Measurements of single top quark production cross sections at ATLAS

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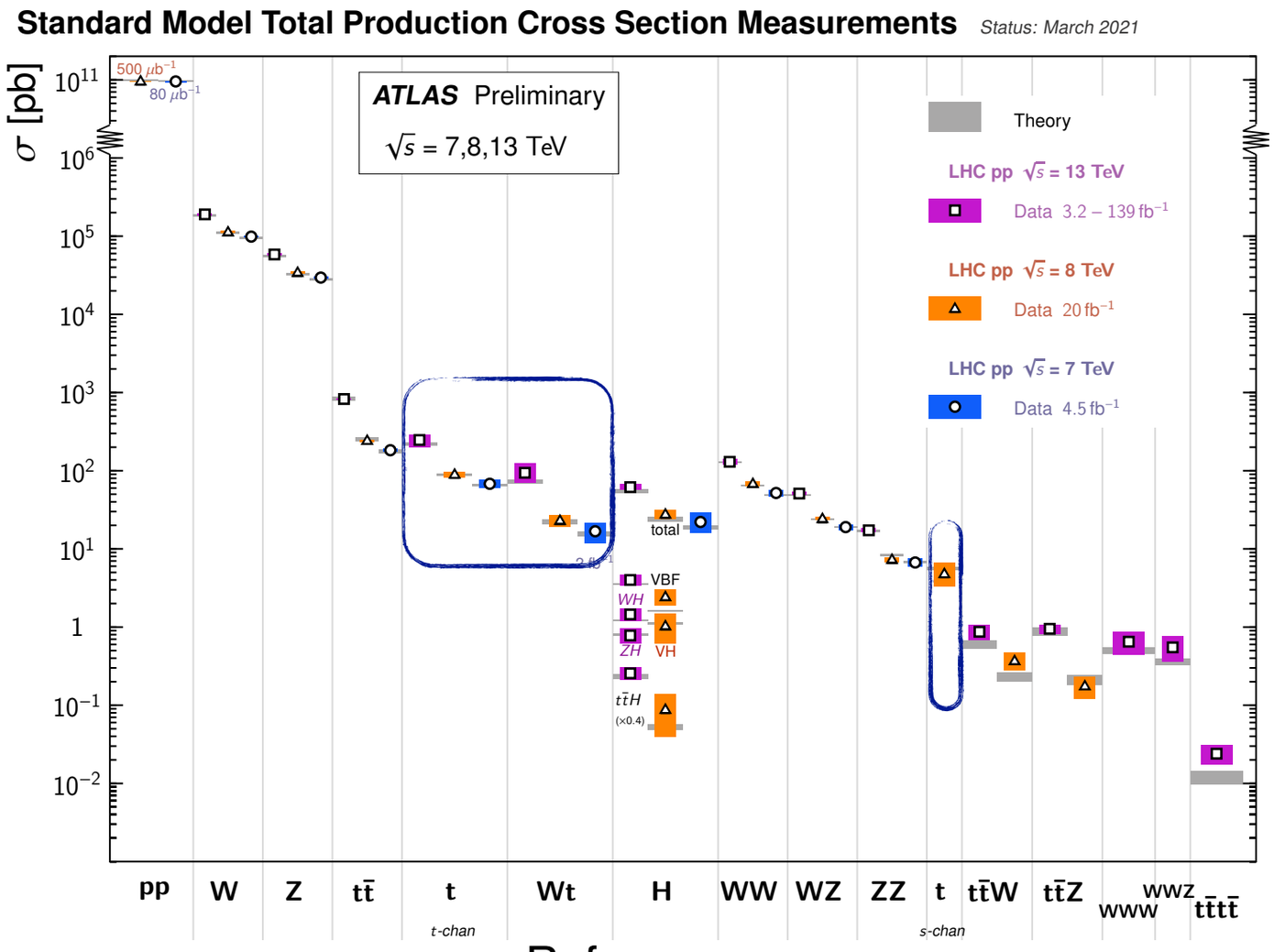
Introduction

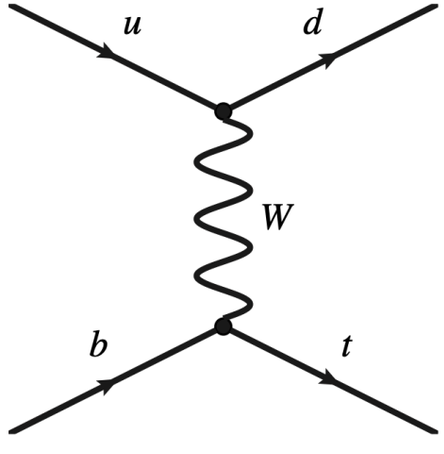
- LHC is a top-quark factory
  - ~830 pb top quark pair production
    - 100+ Million $t\bar{t}$ events in Run 2
  - ~10—200 pb single top production



Reference

- Single-top production
  - Weak interaction, unlike $t\bar{t}$
  - Probe Wtb vertex for new physics.
  - Important background in direct searches for particles beyond the SM

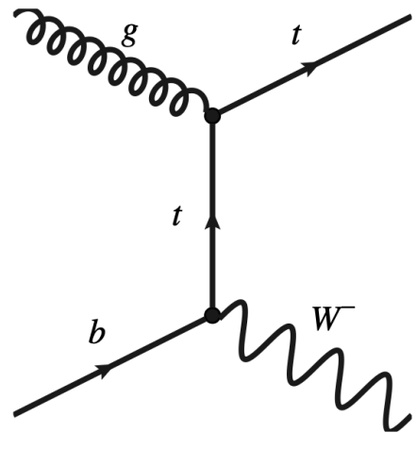
Single top production



t-channel

$\sigma(8\text{TeV}) = 87.76^{+3.44}_{-1.91}$ pb

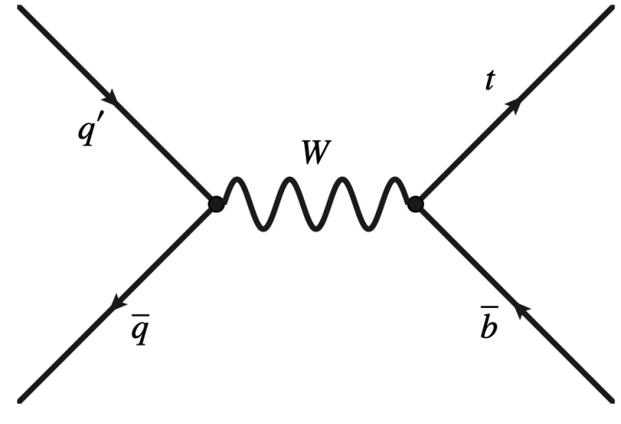
$\sigma(13\text{TeV}) = 216.99^{+9.04}_{-7.71}$ pb



tW-channel

$\sigma(8\text{TeV}) = 24.6^{+1.1}_{-0.8}$pb

$\sigma(13\text{TeV}) = 79.5^{+2.8}_{-2.3}$ pb

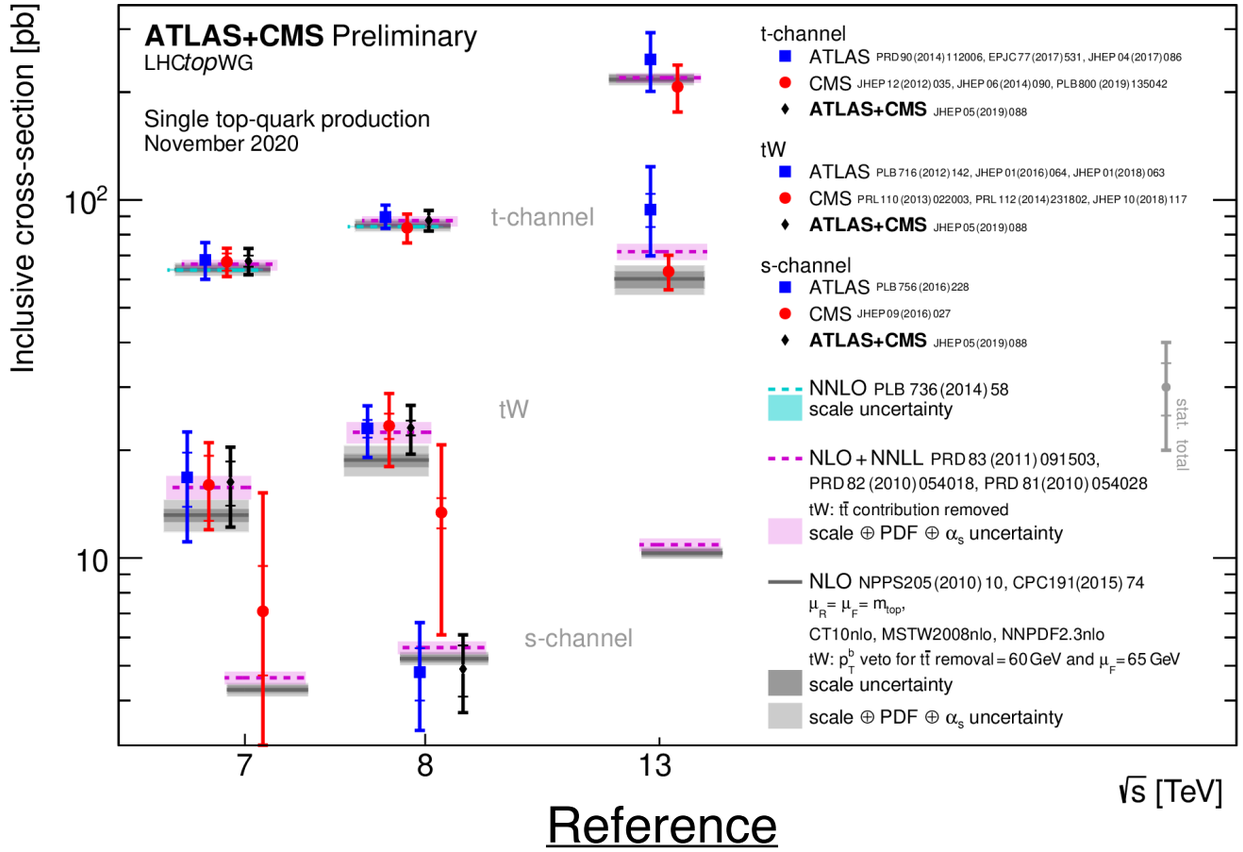


s-channel

$\sigma(8\text{TeV}) = 5.61 \pm 0.22$ pb

$\sigma(13\text{TeV}) = 10.32^{+0.40}_{-0.36}$ pb

- Cross sections
  - t-channel > tW-channel > s-channel
  - tW final-state can test modelling of off-shell tops / interference with $t\bar{t}$
- Today we will be looking at:
  - tW inclusive cross section (l+jets)
  - Top polarisation in single-top production (t-channel)



Reference

tW inclusive cross section

Inspire, arXiv:2007.01554, accepted by EPJC

tW in l+jets

- Most measurements of tW to date use dilepton channel
- Present first evidence for tW production in single lepton (l+jets) final states at 8 TeV
  - 1 electron or muon, 3 jets with 1 b-tag (3j1b)
  - Missing transverse energy $E^{T}_{miss} > 30$ GeV
  - The transverse mass of the leptonically decaying W $m_T(W) > 50$ GeV
- Challenging: S/B ~ 0.05
- Major backgrounds
  - $t\bar{t}$: 58%
  - W+jets: 28%
- Region with an additional b-jet (4j2b) serves as a $t\bar{t}$ validation region

Process	Signal region (3j1b)
tW ($\sigma^{th.}_{tW} = 22.4$ pb)	6300 ± 600
$t\bar{t}$	77000 ± 6000
t, t-channel	4180 ± 290
t, s-channel	307 ± 19
W+ jets, HF	31000 ± 14000
W+ jets, LF	6000 ± 3000
Z + jets	3900 ± 1700
$WW/WZ/ZZ$ + jets	650 ± 280
Fake leptons	4300 ± 1900
Total background	128000 ± 18000
Total signal + background	134000 ± 18000
Observed	134633

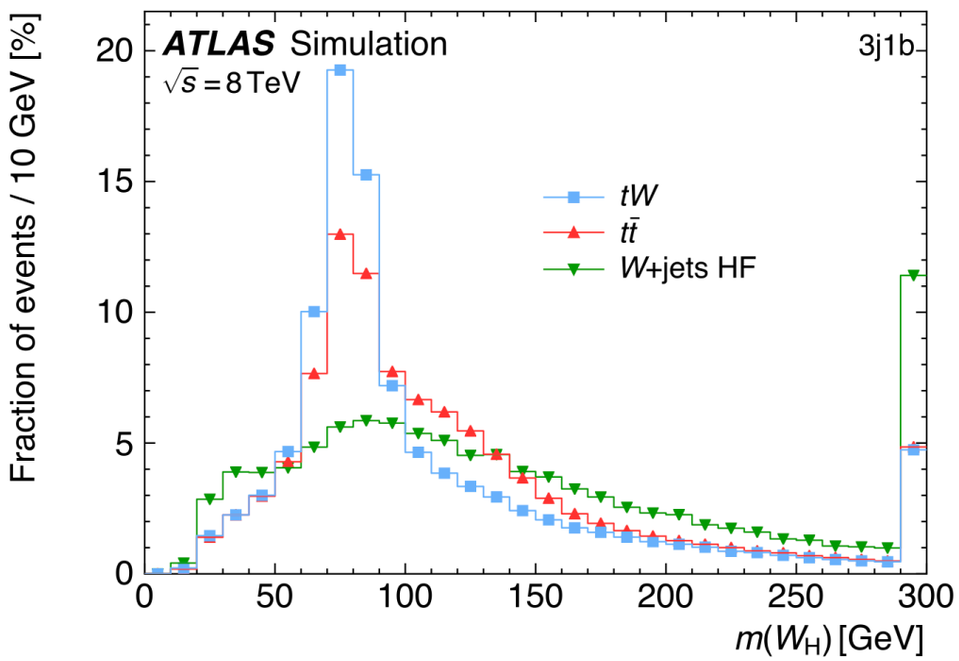
Signal and background separation

- Neural network is used to combine differences in multiple kinematic variables to a stronger discriminant
  - Variable list is carefully selected to avoid an increase of unexpected uncertainty
  - Four variables are selected and trained on signal against $t\bar{t}$:

$$\rho_{\mathrm{T}}(W_H, W_L, j_{\mathrm{B}}) = \frac{p_{\mathrm{T}}(W_{\mathrm{H}} W_{\mathrm{L}} j_{\mathrm{B}})}{p_{\mathrm{T}}(W_{\mathrm{H}}) + p_{\mathrm{T}}(W_{\mathrm{L}}) + p_{\mathrm{T}}(j_{\mathrm{B}})} \qquad m(W_{\mathrm{L}} W_{\mathrm{H}} j_{\mathrm{B}}) \qquad |\Delta\eta(\ell, j_{L1})| \qquad |\eta(\ell)|$$

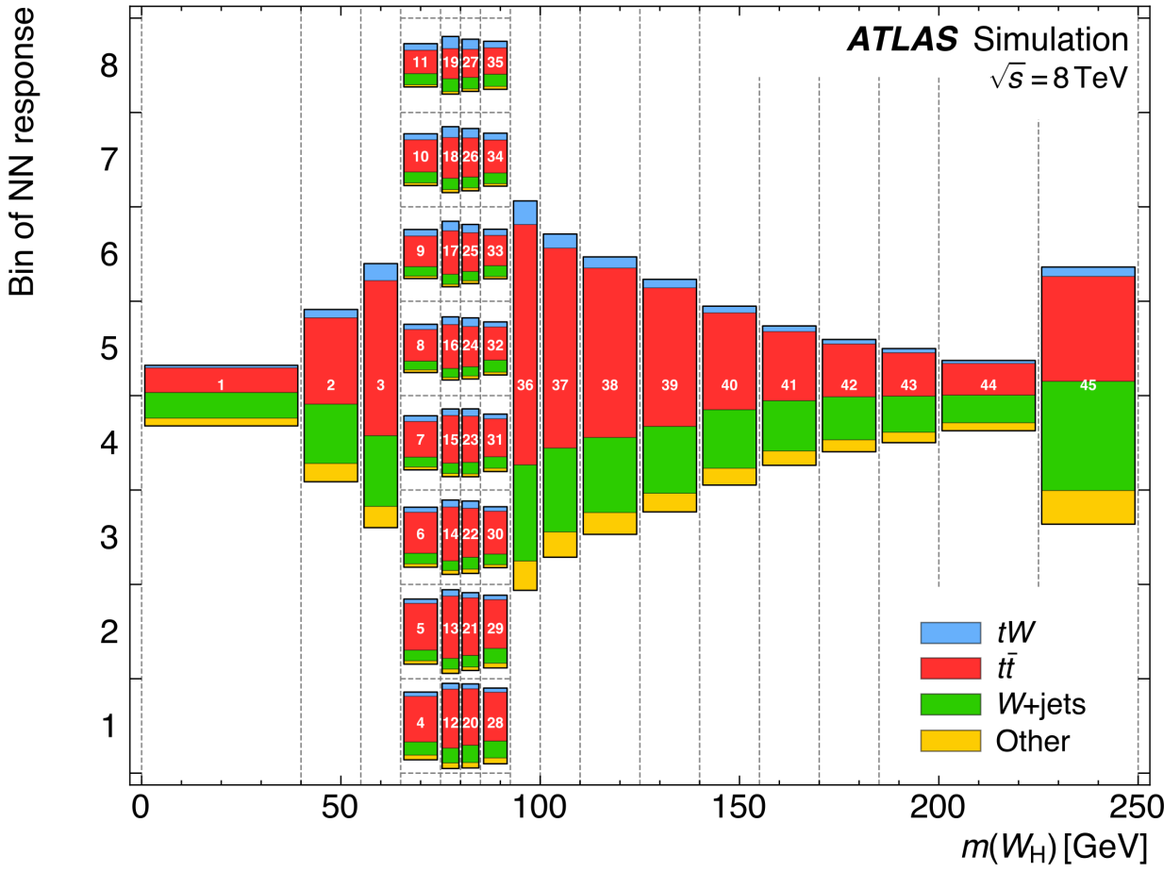
  - Hadronically decaying W mass, $m(W_{\mathrm{H}})$, is strongly affected by uncertainties from reconstructed jet energy, thus is not used in NN

- Strong separation power provided by $m(W_{\mathrm{H}})$
  - For tW and $t\bar{t}$, peak at m(W) when two untagged jets are correctly assigned to W_{H}
  - Lower peak for $t\bar{t}$ due to higher jet multiplicity
  - W+jets does not peak since W must decay leptonically
- How to combine $m(W_{\mathrm{H}})$ with NN?

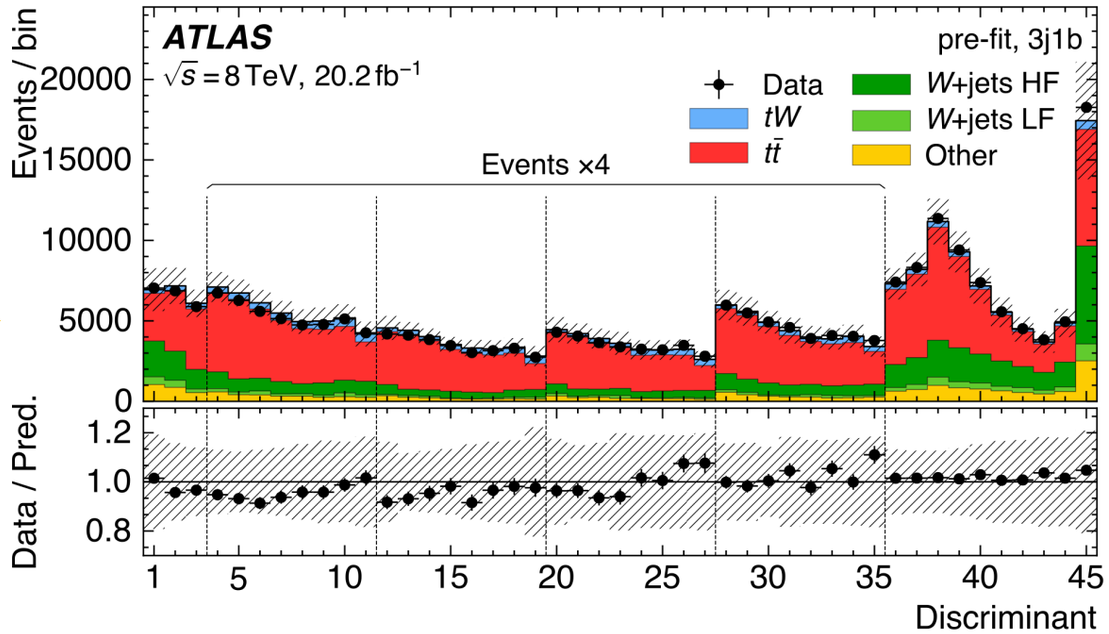


The two-dimensional discriminant

- NN is trained in 65 GeV < m(W_H) < 92.5 GeV
  - Focusing on well-reconstructed hadronic W events, primarily $t\bar{t}$
  - Outside of this range, NN response is ignored



Unroll

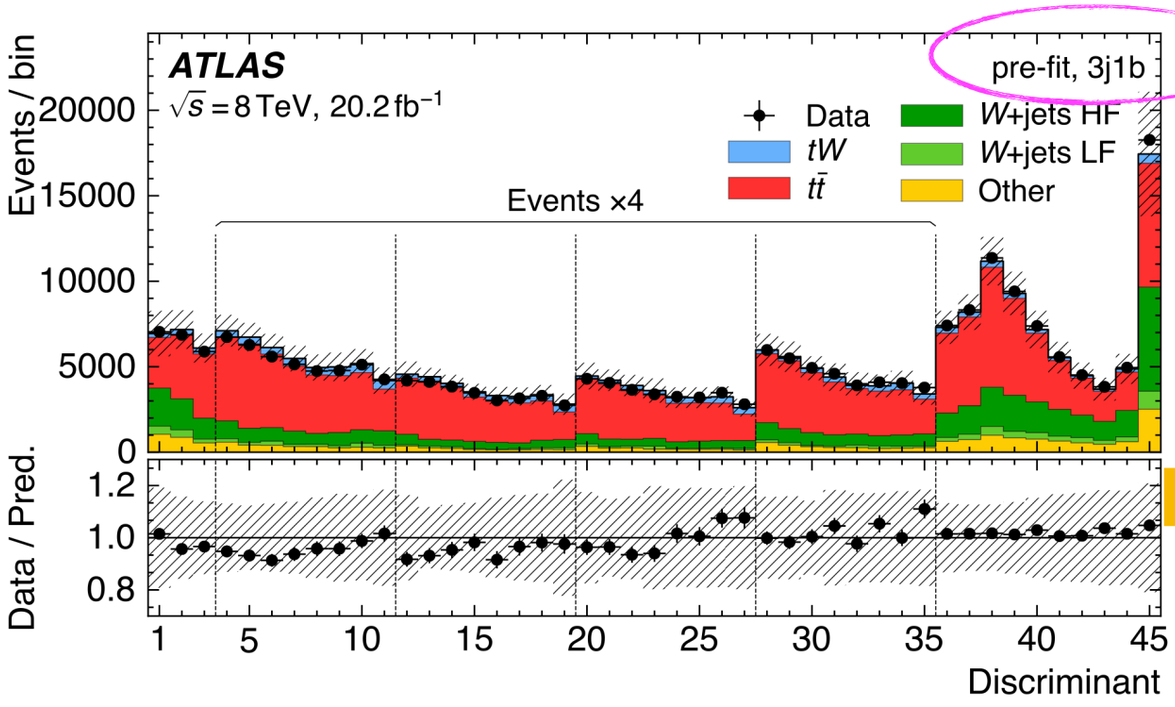


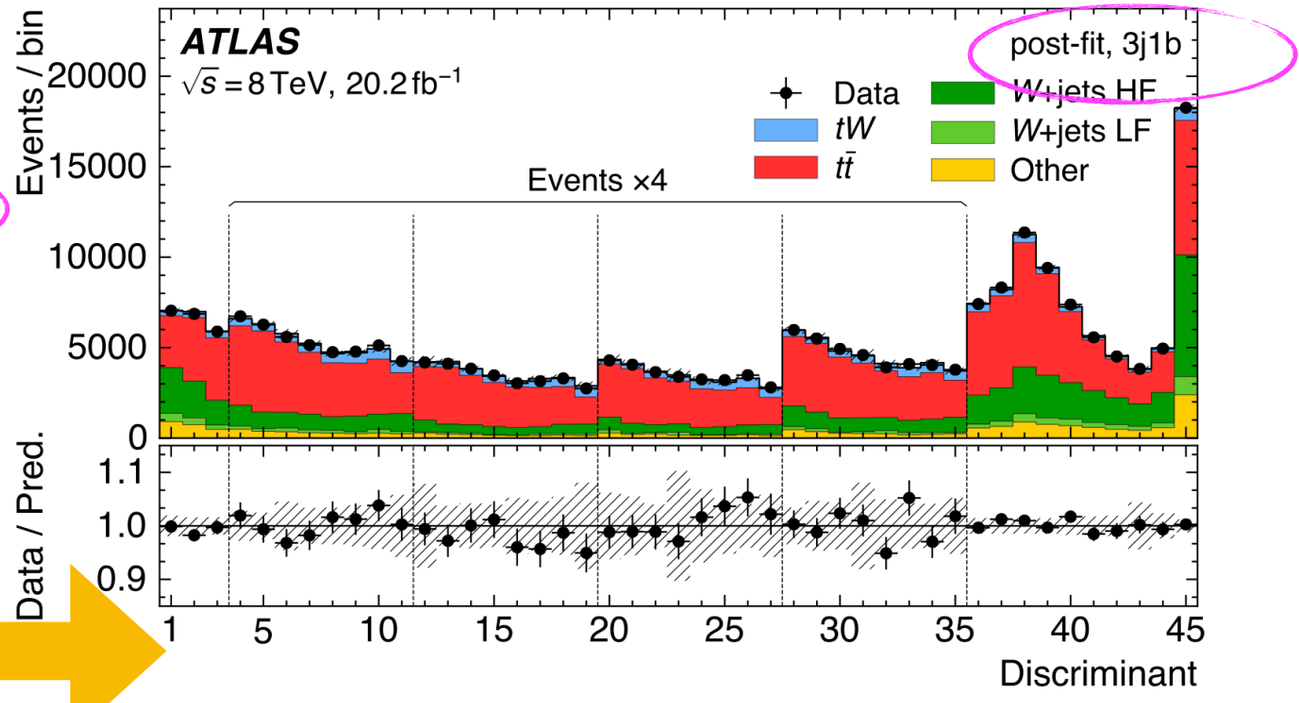
Systematic uncertainties

- Grouped into experimental and theoretical uncertainties
  - Dominated by Jet energy scale, $t\bar{t}$ radiation and MC statistics

Source	Uncertainty [%]
Jet energy scale	10
b-tagging	8
Jet energy resolution	7
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	7
Lepton reconstruction	4
Luminosity	3
Jet vertex fraction	3
$t\bar{t}$ radiation	10
tW radiation	9
tW–$t\bar{t}$ interference	7
$t\bar{t}$ cross-section normalisation	6
Other background cross-section normalisations	5
tW and $t\bar{t}$ parton shower	4
tW and $t\bar{t}$ NLO matching	3
PDF	1
Model statistics	11
Data statistics	4
Total	27

Results

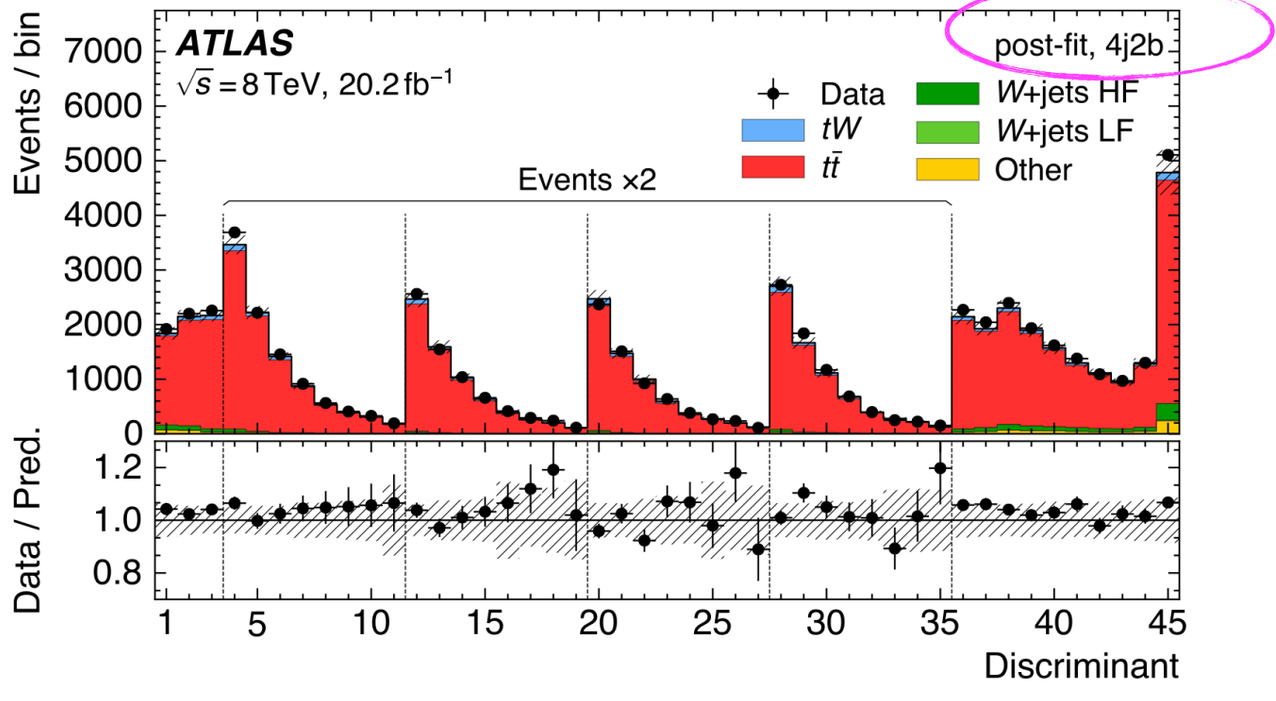




$$\sigma_{tW}^{\text{meas.}} = 26 \pm 7\,\text{pb}$$

$$\sigma_{tW}^{\text{th.}} = 24.6^{+0.6+0.9}_{-0.5-0.6}\,\text{pb}$$ JHEP 278 (2021)

Significance: 4.5σ
(3.9σ expected)



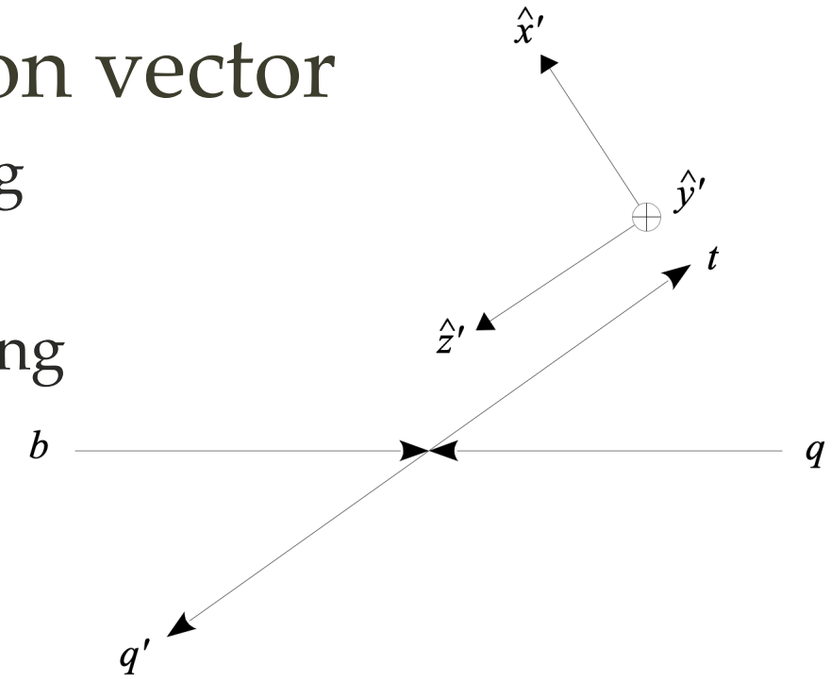
Top polarisation in single-top production (t-channel)

ATLAS-CONF-2021-027

More detailed talk 29/07/2021, 10:05 by Carlos Escobar

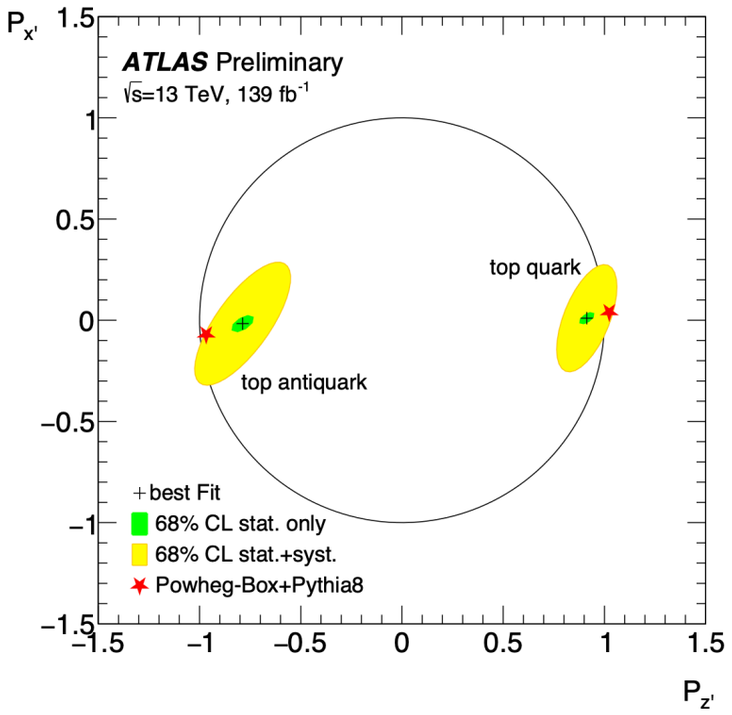
Top quark polarisation

- Unique chance to the polarisation measurement in single top
  - Weakly produced single tops are polarised
  - Top quarks in $t\bar{t}$ production are unpolarised (QCD conserves parity)
- First measurement of the full polarisation vector
  - In the t-channel at LO, top quark spin is aligned along the direction of the down-type quarks.
  - Measured also in two orthogonal axes, hence providing a complete description of the top quark polarisation
  - Measured for both top quark and top anti-quark



- Unfolded to particle level
  - Differential cross sections are extracted for angular variables $\cos\theta_{\ell x'}$, $\cos\theta_{\ell y'}$, $\cos\theta_{\ell z'}$
  - EFT $\mathcal{O}_{tW}$: only tree-level dimension-6 operator sensitive to polarisation
    - $\cos\theta_{\ell x'}$ sensitive to $\mathrm{Re}(C_{tW})$
    - $\cos\theta_{\ell y'}$ sensitive to $\mathrm{Im}(C_{tW})$, hint of CP violation in the tWb vertex if non-zero
    - $\cos\theta_{\ell z'}$ sensitive to many additional operators, thus ignore in the analysis

Results

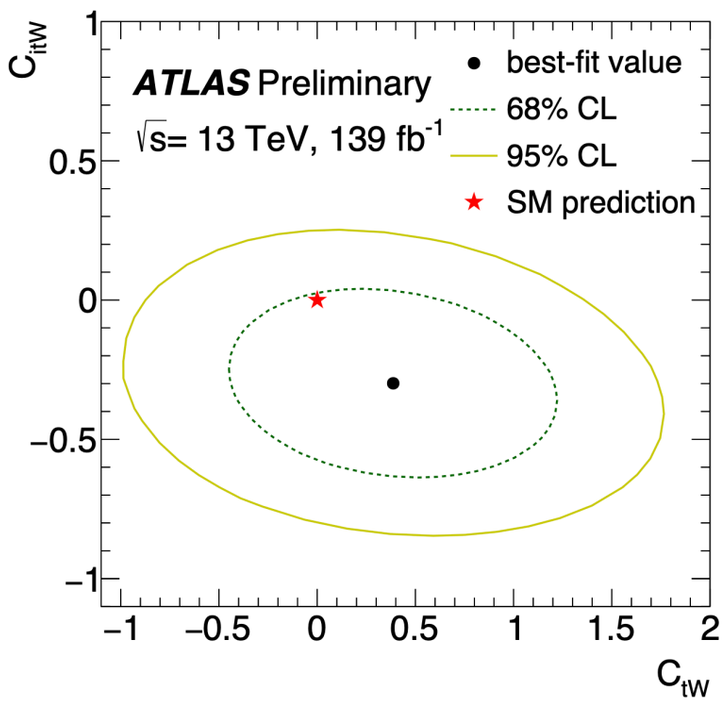


Polarisation measurement

Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
W+jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$	-0.007 ± 0.051	(± 0.017)
$P^{t}_{z'}$	$+0.91 \pm 0.10$	(± 0.02)
$P^{\bar{t}}_{z'}$	-0.79 ± 0.16	(± 0.03)

No deviation from the SM

Refer to a more detailed talk on 29/07/2021, 10:05 given by Carlos Escobar



Limits on Wilson coefficients

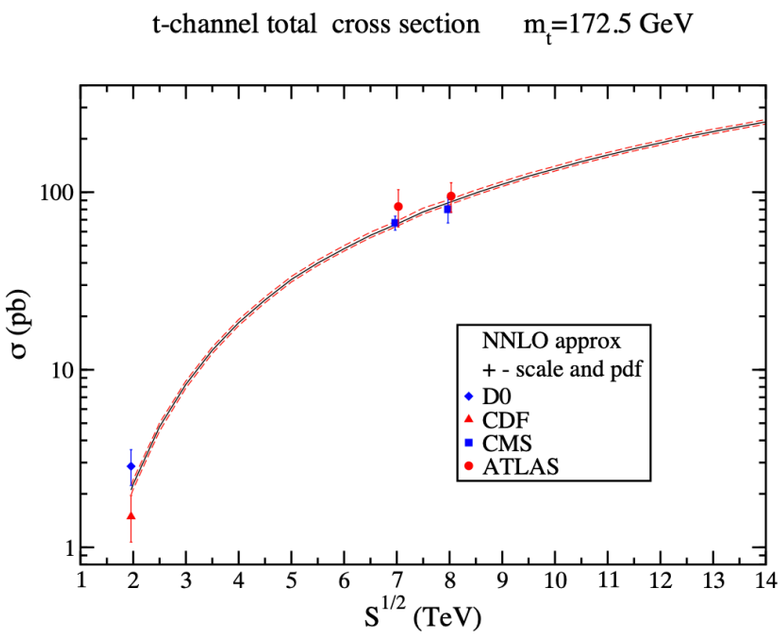
	C_{tW}		C_{itW}	
	68% CL	95% CL	68% CL	95% CL
All terms	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^4$	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^2$	[-0.2, 1.0]	[-0.7, 1.7]	[-0.5, -0.1]	[-0.8, 0.2]

Summary

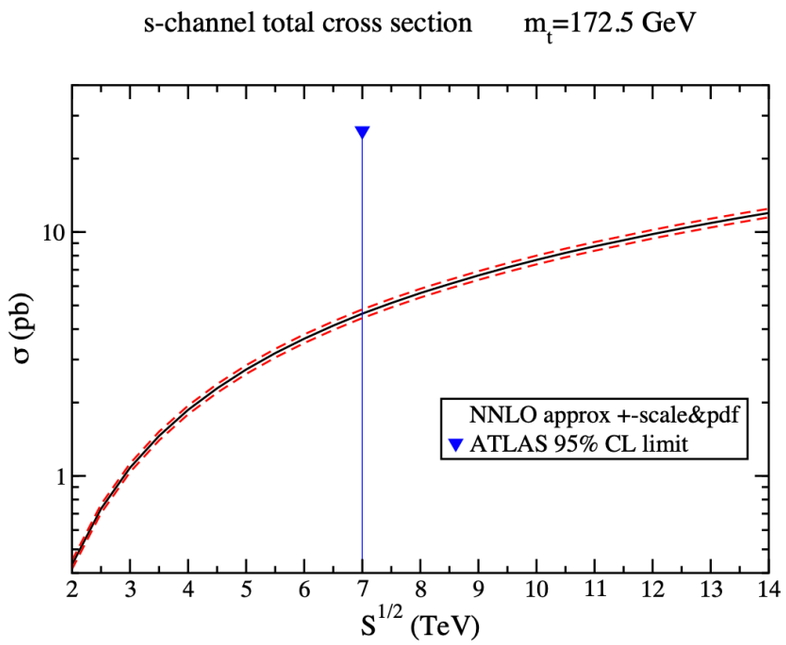
- Overviewed recent single top publications at ALTAS
- First measurements on the tW lepton+jets final state
  - Analysis exploits multivariate techniques to achieve a relatively clean signal
  - No deviations from the SM are seen
- First measurement of the full polarisation vector and for top quarks and antiquarks separately
  - Most stringent limit is set for Wilson coefficients for tWb vertex
  - No deviations from the SM are seen
- More info
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

Thank you for listening!

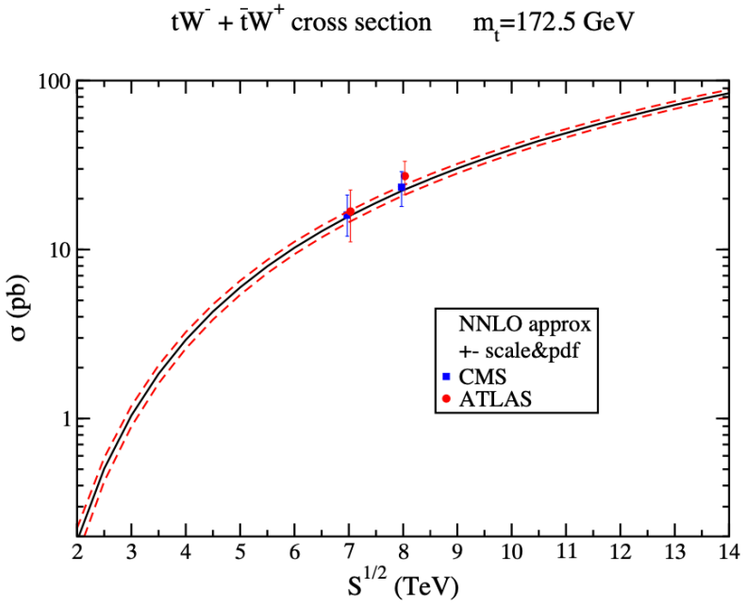
$$\Gamma^{(1)}_{S\,t-11} = C_F \left[\ln\left(\frac{-t}{s}\right) + \ln\left(\frac{m_t^2 - t}{m_t\sqrt{s}}\right) - \frac{1}{2} \right]$$



$$\Gamma^{(1)}_{S\,s-11} = C_F \left[\ln\left(\frac{s - m_t^2}{m_t\sqrt{s}}\right) - \frac{1}{2} \right]$$



$$\Gamma^{(1)}_{S\,tW^-} = C_F \left[\ln\left(\frac{m_t^2 - t}{m_t\sqrt{s}}\right) - \frac{1}{2} \right] + \frac{C_A}{2} \ln\left(\frac{m_t^2 - u}{m_t^2 - t}\right)$$



Reference

Systematic tables from other analysis

ATLAS 13TeV 3.2 ifb dilepton tW

Source	$\Delta\sigma_{Wt}/\sigma_{Wt}$[%]
Jet energy scale	21
Jet energy resolution	8.6
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft terms	5.3
b-tagging	4.3
Luminosity	2.3
Lepton efficiency, energy scale and resolution	1.3
NLO matrix element generator	18
Parton shower and hadronisation	7.1
Initial-/final-state radiation	6.4
Diagram removal/subtraction	5.3
Parton distribution function	2.7
Non-$t\bar{t}$ background normalisation	3.7
Total systematic uncertainty	30
Data statistics	10
Total uncertainty	31

ATLAS 8TeV 20.3 ifb dilepton tW

Uncertainty	Impact on $\hat{\mu}$ [%]
Statistical	±5.8
Luminosity	±4.7
Theory modelling	
ISR/FSR	$^{+8.2}_{-9.4}$
Hadronisation	±1.7
NLO matching method	±2.5
PDF	±0.6
DR/DS	$^{+2.2}_{-4.8}$
Detector	
Jet	$^{+9.0}_{-9.9}$
Lepton	±3.0
$E_{\mathrm{T}}^{\mathrm{miss}}$	±5.5
b-tag	±1.0
Background norm.	$^{+2.9}_{-2.6}$
Total	$^{+16}_{-17}$

MC simulator

- tW, $t\bar{t}$: Baseline Powheg-box + Pythia 6
  - Radiation: higher (radHi) and lower (radLo) radiation relative to the nominal set, together with varied renormalisation and factorisation scales
  - PS: Pythia with Herwig
  - NLO: MC@NLO and Powheg-Box