Top-quark production measurements using the ATLAS detector at the LHC

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UNIVERSITÄT SIEGEN

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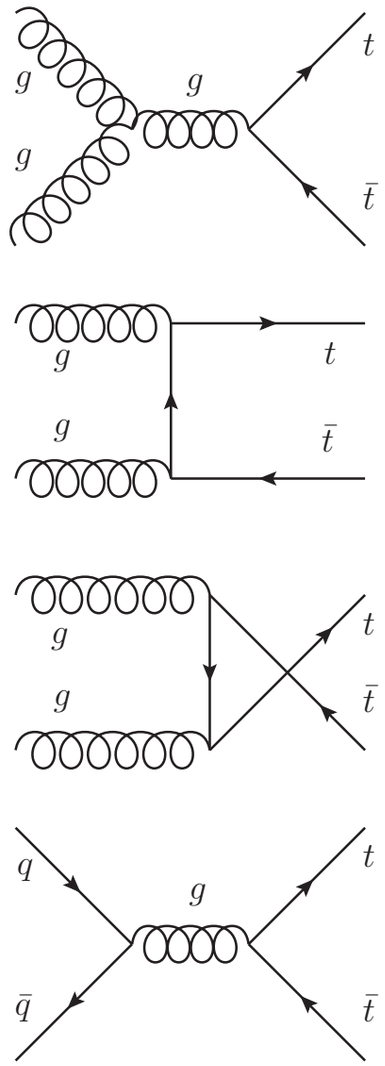
Bundesministerium für Bildung und Forschung

ATLAS EXPERIMENT

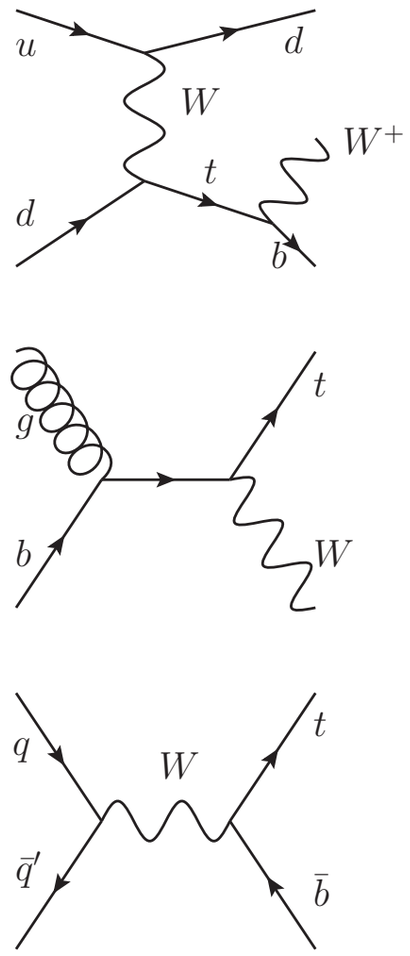
The top-quark

- The only ‘bare’ quark
- Yukawa coupling to Higgs ~ $\mathcal{O}$(I)
- Important to test the SM
- Top-quark pairs + vector boson
  probes electroweak couplings in the SM
- Produced in either pairs or as a single quark
- Decays almost exclusively in *Wb* pair
- Top-quark pair decay channels depending on the

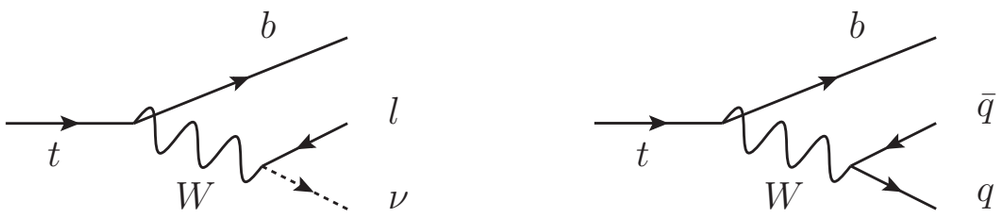
Pair Production



Single Production



Top-quark decay



Outline

- Top-quark pair production
  - in *dilepton(eμ) channel* events at $\sqrt{s}$ = 13 TeV
  - *differential* cross sections in *lepton+jets* channel at $\sqrt{s}$ = 8 TeV
  - *associated production with Z/W* in multilepton final states at $\sqrt{s}$ = 13 TeV

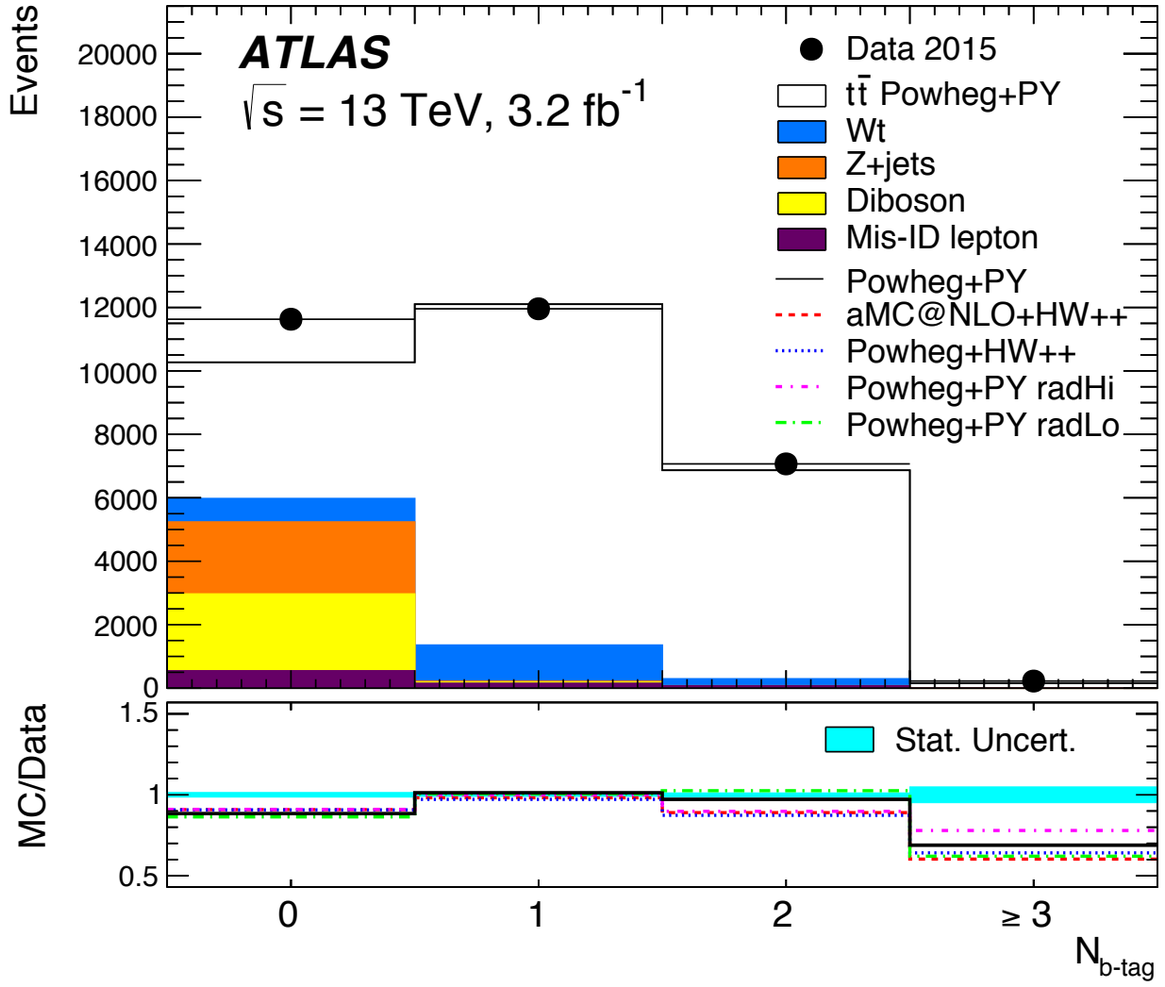
- Single top-quark production
  - inclusive cross section in *t-channel* at $\sqrt{s}$ = 13 TeV
  - cross section in *Wt-channel* at $\sqrt{s}$ = 8 TeV
  - evidence in the *s-channel* at at $\sqrt{s}$ = 8 TeV

Pair Production

Pair production cross-section using eμ events 3.2 fb^{-1} $\sqrt{s}$ = 13 TeV

arXiv:1606.02699

- A very clean signal
  - one isolated $e^{\pm}$ $\mu^{\mp}$ pair
  - one or two *b*-jet(s)
  - leptons and jets p_T>25 GeV, $|\eta|$< 2.5
- Backgrounds: mostly from simulation
  - *Wt*
  - *Z+jets*
  - diboson
  - misidentified (fake) lepton events ->*data*
- $t\bar{t}$ purity in the simulation:
  - with one b-tag -> 89%
  - with two b-tags -> 96%



$$N_1 = \mathcal{L}\ \sigma_{t\bar{t}}\ \epsilon_{e\mu}\ 2\epsilon_b(1 - C_b\epsilon_b) + N_1^{bkg}$$

$$N_2 = \mathcal{L}\ \sigma_{t\bar{t}}\ \epsilon_{e\mu}\ C_b\ \epsilon_b^2\ +\ N_2^{bkg}$$

$\epsilon_{e\mu}$: Efficiency for eμ selection

C_b : Correlations between the two b-jets

ϵ_b : b-tagging efficiency

Pair production cross-section using eμ events 3.2 fb^{-1} $\sqrt{s}$ = 13 TeV

arXiv:1606.02699

- The inclusive cross-section reads:

$$\sigma_{t\bar{t}} = 818 \pm 8(\text{stat.}) \pm 27(\text{syst.}) \pm 19(\text{lumi}) \pm 12(\text{beam})\text{pb}$$

- To be compared with $\sigma_{theo} = 832^{+40}_{-46}\text{pb}$ **(NNLO+NNLL)**

- Systematics are dominated by:

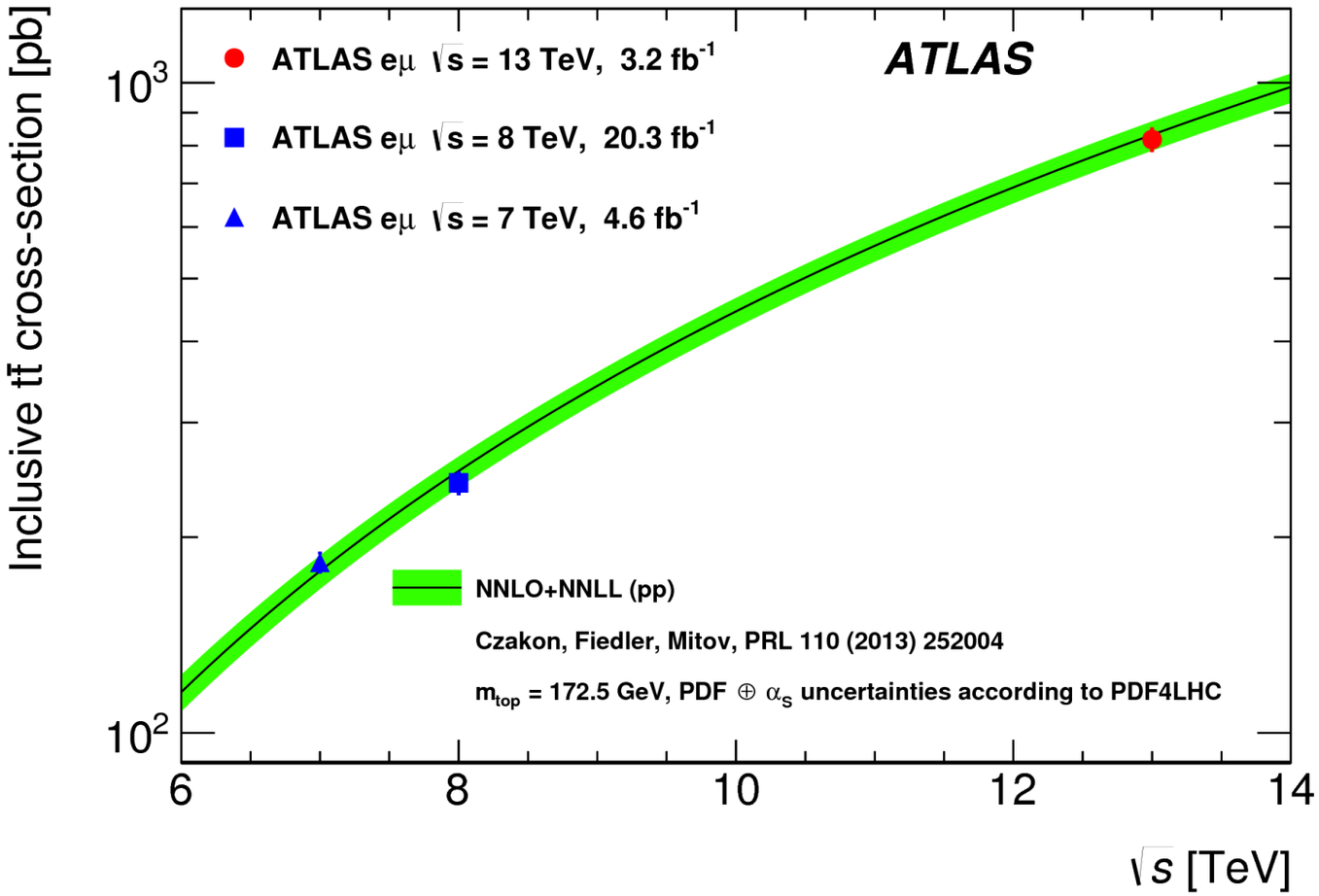
  $t\bar{t}$ hadronisation

  $t\bar{t}$ NLO modelling

  misidentified leptons

  single top / $t\bar{t}$ interference

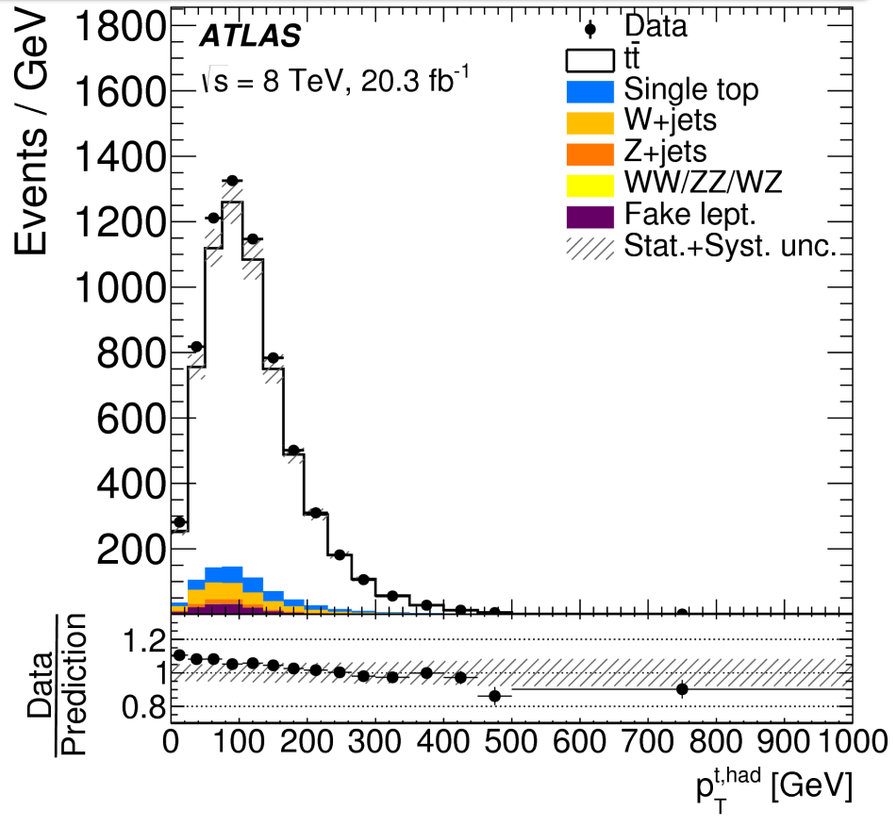
  parton distribution functions



Differential Cross Section in l+jets Channel 20.3 fb^{-1} $\sqrt{s}$ = 8 TeV

arXiv:1511.04716

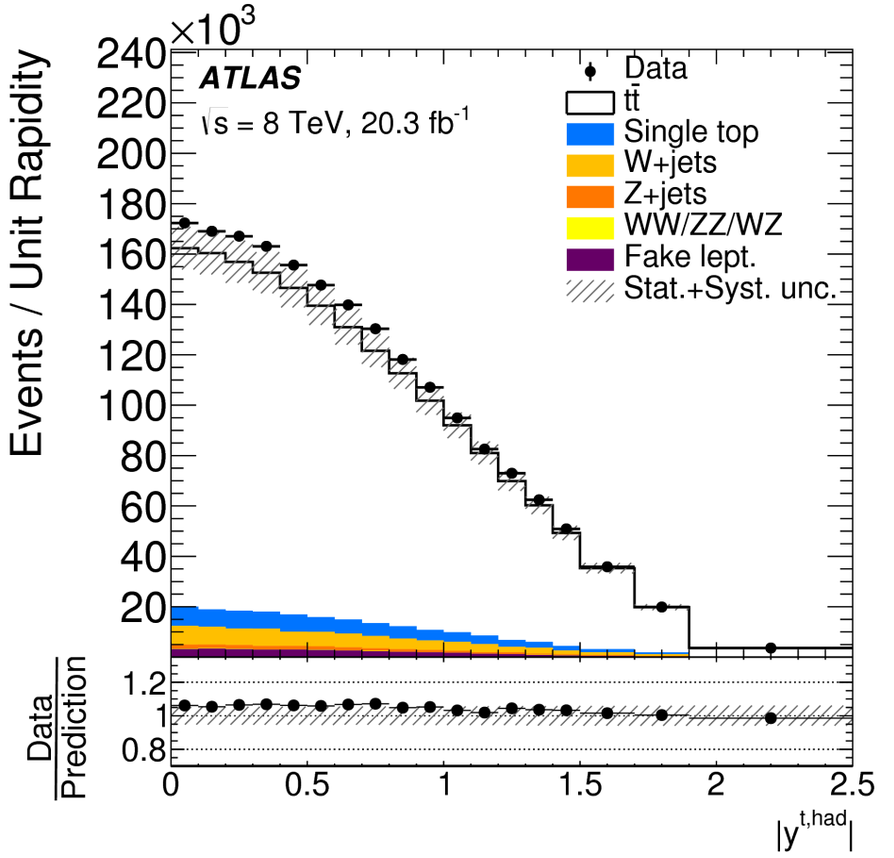
- $t\bar{t}$ production w.r.t. different kinematic variables to test the SM at the TeV scale
- Effects beyond the SM as modifications of diff. measurements
- Observables to emphasise:
  - the $t\bar{t}$ production process with sensitivity:
    to effects of I/FSR
    to the different PDFs
    to non-resonant processes
    and higher order corrections



- Baseline observables:

$$p_T^{t,had},\ |y^{t,had}|,\ p_T^{t\bar{t}},\ |y^{t\bar{t}}|,\ m^{t\bar{t}}$$

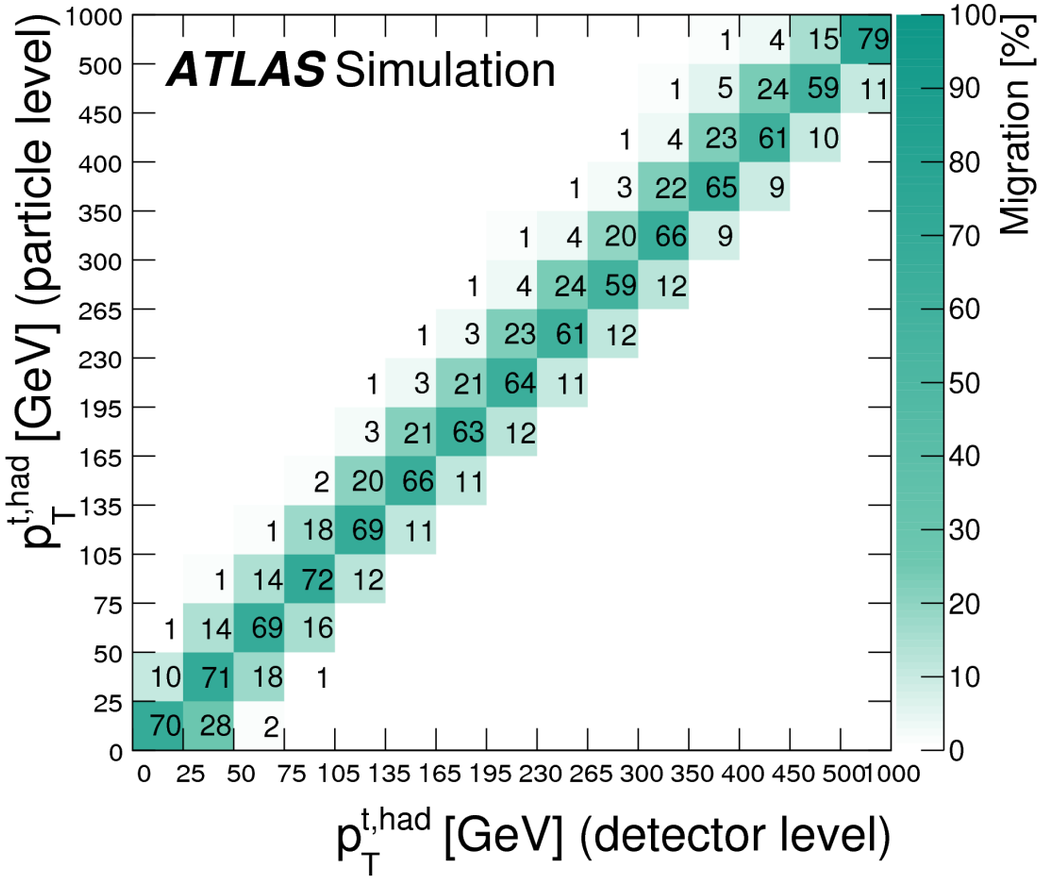
- Lepton+jets channel
  - one iso. *e* or μ
  - at least four jets
  - at least two *b*-jets
- Backgrounds
  - *W+jets*
  - $t\bar{t}$ dilepton events
  - single top
  - QCD multijet



Differential Cross Section in l+jets Channel 20.3 fb^{-1} $\sqrt{s}$ = 8 TeV

arXiv:1511.04716

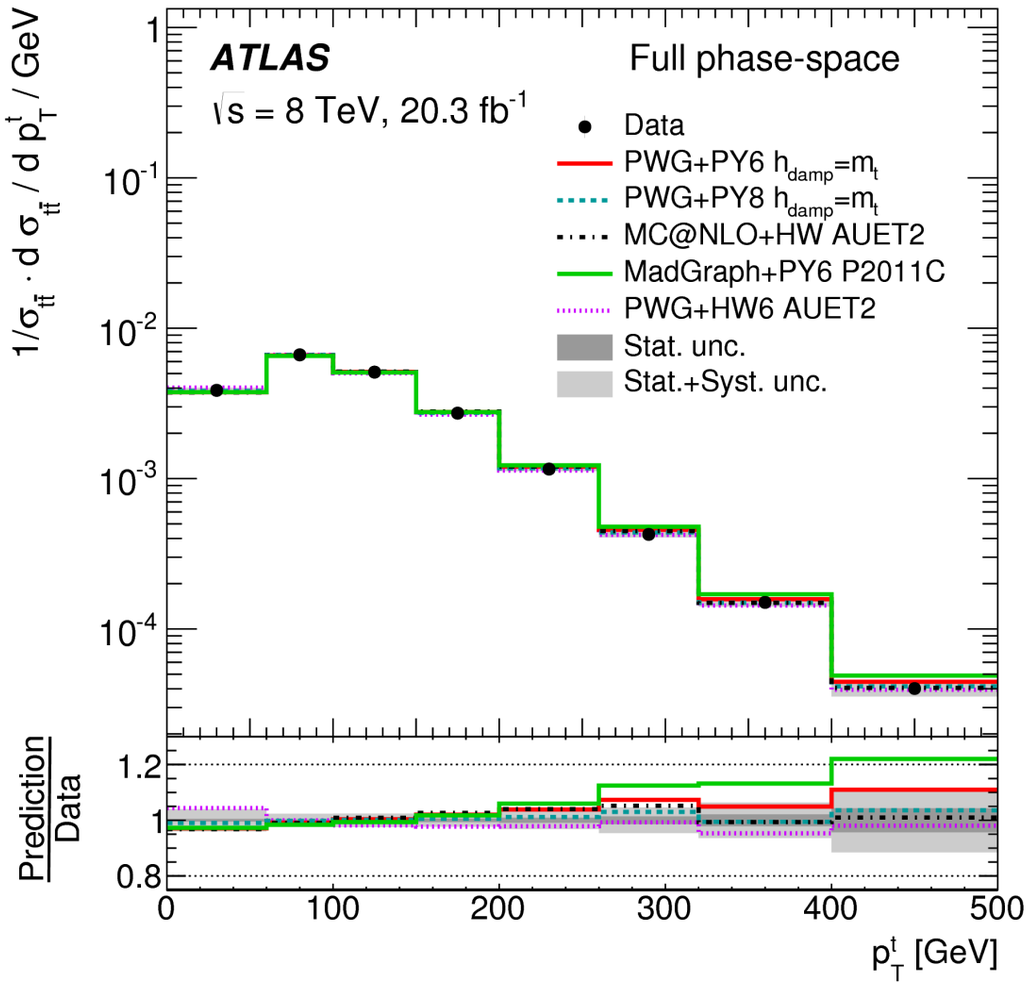
- Results unfolded both to a fiducial particle-level (PL) phase space and to the full phase space
- Unfolding to a fiducial PL phase space and using variables directly related to detector observables
  - allows precision tests of QCD, avoiding large model-dependent extrapolation corrections
- A migration matrix to map the binned generated particle-level events to the binned detector-level events

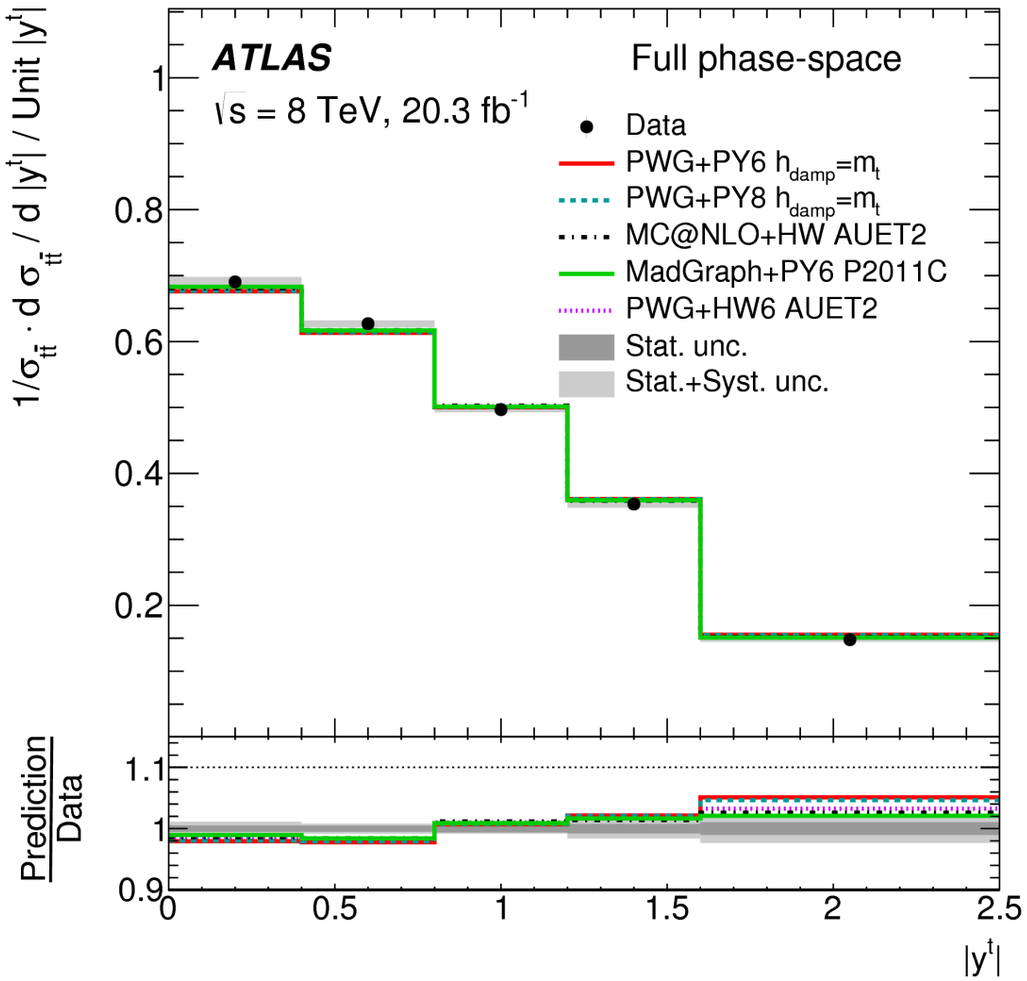


Differential Cross Section in l+jets Channel 20.3 fb^{-1} $\sqrt{s}$ = 8 TeV

arXiv:1511.04716 (2016)

- Good agreement with the predictions over a wide kinematic range
- Most generators predict a harder top-quark transverse momentum distribution at high values than what is observed in the data
- Agreement for this observable improves when NNLO corrections are taken into account
- Uncertainty dominated by jet energy scale, *b*-tagging, $t\bar{t}$ modelling

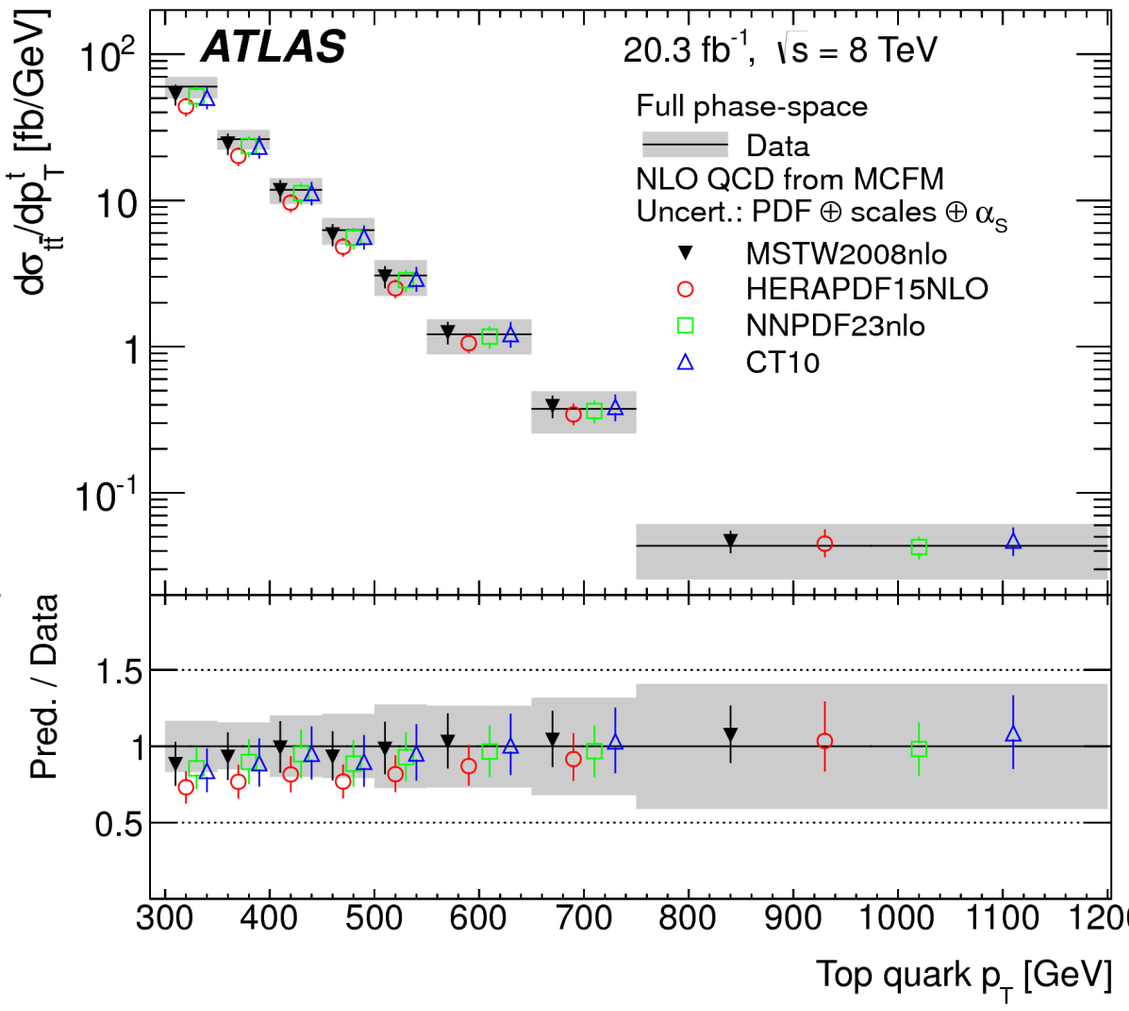




Differential cross-section of highly boosted top quarks 20.3 fb^{-1} $\sqrt{s}$ = 8 TeV

Phys. Rev. D 93, 032009 (2016)

- BSM $t\bar{t}$ production can distort top-p_T at high p_T region
- Precise measurement of boosted top-quarks might reveal hint for BSM
- Lepton+jets channel using hadronically decaying top-quarks with p_T > 300 GeV
- Boosted top-quarks reconstruction
  anti-k_T with radius parameter $R = 1.0$
- Cross-section as a function of top-quark p_T
- The measurement uncertainty dominated by jet energy resolution of large-R jets.



- The predictions of a majority of NLO and LO ME Monte Carlo generators agree with the measured cross-sections.

Pair production in association with Z/W boson 3.2 fb^{-1} $\sqrt{s}$=13 TeV

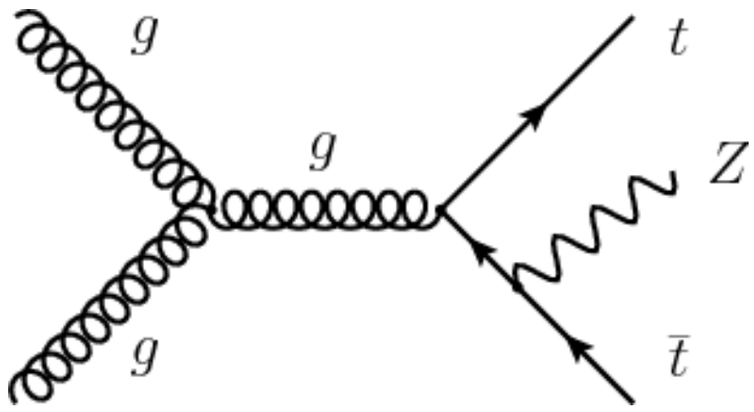
- Allow to extract information on the neutral current coupling of the top-quark($t\bar{t}Z$)
- Important checks for the validity of the SM at the new energy regime ~13 TeV
- Three channels based on the number of reconstructed leptons:

1. Same-sign dimuon analysis (2μ-SS): $t\bar{t}W$

two muons p_T >25 GeV, E_T^{miss}>40 GeV, H_T > 240 GeV, ≥2 *b*-jets

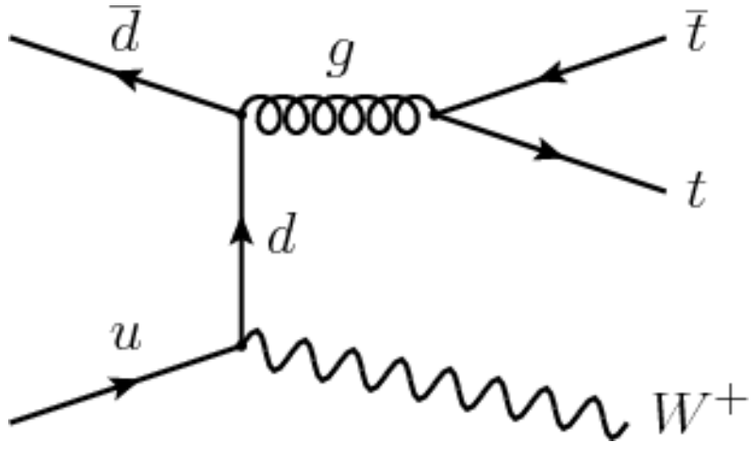
2. Trilepton analysis: $t\bar{t}Z$ $t\bar{t}W$

Variable	3ℓ-Z-1b4j	3ℓ-Z-2b3j	3ℓ-Z-2b4j	3ℓ-noZ-2b
Leading lepton p_T	> 25 GeV			
Other leptons' p_T	> 20 GeV			
Sum of lepton charges	±1			
Z-like OSSF pair	$\lvert m_{\ell\ell} - m_Z \rvert$ < 10 GeV			$\lvert m_{\ell\ell} - m_Z \rvert$ > 10 GeV
n_{jets}	≥ 4	3	≥ 4	≥ 2 and ≤ 4
$n_{b-\text{jets}}$	1	≥ 2	≥ 2	≥ 2



3. Tetralepton analysis: $t\bar{t}Z$

Region	Z_2 leptons	p_{T34}	$\lvert m_{Z_2} - m_Z \rvert$	E_T^{miss}	$N_{b\text{-jets}}$
4ℓ-DF-1b	$e^{\pm}\mu^{\mp}$	> 35 GeV	-	-	1
4ℓ-DF-2b	$e^{\pm}\mu^{\mp}$	-	-	-	≥ 2
4ℓ-SF-1b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	> 25 GeV	> 10 GeV	> 40 GeV	1
			< 10 GeV	> 80 GeV	
4ℓ-SF-2b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	-	> 10 GeV	-	≥ 2
			< 10 GeV	> 40 GeV	

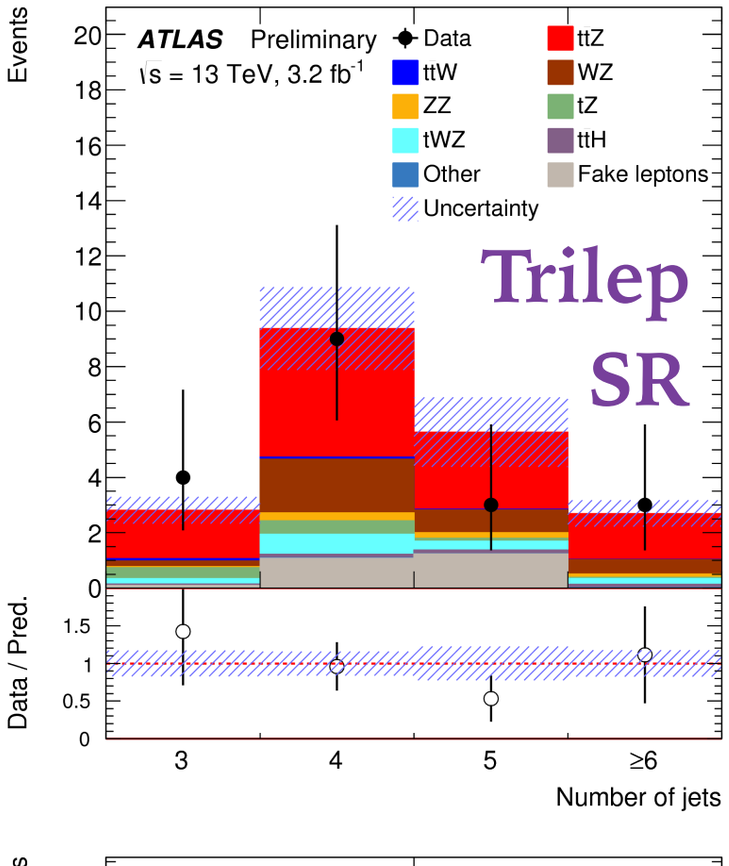


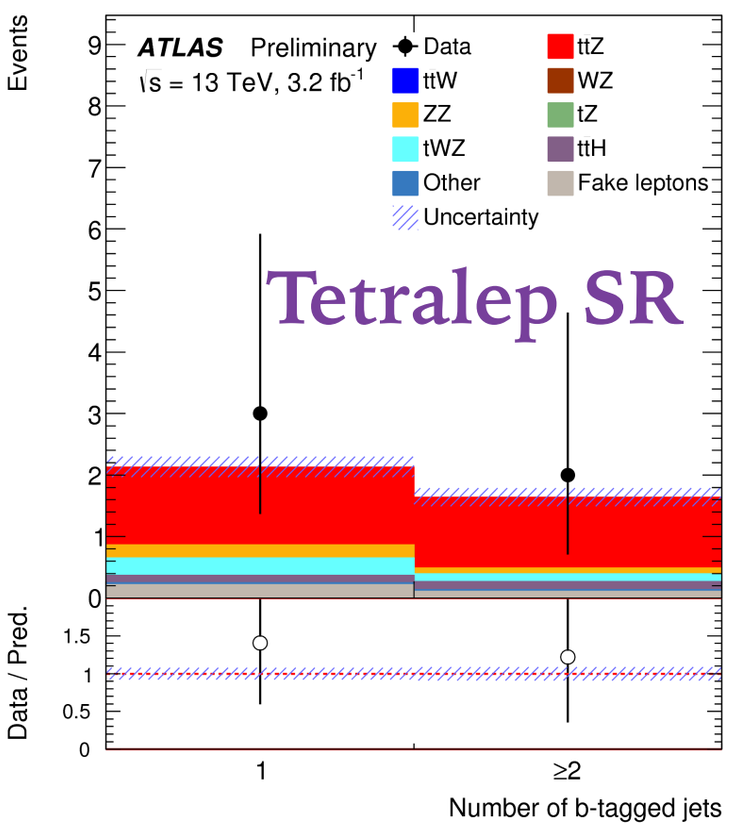
ATLAS-CONF-2016-003

Pair production in association with Z/W boson 3.2 fb^{-1} $\sqrt{s}$=13 TeV

ATLAS-CONF-2016-003

(2mu-SS)	Trilepton	Tetralepton
Dominant background: fake leptons. Backgrounds from the production of prompt leptons w/ correct charges come from *WZ* The fake lepton bkg. is estimated using matrix method.	Dominant background from diboson, *tZ*, *Z+jets* w/ fake lepton, The fake lepton bkg. is estimated using matrix method.	Dominant background from diboson. Backgrounds w/ fake leptons estimated from simulation and corrected w/ SFs from CRs.





- **Backgrounds containing prompt leptons are modelled by simulation.**
- **Normalisations are estimated from data when possible.**

Pair production in association with Z/W boson 3.2 fb^{-1} $\sqrt{s}$=13 TeV

- Expected yields after the fits: in the relevant SRs and two CRs used to constrain *WZ* and *ZZ*.

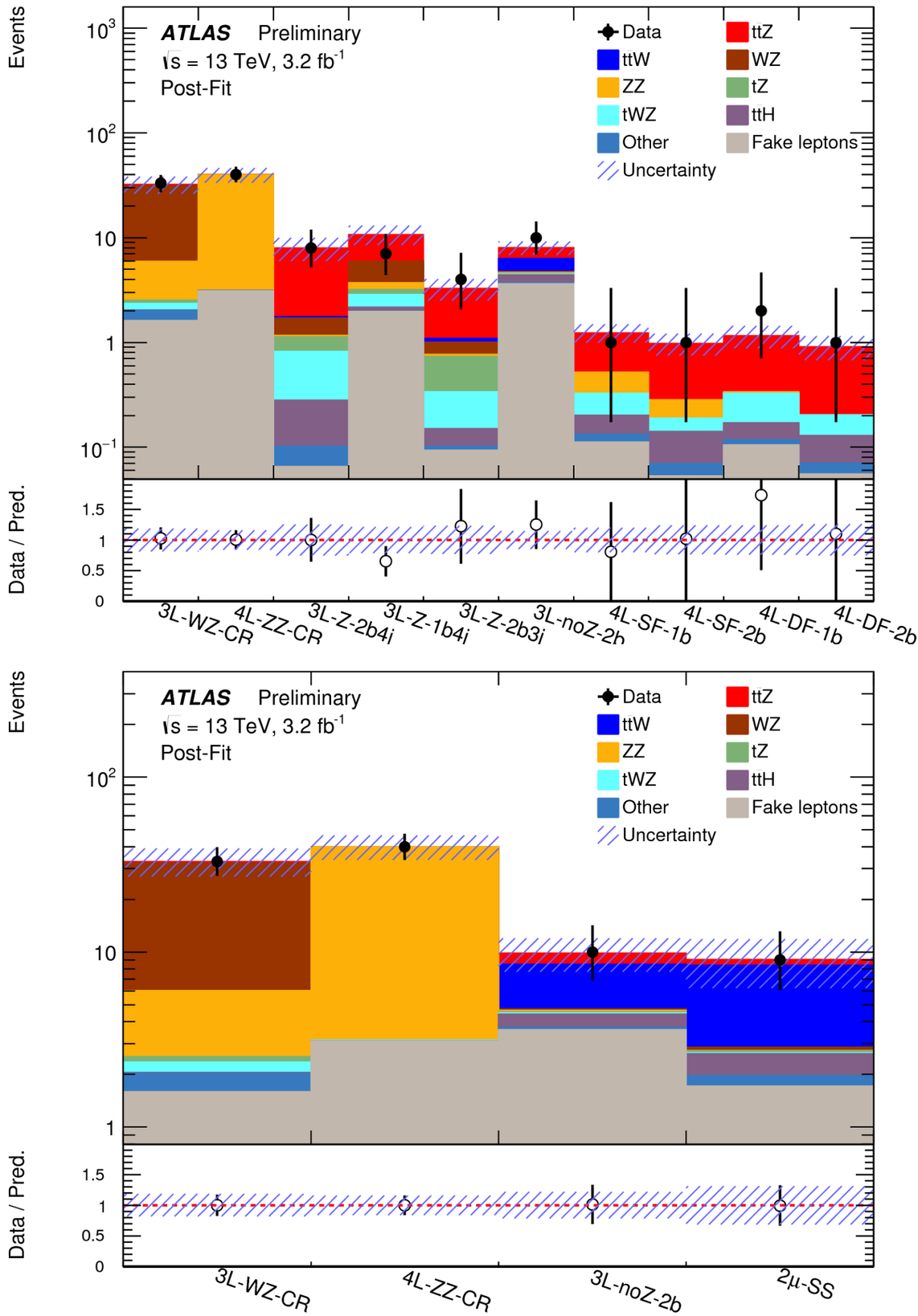
- From a fit to eight SRs and two CRs:

$$\sigma_{t\bar{t}Z} = 0.9 \pm 0.3 \text{ pb}$$
$$\sigma_{t\bar{t}W} = 1.4 \pm 0.8 \text{ pb}$$

- Both measurements are consistent with the NLO QCD theoretical predictions:

$$\sigma^{theo}_{t\bar{t}Z} = 0.76 \pm 0.08 \text{ pb}$$
$$\sigma^{theo}_{t\bar{t}W} = 0.57 \pm 0.06 \text{ pb}$$

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	6.4%	7.0%
Reconstructed objects	7.0%	7.3%
Backgrounds from simulation	5.5%	3.7%
Fake leptons and charge misID	3.9%	21%
Total systematic	12%	24%
Statistical	32%	51%
Total	34%	56%

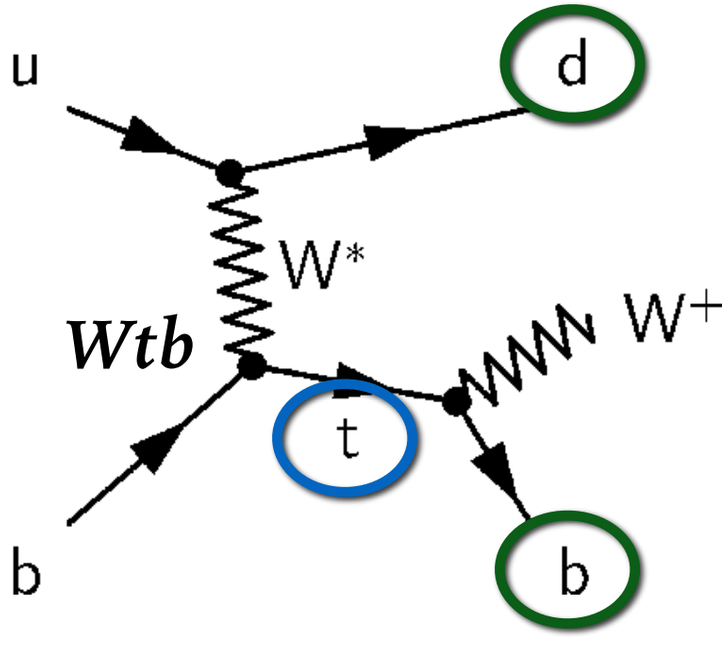


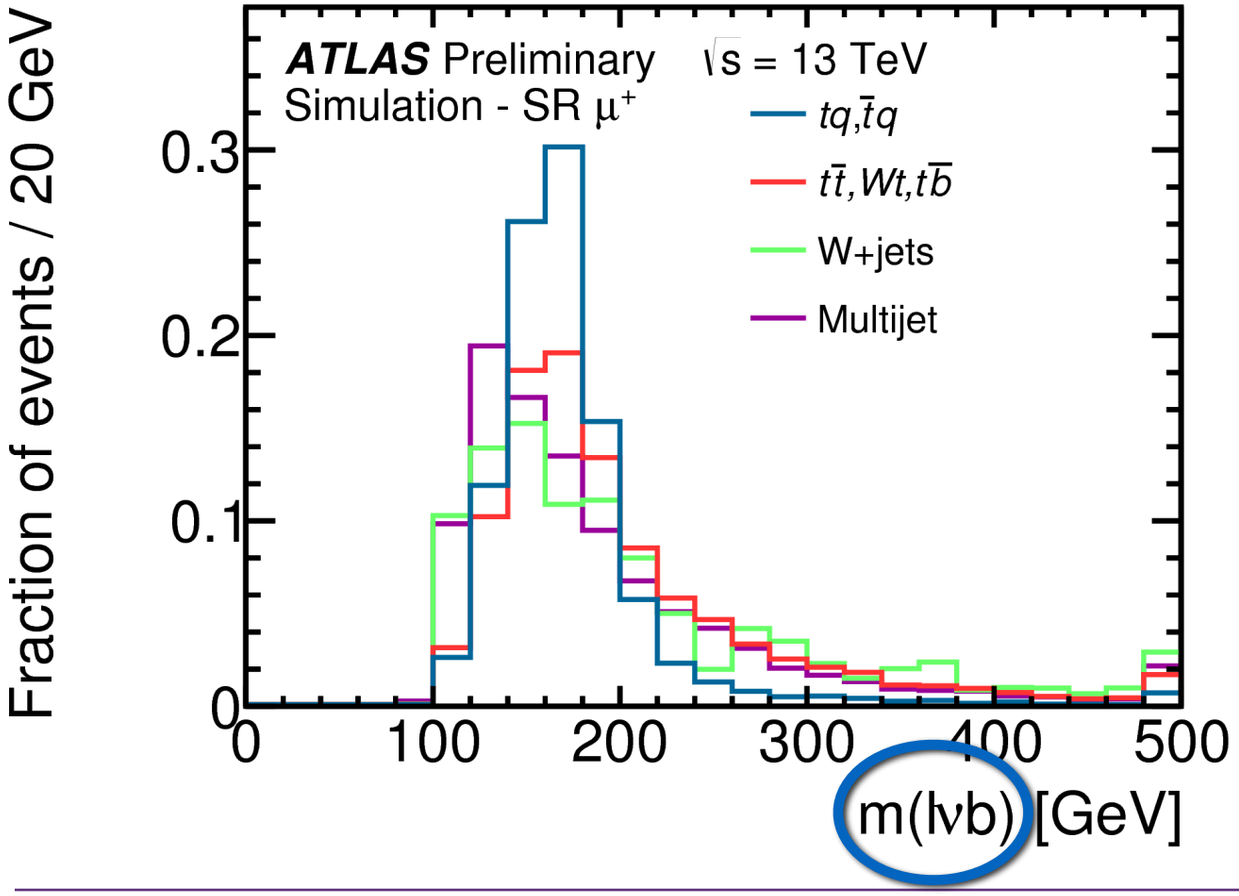
Single Production

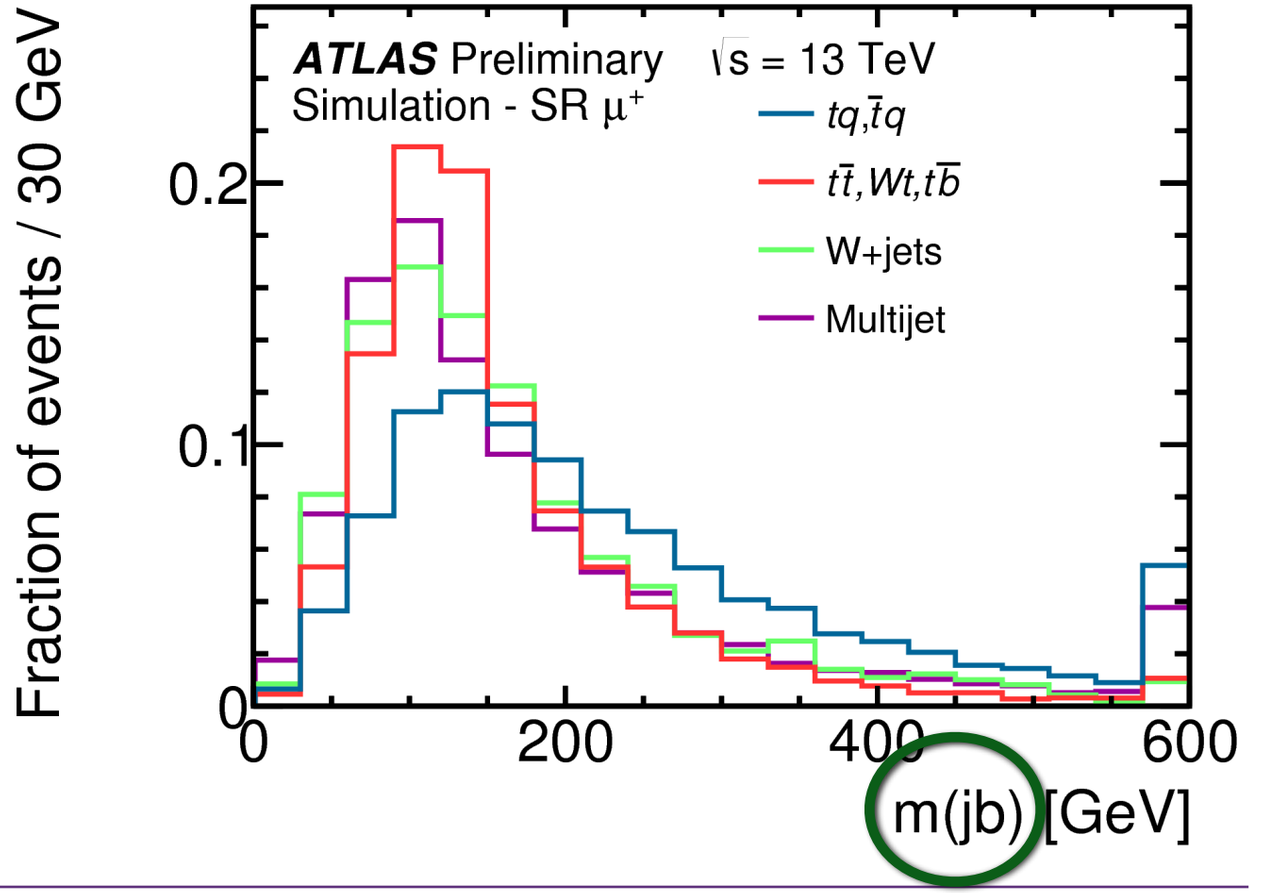
Inclusive cross section single top-quark in t-channel 3.2 fb^{-1} $\sqrt{s}$=13 TeV

ATLAS-CONF-2015-079

- Dominant single production channel
- One muon, E_T^{miss}, two high p_T jets, one *b*-jet
- Signal discrimination using neural network (NN)
- Most discriminating variables: reconstructed top-quark mass and jet-pair mass
- Binned maximum likelihood fit to the NN output







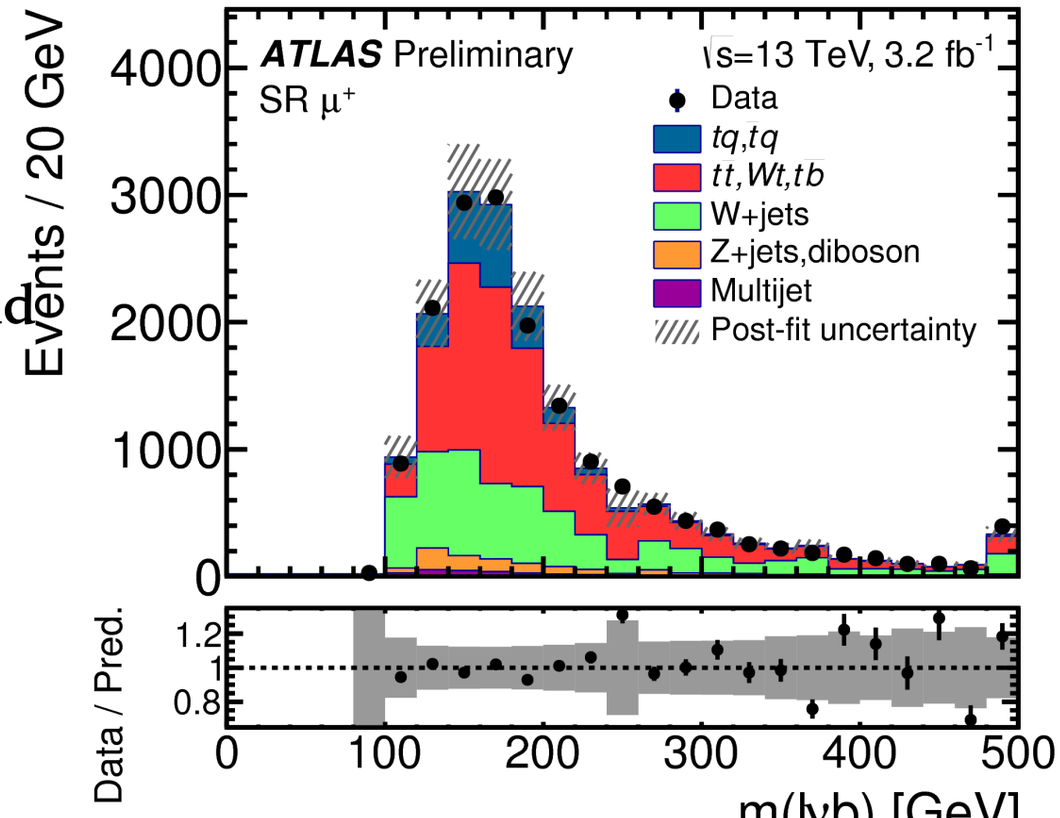
Inclusive cross section single top-quark in t-channel 3.2 fb^{-1} $\sqrt{s}$=13 TeV

ATLAS-CONF-2015-079

- Most important backgrounds: $t\bar{t}$ events, *W+jets*
- Smaller backgrounds: *s*-channel, *Wt*-channel, diboson and *Z+jets*
- All backgrounds except QCD -> simulation based and scaled to the SM predictions
- After maximum likelihood fit:

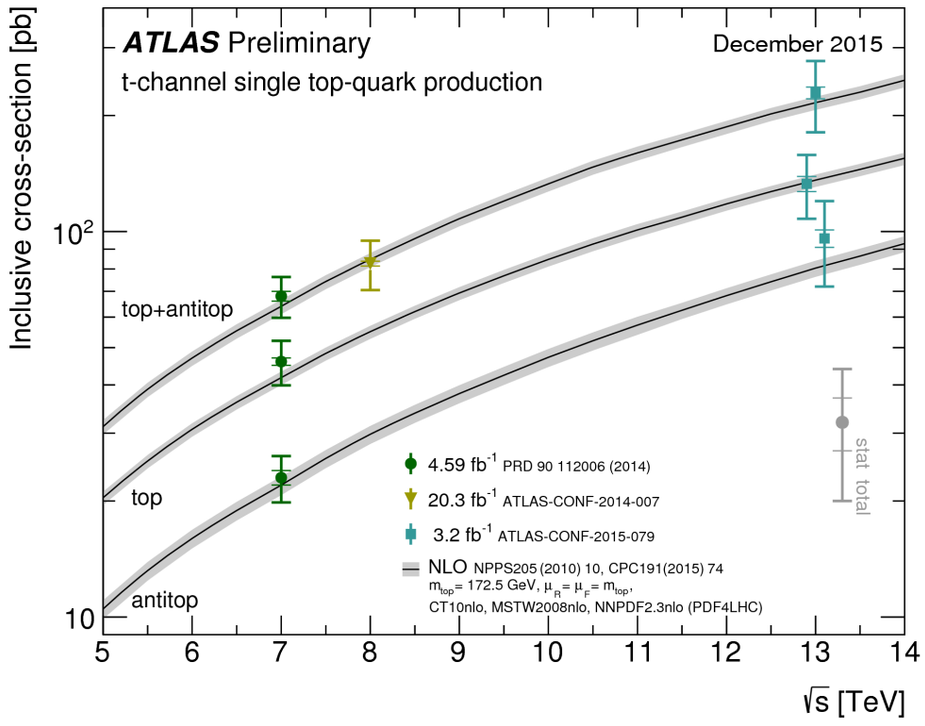
$$\sigma_{tq} = 133 \pm 6(\text{stat.}) \pm 24(\text{syst.}) \pm 7(\text{lumi.})\text{pb}$$

$$\sigma_{\bar{t}q} = 96 \pm 5(\text{stat.}) \pm 23(\text{syst.}) \pm 5(\text{lumi.})\text{pb}$$



- Measured cross-section is proportional to $|f_{LV} \cdot V_{tb}|^2$
- $|f_{LV} \cdot V_{tb}|$ is extracted by dividing the cross-section by the NLO prediction:

$$|f_{LV} \cdot V_{tb}| = 1.03 \pm 0.02 \pm 0.11 \pm 0.02 \pm 0.03$$
$$\text{(stat.) (syst.) (theo.) (lumi.)}$$

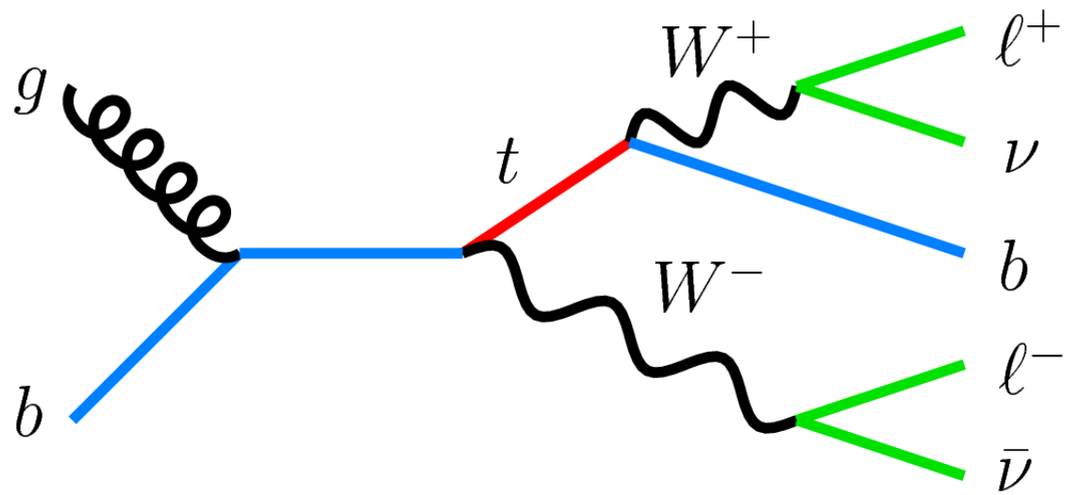


Single top-quark production in Wt-channel 20.3 fb^{-1} $\sqrt{s}$ = 8 TeV

JHEP01 (2016) 064

- Production via b-quark-induced partonic channels

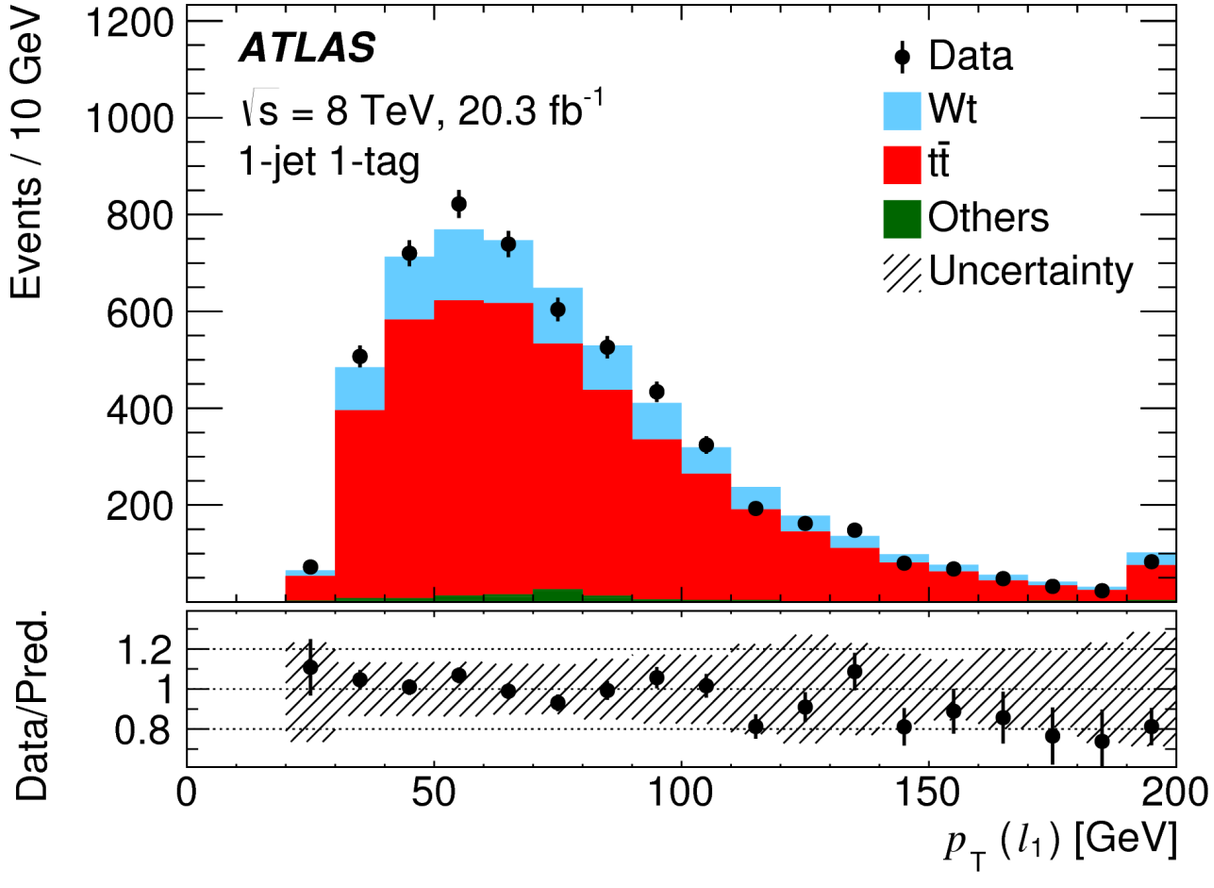
$$gb \text{ —> } Wt \text{ —>} W^-W^+b$$



- Only one *b*-jet in the final state is a distinctive feature

- Two opposite sign high-p_T leptons, E_T^{miss} and one high-p_T central *b*-jet

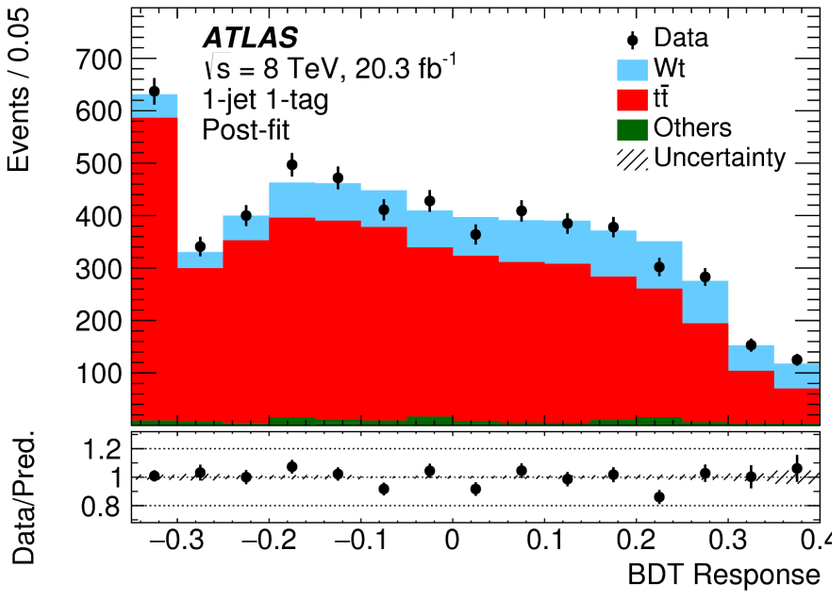
- Signal separation through the use of a *boosted decision tree* (BDT) algorithm in the TMVA* framework

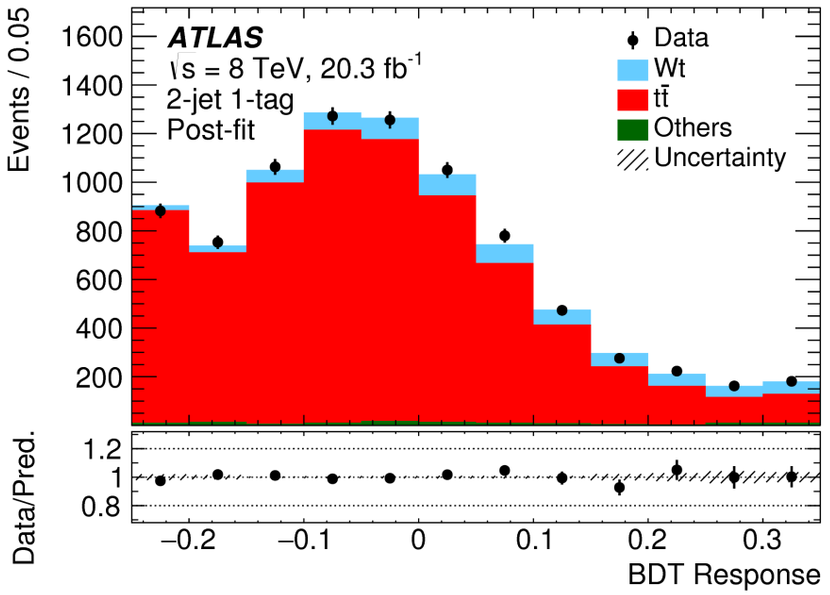


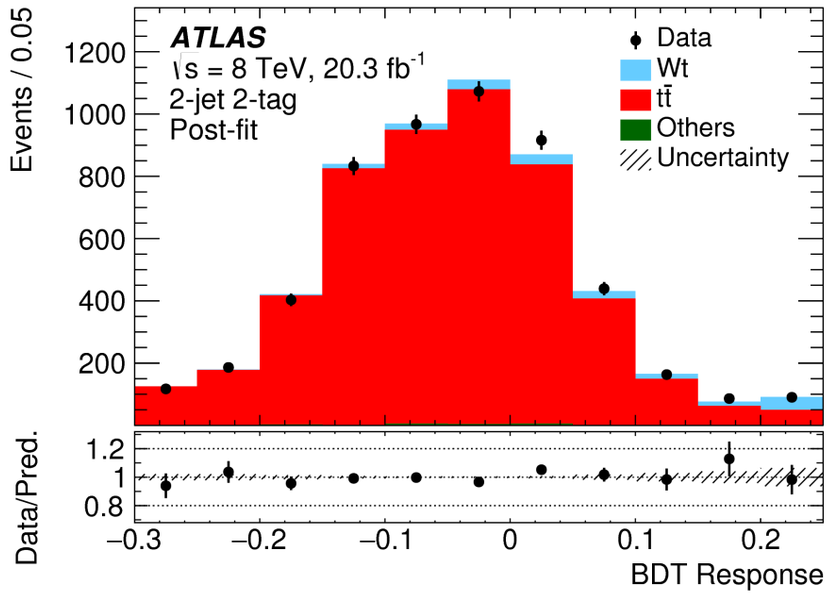
* Toolkit for Multivariate Data Analysis

Single top-quark production in Wt-channel 20.3 fb^{-1} $\sqrt{s}$ = 8 TeV

- The BDTs are trained separately in three regions, *1jet-1tag, 2jets-1tag* and *2jets-2tag* using simulated Wt (signal), and $t\bar{t}$ (main background) samples







- A profile likelihood fit to the BDT classifier utilising all regions

$$\sigma_{Wt} = 23.0 \pm 1.3(\text{stat.})^{+3.2}_{-3.5}(\text{syst.}) \pm 1.1(\text{lumi.})\text{pb}$$

$$|f_{LV} \cdot V_{tb}| = 1.01 \pm 0.10$$

- Fid. XS with 2 leptons p_T>25 GeV, $|\eta|$< 2.5, 1 jet p_T>20 GeV, $|\eta|$< 2.5 and E_T^{miss}> 20 GeV

$$\sigma_{Wt} = 0.85 \pm 0.01(\text{stat.})^{+0.06}_{-0.07}(\text{syst.}) \pm 0.03(\text{lumi.})\text{pb}$$

- Jet energy resolution and I/FSR are the dominant uncertainties

Evidence for single top-quark in s-channel $20.3\ fb^{-1}$ $\sqrt{s} = 8$ TeV

Physics Letters B 756 (2016) 228–246

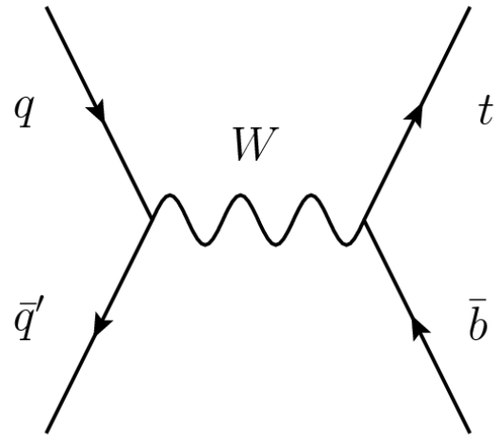
- Sensitive to new particles in several models of physics beyond the SM such as:

  charged Higgs, W' boson

- Important role for anomalous coupling models in an effective quantum field theory*

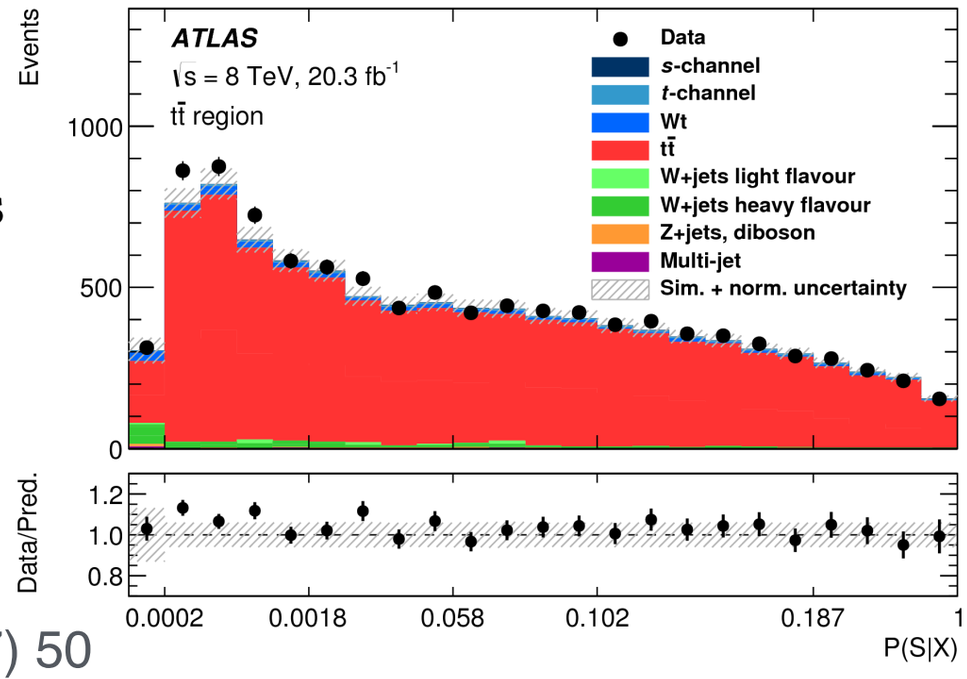
- Theoretical calculations are available in NLO QCD including NNLL correction

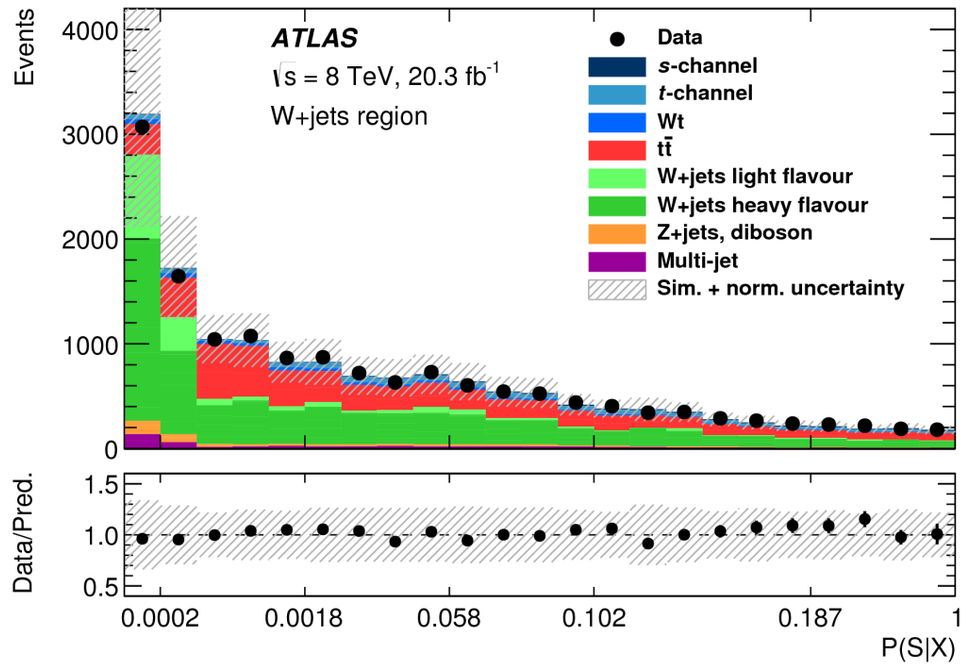
- Lepton+jet channel
  - one iso. e or μ
  - large E_T^{miss}
  - two high p_T b-jets



- Signal extraction using matrix element method

- Main backgrounds
  - $t\bar{t}$
  - W+jets





*Phys. Lett. B658 (2007) 50

Evidence for single top-quark in s-channel 20.3 fb^{-1} $\sqrt{s}$ = 8 TeV

- The result of the maximum LH fit

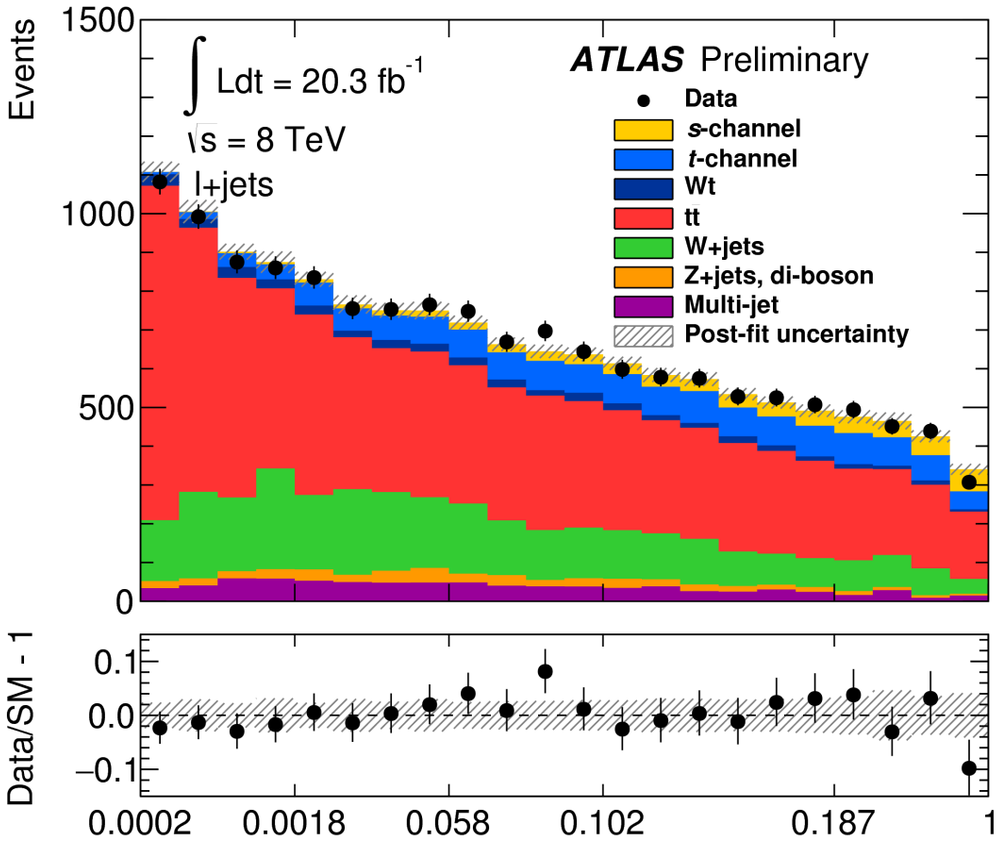
$$\sigma_s = 4.8 \pm 0.8(\text{stat.})^{+1.6}_{-1.3}(\text{syst.})\text{pb}$$

- The signal contribution for the matrix element discriminant in the data (all backgrounds subtracted)

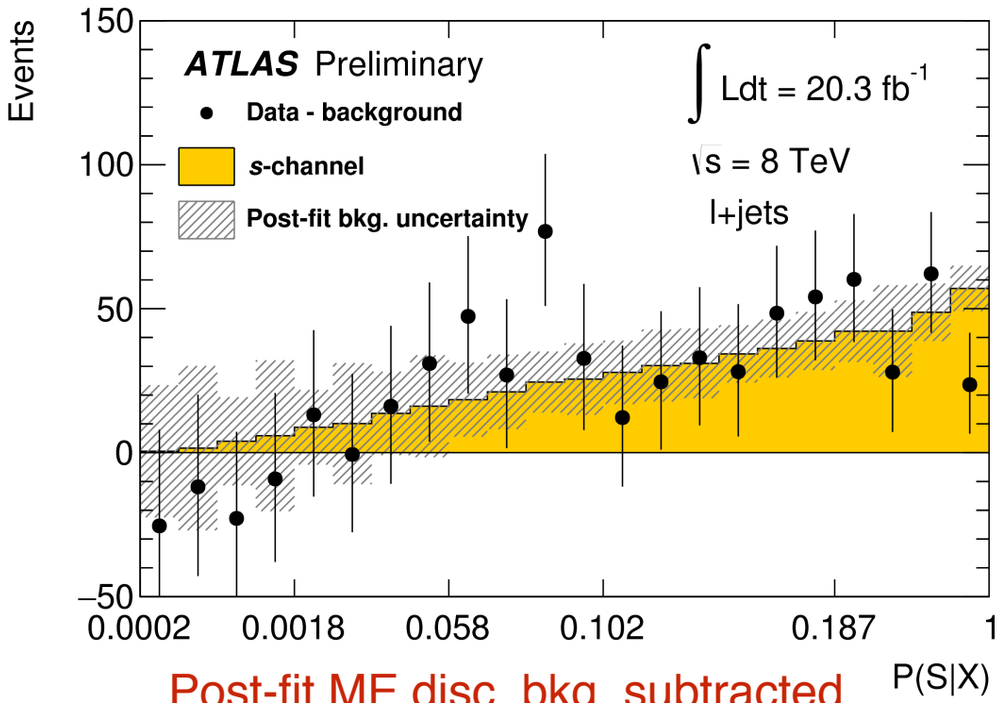
- The largest uncertainties:
  - the limited sample sizes for data and the simulation
  - jet energy resolution
  - modelling of single top *t*-channel

- Obs. sig.: 3.2σ (Exp. 3.9σ)

$$|f_{LV} \cdot V_{tb}| = 0.93\ ^{+0.18}_{-0.20}$$



Post-fit ME disc.

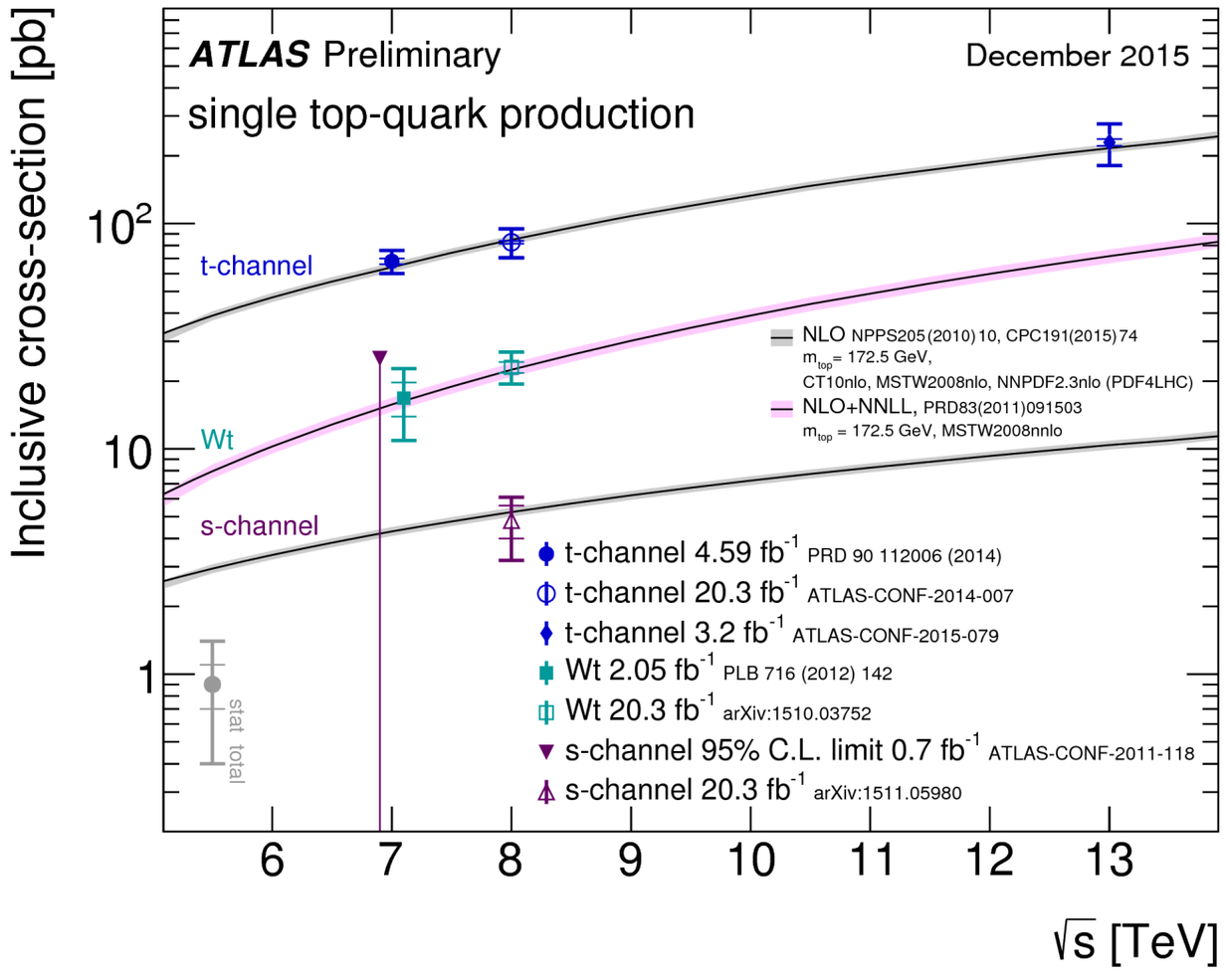


Post-fit ME disc. bkg. subtracted

Summary

- Latest result for pair production in dilepton($e\mu$) channel
- Differential measurements of the top-quark transverse momentum and kinematic properties of the $t\bar{t}$ pair including results using boosted top-quarks
- Pair production in association with *Z*/*W* boson

- *t*-channel cross section at 13 TeV
- Inclusive and fiducial cross sections using BDTs in Wt channel
- Evidence in s-channel using ME method 3.2σ
- Coupling strength at the *Wtb* vertex is determined for all channels



Further Material

Pair production cross-section using eμ events - Systematics

Event counts	N_1	N_2
Data	11958	7069
Single top	1140 ± 100	221 ± 68
Dibosons	34 ± 11	1 ± 0
$Z(\to \tau\tau \to e\mu)$+jets	37 ± 18	2 ± 1
Misidentified leptons	164 ± 65	116 ± 55
Total background	1370 ± 120	340 ± 88

Uncertainty (inclusive $\sigma_{t\bar{t}}$)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ [%]	$\Delta C_b/C_b$ [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics			0.9
$t\bar{t}$ NLO modelling	0.7	-0.1	0.8
$t\bar{t}$ hadronisation	-2.4	0.4	2.8
Initial- and final-state radiation	-0.3	0.1	0.4
$t\bar{t}$ heavy-flavour production	-	0.4	0.4
Parton distribution functions	0.5	-	0.5
Single-top modelling	-	-	0.3
Single-top/$t\bar{t}$ interference	-	-	0.6
Single-top Wt cross-section	-	-	0.5
Diboson modelling	-	-	0.1
Diboson cross-sections	-	-	0.0
Z+jets extrapolation	-	-	0.2
Electron energy scale/resolution	0.2	0.0	0.2
Electron identification	0.3	0.0	0.3
Electron isolation	0.4	-	0.4
Muon momentum scale/resolution	-0.0	0.0	0.0
Muon identification	0.4	0.0	0.4
Muon isolation	0.2	-	0.3
Lepton trigger	0.1	0.0	0.2
Jet energy scale	0.3	0.1	0.3
Jet energy resolution	-0.1	0.0	0.2
b-tagging	-	0.1	0.3
Misidentified leptons	-	-	0.6
Analysis systematics	2.7	0.6	3.3
Integrated luminosity	-	-	2.3
LHC beam energy	-	-	1.5
Total uncertainty	2.7	0.6	4.4

Uncertainty (fiducial $\sigma^{\text{fid}}_{t\bar{t}}$)	$\Delta G_{e\mu}/G_{e\mu}$ [%]	$\Delta C_b/C_b$ [%]	$\Delta\sigma^{\text{fid}}_{t\bar{t}}/\sigma^{\text{fid}}_{t\bar{t}}$ [%]
$t\bar{t}$ NLO modelling	0.5	-0.1	0.6
$t\bar{t}$ hadronisation	-1.6	0.4	1.9
Parton distribution functions	0.1	-	0.1
Other uncertainties (as above)	0.8	0.4	1.5
Analysis systematics ($\sigma^{\text{fid}}_{t\bar{t}}$)	1.8	0.6	2.5
Total uncertainty ($\sigma^{\text{fid}}_{t\bar{t}}$)	1.8	0.6	3.9

Differential distributions (Full phase-space)

$$\frac{\mathrm{d}\sigma^{\mathrm{full}}}{\mathrm{d}X^i} \equiv \frac{1}{\mathcal{L}\cdot\mathcal{B}\cdot\Delta X^i}\cdot\hat{f}^i_{\mathrm{eff}}\cdot\sum_j \hat{\mathcal{M}}^{-1}_{ij}\cdot\hat{f}^j_{\mathrm{acc}}\cdot\hat{f}^i_{\mathrm{ljets}}\cdot\left(N^j_{\mathrm{reco}}-N^j_{\mathrm{bg}}\right)$$

f_{eff} : eff. correction for events passing PL sel. but failing DL

f_{ljets} : the fraction of single lepton tt events in the nom. sample

f_{acc} : correction for events generated outside the FR but passed the detector-level selection

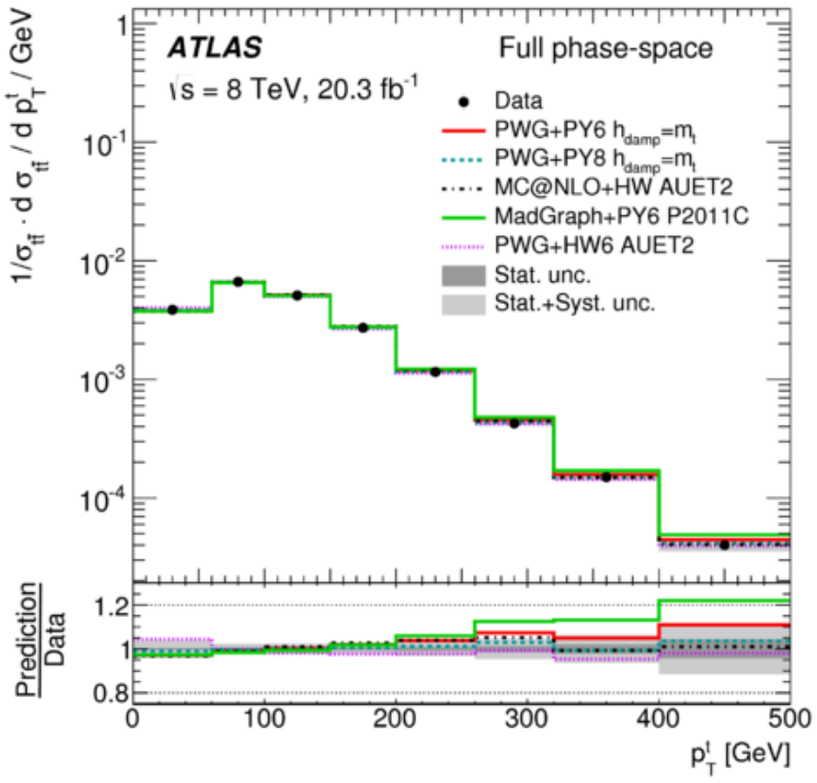
X observable at particle level (PL)

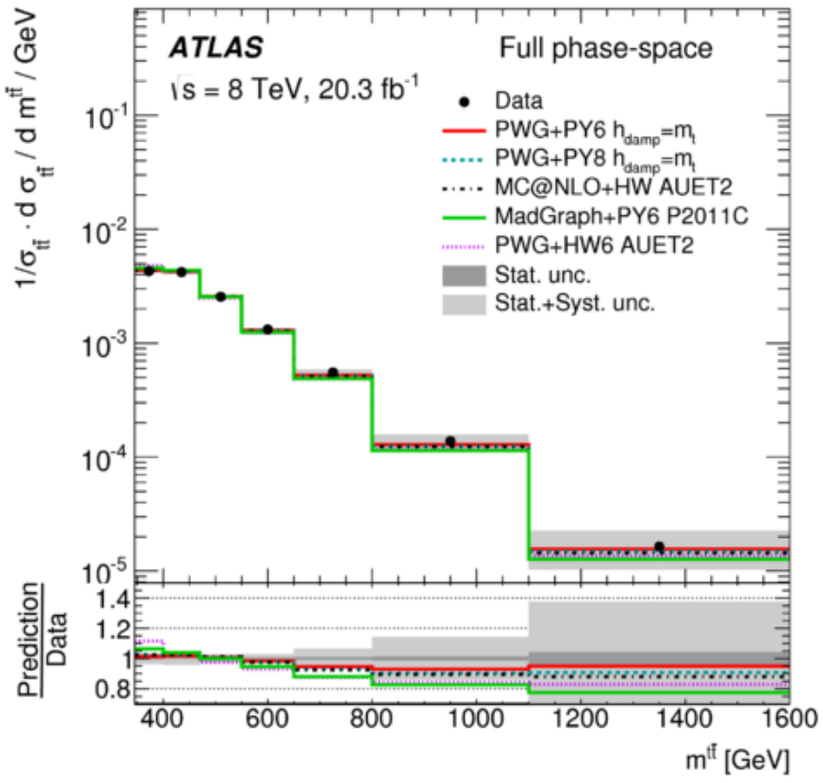
j bins of X at DL and i bins at PL

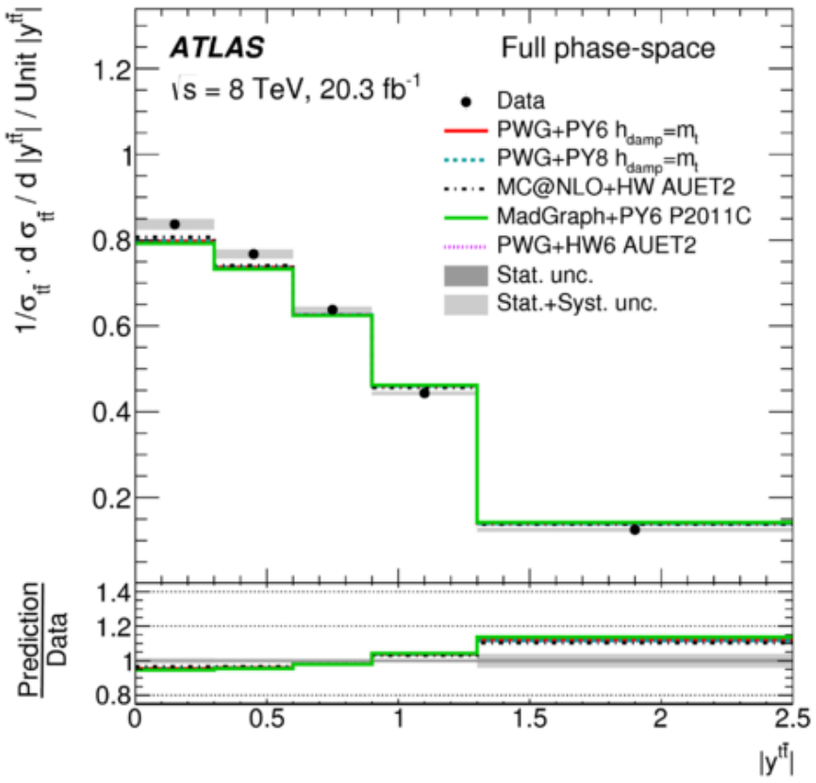
ΔX^i bin width

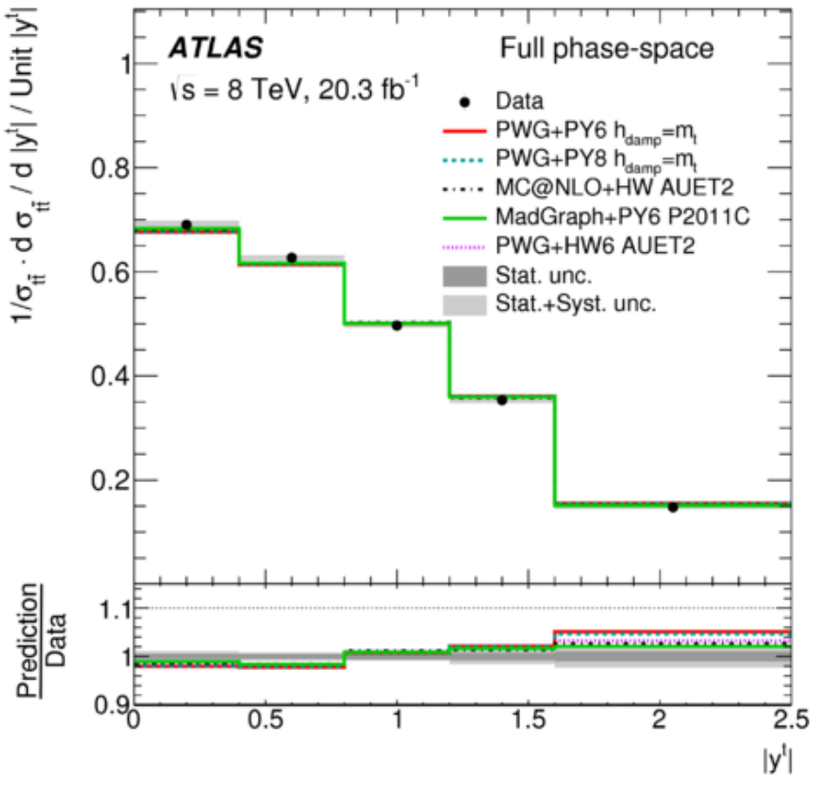
$\mathcal{M}_{ij}{}^{-1}$ is the Bayesian unfolding

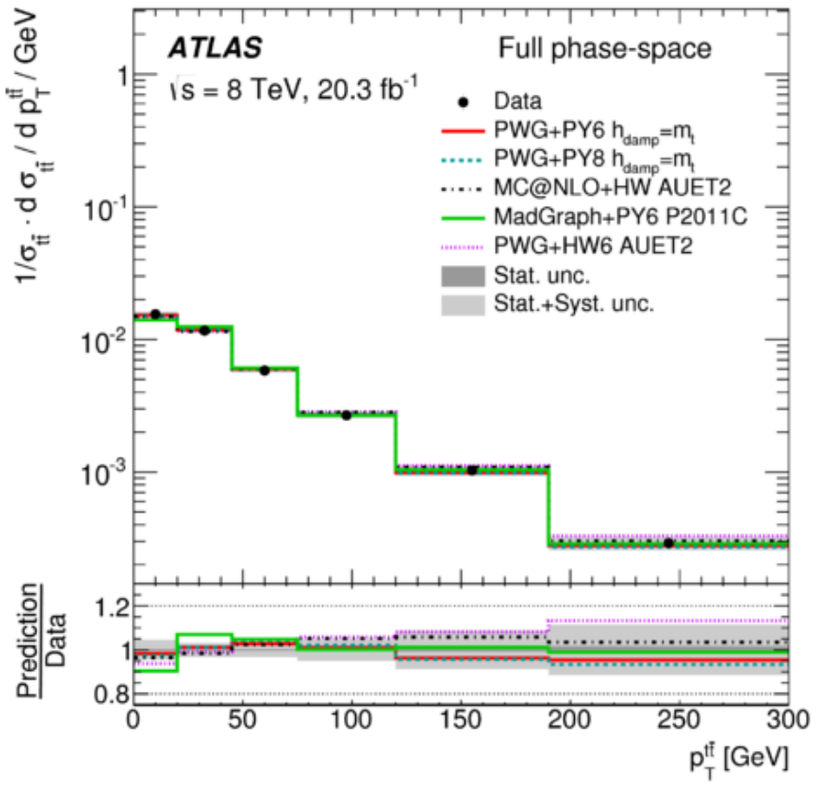
Differential distributions (Full phase-space)

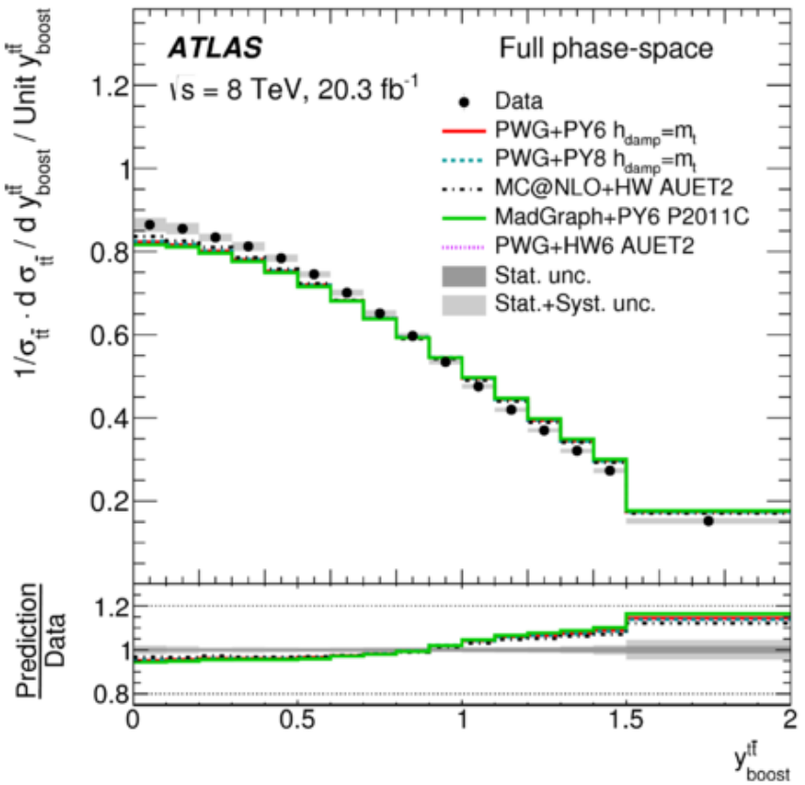




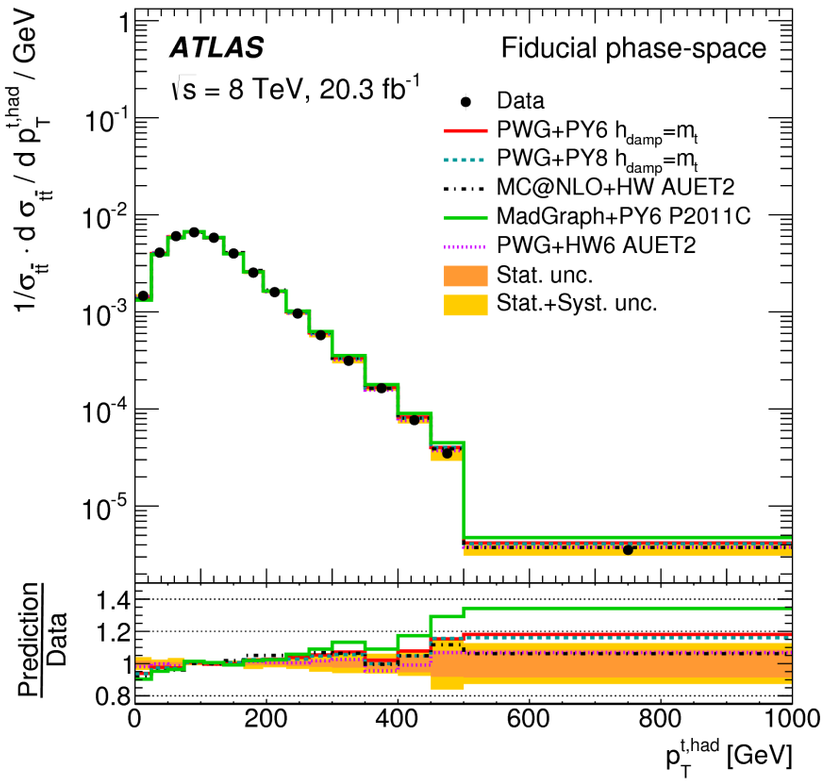


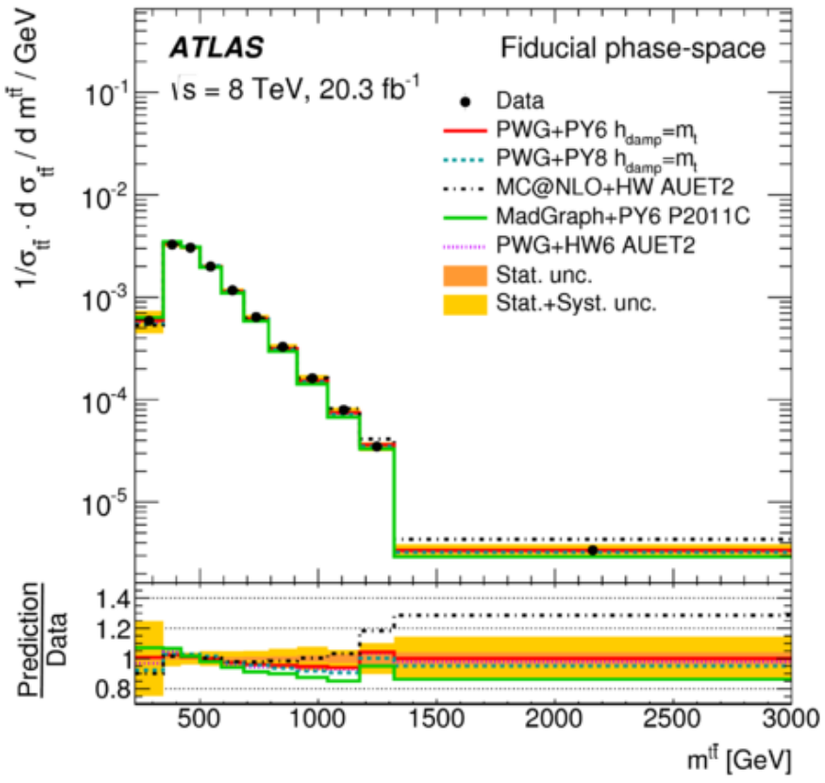


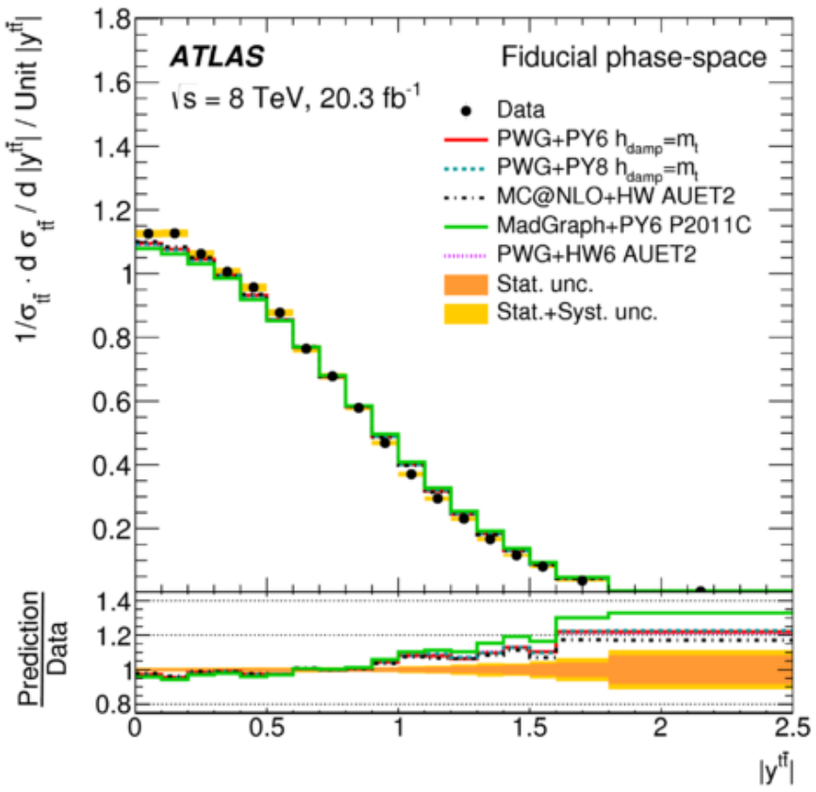


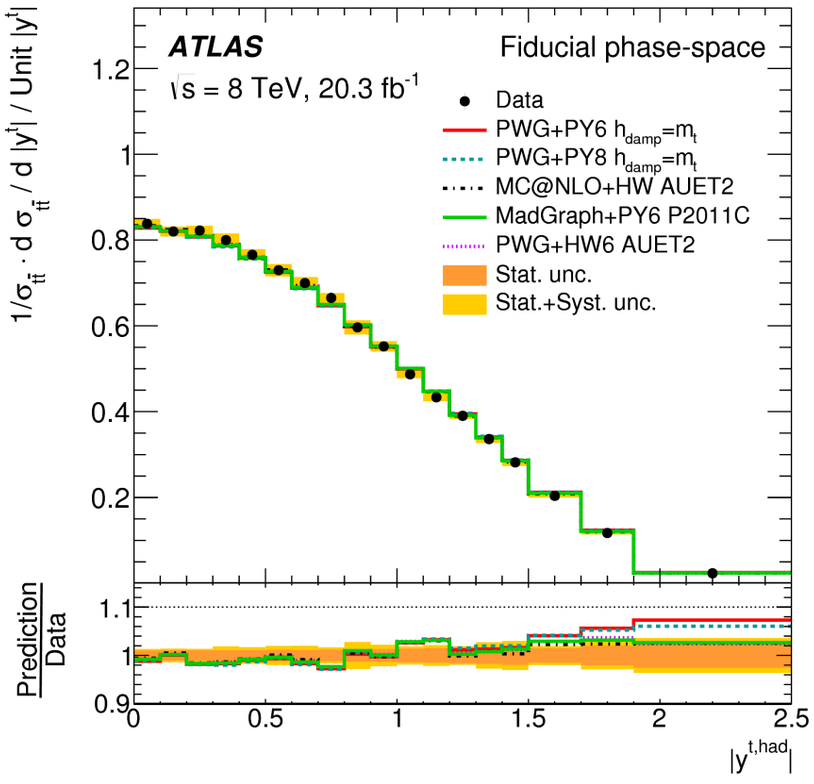


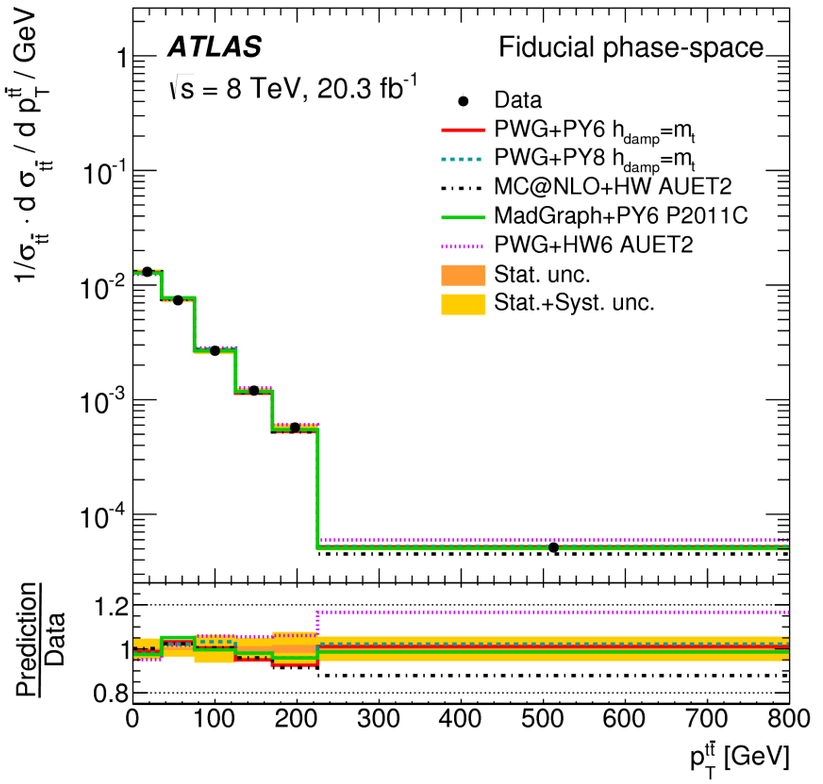
Differential distributions (Fiducial phase-space)

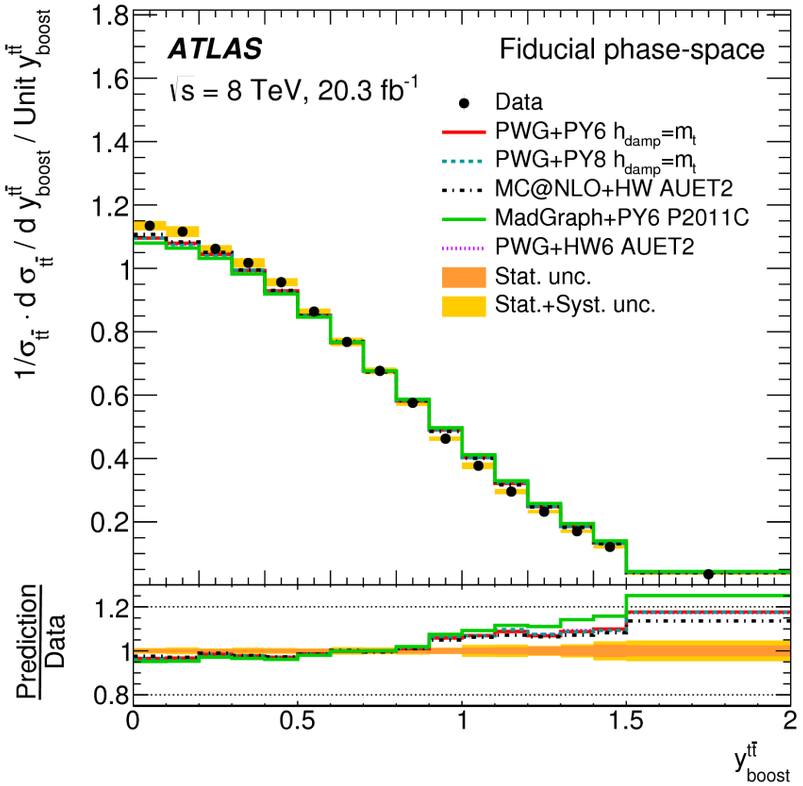




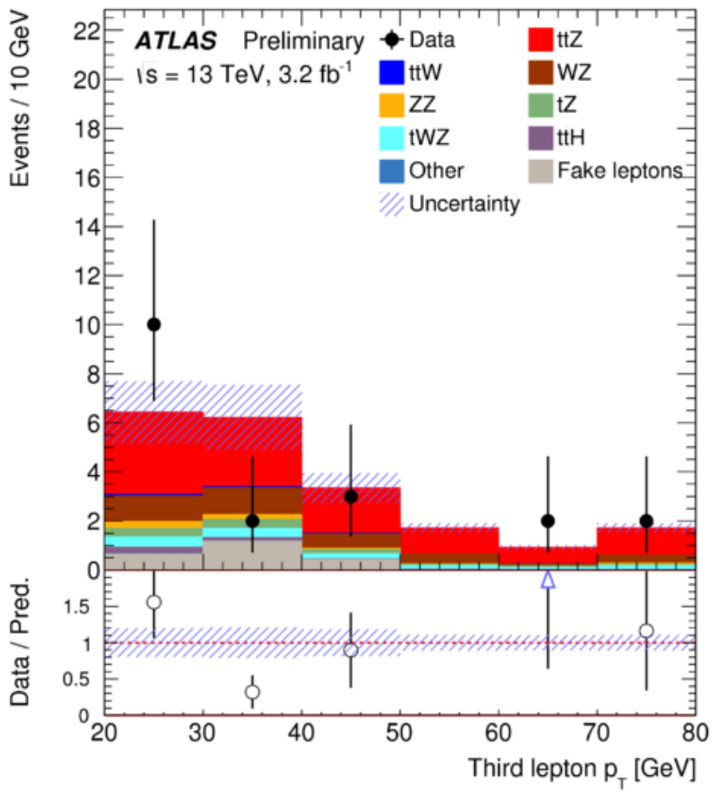


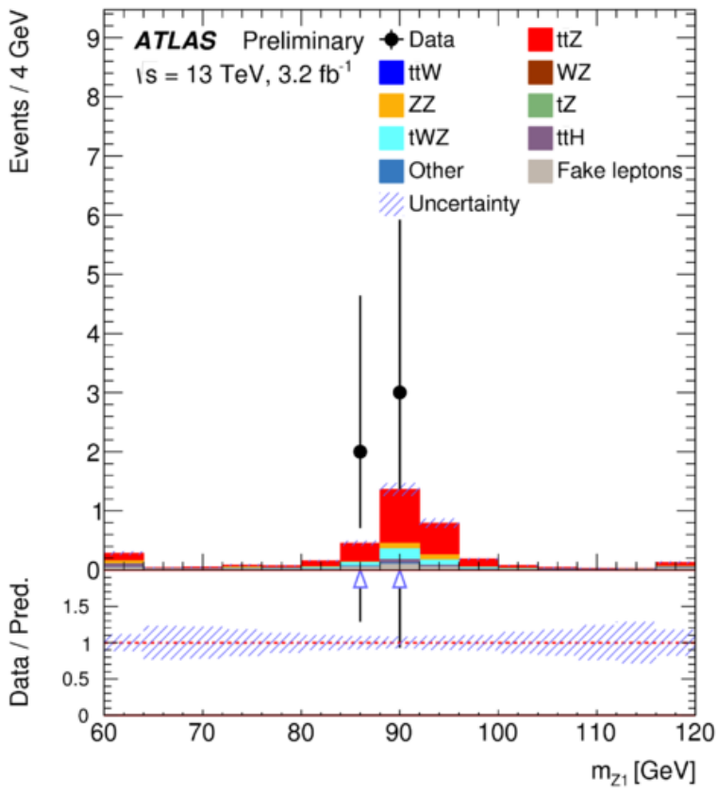






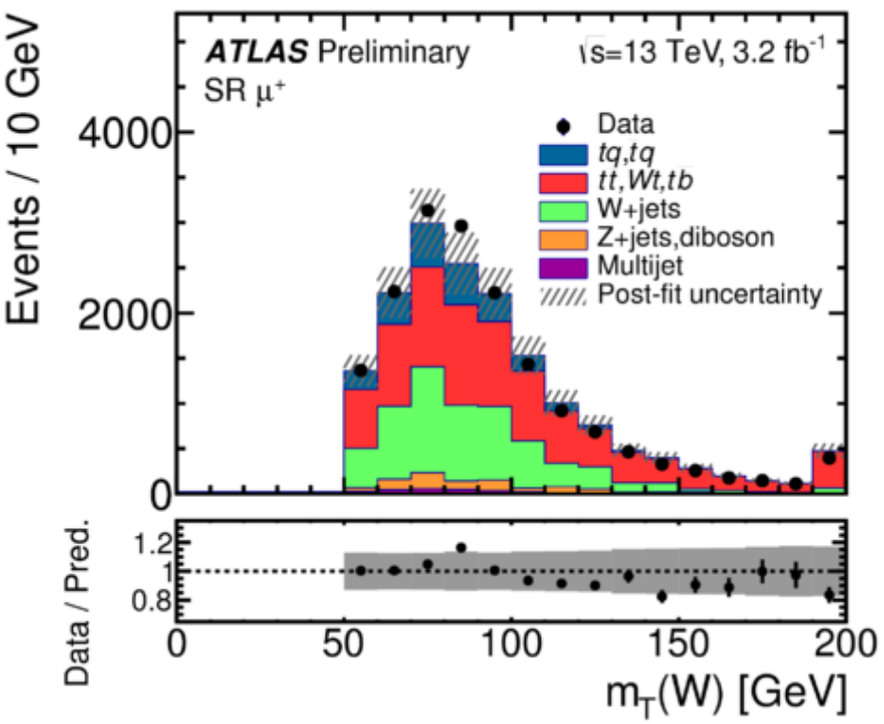
Pair production in association with Z/W boson - Systematics

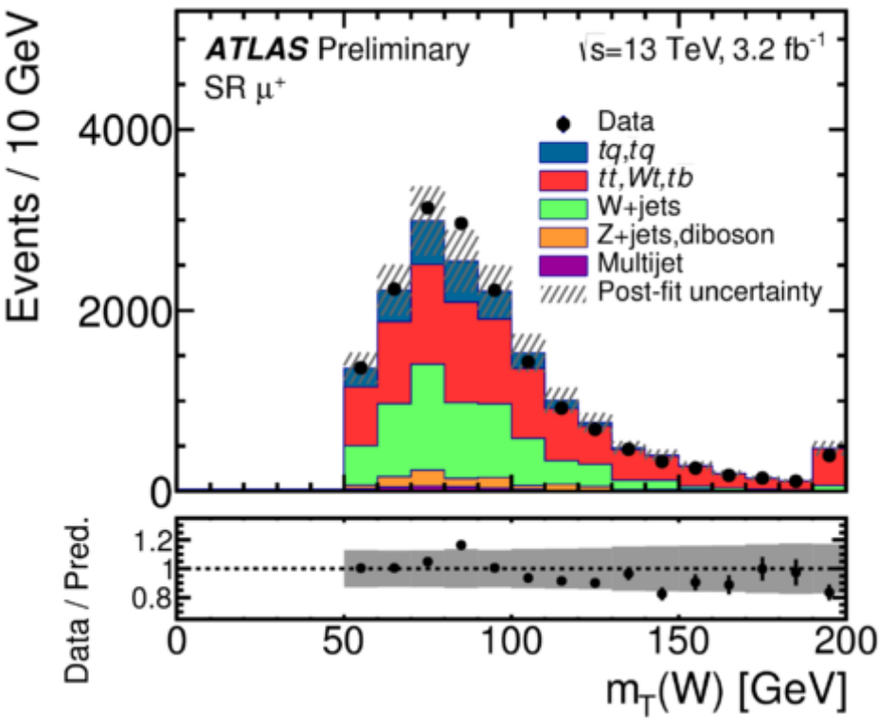




Region	$t+X$	Bosons	Fake leptons	Total bkg.	$t\bar{t}W$	$t\bar{t}Z$	Data
3ℓ-WZ-CR	0.51 ± 0.13	26.9 ± 2.5	1.6 ± 1.7	29.0 ± 3.0	0.017 ± 0.005	0.71 ± 0.08	33
4ℓ-ZZ-CR	0.007 ± 0.006	37.9 ± 2.5	3.1 ± 0.9	41.0 ± 2.7	< 0.001	0.031 ± 0.006	40
2μ-SS	1.00 ± 0.19	0.14 ± 0.06	1.7 ± 1.5	2.9 ± 1.5	2.28 ± 0.34	0.65 ± 0.07	9
3ℓ-Z-2b4j	1.06 ± 0.25	0.5 ± 0.4	0.1 ± 0.6	1.7 ± 0.8	0.061 ± 0.013	5.1 ± 0.5	8
3ℓ-Z-1b4j	1.23 ± 0.26	3.4 ± 2.2	2.0 ± 1.7	6.6 ± 2.8	0.037 ± 0.010	4.0 ± 0.4	7
3ℓ-Z-2b3j	0.64 ± 0.23	0.25 ± 0.18	0.1 ± 0.4	1.0 ± 0.5	0.082 ± 0.015	1.75 ± 0.20	4
3ℓ-noZ-2b	0.95 ± 0.15	0.18 ± 0.09	3.6 ± 2.2	4.7 ± 2.2	1.55 ± 0.24	1.35 ± 0.16	10
4ℓ-SF-1b	0.198 ± 0.035	0.22 ± 0.08	0.112 ± 0.032	0.53 ± 0.09	< 0.001	0.59 ± 0.05	1
4ℓ-SF-2b	0.130 ± 0.035	0.11 ± 0.05	0.053 ± 0.016	0.29 ± 0.07	< 0.001	0.57 ± 0.05	1
4ℓ-DF-1b	0.21 ± 0.04	0.022 ± 0.011	0.105 ± 0.027	0.34 ± 0.05	< 0.001	0.67 ± 0.05	2
4ℓ-DF-2b	0.15 ± 0.05	< 0.001	0.055 ± 0.017	0.20 ± 0.05	< 0.001	0.58 ± 0.05	1

Inclusive cross section single top-quark in t-channel - Systematics





Source	$\Delta\sigma_{tq}/\sigma_{tq}$ [%]	$\Delta\sigma_{\bar{t}q}/\sigma_{\bar{t}q}$ [%]
Data statistics	$\pm$ 4.6	$\pm$ 5.0
MC statistics	$\pm$ 6.3	$\pm$ 6.5
Multijet normalisation	$\pm$ 0.8	$\pm$ 2.4
Other background normalisation	$\pm$ 1.4	$\pm$ 0.5
Muon uncertainties	$\pm$ 1.6	$\pm$ 1.6
JES	$\pm$ 5.5	$\pm$ 1.6
Jet energy resolution	$\pm$ 4.3	$\pm$ 3.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	$\pm$ 4.2	$\pm$ 4.5
b-tagging efficiency	$\pm$ 7.1	$\pm$ 7.5
c-tagging efficiency	$<$ 0.5	$<$ 0.5
Light-jet tagging efficiency	$<$ 0.5	$<$ 0.5
Pile-up reweighting	$\pm$ 1.2	$\pm$ 3.2
W+jets modelling	$\pm$ 2.3	$\pm$ 1.0
$t\bar{t}$,Wt and s-channel shower generator	$<$ 0.5	$\pm$ 2.3
$t\bar{t}$,Wt and s-channel NLO matching	$\pm$ 2.7	$\pm$ 7.0
$t\bar{t}$,Wt and s-channel scale	$\pm$ 2.6	$\pm$ 0.9
t-channel scale	$\pm$ 5.9	$\pm$ 7.7
t-channel generator	$\pm$ 11.0	$\pm$ 15.0
PDF	$<$ 0.5	$\pm$ 1.0
Luminosity	$\pm$ 5.0	$\pm$ 5.0
Total systematic uncertainty	$\pm$ 18.4	$\pm$ 24.4
Total uncertainty	$\pm$ 19.0	$\pm$ 25.0

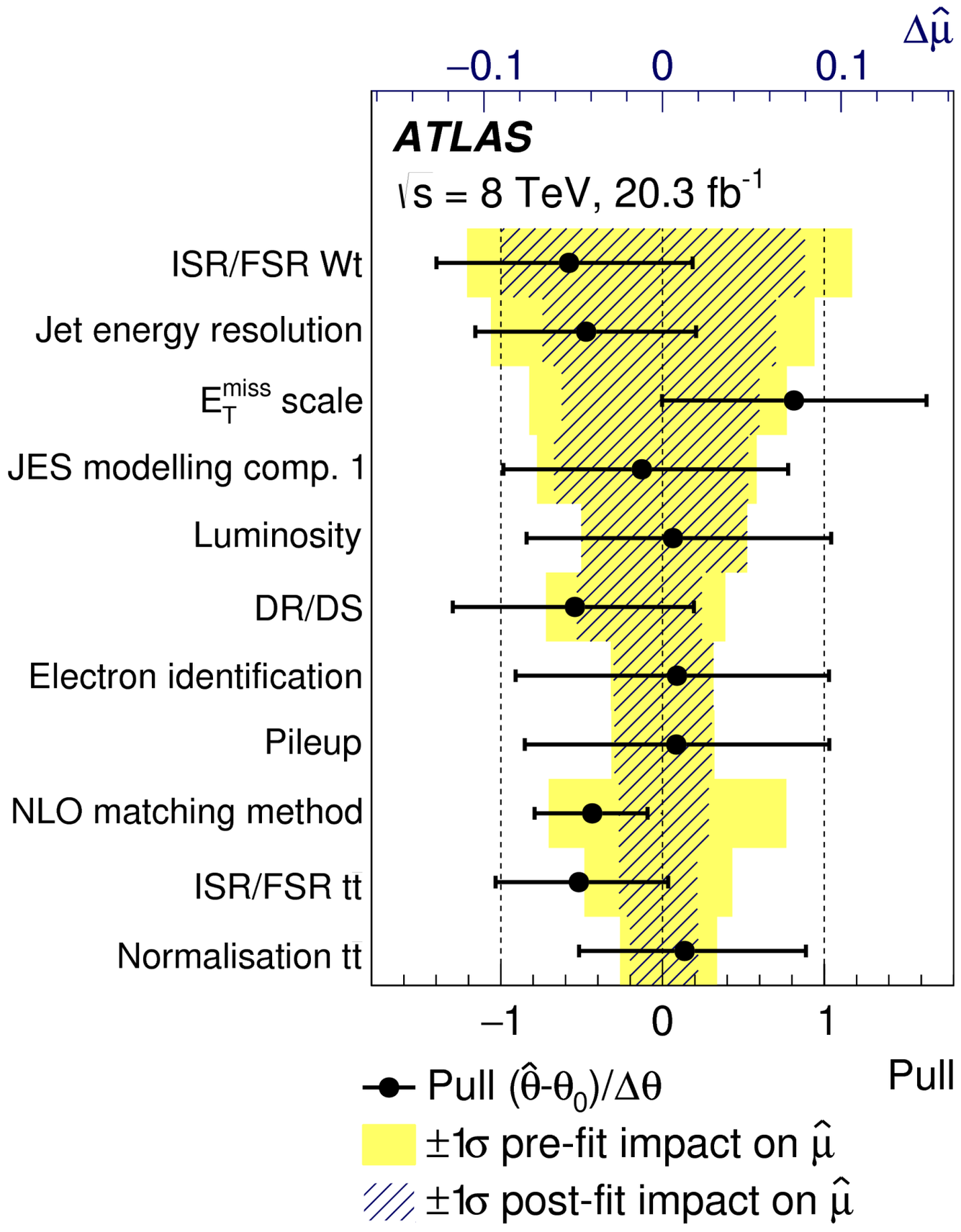
Inclusive cross section single top-quark in t-channel - Variables

- **The ten variables which are used in the training of the neural network ordered by their importance.**

Variable	Corr. loss	Definition
$m(\ell\nu b)$	31.8 %	top-quark mass reconstructed from the charged lepton, neutrino and b-quark jet
$m(jb)$	29.0 %	invariant mass of the tagged (b) and light-jet (j)
$m_{\mathrm{T}}(W)$	23.1 %	transverse mass of the reconstructed W boson
$\lvert\eta(j)\rvert$	15.8 %	pseudorapidity of the light-jet (j)
$m(\ell b)$	8.5 %	invariant mass of the charged lepton (ℓ) and the tagged jet (b)
$\cos\Theta(\ell, j)_{\ell\nu b\ \mathrm{r.f.}}$	6.6 %	cosine of the angle θ between the charged lepton and the light-jet (j) in the rest frame of the reconstructed top quark
$\Delta R(\ell\nu b, j)$	7.4 %	ΔR of the reconstructed top quark and the light-jet (j)
$\eta(W)$	6.8 %	rapidity of the reconstructed W boson
$\Delta p_{\mathrm{T}}(\ell\nu b, j)$	5.5 %	Δp_{T} of the reconstructed top quark and the light-jet (j)
$\Delta R(\ell, j)$	2.1 %	ΔR of the charged lepton and the light-jet (j)

Single top-quark production in Wt-channel

Variable	1-jet, 1-tag	2-jet 1-tag	2-jet 2-tag
$p_{\mathrm{T}}^{\mathrm{sys}}$ $(\ell_1, \ell_2, E_{\mathrm{T}}^{\mathrm{miss}}, j_1)$	1		
$p_{\mathrm{T}}^{\mathrm{sys}}$ (ℓ_1, ℓ_2, j_1)	7		
$p_{\mathrm{T}}^{\mathrm{sys}}$ (ℓ_1, ℓ_2)	13		
$p_{\mathrm{T}}^{\mathrm{sys}}$ (j_1, j_2)		10	1
$p_{\mathrm{T}}^{\mathrm{sys}}$ $(\ell_1, \ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$		12	2
$p_{\mathrm{T}}^{\mathrm{sys}}$ $(\ell_1, \ell_2, E_{\mathrm{T}}^{\mathrm{miss}}, j_1, j_2)$		13	
$p_{\mathrm{T}}^{\mathrm{sys}}$ (ℓ_1, j_1)			13
$\sigma(p_{\mathrm{T}}^{\mathrm{sys}})$ $(\ell_1, \ell_2, E_{\mathrm{T}}^{\mathrm{miss}}, j_1)$	4	5	
p_{T} (j_2)			8
Δp_{T} (ℓ_1, ℓ_2)	8		
Δp_{T} $((\ell_1, \ell_2, j_1),(E_{\mathrm{T}}^{\mathrm{miss}}))$	9		
Δp_{T} $(E_{\mathrm{T}}^{\mathrm{miss}}, j_1)$		9	
Δp_{T} $(\ell_1, \ell_2, E_{\mathrm{T}}^{\mathrm{miss}}, j_1)$		16	
Δp_{T} (ℓ_2, j_2)			14
ΔR (ℓ_1, j_1)	2		5
ΔR (ℓ_2, j_1)		4	10
ΔR (ℓ_2, j_2)		6	
ΔR (ℓ_2, j_1)		11	
ΔR (ℓ_1, ℓ_2)		14	
ΔR $((\ell_1, \ell_2), j_2)$			9
m (ℓ_2, j_1)	10	3	3
m (ℓ_1, j_2)		1	4
m (j_1, j_2)		2	
m (ℓ_2, j_2)		7	7
m (ℓ_1, j_1)		8	6
m (ℓ_1, ℓ_2)		15	
m (ℓ_2, j_1, j_2)			11
m $(\ell_1, \ell_2, j_1, j_2)$			15
m_{T} $(j_1, E_{\mathrm{T}}^{\mathrm{miss}})$	5		
m_{T2}	11		
E/m (ℓ_1, ℓ_2, j_2)			16
$\sum E_{\mathrm{T}}$	3		
Centrality(ℓ_1, ℓ_2)	6		
Centrality(ℓ_1, j_1)	12		
Centrality(ℓ_2, j_2)			12



Evidence for single top-quark in s-channel - ME method

- The ME method directly uses theoretical calculations to compute a per-event signal probability

- The discrimination between signal and background is based on the computation of likelihood values $\mathcal{P}(X|H_{proc})$ for the hypothesis that a measured event with final state X is of a certain process type H_{proc}

$$P(S|X) = \frac{\Sigma_i \alpha_{S_i} \mathcal{P}(X|S_i)}{\Sigma_i \alpha_{S_i} \mathcal{P}(X|S_i) + \Sigma_j \alpha_{B_j} \mathcal{P}(X|B_j)}$$

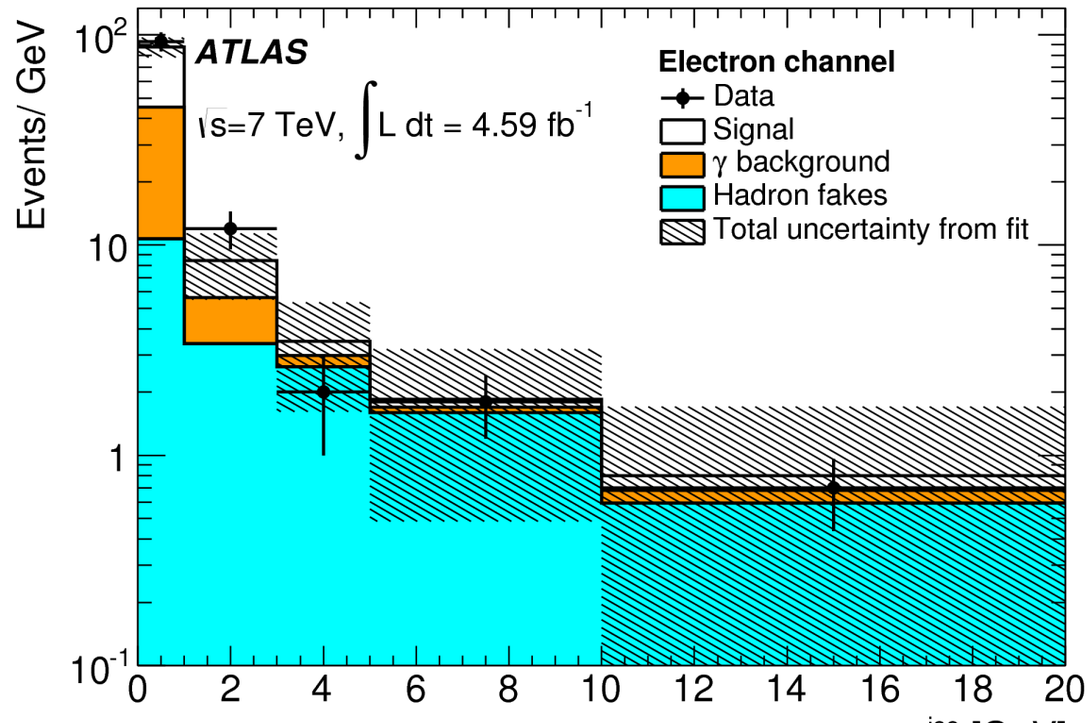
- S_i and B_j denote all signal and background processes that are being considered

- a priori probabilities α_{S_i} and α_{B_j} given by the exp. fraction of events of each process in the set of selected events within the signal region

- $P(S|X)$ is the value taken as the main discriminant in the signal extraction

Top pair production with an associated photon 4.59 fb^{-1} $\sqrt{s}$ = 7 TeV

- Event selection:
  - PV with > 4 tracks, one electron or muon, > 3 jets, at least one b-jet, one photon
- Main uncertainties
  - Signal template modelling (6.6%), parton shower (7.3%) and jet modelling (16%)



- Theoretical NLO production

$$\sigma_{t\bar{t}\gamma}^{Whizard} = 48.4 \pm 0.5(stat.) \pm 9.7(theo.) \text{ fb}$$
$$\sigma_{t\bar{t}\gamma}^{MadGraph} = 47.2 \pm 0.4(stat.) \pm 9.4(theo.) \text{ fb}$$

- First observation of tty process: 5.3σ

$$\sigma_{t\bar{t}\gamma} \times BR = 63 \pm 8(stat.)^{+17}_{-13}(syst.) \pm 1(lumi.) \text{ fb}$$