ATLAS $t\bar{t}$ Resonance Searches

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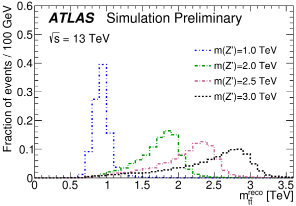
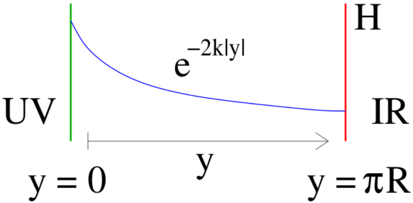
Motivation

Tons of top quarks produced at the LHC! Search for new signatures of new physics in the $t\bar{t}$ mass spectrum

- Leptophobic Z'(TC2)[1] resonance, widths $\Gamma/m = 1.2, 2$ and 3%
- Kaluza-Klein gluon g_{KK}[2]: width $\Gamma/m = 15.3\%$
- Kaluza-Klein graviton G_{KK}[2]
- singlet scalar[3]



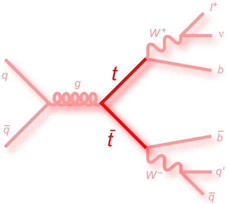


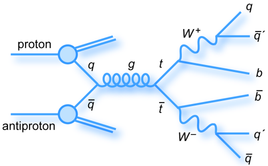
[1] Phys. Lett. B345 (1995) 483–489

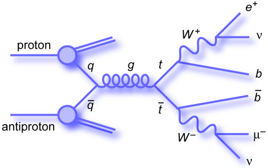
[2] Phys. Rev. Lett. 83 (1999) 3370–3373, JHEP 0308(2003) 050, Phys. Lett. B473 (2000) 43–49, Phys. Lett. B486(2000) 153–157

[3] Phys. Rev. Lett.111 (2013) 211804

- Boosted and resolved $t\bar{t}$ lepton + jets channel
  - 13 TeV CONF Note New
  - 8 TeV JHEP08 (2015) 148
- all-hadronic at 7 TeV JHEP 1301 (2013) 116
- di-lepton at 7 TeV Eur.Phys.J. C72 (2012) 2083





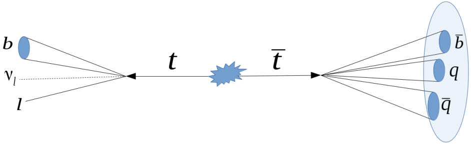


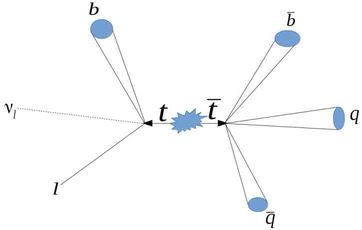
DO Public Top Diagrams

Lepton + Jets - Topology

- lepton trigger, == 1 lepton (with p_{T}-dependent isolation)
- E_T^{miss}, $E_T^{miss} + m_T^W$

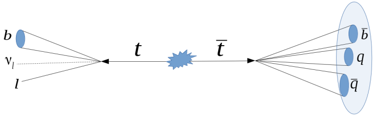
- Aiming for two topologies: boosted and resolved
- Large-R jet for boosted, $\geq$ 4 small-R jets for resolved
- 1 or more *b*-tagged small-R jets
- Remove overlap between leptons and small-R jets

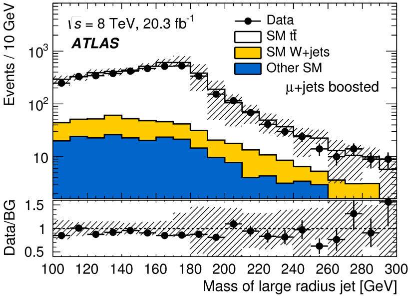


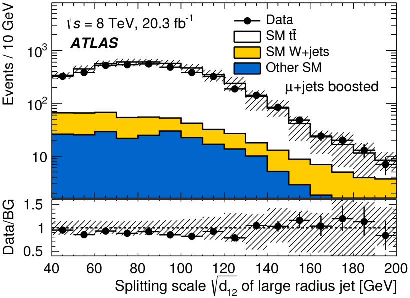


Lepton + Jets - Boosted Selection 8 TeV

- Hadronic top products well separated from leptonic top products
- Lepton requirement achieves great reduction in QCD background
- Substructure cuts further reduce W+jets background, keeping a high top-tagging efficiency



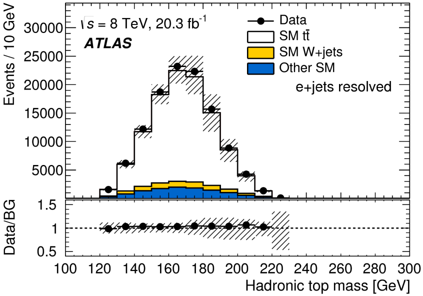


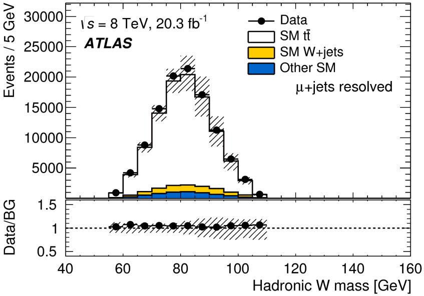


Lepton + Jets - Resolved Selection

- Events failing the boosted selection are required to pass the resolved selection $\rightarrow$ enforces orthogonality
- $\geq$ 4 anti-k_t R=0.4 jets, $\geq$ 1 b-tag.
- $log_{10}(\chi^2) < 0.9$

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





Lepton + Jets - Background Estimation

- Normalization factors for W charge asymmetry: at the LHC more W^++jets than W^-+jets

$$N_{W^+} + N_{W^+} = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)(D^- - D^+)$$

- Multijet estimate from efficiencies for leptons produced by prompt and non-prompt sources
- resolved selection: 184000 $t\bar{t}$ candidates
  boosted selection: 8100 $t\bar{t}$ candidates

Resolved-topology selection			
Type	e+jets	μ+jets	Sum
$t\bar{t}$	93,000 ± 11,000	91,000 ± 11,000	184,000 ± 22,000
Single top	3,800 ± 500	3,800 ± 500	7,600 ± 1,000
$t\bar{t}V$	274 ± 40	267 ± 40	541 ± 80
Multi-jet e	5,300 ± 1,100	–	5,300 ± 1,100
Multi-jet μ	–	1,050 ± 240	1,050 ± 240
W+jets	6,600 ± 800	7,100 ± 800	13,700 ± 1,500
Z+jets	1,400 ± 750	650 ± 340	2,000 ± 1,080
Dibosons	320 ± 120	310 ± 120	620 ± 240
Total	110,000 ± 12,000	105,000 ± 12,000	215,000 ± 24,000
Data	114,377	108,953	223,330

Boosted-topology selection			
Type	e+jets	μ+jets	Sum
$t\bar{t}$	4,100 ± 600	4,000 ± 600	8,100 ± 1,200
Single top	138 ± 20	154 ± 20	290 ± 40
$t\bar{t}V$	37 ± 6	38 ± 7	75 ± 13
Multi-jet e	91 ± 18	–	91 ± 18
Multi-jet μ	–	8.6 ± 1.6	8.6 ± 1.6
W+jets	260 ± 50	290 ± 50	550 ± 100
Z+jets	31 ± 16	17 ± 9	48 ± 25
Dibosons	21 ± 8	20 ± 8	41 ± 16
Total	4,700 ± 600	4,500 ± 600	9,200 ± 1,200
Data	4,148	4,058	8,206

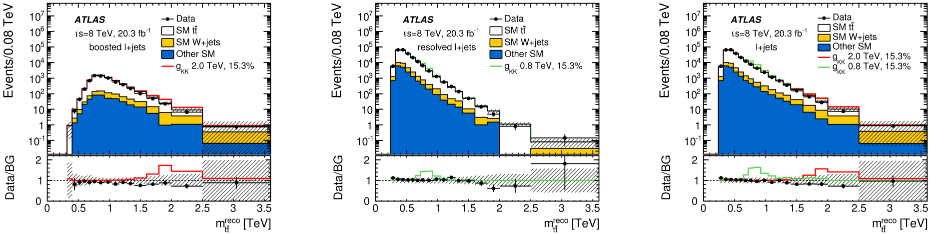
Lepton + Jets - Systematic Uncertainties

- Modeling of signal or background systematics important in both regimes
- Boosted: large-*R* jet JES+JMS and b-tagging b-jet efficiency
- Z' uncertainty dominated by *b*-tag high-p_{T} extrapolation uncertainty
- Resolved: JES for small-R jets

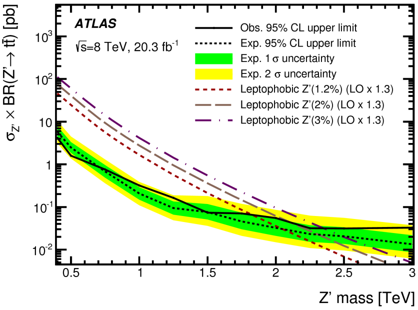
Systematic Uncertainties	Resolved selection yield impact [%] total bkg.	Resolved selection yield impact [%] Z'	Boosted selection yield impact [%] total bkg.	Boosted selection yield impact [%] Z'
Luminosity	2.5	2.8	2.6	2.8
PDF	2.4	3.6	4.7	2.3
ISR/FSR	3.7	–	1.2	–
Parton shower and fragmentation	4.8	–	1.5	–
$t\bar{t}$ normalisation	5.3	–	5.5	–
$t\bar{t}$ EW virtual correction	0.2	–	0.5	–
$t\bar{t}$ generator	0.3	–	2.6	–
$t\bar{t}$ top quark mass	0.6	–	1.4	–
W+jets generator	0.3	–	0.1	–
Multi-jet normalisation, e+jets	0.5	–	0.2	–
Multi-jet normalisation, μ+jets	0.1	–	< 0.1	–
JES+JMS, large-radius jets	0.1	2.1	9.7	2.8
JER+JMR, large-radius jets	< 0.1	0.3	1.0	0.2
JES, small-radius jets	5.6	2.6	0.4	1.4
JER, small-radius jets	1.8	1.4	< 0.1	0.2
Jet vertex fraction	0.8	0.8	0.2	< 0.1
b-tagging b-jet efficiency	1.1	2.0	2.9	17.1
b-tagging c-jet efficiency	0.1	0.7	0.1	2.1
b-tagging light-jet efficiency	< 0.1	< 0.1	0.5	0.2
Electron efficiency	0.3	0.6	0.6	1.3
Muon efficiency	0.9	1.0	1.0	1.1
MC statistical uncertainty	0.4	6.0	1.3	1.8
All systematic uncertainties	10.8	8.8	13.4	18.0

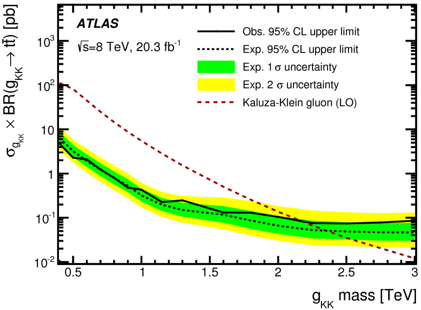
Results I

- Twelve $m_{t\bar{t}}$ spectra used:
  - three b-tag categories (b-tag leptonic top, b-tag hadronic top, tag both)
  - resolved and boosted
  - μ, *e*
- Search performance in combinations of spectra: 6 channel of resolved, 6 channels of boosted, and 12 channels of combined
- Data and expected bkg distributions compared using BumpHunter
- No significant deviations from expected bkg $\rightarrow$ 95% C.L. limits on $\sigma \times$ BR



Results II





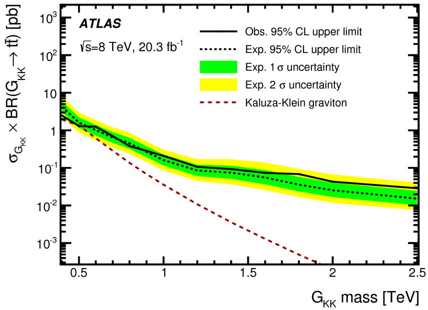
95% C.L. excluded rate:

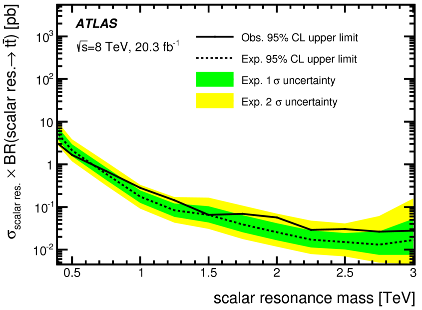
- Z'(1.2%): from 4.2 pb at $m_{Z'} = 0.4\ \mathrm{TeV}$ to 0.03 pb at $m_{Z'} = 3\ \mathrm{TeV}$
- g_{KK}: from 4.8 pb at $m_{g_{KK}} = 0.4\ \mathrm{TeV}$ to 0.09 pb at $m_{g_{KK}} = 3\ \mathrm{TeV}$

95% C.L. excluded mass ranges:

- Z'(1.2%): masses $< 1.8\ \mathrm{TeV}$
- g_{KK}: masses $< 2.2\ \mathrm{TeV}$

Results III





95% C.L. excluded rate:

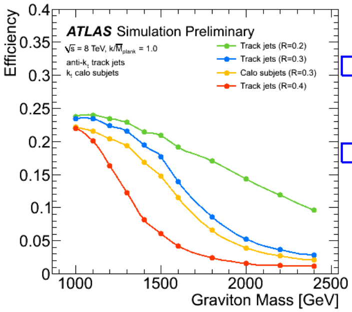
- G_{KK}:: from 2.5 pb at $m = 0.4\ \mathrm{TeV}$ to 0.03 pb at $m = 2.5\ \mathrm{TeV}$
- scalar: from 3.0 pb at $m = 0.4\ \mathrm{TeV}$ to 0.03 pb at $m = 2.5\ \mathrm{TeV}$

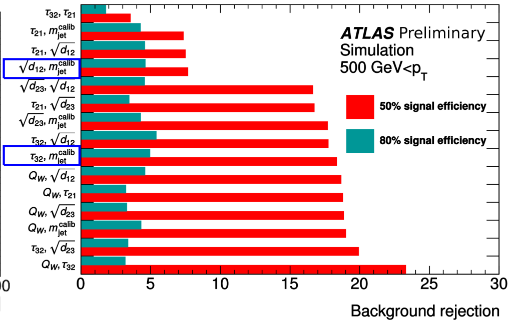
95% C.L. excluded mass ranges:

- G_{KK}: No mass excluded in the benchmark scenario

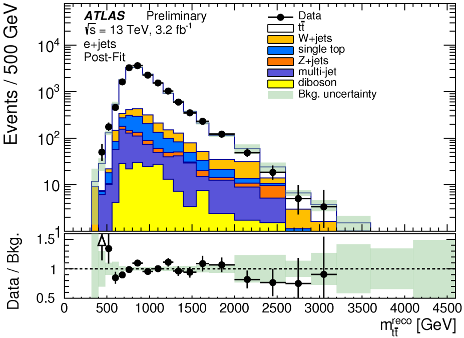
Selection 8 TeV vs. 13 TeV

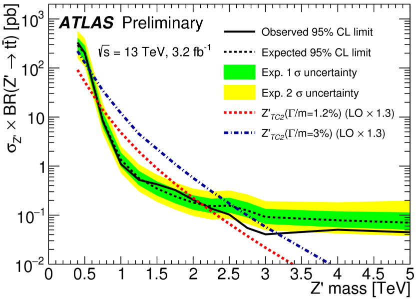
- Repeated $t\bar{t}$ lepton+jets (boosted) resonance search with 13 TeV data
- Improved *b*-tagging algorithm
- Use of track jets *b*-tagging $\rightarrow$ higher efficiency at heavier masses
- Changed top tagging from $\sqrt{d_{12}}$ to τ_{32} $\rightarrow$ higher background rejection
- New top tagger has flatter efficiency as a function of $m_{t\bar{t}}$ and top p_{T}





Preliminary Results at 13 TeV

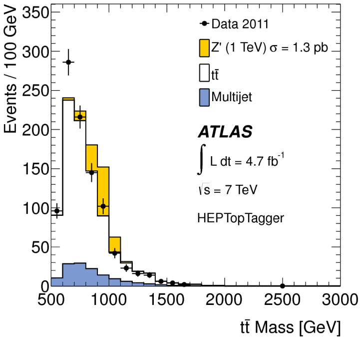


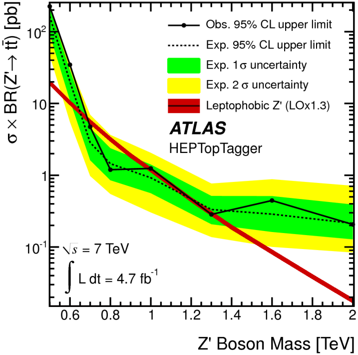


- Rate limits: 300-0.05 pb for Z' masses 0.4 - 5 TeV
- Mass limits: 0.7 $> m_{Z'} >$ 2.0 TeV
- Increase in $\sigma_{Z'}$ allows for competitive mass limits with 8 TeV search

$t\bar{t}$ Searches in the Fully Hadronic Channel

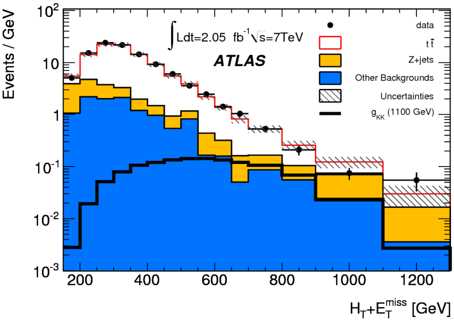
- Boosted techniques allow for search in the all-hadronic channel
- Need very high rejection $\rightarrow$ used HEPTopTagger and Top Template Tagger
- Multijet background extracted from data
- Exclusion of Z' masses between $0.70 < m_{Z'} < 1.0$

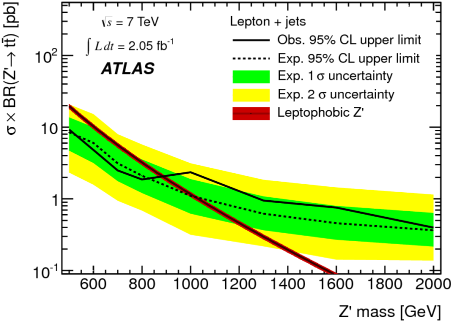




$t\bar{t}$ Searches in the Dileptonic Channel

- Search performed with 2.05 pb^{-1} at 7 TeV
- Uses sum transverse momentum of all objects (H_T) + missing transverse energy (E_T^{miss}) as discriminating variables
- Main background Z+jets: scale factors determined from data control region
- Z' masses below 1 TeV excluded





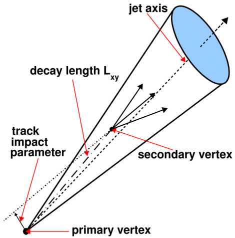
Summary

- Presented status of the ATLAS $t\bar{t}$ resonance searches
- Searches in the lepton+jets channel offer the most competitive limits
- $t\bar{t}$ resonance searches have been performed additionally in dileptonic and all-hadronic decay channels
- No significant deviations from the Standard Model observed
- With only 3.2 fb^{-1} of integrated luminosity, the 13 TeV search has competitive mass limits with 8 TeV search

Backup

b-tagging in ATLAS: from MV1 to MV2

- IP2D, IP3D: use impact parameter significance of tracks matched to jet.
- SV: Secondary vertex algorithm: explicitly reconstruct an inclusive displaced secondary vertex within the jet
- The decay chain multi-vertex reconstruction algorithm, JetFitter used the topological structure of weak b- and c-hadron decays and reconstructs the full PV $\rightarrow$ b $\rightarrow$ c-hadron decay chain.
- MV2 constitutes a significant revision of the main Run1 b-tagging algorithm (MV1):
    - MV1 was based on neural network, MV2 uses BDT.
    - New approach not only improves performance, but also add significant simplification



Lepton + Jets - Boosted Selection 13 TeV

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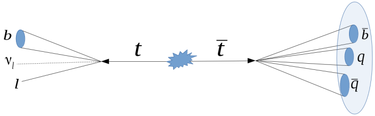
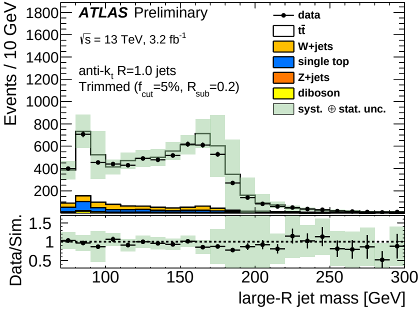
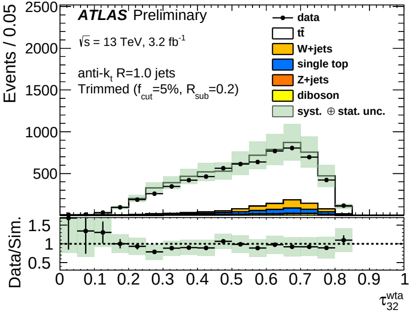
- Substructure cuts further reduce W+jets background, keeping a high top-tagging efficiency







MV2+c20

- c20: training with b-jets as signal, and mixture of 80% light jets and 20% c-jets
- c00, c10 also available
- MV2c20 increases significantly c-jet rejection, with practically no decrease in light-jet rejection

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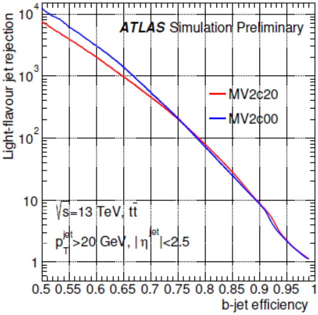
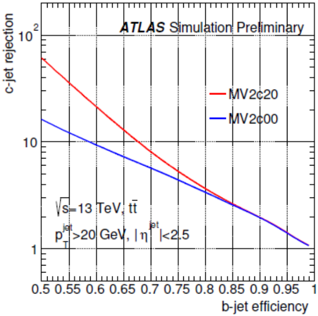


(a)



(b)

Run2 MV2c20 vs. Run 1 MV1c

- MV1c: Optimized for c-jet rejection
- MV2c20 at 70% :
  4x increase in light-jet rejection
  1.6x increase in c-jet rejection

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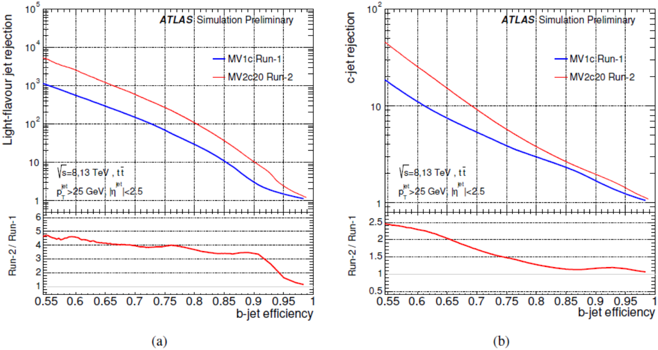
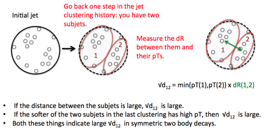
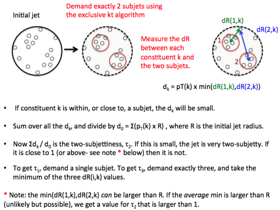


Figure 11: The light (a) and c-jet rejection (b) versus b-jet efficiency for the MV1c b-tagging algorithm using the Run-1 detector and reconstruction software (blue) compared to the MV2c20 b-tagging algorithm using the Run-2 setup (red).

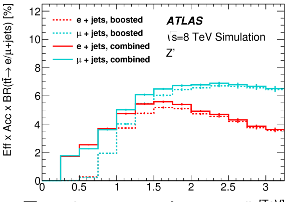
Top Tagging

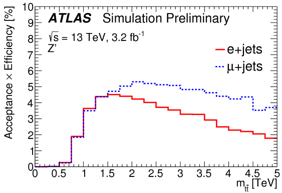




- Top tagging at 8 TeV: $p_{\mathrm{T}} > 300$ GeV (380 GeV for muon-plus-jets selected by the large-radius-jet trigger), m_{jet} 100 GeV and $\sqrt{d_{12}}$ 40 GeV
- $\sqrt{d_{12}}$ *min*()
- Top tagging at 13 TeV: $p_{\mathrm{T}} > 300$ GeV $m_{jet} > 100$ GeV and N-subjettiness ratio τ_{32}

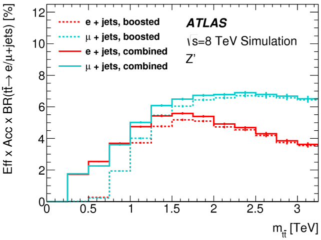
electron-in-jet overlap removal

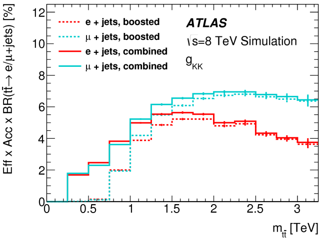


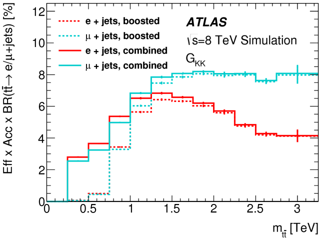


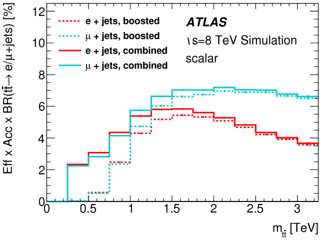
- For 8 TeV: electron and small jets considered for overlap removal if the cluster associated with the electron is within R=0.4 Jets have their momentum and JVT after subtracting the electron 4-mom and removed if they don't pass the selection criteria. If ΔR between electron and recalculated jet is < 0.2. remove electron and its 4 mom is added to the jet.
- For 13 TeV: if any selected small-R jets has $R(electron; jet) < 0.2$, the jet is rejected. After this first overlap removal, if an electron is found to be close to a jet such that $R(electron; jet) < 0.4$, the electron is rejected

Acceptance Comparison 8 TeV









Lepton + Jets - Event Selection

Leptons

- == 1 e, μ, lepton trigger and lepton trigger matching
- e, μ, isolation: $MI_{10}/E_T < 0.05$

$$MI_{10} = \sum_{tracks} p_T^{track}$$

for all tracks within $\Delta R < \frac{10\mathrm{GeV}}{E_T}$

Jets

- Small-R jets: anti-k_t R=0.4, $p_{\mathrm{T}} > 25\mathrm{GeV}, |\eta| < 2.5$
- Large-R jets: trimmed anti-k_t R=1.0, $p_{\mathrm{T}} > 300\mathrm{GeV}, |\eta| < 2.0$

b-tagging

- # b-jets at 70% efficiency ≥ 1

- $E_T^{miss} > 20\mathrm{GeV}$ and $E_T^{miss} + m_T^W > 60\mathrm{GeV}$

Overlap in identification possible $\rightarrow$ remove duplication

Electrons and small-R Jets

- If $\Delta R(e_{cluster}, jet) < 0.4$, subtract electron 4-momentum from jet
- If $\Delta R(e_{cluster}$, recalculated jet$) < 0.2$, remove electron

Muons

- If $\Delta R(\mu, \text{jet}) < 0.04 + \frac{10\mathrm{GeV}}{p_{\mathrm{T}}}$