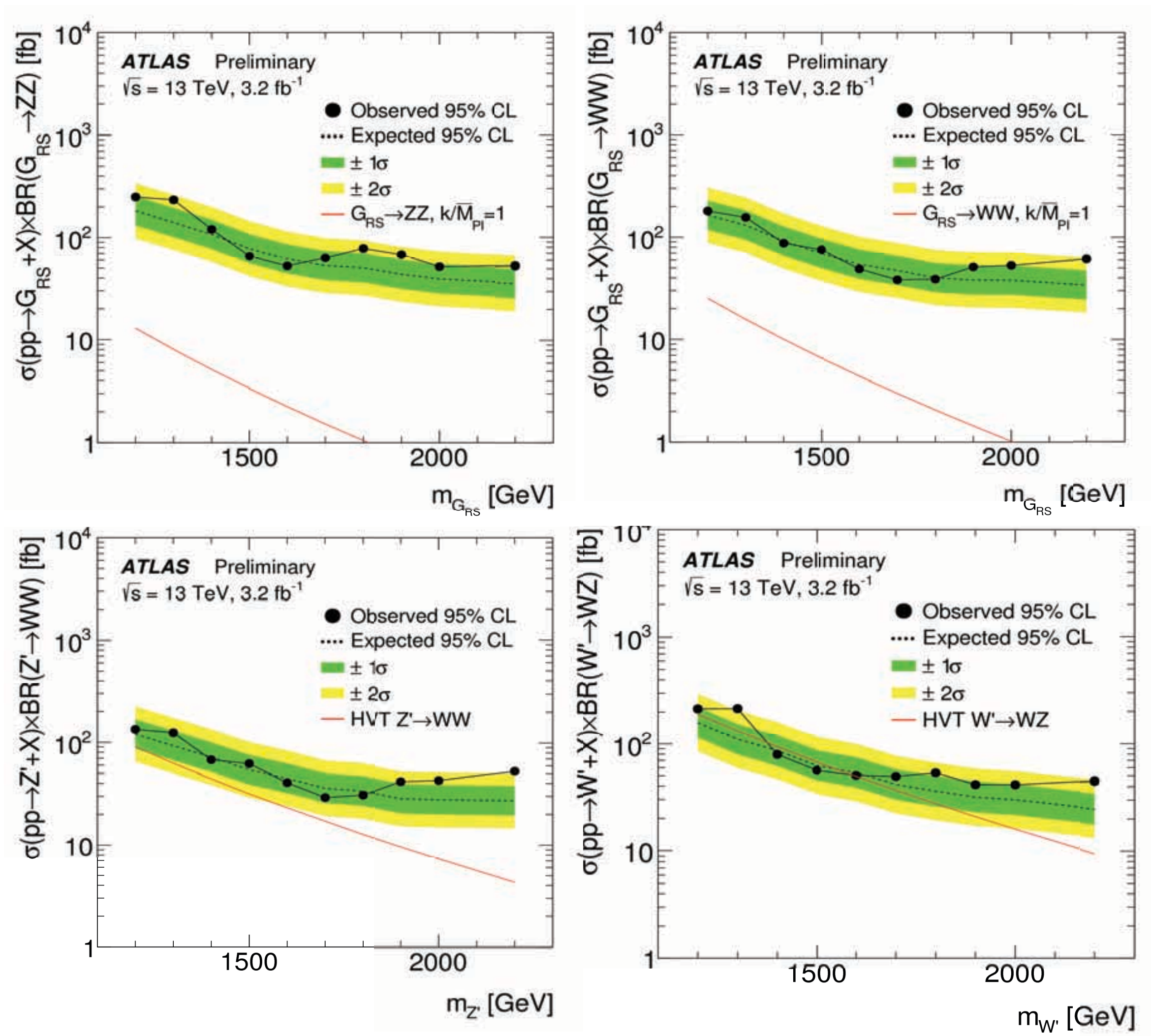




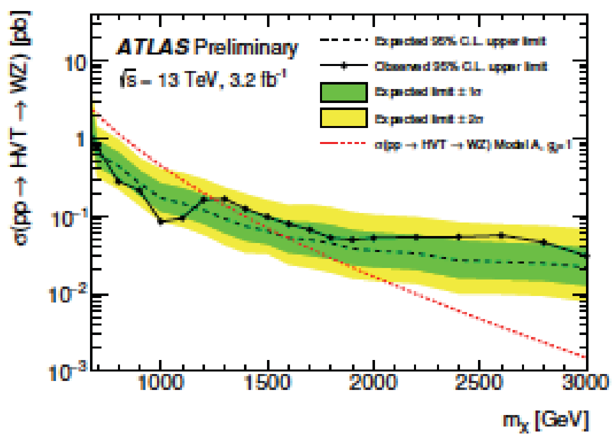
WW/WZ/ZZ Search Results (II)

Observed limits consistent with expected limits

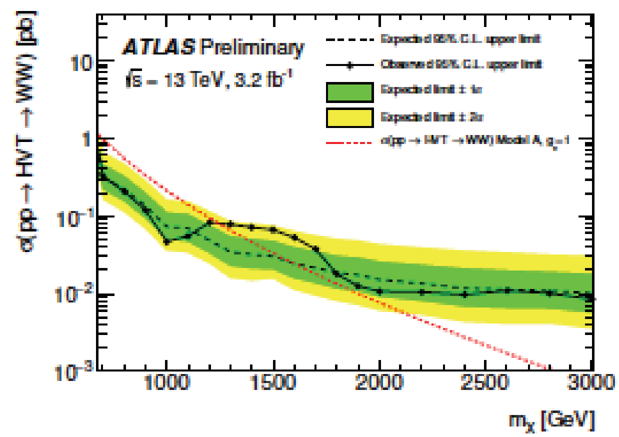
- Not sensitive to G_{KK} or HVT Z' production
- Can exclude W' → VV for $M_{W'}$ between 1.39 and 1.6 TeV
- ~20% more sensitive than lepton+jets (based on CL)



WW/WZ Search Results (III)



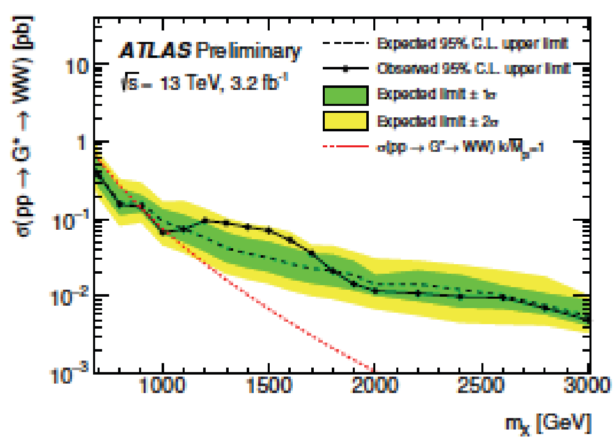
(a) $HVT \to WZ$



(b) $HVT \to WW$

Similar analysis with one W boson decaying leptonically

- Use similar boosted jet selection
- Standard lepton and E_T^{miss} selection
- Can exclude HVT → VV for M_X < 1.25 TeV, and G_{KK}→ VV for M_X < 1.06 TeV



(c) $G \to WW$

Summary and Conclusions

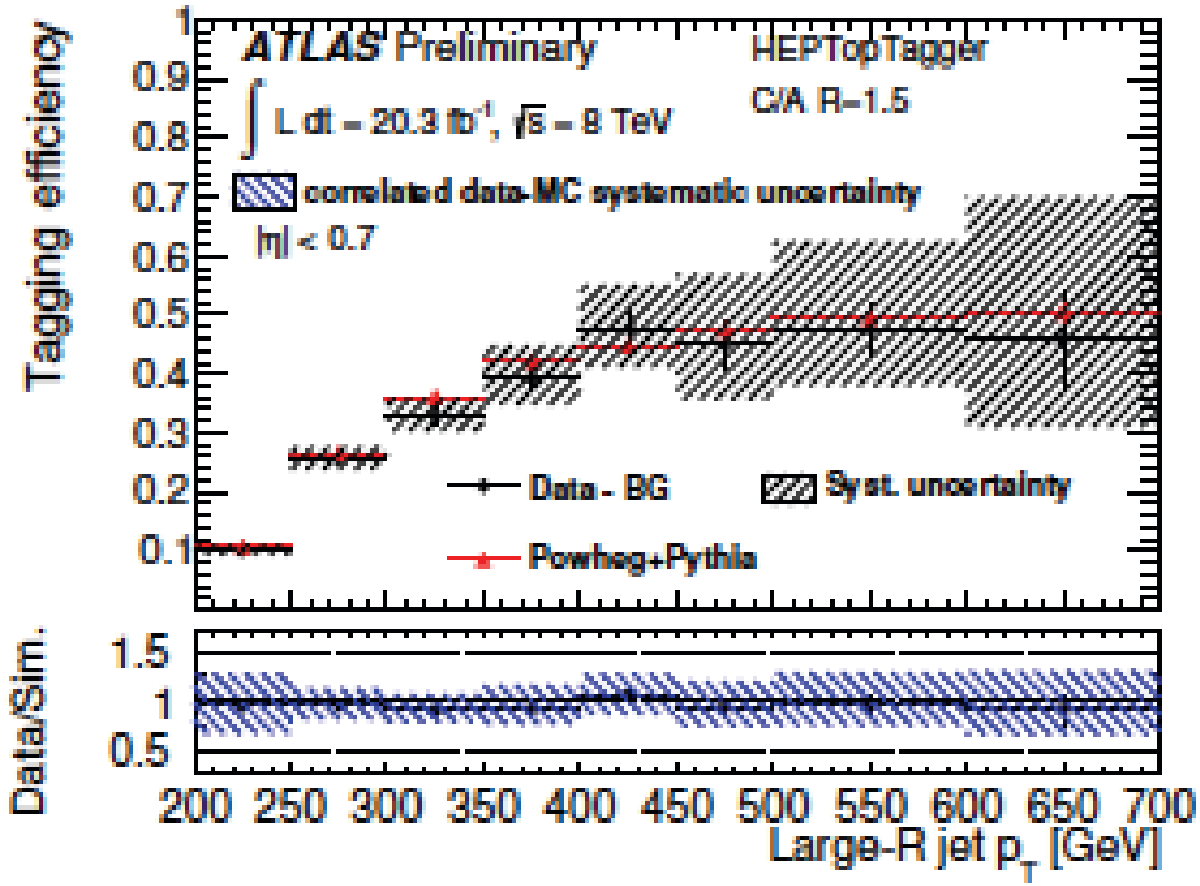
Boosted top quarks are now becoming a standard "tagged" object

- Can measure SM production of high-p_T top quark production
- Extend searches for new phenomena up to the 2-3 TeV range
- Has taught us much about QCD jets
- Applying same strategies to detect boosted W's and Z's – competitive approach

We can look forward to increasingly sensitive searches over the coming year

"Boost" has a very significant Israeli heritage!

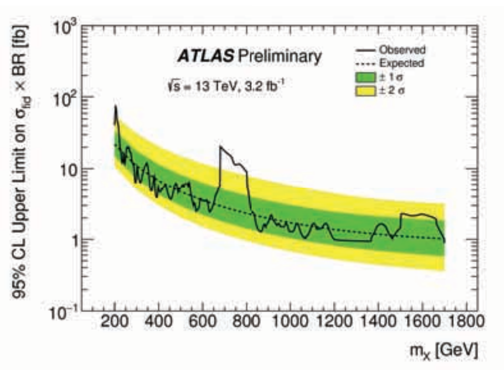
Backup HEPTopTagger

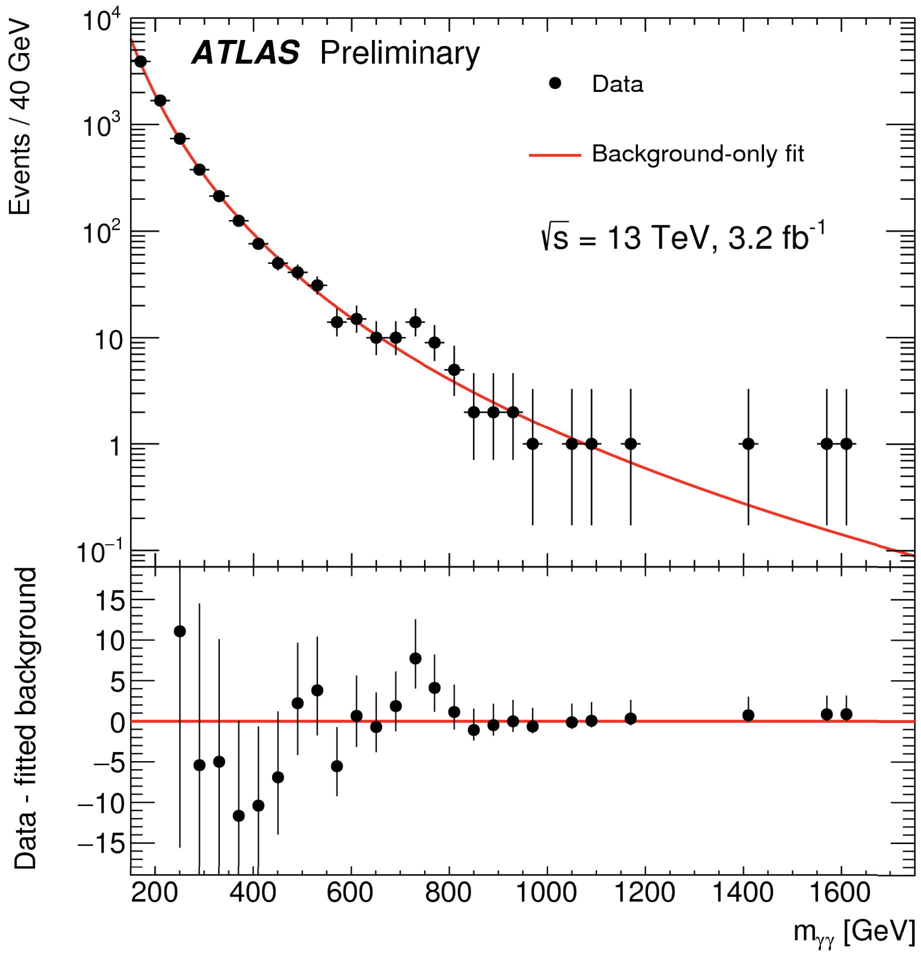


Backup: Di-Photon Search

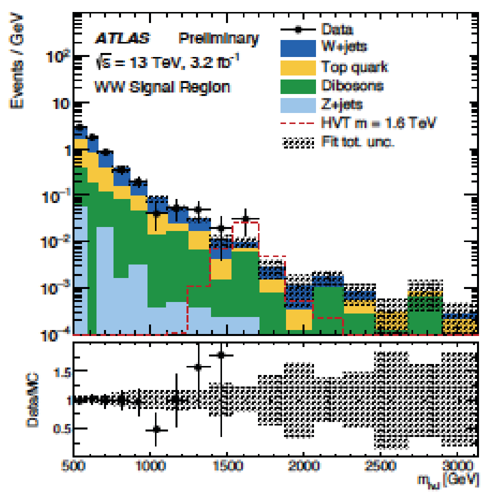
Searched for new states decaying to two photons

- Clean sample, with non-photon bkgds < 10%
- Largest excess in $m_{\gamma\gamma}$ seen around 750 GeV
  - About a dozen events excess, with S/B~1
  - Width appears to be about 45 GeV if interpreted as a resonance
- 3.6σ local p-value, and 2σ effect, taking into account the "look-elsewhere effect"

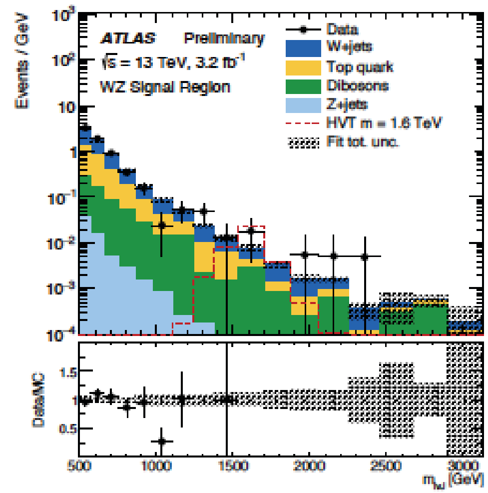




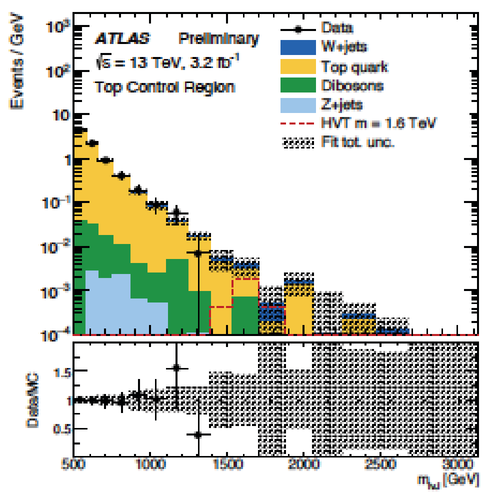
Backup Diboson Search



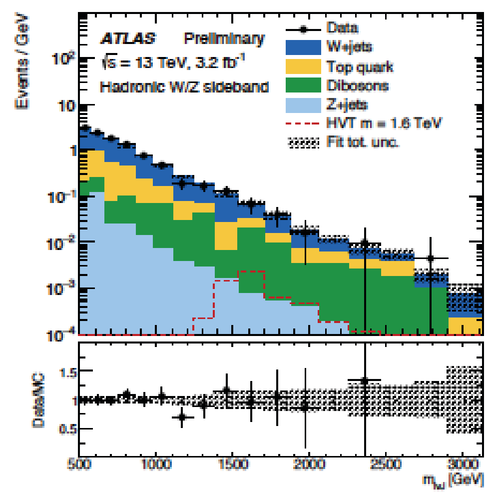
(a) WW Signal Region



(b) WZ Signal Region



(c) Top Control Region



(d) W+jets Control Region