Measurements of top-quark production and properties at ATLAS

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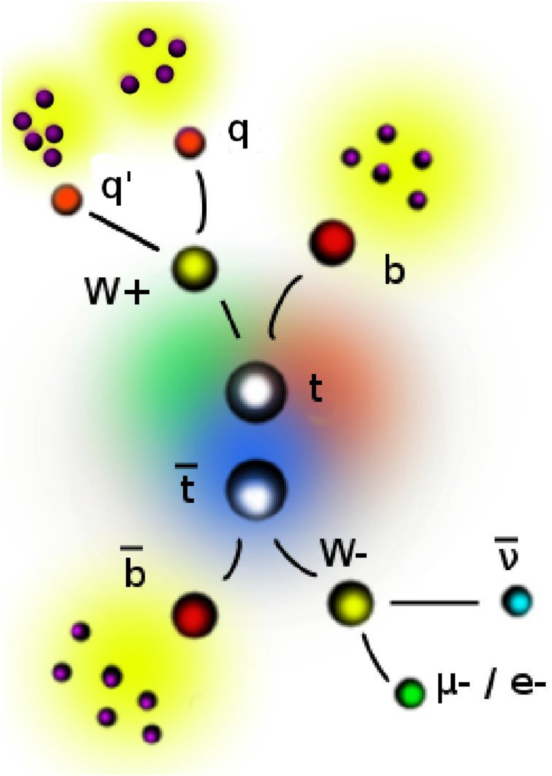
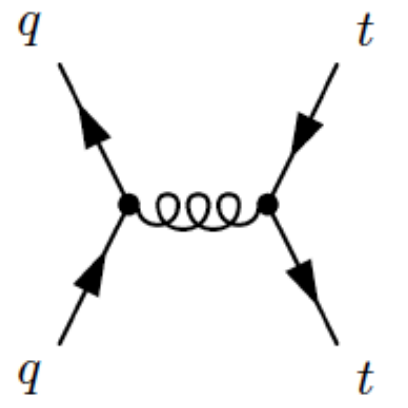
1) Latest cross-section measurements
   (5 analyses)
2) Measurements of spin-related observables
   (3 analyses)



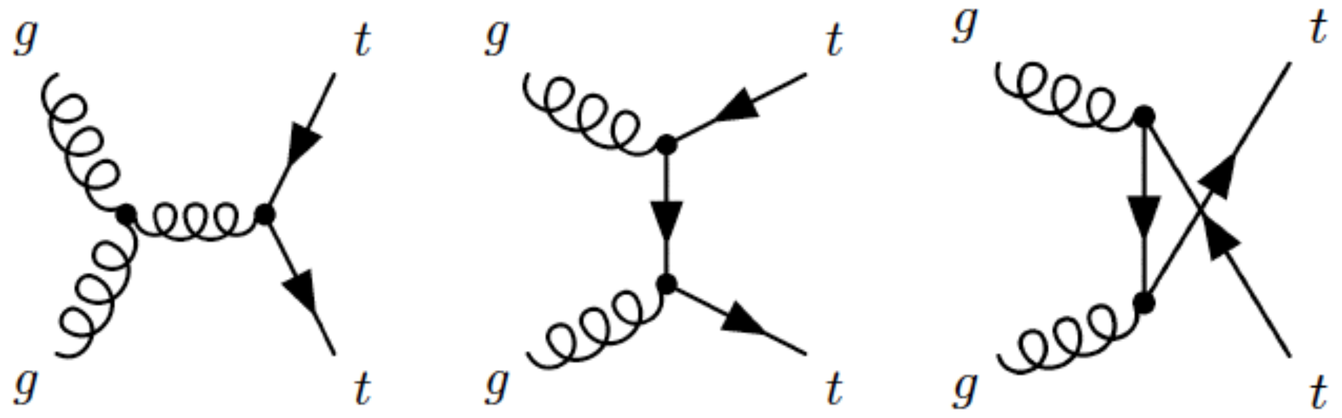
Top-quark production

Leading-order Feynman diagrams

$t\bar{t}$ pairs

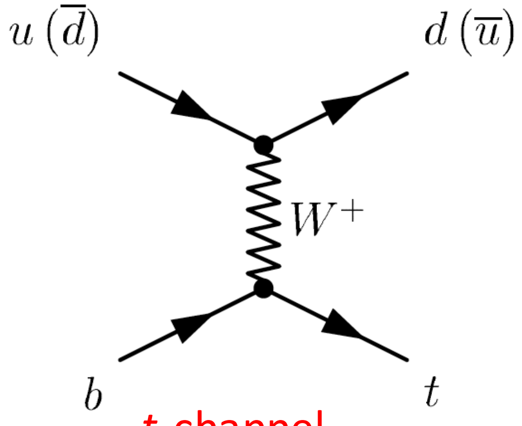


quark-antiquark annihilation (~ 10 %)

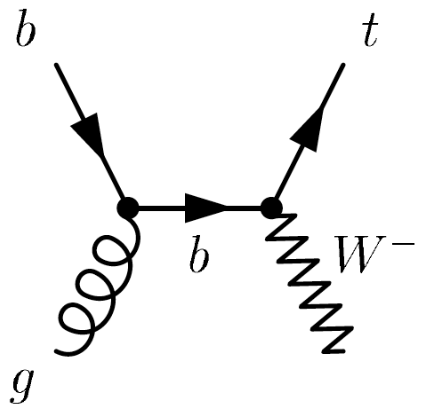


gluon-gluon fusion (~ 90 % @ 13 TeV)

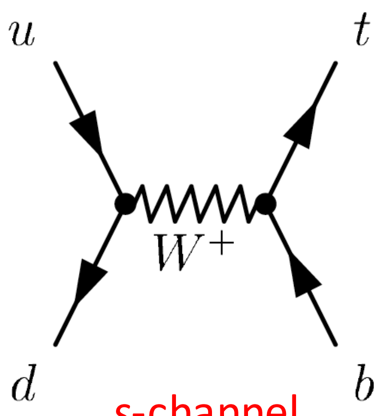
Single top-quark processes



t-channel
(*tq* production)



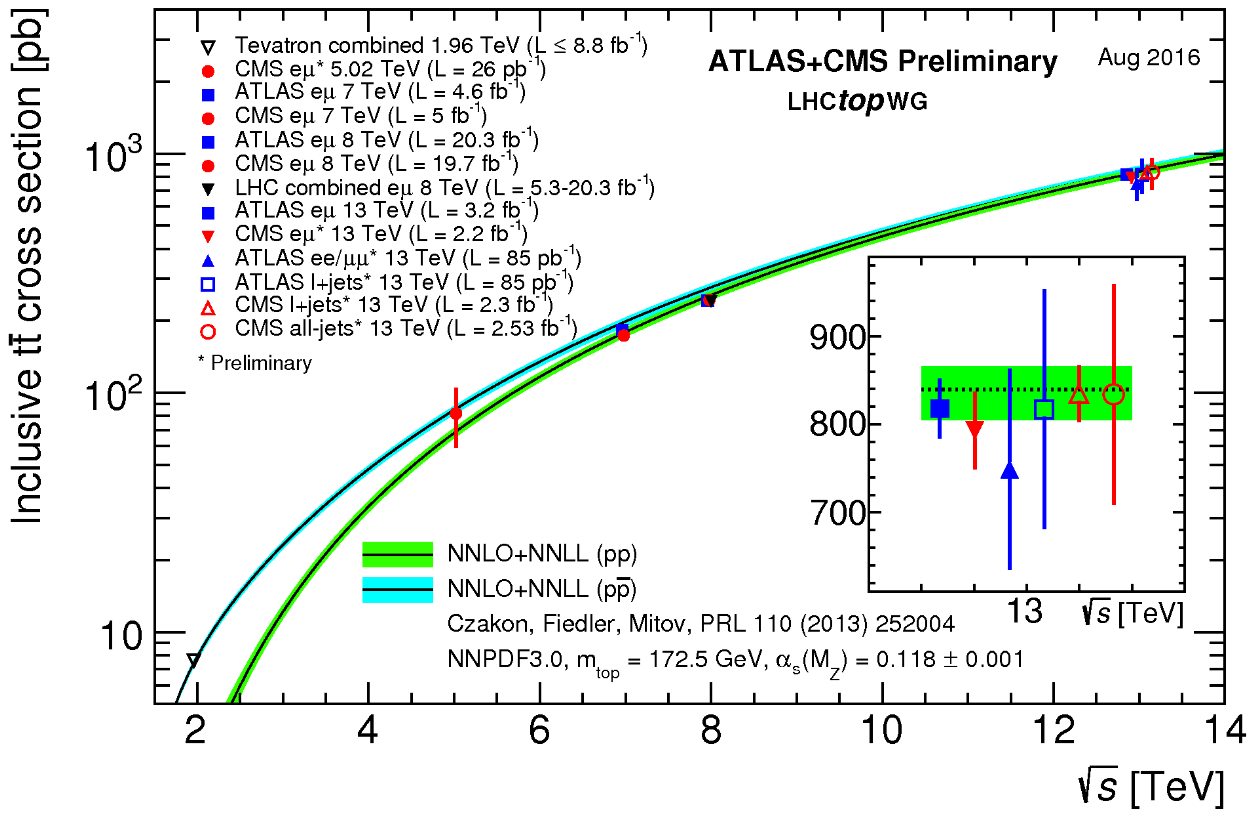
tW production



s-channel
($t\bar{b}$ production)

Aims of analyses

- Large cross-sections $\mathcal{O}$ (100 pb) and data sets
  ➽ top-quark factory
- Test pQCD at NNLO precision (fixed-order)
- Tune MC generators
  - NLO ME generators
  - (New) parton shower generators
- Constrain parton distribution functions (PDFs)
- Determine SM parameters (m_t, $|V_{tb}|$)
- Measure rare processes: $t\bar{t}$+W, $t\bar{t}$+Z, $t\bar{t}$+H; tZ, tH
  (not in this talk)
- Constrain new physics models
  - Anomalous couplings
  - Effective Field Theory operators
- Direct searches: $t\bar{t}$ resonances, W' → $t\bar{b}$
  (not in this talk)



Predictions made at NNLO+NNLL:

	7 TeV	8 TeV	13 TeV
σ ($t\bar{t}$)	182 pb	259 pb	842 pb
Δσ / σ	± 6 %	± 6 %	± 6 %

Part 1: Latest cross-section measurements

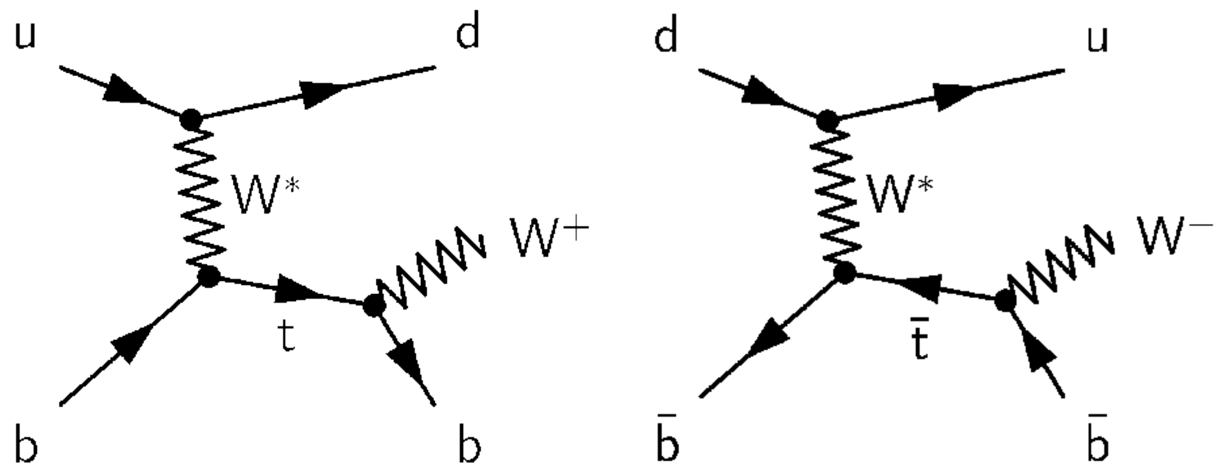
$t\bar{t}$ production

1) Differential cross-sections in the eμ channel at $\sqrt{s}$ = 13 TeV
2) Ratios of $t\bar{t}$ to *Z*-boson cross-sections at $\sqrt{s}$ = 13, 8, 7 TeV
3) Differential cross-sections in the all-hadronic channel using **highly boosted** top quarks at $\sqrt{s}$ = 13 TeV

Single top-quarks

1) t-channel production at $\sqrt{s}$ = 8 TeV
   fiducial, total, differential cross-sections
2) tW production at $\sqrt{s}$ = 13 TeV

Single top-quark production in the *t*-channel



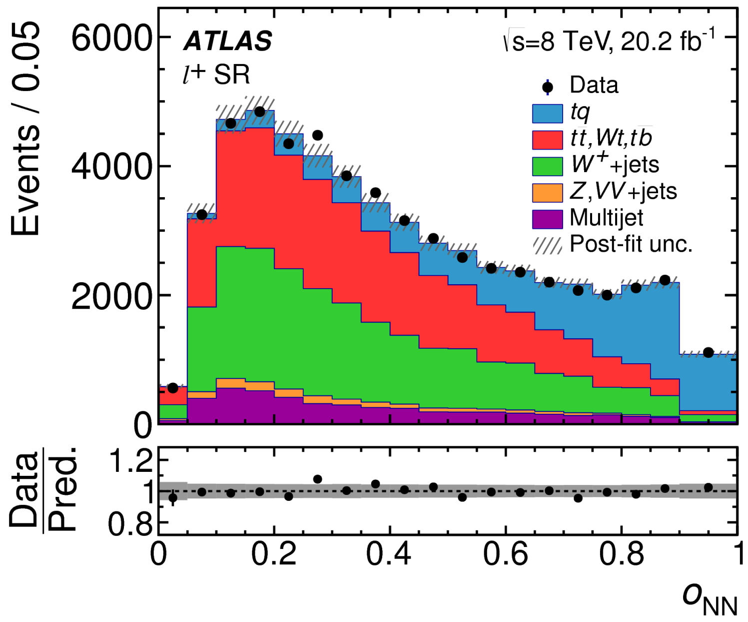
[arXiv: 1702.02859 [hep-ex]]

Measured cross-sections:

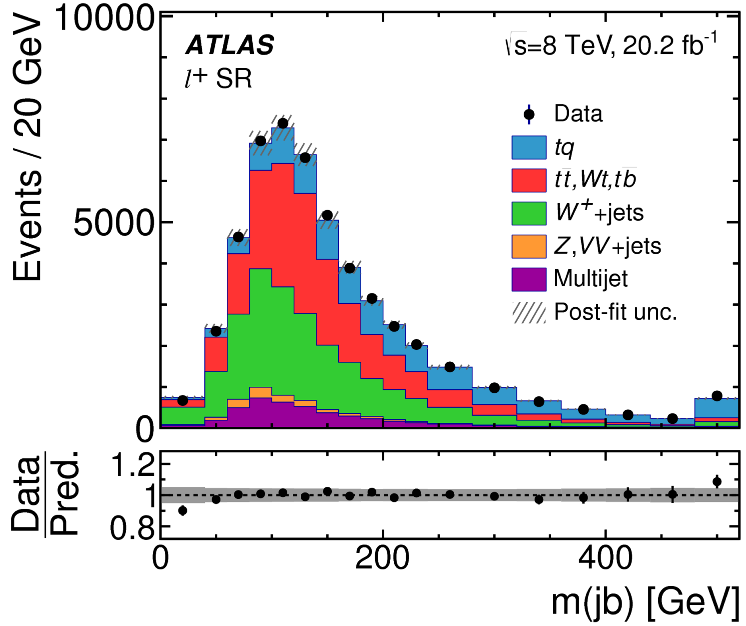
- Fiducial
- Total (cross-section ratio, $f_{LV} \cdot |V_{tb}|$ extraction)
- Differential (particle-level and parton-level)

- Separate tq and $\bar{t}q$ production (lepton charge)
- Two jets, charged lepton, E_T^{miss}
- Neural network to separate signal and background
- Binned maximum-likelihood fit

NN discriminant (post fit):



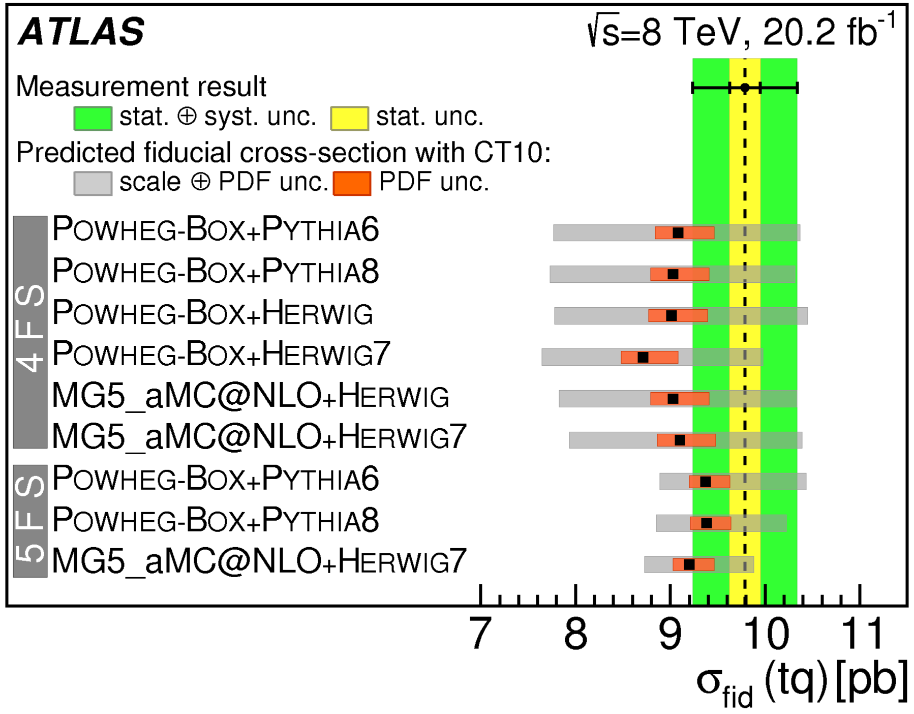
Most important variable:



Fiducial and total tq and $\bar{t}q$ cross-sections

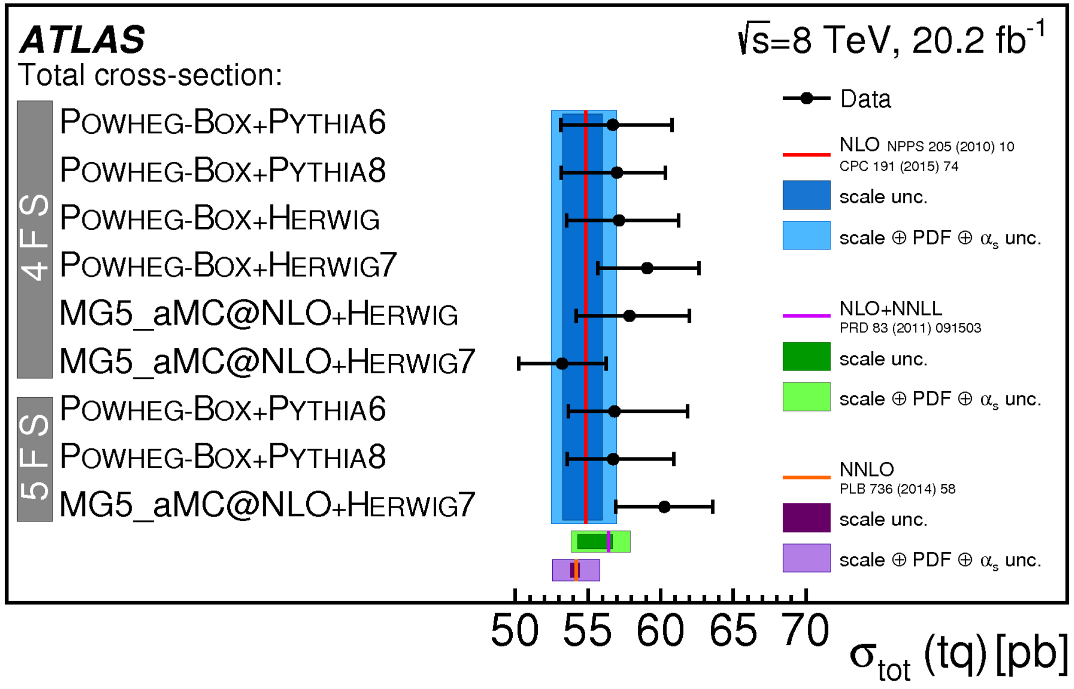
$$\sigma_{\text{fid}} = \frac{N_{\text{fid}}}{N_{\text{sel}}} \cdot \frac{\hat{\nu}}{L_{\text{int}}}$$

- Total uncertainties: 5.8 % (top-quark) and 7.8 (top-antiquark)
- Comparison to predictions with NLO ME generators + different parton-shower programs



$$\sigma_{\text{tot}} = \frac{1}{A_{\text{fid}}} \cdot \sigma_{\text{fid}} \quad \text{with} \quad A_{\text{fid}} = \frac{N_{\text{fid}}}{N_{\text{total}}}$$

- Total uncertainties: +7.6 % / -6.7 % (top-quark) and +9.1 % / -8.4 % (top-antiquark)
- Comparison to fixed-order calculations.



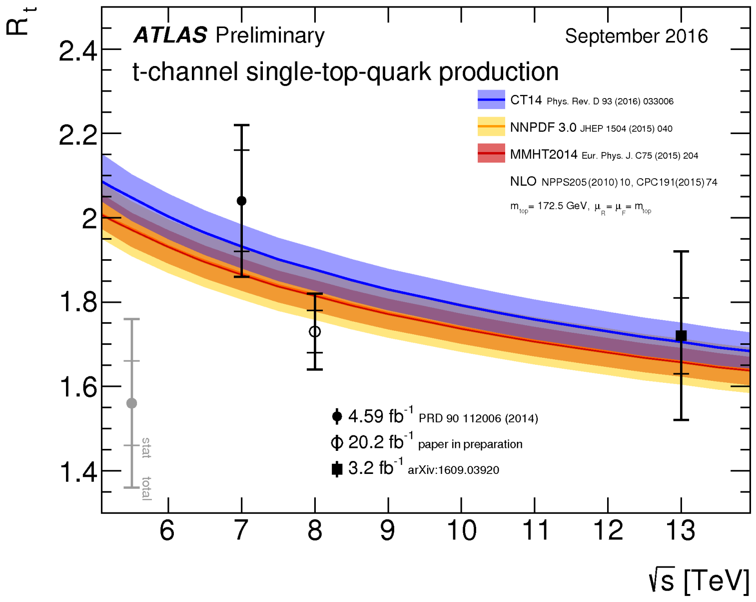
arXiv: 1702.02859 [hep-ex]

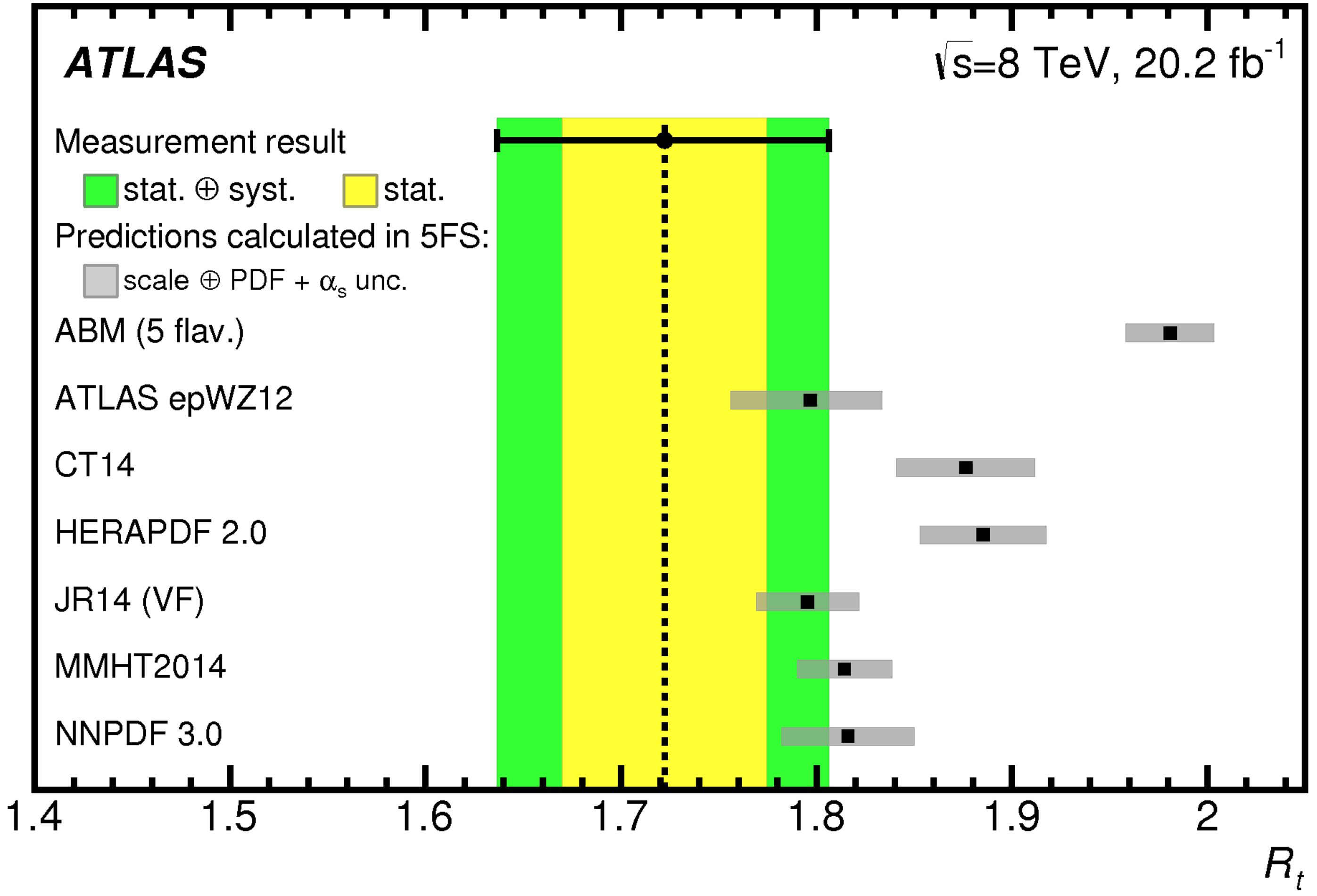
Cross-section ratio R_t of tq to $\bar{t}q$ production

$$R_t = \frac{\sigma_{\text{tot}}(tq)}{\sigma_{\text{tot}}(\bar{t}q)}$$

$$R_t = \frac{\sigma_{\text{tot}}(tq)}{\sigma_{\text{tot}}(\bar{t}q)} = 1.72 \pm 0.05\,(\text{stat.}) \pm 0.07\,(\text{exp.}) = 1.72 \pm 0.09$$

- Total uncertainty: **± 5.0 %**
- Statistically limited
- Comparison to predictions with different PDF sets.

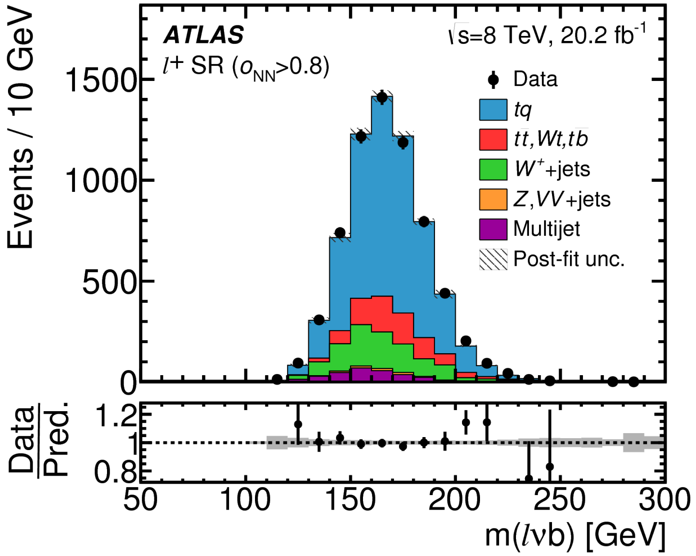


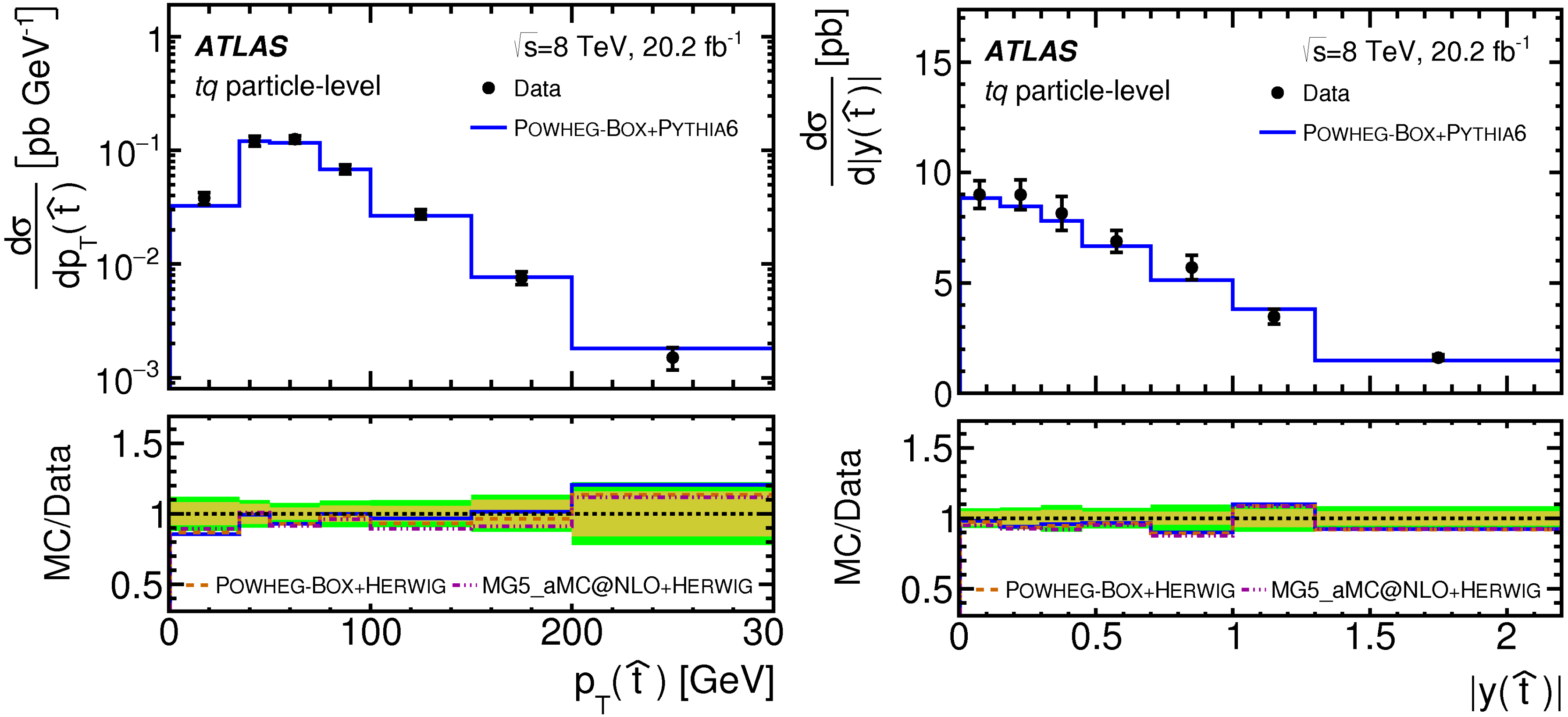


arXiv: 1702.02859 [hep-ex]

Differential tq and $\bar{t}q$ cross-sections

- Enrich *tq* events by cut on NN discriminant
- Particle level: use pseudo-top quark ($\hat{t}$), defined with stable particles
- Parton level: compare unfolded data also to fixed-order calculations



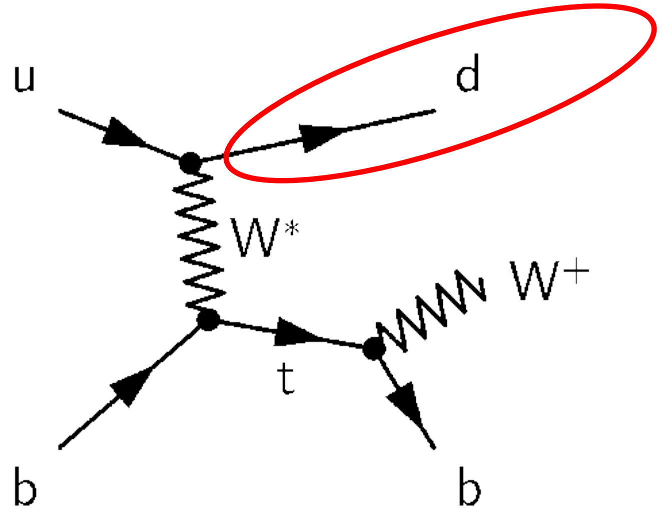


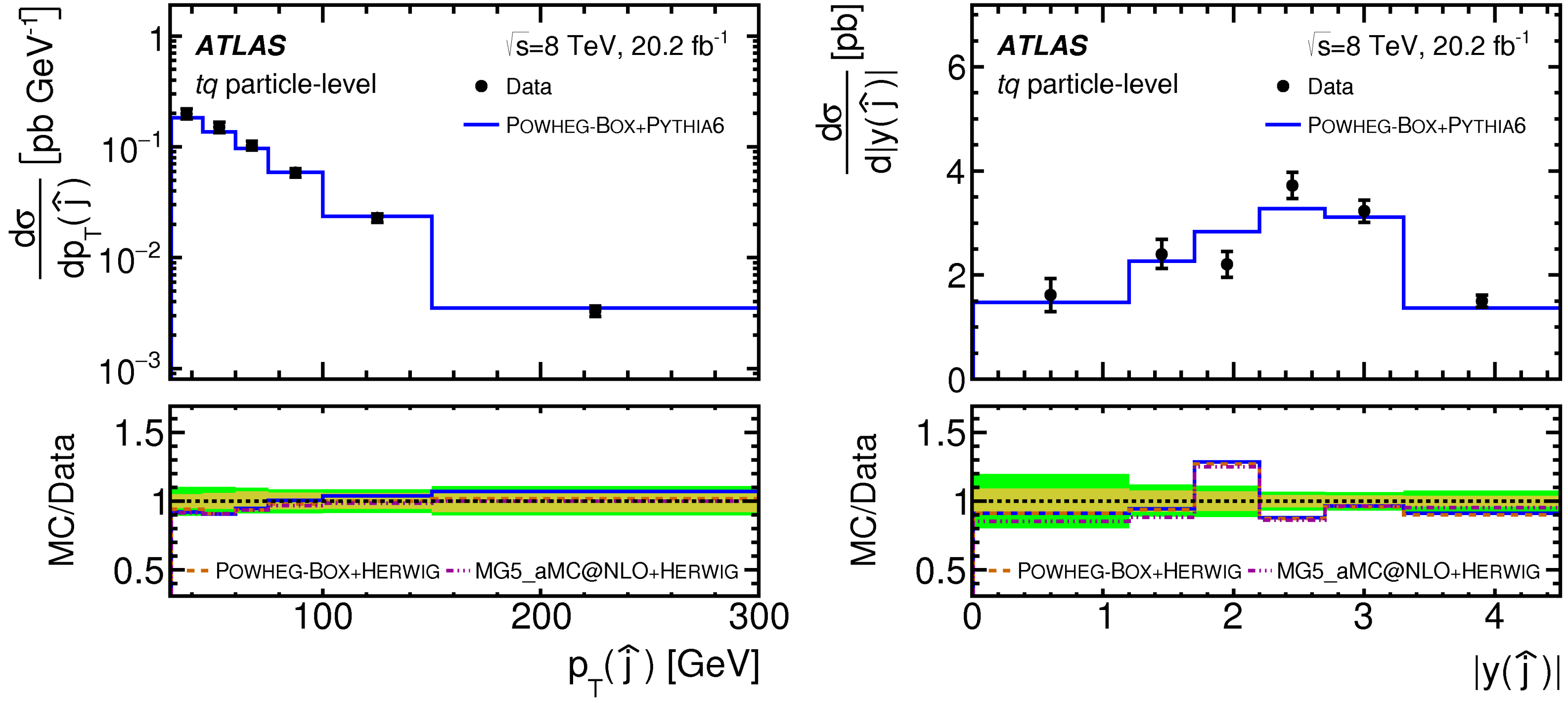
Observe good agreement with predictions by NLO generators.

arXiv: 1702.02859 [hep-ex]

Differential cross-sections: untagged jet

- Unfold p_T and |y| of the untagged (forward) jet at particle level
- Train specific network without |η| to avoid depletion at high rapidity after cutting on the network





Good agreement with predictions by NLO generators, with a slight trend to a softer p_T spectrum.

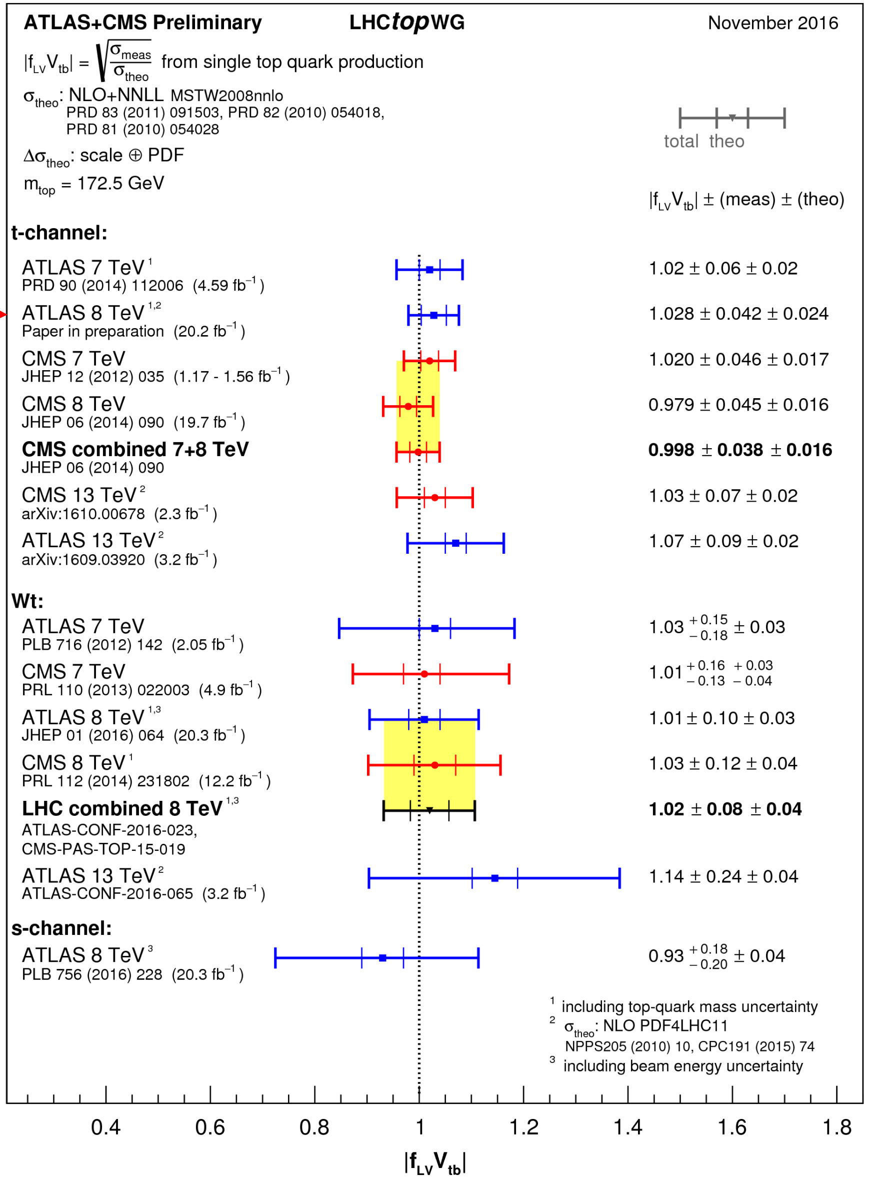
arXiv: 1702.02859 [hep-ex]

Determination of $|f_{LV} \cdot V_{tb}|$

This measurement →

Using

$$|f_{LV} \cdot V_{tb}| = \sqrt{\frac{\sigma_{meas}}{\sigma_{pred}}}$$



$|f_{LV} \cdot V_{tb}|$ = 1.029 ± 0.048

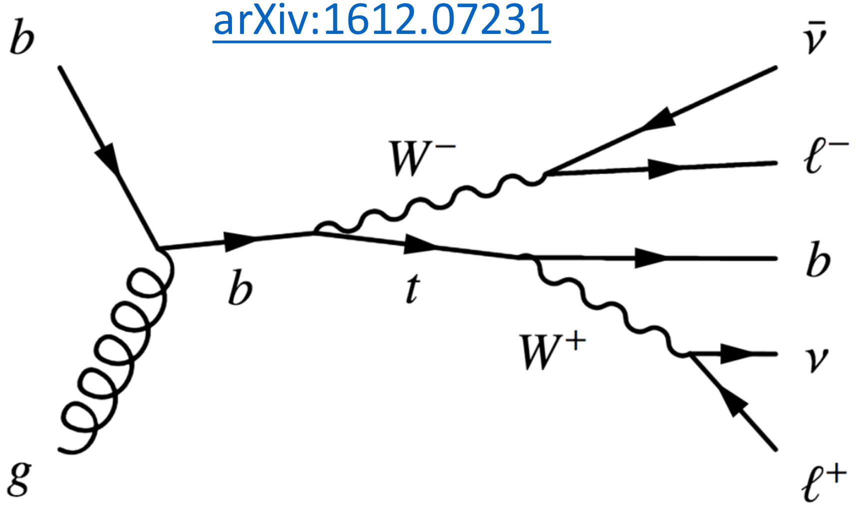
$$\begin{aligned} f_{LV} \cdot |V_{tb}| &= 1.029 \pm 0.007\,(\text{stat.}) \pm 0.029\,(\text{exp.})\, ^{+0.023}_{-0.014}\,(\text{scale}) \pm 0.004\,(\text{PDF}) \\ &\quad \pm 0.010\,(\text{NLO-matching method}) \pm 0.009\,(\text{parton shower}) \pm 0.007\,(\text{lumi.}) \\ &\quad \pm 0.005\,(m_t) \pm 0.024\,(\text{theor.}) \\ &= 1.029 \pm 0.048\,. \end{aligned}$$

- Define the additional left-handed form factor f_{LV} to parameterise deviations from the SM.
- Assume V-A vertex structure to be unchanged.

arXiv: 1702.02859 [hep-ex]

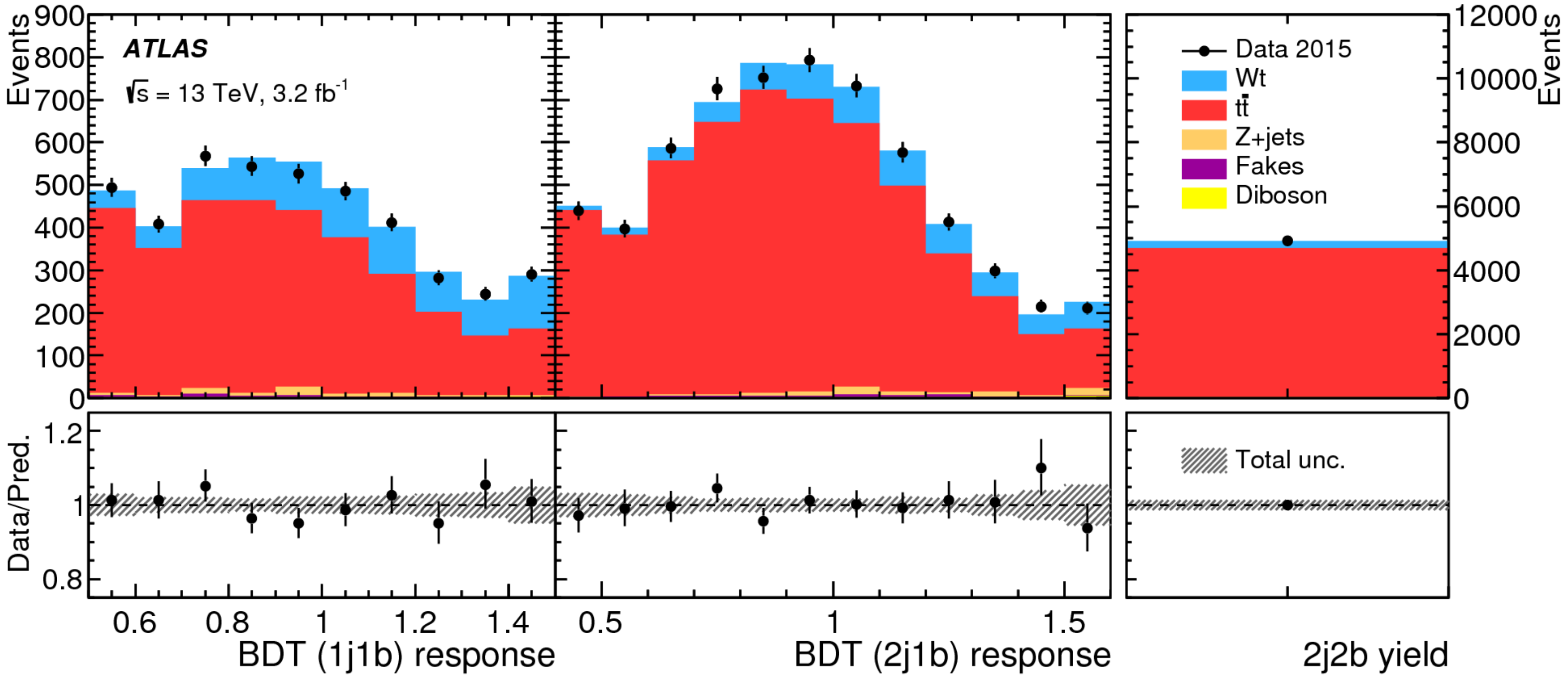
tW production at 13 TeV

arXiv:1612.07231



- Exactly 2 leptons, one with p_T > 25 GeV, one with p_T > 20 GeV
- Use BDTs to separate signal and background
- Constrain $t\bar{t}$ background with event yield in 2j2b channel

Fit regions:



Measured cross-section:

$$\sigma_{Wt} = 94 \pm 10\,(\text{stat.})^{+28}_{-22}\,(\text{syst.}) \pm 2\,(\text{lumi.})\,\text{pb}$$

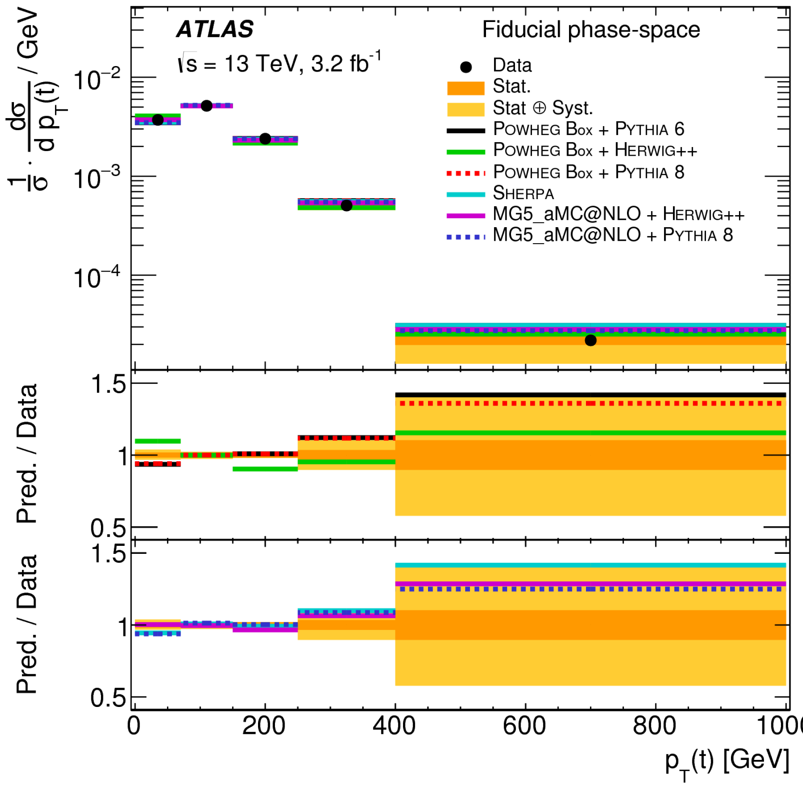
$$\sigma_{\text{theory}} = 71.7 \pm 1.8\,(\text{scale}) \pm 3.4\,(\text{PDF})\,\text{pb}$$

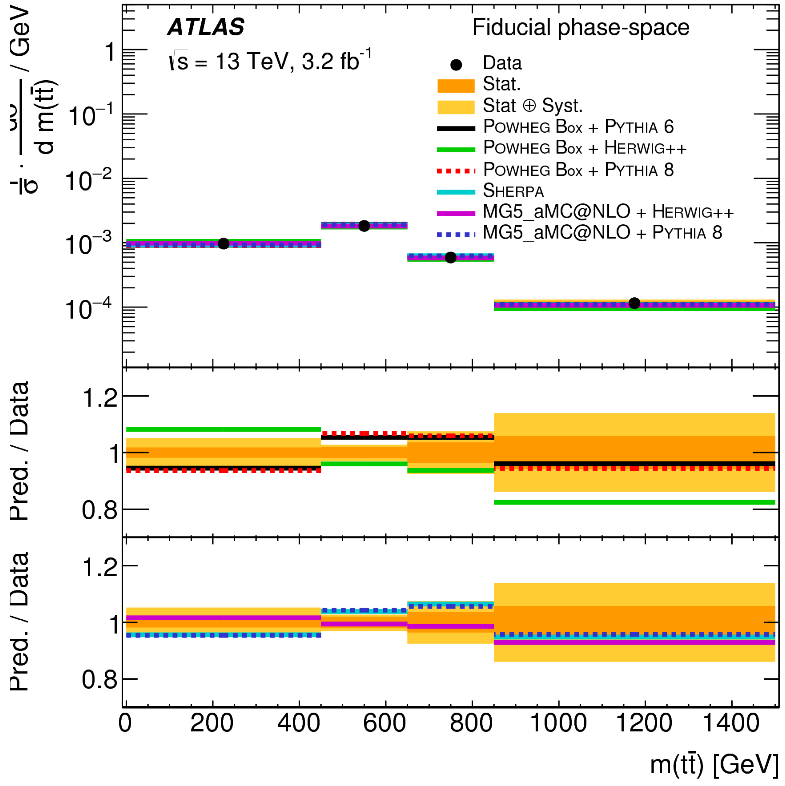
- Total uncertainty: ± 31 %
- Total systematic unc.: ± 30 %
- Main components:
  - Jet energy scale: ± 21 %
  - NLO ME generator: ± 18 %

Differential $t\bar{t}$ cross-sections in the eμ channel

- 5 kinematic variables:
  - Top quark: $p_T(t)$, $|y(t)|$
  - $t\bar{t}$ system: $p_T(t\bar{t})$, $|y(t\bar{t})|$, $m(t\bar{t})$
- Normalised and absolute fiducial differential cross-sections

- Use neutrino-weighting method for reconstruction to solve under-constrained system (weight based on agreement of reconstructed and measured E_T^{miss})
- POWHEG + HERWIG++(7) / PYTHIA8 have been retuned based on these results





arXiv:1612.05220 [hep-ex]

More details in the talk by

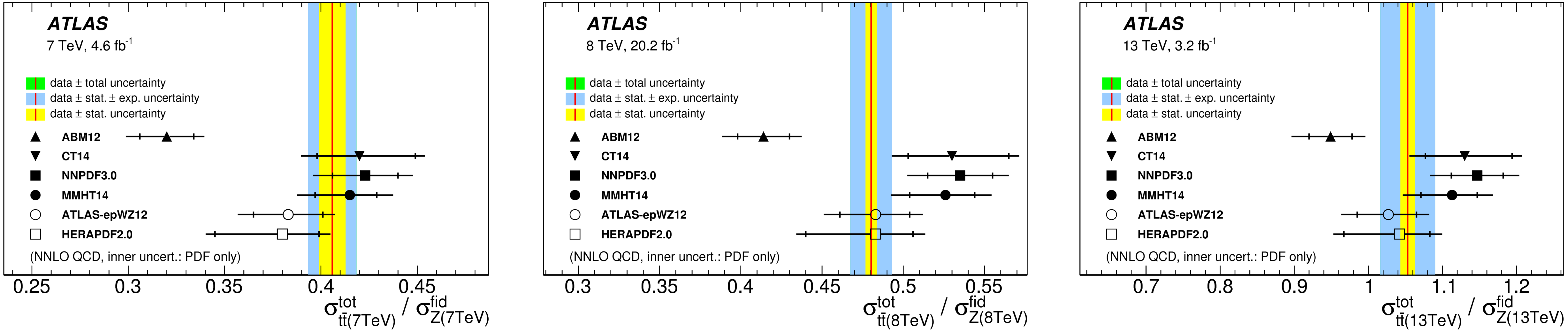
Abigail O'Rourke (DESY)

in the Young Scientists Forum on Friday 18:55 – 20:05 CET

Cross-section ratio: $\sigma^{\text{tot}}(t\bar{t}) \,/\, \sigma^{\text{fid}}(Z)$

arXiv:1612.03636 [hep-ex]   JHEP 1702 (2017) 117

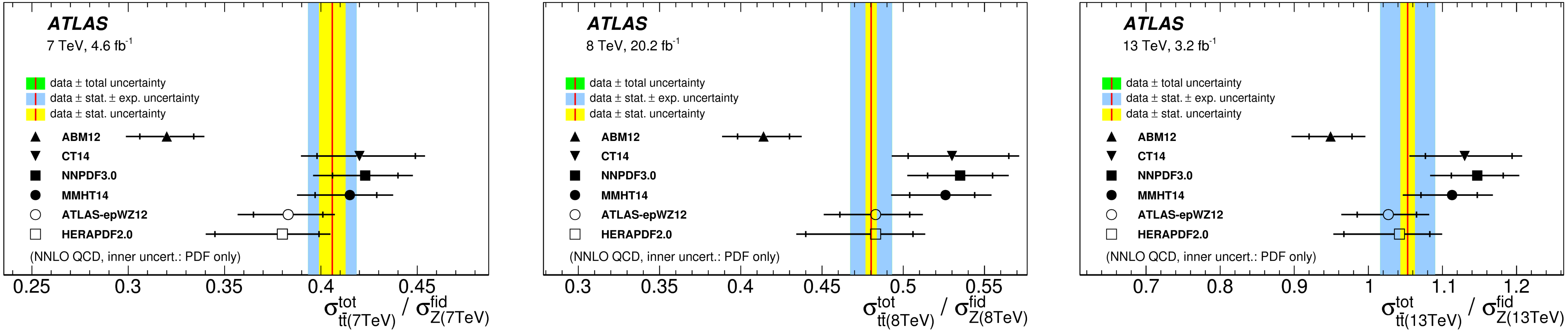
- Use previously published ATLAS measurements and new $Z \to \ell^+\ell^-$ measurement at 13 TeV.
- Correct for common phase space where required.
- Account for correlations of systematic uncertainties.
- Compare to predictions at NNLO(+NNLL) accuracy (DYNNLO 1.5 and Top++v2.0) made with six different PDF sets.



$\sigma^{\text{tot}}(t\bar{t}\,)\;/\;\sigma^{\text{fid}}(Z)$: conclusions, trends

JHEP 1702 (2017) 117

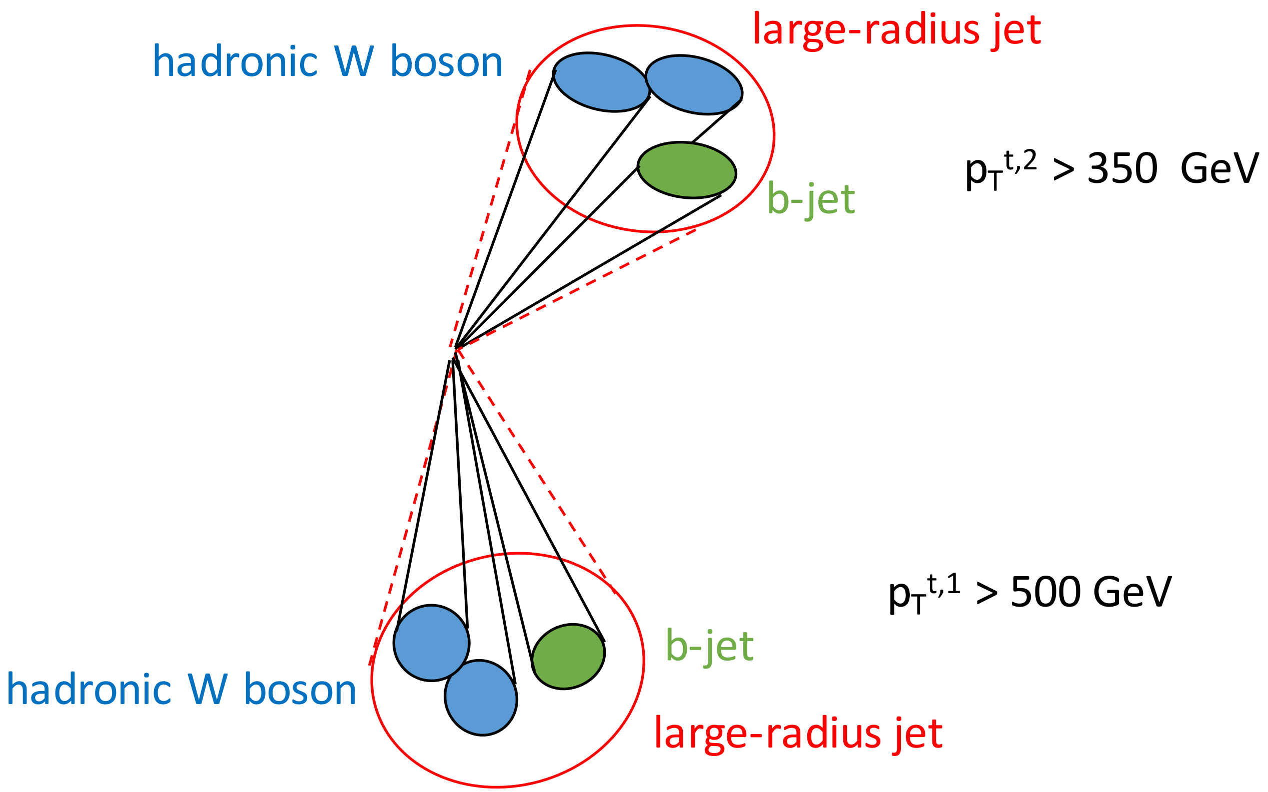
- Common pattern observed.
- ABM12 set yields lowest values.
- CT14, NNPDF3.0, MMHT14 largest values, ATLAS-epWZ12 and HERAPDF2.0 in the middle.
- Reason: differences in the gluon density and α_s values used in the sets.
- ABM12, ATLAS-epWZ12 and HERAPDF2.0 do not include collider data, ABM12 uses lower value of α_s



Boosted $t\bar{t}$ differential cross-section

ATLAS-CONF-2016-100

- All-hadronic channel with boosted top-quarks.
- Use 14.7 fb^{-1} of 2015 and 2016 data at $\sqrt{s}$ = 13 TeV.
- Form top-quark candidates with large-radius jets (DR = 1.0) using Top-Tagging algorithm.



Boosted $t\bar{t}$ differential cross-section

- Use 12 observables of top-quarks and the $t\bar{t}$ system.
- Most important uncertainties:
  large-R jet calibration and reconstruction, $t\bar{t}$ MC modelling, b-tagging

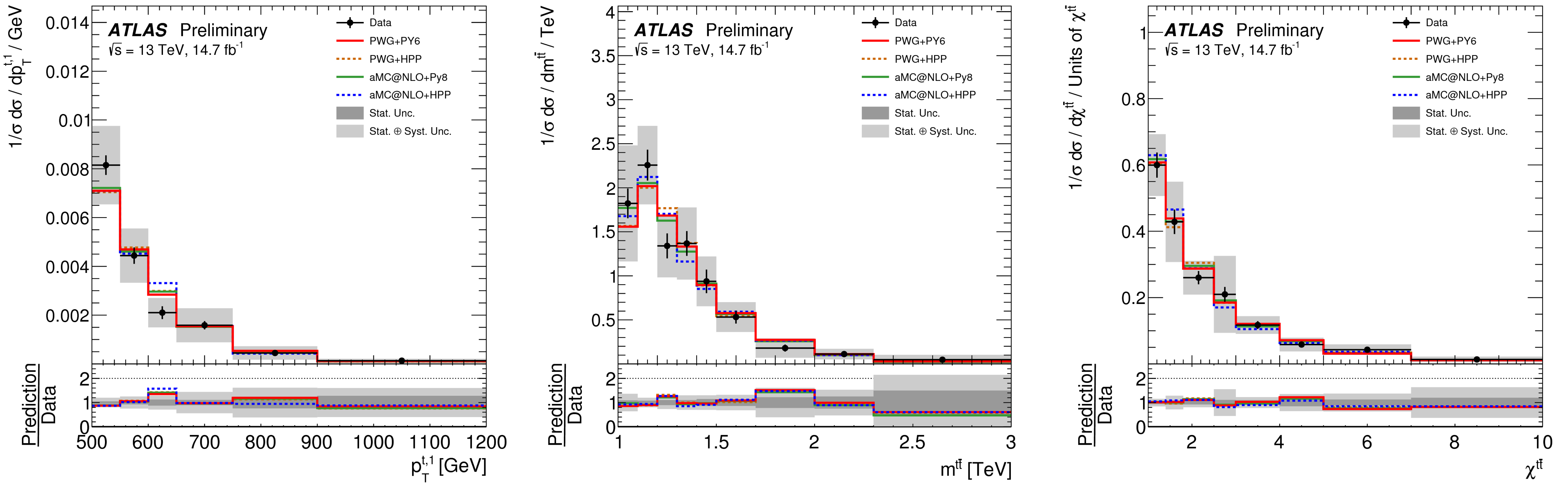
ATLAS-CONF-2016-100

production angle

$\chi(t\bar{t}) = \exp(2|y^*|)$

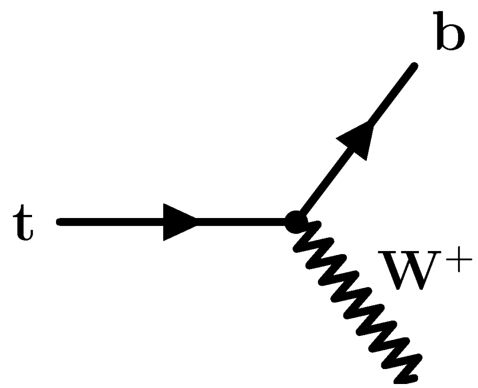
with $y^* = ½ (y^{t,1} - y^{t,2})$

$p_T^{t,1}$ $m(t\bar{t})$



Part 2: Spin-related observables

Top-quark decay



- Large decay width due to large mass: $\Gamma \propto m_t^3$
- Life time ≪ formation time of hadrons, spin de-correlation time
- Polarisation and spin correlations in production are transferred to decay products.
- Source of on-shell polarised *W* bosons.

Top-quark spin observables in $t\bar{t}$ production

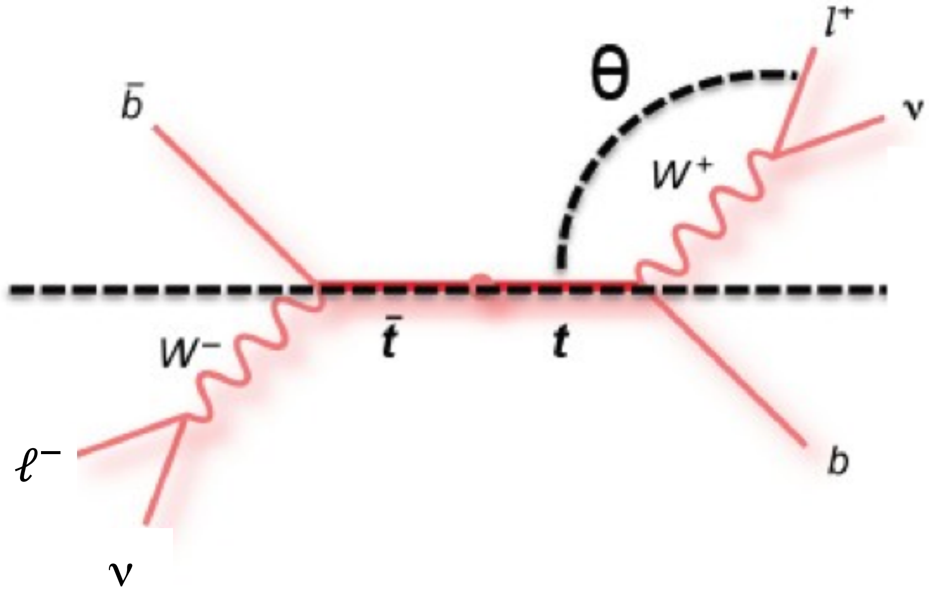
- Use $t\bar{t}$ di-lepton events (ee, eμ, μμ)
- Aim: determine coefficients of spin density matrix
- Measure 15 polarisation and spin correlation observables (follow Bernreuther, Heisler, Si, JHEP 12 (2015) 026)

arXiv:1612.07004 [hep-ex]

- Use 3 orthogonal spin quantisation axes:
  - helicity axis $\vec{k}$: top-quark direction in the $t\bar{t}$ rest frame
  - transverse axis $\vec{n}$: ⊥ production plane
  - r-axis $\vec{r}$: ⊥ $\vec{k}$ and ⊥ $\vec{n}$
- Define 6 angles: 3 axes × 2 charged leptons

θ_+^k θ_+^n θ_+^r

θ_-^k θ_-^n θ_-^r



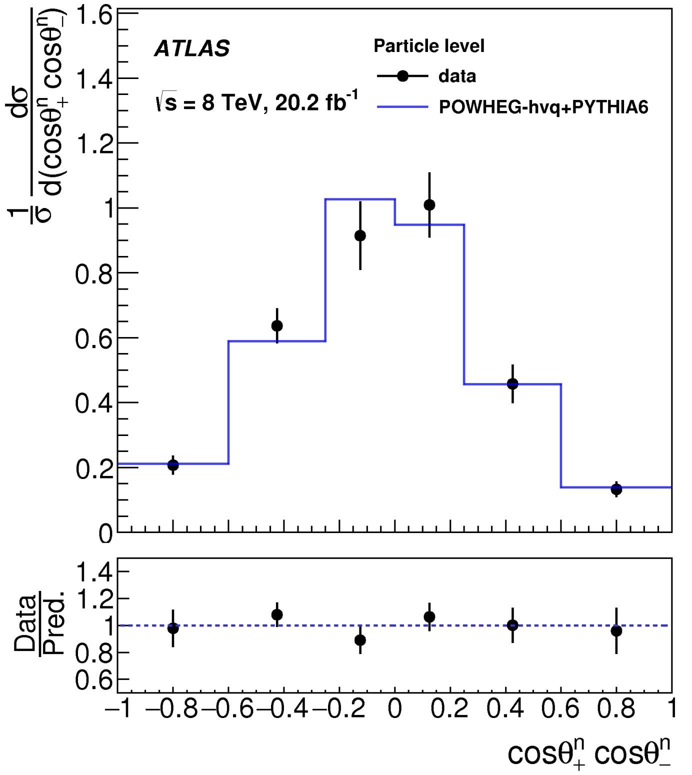
Polarisation and spin correlation coefficients

arXiv:1612.07004 [hep-ex]

- Unfold distributions of
  - Polarisation observables: $\cos\theta^k_+$, $\cos\theta^k_-$, $\cos\theta^n_+$, …
    → 6 distributions
  - Spin correlation observables: $\cos\theta^k_+ \cdot \cos\theta^k_-$, $\cos\theta^n_+ \cdot \cos\theta^n_-$, …
    → 3 distributions
  - Cross correlations observables:
    $\cos\theta^n_+ \cdot \cos\theta^k_- + \cos\theta^k_+ \cdot \cos\theta^n_-$,
    $\cos\theta^n_+ \cdot \cos\theta^k_- - \cos\theta^k_+ \cdot \cos\theta^n_-$, …
    → 6 distributions
- Relate mean values of observables to polarisation and spin correlation coefficients:

  $B^k_+ = 3 < \cos\theta^k_+ >$, …

  $C(k, n) = 9 < \cos\theta^k_+ \cdot \cos\theta^n_- >$, …



Measured polarisations and spin correlations

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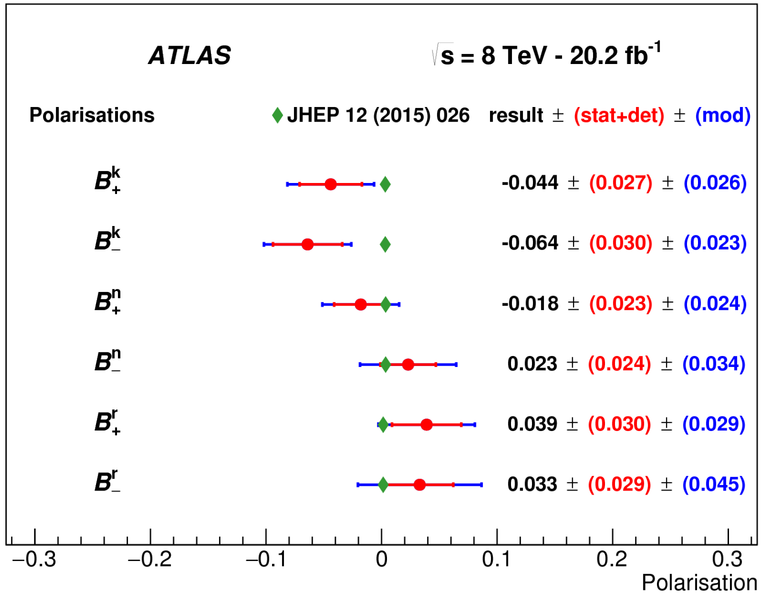
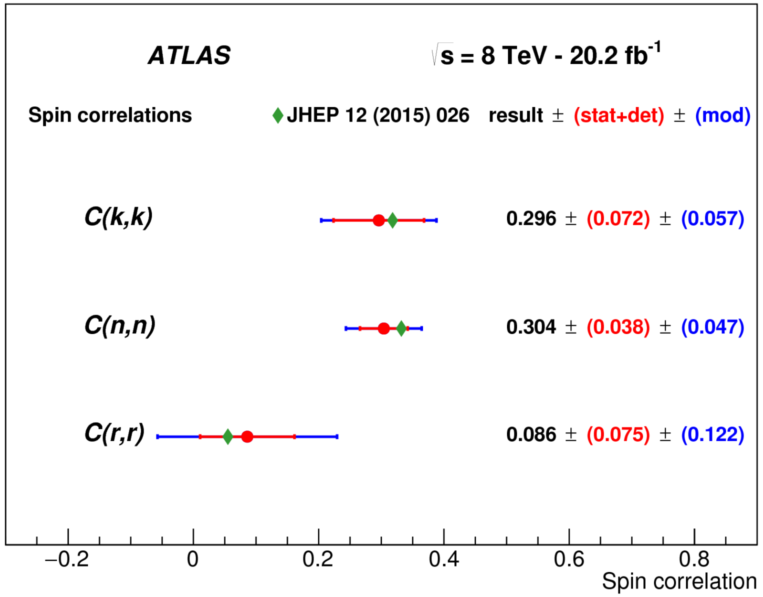
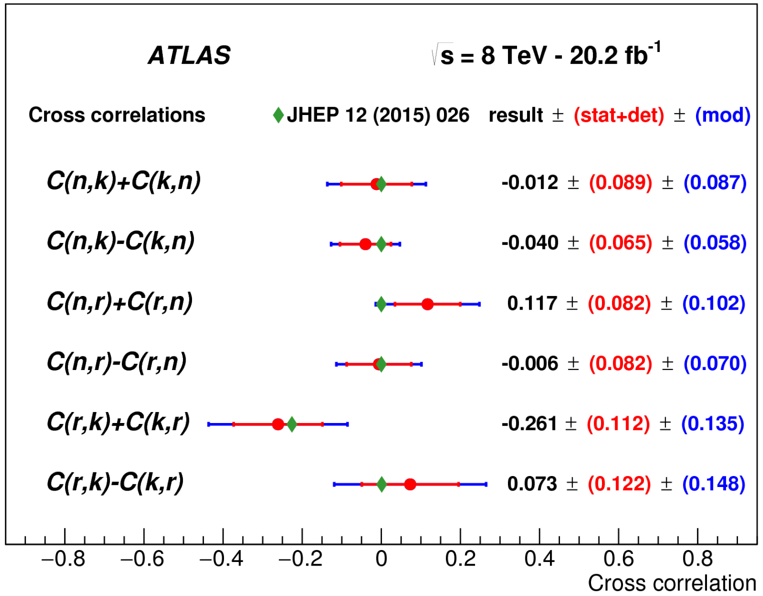
Polarisations



Spin correlations



Cross correlations

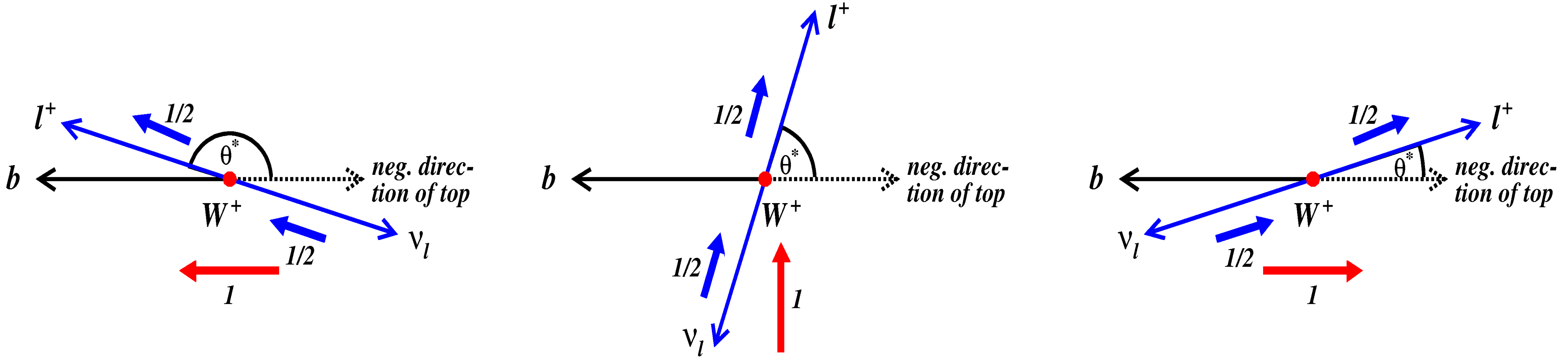


- Measurements at parton-level (and particle-level, not shown)
- Use Bayesian unfolding with marginalisation of systematic uncertainties
- Good agreement to SM.
- Spin polarisation along transverse axis C(n,n) differs from zero by 5.1 standard deviations.

arXiv:1612.07004 [hep-ex]

Measurement of the *W* polarisation in top-quark decays

- W bosons from top-quark decays are polarised due to the V-A structure of the *Wtb* vertex.
- The angle θ^* between the spin analyser (charged lepton or down-type quark) and the reversed direction of flight of the b-quark from the top-quark decay in the W-boson rest frame.



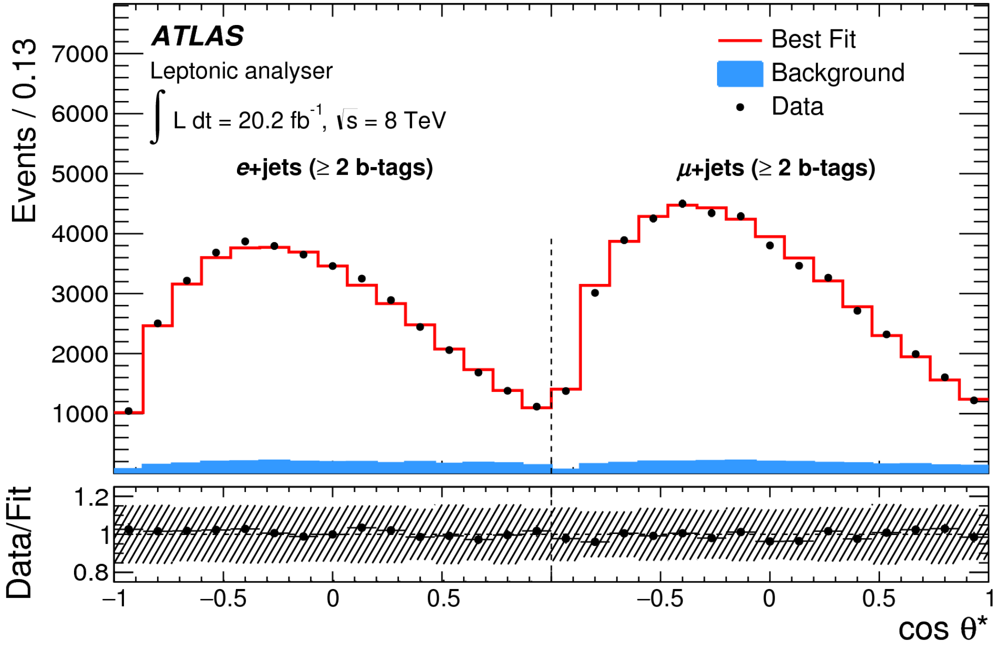
$$\frac{dN(h_W=-1)}{d\cos\theta^*} \propto \frac{3}{8}(1-\cos\theta^*)^2 \qquad \frac{dN(h_W=0)}{d\cos\theta^*} \propto \frac{3}{4}(1-\cos^2\theta^*) \qquad \frac{dN(h_W=+1)}{d\cos\theta^*} \propto \frac{3}{8}(1+\cos\theta^*)^2$$

SM prediction (NNLO) **F_L = 0.311 ± 0.005** **F_0 = 0.687 ± 0.005** **F_R = 0.0017 ± 0.0001**

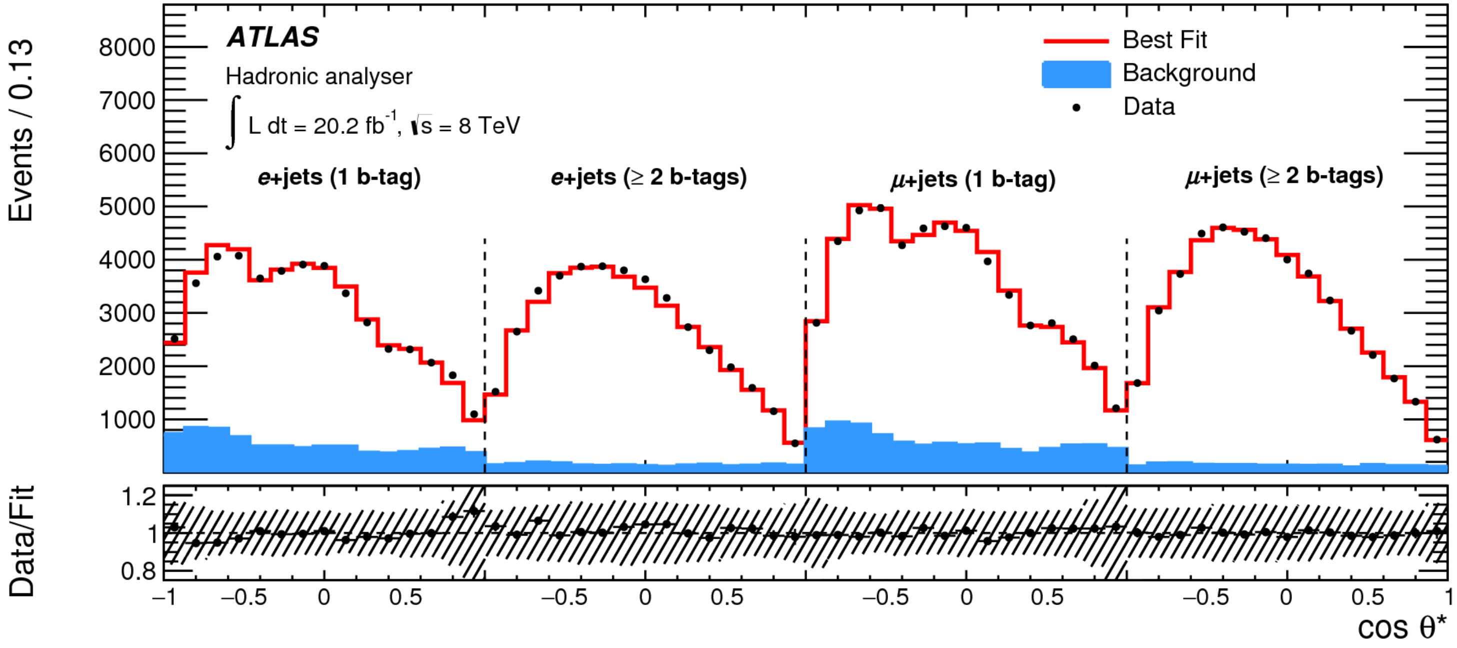
W-boson helicity fractions

Measured W-boson helicity fractions

Leptonic analyser



Hadronic analyser



Leptonic analyser (≥2 b-tags)
$F_0 = 0.709 \pm 0.012$ (stat.+bkg. norm.) $^{+0.015}_{-0.014}$ (syst.)
$F_L = 0.299 \pm 0.008$ (stat.+bkg. norm.) $^{+0.013}_{-0.012}$ (syst.)
$F_R = -0.008 \pm 0.006$ (stat.+bkg. norm.) ± 0.012 (syst.)

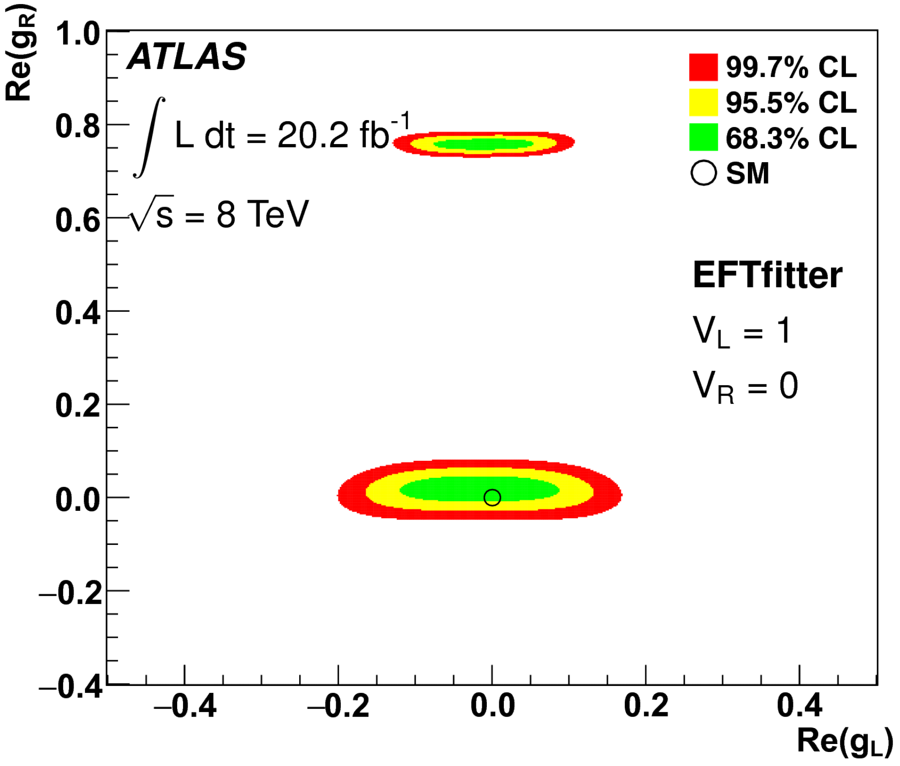
Hadronic analyser (1 b-tag + ≥2 b-tags)
$F_0 = 0.659 \pm 0.010$ (stat.+bkg. norm.) $^{+0.052}_{-0.054}$ (syst.)
$F_L = 0.281 \pm 0.021$ (stat.+bkg. norm.) $^{+0.063}_{-0.067}$ (syst.)
$F_R = 0.061 \pm 0.022$ (stat.+bkg. norm.) $^{+0.101}_{-0.108}$ (syst.)

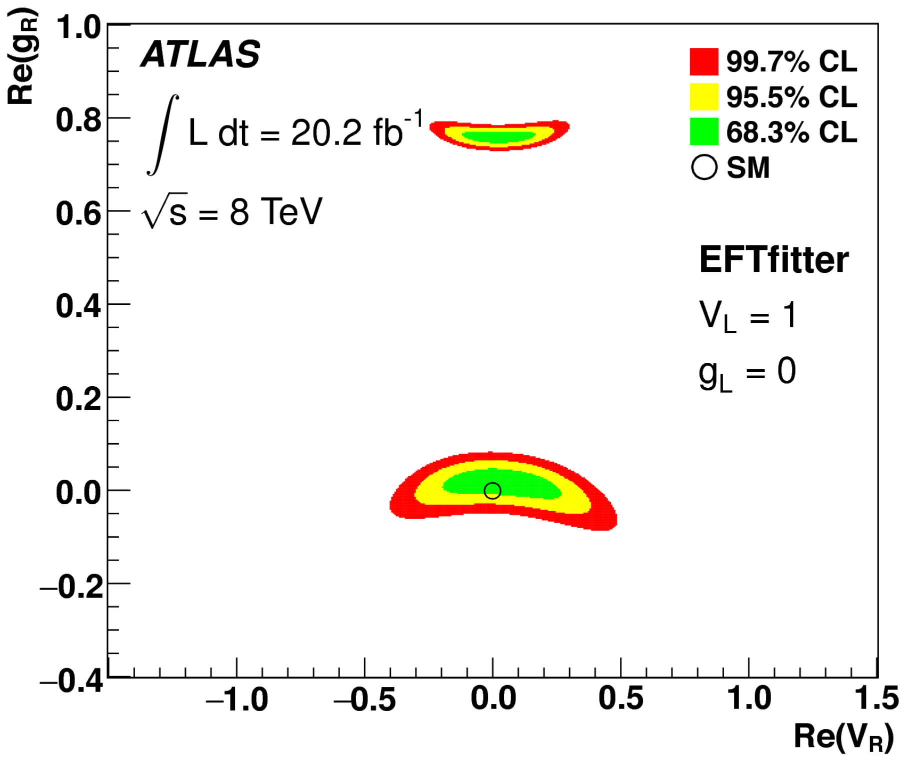
arXiv:1612.02577 [hep-ex]

Limits on anomalous couplings

Generalized *Wtb* Lagrangian:

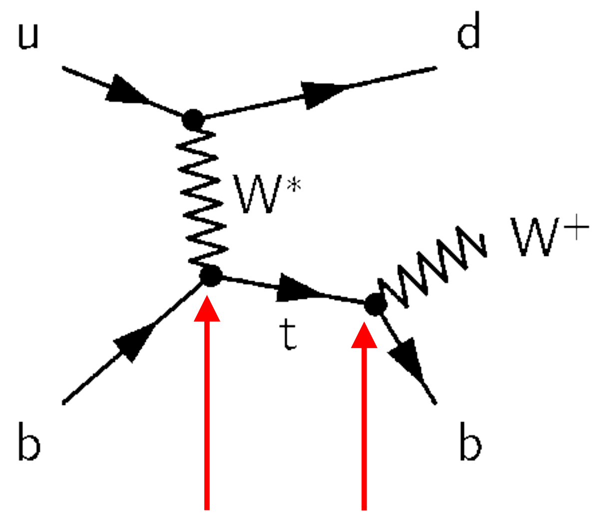
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}}\right)t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{W}}\left(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}}\right)t\,W_{\mu}^{-} + \mathrm{h.c.}$$



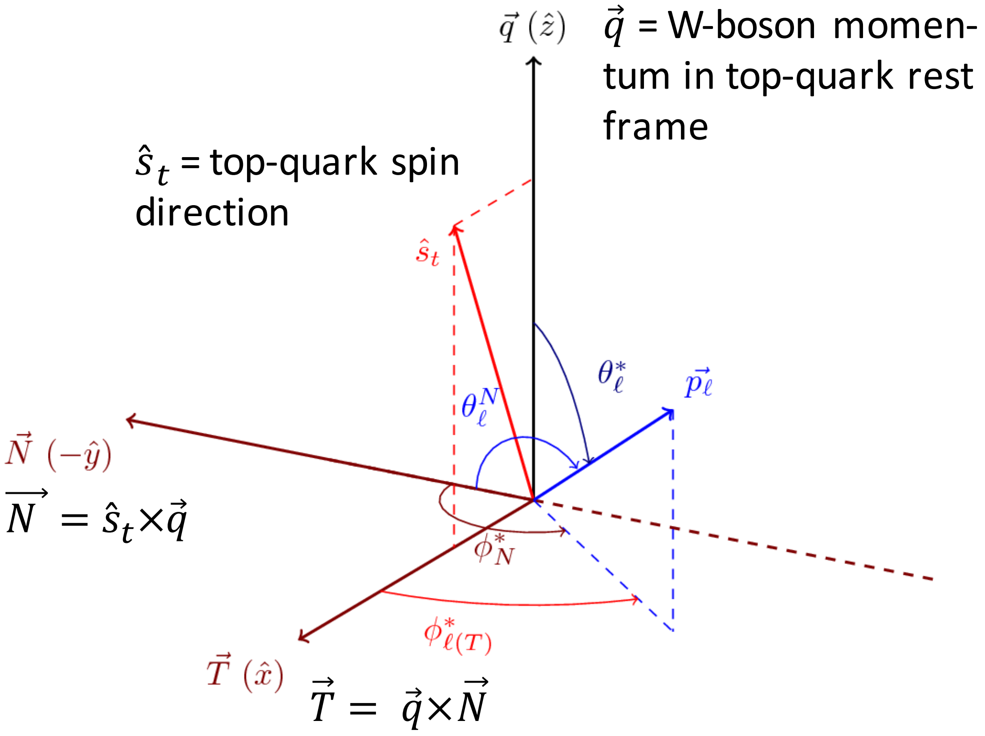


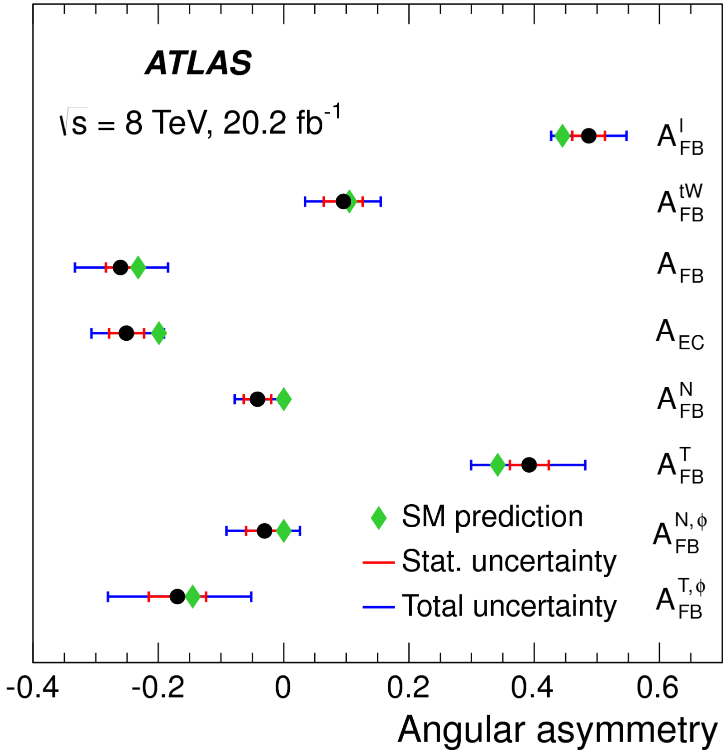
arXiv:1612.02577 [hep-ex]

Wtb vertex structure in production and decay



V – A structure in production and decay



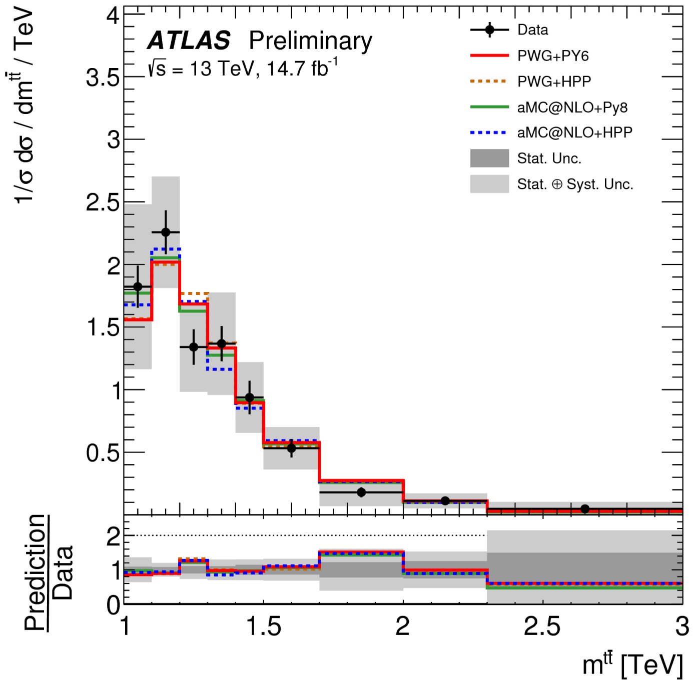


- Measure 8 asymmetries sensitive to polarisation effects in production and decay.
- Good agreement with SM predictions.

arXiv:1702.08309 [hep-ex]

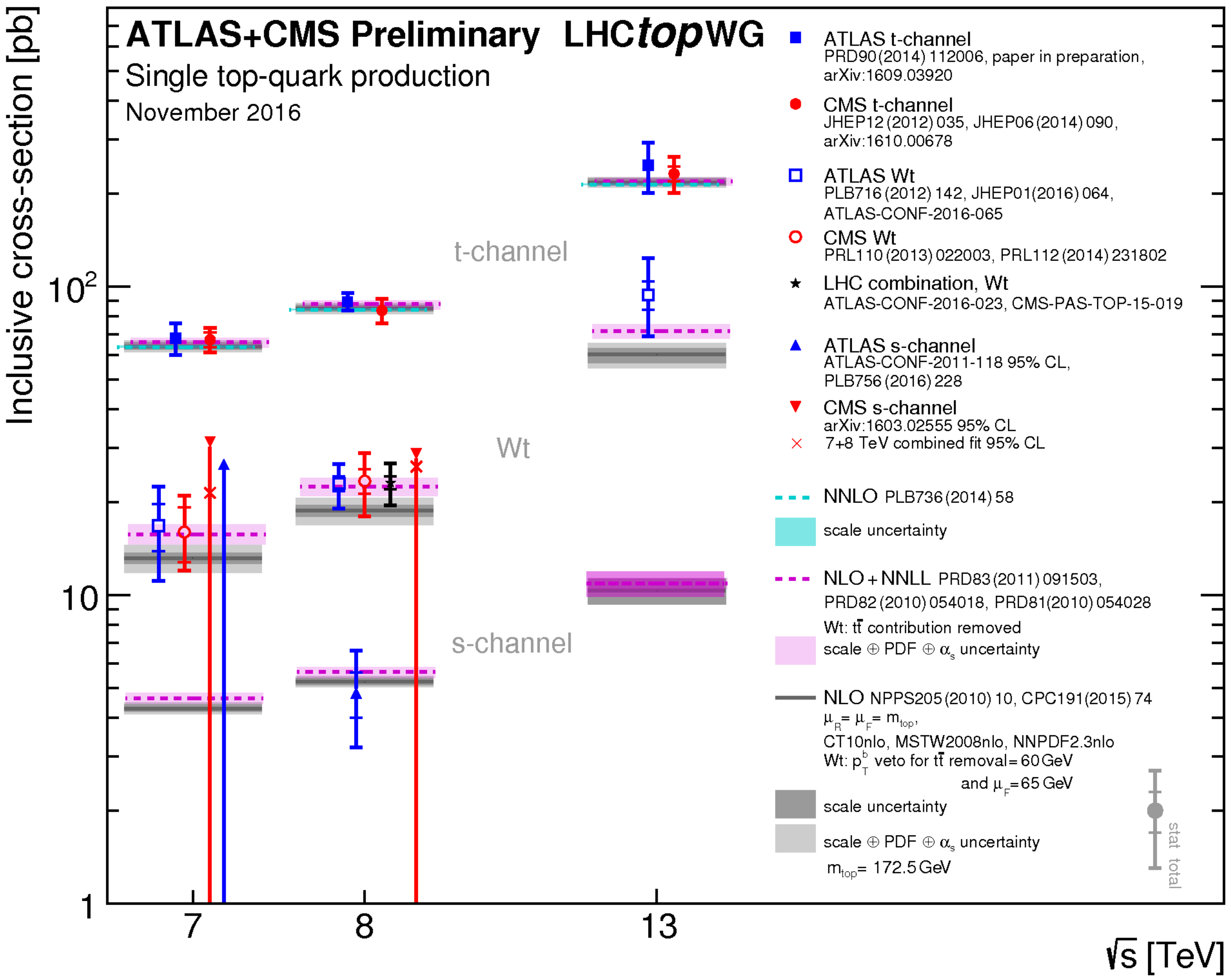
Conclusions

- Splendid performance of LHC ➜ large data sets of top-quark candidate events.
- Precision measurements: ratios, couplings, differential measurements; for example:
  - $f_{LV} \cdot |V_{tb}| = 1.029 \pm 0.048$
  - $R_t = 1.72 \pm 0.09$ @ 8 TeV (5 % precision)
  - $\sigma^{\text{tot}}(t\bar{t}) / \sigma^{\text{fid}}(Z) = 0.480 \pm 0.012$ @ 8 TeV (2.6 % precision)
  - $t\bar{t}$ spin correlation: C(n,n) = 0.304 ± 0.060 (5.1 σ)
- Input for PDF fits, tuning of MC generators, limits on BSM modells
- New opportunities to explore phase space: boosted $t\bar{t}$ differential cross-section
- Looking forward to analyse full Run 2 data set with 100 fb^{-1}.
  - Use high statistics to improve systematic uncertainties (e.g. profiling)
  - Use new PS generators (HERWIG7 and PYTHIA8) for more consistent treatment of modelling uncertainties.
  - Intensive use of Effective Field Theory to investigate BSM physics (foe example: UFO models in MadGraph)



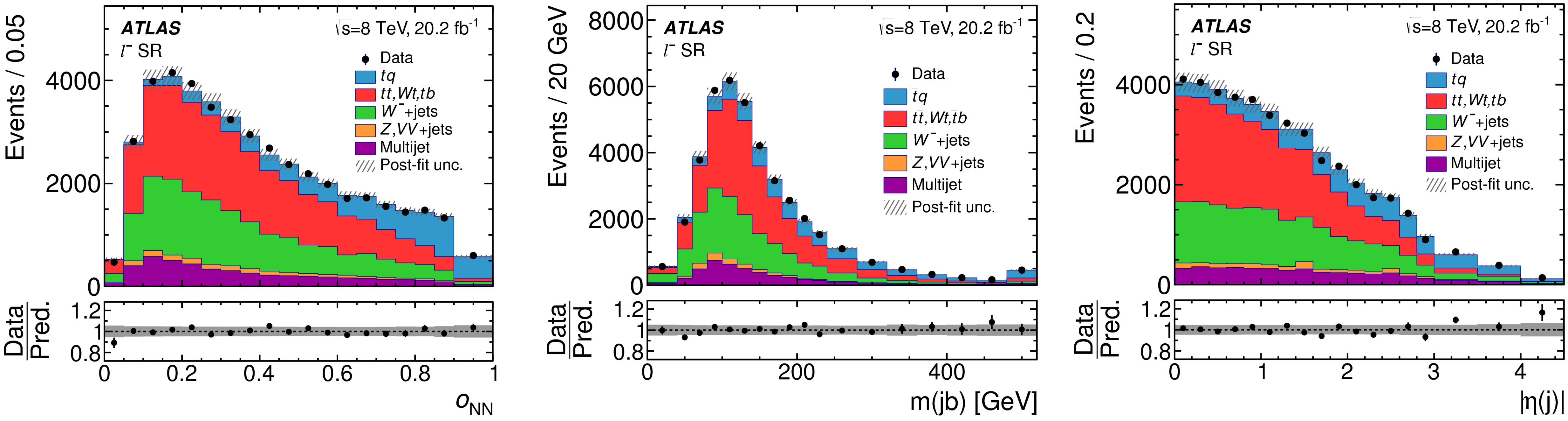
Backup slides

Single top-quark cross-sections



	7 TeV	8 TeV	13 TeV
$\sigma\,(tq + t\bar{q})$	65 pb	85 pb	217 pb
$\Delta\sigma\,/\,\sigma$	± 4 %	± 5 %	± 4 %

Single top-antiquark *t*-channel (post fit)



Uncertainties of the fiducial tq cross-sections

Source	$\Delta\sigma_{\text{fid}}(tq)$ / $\sigma_{\text{fid}}(tq)$ [%]	$\Delta\sigma_{\text{fid}}(\bar{t}q)$ / $\sigma_{\text{fid}}(\bar{t}q)$ [%]
Data statistics	$\pm$ 1.7	$\pm$ 2.5
Monte Carlo statistics	$\pm$ 1.0	$\pm$ 1.4
Background normalisation	$<$ 0.5	$<$ 0.5
Background modelling	$\pm$ 1.0	$\pm$ 1.6
Lepton reconstruction	$\pm$ 2.1	$\pm$ 2.5
Jet reconstruction	$\pm$ 1.2	$\pm$ 1.5
Jet energy scale	$\pm$ 3.1	$\pm$ 3.6
Flavour tagging	$\pm$ 1.5	$\pm$ 1.8
$E_{\text{T}}^{\text{miss}}$ modelling	$\pm$ 1.1	$\pm$ 1.6
$b/\bar{b}$ tagging efficiency	$\pm$ 0.9	$\pm$ 0.9
PDF	$\pm$ 1.3	$\pm$ 2.2
tq ($\bar{t}q$) NLO matching	$\pm$ 0.5	$<$ 0.5
tq ($\bar{t}q$) parton shower	$\pm$ 1.1	$\pm$ 0.8
tq ($\bar{t}q$) scale variations	$\pm$ 2.0	$\pm$ 1.7
$t\bar{t}$ NLO matching	$\pm$ 2.1	$\pm$ 4.3
$t\bar{t}$ parton shower	$\pm$ 0.8	$\pm$ 2.5
$t\bar{t}$ scale variations	$<$ 0.5	$<$ 0.5
Luminosity	$\pm$ 1.9	$\pm$ 1.9
Total systematic	$\pm$ 5.6	$\pm$ 7.3
Total (stat. + syst.)	$\pm$ 5.8	$\pm$ 7.8

Uncertainties of the R_t measurement

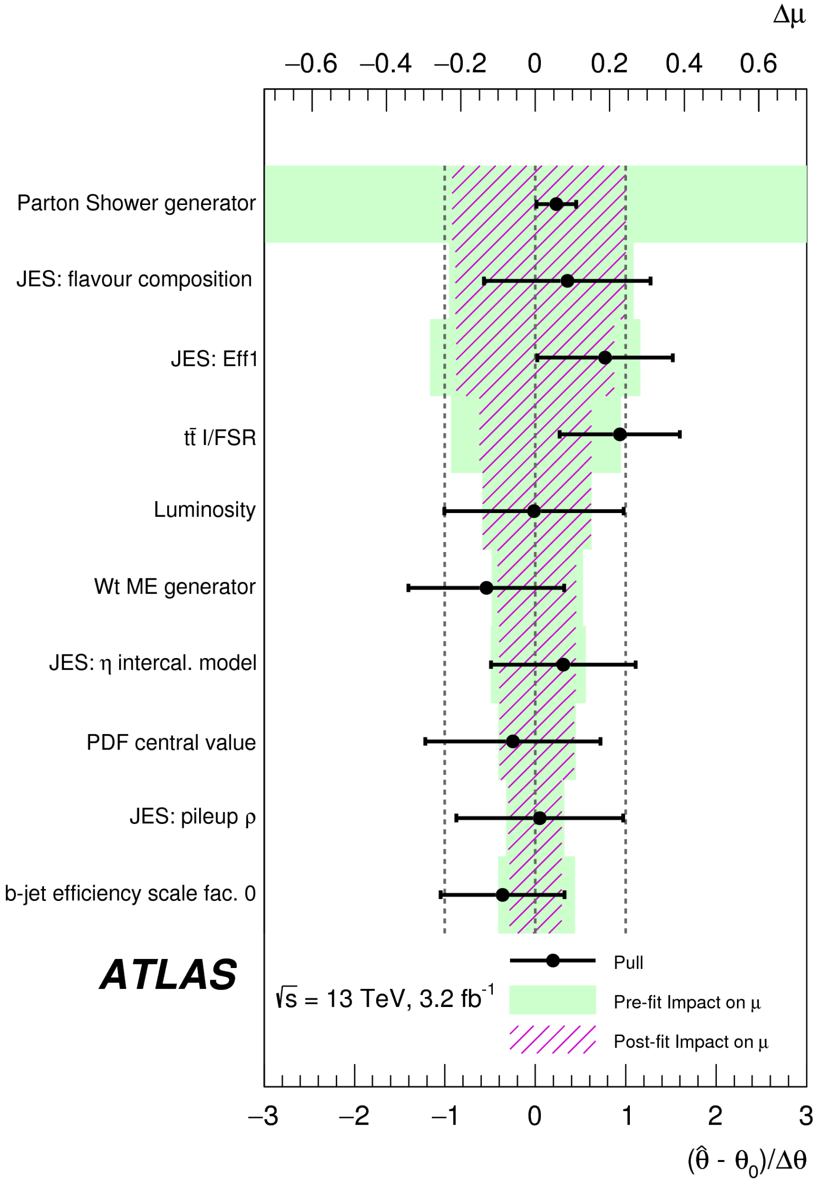
Source	$\Delta R_t / R_t$ [%]
Data statistics	± 3.0
Monte Carlo statistics	± 1.8
Background modelling	± 0.7
Jet reconstruction	± 0.5
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	± 0.6
tq ($\bar{t}q$) NLO matching	± 0.5
tq ($\bar{t}q$) scale variations	± 0.7
$t\bar{t}$ NLO matching	± 2.3
$t\bar{t}$ parton shower	± 1.7
PDF	± 0.7
Total systematic	± 3.9
Total (stat. + syst.)	± 5.0

tW event selection

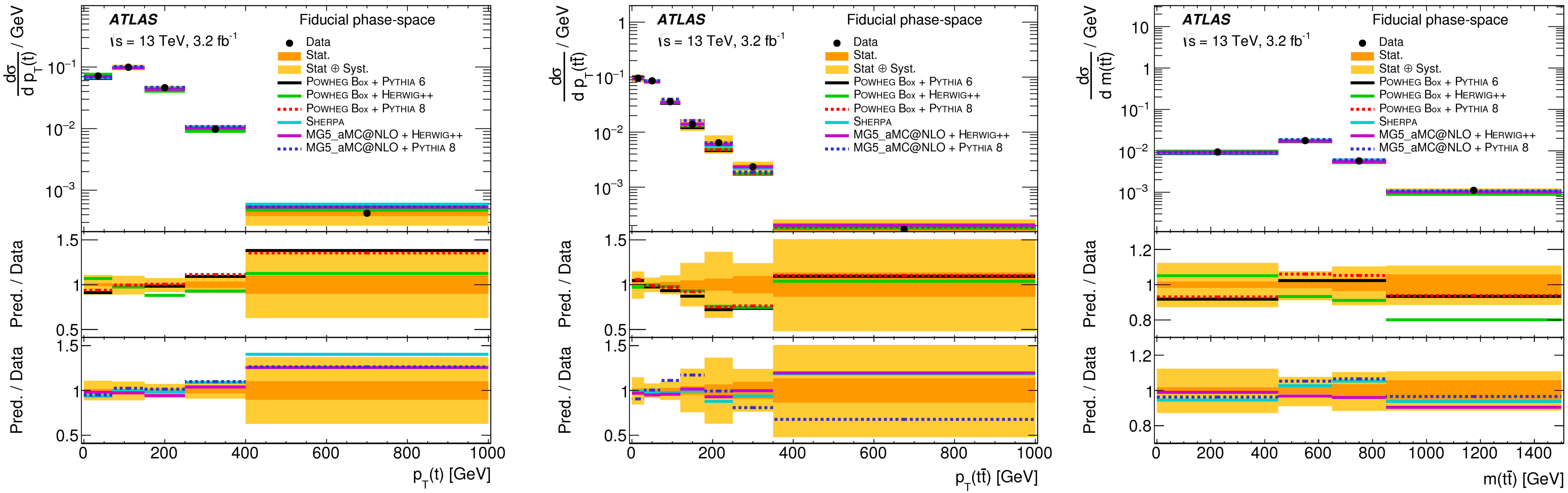
At least one jet with $p_T > 25\,\text{GeV}$, $\lvert\eta\rvert < 2.5$		
Exactly two leptons of opposite charge with $p_T > 20\,\text{GeV}$,		
$\lvert\eta\rvert < 2.5$ for muons and $\lvert\eta\rvert < 2.47$ excluding $1.37 < \lvert\eta\rvert < 1.52$ for electrons		
At least one lepton with $p_T > 25\,\text{GeV}$, veto if third lepton with $p_T > 20\,\text{GeV}$		
At least one lepton matched to the trigger object		
Different flavour	$E_T^{miss} > 50\,\text{GeV}$,	if $m_{\ell\ell} < 80\,\text{GeV}$
	$E_T^{miss} > 20\,\text{GeV}$,	if $m_{\ell\ell} > 80\,\text{GeV}$
Same flavour	$E_T^{miss} > 40\,\text{GeV}$,	always
	veto,	if $m_{\ell\ell} < 40\,\text{GeV}$
	$4E_T^{miss} > 5m_{\ell\ell}$,	if $40\,\text{GeV} < m_{\ell\ell} < 81\,\text{GeV}$
	veto,	if $81\,\text{GeV} < m_{\ell\ell} < 101\,\text{GeV}$
	$2m_{\ell\ell} + E_T^{miss} > 300\,\text{GeV}$,	if $m_{\ell\ell} > 101\,\text{GeV}$

tW cross-section uncertainties

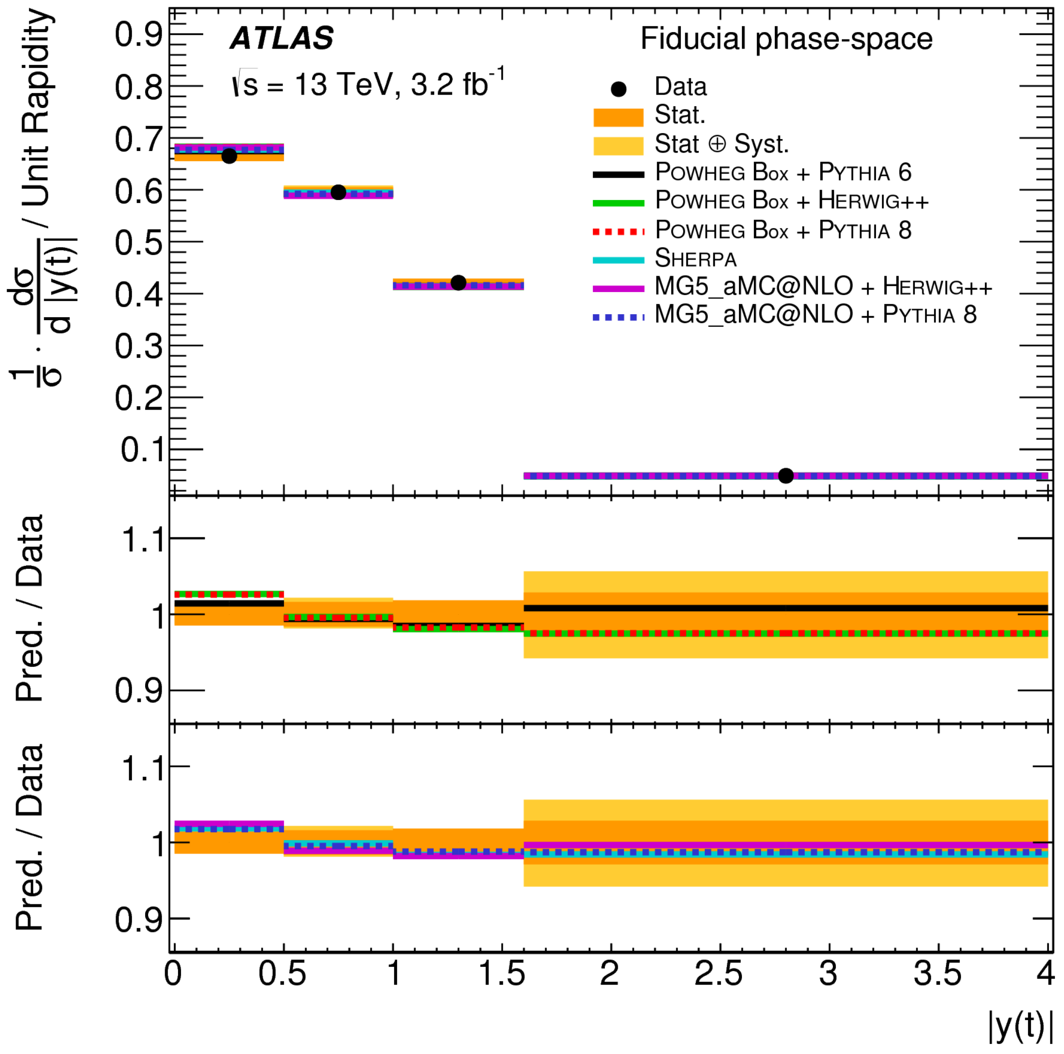
Source	$\Delta\sigma_{Wt}/\sigma_{Wt}[\%]$
Jet energy scale	21
Jet energy resolution	8.6
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft terms	5.3
b-tagging	4.3
Luminosity	2.3
Lepton efficiency, energy scale and resolution	1.3
NLO matrix element generator	18
Parton shower and hadronisation	7.1
Initial-/final-state 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

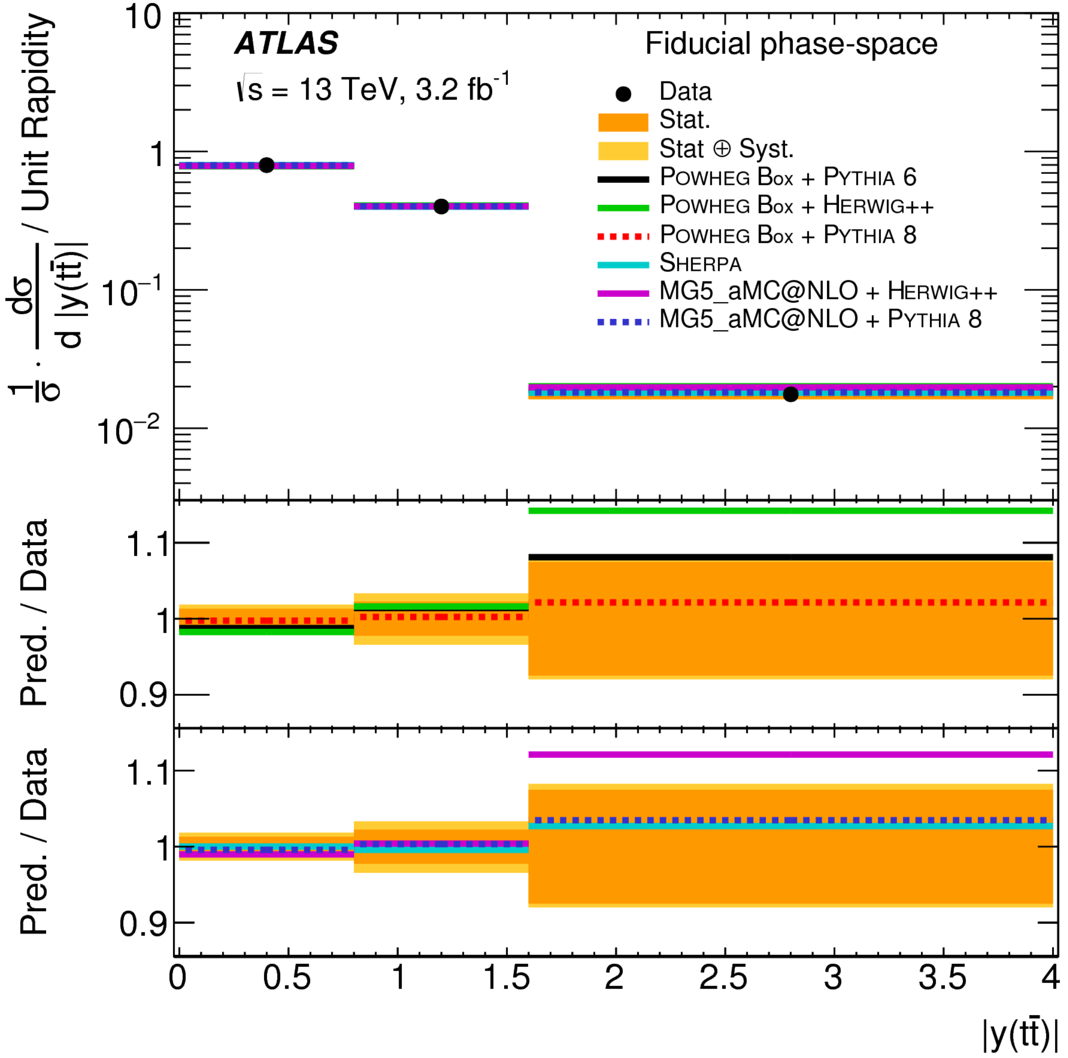


Differential $t\bar{t}$ cross-sections (absolute)



Differential $t\bar{t}$ cross-sections: rapidity distributions



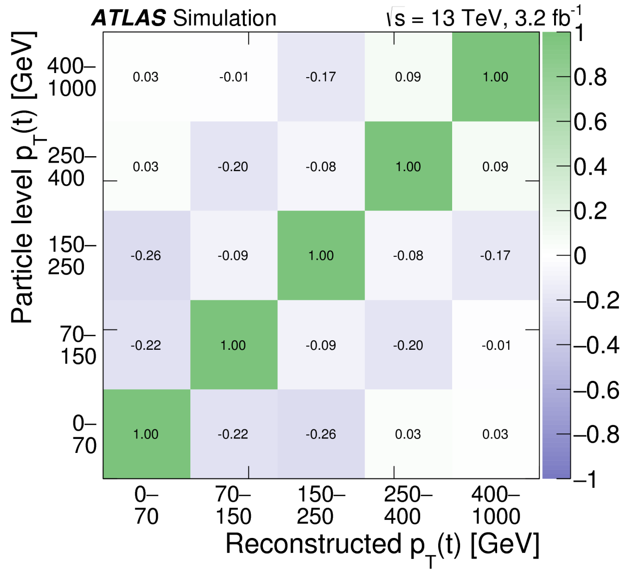


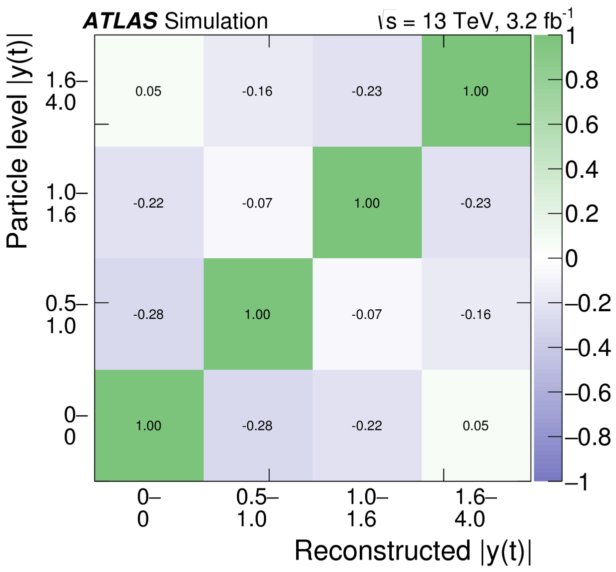
Significance of disagreements

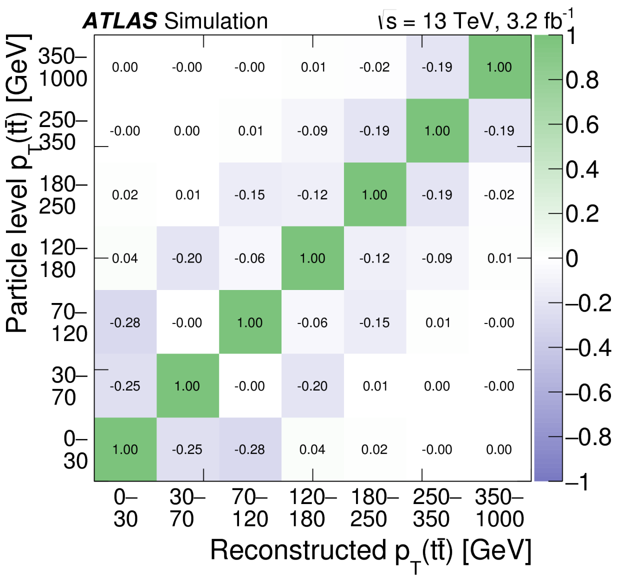
Predictions	$p_T(t)$ χ^2/NDF	$p_T(t)$ p-value	$\|y(t)\|$ χ^2/NDF	$\|y(t)\|$ p-value	$p_T(t\bar{t})$ χ^2/NDF	$p_T(t\bar{t})$ p-value	$\|y(t\bar{t})\|$ χ^2/NDF	$\|y(t\bar{t})\|$ p-value	$m(t\bar{t})$ χ^2/NDF	$m(t\bar{t})$ p-value
Powheg + Pythia 6	5.2/4	0.27	0.5/3	0.92	5.5/6	0.48	0.6/2	0.74	3.9/4	0.42
Powheg + Pythia 8	4.6/4	0.33	1.3/3	0.73	5.1/6	0.53	0.0/2	1.00	5.7/4	0.22
Powheg + Herwig++	14.6/4	0.01	1.4/3	0.71	4.1/6	0.66	1.0/2	0.61	12.0/4	0.02
MG5_aMC@NLO + Herwig++	2.0/4	0.74	1.3/3	0.73	0.6/6	1.00	0.2/2	0.90	0.9/4	0.92
MG5_aMC@NLO + Pythia 8	3.6/4	0.46	0.6/3	0.90	10.7/6	0.10	0.1/2	0.95	2.7/4	0.61
Sherpa	3.8/4	0.43	0.8/3	0.85	0.7/6	0.99	0.0/2	1.00	2.3/4	0.68
Powheg + Pythia 6 (radHi)	7.8/4	0.10	0.6/3	0.90	0.9/6	0.99	0.4/2	0.82	3.8/4	0.43
Powheg + Pythia 6 (radLow)	5.5/4	0.24	0.8/3	0.85	9.6/6	0.14	0.8/2	0.67	4.5/4	0.34

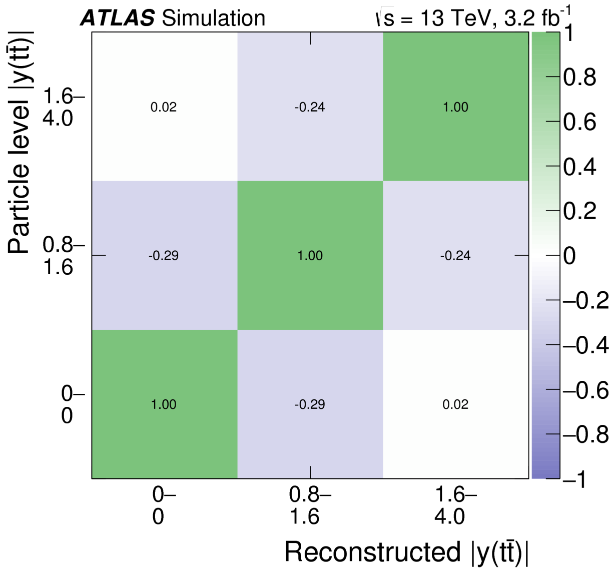
Overall there is good agreement between the distributions predicted by MC generators and data, except for Powheg+HERWIG++ (low p-value).

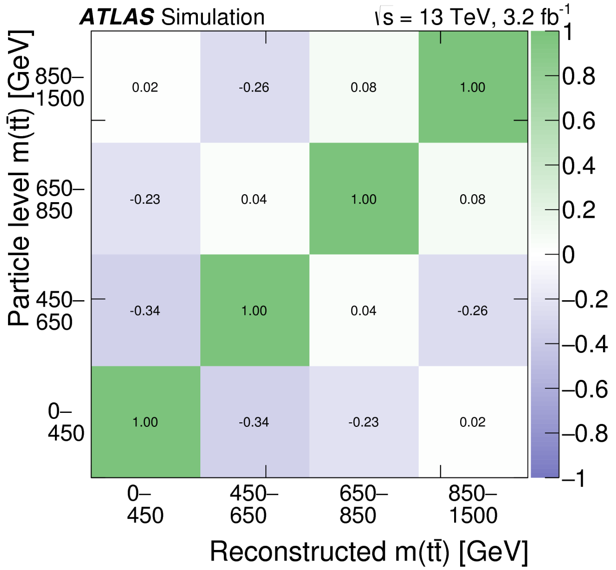
Statistical correlation matrices











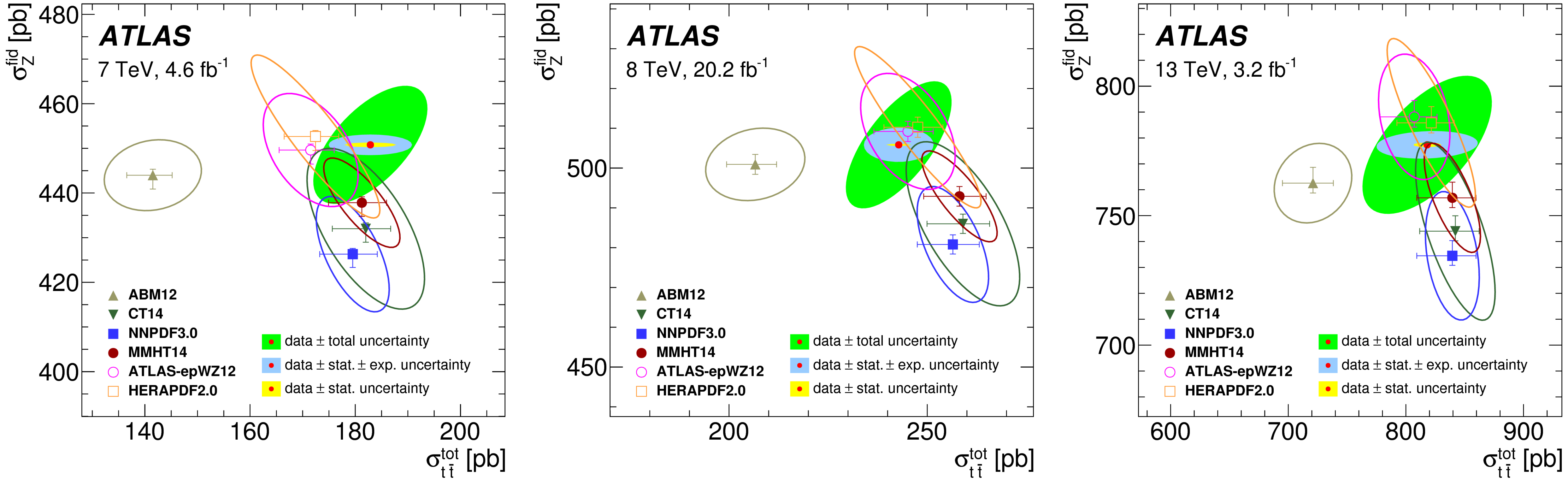
$\sigma(t\bar{t}\,)$ / $\sigma\,(Z)$: primary inputs

$\sqrt{s}$ [TeV]	$\sigma \pm$ stat $\pm$ syst [pb] 13	8	7
$\sigma^{\text{fid}}_{Z\to ee}$	$778.3 \pm 0.7 \pm 17.7$	$507.0 \pm 0.2 \pm 11.0$	$451.2 \pm 0.5 \pm 8.7$
$\sigma^{\text{fid}}_{Z\to \mu\mu}$	$774.4 \pm 0.6 \pm 18.2$	$504.7 \pm 0.2 \pm 10.8$	$450.0 \pm 0.3 \pm 8.8$
$\sigma^{\text{fid}}_{t\bar{t}\to e\mu+X}$	$9.94 \pm 0.09 \pm 0.37$	$3.04 \pm 0.02 \pm 0.10$	$2.30 \pm 0.04 \pm 0.08$
$\sigma^{\text{tot}}_{t\bar{t}}$	$818 \pm 8 \pm 35$	$243 \pm 2 \pm 9$	$183 \pm 3 \pm 6$

$\sigma(t\bar{t})$ / $\sigma(Z)$: correlation model

Source / $\sqrt{s}$ [TeV]	$\delta\,\sigma_Z^{\text{fid}}$ 13	8	7	$\delta\,\sigma_{t\bar{t}}^{\text{tot}}$ 13	8	7
Luminosity	A	B	C	A	B	C
Beam energy	A	A	A	A	A	A
Muon (lepton) trigger	A	A*	A	A	B	B
Muon reconstruction/ID	A	B	C	A	D	D
Muon isolation	A	A	A	B	C	D
Muon momentum scale	A	A	A	A	A	A
Electron trigger	A	A	A	A	—	—
Electron reconstruction/ID	A	B	C	A	D	D
Electron isolation	A	A	—	B	C	D
Electron energy scale	A	A	A	A	A	A
Jet energy scale	—	—	—	A	B	B
b-tagging	—	—	—	A	B	B
Background	A	A	A	B	B	B
Signal modelling (incl. PDF)	A	A	A	B*	B	B

2D analysis: $\sigma^{\mathrm{tot}}(t\bar{t})$ versus $\sigma^{\mathrm{fid}}(Z)$



Quantitative analysis of agreement between measurements and predictions with different PDF sets:

	ATLAS-epWZ12	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12
χ^2/NDF	8.3 / 6	15 / 6	13 / 6	17 / 6	10 / 6	25 / 6
p-value	0.22	0.02	0.05	0.01	0.11	< 0.001

Boosted $t\bar{t}$ differential cross-section

Differential cross-sections in:

- $p_T^{t,1}$, $p_T^{t,2}$, $|y^{t,1}|$, $|y^{t,2}|$, $p_T(t\bar{t})$,
- $|y(t\bar{t})|$, $m(t\bar{t})$, $H_T(t\bar{t})$
- $\cos\theta^*$ (production angle in the Collins-Soper frame)
- $y_B(t\bar{t}) = ½ (y^{t,1} + y^{t,2})$ (longitudinal boost)
- $\Delta\phi(t_1, t_2)$
- $\chi(t\bar{t}) = \exp 2|y^*|$ with $y^* = ½ (y^{t,1} - y^{t,2})$ production angle

Large-R jet reconstruction

- $|\eta| < 2.0$
- Trimming algorithm with $R_{sub} = 0.2$ and $f_{cut} = 0.05$ to suppress QCD radiation and pile-up effects
- Top-tagging mass requirement: 122.5 GeV $< m_J <$ 222.5 GeV
- Use N-subjetiness ratio τ_{32} requirement, p_T dependent
- Top-tagging efficiency is 50 % constant in p_T

Predicted polarisations and spin correlations

Expectation values	NLO predictions	Observables
B^k_+	0.0030 ± 0.0010	$\cos\theta^k_+$
B^k_-	0.0034 ± 0.0010	$\cos\theta^k_-$
B^n_+	0.0035 ± 0.0004	$\cos\theta^n_+$
B^n_-	0.0035 ± 0.0004	$\cos\theta^n_-$
B^r_+	0.0013 ± 0.0010	$\cos\theta^r_+$
B^r_-	0.0015 ± 0.0010	$\cos\theta^r_-$
$C(k,k)$	0.318 ± 0.003	$\cos\theta^k_+ \cos\theta^k_-$
$C(n,n)$	0.332 ± 0.002	$\cos\theta^n_+ \cos\theta^n_-$
$C(r,r)$	0.055 ± 0.009	$\cos\theta^r_+ \cos\theta^r_-$
$C(n,k) + C(k,n)$	0.0023	$\cos\theta^n_+ \cos\theta^k_- + \cos\theta^k_+ \cos\theta^n_-$
$C(n,k) - C(k,n)$	0	$\cos\theta^n_+ \cos\theta^k_- - \cos\theta^k_+ \cos\theta^n_-$
$C(n,r) + C(r,n)$	0.0010	$\cos\theta^n_+ \cos\theta^r_- + \cos\theta^r_+ \cos\theta^n_-$
$C(n,r) - C(r,n)$	0	$\cos\theta^n_+ \cos\theta^r_- - \cos\theta^r_+ \cos\theta^n_-$
$C(r,k) + C(k,r)$	-0.226 ± 0.004	$\cos\theta^r_+ \cos\theta^k_- + \cos\theta^k_+ \cos\theta^r_-$
$C(r,k) - C(k,r)$	0	$\cos\theta^r_+ \cos\theta^k_- - \cos\theta^k_+ \cos\theta^r_-$

Angular asymmetries in single top-quark production

Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P\,(F_{\mathrm{R}}+F_{\mathrm{L}})$	0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}\,(F_{\mathrm{R}}-F_{\mathrm{L}})$	−0.23
A_{EC}	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}\,(1-3F_0)$	−0.20
A_{FB}^{T}	$\cos\theta_\ell^T$	$\frac{3}{4}\langle S_1\rangle$	0.34
A_{FB}^{N}	$\cos\theta_\ell^N$	$-\frac{3}{4}\langle S_2\rangle$	0
$A_{\mathrm{FB}}^{T,\phi}$	$\cos\theta_\ell^* \cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	−0.14
$A_{\mathrm{FB}}^{N,\phi}$	$\cos\theta_\ell^* \cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0