Search for new resonances coupling to third generation quarks in pp collisions at 13 TeV at ATLAS

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on behalf of the *ATLAS Collaboration*

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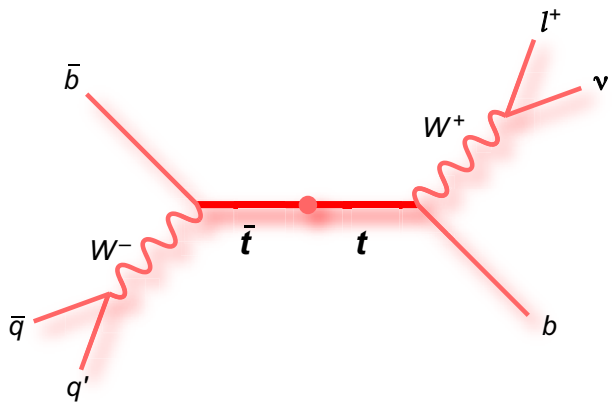
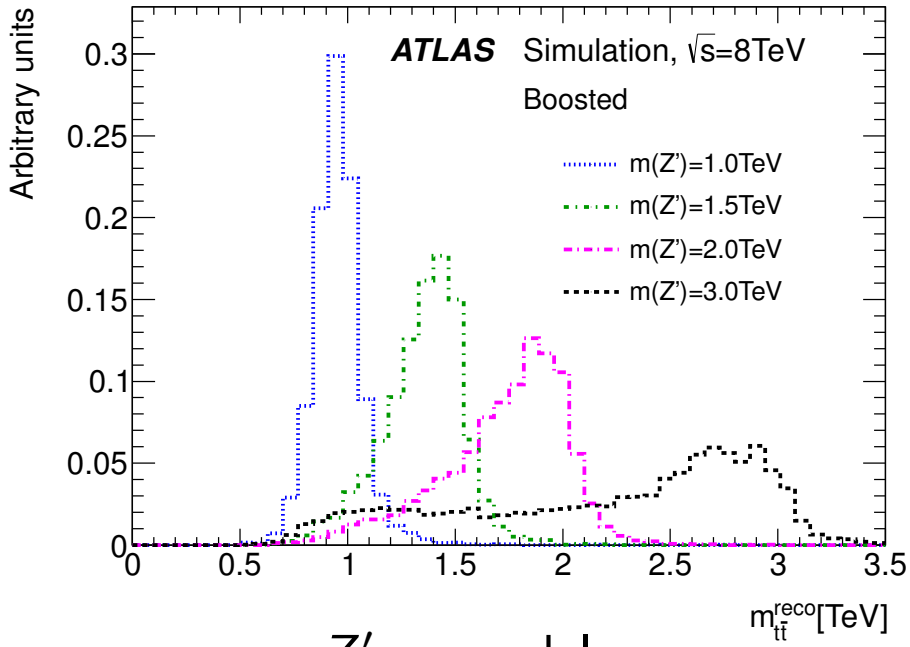
Introduction

- Some important updates on top- and bottom-related analyses produced by ATLAS will be shown.
- **Top-antitop resonances** searches at **8 TeV** and a preliminary result at **13 TeV**.
- Re-interpretation of the 8 TeV top-antitop resonance search to tackle **scalar 2HDM signal H/A** $\rightarrow t\bar{t}$ at 8 TeV.
  - An important update on the 8 TeV results.
  - Includes interference effects.
- **Di-jet resonances** with at least one b-tagged jet at 13 TeV.

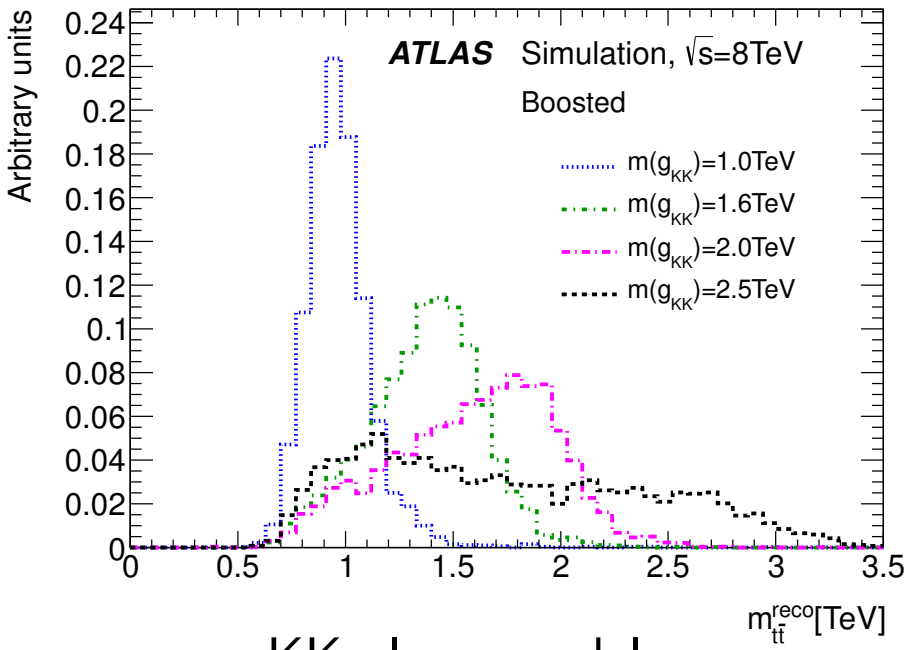
Search for $t\bar{t}$ resonances at 8 TeV[1]

- Search for a bump in the top-antitop mass spectrum.
- Main backgrounds are SM $t\bar{t}$, W+jets, single top and Z+jets.
- Different benchmarks used, but attempt to keep analysis model agnostic.





Z'_{TC2} model



KK gluon model

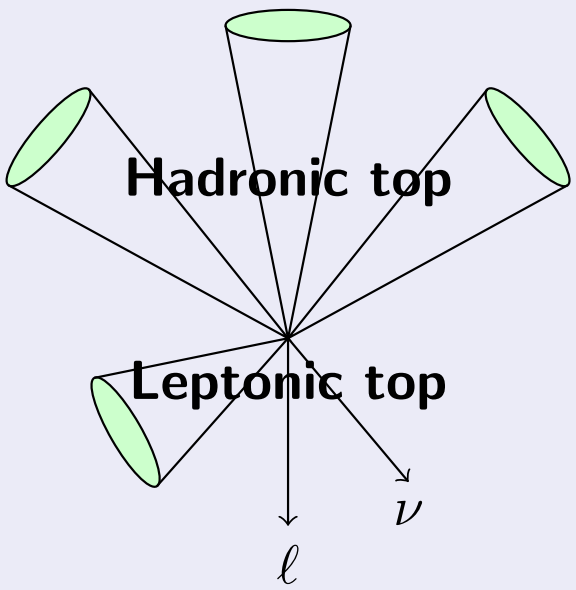
[1] ATLAS Collaboration. In: *JHEP* 08 (2015), p. 148. arXiv: 1505.07018 [hep-ex].

Event selection

- Exactly one electron or muon ($p_T > 25$ GeV).
- $E_T^{\mathrm{miss}} > 20$ GeV and $E_T^{\mathrm{miss}} + m_{T,W} > 60$ GeV.
- Assuming W mass constrain to reconstruct the neutrino z momentum component.
- ≥ 1 b-tagged jet (anti-k_t $R = 0.4$ calorimeter jet) @ 70% eff.
- Anti-k_t $R = 0.4$ jets with $p_T > 25$ GeV and $|\eta| < 2.5$.

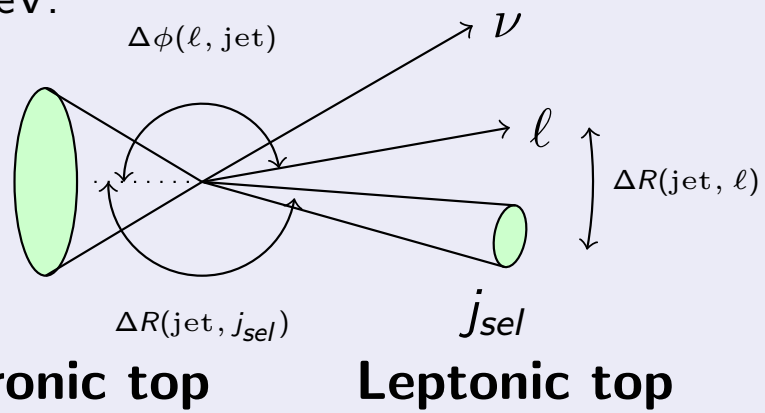
Resolved channel

- ≥ 4 anti-k_t calorimeter $R = 0.4$ jets required.



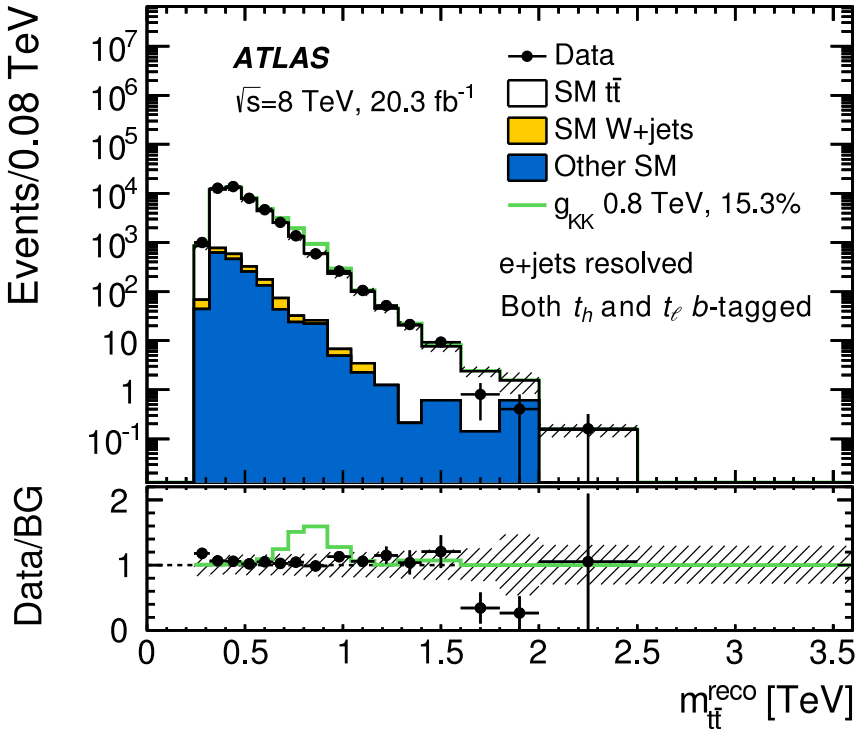
Boosted channel

- ≥ 1 anti-k_t calo. $R = 0.4$ jet ($p_T > 25$ GeV) that has $\Delta R(\mathrm{jet}, \ell) < 1.5$ (j_{sel}).
- ≥ 1 top-tagged anti-k_t calo. $R = 1.0$ jet ($p_T > 300$ GeV, $|\eta| < 2.0$) with $\Delta\phi(\ell, \mathrm{jet}) > 2.3$ and $\Delta R(\mathrm{jet}, j_{\mathrm{sel}}) > 1.5$.
- Top-tagging: $m > 100$ GeV, $\sqrt{d_{12}} > 40$ GeV.

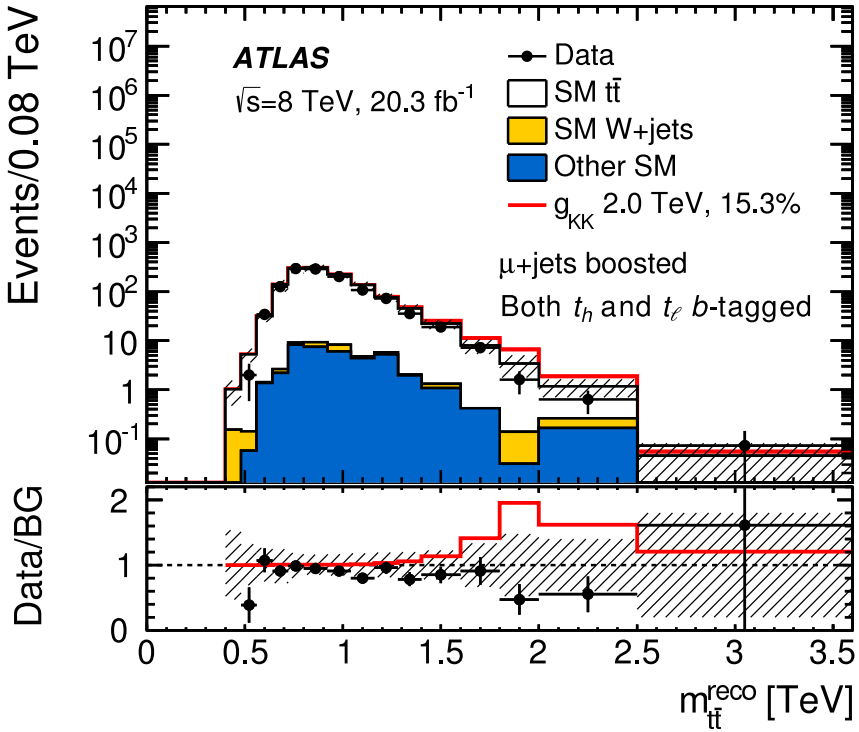


Mass spectrum reconstruction

- Kinematic χ^2 fit to select small-R jets in resolved channel.
- Large-R jet used to reconstruct hadronic top in boosted channel.



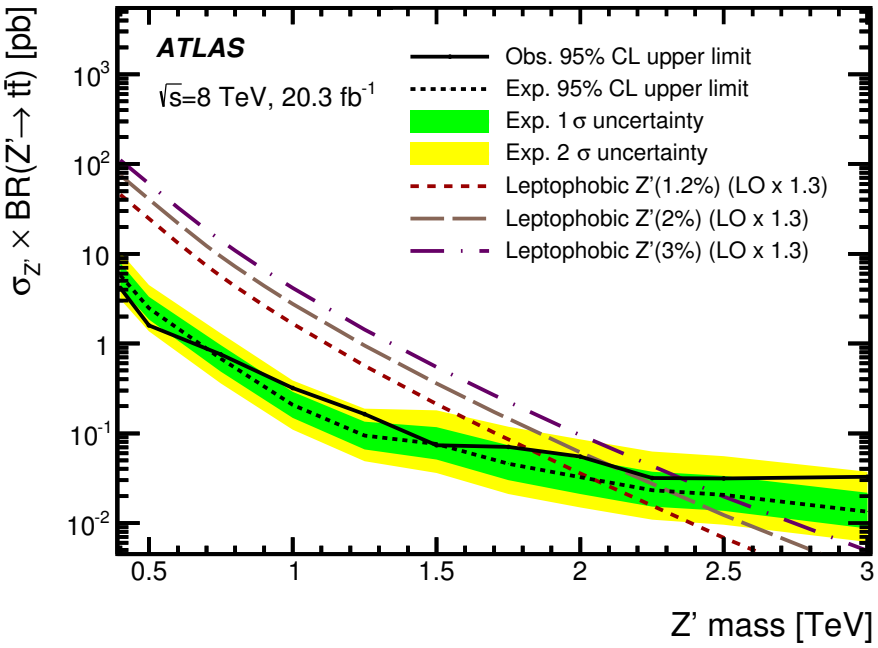
Resolved spectrum in e channel

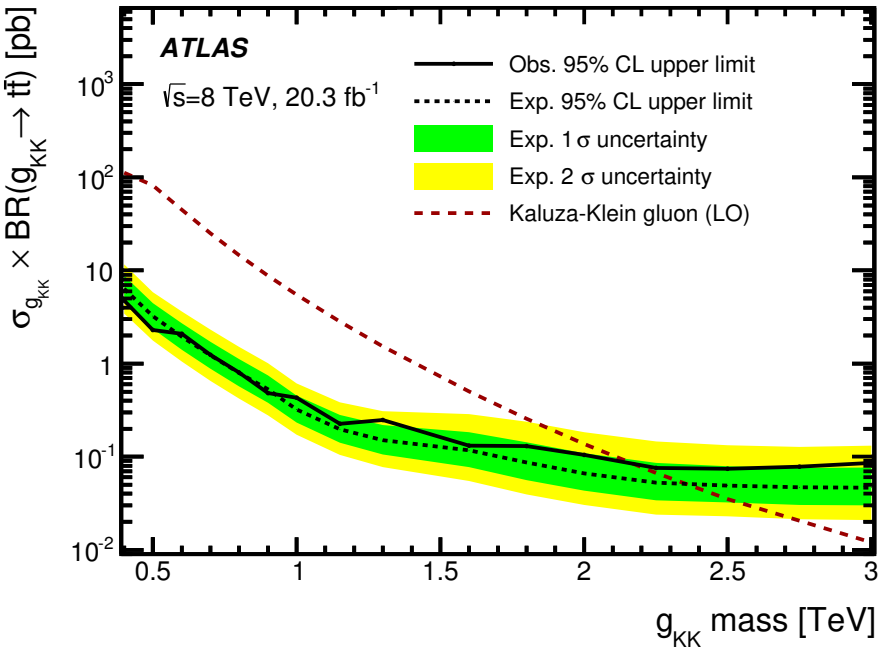


Boosted spectrum in μ channel

Limit setting

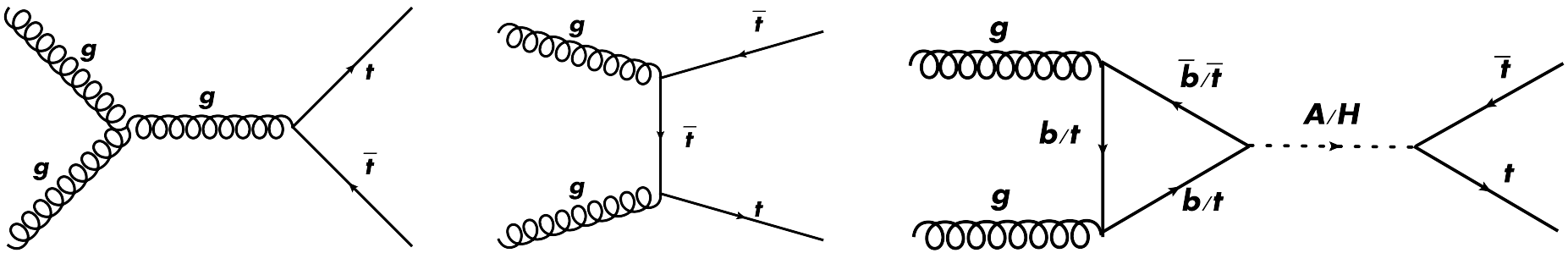
- No excess observed, so we set limits on our benchmark models.
- Analysis also sets limits on Kaluza-Klein graviton and scalar.
- Different *b*-tag categories considered: *b*-jets matched to both tops (1), only the hadronically decaying top (2) or only the leptonically decaying top (3).





Search for $t\bar{t}$ scalar resonances at 8 TeV[2]

- Signal in the right-hand-side diagram interferes with SM production of $t\bar{t}$.
- 8 TeV paper did not include interference effects.
- Re-interpretation including the **interference effects of 2HDM type-II** $H/A \to t\bar{t}$.
- We also want to keep the good description of the background provided by Powheg+Pythia6.

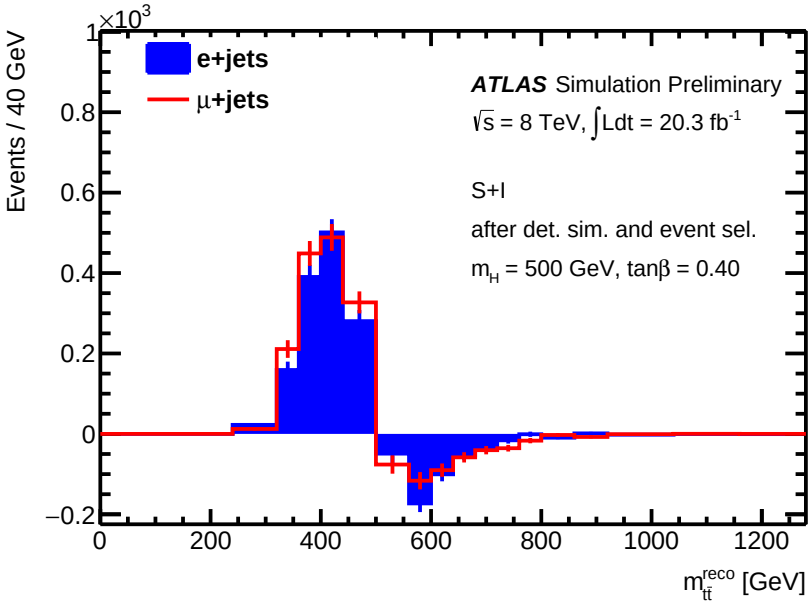


[2] ATLAS Collaboration. In: ATLAS-CONF-2016-073 (2016). URL: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-073/.

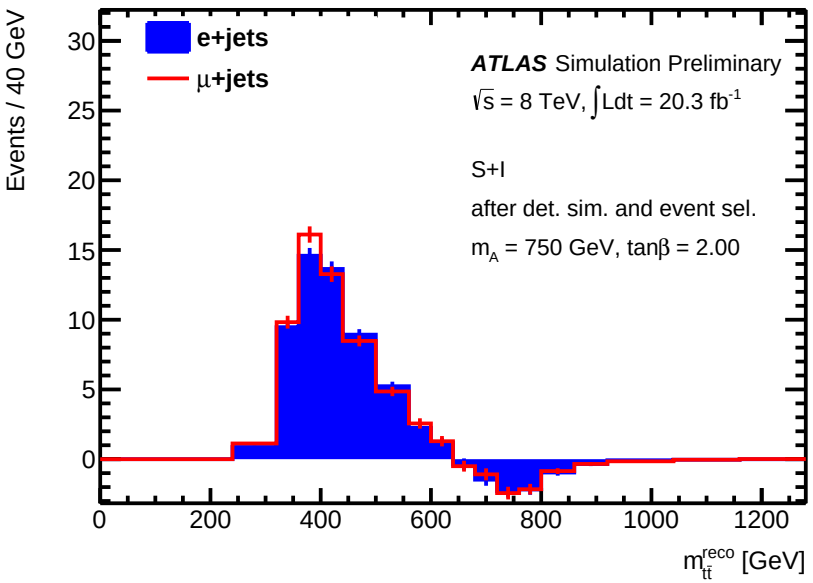
Including interference effects

- Using only resolved channel, and same setup as described previously.
- Generated events removing background $|ME|^2$ in MadGraph to keep only signal and interference terms.
- Validated this by generating full signal, interference and background out of the box.

$H(500\ \mathbf{GeV}) \to t\bar{t}$, $\tan\beta = 0.40$

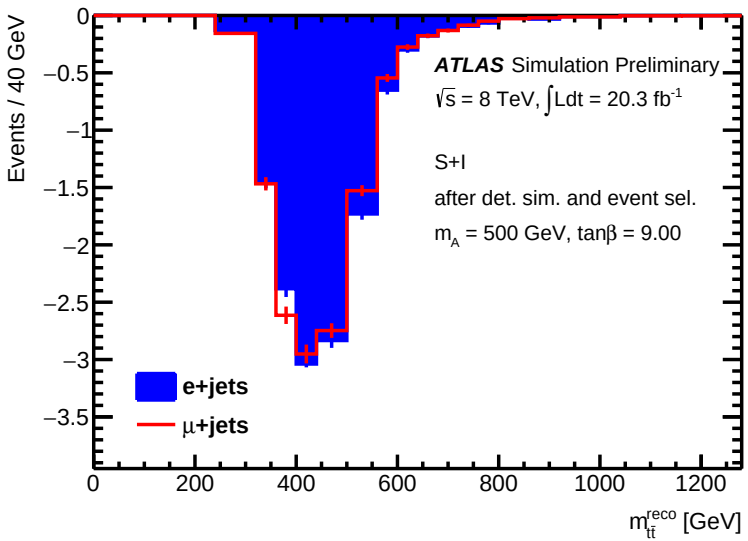


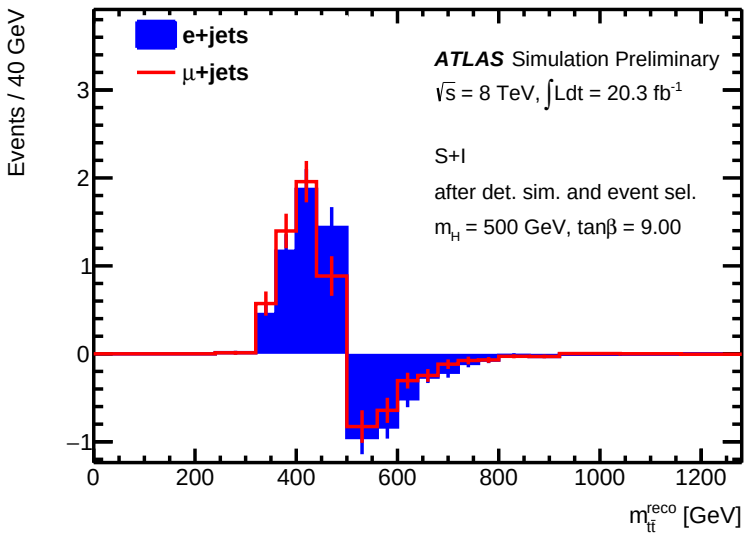
$A(750\ \mathbf{GeV}) \to t\bar{t}$, $\tan\beta = 2.00$



Strong destructive interference

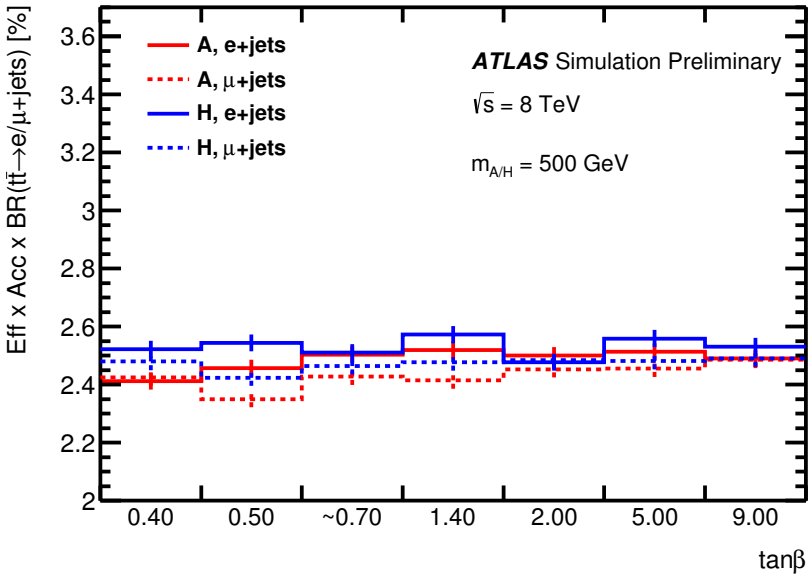
- Assumes $\sin(\beta - \alpha) = 1$.
- Results not including interference would not model all regions of the parameter space well.
- In some parameter configurations of the 2HDM signals, we can even have a fully negative "signal + interference".

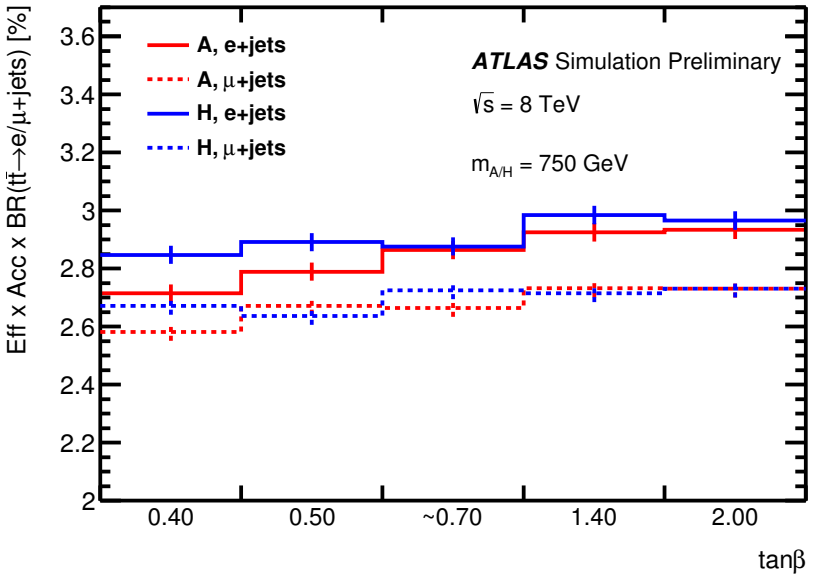




Acceptance of signal

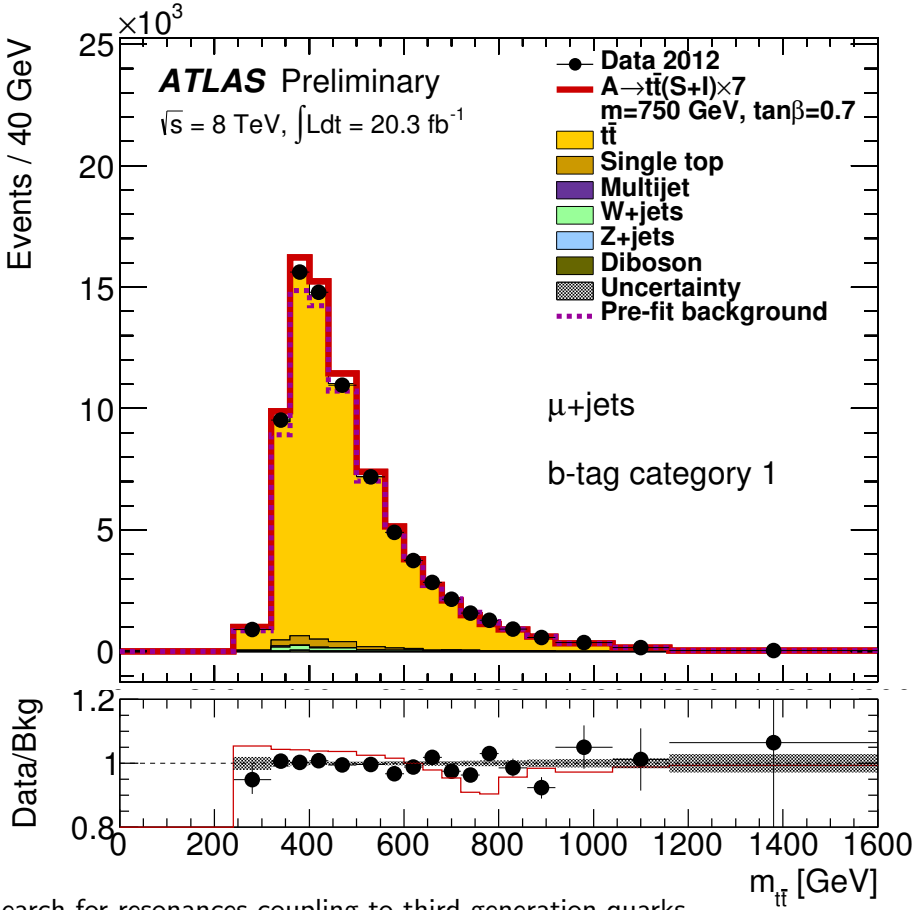
- Heavy (pseudo-)scalar acceptance in such selection does not depend heavily on $\tan\beta$, although the acceptance has a slight slope.
- In this study, high boost events that also satisfy the resolved selection are kept in the resolved result $\rightarrow$ maximise acceptance at low $m_{t\bar{t}}$.

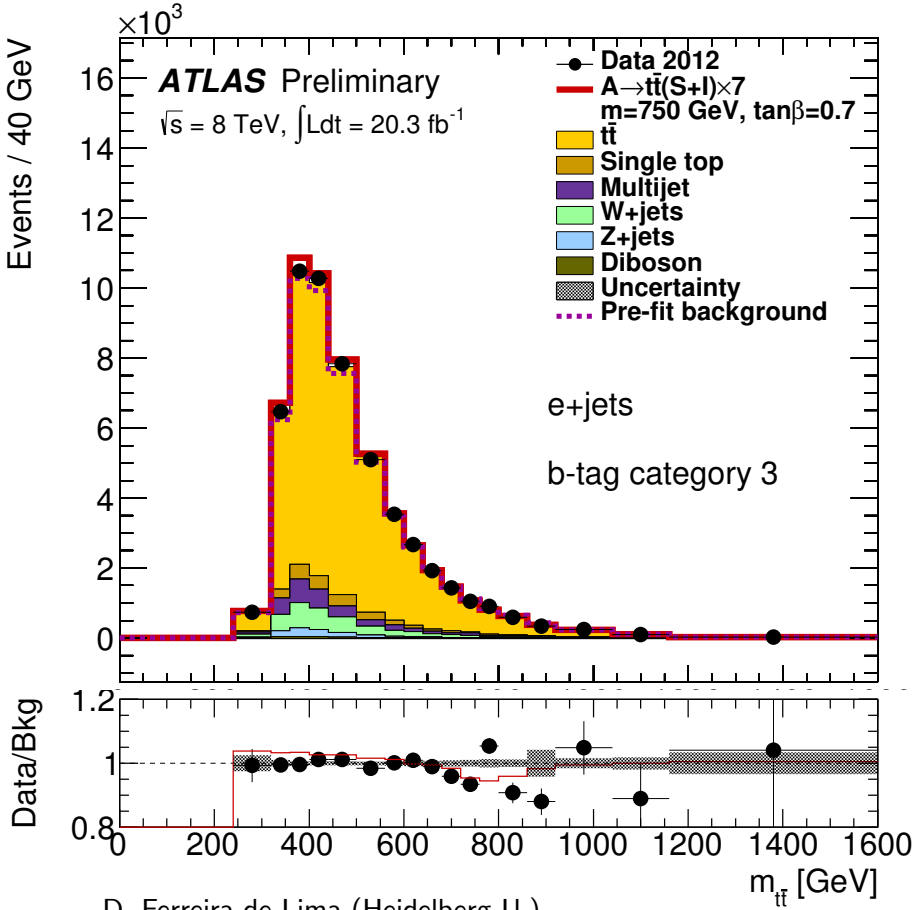




Expected impact in final observable

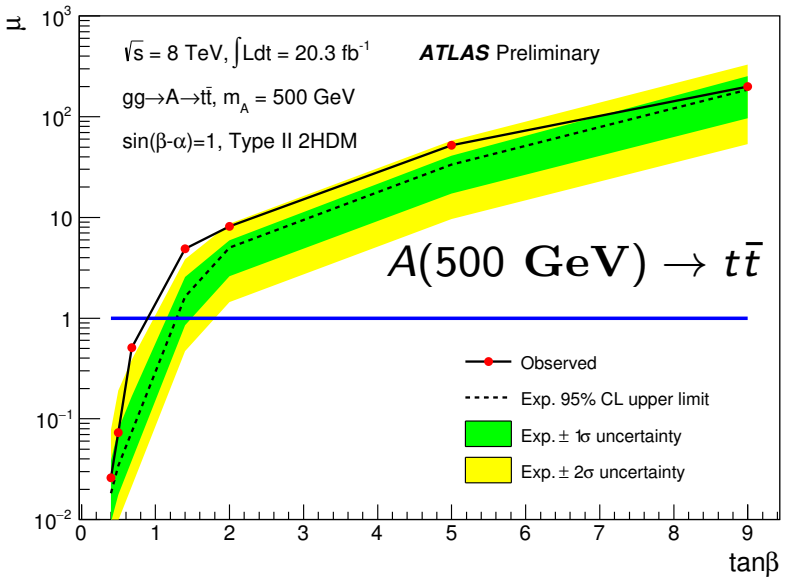
- The "signal+interference" effect is added on top of the Powheg+Pythia 6 $t\bar{t}$ SM background and all others.
- Signal modelling uncertainties include PDF and renormalisation and factorisation scale uncertainties.
- Limits are set parametrising $S + I$ and S as a function of $\sqrt{\mu}$: $\mu S + \sqrt{\mu} I + B = \sqrt{\mu}(S + I) + (\mu - \sqrt{\mu})S + B$.

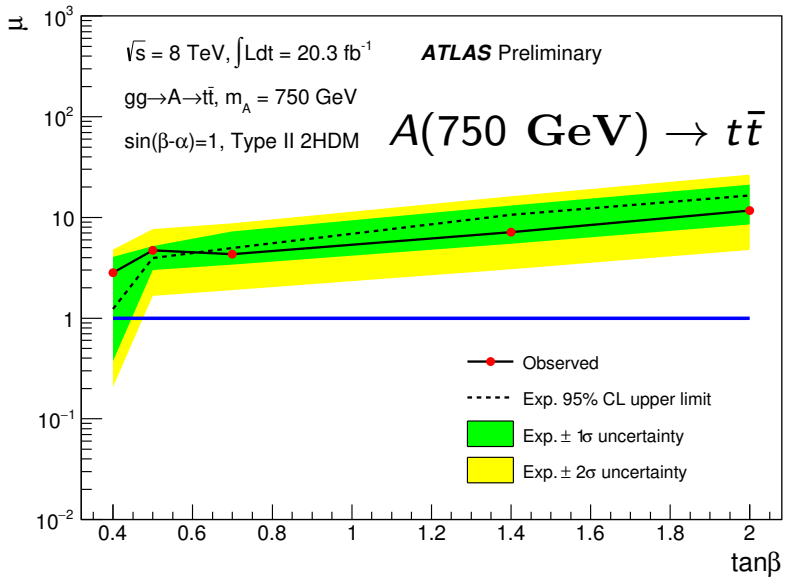


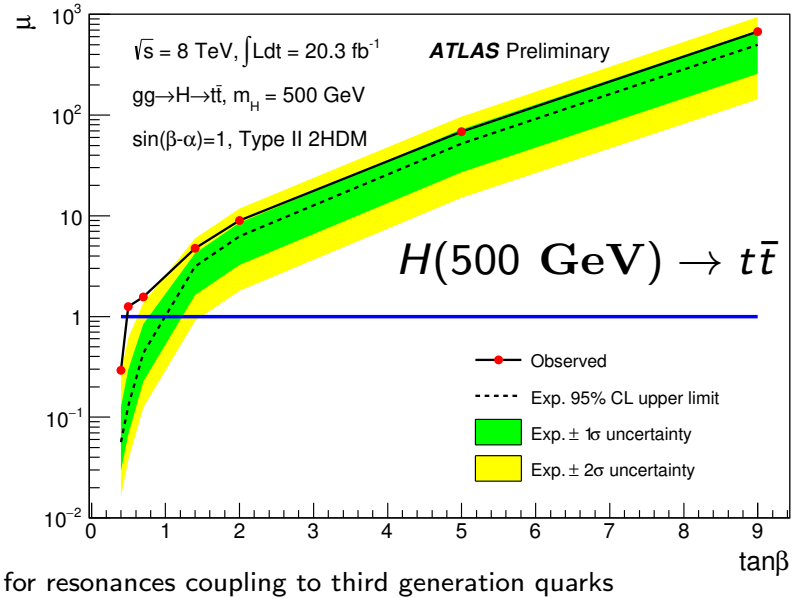


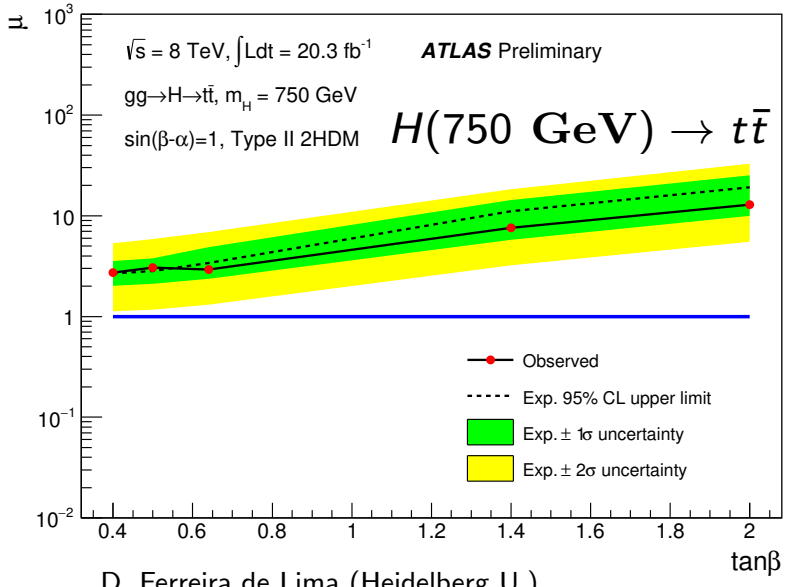
Scalar model limits at 8 TeV

- Limits set on $\tan\beta$ for $\mu = 1$ on both scalar and pseudo-scalar.



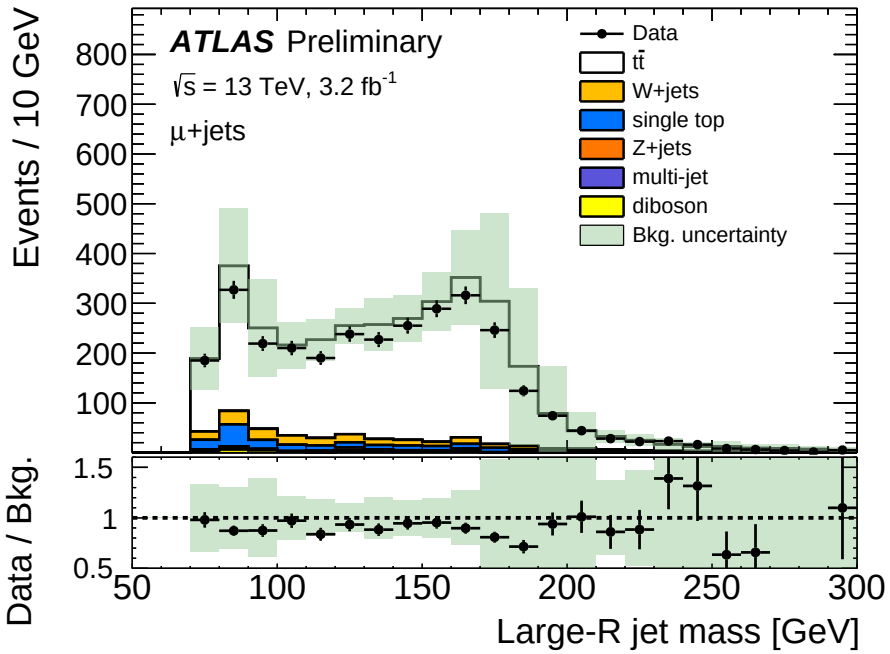




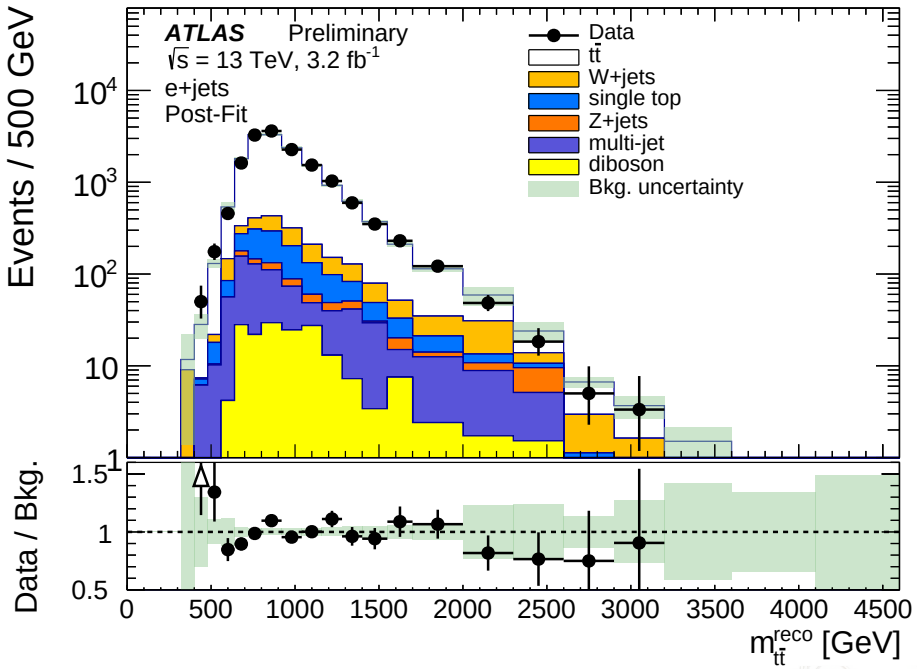


Search for $t\bar{t}$ resonances at 13 TeV[3]

- Study redone at 13 TeV with first data (3.2 fb^{-1}), using only the boosted channel.
- Using anti-k_t $R = 0.2$ track jet b-tagging $\rightarrow$ better performance at high $m_{t\bar{t}}$.



Large-R jet mass in μ channel

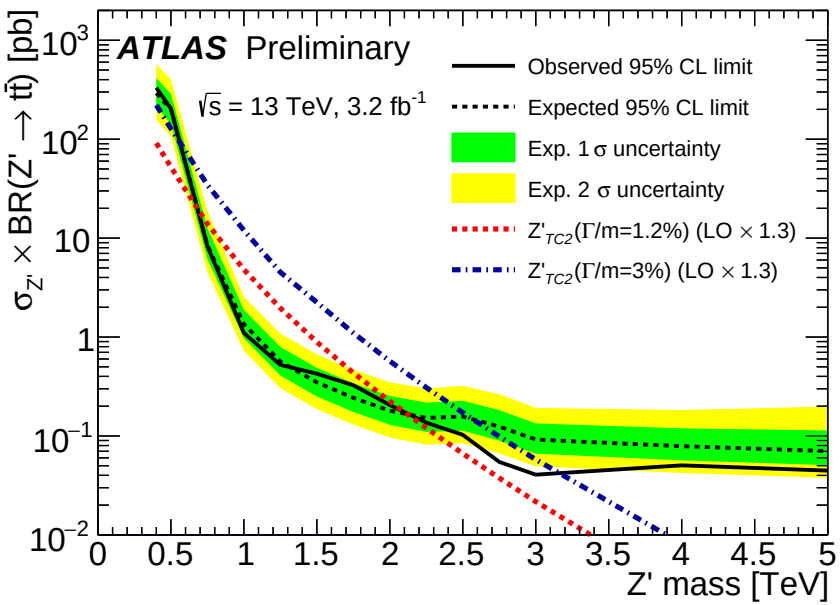


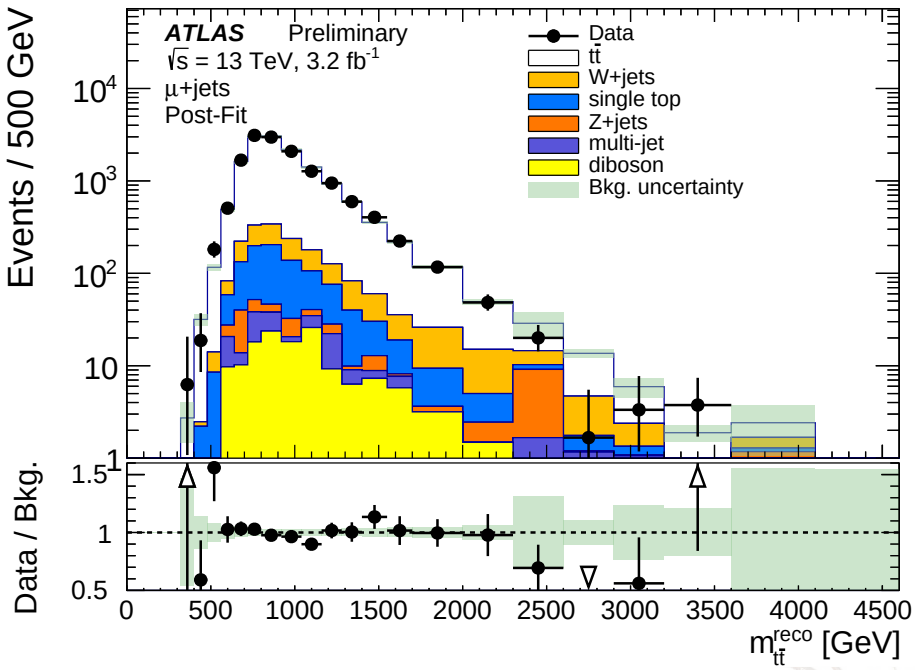
$m_{t\bar{t}}$ in e channel

[3] ATLAS Collaboration. In: ATLAS-CONF-2016-014 (2016). URL: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-014/.

13 TeV limits

- No excess found.
- Limits set on the Z'_{TC2} model only.
- Small deficit observed.
- Expected to be a statistical fluctuation.

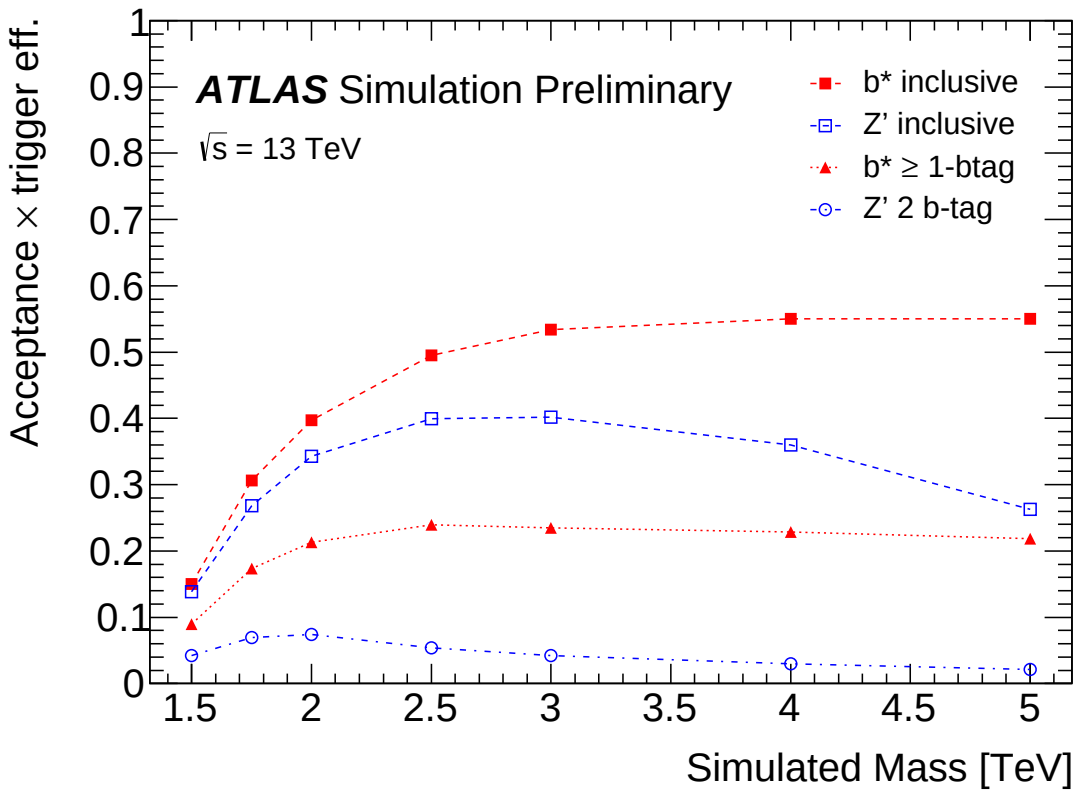


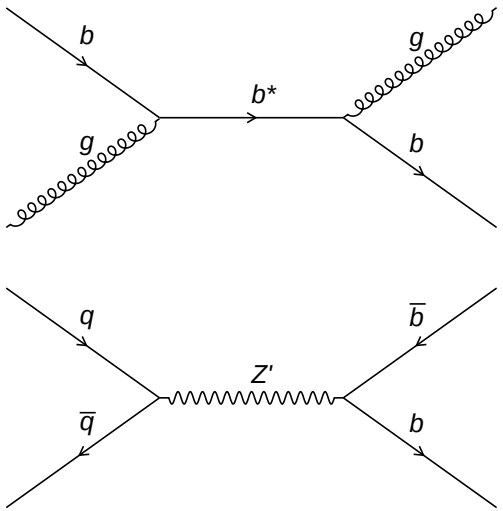


$m_{t\bar{t}}$ in μ channel

Di-jet resonances with at least one b-tag[4]

- Jet trigger with a $p_T > 360$ GeV in 2015 and $p_T > 380$ GeV in 2016.
- 2 anti-k_t $R = 0.4$ calorimeter jets: $p_{T1} > 430$ GeV, $p_{T2} > 60$ GeV.
- Rapidity difference requirement: $|y^*| = |(y_1 - y_2)/2| < 0.6 \rightarrow$ favours s-production.
- At least one 85% eff. b-tag is required and events are split in 1 b-tag and 2 b-tag categories.
- $m_{jj} > 1.38$ TeV.

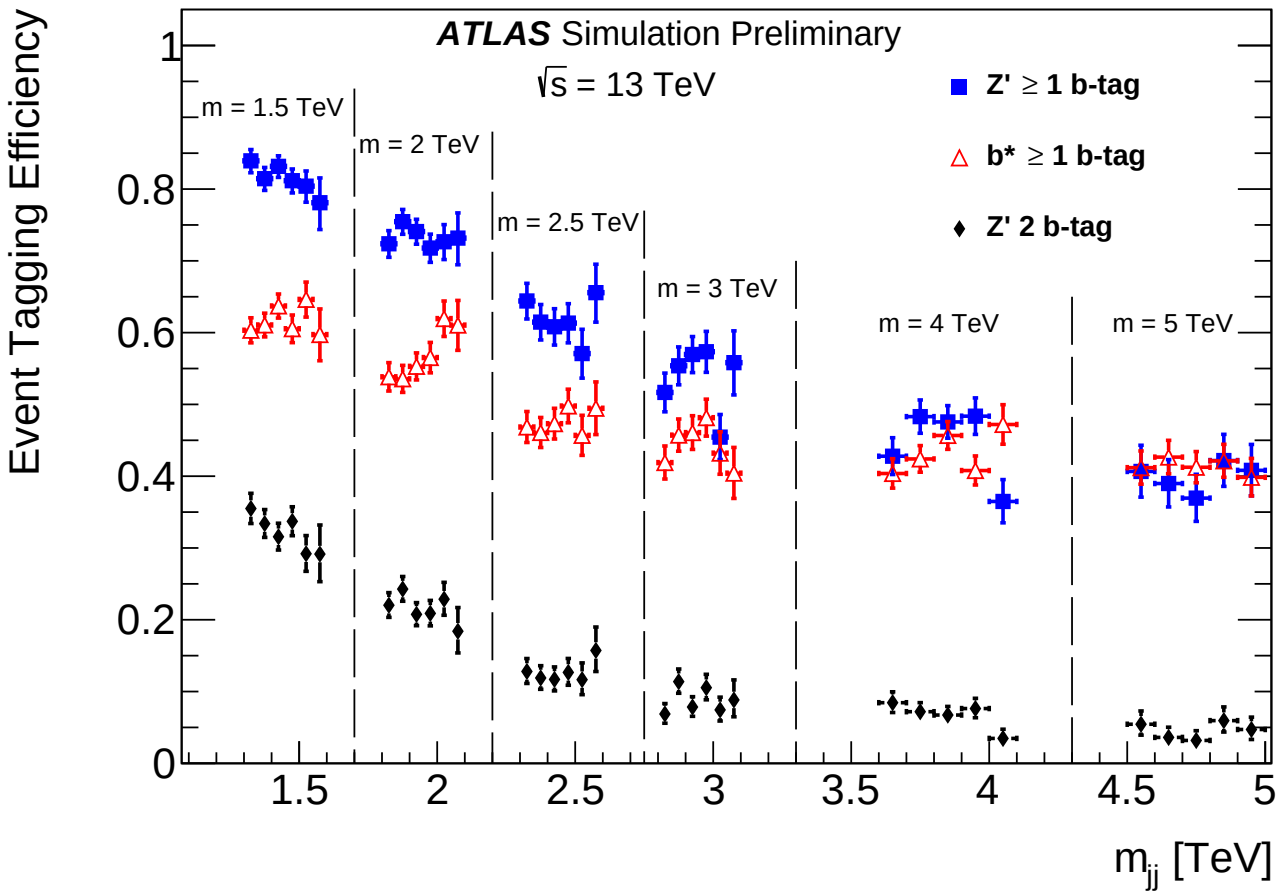




[4] ATLAS Collaboration. In: ATLAS-CONF-2016-060 (2016). URL: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-060/.

Di-jet resonances – tagging efficiency

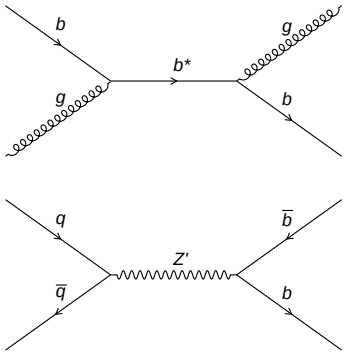
- Acceptance in ≥ 1 b-jet for high masses is the same for the $Z' \to b\bar{b}$ and $b^\star \to gb$.
- The fake rate is not negligible and contributes to this acceptance.

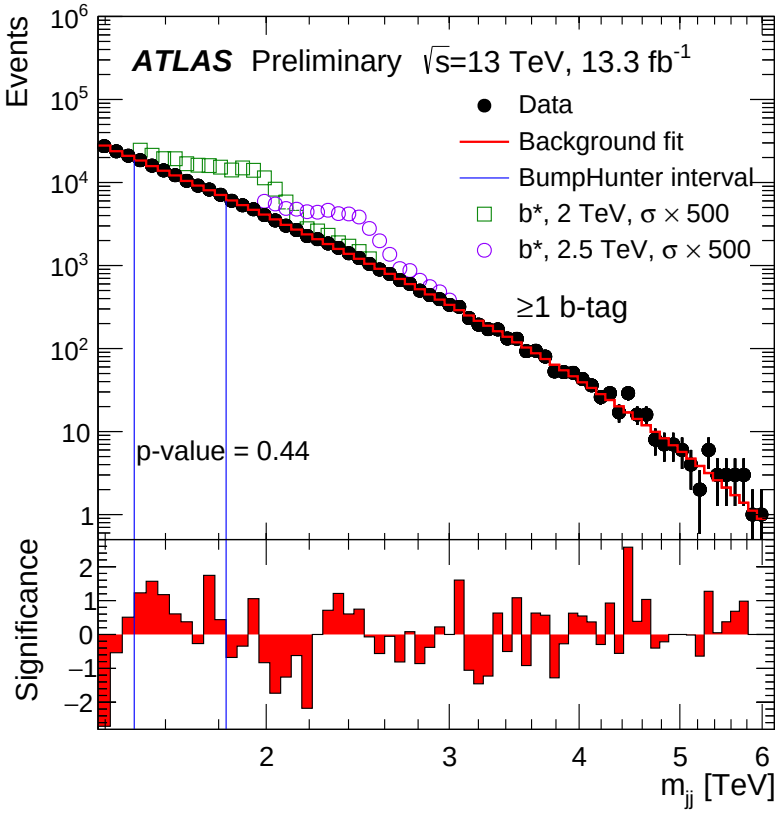


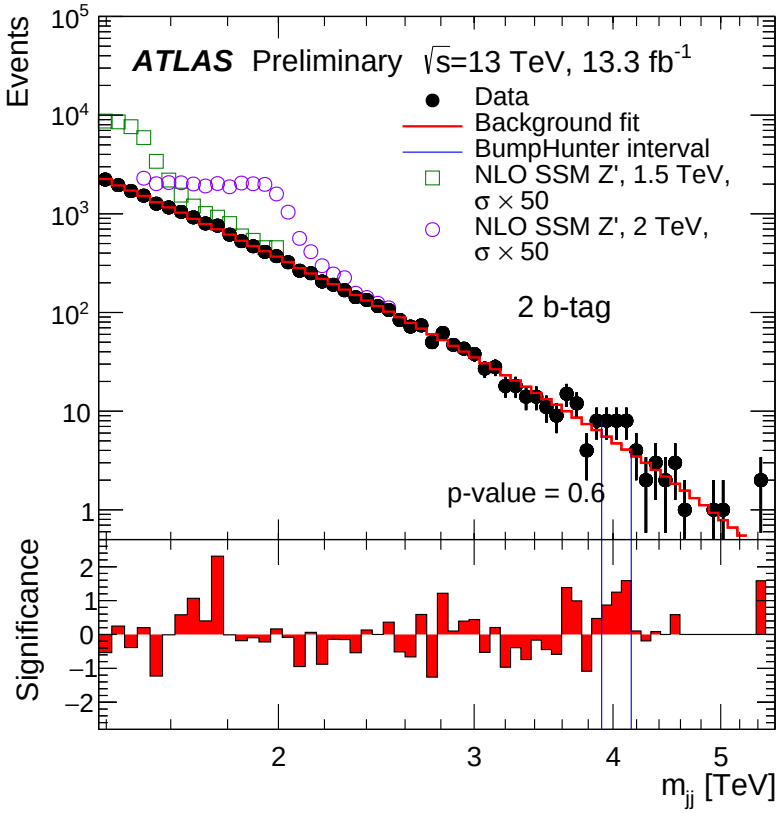
Background fit

- m_{jj} spectrum fit from data as follows, with $x = m_{jj}/\sqrt{s}$.
- Other fit functions are used to estimate the systematic uncertainty of the fit function choice.
- Main background: QCD multi-jet.

$$f(x) = p_1(1-x)^{p_2}x^{p_3}$$

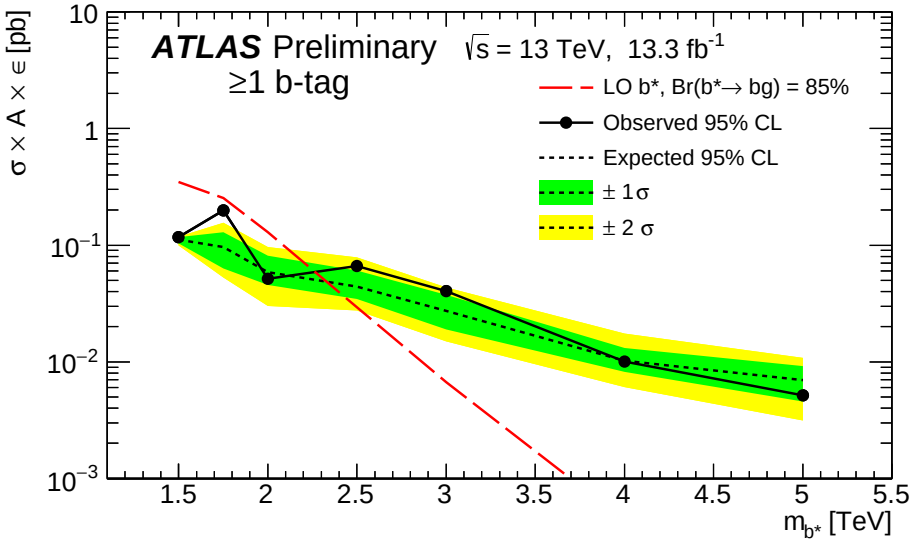


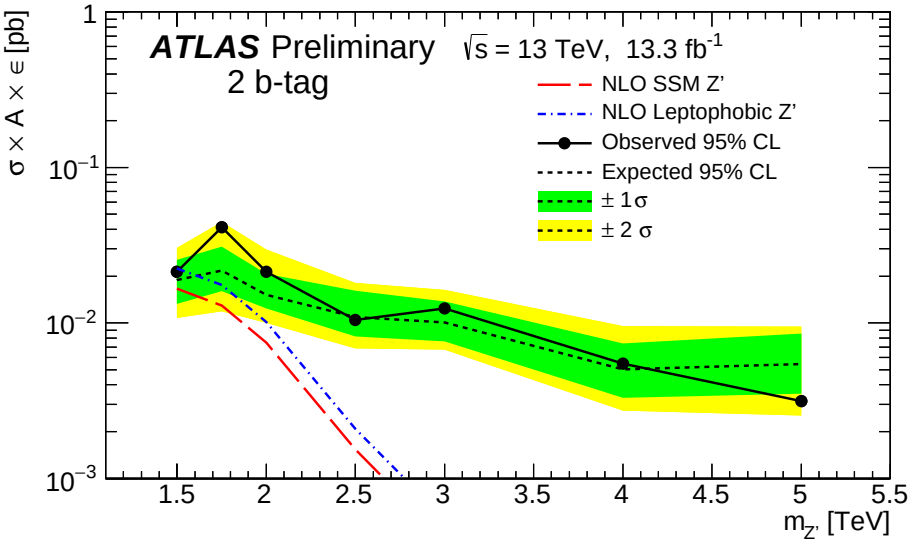


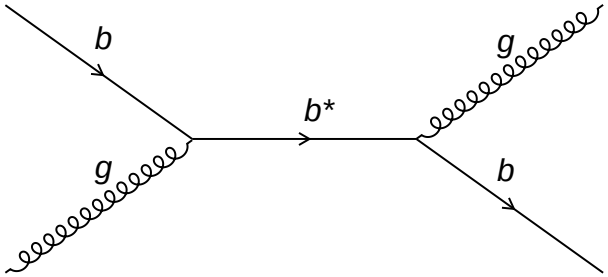


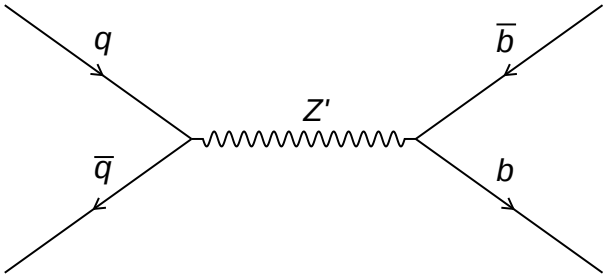
Limits

- No excess found.
- Limits set for two benchmark models.









Summary

- **8 TeV and 13 TeV top-antitop resonance** search results.
  - Increased limits on 13 TeV results, in the boosted $t\bar{t}$ selection.
  - Usage of track jets improves sensitivity at high $m_{t\bar{t}}$.
- Scalar signal interference is not simulated in the signal model for the original 8 TeV $t\bar{t}$ paper.
  - **Result including scalar interference** assuming a (pseudo-)scalar in 2HDM.
  - First experimental result including such an effect.
- New search for **dijet resonances** with at least on b-tagged jet released.
  - Set cross section limits on b^* model and Z' model.
  - Updated limits on the benchmark models.

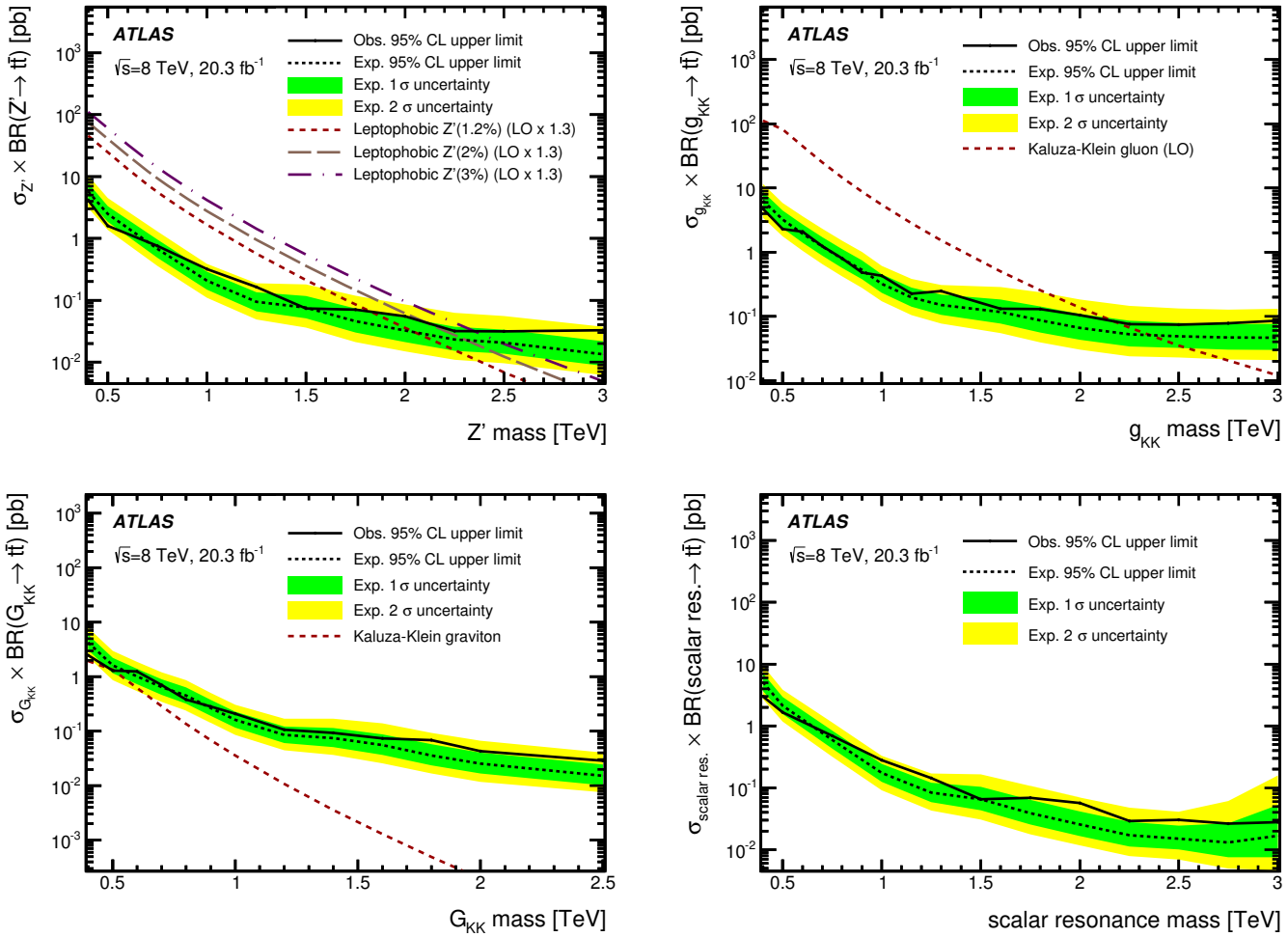
References

- ATLAS Collaboration. In: *JHEP* 08 (2015), p. 148. arXiv: 1505.07018 [hep-ex]
- ATLAS Collaboration. In: ATLAS-CONF-2016-014 (2016). URL: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-014/
- ATLAS Collaboration. In: ATLAS-CONF-2016-073 (2016). URL: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-073/
- ATLAS Collaboration. In: ATLAS-CONF-2016-060 (2016). URL: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-060/
- Not shown here, but recommended for other related ATLAS results:
  - ATLAS Collaboration. In: *Phys. Lett.* B743 (2015), pp. 235–255. arXiv: 1410.4103 [hep-ex]
  - ATLAS Collaboration. In: *Eur. Phys. J.* C75.4 (2015), p. 165. arXiv: 1408.0886 [hep-ex]
  - ATLAS Collaboration. In: *JHEP* 01 (2013), p. 116. arXiv: 1211.2202 [hep-ex]
  - ATLAS Collaboration. In: *Eur. Phys. J.* C75.2 (2015), p. 79. arXiv: 1410.5404 [hep-ex]

Backup

Limit setting

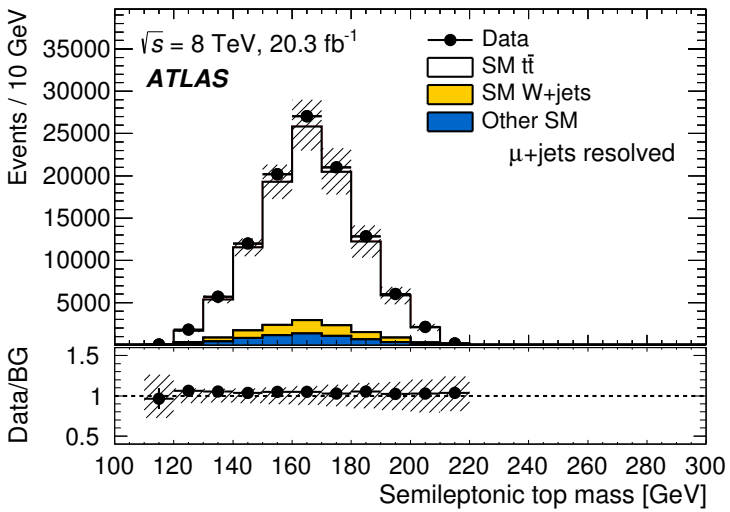
- No excess observed, so we set limits on our benchmark models.

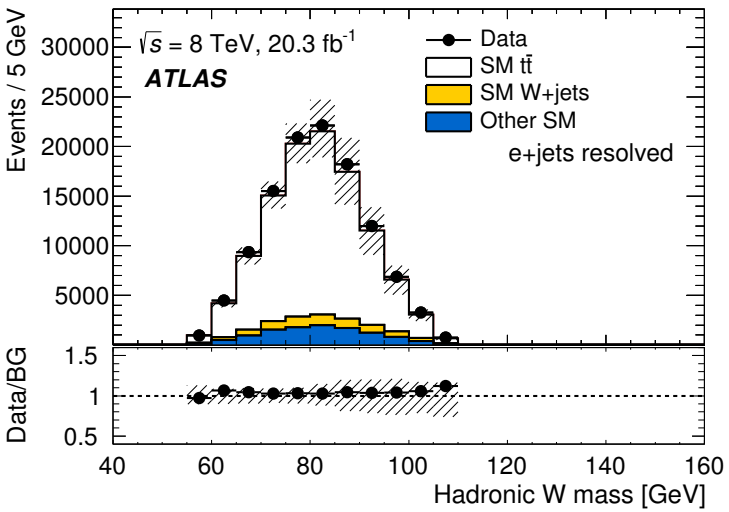


Unmerged events top-antitop system reconstruction

- The χ^2 kinematic fit is used to choose the small-R jets contributing to the $m_{t\bar{t}}$: select the combination which minimizes the cost function.
- The neutrino is estimated in the same way as in the merged channel: assuming the W boson is on-shell.

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{th-W}}{\sigma_{th-W}}\right]^2 + \left[\frac{m_{jl\nu} - m_{tl}}{\sigma_{tl}}\right]^2 + \left[\frac{(p_{T,jjb} - p_{T,jl\nu}) - (p_{T,th} - p_{T,tl})}{\sigma_{diffpT}}\right]^2$$

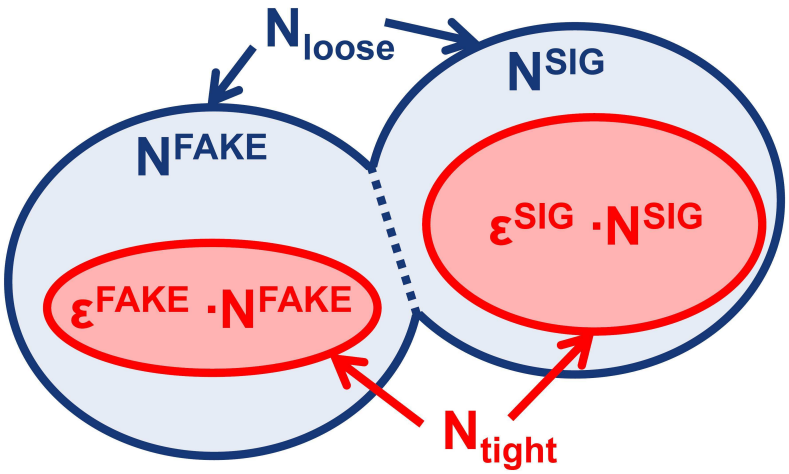




Background estimate - QCD using the Matrix Method

- An efficiency ϵ^{sig} is defined as the probability that a "loose" lepton from a $t\bar{t}$ decay passes the "tight" selection.
- A false-identification rate ϵ^{fake} is defined as the probability for a non-prompt lepton from multi-jets passes the same selection (estimated from data in a Control Region).
- "tight" definition $\rightarrow$ "isolated" lepton.
- "loose" definition $\rightarrow$ may have other particles very close to it.

- Jets can fake leptons $\rightarrow$ a "loose" criteria is used to estimate multi-jets background events.
- We can calculate weights to apply on real data to estimate the amount of multi-jets backgrounds.



(Credits to F. Kohn for the picture)

Background estimate - QCD using the Matrix Method

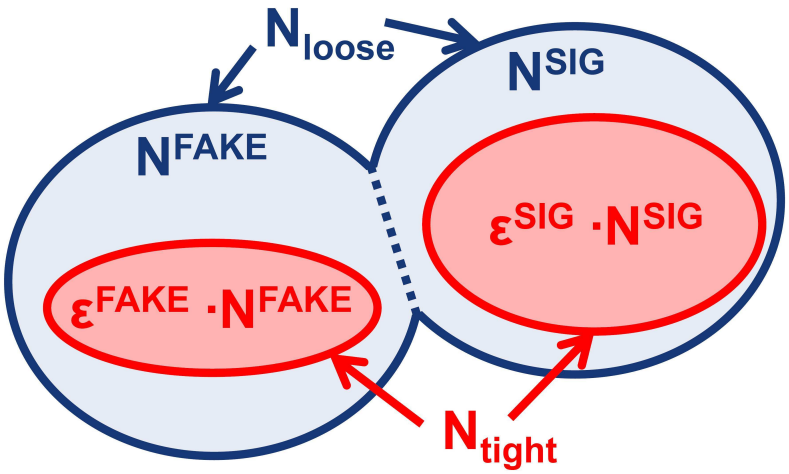
- Jets can fake leptons → a "loose" criteria is used to estimate multi-jets background events.
- We can calculate weights to apply on real data to estimate the amount of multi-jets backgrounds.

- Each event that passes only the "loose" selection will have the weight:

$$w_{\text{loose}} = \frac{1}{\epsilon^{sig} - \epsilon^{fake}} \times (\epsilon^{sig} \times \epsilon^{fake})$$

- Each event that passes the "tight" and "loose" selections will have the weight:

$$w_{\text{tight}} = \frac{\epsilon^{fake}}{\epsilon^{sig} - \epsilon^{fake}} \times (\epsilon^{sig} - 1)$$



(Credits to F. Kohn for the picture)

W+jets estimate

- Relies on the hypothesis that the ratio of positively charged W's to negatively charged W's is well understood in simulation.
- We can then use this in simulation to get the number of expected W+jets.
- This is done in a pre-tag 2-jet region and then weighted by the ratio of events between the signal region and the control region.

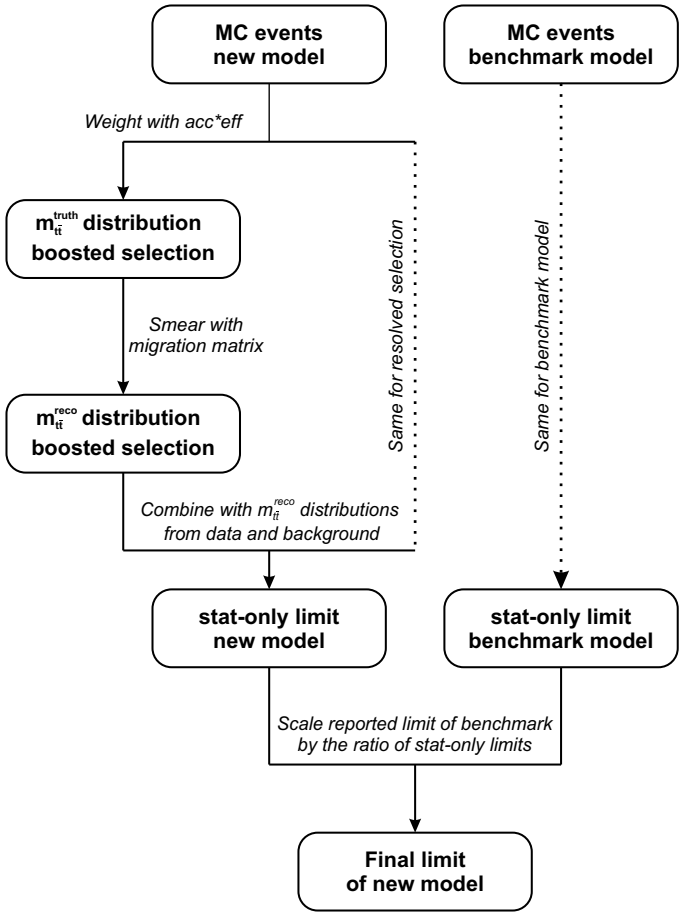
$$\frac{N^{d,+} + N^{d,-}}{N^{d,+} - N^{d,-}} = \frac{N^{MC,+} + N^{MC,-}}{N^{MC,+} - N^{MC,-}}$$

$$N^{d,+} + N^{d,-} = \frac{r_{MC} + 1}{r_{MC} - 1}(N^{d,+} - N^{d,-})$$

$$r_{MC} = \frac{N^{MC,+}}{N^{MC,-}}$$

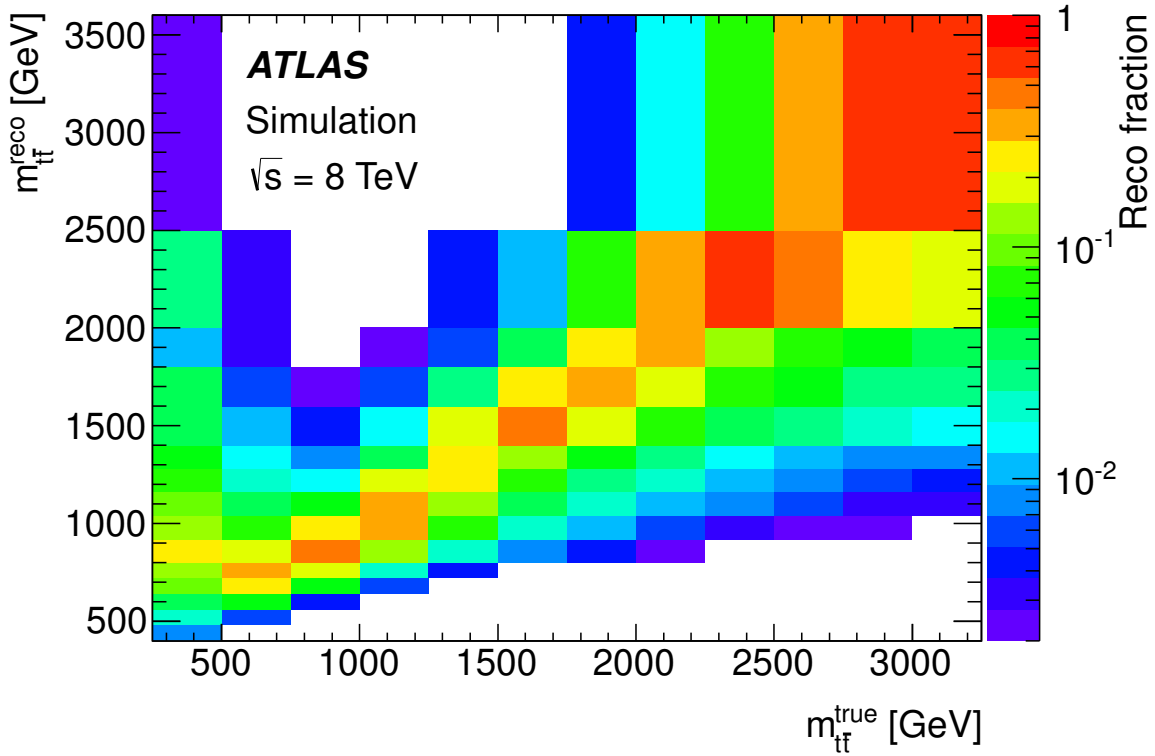
How to generalise it? (I)

- One can simulate a new signal and test whether this signal exists using these results.
- Theorists can take advantage of this.



How to generalise it? (II)

- Theorists only need the migration matrix and the signal acceptance.



Systematic uncertainties effect

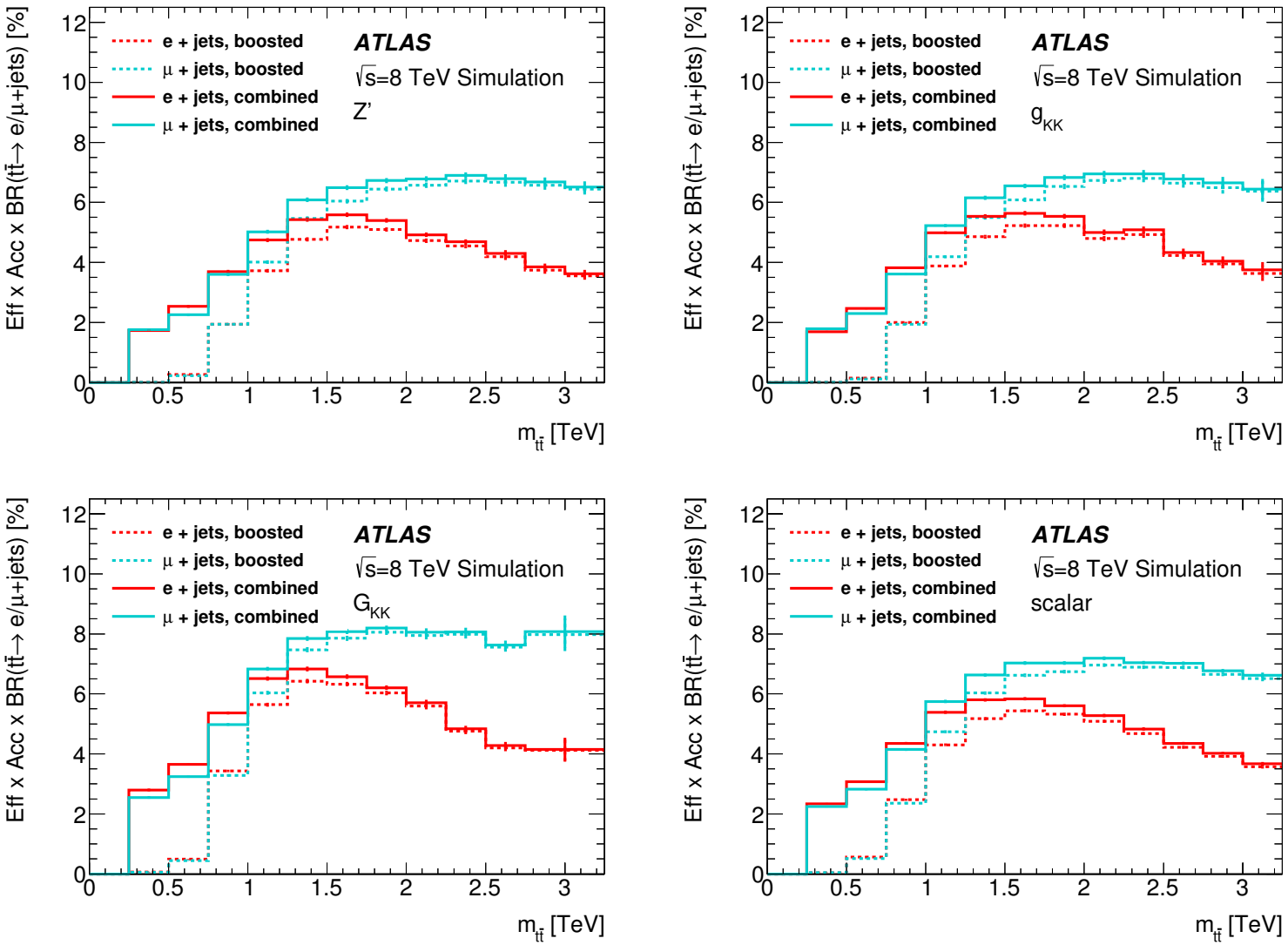
- Big effect coming from b-tagging uncertainty in signal.

Systematic Uncertainties	Resolved selection yield impact [%] total bkg.	Z'	Boosted selection yield impact [%] total bkg.	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

Impact of systematic uncertainties on the yield

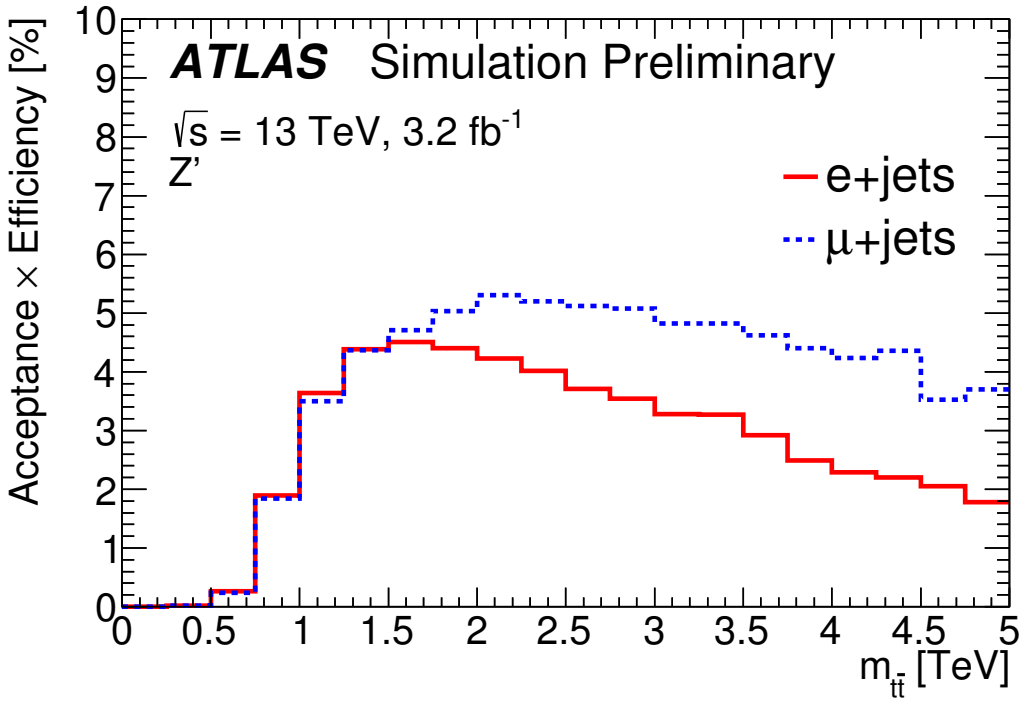
Signal acceptance at 8 TeV $t\bar{t}$ resonance search

- Effect of signal acceptance as a function of $m_{t\bar{t}}$, at truth level.



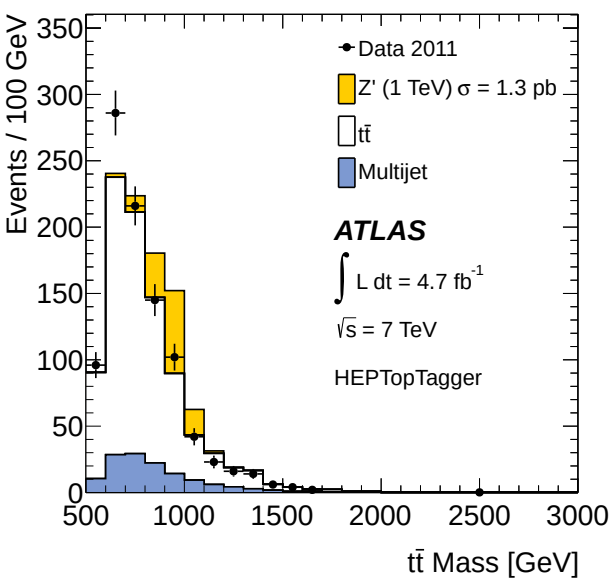
Signal acceptance at 13 TeV $t\bar{t}$ resonance search

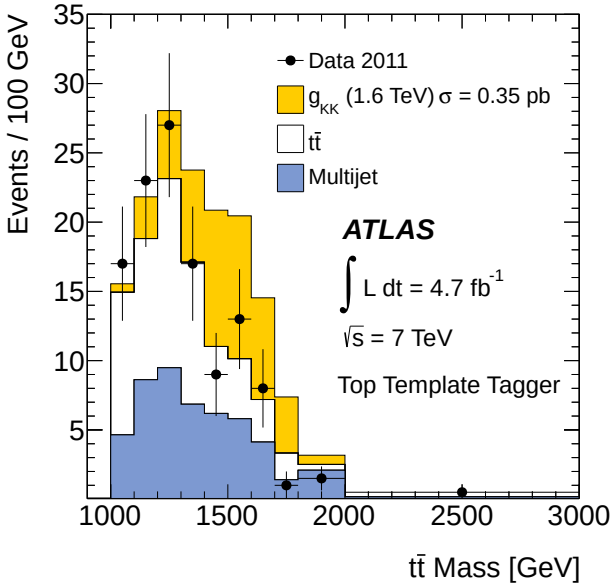
- Effect of signal acceptance as a function of $m_{t\bar{t}}$, at truth level.
- Muon-jet variable ΔR overlap removal expected to increase signal acceptance at high momenta. While current electron-jet ΔR overlap removal is known to affect significantly high momentum signals.



All hadronic final state $t\bar{t}$ resonances search at 7 TeV

- Search done using two methods for top identification: HEPTopTagger[5] and template method[6].
- HEPTopTagger (HTT) method: two C/A jets $R = 1.5$ with $p_T > 200$ GeV are required to be top-tagged.
- Template overlap (TO) method: two anti-k_t $R = 1.0$ with leading $p_T > 500$ GeV and sub-leading $p_T > 450$ GeV are required to be top-tagged.



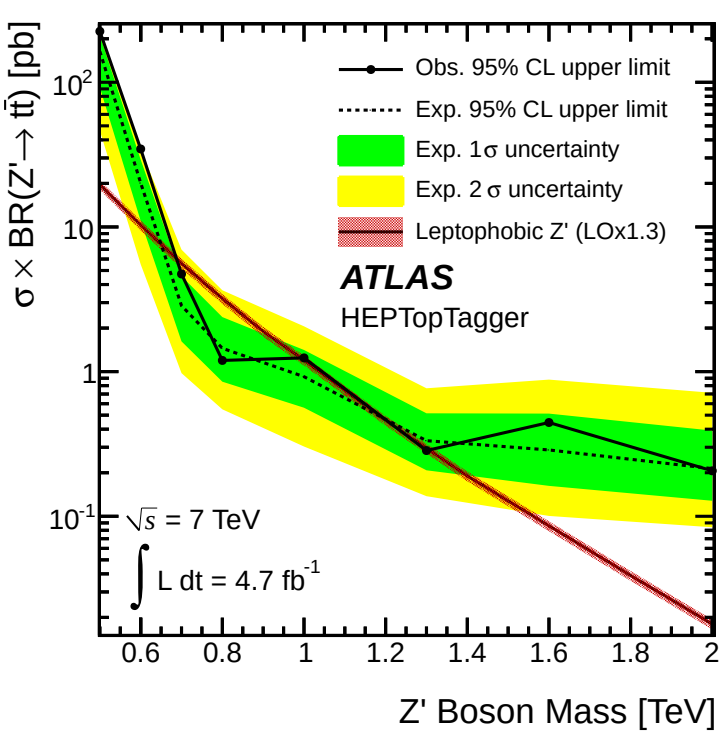


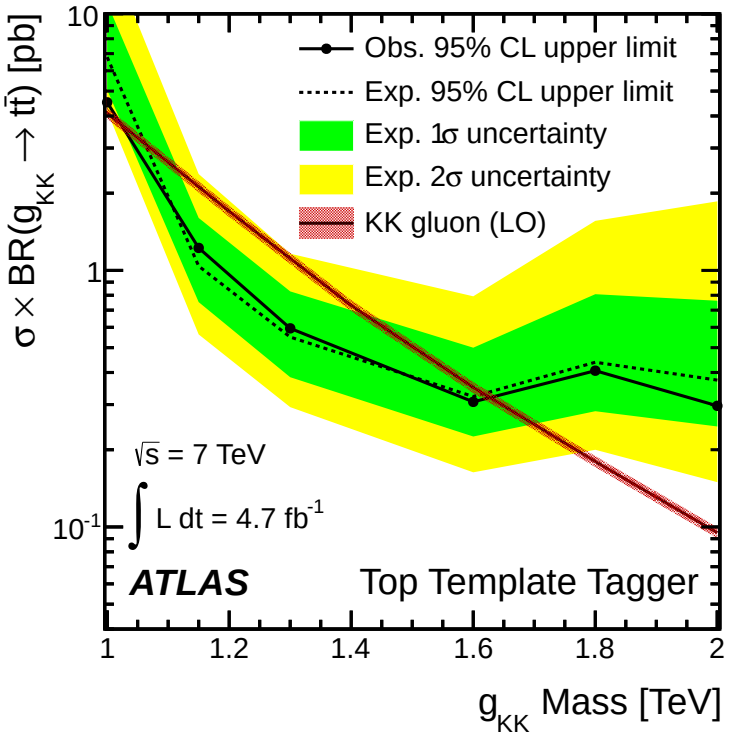
[5] Tilman Plehn, Gavin P. Salam, and Michael Spannowsky. In: *Phys. Rev. Lett.* 104 (2010), p. 111801. arXiv: 0910.5472 [hep-ph].

[6] Leandro G. Almeida et al. In: *Phys. Rev.* D82 (2010), p. 054034. arXiv: 1006.2035 [hep-ph].

Limit setting

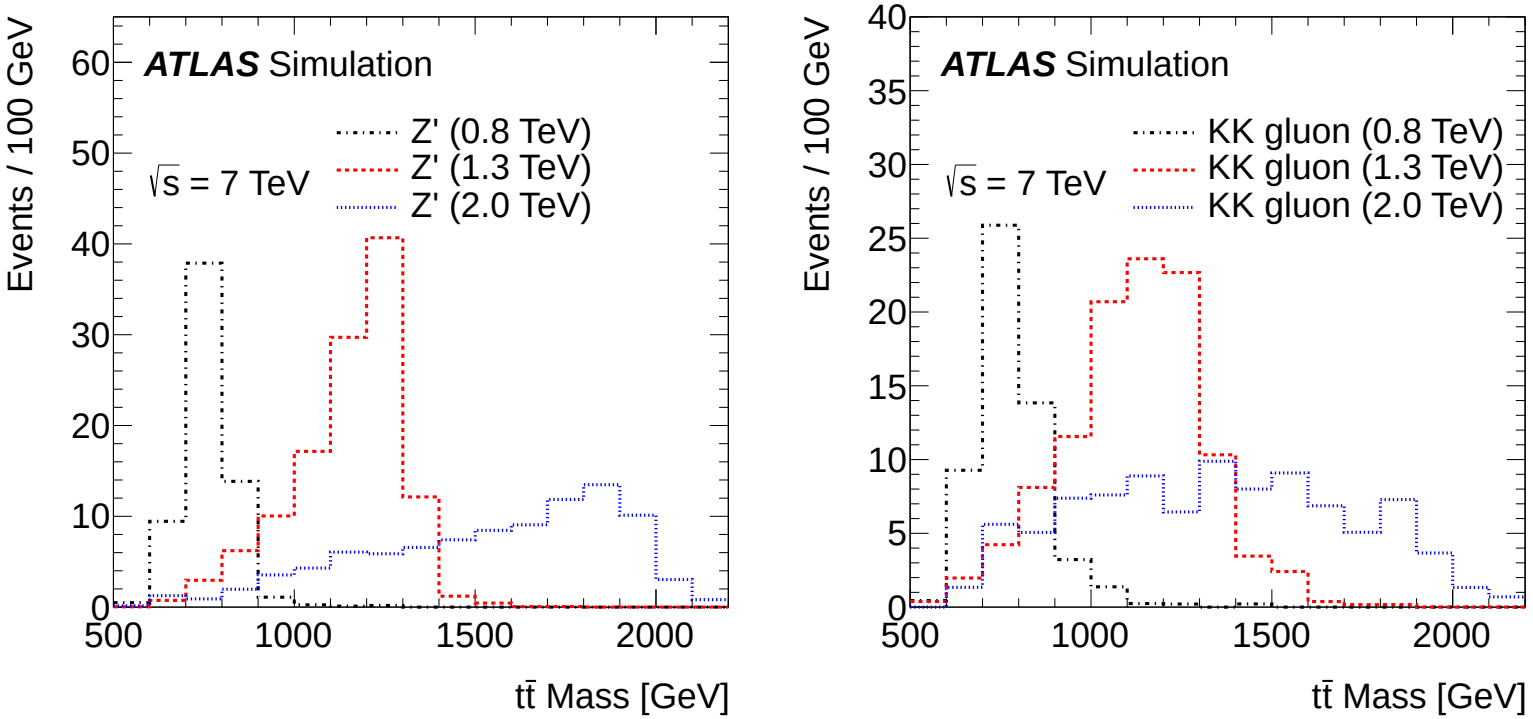
- No excesses are observed and 95% CLs limits are set with the two methods.
- The HEPTopTagger method leads to a better limit for the narrow Z' resonance, while the template overlap method sets stronger cross section limits in the Kaluza-Klein gluon model.





Signal reconstruction with HEPTopTagger

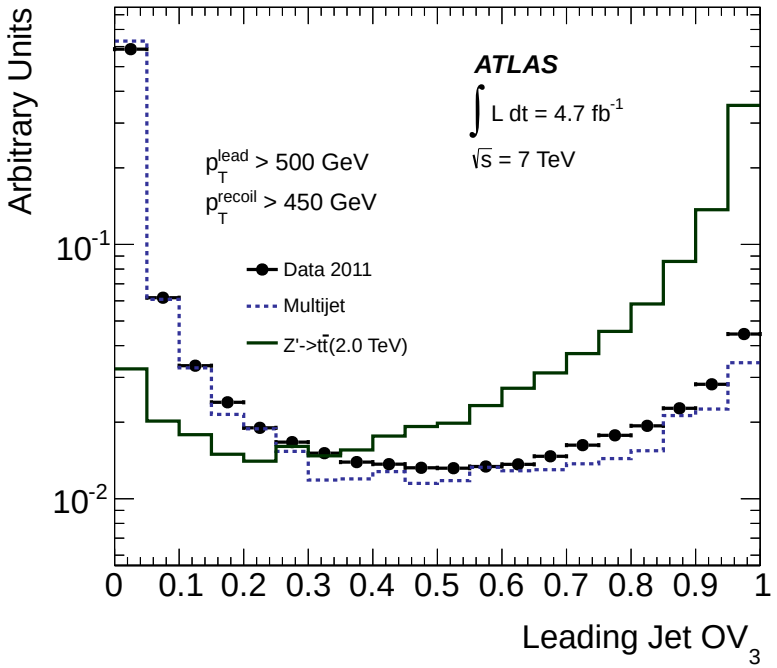
- Mass of the top-antitop system is well reconstructed in the Z' and Kaluza-Klein gluon models.



Top template method

- An overlap function quantifies the agreement in energy flow between templates of the top quark shower hypothesis and the observed jet.
- A set of approximately 300 000 library templates (τ_n) are generated.
- The weighting variable is $\sigma_i = E_i/3$.

$$OV_3 = \max_{\tau_n} \exp\left[-\sum_{i=1}^{3} \frac{1}{2\sigma_i^2}\Big(E_i - \sum_{\Delta R(\mathrm{topo},i)<0.2} E_{\mathrm{topo}}\Big)^2\right]$$

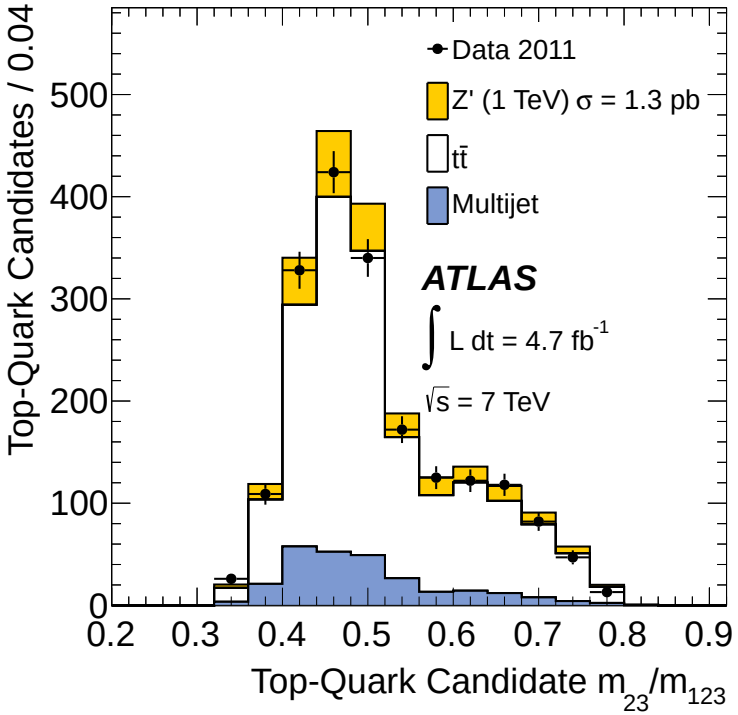


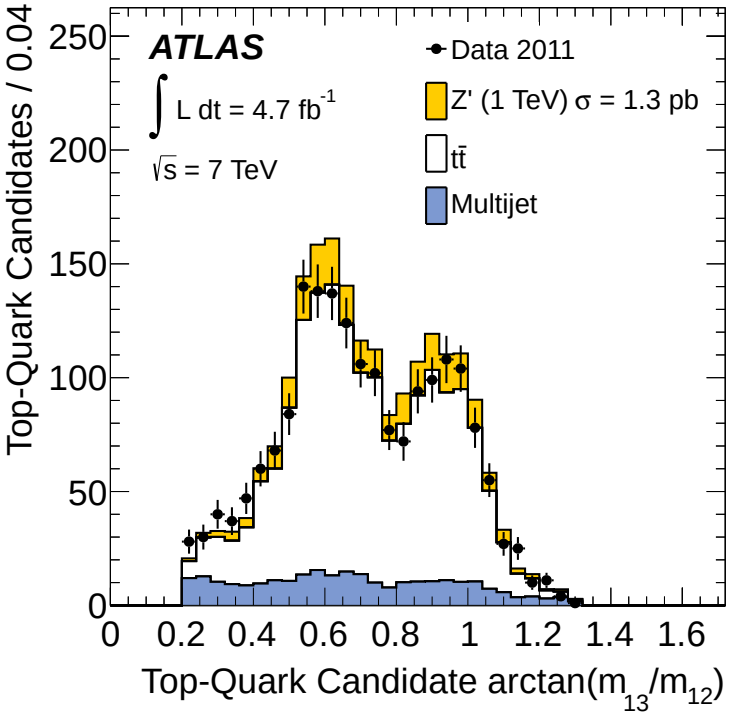
HEPTopTagger method (I)

- The input large-R jet is split in subjets, undoing the last jet clustering step.
- The procedure is repeated until all subjets have masses below 50 GeV.
- All combinations of 3 subjets are tested for compatibility with the top shower.
  - C/A algorithm is rerun on the topoclusters of the triplet subjets. with R set to half the smallest distance between the subjets (but at most 0.3), keeping only the five leading subjets.
  - Constituents of the five subjets are reclustered exclusively into three subjets with the C/A algorithm.
  - The calibrated three subjets are tested for top compatibility using the mass ratios.

HEPTopTagger method (II)

- The resulting top four-momentum is set to the sum of the calibrated subjets and its mass is required to be $\in [140, 210]$ GeV.

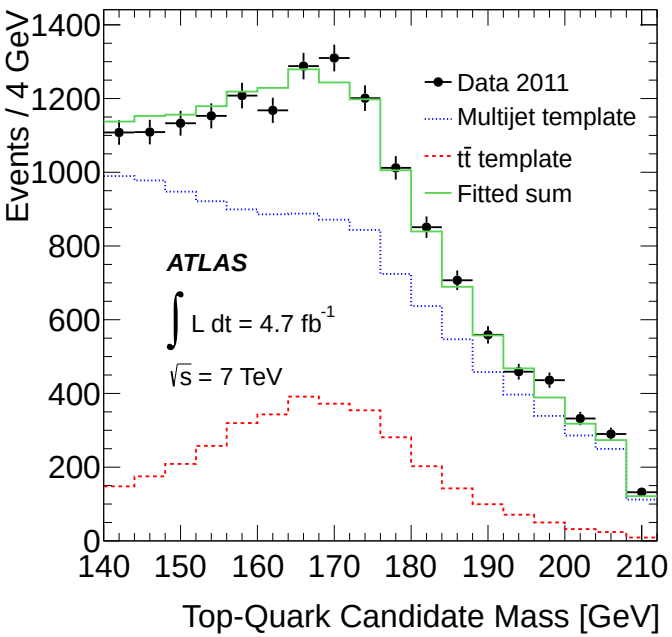




Background estimate in the HTT method

- A set of Control regions are used to obtain a template of the Signal Region m_{tt} distribution.
- The templates are normalised to a ratio of yields in orthogonal Control Regions.

$$\frac{dn_Z}{dm_{tt}} = \left(\frac{1}{n_U} \times \frac{dn_V}{m_{tt}} + \frac{1}{n_W} \frac{dn_X}{dm_{tt}} \right) \times \frac{n_Y}{2}$$



Top mass in sideband Y

	1 top-tag	$\geq$ 2 top-tags
no b-tag	U(0.3%)	V(2.4%)
1 b-tag	W(3.2%)	X(24.3%)
$\geq$ 2 b-tags	Y(22.5%)	Z(80.9%)

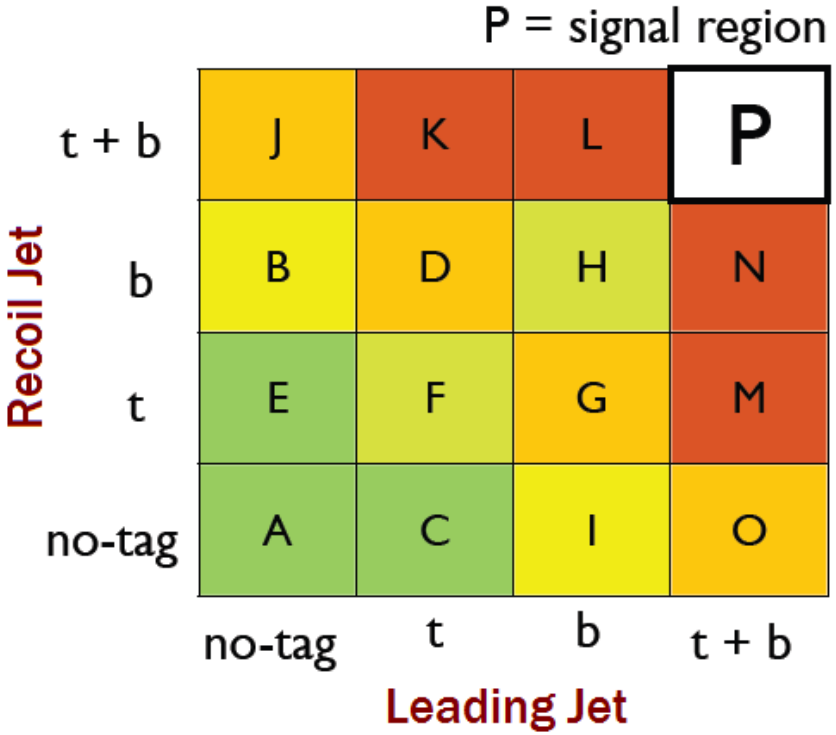
$t\bar{t}$ purity

Background est. in the Template Overlap method (I)

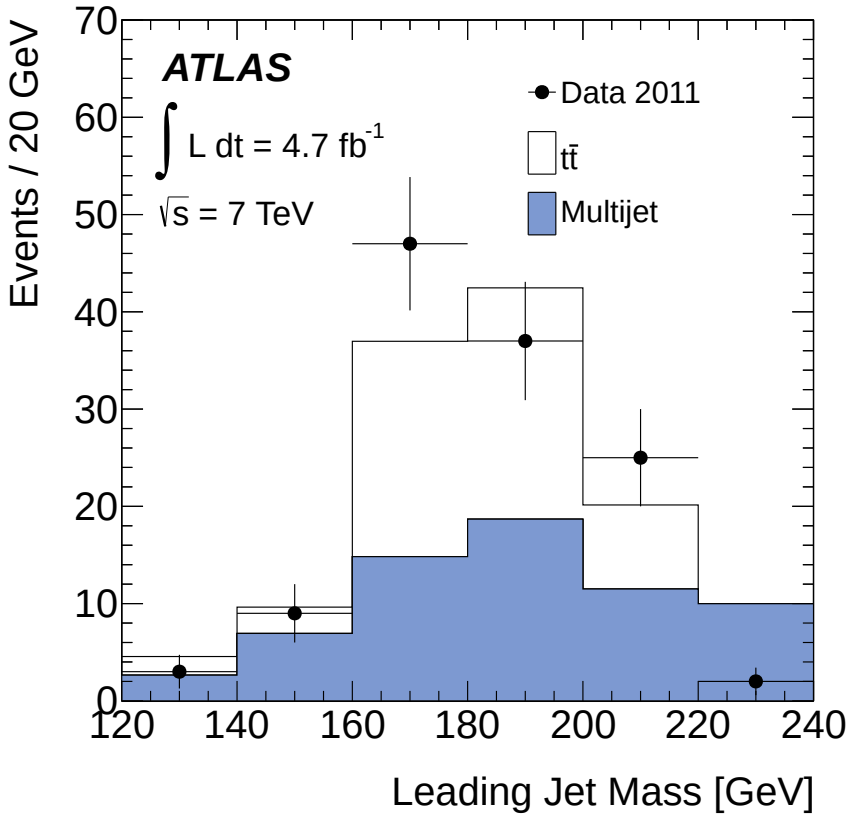
- A set of Control regions are used to obtain a template of the Signal Region m_{tt} distribution.
- The templates are normalised to a ratio of yields in orthogonal Control Regions.
- An iterative procedure is used.
- N_X indicate number of events and K', M', P' indicate the templates in those subsamples.

$$
\begin{aligned}
K' &= N_J \times \frac{N_F}{N_E} \\
M' &= N_F \times \frac{N_O}{N_C} \\
P' &= K' \times \frac{M'}{N_F}
\end{aligned}
$$

Background est. in the Template Overlap method (II)

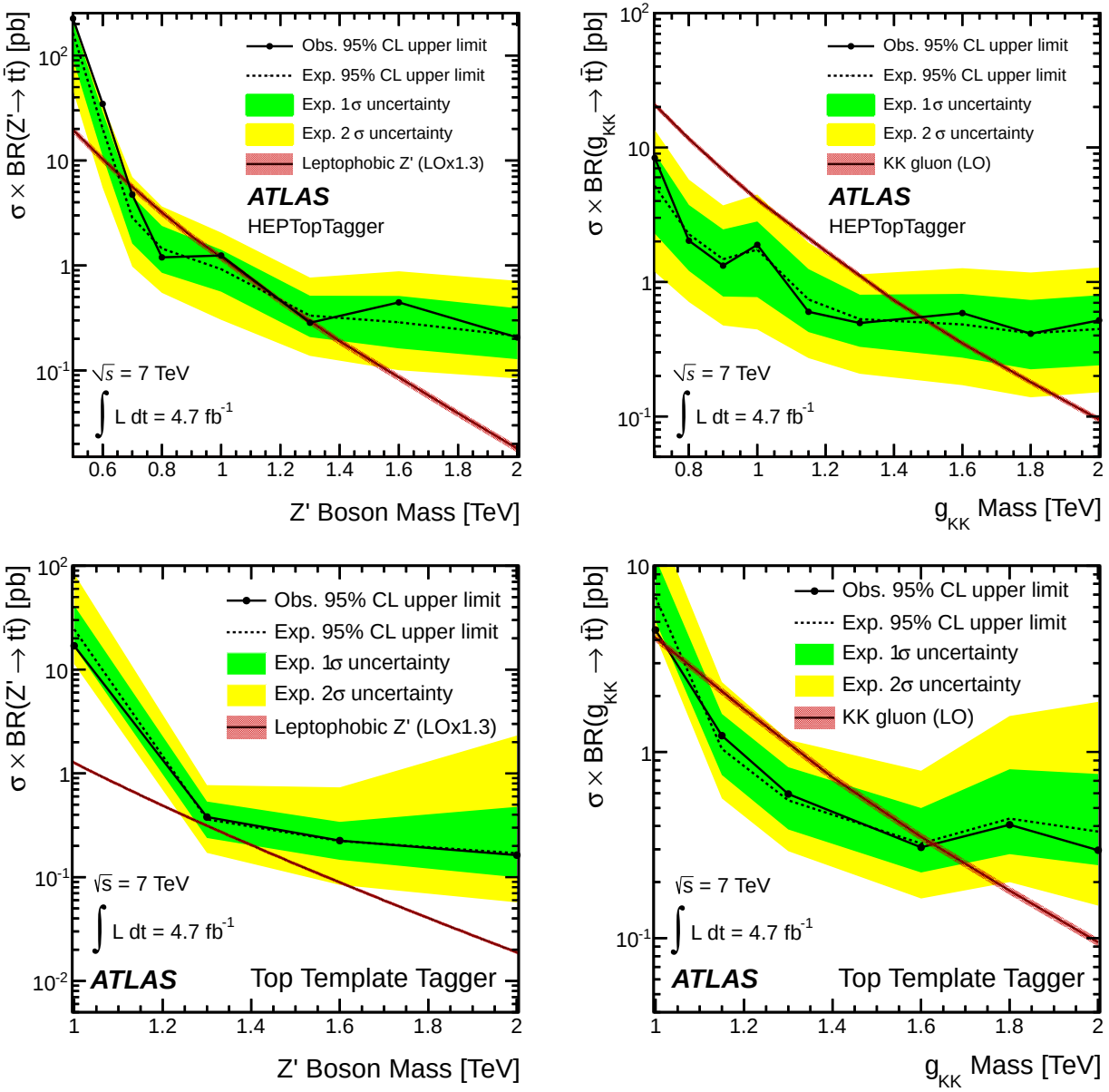


Signal and Control Regions



Leading jet mass

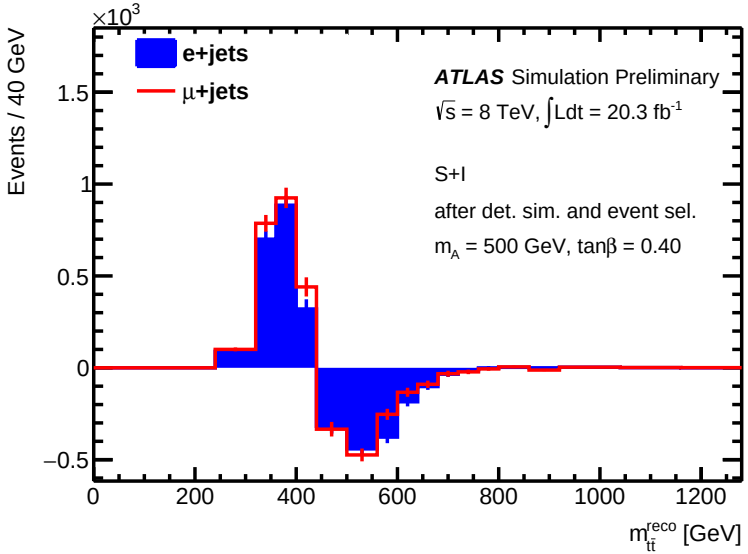
Limit setting

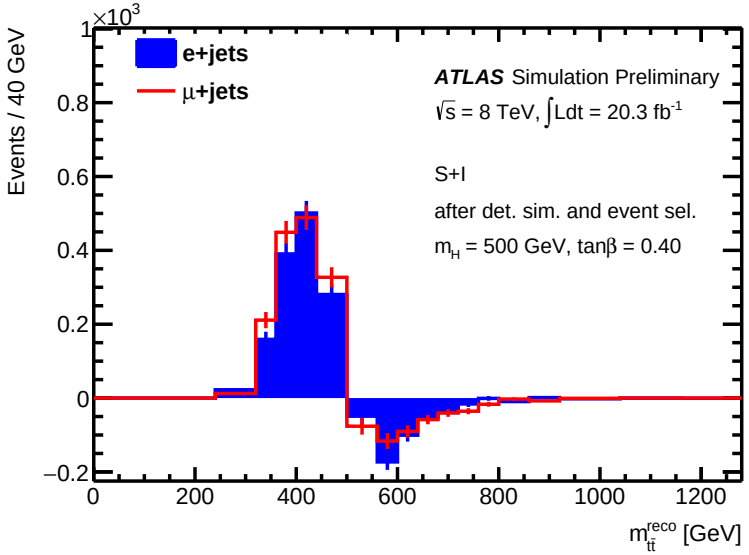


Search for $t\bar{t}$ scalar resonances at 8 TeV – yields

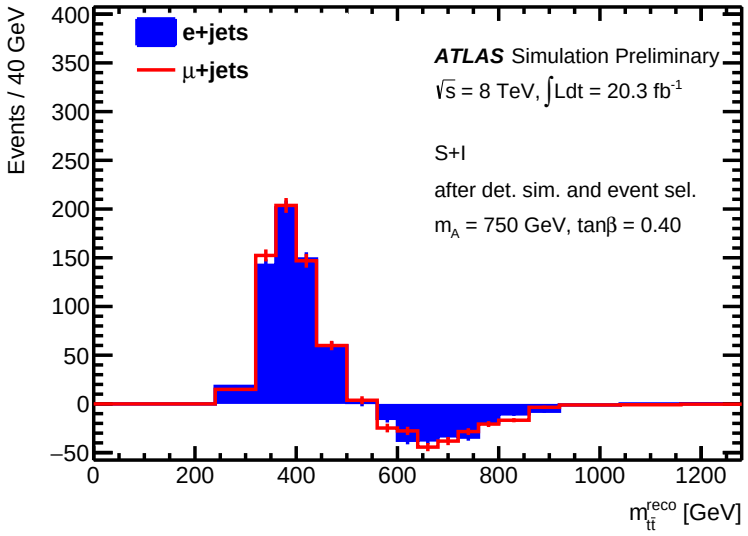
Type	e+jets		μ+jets		Sum	
$t\bar{t}$	95,000	± 11,000	93,000	± 11,000	188,000	± 22,000
Single top quark	3,900	± 500	3,800	± 500	7,700	± 1,000
$t\bar{t}V$	290	± 40	280	± 40	560	± 80
W+jets	6,600	± 2,100	7,200	± 2,300	13,800	± 4,300
Z+jets	1,400	± 620	650	± 250	2,100	± 900
Diboson	320	± 120	310	± 120	630	± 240
Multijet e	5,300	± 1,100	-		5,300	± 1,100
Multijet μ	-		1,060	± 230	1,060	± 30
Total	112,000	± 13,000	106,000	± 12,000	219,000	± 25,000
Data	115,785		110,218		226,003	

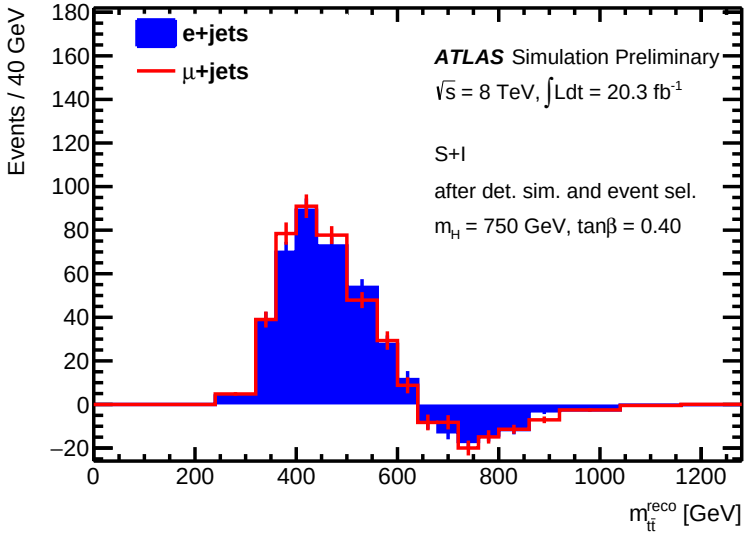
Search for $t\bar{t}$ scalar resonances at 8 TeV (I)



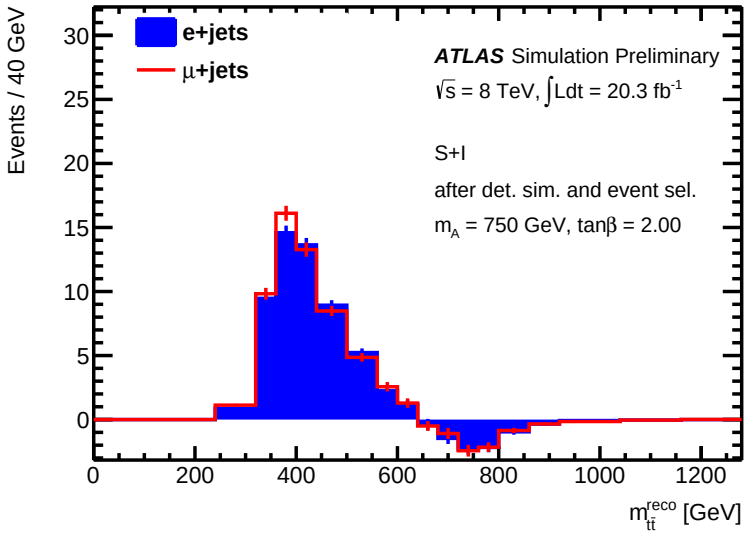


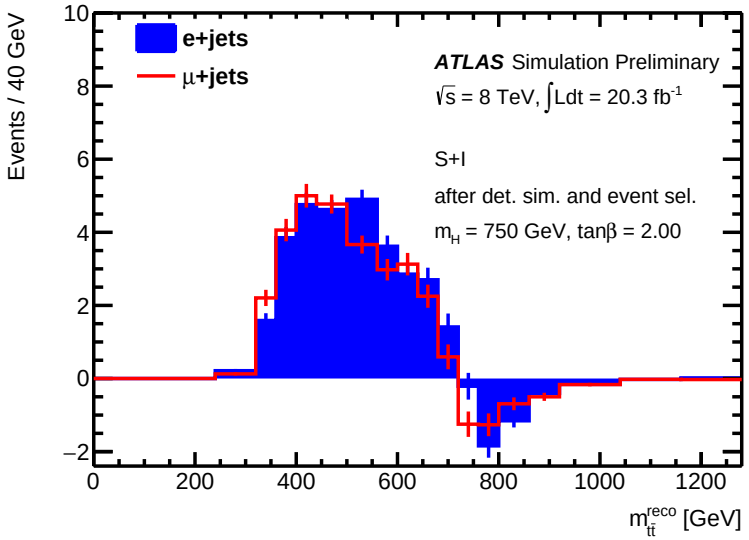
Search for $t\bar{t}$ scalar resonances at 8 TeV (II)





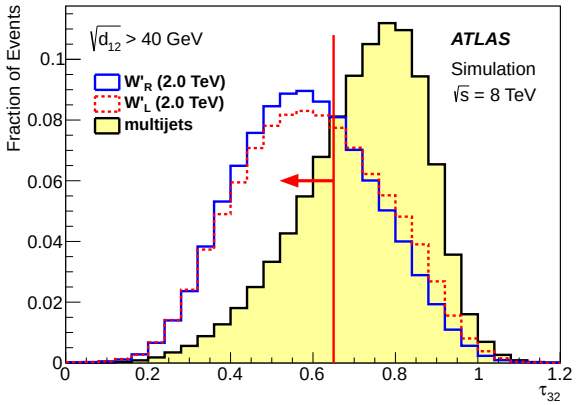
Search for $t\bar{t}$ scalar resonances at 8 TeV (III)

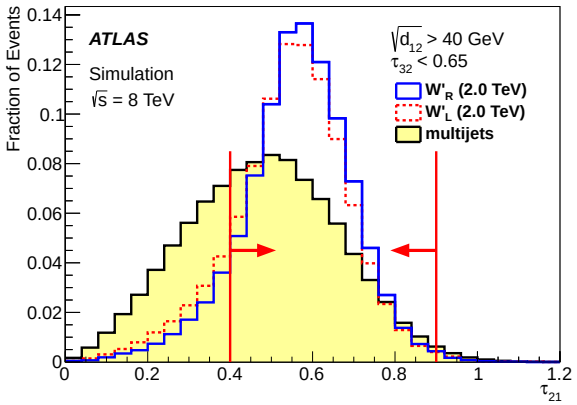


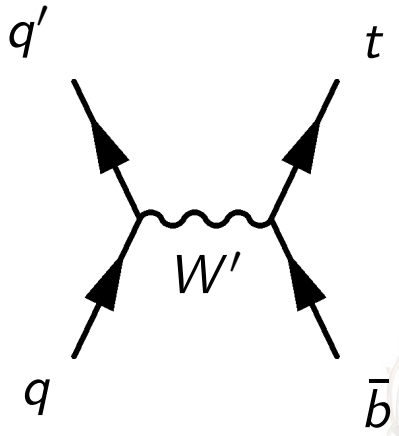


Search for tb resonances

- $X \to t\bar{b}$ or $X \to \bar{t}b$ in the lepton+jets and all hadronic channels.
- In the lepton+jets analysis[7]:
  - One lepton with $p_T > 30$ GeV.
  - $E_T^{miss} > 35$ GeV and $m_{TW} + E_T^{miss} > 60$ GeV.
  - 2 anti-k_t $R = 0.4$ jets b-tagged (70% eff.).
  - 2 channels: **2** or **3** anti-k_t $R = 0.4$ jets.
- In the all hadronic analysis[8]:
  - Top-tagged large-R jet ($\sqrt{d_{12}} > 40$ GeV, $\tau_{32} < 0.65$ and $\tau_{21} \in [0.4, 0.9]$).
  - Top selection eff. is 50% for jets with $p_T > 500$ GeV (fake rate $< 10\%$).



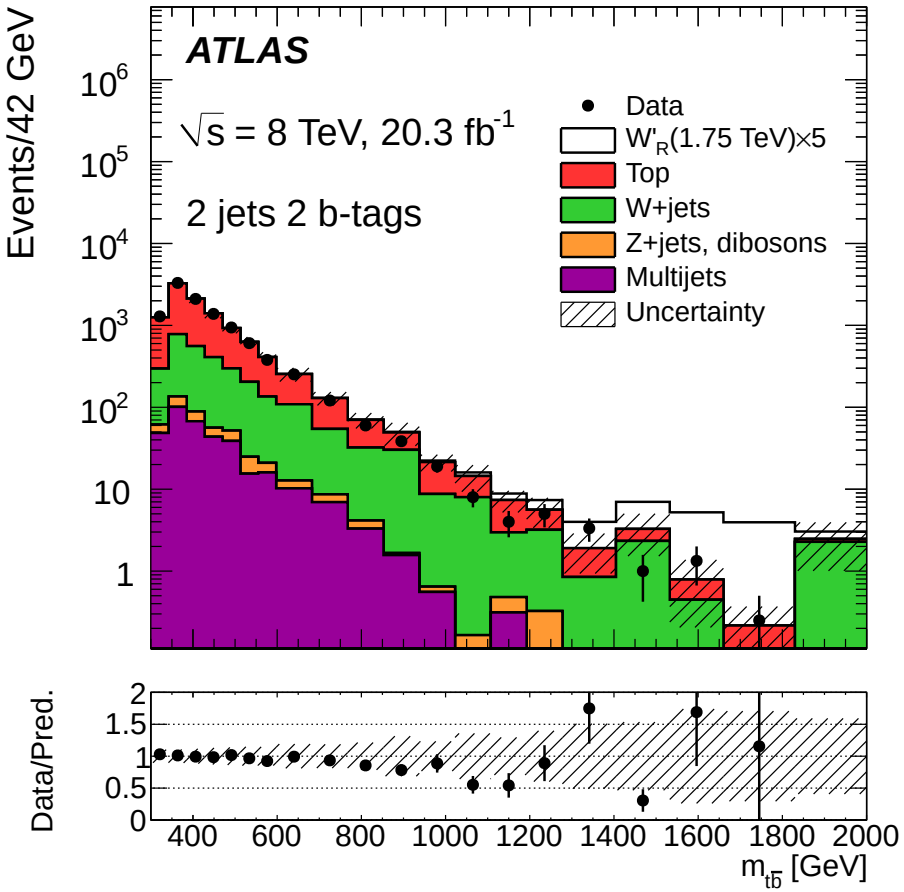




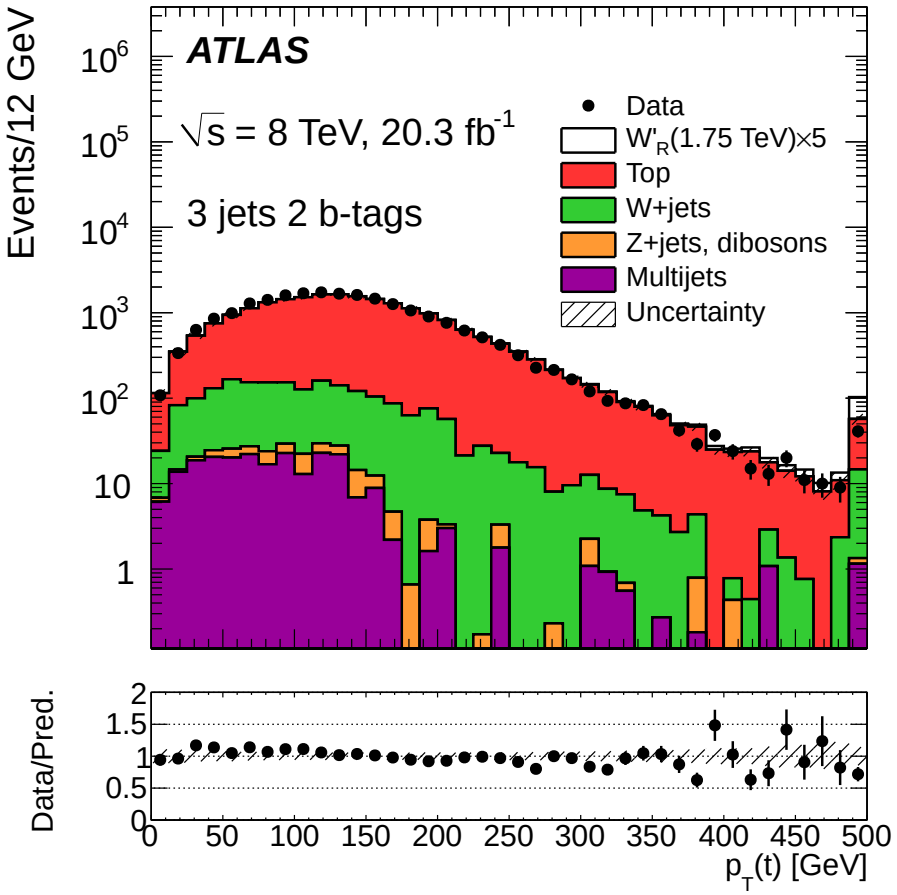
[7] ATLAS Collaboration. In: *Phys. Lett.* B743 (2015), pp. 235–255. arXiv: 1410.4103 [hep-ex].
[8] ATLAS Collaboration. In: *Eur. Phys. J.* C75.4 (2015), p. 165. arXiv: 1408.0886 [hep-ex].

Lepton+jets channel

- Signal Region plot of m_{tb} is used in the limit setting in four channels (e and μ channels; 2 and 3 jet regions).
- There is good modelling of the backgrounds, including the data-driven matrix method for the QCD estimate.



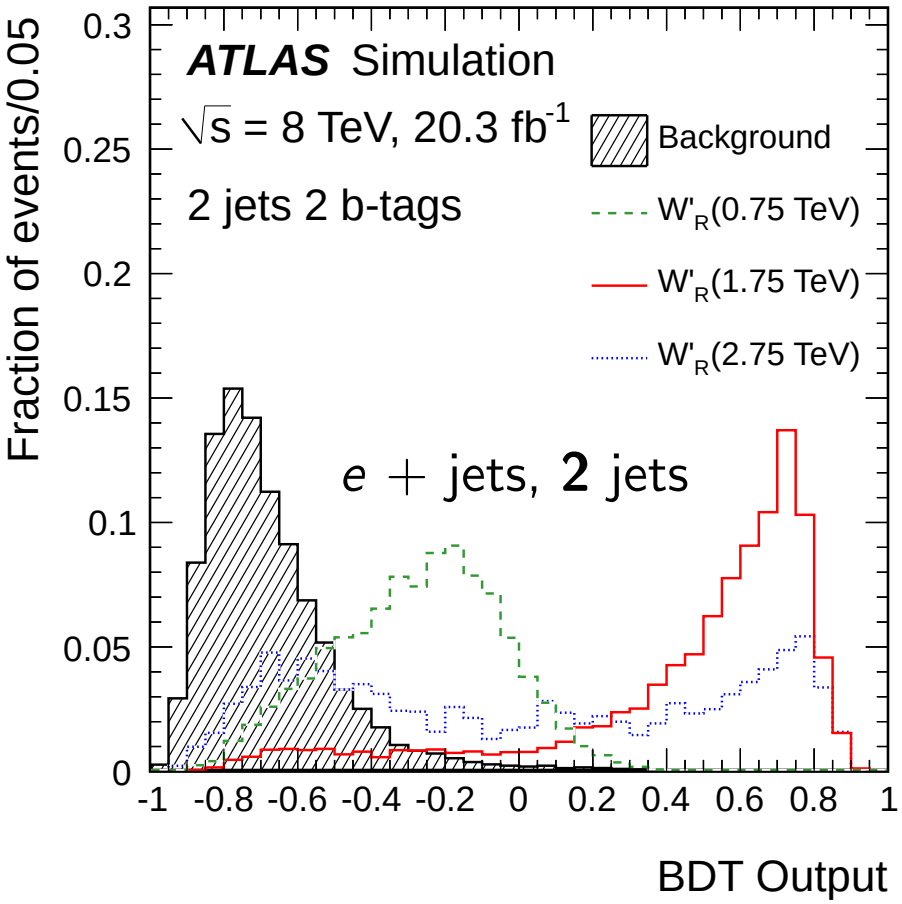
e + jets, **2** jets

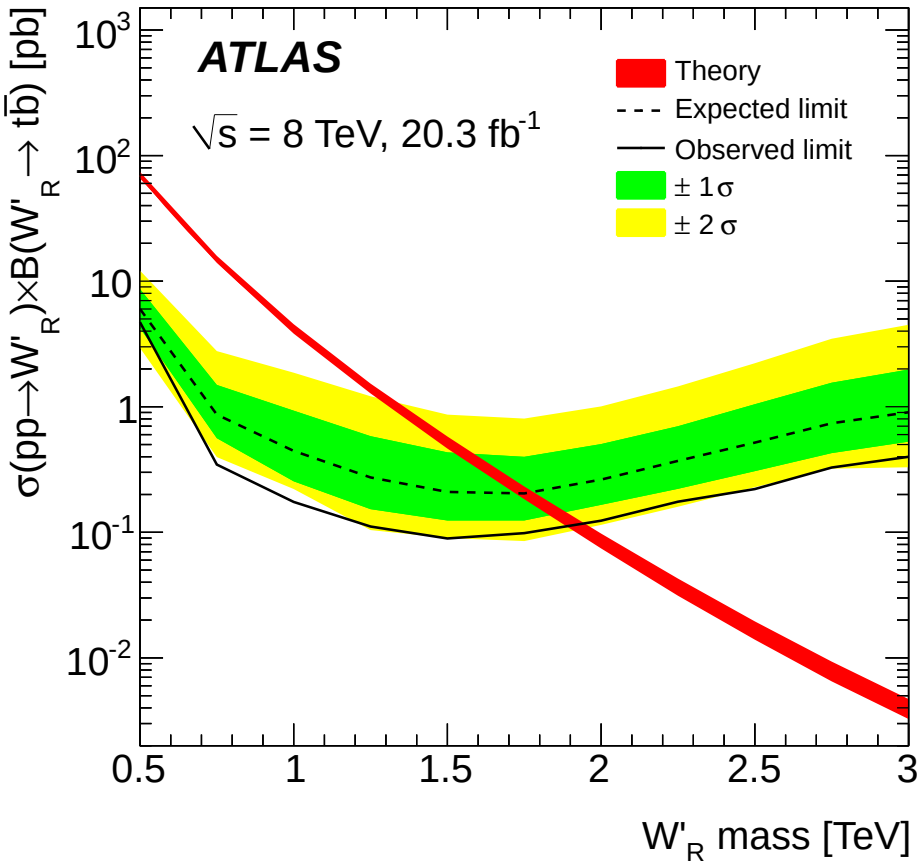


μ + jets, **3** jets

Lepton+jets analysis

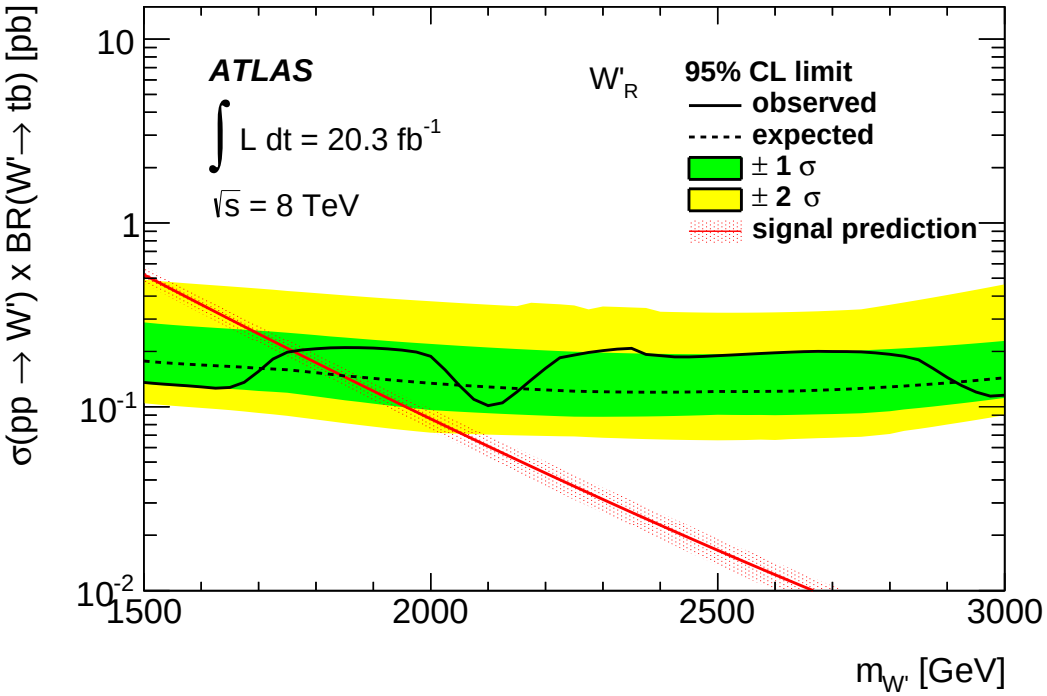
- To try to maximise sensitivity by using a Boosted Decision Tree.
- Inputs of the BDT depend on the signal chirality, but a few variables are relevant in both left-handed and right-handed studies.
- No excess is observed.
- Observed mass limit of 1.8 TeV for W'_L and 1.9 TeV for W'_R.

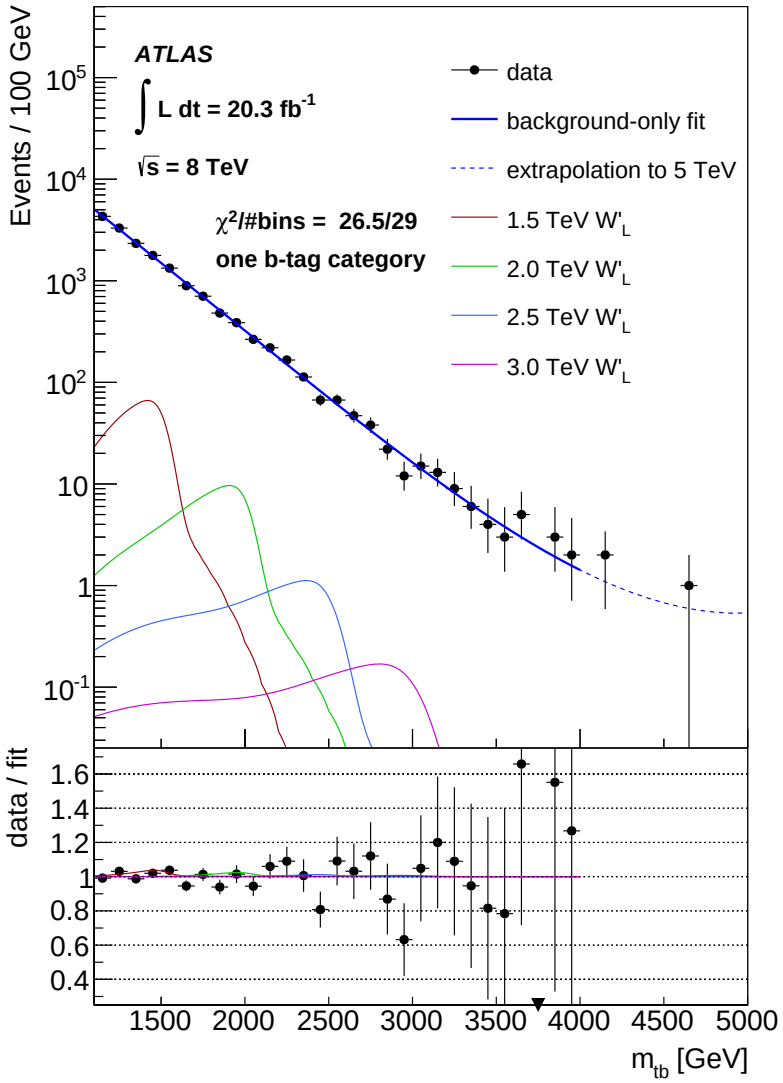




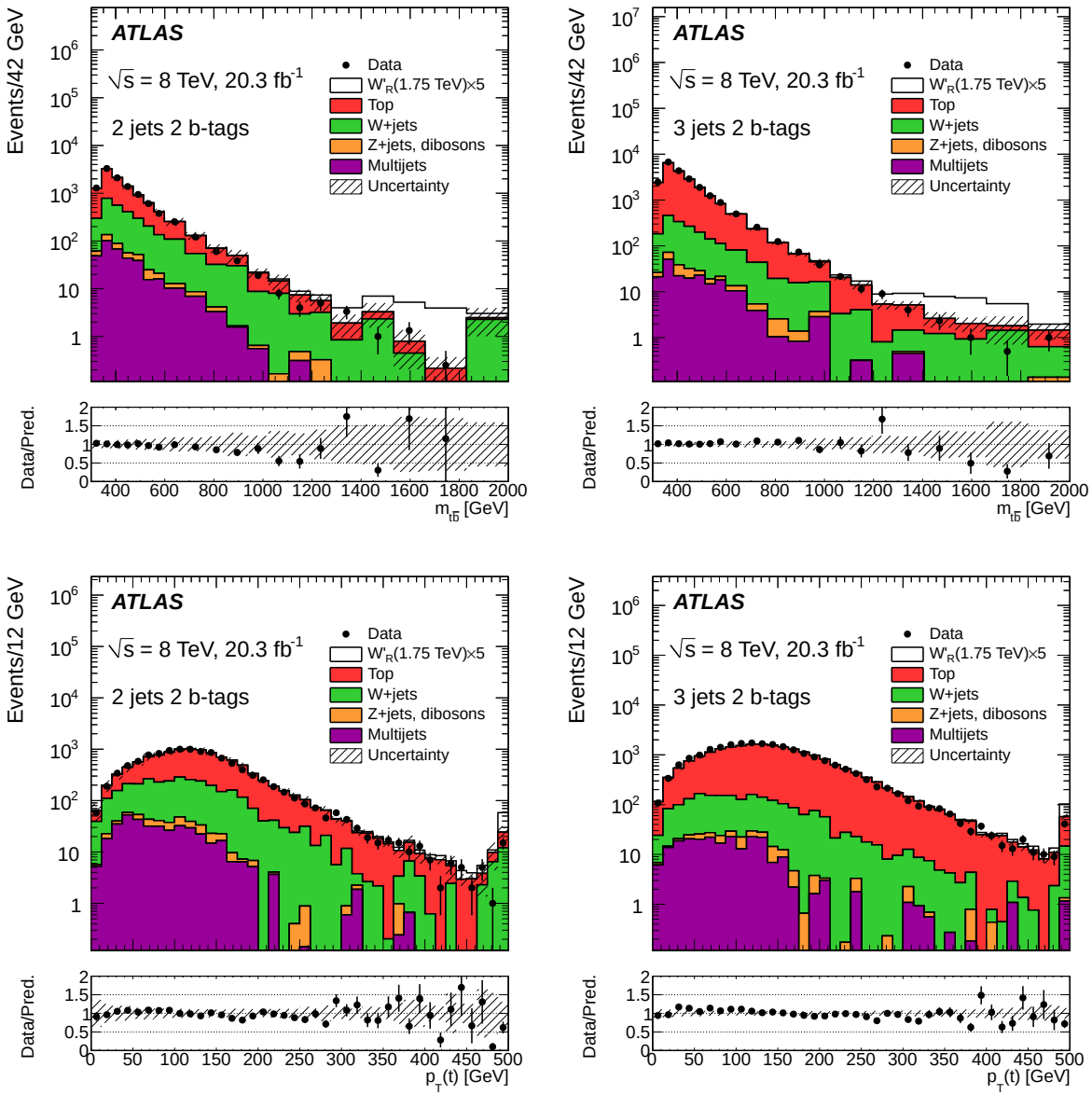
All hadronic channel

- Unbinned likelihood fit of the m_{tb} combining 1 and 2 b-tag regions.
- Signal fitted from MC. Systematic unc. due to the choice of the fit function estimated.
- Fit of signal allows interpolation of mass points.



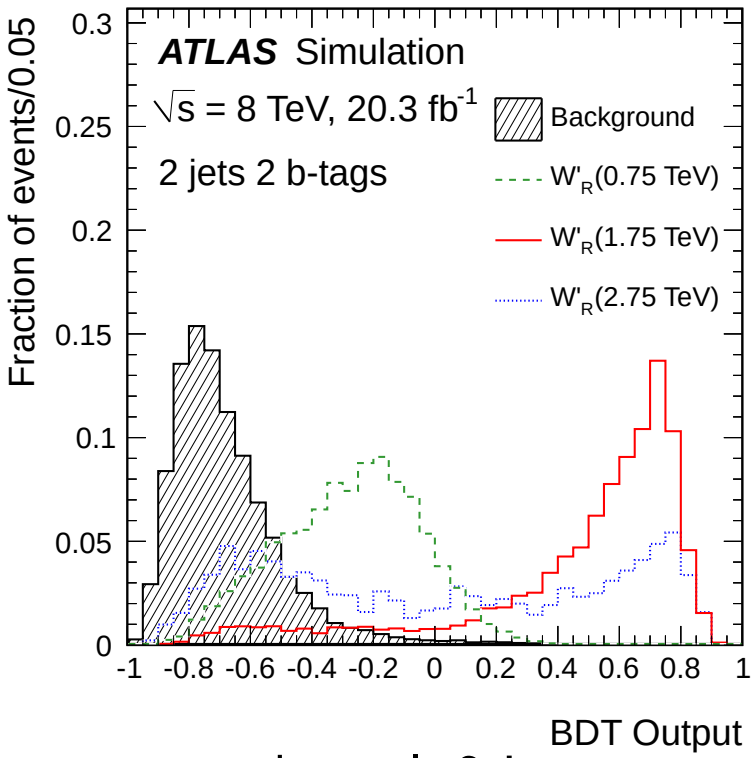


m_{tb} spectrum for all signal regions

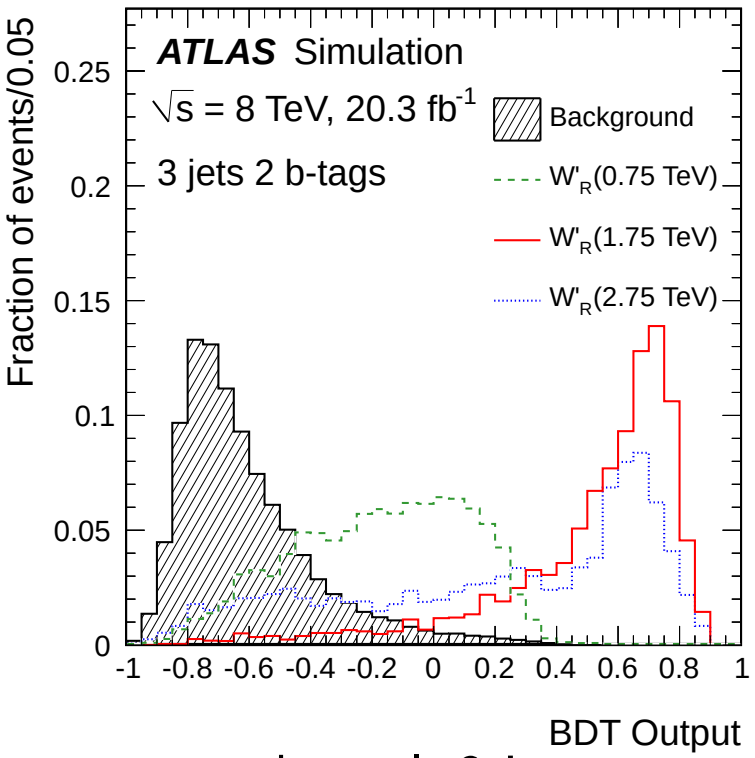


Lepton+jets analysis

- To try to maximise sensitivity by using a Boosted Decision Tree.
- Inputs of the BDT depend on the signal chirality, but a few variables are relevant in both left-handed and right-handed studies:
  - m_{tb} and transverse momentum of the reconstructed top (most relevant for separation).
  - $\Delta R(b_{W'}, b_t)$.



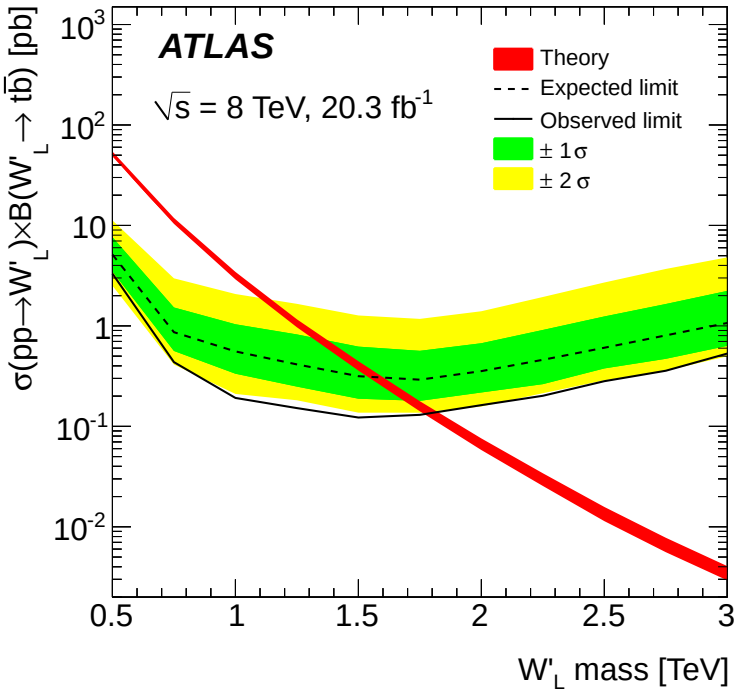
e channel, 2 jets

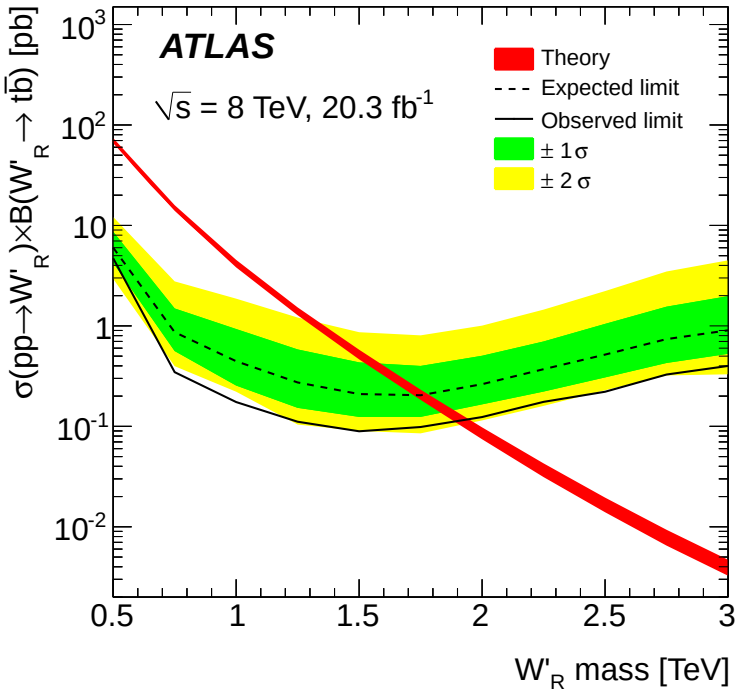


μ channel, 3 jets

Lepton+jets channel limits

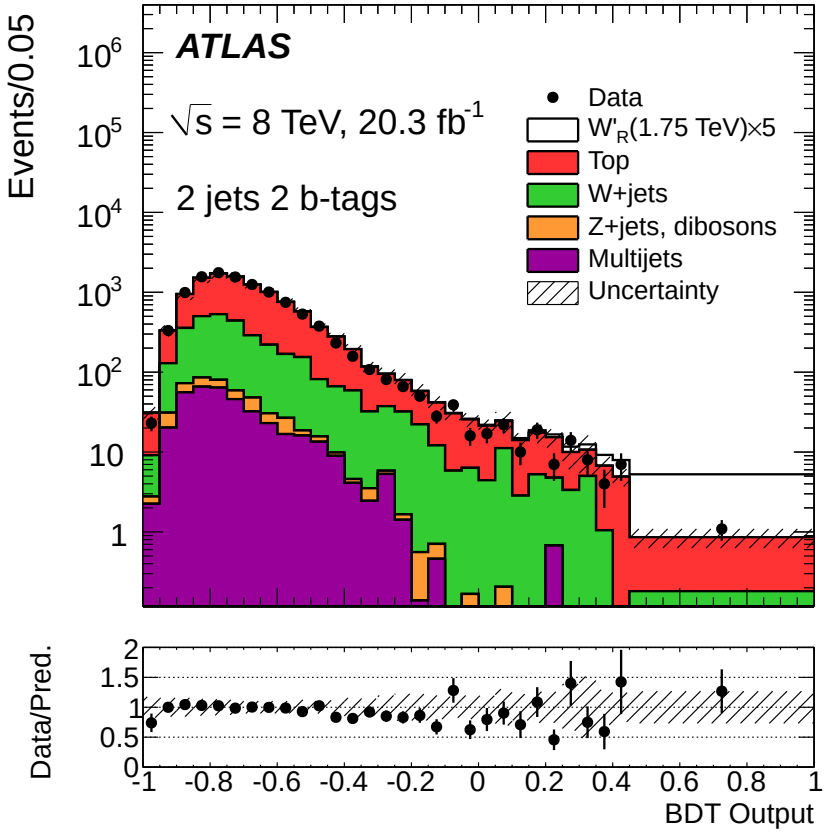
- No excess is observed.
- Observed mass limit of 1.8 TeV for W'_L and 1.9 TeV for W'_R.

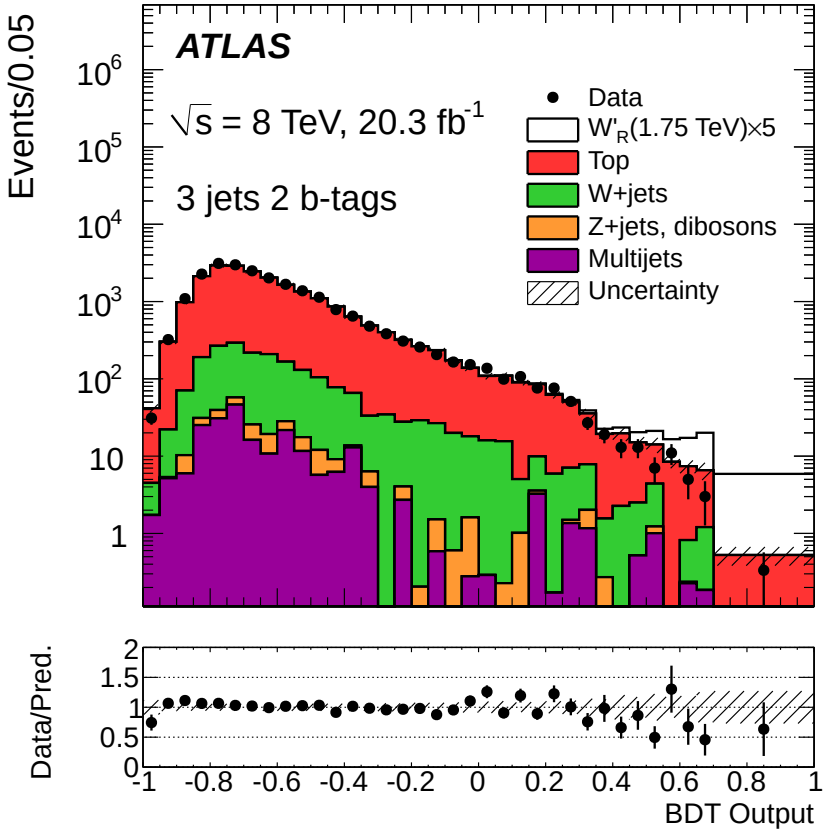




BDT output comparison in data

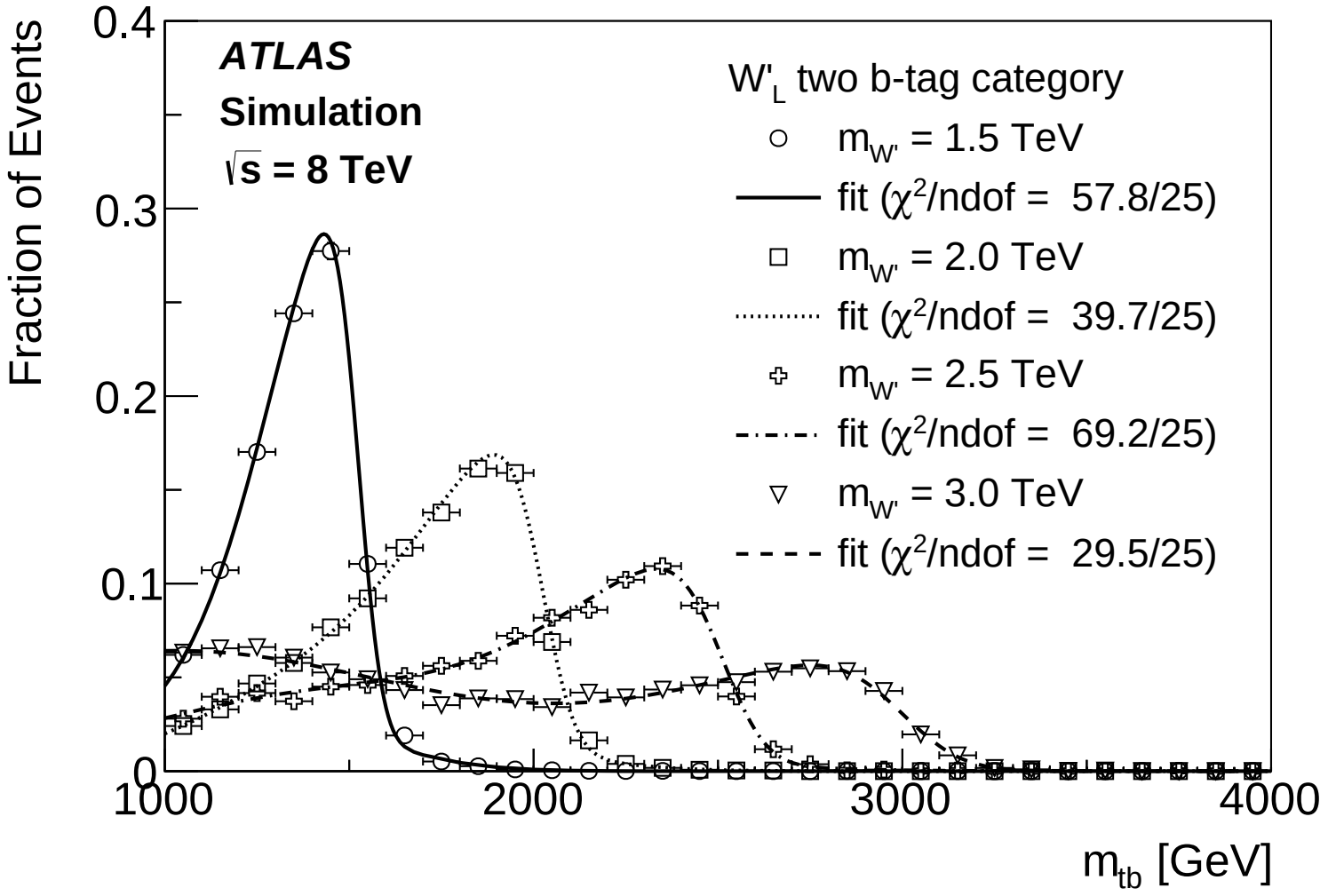
- BDT output is well modelled in data.





Signal fit

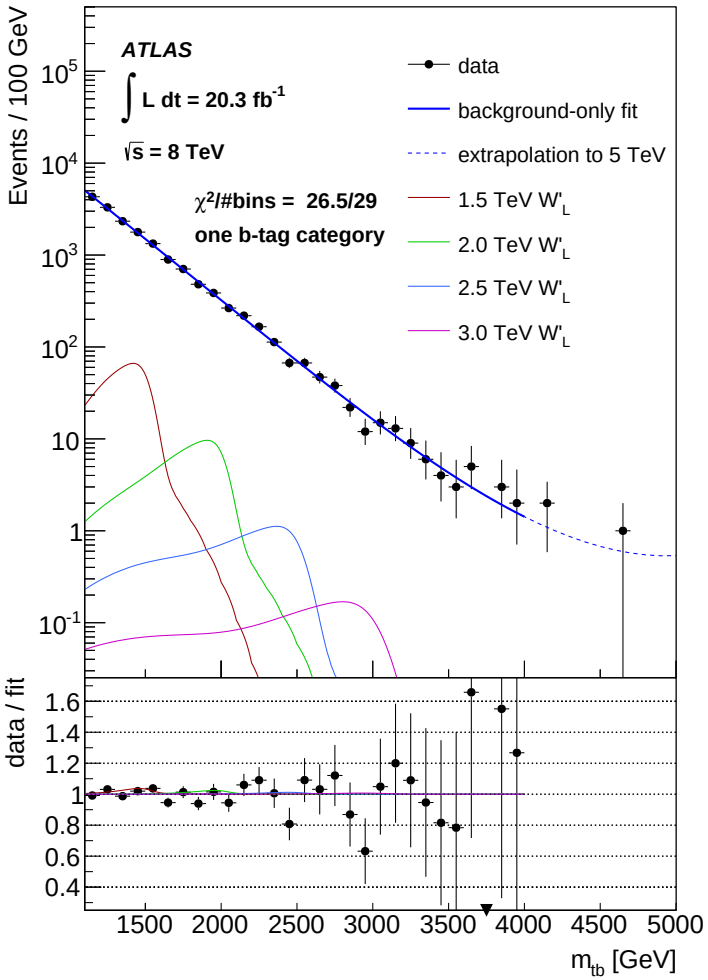
- Signal shape fit in analytically parametrised function.
- Parameters interpolated to obtain intermediate mass points.

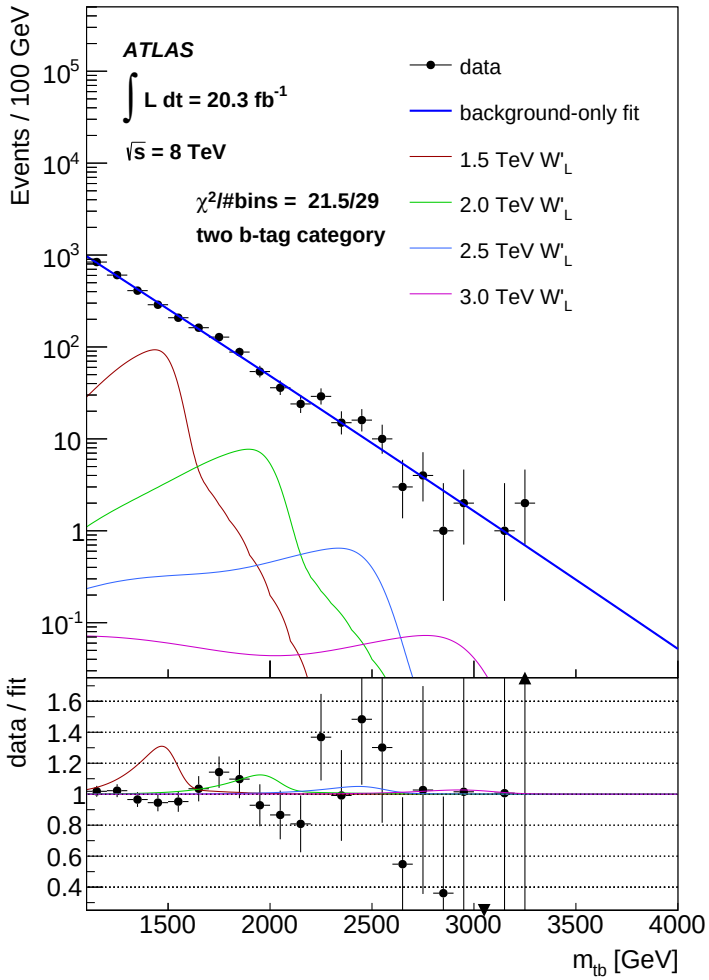


Signal fits

All hadronic channel

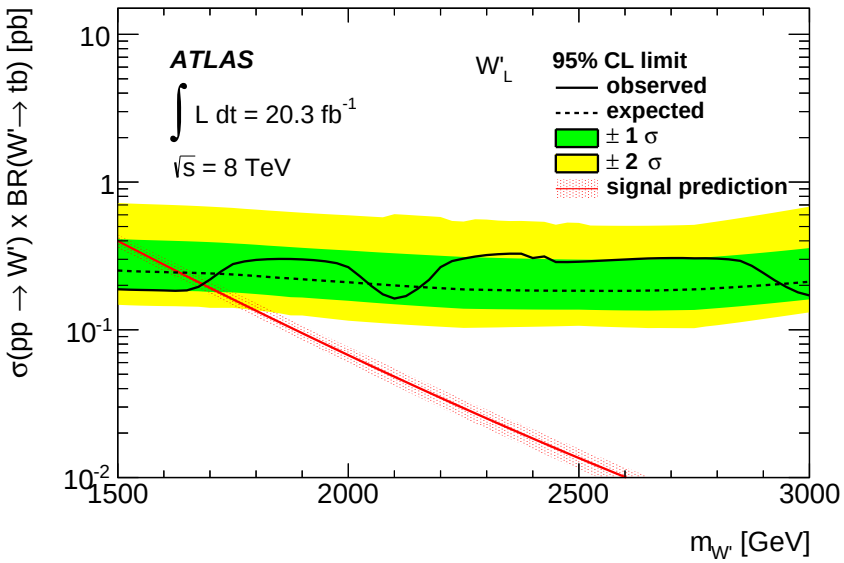
- Unbinned likelihood fit of the m_{tb} is done combining the one b-tag region and the two b-tag regions.
- The signal is also fitted from MC simulation. Systematic uncertainties due to the choice of the fit function are estimated.

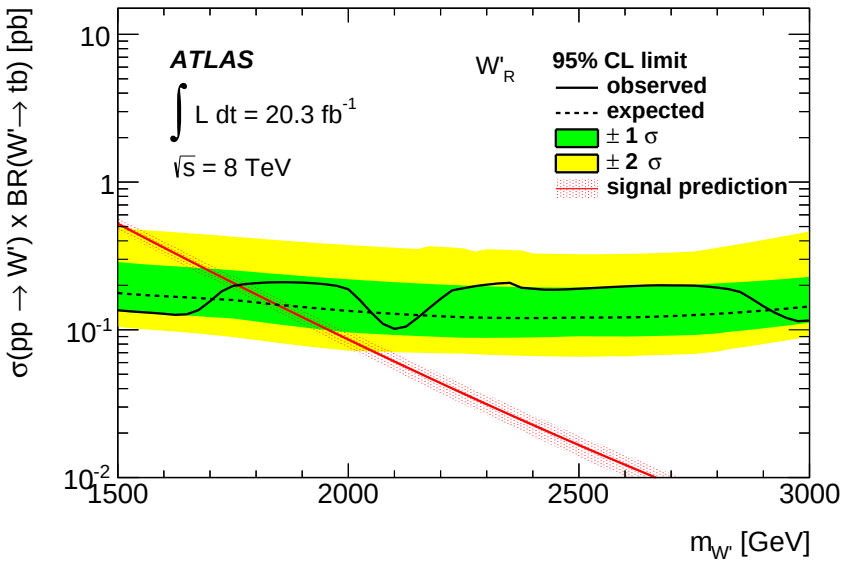




All hadronic limits

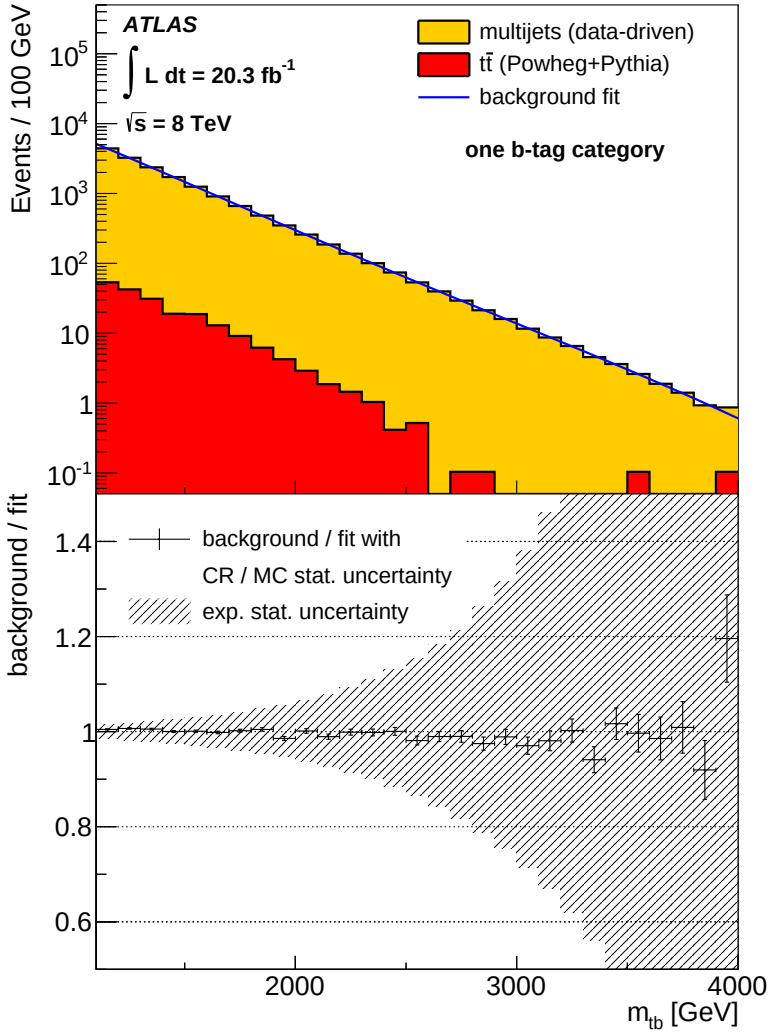
- Setting limits on a left-handed and a right-handed W' signal, used as a benchmark.
- Fit of signal shapes allows interpolation of mass points, used to get a continuous cross section limit.
- No excesses found.

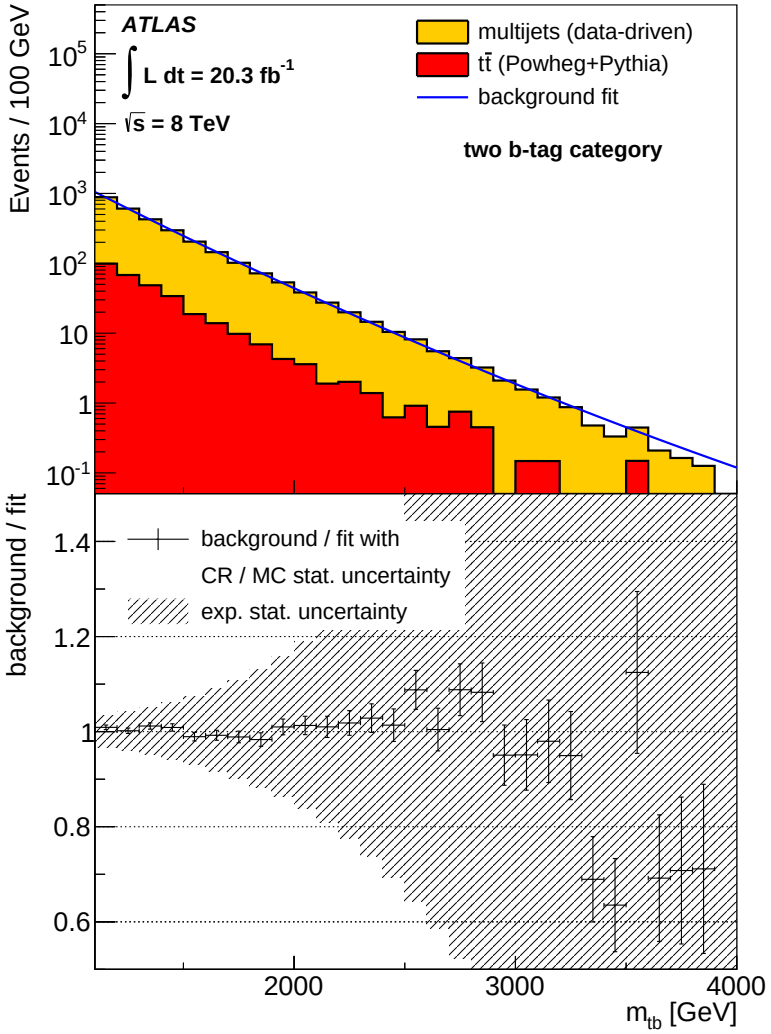




Background fit

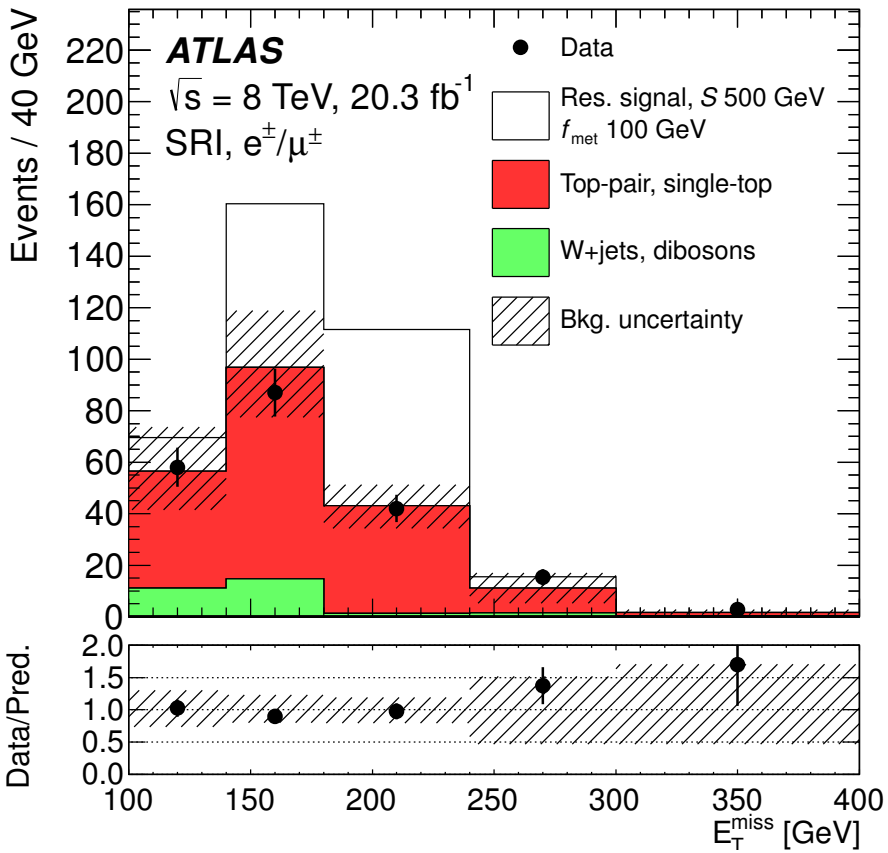
- Background fit also done analytically to set limits in an unbinned likelihood ratio method.

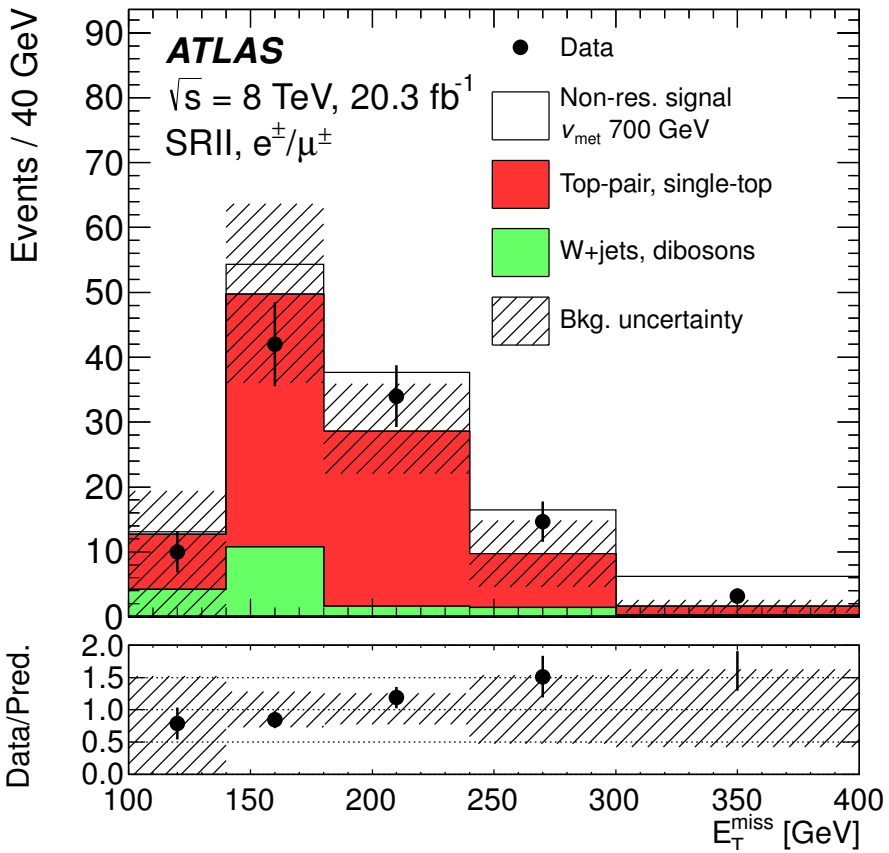




Signal Regions data/background comparison

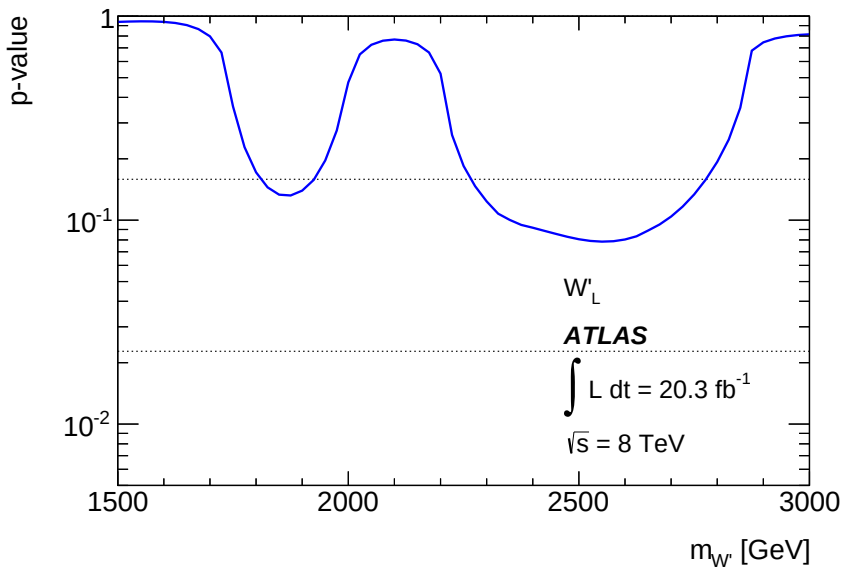
- No observed disagreement in the SRs.
- Control Regions are well modelled.

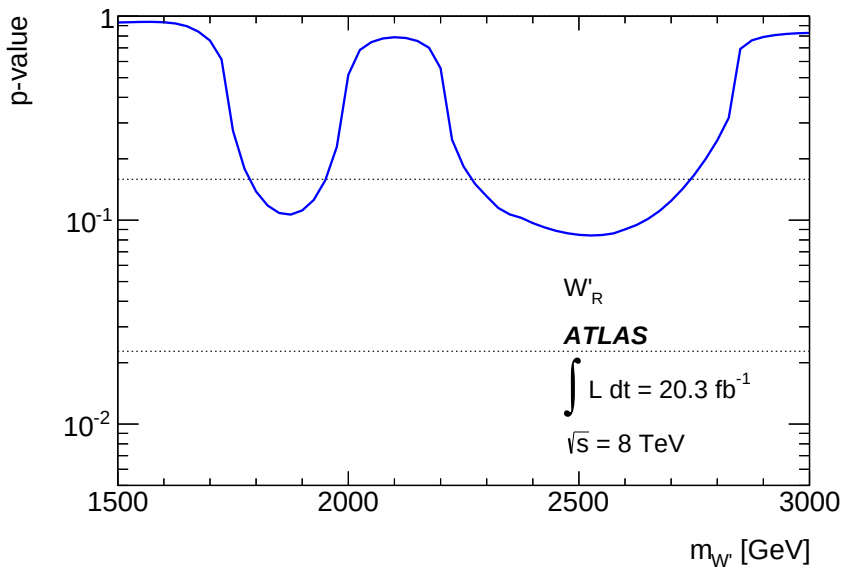




p-values

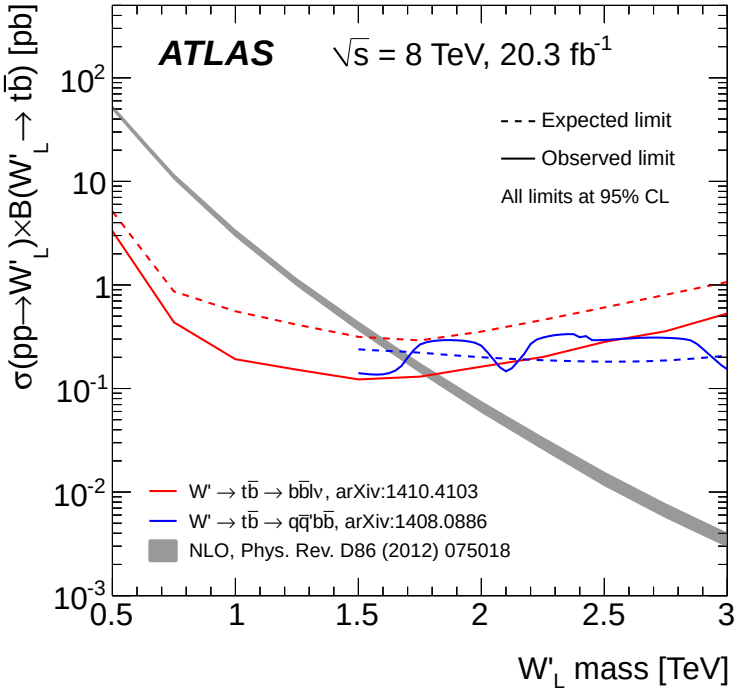
- Using signal mass points interpolation, one can set the p-value by varying the mass continuously.

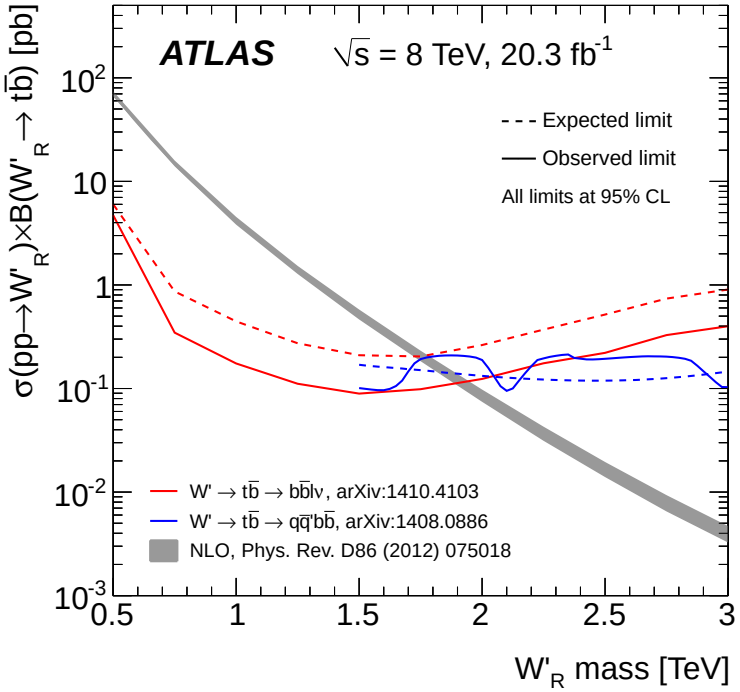




Combination of all hadronic and lepton+jets limits

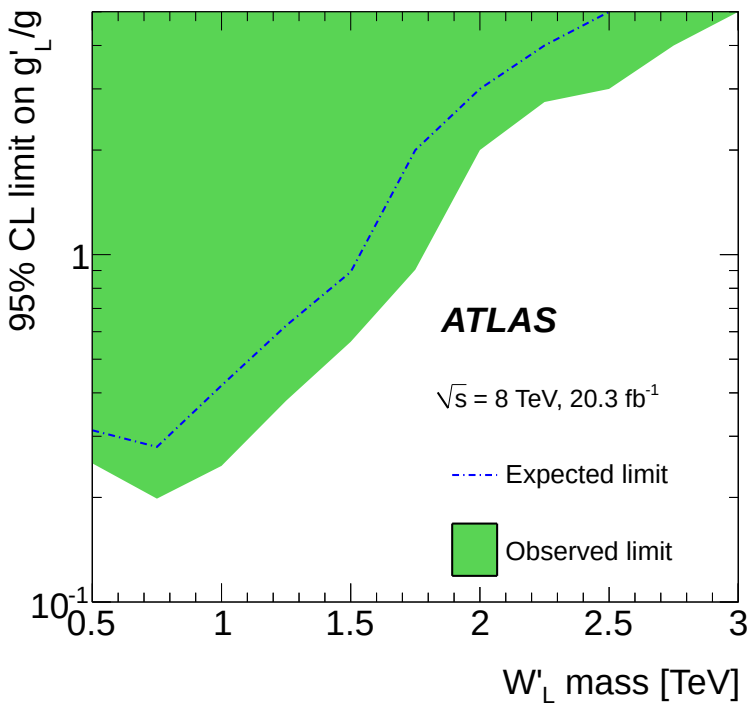
- Combination of the lepton+jets and all hadronic channels improve limits.

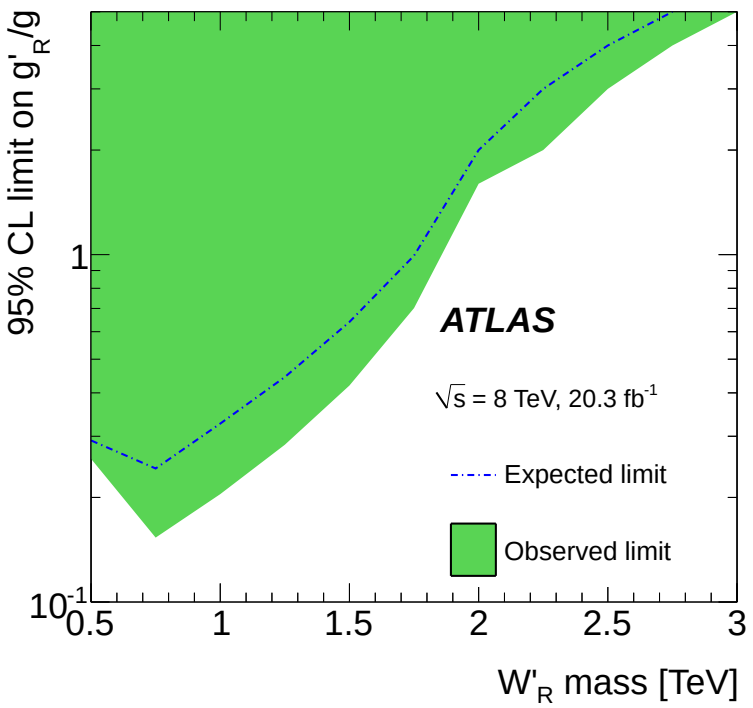




Coupling limits on the *tb* resonance

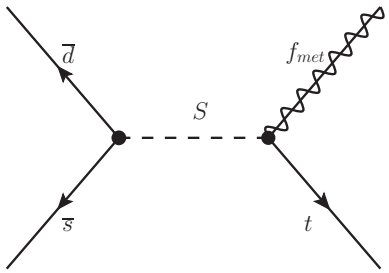
- Limit results can be reinterpreted as a limit in the coupling and mass plane.
- Assumes no interference for the W'_L.



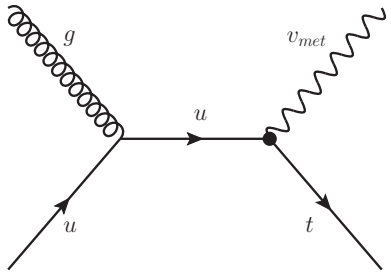


Search for top + E_T^{miss}

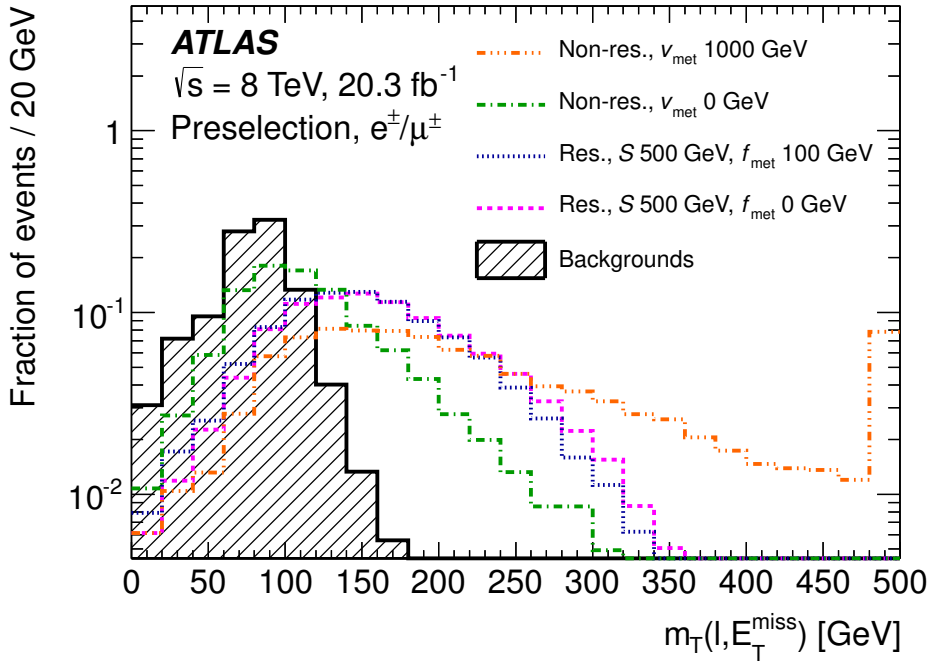
- Resonant and a non-resonant search.
- One electron or muon, a b-tagged jet, $E_T^{\text{miss}} > 35$ GeV and $m_T(l, E_T^{\text{miss}}) + E_T^{\text{miss}} > 60$ GeV.
- Dileptonic final state of $t\bar{t}$ and W+jets are the main backgrounds.
- Two signal regions are defined: SRI for resonant and SRII for non-resonant models.

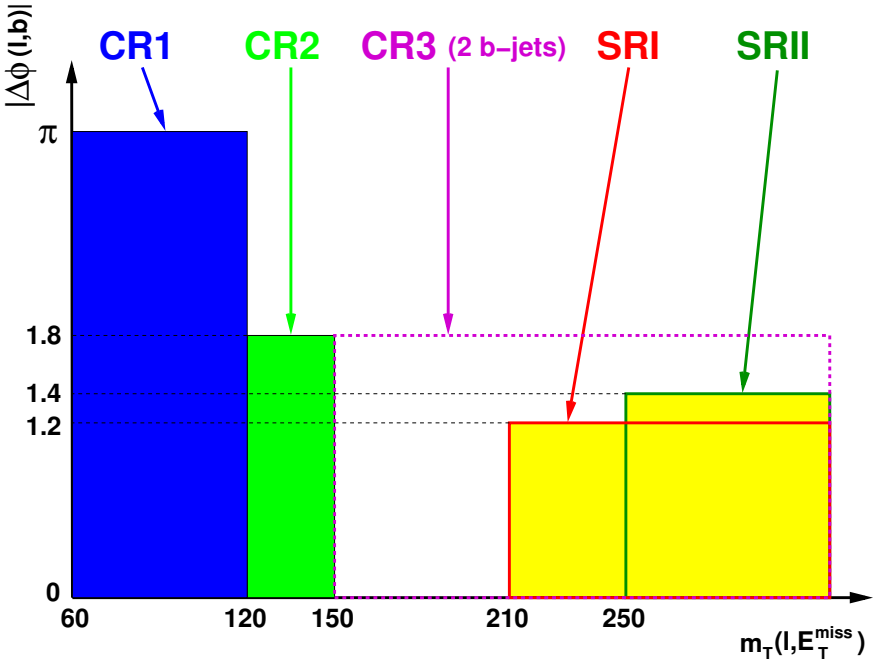


Resonance benchmark



Non-resonant example diagram



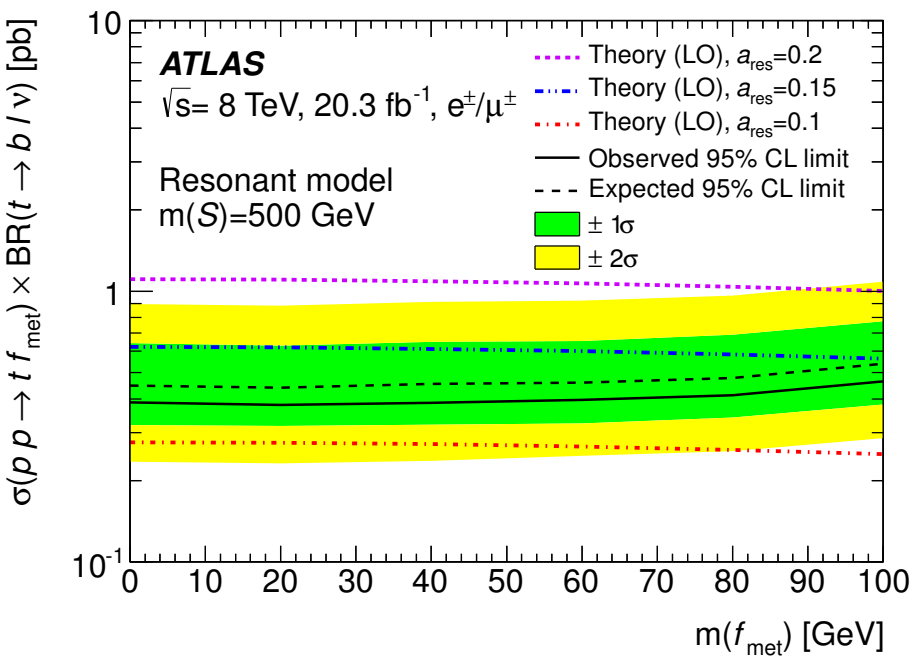


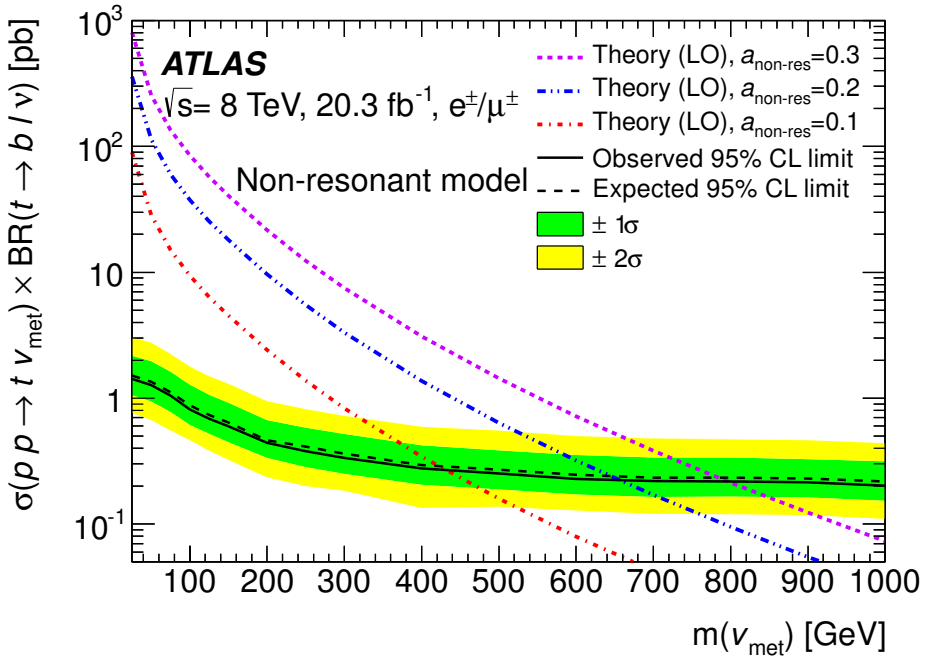
Limit setting

- Cut and count experiment.
- Cross section upper limit as a function of the invisible particle mass for different coupling strengths.
- Fields ϕ, χ and V_μ correspond to S, $f_{\rm met}$ and $v_{\rm met}$ respectively.

$$\mathcal{L}_{\rm res} = \epsilon^{\alpha\beta\gamma}\phi_\alpha \bar{d}^{i,c}_{\beta,R}(a^q_{\rm res})_{ij} d^j_{\gamma,R} + \phi \bar{u}^k_R (a^{1/2}_{\rm res})_k \chi + h.c.$$

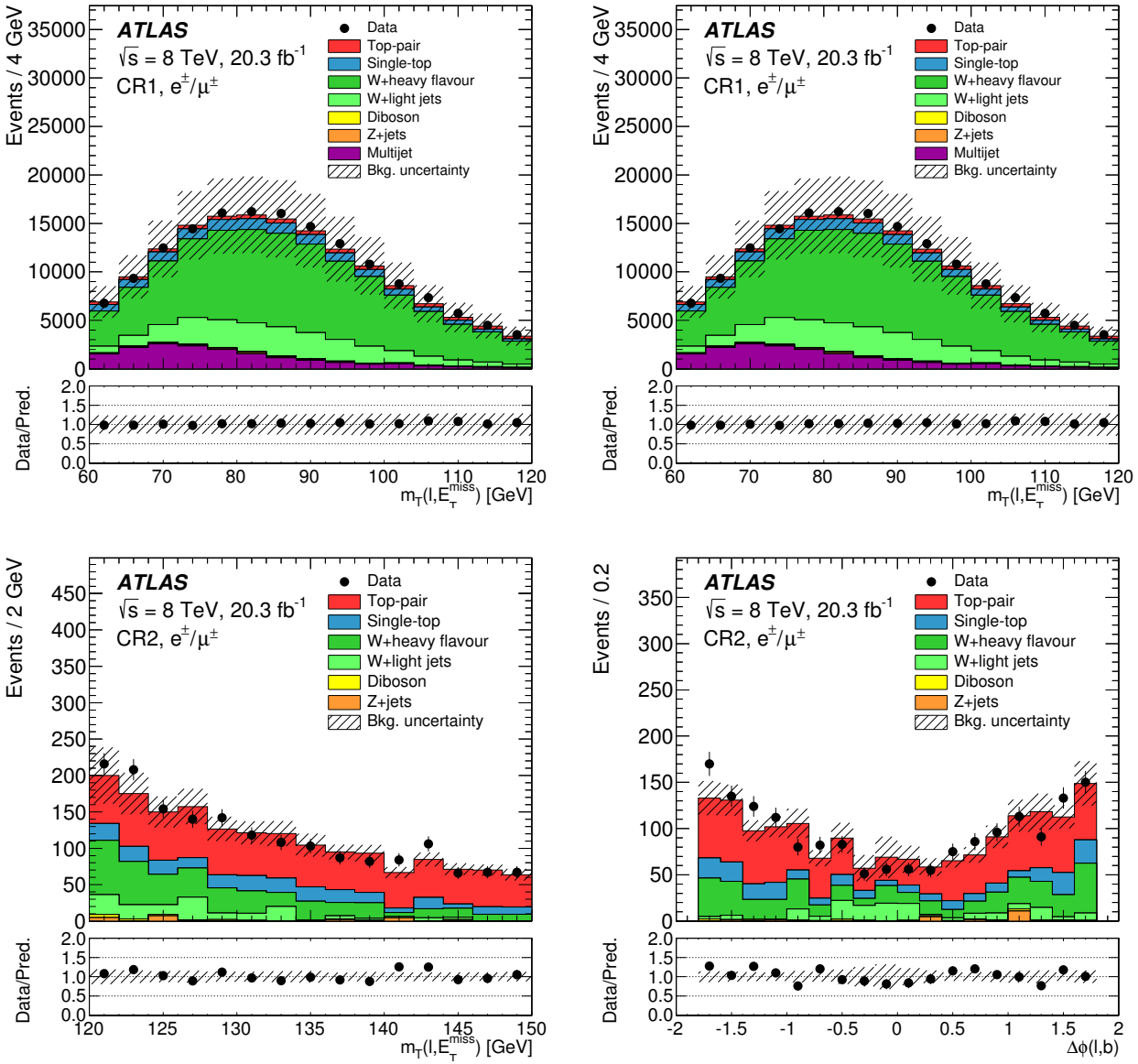
$$\mathcal{L}_{\rm non\text{-}res} = (a_{\rm non\text{-}res})_{ij} V_\mu \bar{u}^i_R \gamma^\mu u^j_R + h.c.$$





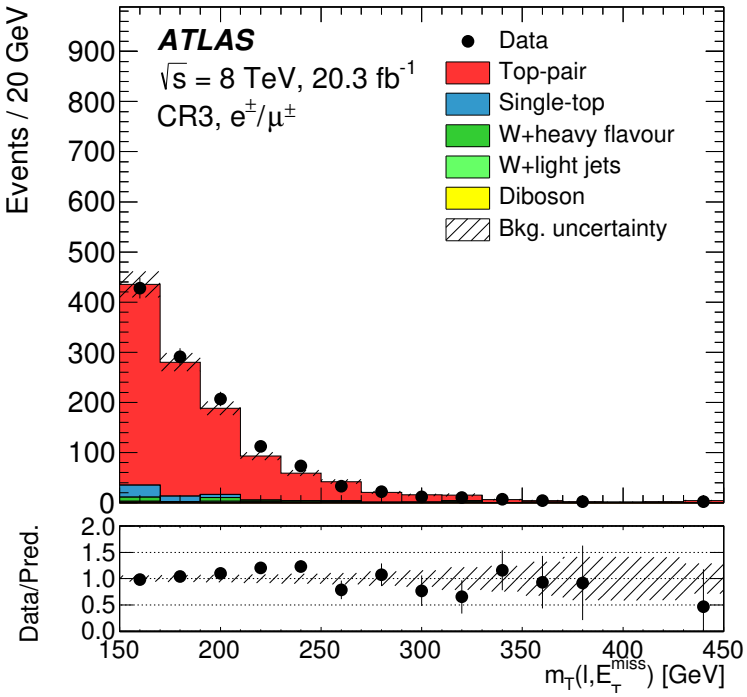
Control Regions (I)

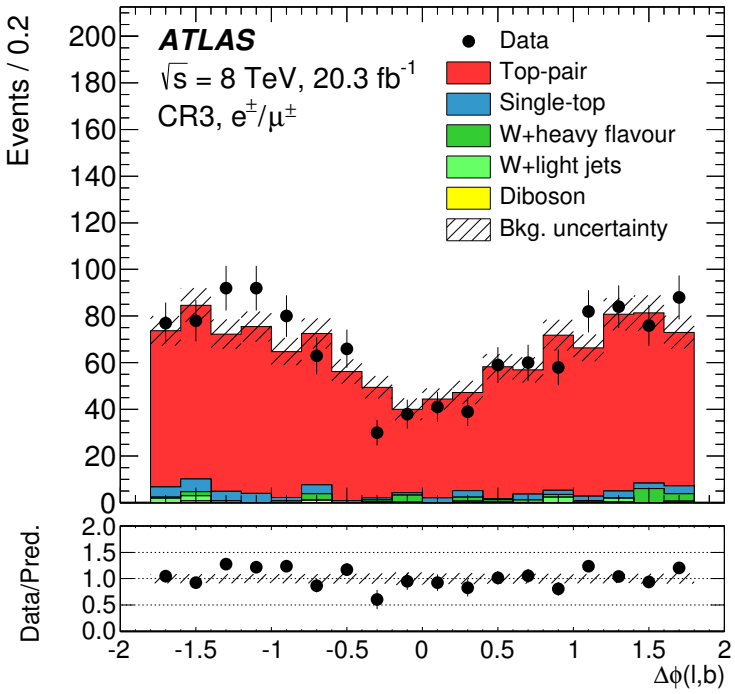
- Good agreement seen in the Control Regions.



Control Regions (II)

- Good agreement seen in the Control Regions.





Exclusion of couplings strength

- Limits re-interpreted as a function of the coupling strength.
- 95% CLs limits set on the mass $\times$ coupling plane.