Searches for $t\bar{t}$ resonances with the ATLAS detector at the LHC

Lorenzo Feligioni
on behalf of ATLAS collaboration
25/08/2015

SUSY 2015
August 23-29 Lake Tahoe, California

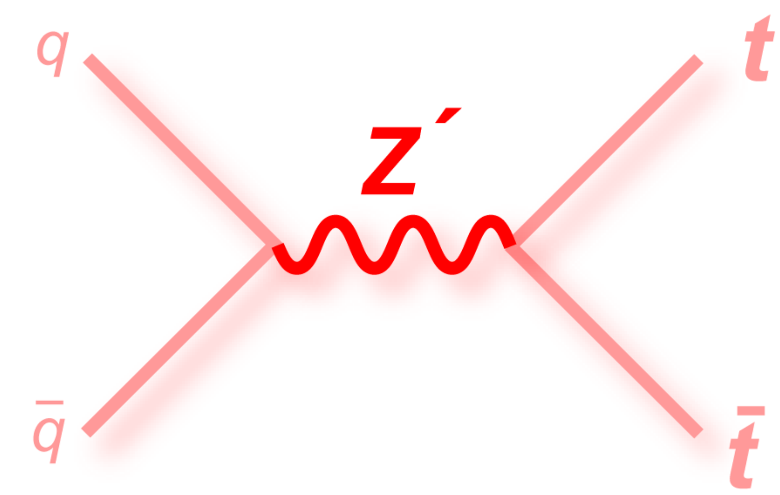
Outline

- Introduction
- High p_T top quark identification algorithms
- Searches for $t\bar{t}$ resonances in fully hadronic final states at $\sqrt{s} = 7$ TeV [1]
- Searches for $t\bar{t}$ resonances in lepton+jets channel at $\sqrt{s} = 8$ TeV [2]
- Conclusions

1. JHEP 1301 (2013) 116 arXiv:1211.2202 [hep-ex]
2. arXiv:1505.07018 [hep-ex]

top quark coupling to BSM

- Many BSM models predicts new particles with masses at the TeV scale
- The top quark is the most massive among fundamental particles
  - Could have a fundamental role in EWSB
    - larger coupling to new physics than any other lighter fermions



- Topcolour-assisted Technicolor, composite Higgs scenarios and warped extra-dimensions all predicts new particles that disintegrate in top quark pairs
  - Underlying colour structure of the decaying resonance affects the experimental performance

benchmark processes

Spin 1 Colour Singlet

- Topcolour assisted Technicolor (Z'_{TC2})
  - Z' helps TC to bring top mass to its physical value
- Model IV higher cross section at hadron collider
  - couples only to first and third generation quarks
  - $f_1 = 1$, $f_2 = 0$ maximize decay into top quark pairs
  - cot θ_H set to have Γ/m =1.2%

Spin 1 Colour octet

- Randall-Sundrum model with a single warped extra dimension g_{kk}
  - in this model g_{kk} Γ/m =15.3%

Spin 0 Colour singlet

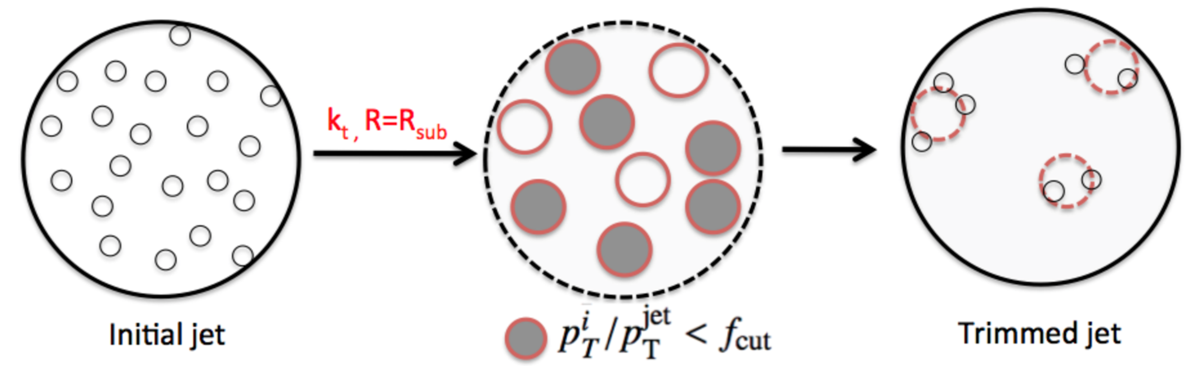
- no SM interference, not predicted by any particular BSM model
  - narrow scalar benchmark

Spin 2 Colour octet

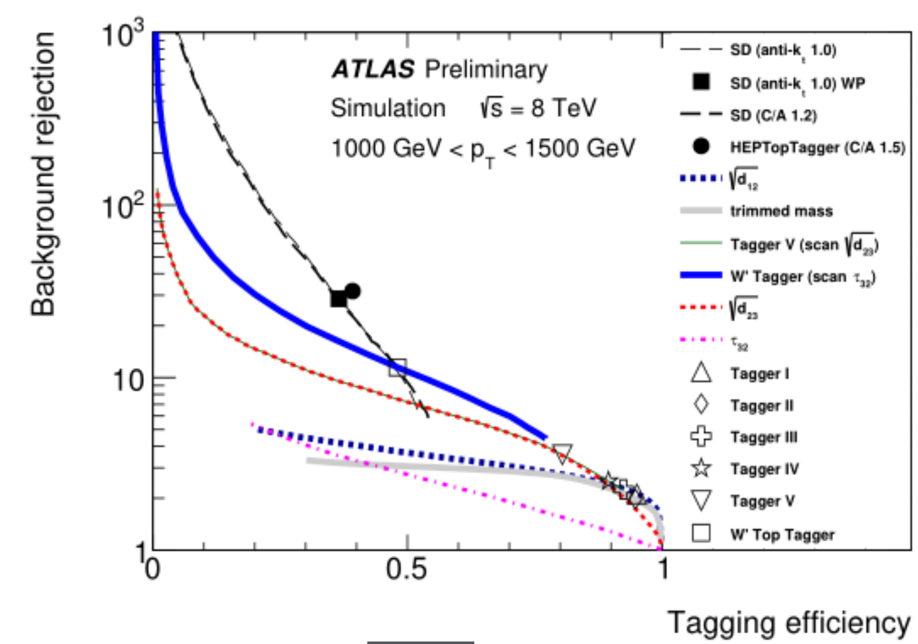
- KK excitation of the graviton G_{KK}
  - Bulk RS gravitons have suppressed decay to light quarks
  - BR to $t\bar{t}$ pairs varies from 18% at low masses up to a plateau of 68% for masses larger than 1 TeV
  - Γ/m vary from 3% to 6%

top tagging methods in ATLAS

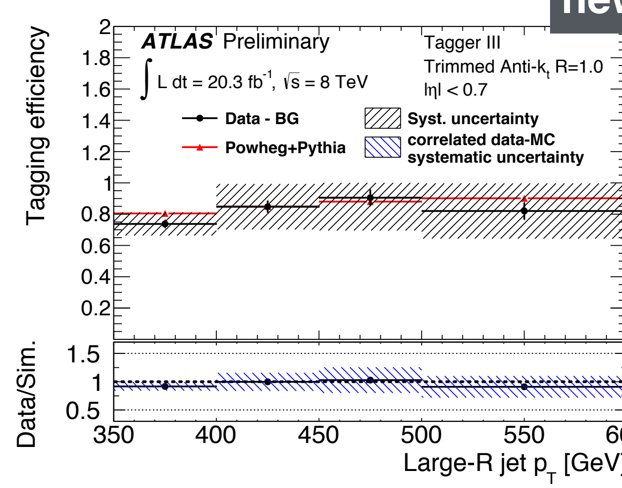
- Presence of large R jets (fat-jets) from high boosted decays is identified with different algorithms
  - Substructure Cut-Based anti-k_t R=1:
    - Trimming: $R_{sub} = 0.2$, $f_{cut} = 0.05$
    - Working points defined by cutting on
      - trimmed mass
      - k_t splitting scale $\sqrt{d_{12}}$, $\sqrt{d_{23}}$
      - N-subjettines τ_{23}
  - HepTopTaggers C/A R=1.5:
    - find all hard subjets using a mass drop criterion until no masses below m_{cut}
    - Iterate on all pairings of three hard subjets
    - After filtering contribution from underlying event and pile up keep 5 most energetic subjects
      - more than three subjets are kept to take into account possible QCD radiation



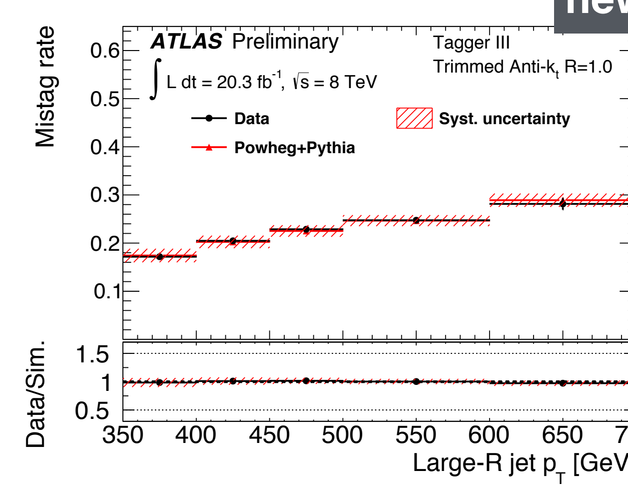
ATLAS-CONF-2015-036



new



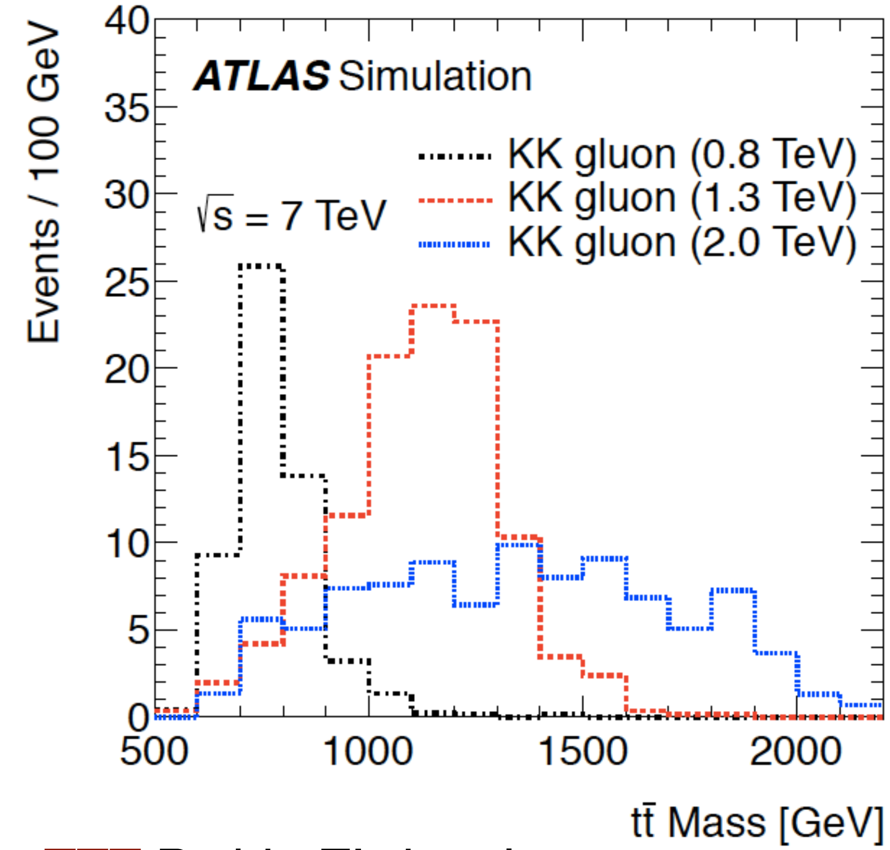
new



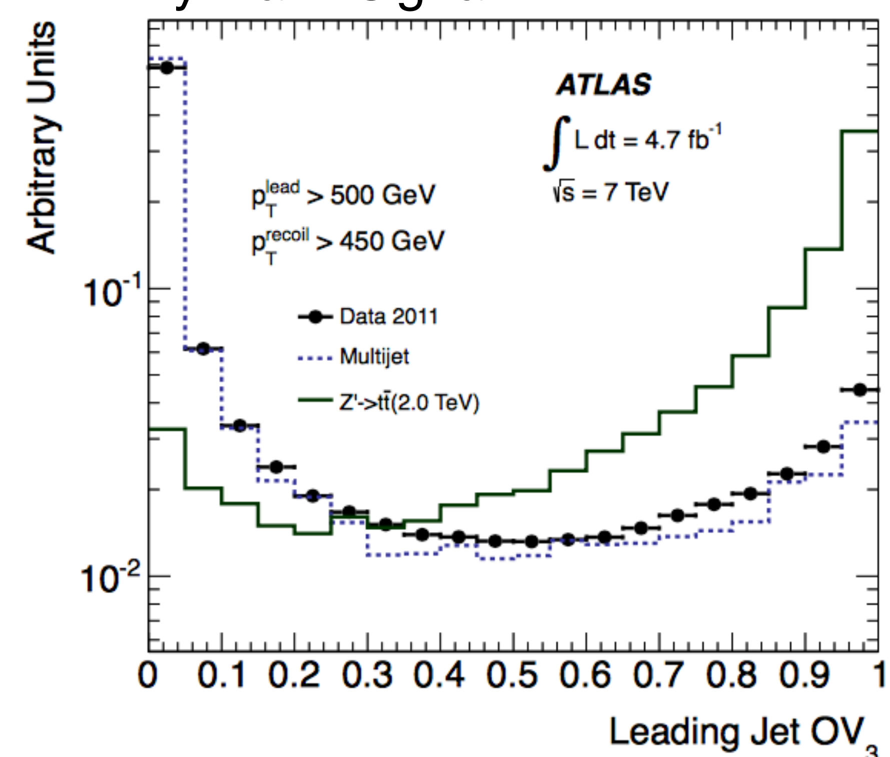
fully hadronic analysis

- 4.7 fb^{-1} *p-p* collisions at $\sqrt{s}$ =7 TeV collected in 2011
- Fully hadronic signatures have the largest branching ratio but suffer from large multi-jet contamination
  - <u>Two TopTaggers used for the analysis:</u>
    - HEPTopTagger (HEPTT)
    - Top Template Tagger (TTT)
      - Overlap function (OV_3) quantifies agreement in energy flow between top-quark hypothesis and the observed jet
        - mass window around top mass to reduce gluon/quark background
- <u>Preselection:</u>
  - High p_T jet selection
    - HEPTT: 2 C/A R=1.5 jets $p_T > 200$ GeV
    - TTT: 2 anti-k_t R=1.0 1st jet $p_T > 500$ GeV 2nd jet $p_T > 450$ GeV
  - Neural network based *b*-tagging algorithm
    - efficiency of 50-70% vs. 3.5-7% mistag rate depending on jet p_T

HEPTT Madgraph+Pythia KK gluon signal



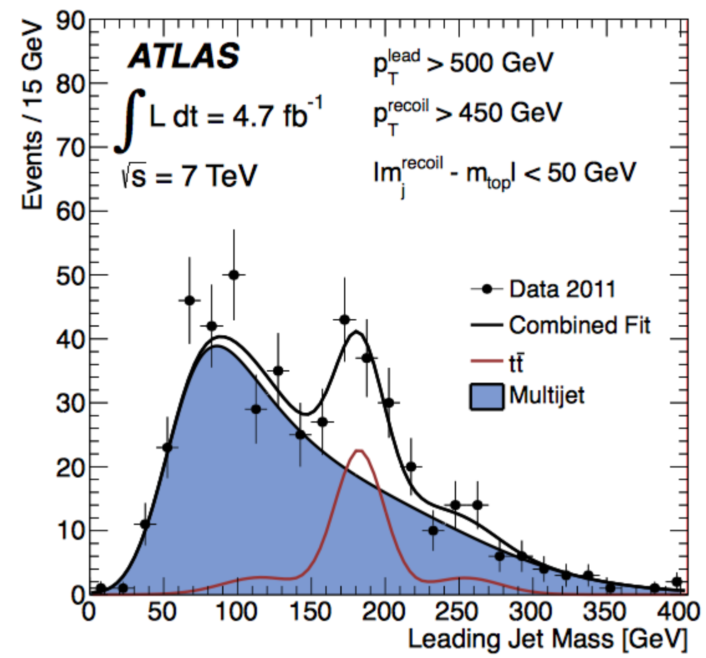
TTT Pythia Z' signal



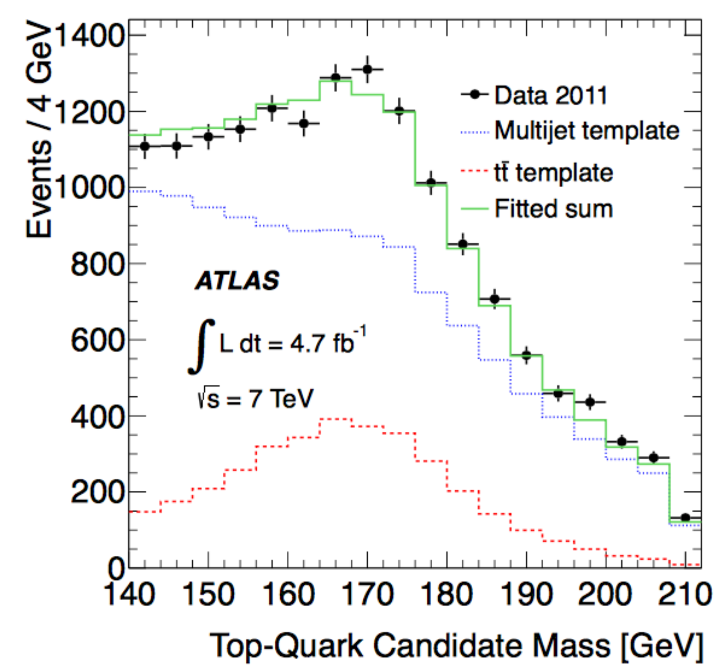
background estimation

- Signal region defined as having two large jets top-tagged and two b-tagged jets
- Background mainly from $t\bar{t}$ production
  - simulated with MC@NLO+Herwig
  - normalized at NNLO σ_{tt} =167 pb
- All other light-quark/gluon jets background (multi-jet,W/Z+jets,…) estimated with data
  - control samples in low b-tagged and top-tagged jet multiplicity
    - top and *b*-tagging uncorrelated
    - background normalization and shapes propagated to the signal region

TTT relaxed cuts on the away jet measured efficiency 0.81 ± 25

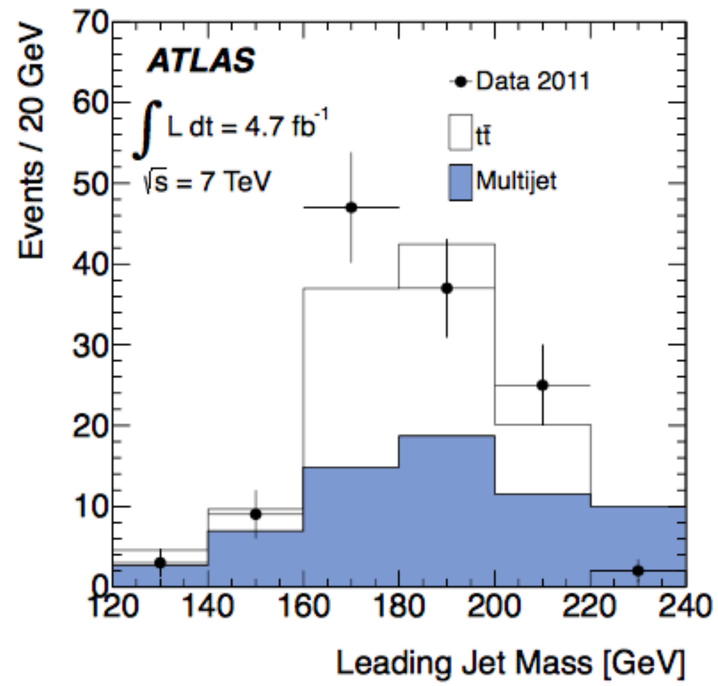


HepTT region with only 1 top tagged jet fit $t\bar{t}$ content to 1.01 ± 0.09 SM expectation

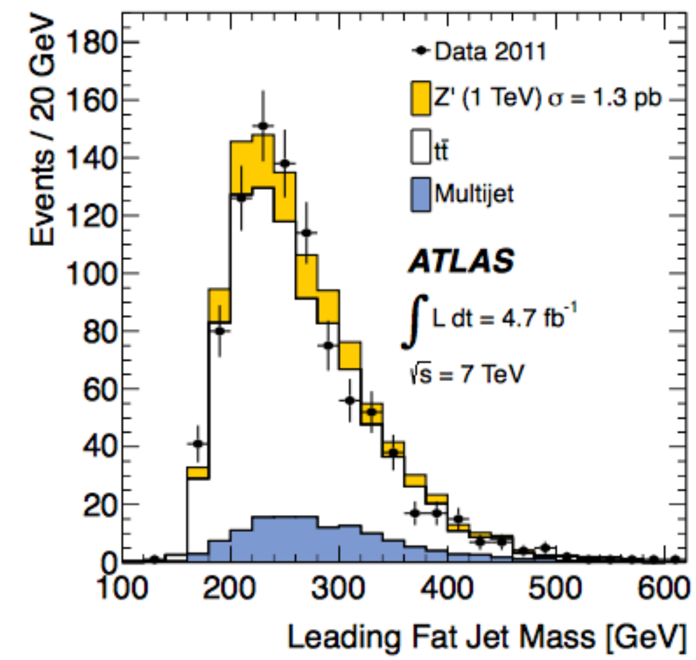


agreement data-prediction after selection

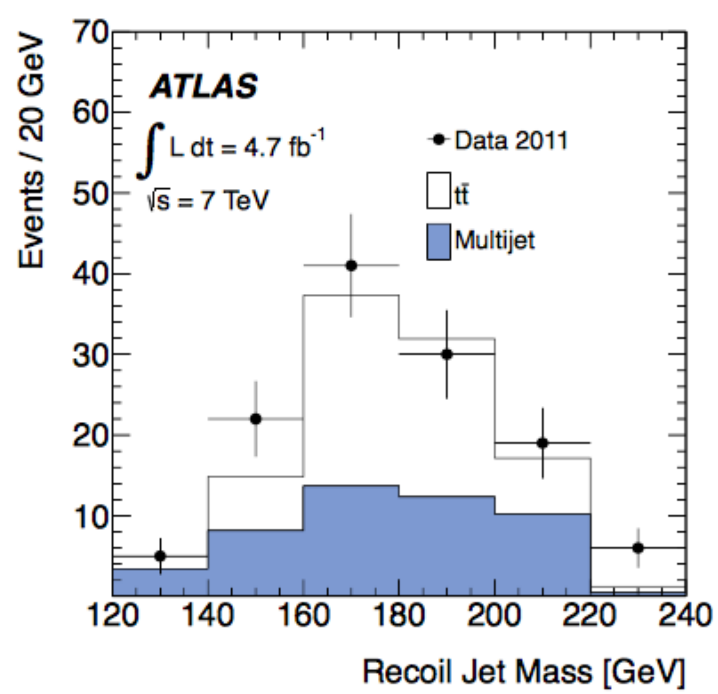
- HEPTT: 953 observed events
  - MC $t\bar{t}$ 700^{+220}_{-180} (stat+syst)
  - multijets 130 ± 70 (stat+syst)
  - Signal efficiencies:
    - Z': 0.03-4.4% for $m_{Z'}$ 0.5-2 TeV
    - g_{KK}: 1.7-4.4% for m_{gKK} 0.7-2 TeV
- TTT: 123 observed events
  - MC $t\bar{t}$ 59^{+27}_{-26} (stat+syst)
  - multijets 53 ± 6 (stat+syst)
  - Signal efficiencies:
    - Z': 0.5-6.3% for $m_{Z'}$ 1-2 TeV
    - g_{KK}: 0.7-5.2% for m_{gKK} 1-2 TeV
- Main systematics:
  - b-tagging, JES, JER, PDF

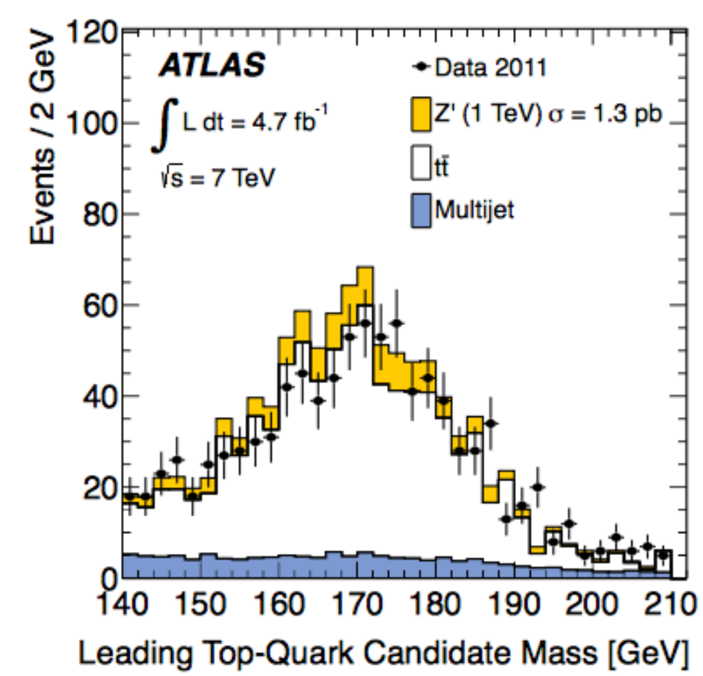


(a)



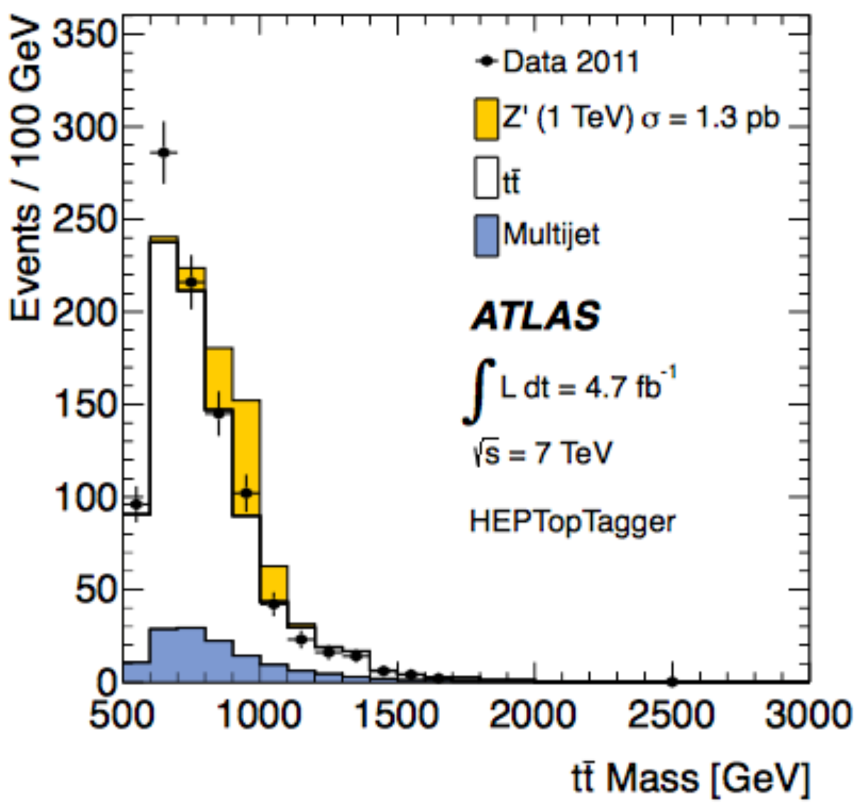
(a)



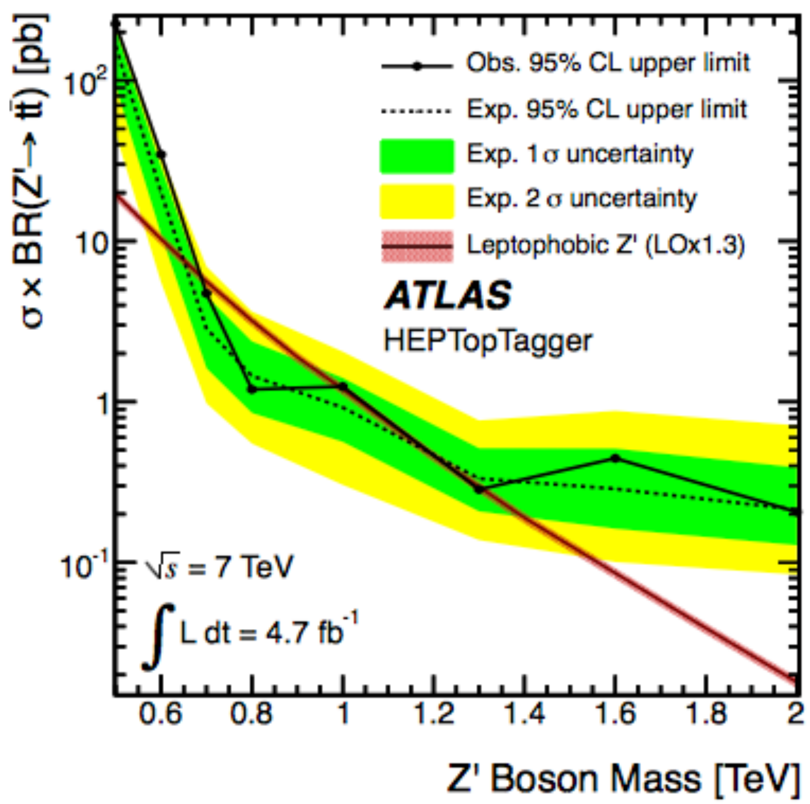


fully hadronic analysis

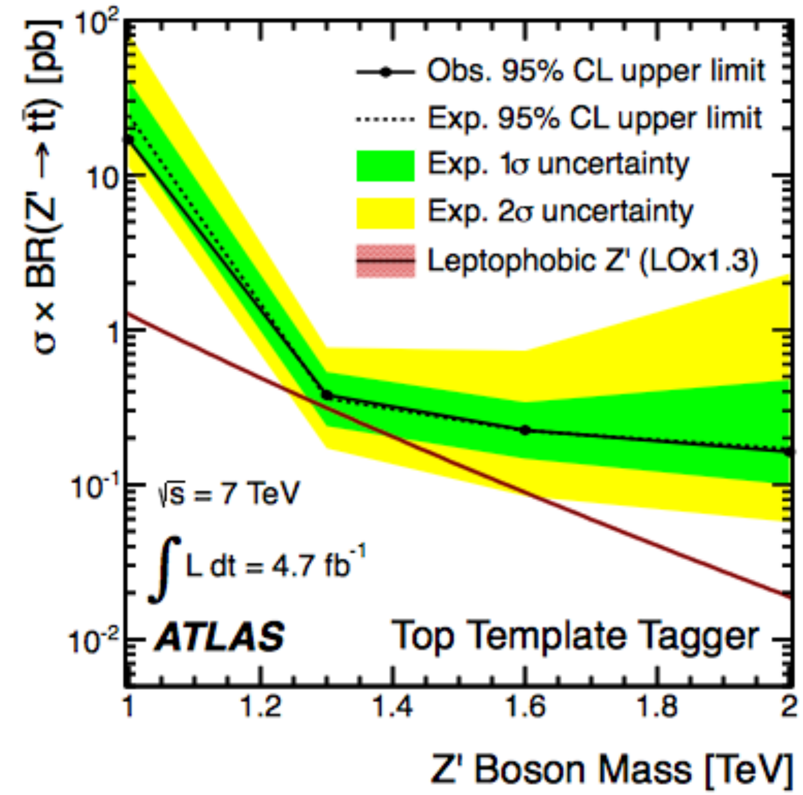
results



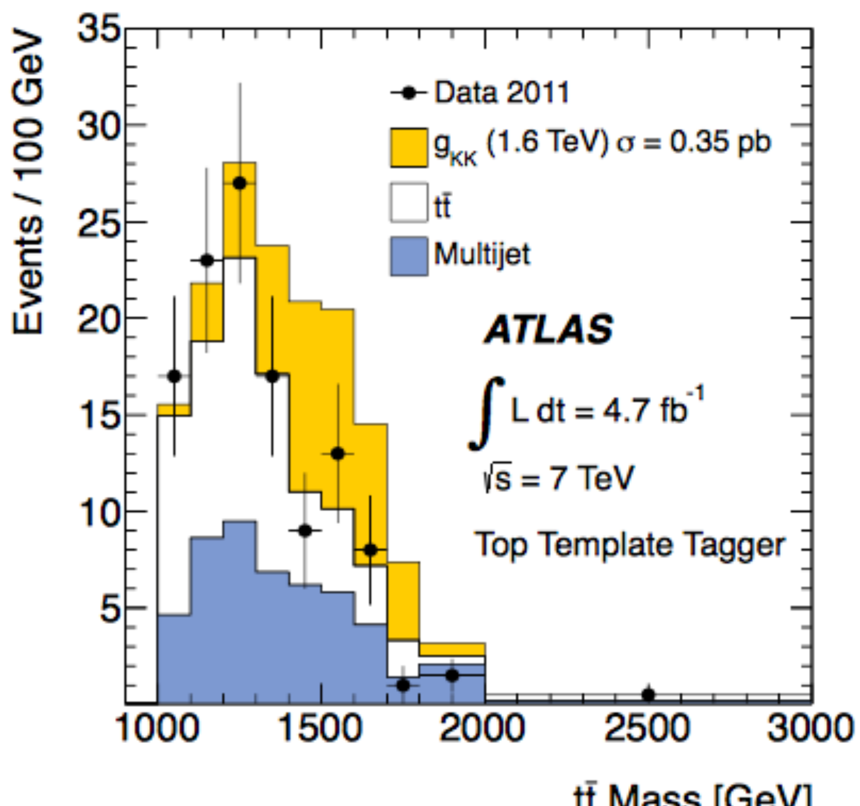
(a)

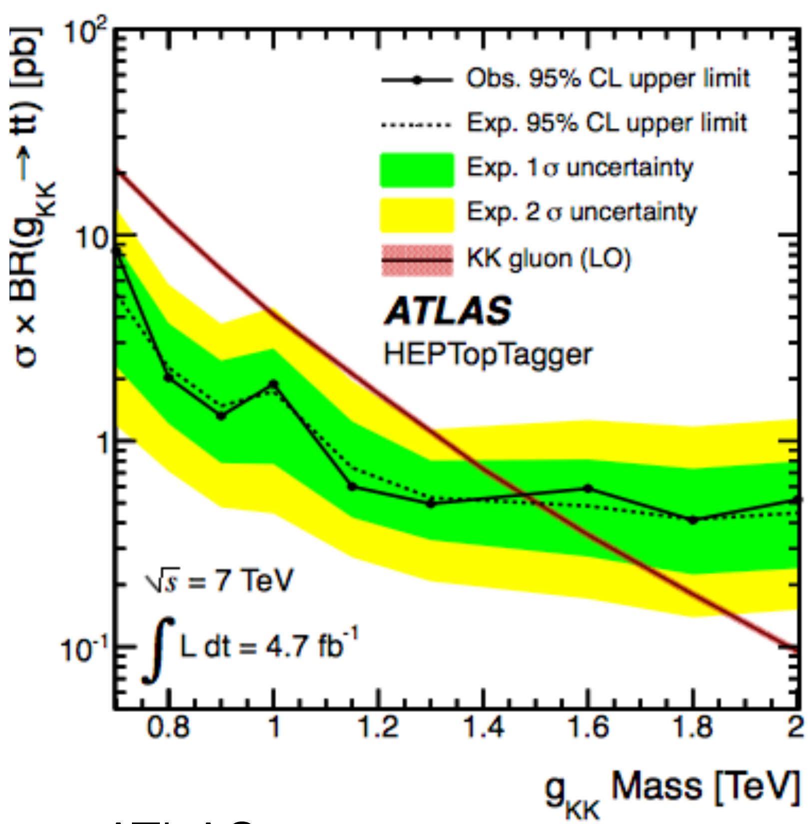


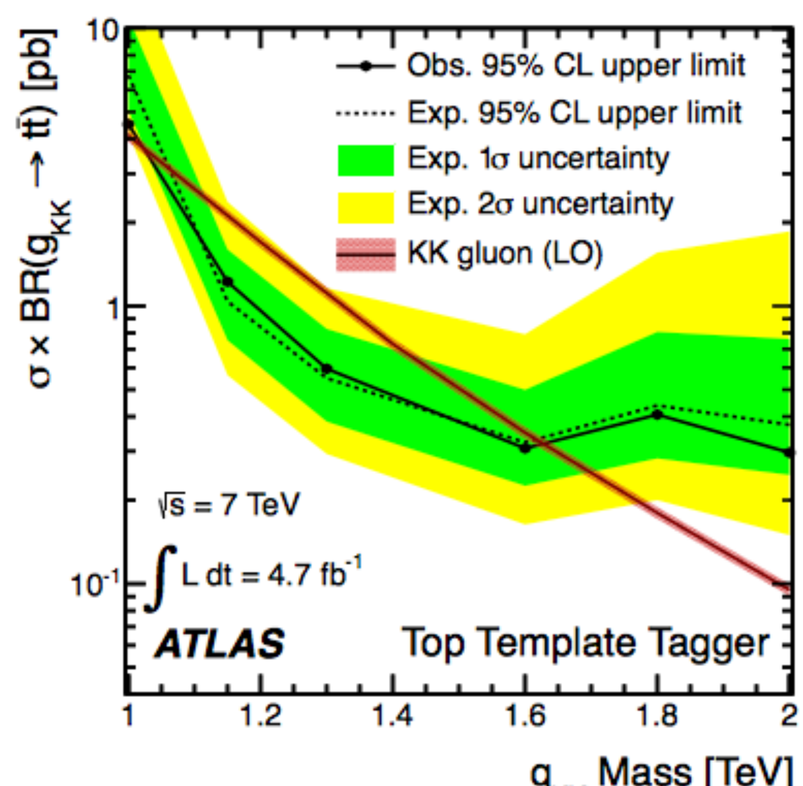
(a)



(a)

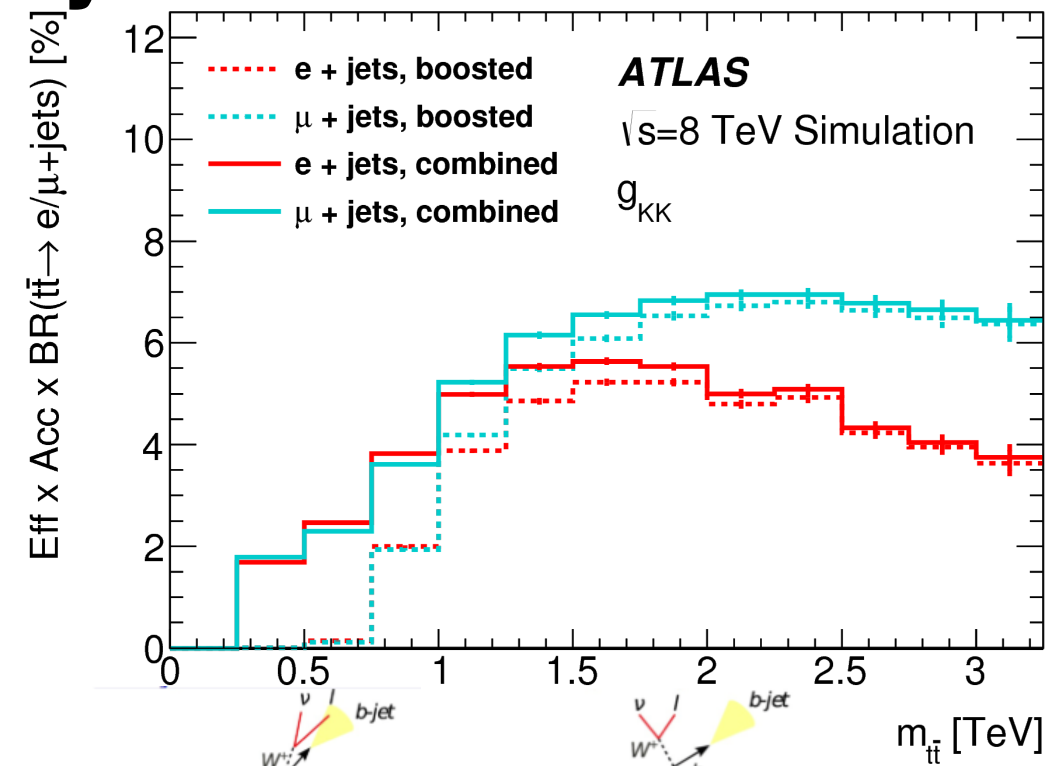


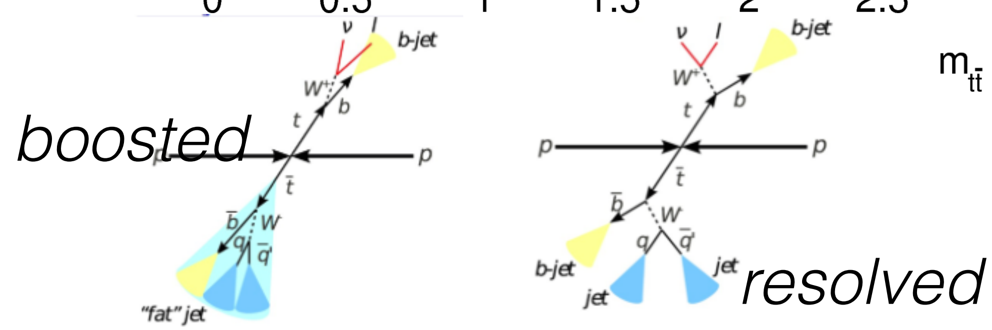


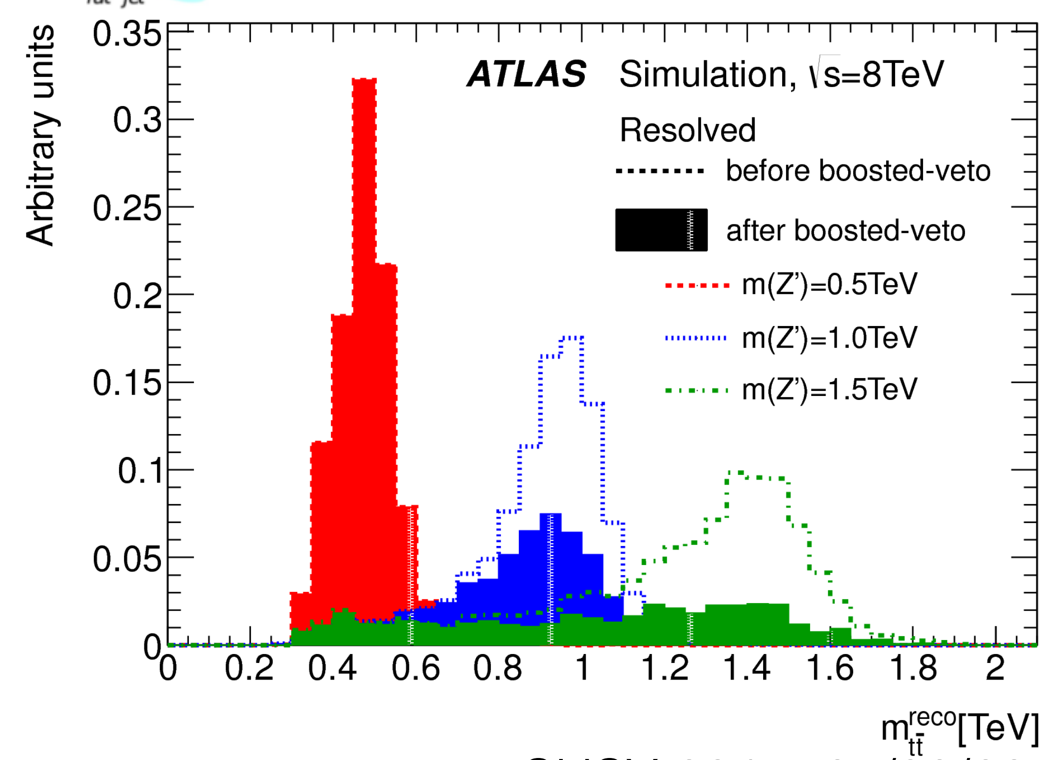


lepton+jets analysis

- Search performed using p-p collision data at $\sqrt{s}$ = 8 TeV
- <u>Preselection:</u>
  - isolated lepton $p_T > 25$ GeV
  - small radius jets (anti-k_t R=0.4) $p_T > 25$ GeV, $|\eta| < 2.5$
  - large radius jets (anti-k_t R=1) $p_T > 300$ GeV, $|\eta| < 2$
  - *b*-tagging 70% efficient applied only to small radius jets
  - $E_T^{miss} > 20$ GeV, $E_T^{miss} + m_T > 60$ GeV
- <u>Boosted topology</u>
  - ΔR(lepton,small-radius jet)<1.5
  - one top-tagged (Tagger III) jets on the opposite side
- <u>Resolved topology</u>
  - Events failing the boosted topology
  - ≥ 4 small radius jets, ≥ 1 b-tagged jet
  - χ^2 algorithm used to reconstruct the tt system

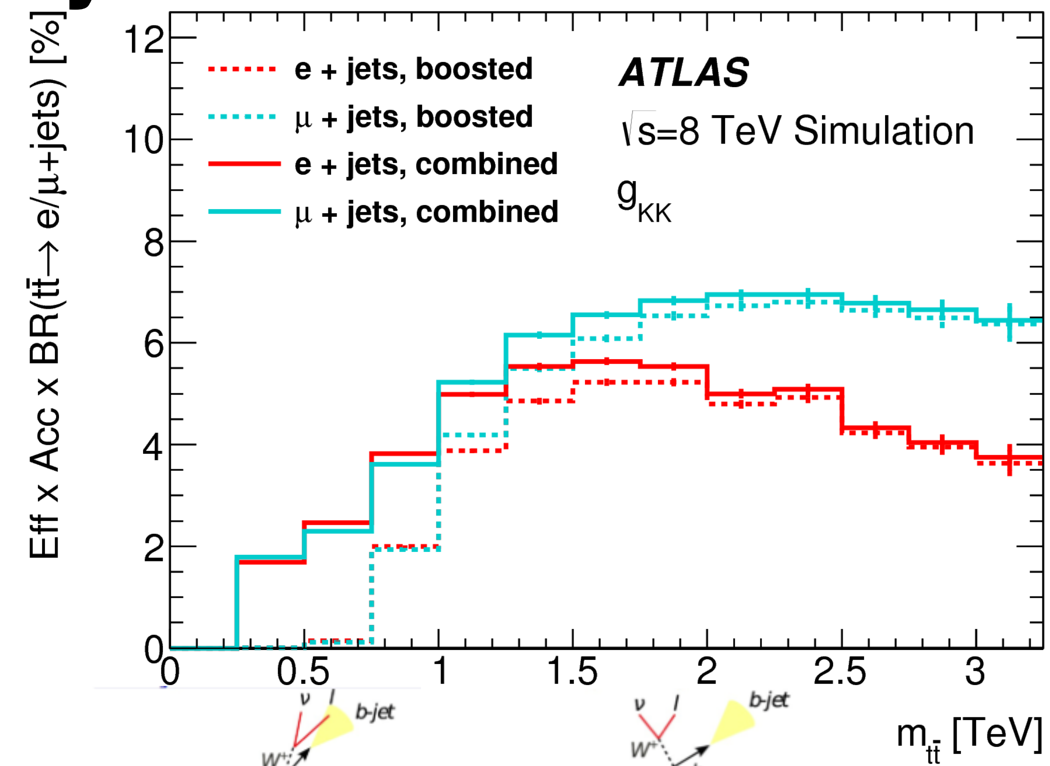


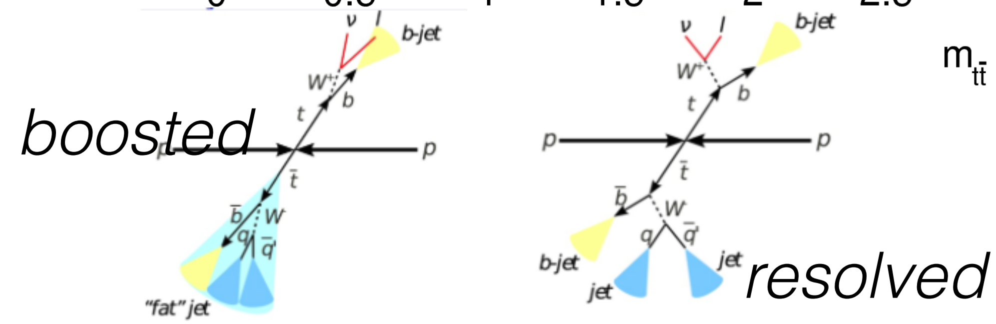


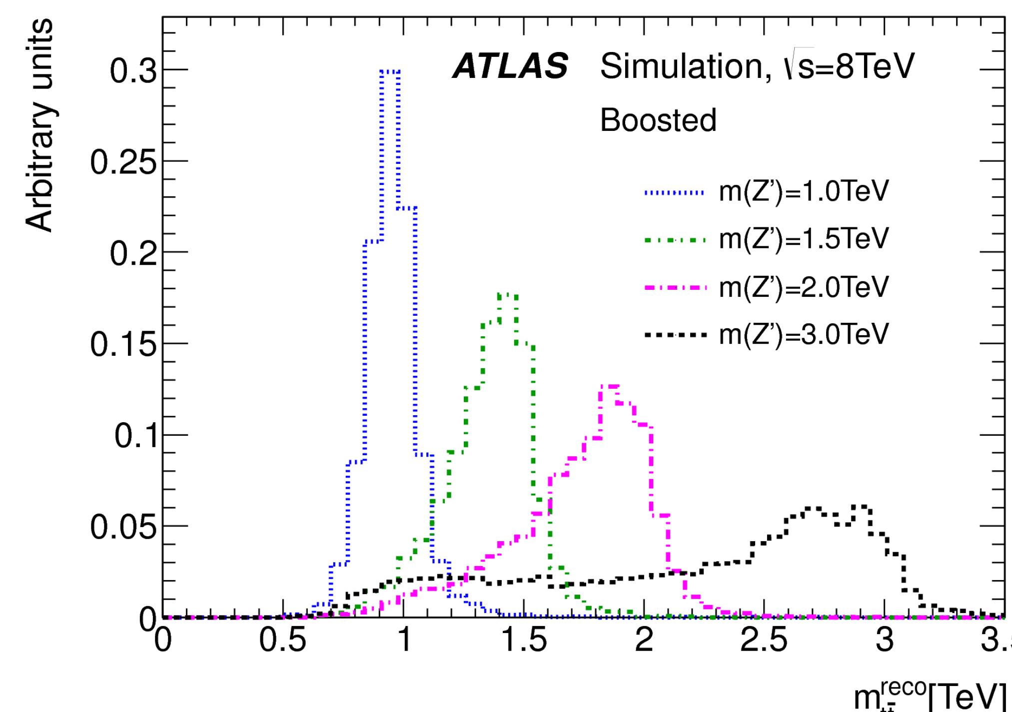


lepton+jets analysis

- Search performed using p-p collision data at $\sqrt{s}$ = 8 TeV
- <u>Preselection:</u>
  - isolated lepton $p_T > 25$ GeV
  - small radius jets (anti-k_t R=0.4) $p_T > 25$ GeV, $|\eta| < 2.5$
  - large radius jets (anti-k_t R=1) $p_T > 300$ GeV, $|\eta| < 2$
  - *b*-tagging 70% efficient applied only to small radius jets
  - $E_T^{miss} > 20$ GeV, $E_T^{miss} + m_T > 60$ GeV
- <u>Boosted topology</u>
  - ΔR(lepton,small-radius jet)<1.5
  - one top-tagged (Tagger III) jets on the opposite side
- <u>Resolved topology</u>
  - Events failing the boosted topology
  - ≥ 4 small radius jets, ≥ 1 b-tagged jet
  - χ^2 algorithm used to reconstruct the tt system



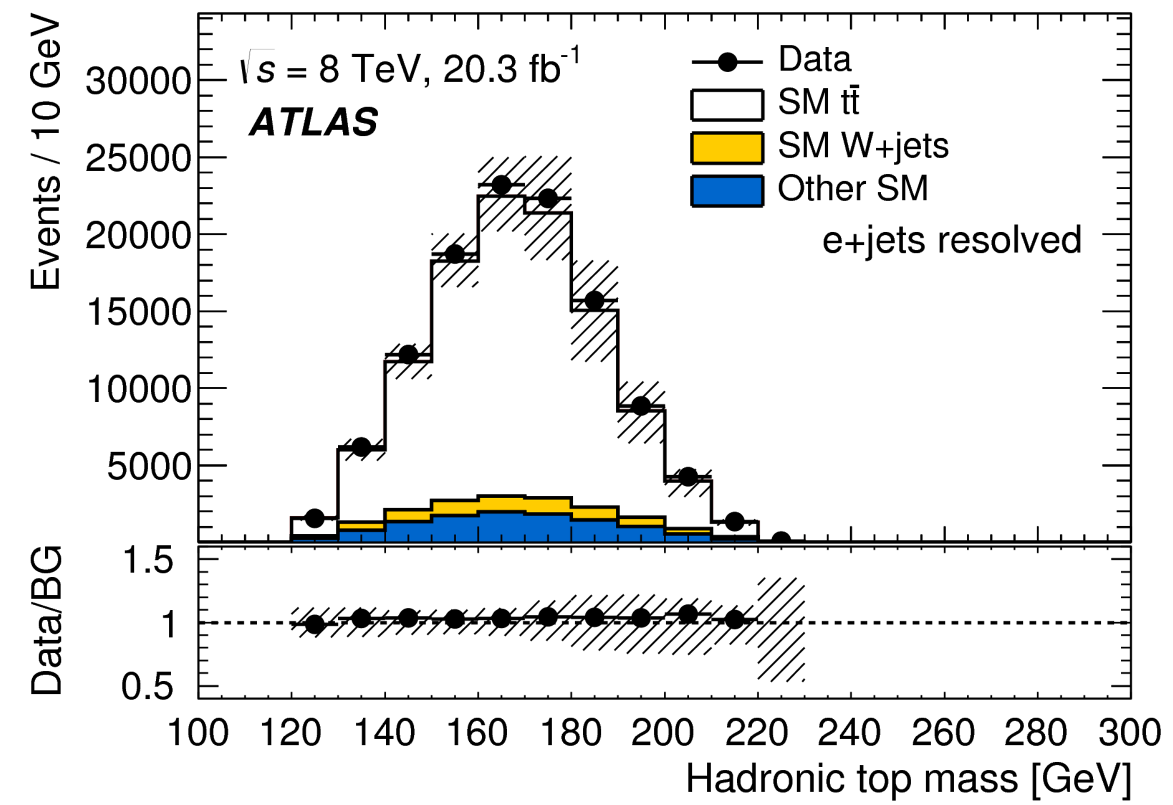


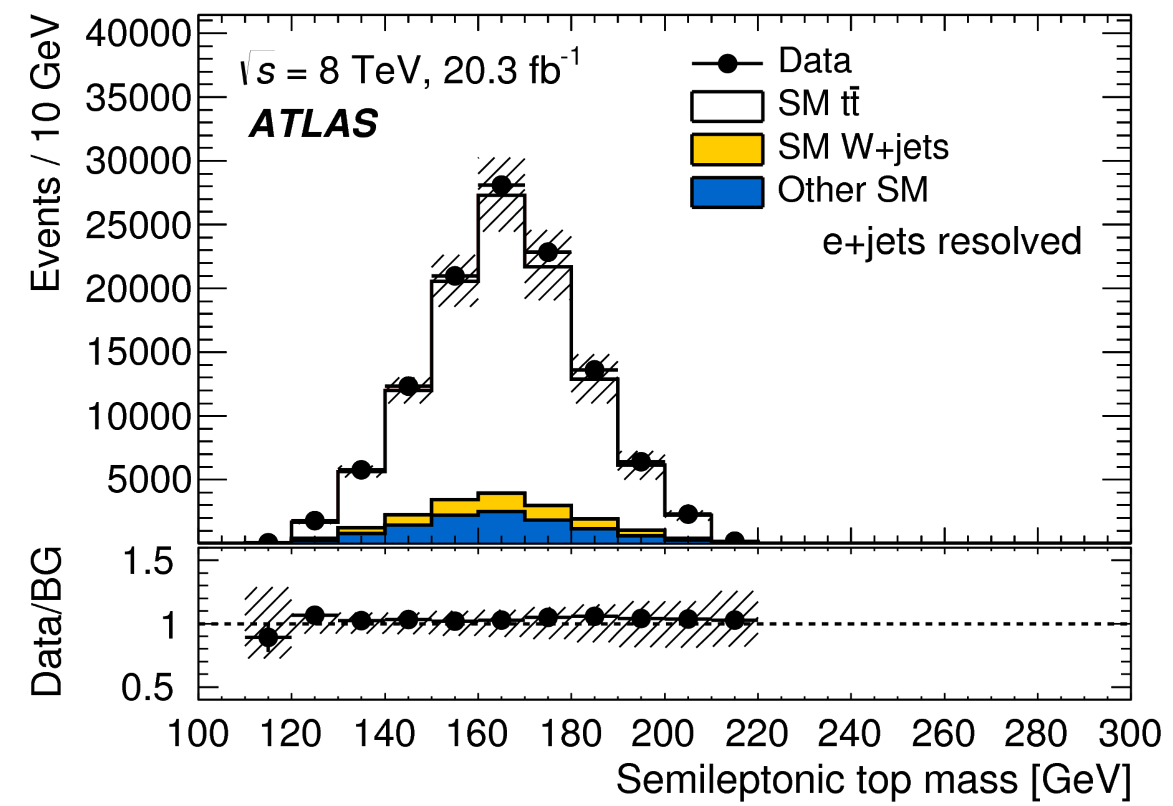


lepton+jets analysis

signal and background estimation

- <u>Signal simulation</u>
  - Bulk RS gravitons and gluons MadGraph+Pythia
  - *Z'* Pythia
  - Heavy scalars MadGraph_aMC@NLO
- <u>Background estimation</u>
  - $t\bar{t}$ Powheg+Pythia
    - calculated with Top++ NNLO plus resummation of NNLL soft gluon terms
  - *W*+jets Alpgen+Pythia
    - normalized in data using charge asymmetry in inclusive and 1 *b*-tag sample
      - different scale factors for *Wcc,Wbb,Wc*
  - Single top Powheg+Pythia
    - normalized to NNLO cross section
  - fake isolated leptons coming from multi-jets
    - data driven (matrix) method

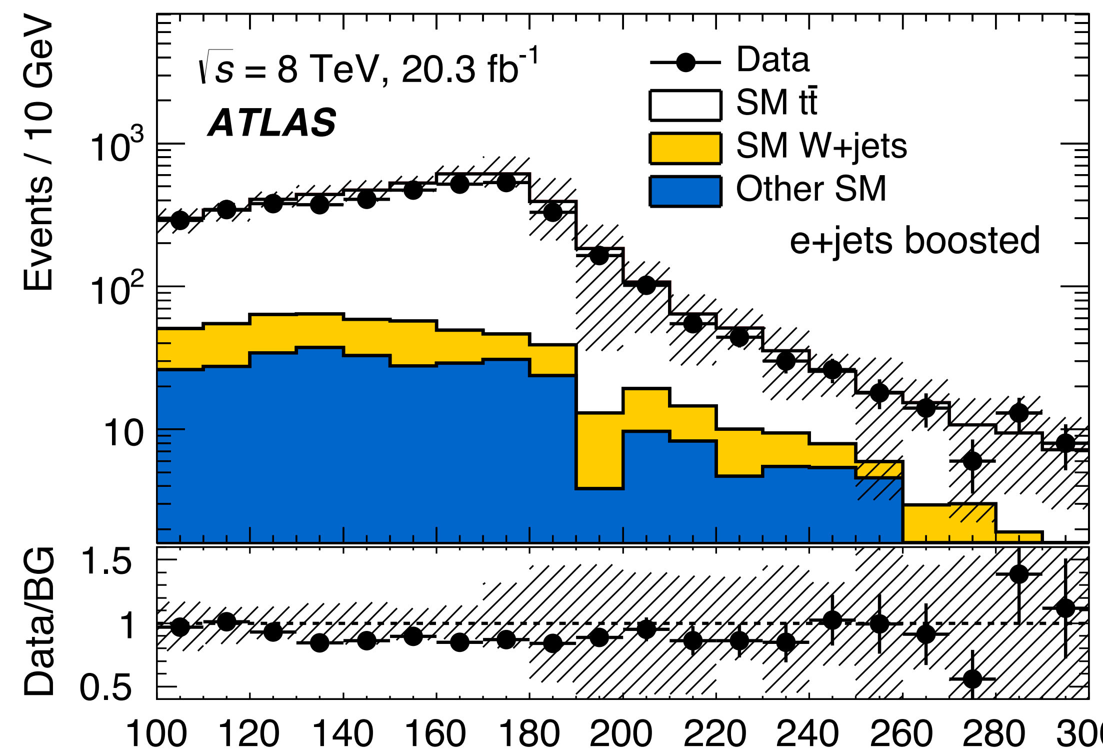


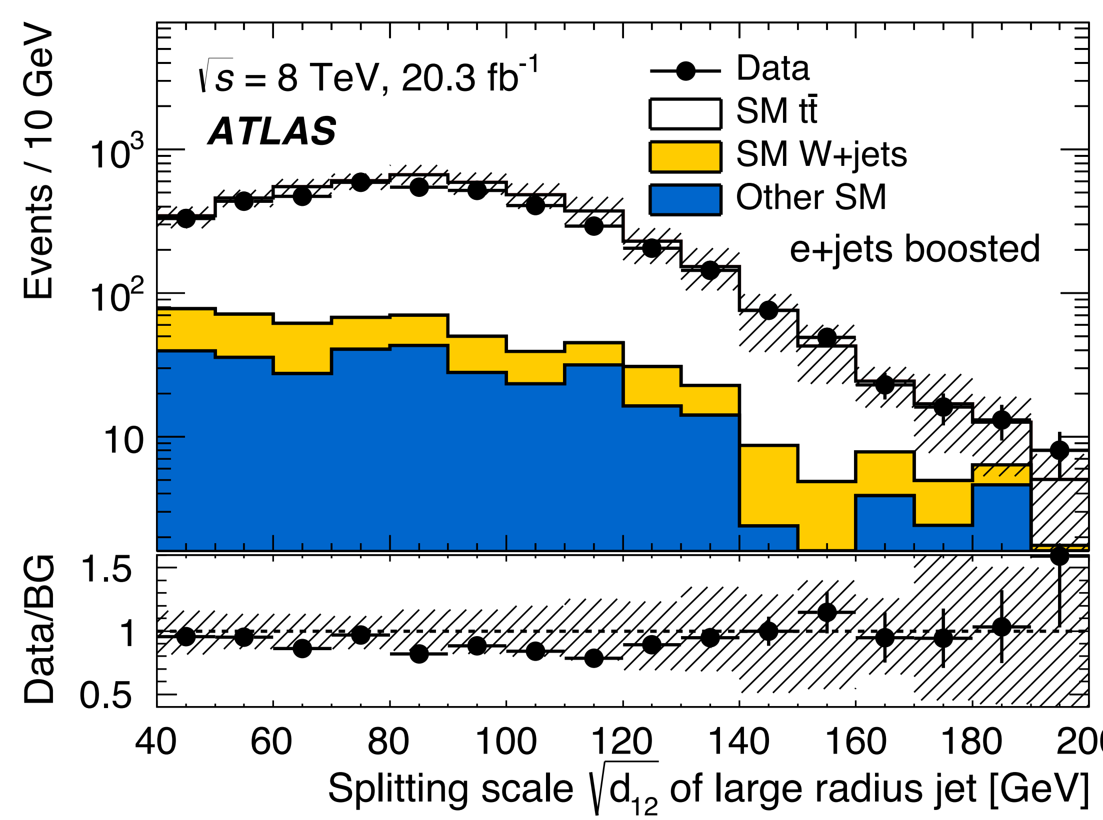


lepton+jets analysis

signal and background estimation

- <u>Signal simulation</u>
  - Bulk RS gravitons and gluons MadGraph+Pythia
  - *Z'* Pythia
  - Heavy scalars MadGraph_aMC@NLO
- <u>Background estimation</u>
  - $t\bar{t}$ Powheg+Pythia
    - calculated with Top++ NNLO plus resummation of NNLL soft gluon terms
  - *W*+jets Alpgen+Pythia
    - normalized in data using charge asymmetry in inclusive and 1 *b*-tag sample
      - different scale factors for *Wcc,Wbb,Wc*
  - Single top Powheg+Pythia
    - normalized to NNLO cross section
  - fake isolated leptons coming from multi-jets
    - data driven (matrix) method





systematic uncertainties

- one of the dominant uncertainty is JES, especially for fat jets
  - jet mass scale and k_t splitting scale
- Additional *b*-tagging uncertainties are considered for high pT
  - from dense environment tracking in high mass signals
- Parton shower systematics simulated with different choice of MC generators
  - i.e. for $t\bar{t}$ Powheg+Pythia and Powheg+Herwig
- dominant uncertainty on the background normalization is 6.5% on tt cross section

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

lepton+jets analysis

systematic uncertainties

- one of the dominant uncertainty is JES, especially for fat jets
  - jet mass scale and k_t splitting scale
- Additional *b*-tagging uncertainties are considered for high pT
  - from dense environment tracking in high mass signals
- Parton shower systematics simulated with different choice of MC generators
  - i.e. for $t\bar{t}$ Powheg+Pythia and Powheg+Herwig
- dominant uncertainty on the background normalization is 6.5% on tt cross section

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

lepton+jets analysis

systematic uncertainties

- one of the dominant uncertainty is JES, especially for fat jets
  - jet mass scale and k_t splitting scale
- Additional *b*-tagging uncertainties are considered for high pT
  - from dense environment tracking in high mass signals
- Parton shower systematics simulated with different choice of MC generators
  - i.e. for $t\bar{t}$ Powheg+Pythia and Powheg+Herwig
- dominant uncertainty on the background normalization is 6.5% on tt cross section

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

lepton+jets analysis

systematic uncertainties

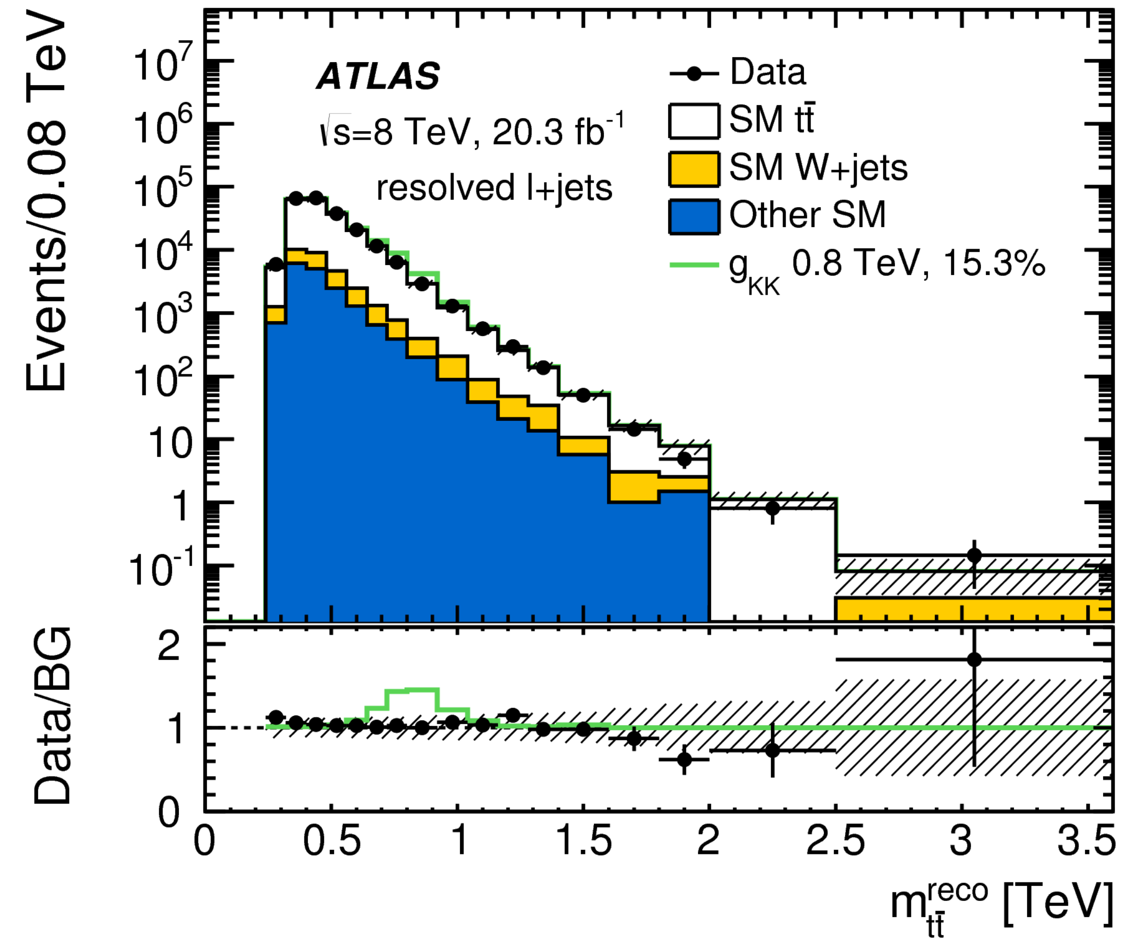
- one of the dominant uncertainty is JES, especially for fat jets
  - jet mass scale and k_t splitting scale
- Additional *b*-tagging uncertainties are considered for high pT
  - from dense environment tracking in high mass signals
- Parton shower systematics simulated with different choice of MC generators
  - i.e. for $t\bar{t}$ Powheg+Pythia and Powheg+Herwig
- dominant uncertainty on the background normalization is 6.5% on tt cross section

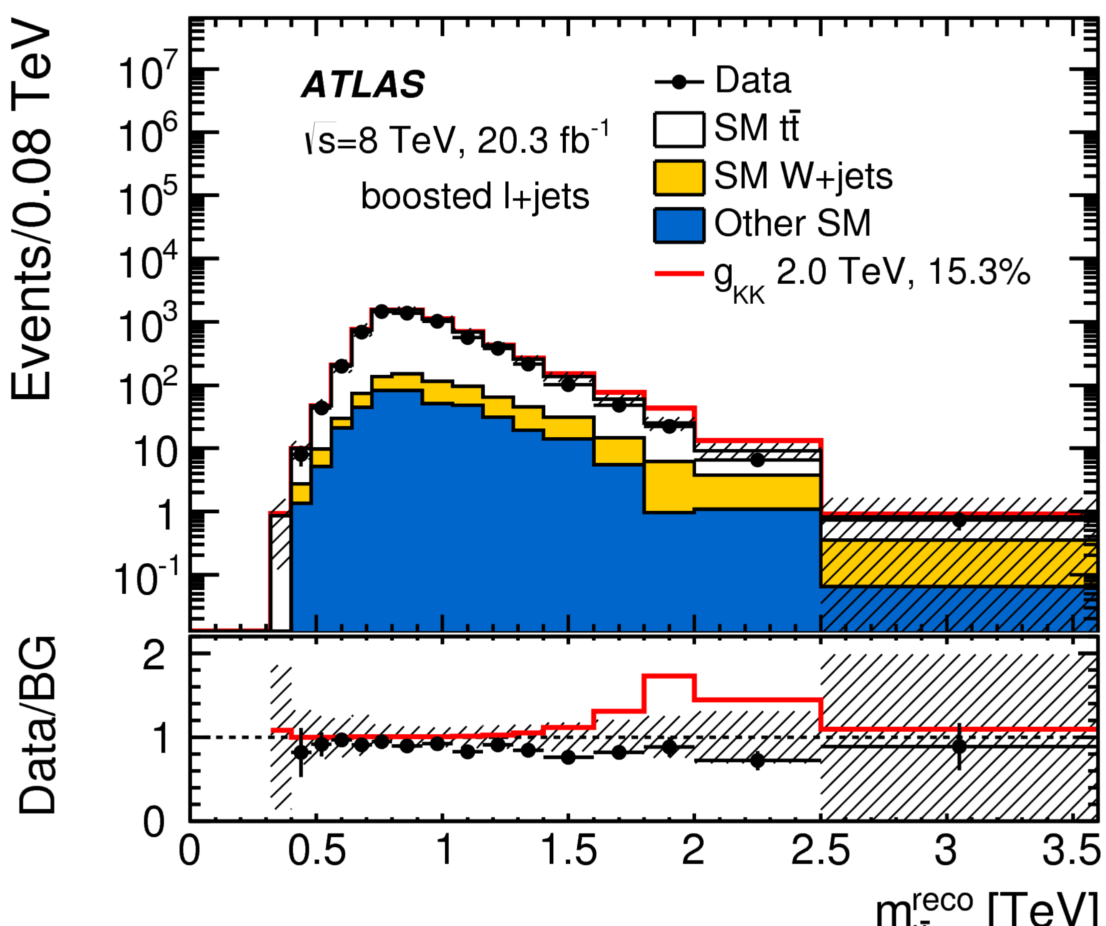
Systematic Uncertainties	Resolved selection yield impact [%] total bkg.	Resolved selection yield impact [%] Z'	Boosted selection yield impact [%] total bkg.	Boosted selection yield impact [%] Z'
Luminosity	2.5	2.8	2.6	2.8
PDF	2.4	3.6	4.7	2.3
ISR/FSR	3.7	–	1.2	–
Parton shower and fragmentation	4.8	–	1.5	–
$t\bar{t}$ 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

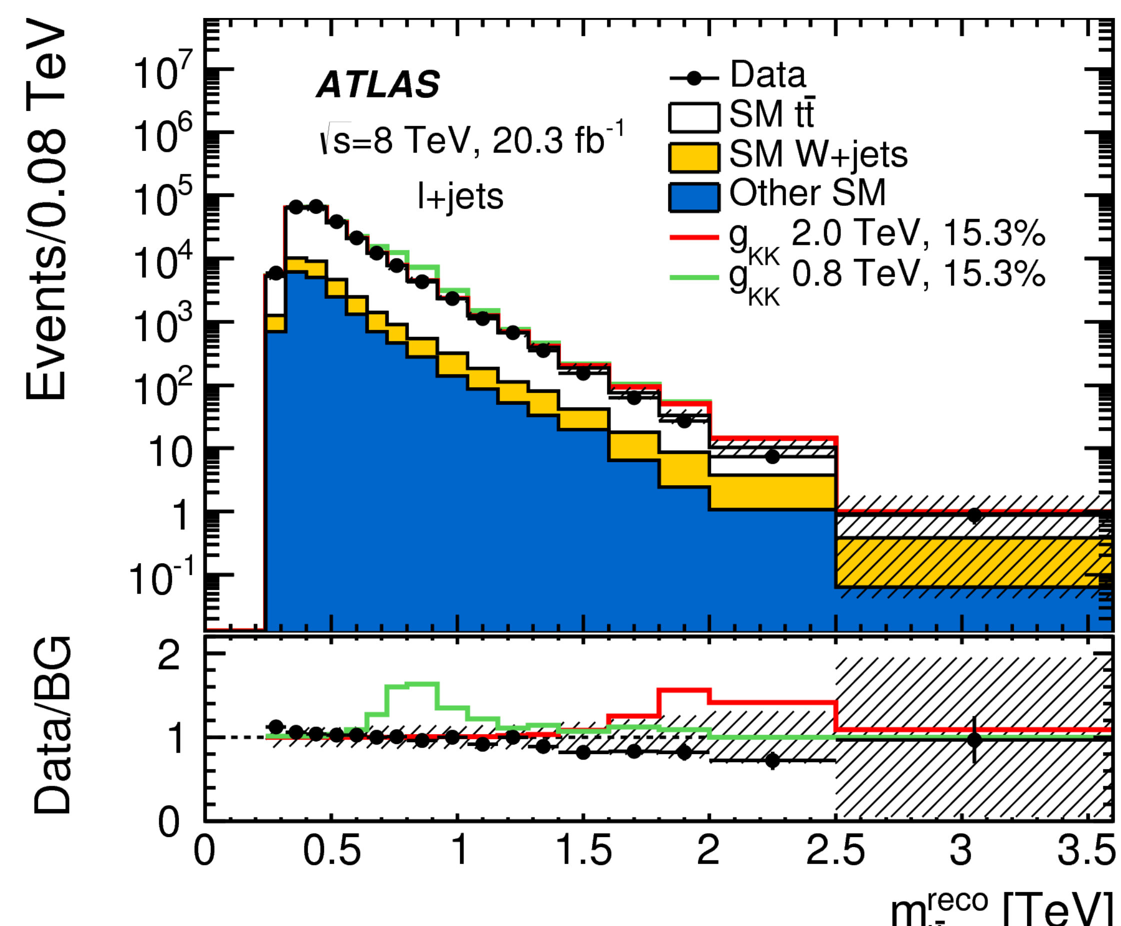
lepton+jets analysis

pre-fit plots

- Overall good agreement between data and expected background
- 12 channels are fitted at the same time
  - 2 channels, 2 boosted regimes, leptonic, hadronic or both *b*-tagged top jets
  - statistical and systematic uncertainties are included as nuisance parameters in the fit



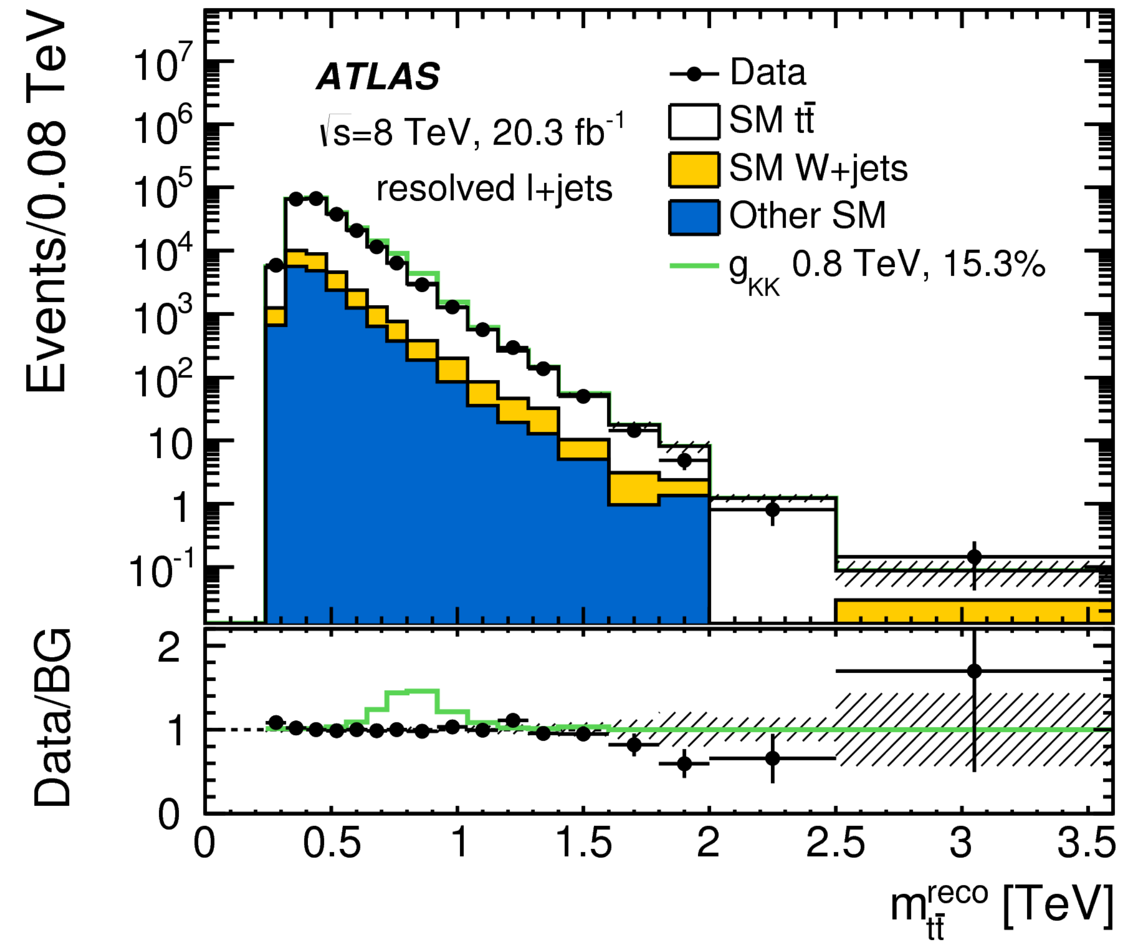


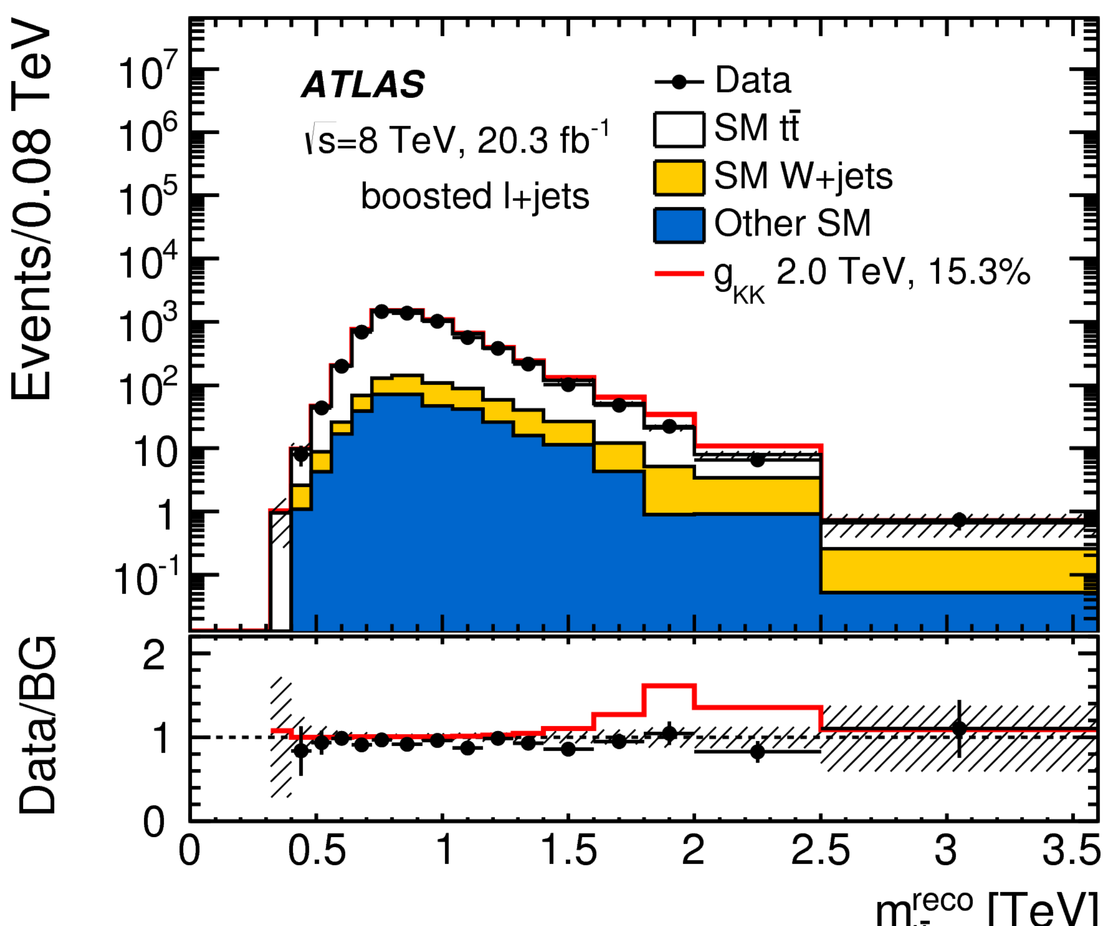


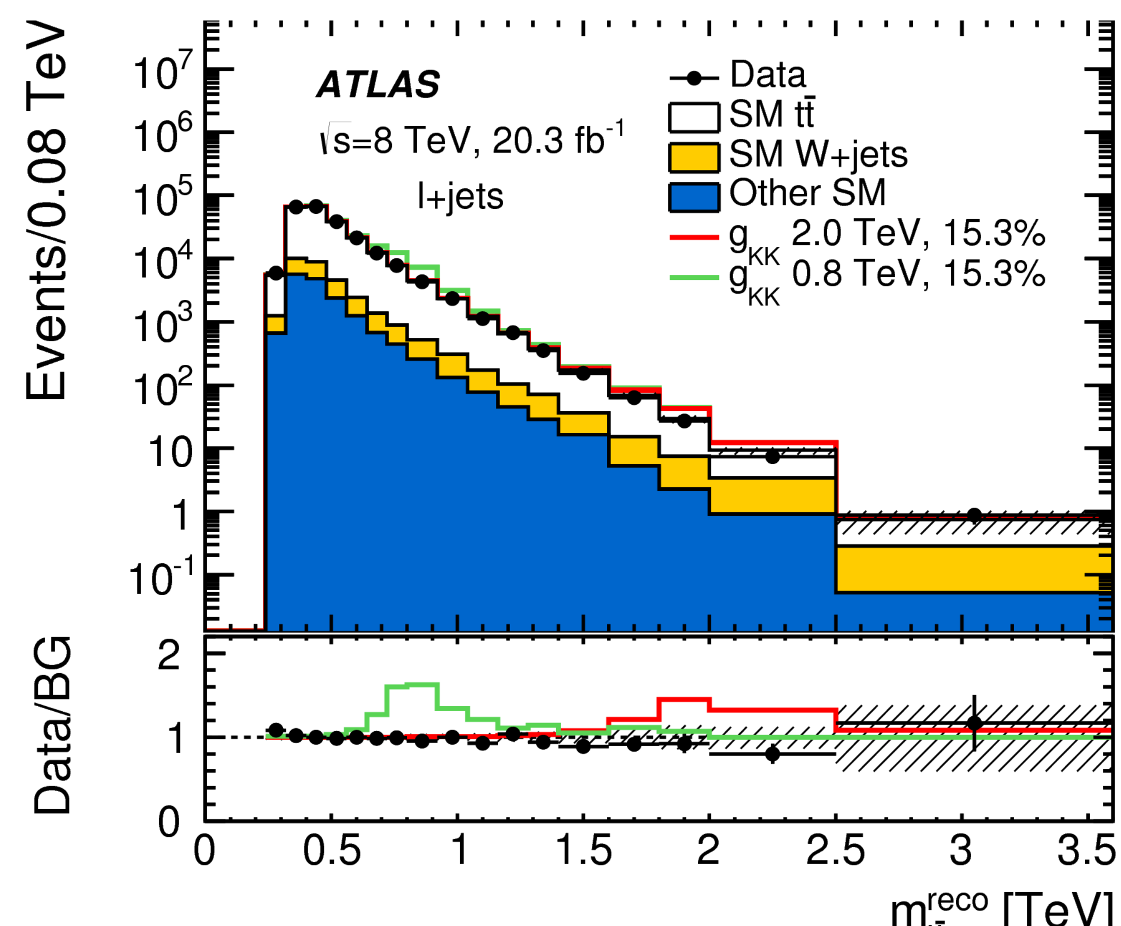
lepton+jets analysis

post-fit plots

- Overall good agreement between data and expected background
- 12 channels are fitted at the same time
  - 2 channels, 2 boosted regimes, leptonic, hadronic or both *b*-tagged top jets
  - statistical and systematic uncertainties are included as nuisance parameters in the fit

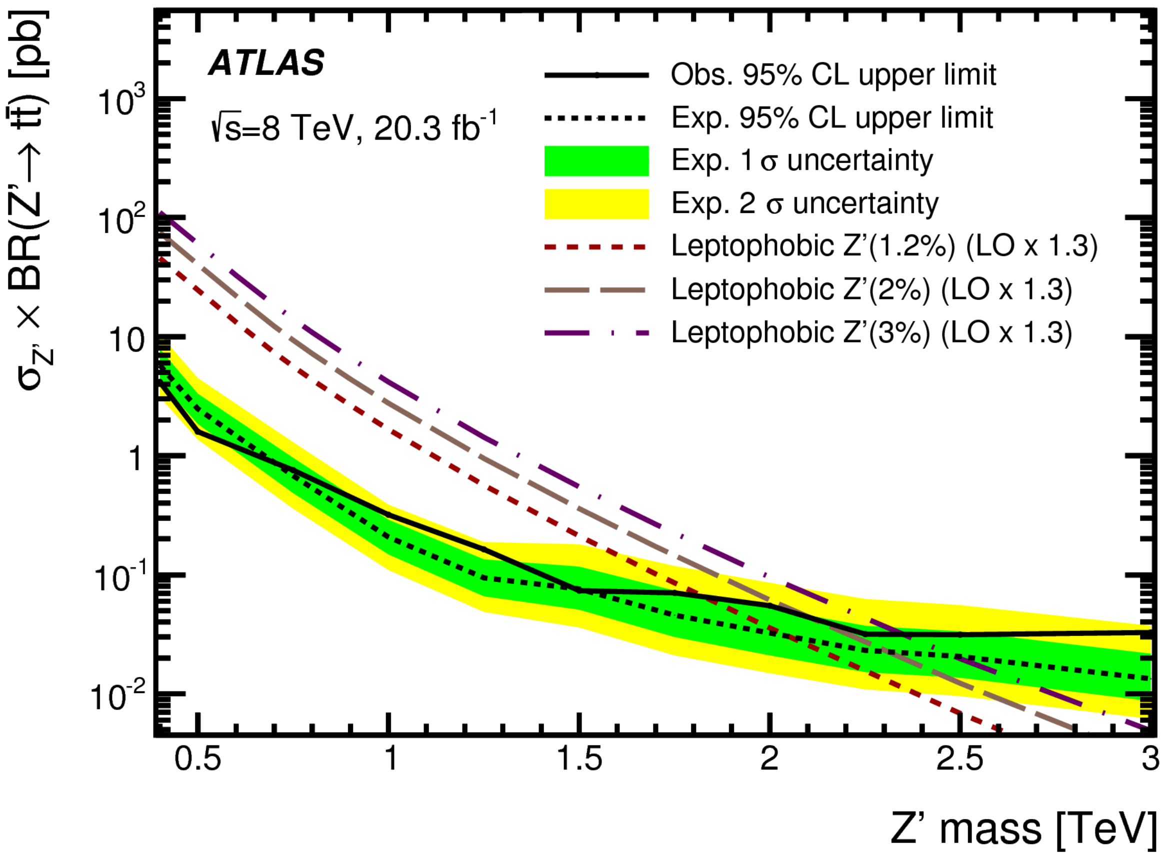


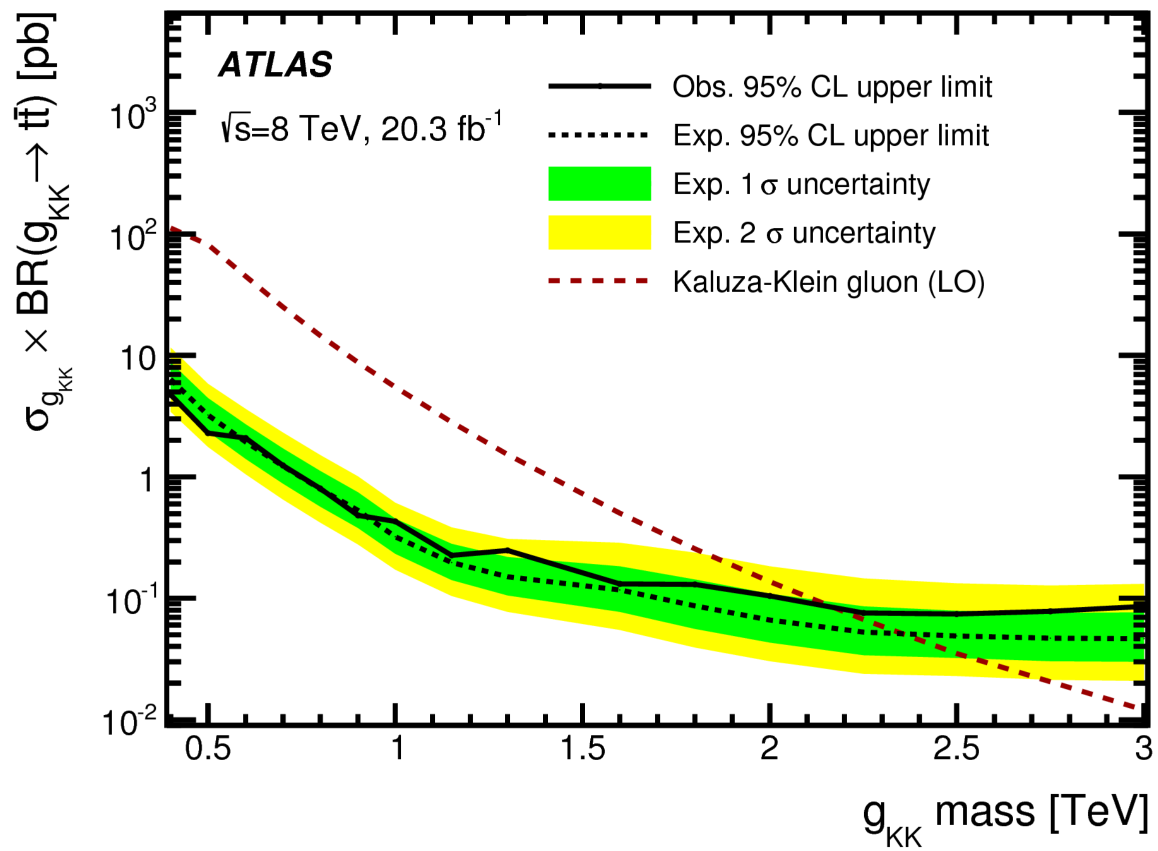


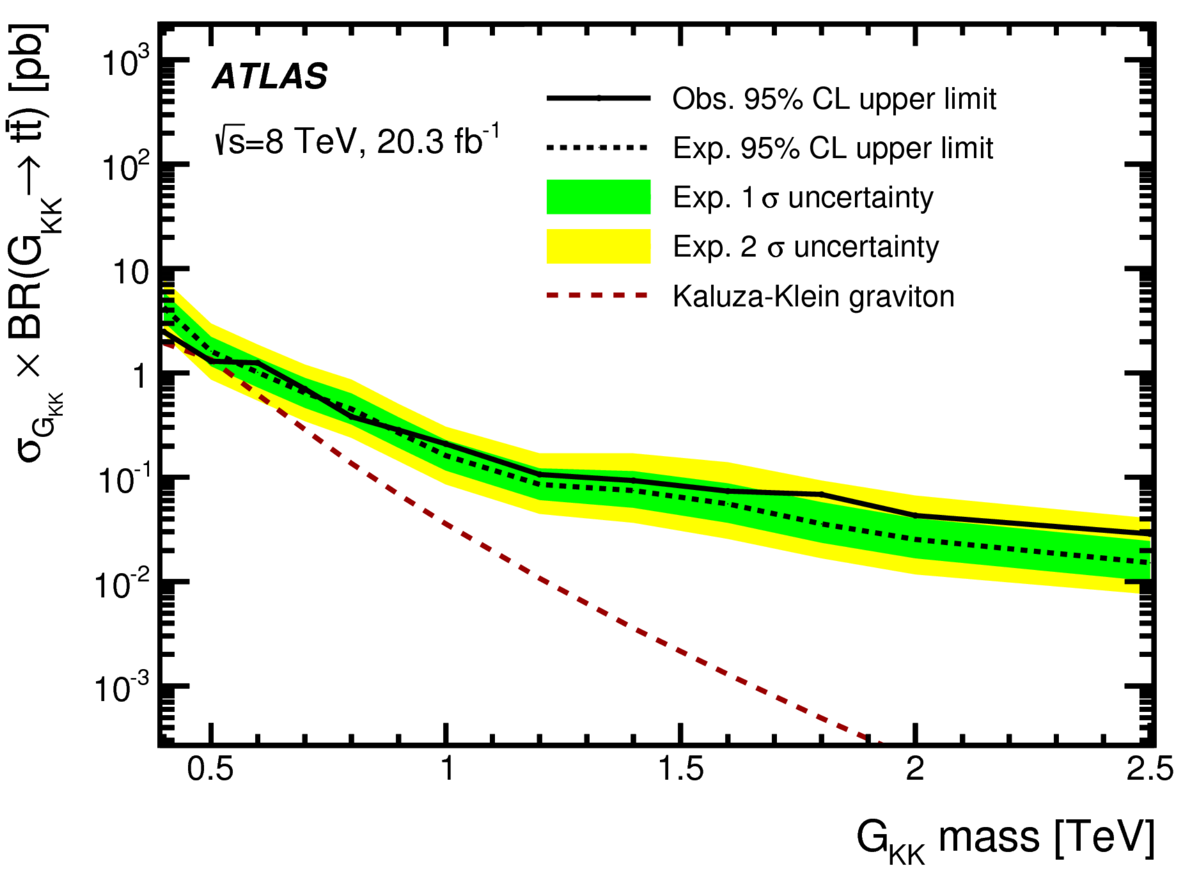


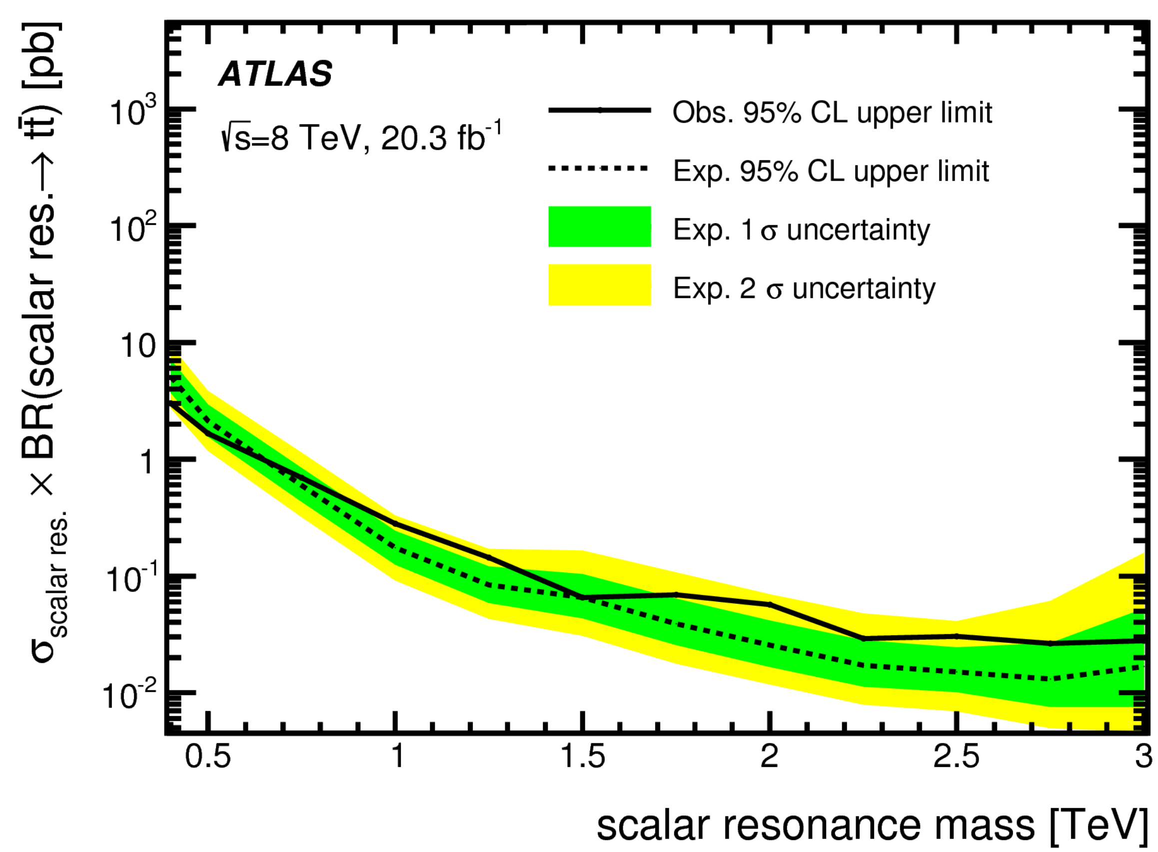
lepton+jets analysis

results





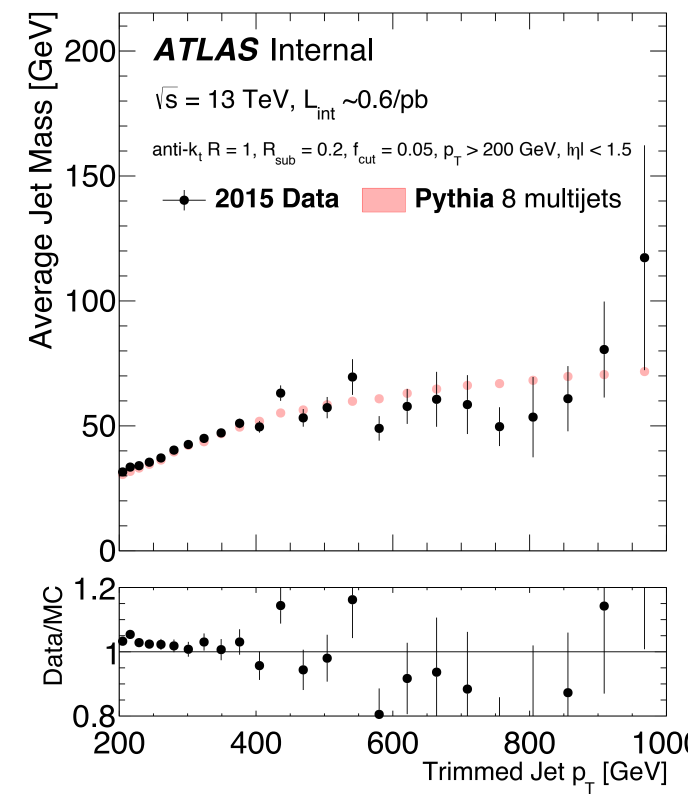


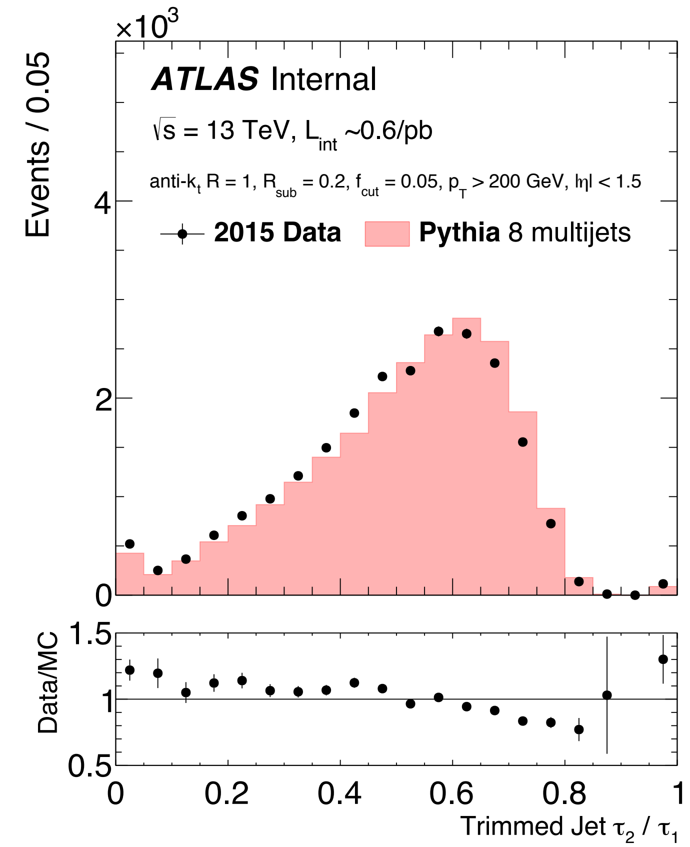


Conclusions

ATL-PHYS-PUB-2015-036

- A search for heavy particles decaying to tt in the lepton-plus-jets and all hadronic decay channels was carried out with the ATLAS experiment at the LHC
  - search corresponds respectively to 4.7 fb^{-1} and 20.3 fb^{-1} of *p-p* collisions at $\sqrt{s}$ = 7 and 8 TeV
- No excess of events beyond the Standard Model predictions
  - Upper limits on the cross-section times branching ratio are set for four different signal models
    - Z'_{TC2} with Γ/m = 1.2% is excluded for $m_{Z'}$ < 1.8 TeV
    - g_{KK} with Γ/m = 15.3% is excluded for m_{gkk} < 2.2 TeV
    - Cross section limits for G_{kk} range from 2.5 pb for m_{Gkk} = 0.4 TeV to 0.03 pb for m = 2.5 TeV
    - Cross section limits for narrow scalar resonances range from 3.0 pb for m = 0.4 TeV to 0.03 pb for m = 2.5 TeV
- ATLAS Run 2 analyses will soon outperform Run 1 ones
  - First look already at large radius jets properties with Run 2 data





back up

data MC yield

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