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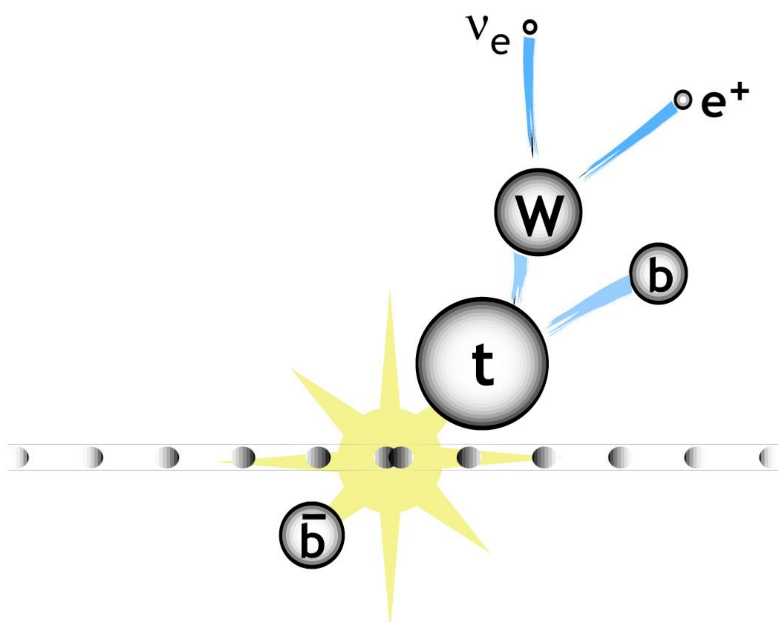
ATLAS

Comprehensive measurements of t-channel single top-quark production cross-sections at $\sqrt{s}$ = 7 TeV with the ATLAS detector



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November 25, 2014

1) Motivation
2) Theoretical predictions
3) Event selection and analysis strategy
4) Measurement results

   to be published in Phys. Rev. D
   arXiv:1406.7844

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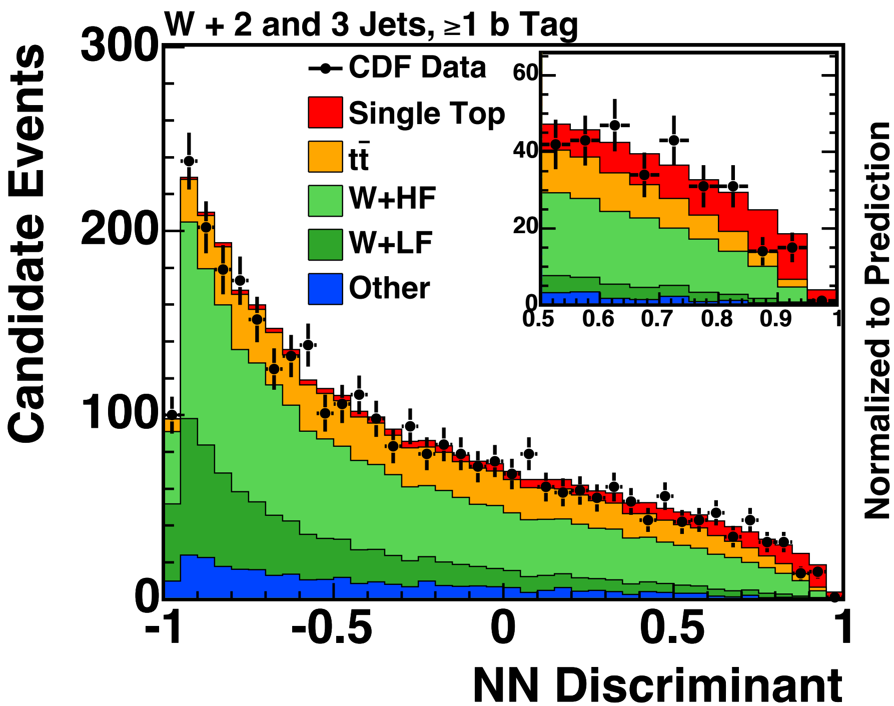
PHYSICS AT THE TERA SCALE
Helmholtz Alliance

FSP 101 ATLAS

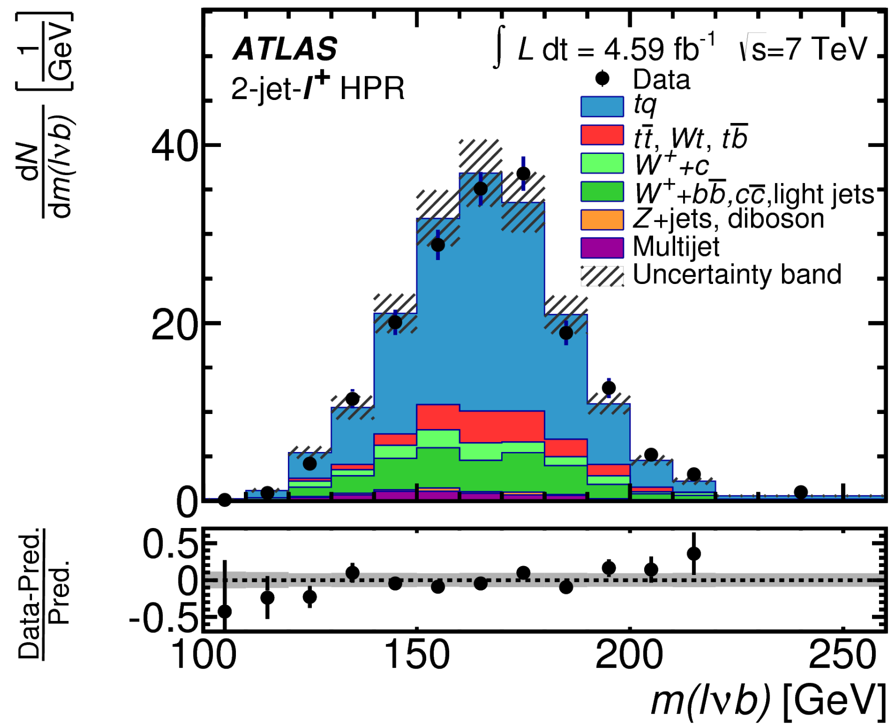
A new era in (single) top-quark physics

Single Top-Quark Discovery Tevatron 2009



number of signal events: ≈ 200

High purity region in the 7 TeV ATLAS data set



number of signal events:

- 3,900 in total
- 1,800 in the high-purity region

Large sets of single top-quark candidate events offer new possibilities: precision measurements, differential cross-sections, properties

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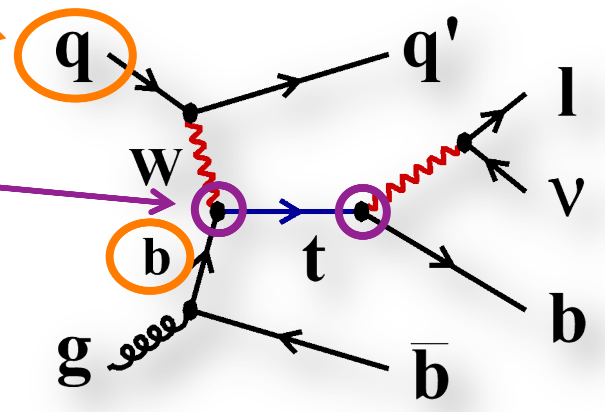
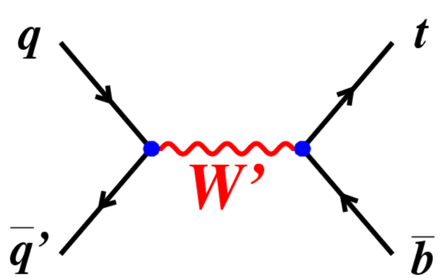
Motivation for single-top measurements

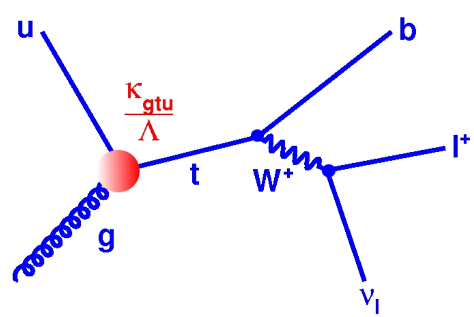
parton distribution functions:
u-quark, *d*-quark, *b*-quark

weak coupling
- V_{tb}
- Lorentz structure



search for new processes (not covered):





Observables

- total cross-sections

$$\sigma(tq) \qquad \sigma(\bar{t}q)$$

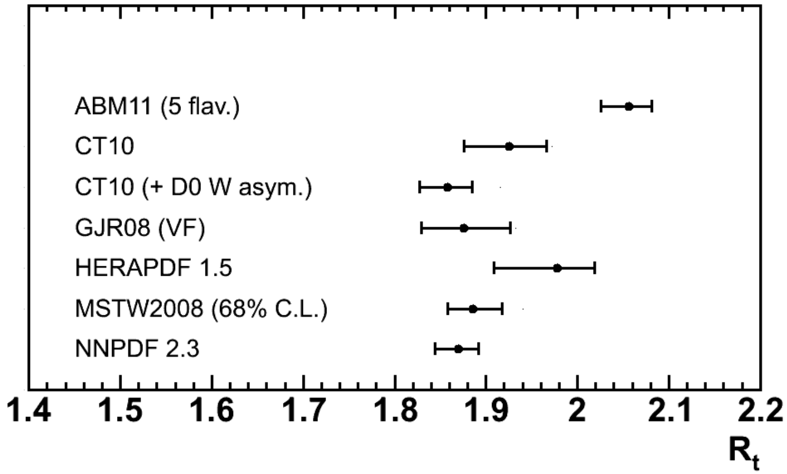
- cross-section ratio

$$R_t = \frac{\sigma(tq)}{\sigma(\bar{t}q)}$$

- differential cross-sections

$$\frac{d\sigma(tq)}{dp_{\mathrm{T}}(t)} \qquad \frac{d\sigma(tq)}{d|y(t)|}$$

Theory predictions on R_t



Calculation done with MCFM 6.5 and Hathor

$$R_t = \frac{\sigma(tq)}{\sigma(\bar{t}q)}$$

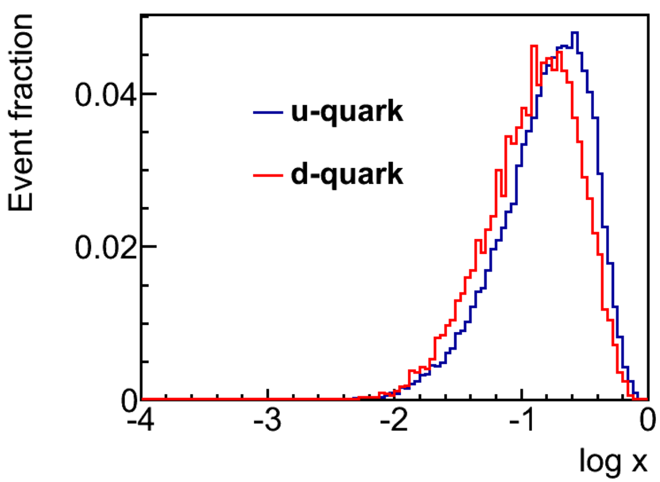
shows *significant* differences between different PDF sets

Uncertainties:

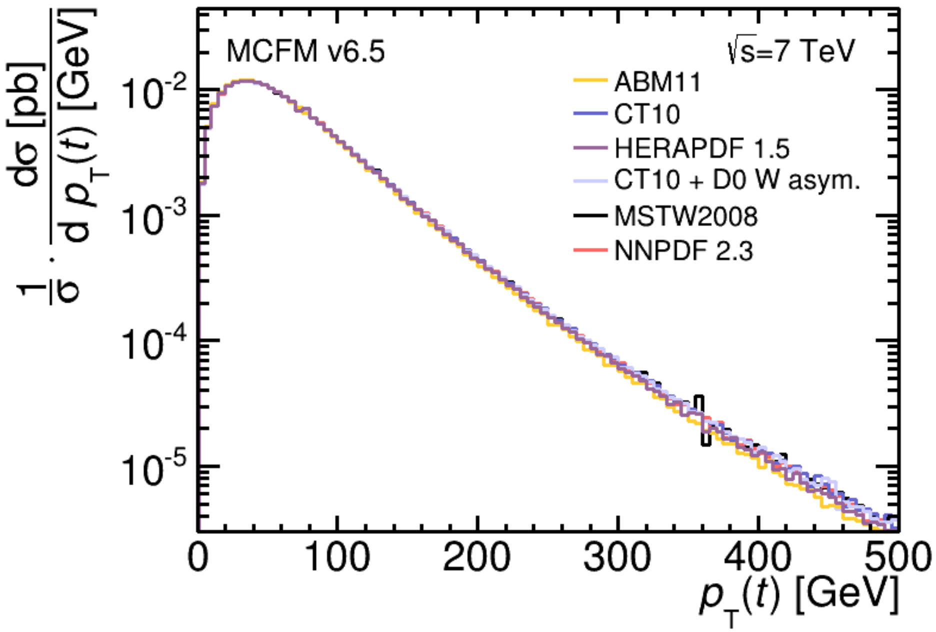
- Statistical uncertainty from integration
- Scale uncertainty (independent restricted scale variations)
- PDF internal uncertainties
- α_s ± 0.002 or correlated with PDF uncertainty
- Proposed procedure has been adopted by the TOPLHCWG

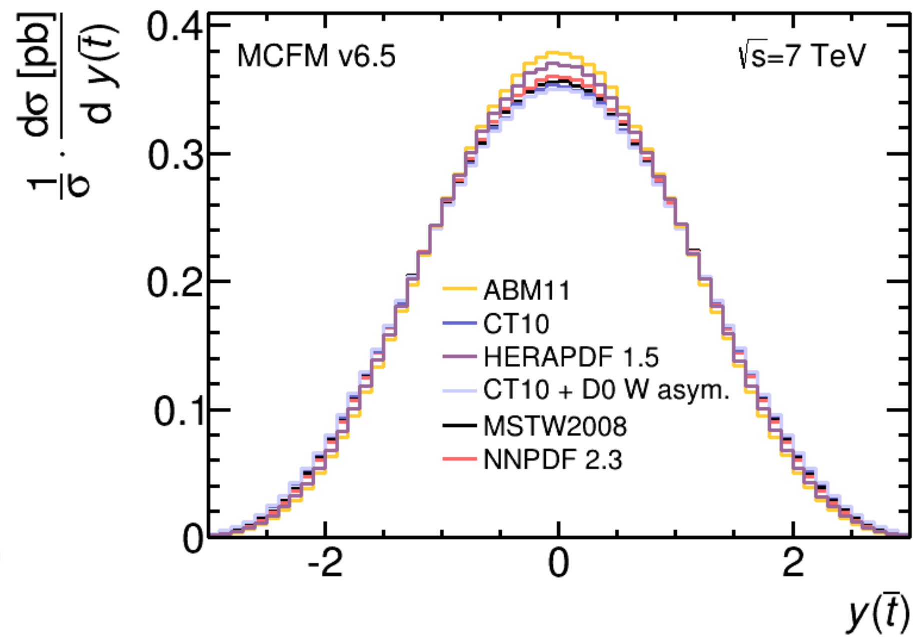
Range in Bjorken x:

0.02 < x < 0.5



Predictions on differential cross-sections





Differential top p_T and y distributions do *not* show big differences for different PDF sets.

➔ publication does not contain comparison for different PDF sets

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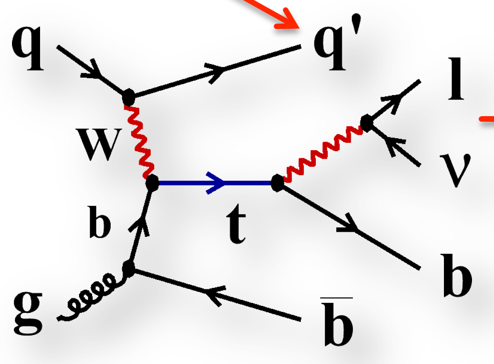
Selection of candidate events

Measurement of forward jets is crucial for t-channel analyses.



- Select only events with leptonic W decays, to suppress QCD-multijet background.
- Some acceptance due to $W \rightarrow \tau\nu$ decays.

- Data sets defined by single lepton (e / μ) trigger
- Charged lepton (e, μ) selection:
  - $p_T > 25$ GeV
  - $|\eta(\mu, e)| < 2.5$
  - Isolation in η-ϕ space
- Missing transverse momentum: $E_T^{miss} > 30$ GeV
- QCD-multijet veto: $M_T(lE_T^{miss}) > 30$ GeV

$$p_{\mathrm{T}}(\ell) > 40\ \mathrm{GeV} \cdot \left(1 - \frac{\pi - |\Delta\phi(j_1, \ell)|}{\pi - 1}\right)$$

- Jet definition and selection
  - Anti-k_T algorithm ($R = 0.4$)
  - $p_T > 30$ GeV
  - $|\eta| < 4.5$
  - number of jets: 2 or 3
  - Exactly one b-tagged jet (@ 54% efficiency)

    (in 95% of all selected 2-jets events the b-quark jet from top decay is tagged)

Analysis Strategy

Candidate events are separated into 5 channels:
Split into + and – of the lepton charge and split into 2-jet and 3-jet channel

2 Jets 1 tag → plus / minus

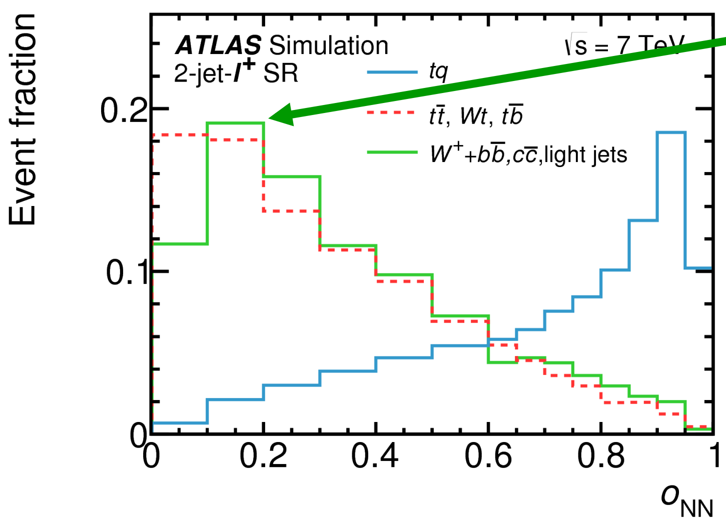
3 Jets 1 tag → plus / minus

3-jet channels constrain the rate of top-quark-pair-production

3 Jets 2 tags

Used to constrain the b-tagging uncertainty (reduced by ≈50%)

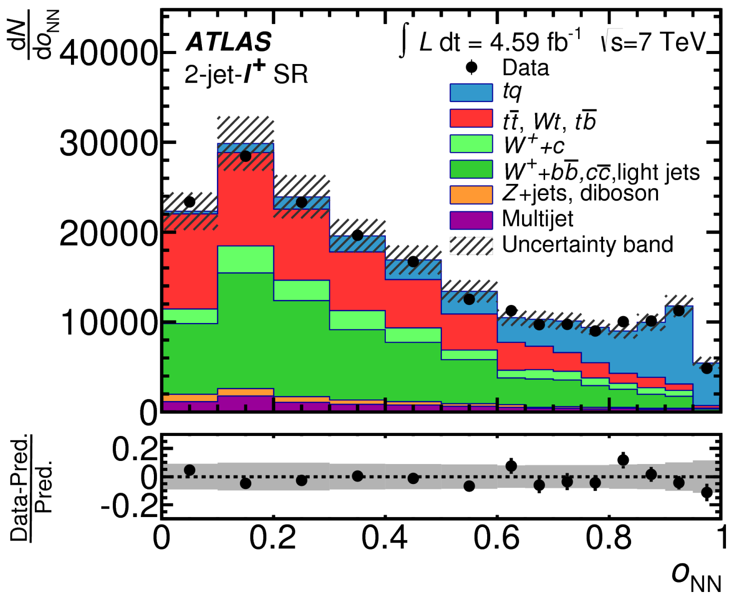
Neural networks are used to separate signal from background processes

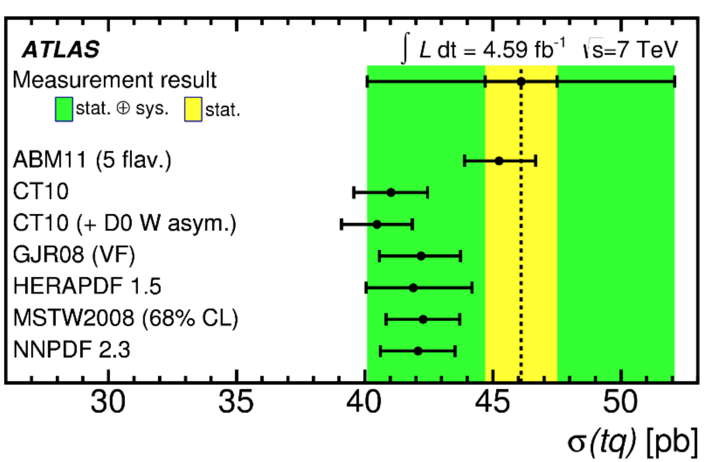


- W + jets background rate determined by background dominated region in simultaneous fit with the signal rate
- Top-quark backgrounds (top-quark pairs, Wt, and tb production) constraint to theory prediction
- Multijet background rate determined by a fit to the MET distribution (electrons) and matrix method (muons)

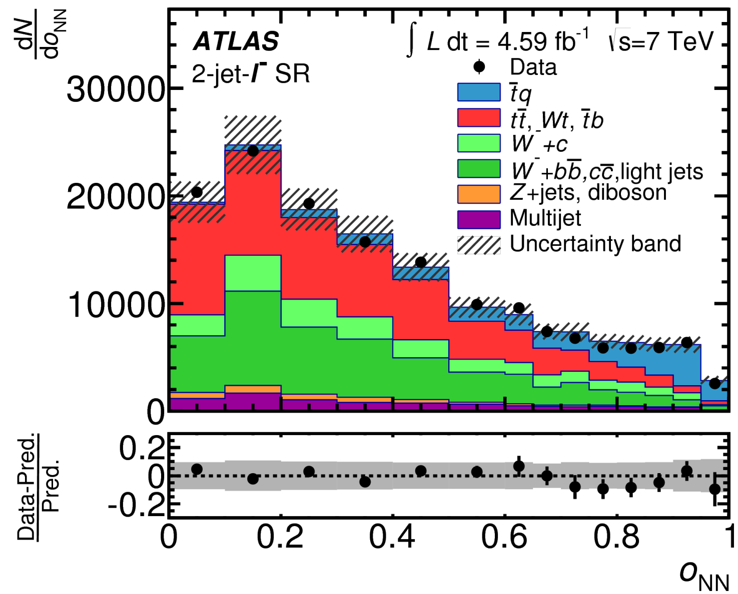
Inclusive cross-sections

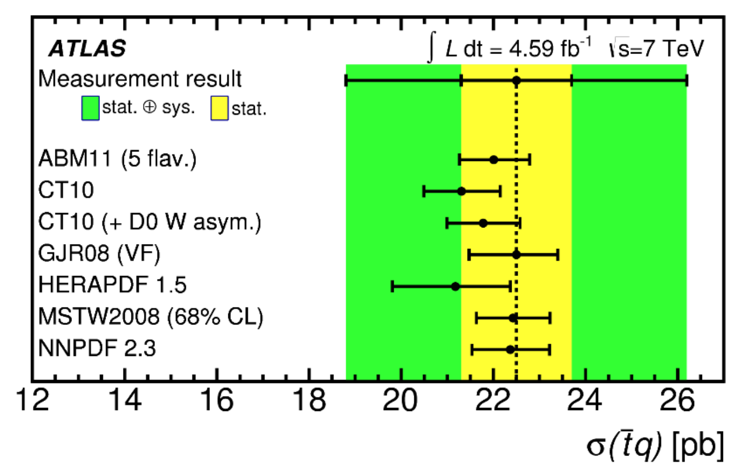
top quarks





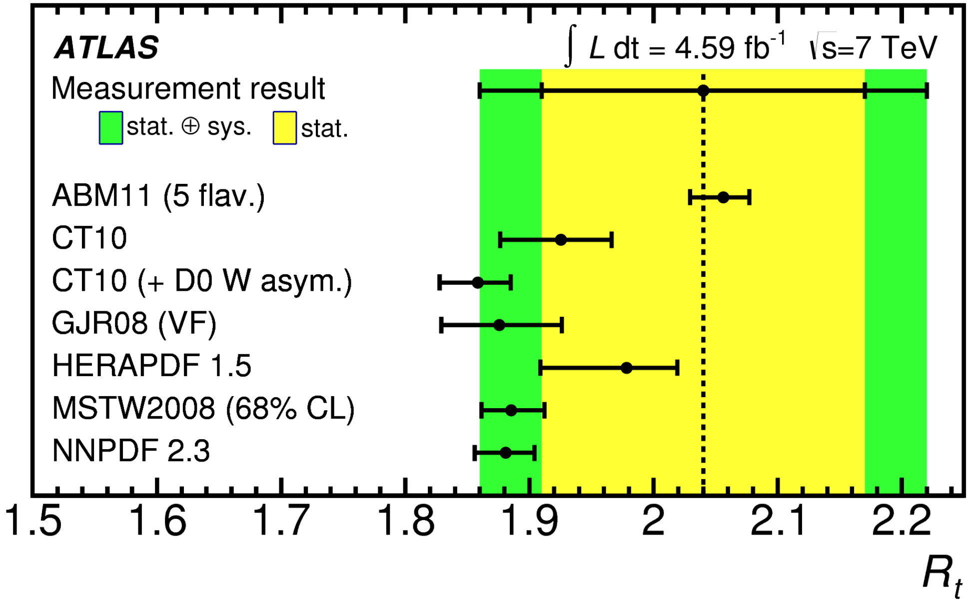
top antiquarks





Result on R_t

$$R_t = 2.04 \pm 0.13\,(\text{stat.}) \pm 0.12\,(\text{syst.}) = 2.04 \pm 0.18$$



- Statistical and systematic uncertainties are at the same level
- Relative precision: 8.7%
- Result is compatible with all predictions

Main uncertainties:

Uncertainty	$\Delta R_t / R_t$
Data statistical	± 6.2%
Monte Carlo statistical	± 3.6%
PDF	± 2.5%
Background normalization	± 1.9%

Extraction of V_{tb}

- Combine top-quark and top-antiquark production to one process and refit.
- Measure: $\sigma(tq+\bar{t}q)$
- Result: $\sigma(tq+\bar{t}q) = 68 \pm 2\ (\mathrm{stat.}) \pm 8\ (\mathrm{syst.}) = 68 \pm 8\ \mathrm{pb}$
- Use: $\sigma(tq+\bar{t}q) \propto |V_{tb}|^2$

$$|V_{tb}|^2_{\mathrm{meas}} = \frac{\sigma(tq+\bar{t}q)_{\mathrm{meas}}}{\sigma(tq+\bar{t}q)_{\mathrm{pred}}} \cdot |V_{tb}|^2_{\mathrm{SM}}$$

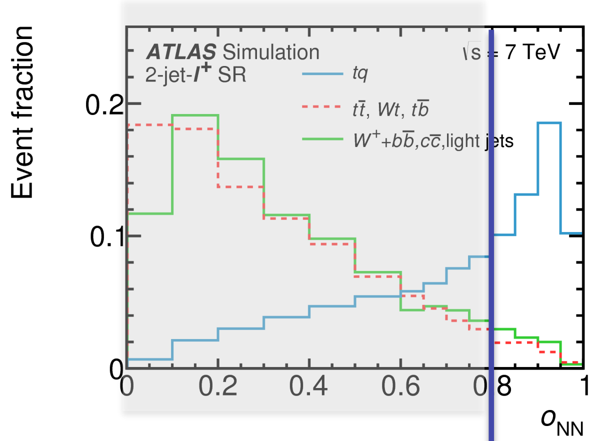
Assume: Wtb vertex has Standard Modell (V - A) structure
and $|V_{tb}| >> |V_{ts}|, |V_{td}|$ (using BR($t \rightarrow Wb$) measurements)

$$\begin{aligned}|V_{tb}| &= 1.02 \pm 0.01\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.}) \pm 0.02\,(\mathrm{theo.})\,{}^{+0.01}_{-0.00}\,(m_t) \\ &= 1.02 \pm 0.07.\end{aligned}$$

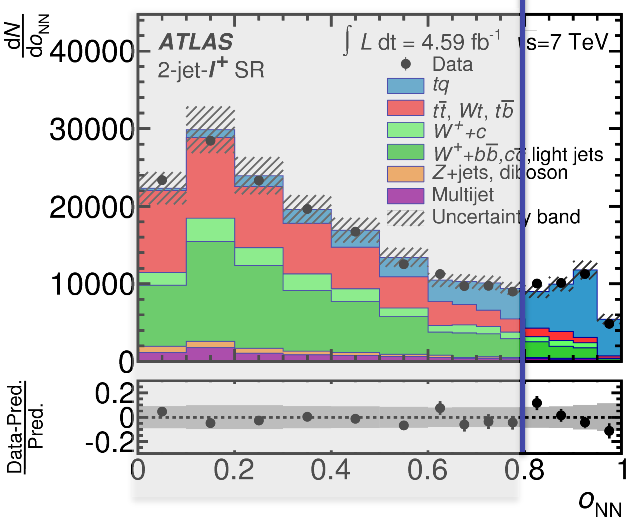
Dominant uncertainties:

JES of jets at high $|\eta|$, b-tagging efficieny, W+jets modelling

Defining a high-purity region



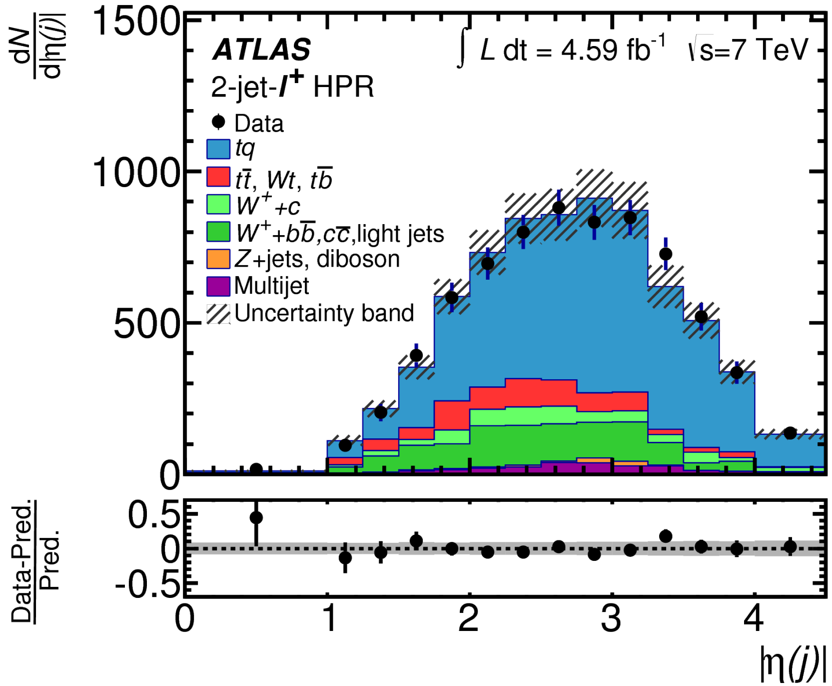
require $o_{NN} > 0.8$



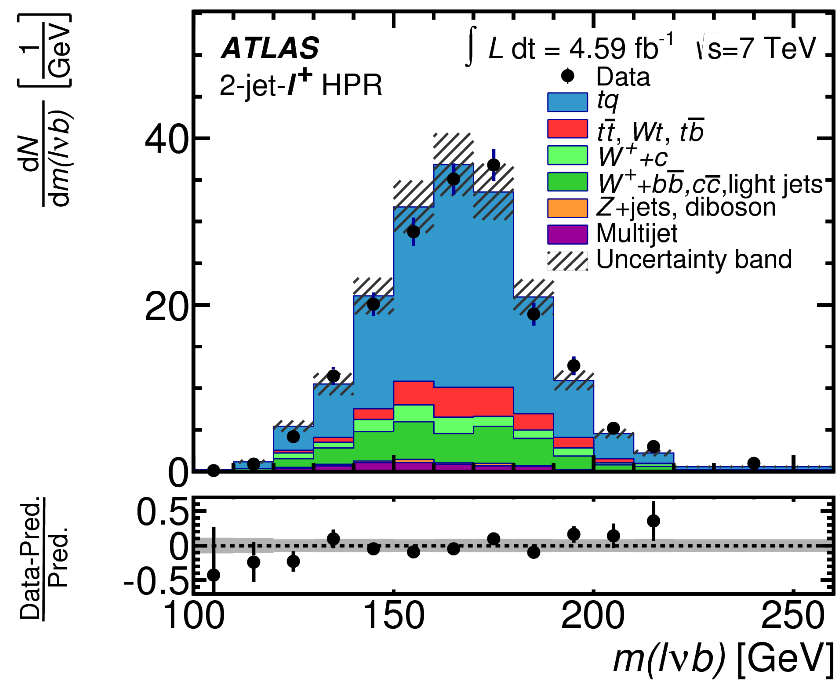
	2-jet-ℓ^+ HPR	2-jet-ℓ^- HPR
tq	1210 ± 150	1.3 ± 0.2
$\bar{t}q$	0.29 ± 0.05	549 ± 87
$t\bar{t}, Wt, t\bar{b}, \bar{t}b$	161 ± 18	175 ± 19
W^++$b\bar{b}$,$c\bar{c}$,light jets	250 ± 48	0.35 ± 0.07
W^-+$b\bar{b}$,$c\bar{c}$,light jets	0.7 ± 0.2	166 ± 40
W+c	110 ± 26	125 ± 30
Z+jets, diboson	15 ± 10	11.4 ± 6.8
Multijet	59 ± 30	62 ± 31
Total expectation	1810 ± 160	1090 ± 110
Data	1813	1034
purity	67%	50%

Event kinematics

Distribution of kinematic variables have signal shape.

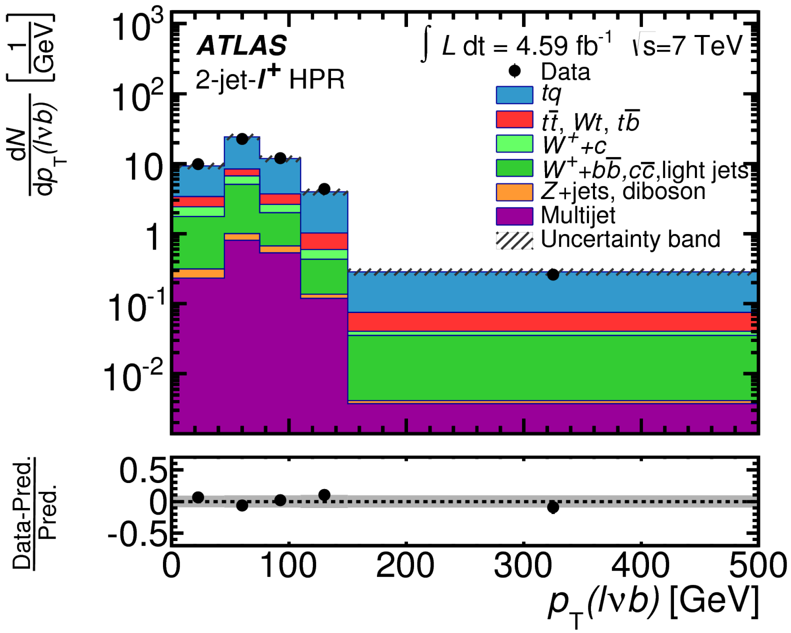


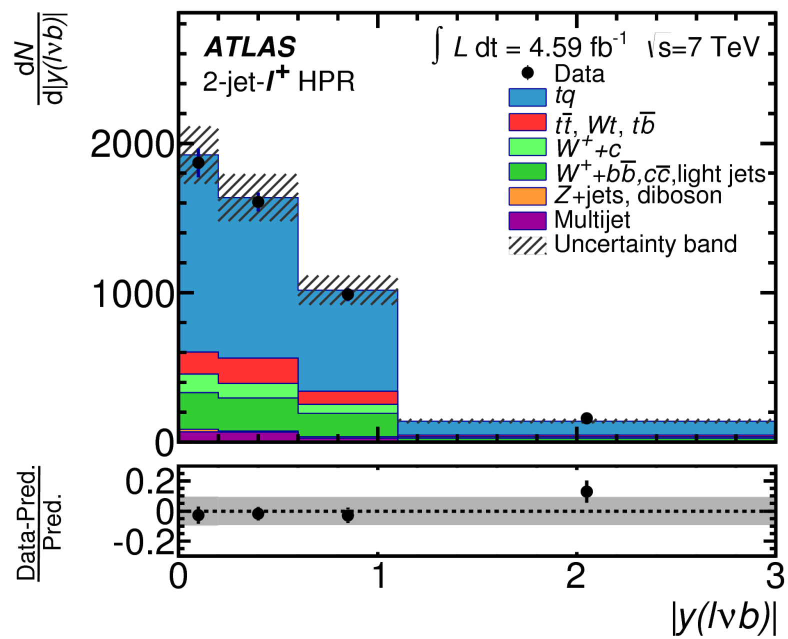
Forward jet at high |η|.



Peak at the reconstructed top-quark mass.

Unfold top-quark p_T and |y|

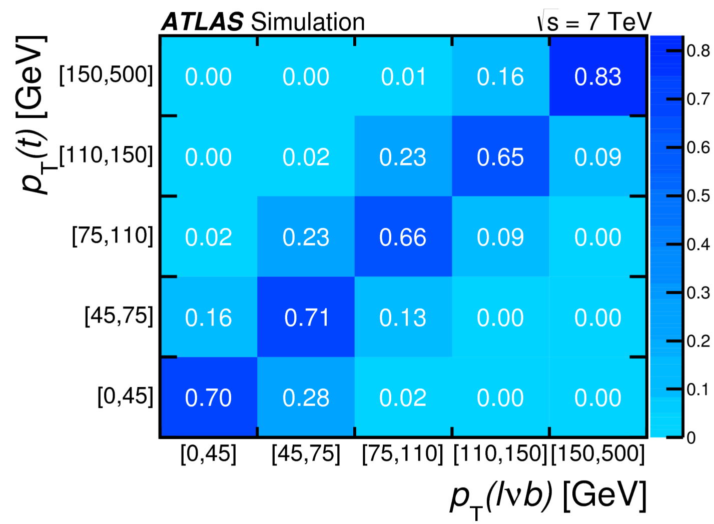




Top-quark and top-antiquark are treated separately.

Correct for selection efficieny and migration effects:

$$\frac{d\sigma}{dX_j} = \frac{1}{\Delta X_j} \cdot \frac{\sum_i M_{ij}^{-1} \cdot (N_i - B_i)}{\mathscr{L} \cdot \varepsilon_j \cdot B(t \to \ell \nu b)}$$



migration matrix of top-quark p_T

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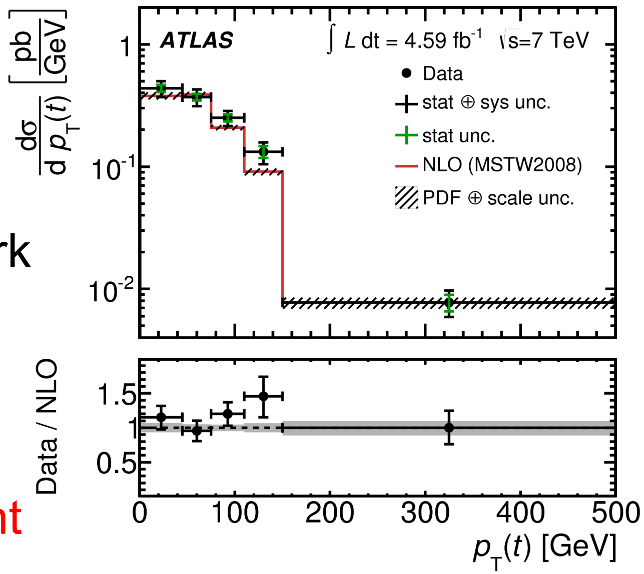
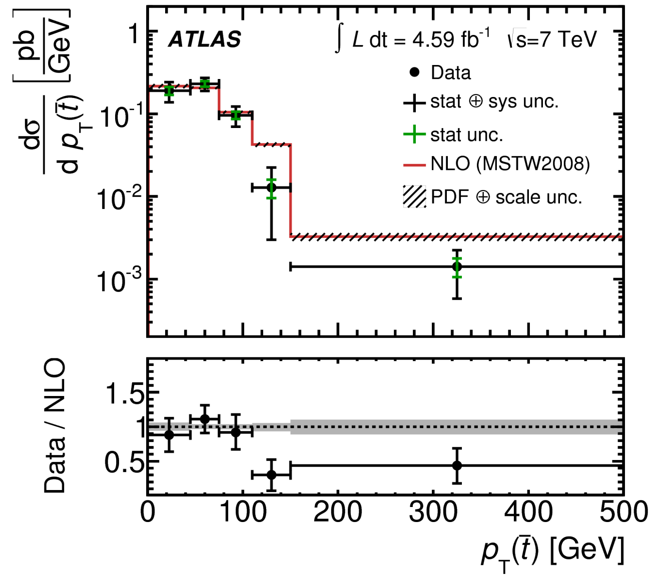
Differential cross-sections

ATLAS

top-quark p_T

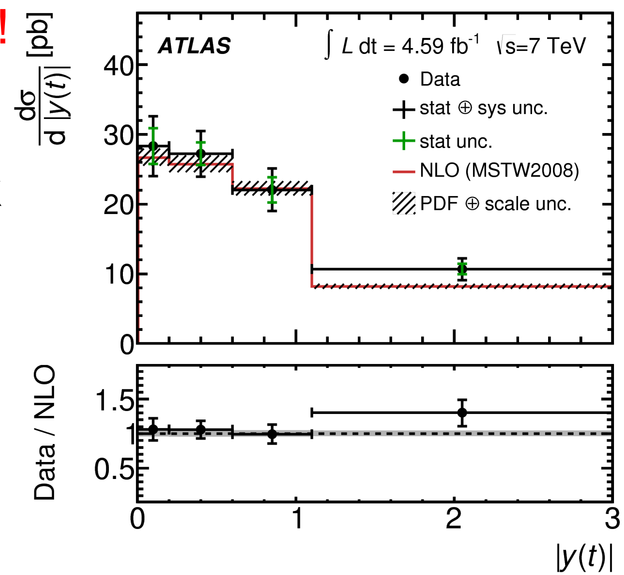


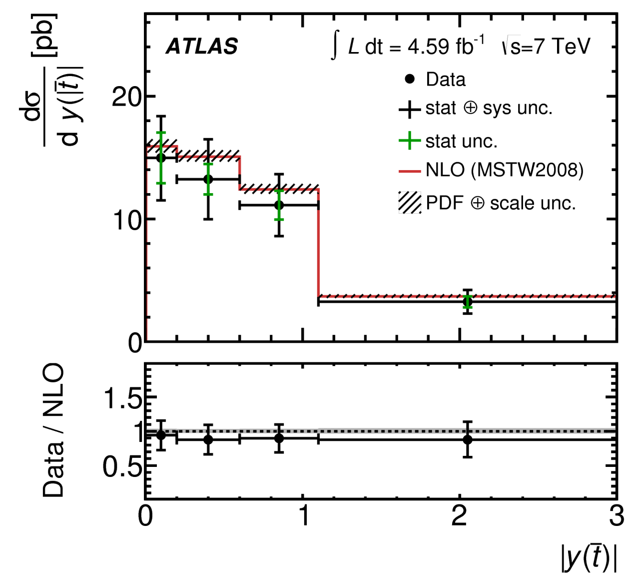


top-antiquark p_T

Good agreement with NLO prediction!

top-quark |y|





top-antiquark |y|

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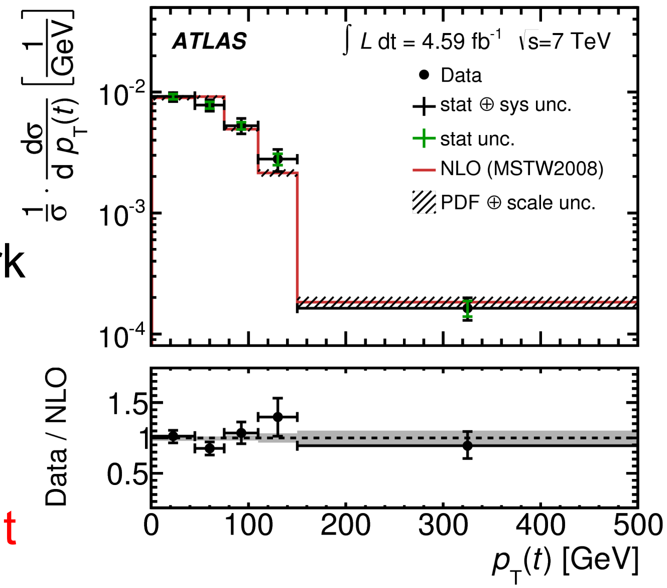
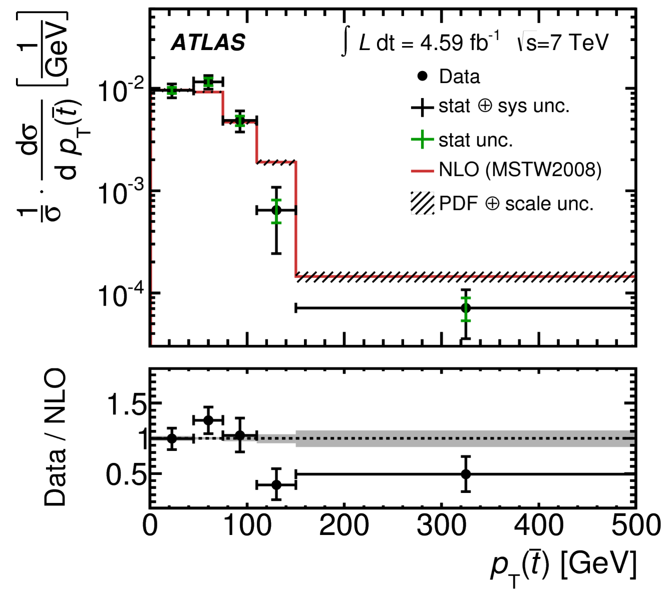
Normalized Distributions

top-quark p_T

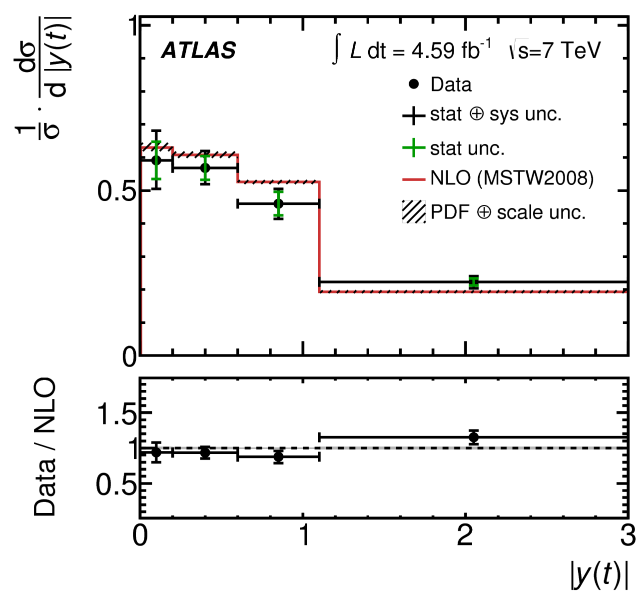


top-antiquark p_T

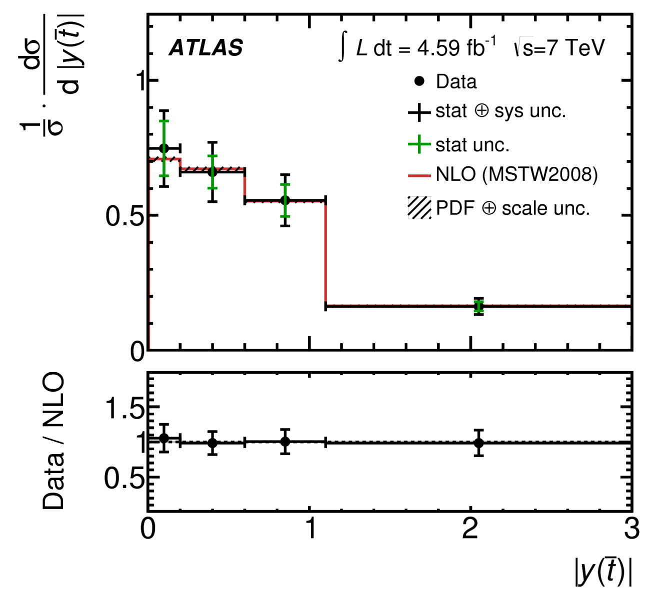


Good agreement with NLO prediction!

top-quark |y|



top-antiquark |y|



A glimpse ahead to 8 TeV

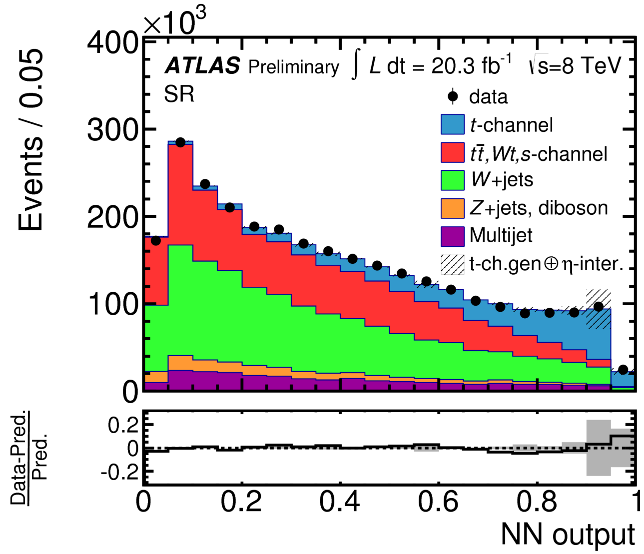
Measurement of a fiducial cross-section:

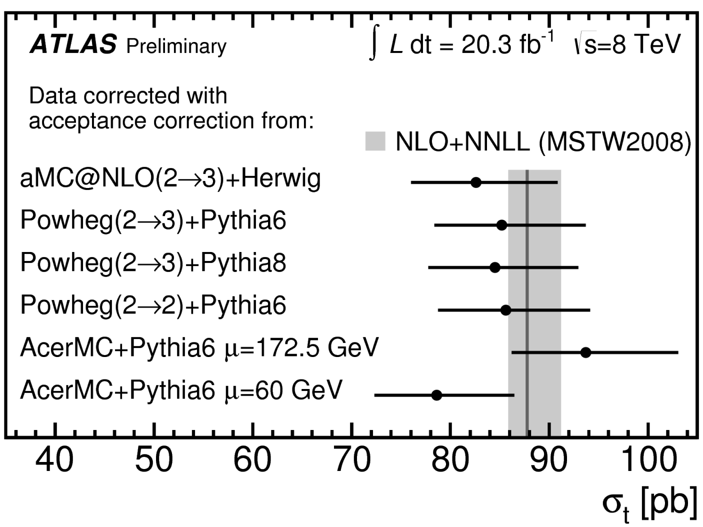
- Measurement within the accessible phase space.
- Reduced dependence on the extrapolation to the full phase space using Monte Carlo generators.
- Measurement based on ≈ 18,000 events!

$$\sigma_{\mathrm{fid}} = \frac{\epsilon_{\mathrm{corr,sel}}}{\epsilon_{\mathrm{corr,fid}}} \cdot \frac{\hat{\nu}}{\mathcal{L}} = R_f \cdot \frac{\hat{\nu}}{\mathcal{L}}$$

$$\sigma = \frac{1}{\epsilon_{\mathrm{fid}}} \cdot \sigma_{\mathrm{fid}}$$

ATLAS-CONF-2014-007





Comparison of different MC generators and parton showers.

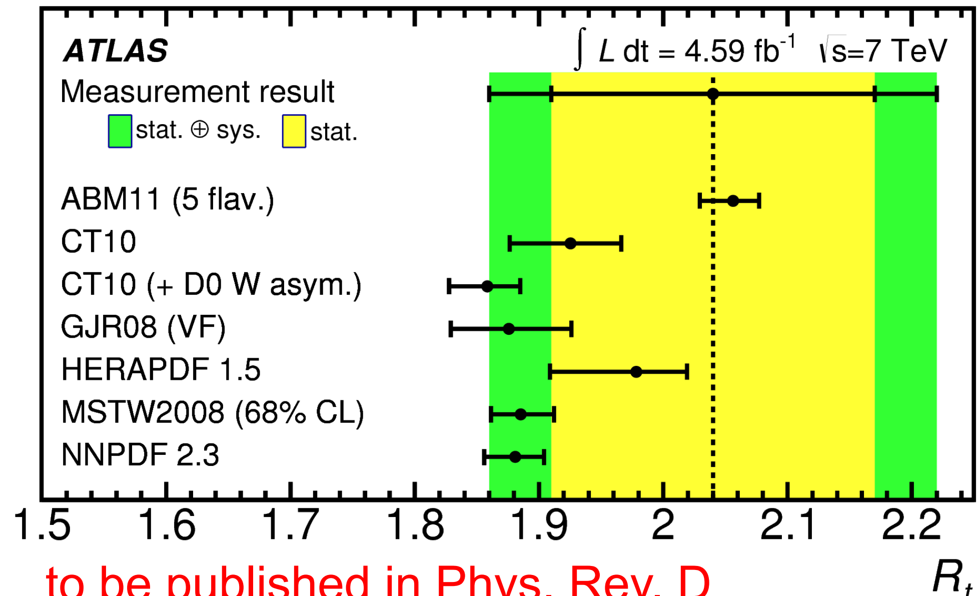
NLO generators clearly improve scale dependence compared to LO (AcerMC).

Conclusion

- Thorough investigation of single top-quark production in the t-channel at $\sqrt{s}$ = 7 TeV ➔ measurement of several cross-sections:

$$\sigma(tq) = 46 \pm 6 \text{ pb} \qquad \sigma(\bar{t}q) = 23 \pm 4 \text{ pb} \qquad \sigma(tq + \bar{t}q) = 68 \pm 8 \text{ pb}$$

- Measurement of the cross-section ratio: $R_t = 2.04 \pm 0.18$
- All measurements are in agreement with the SM prediction.
- Data are available in HEPDATA.
- R_t has the potential to discriminate among some PDF sets, but need reduced uncertainties.
- Improvements are expected for 8 TeV data sets:
  - ➢ data statistical uncertainty reduced by factor of 2
  - ➢ reduced uncertainties on jets and signal model



to be published in Phys. Rev. D
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Backup

Theory cross-section

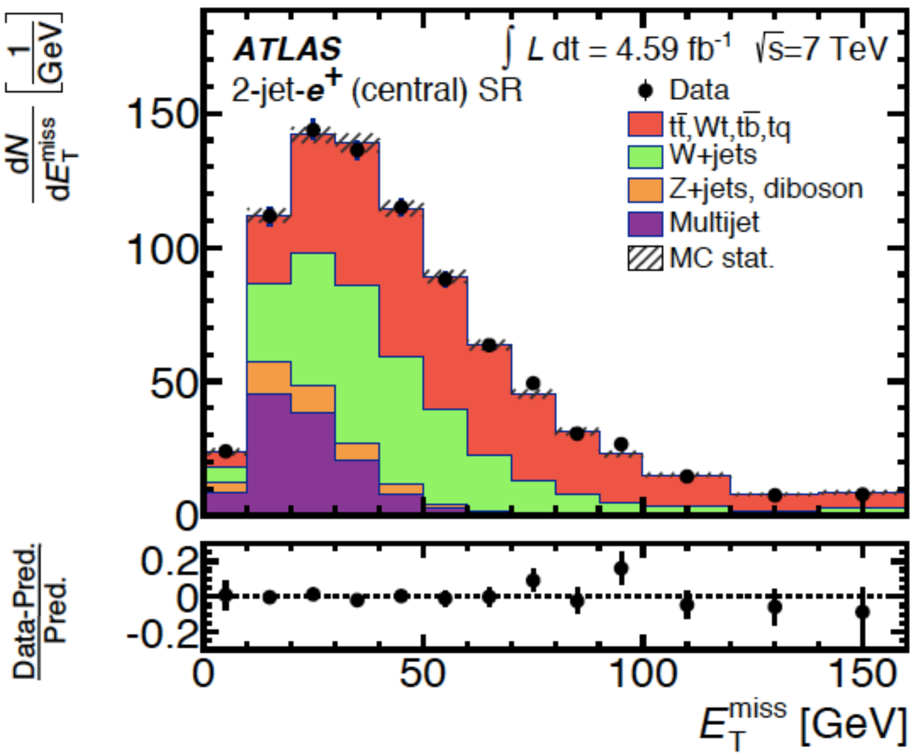
$$\sigma(tq) = 41.9^{+1.8}_{-0.9}\ \mathrm{pb}$$

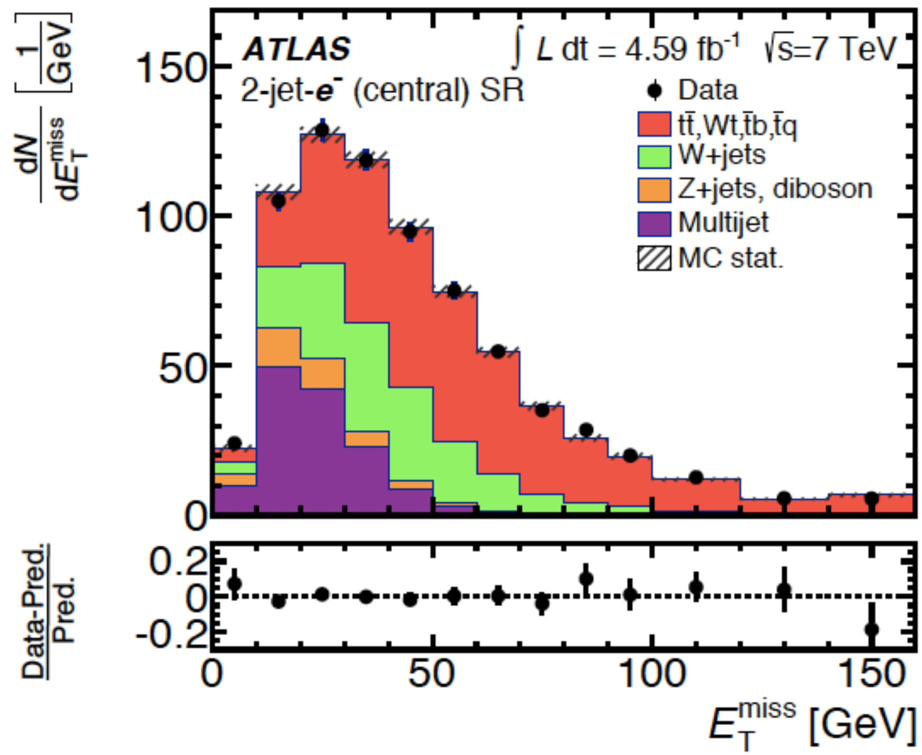
$$\sigma(\bar{t}q) = 22.7^{+0.9}_{-1.0}\ \mathrm{pb}$$

$$\sigma(tq+\bar{t}q) = 64.6^{+2.7}_{-2.0}\ \mathrm{pb}$$

NLO + NNLL resummation by N. Kidonakis

E_T^{miss} fit


ATLAS
∫ L dt = 4.59 fb-1 √s=7 TeV
2-jet-e+ (central) SR
Data
tt̄,Wt,tb̄,tq
W+jets
Z+jets, diboson
Multijet
MC stat.
dN/dE_T^miss [1/GeV]
Data-Pred./Pred.
E_T^miss [GeV]


ATLAS
∫ L dt = 4.59 fb-1 √s=7 TeV
2-jet-e- (central) SR
Data
tt̄,Wt̄,t̄b,t̄q
W+jets
Z+jets, diboson
Multijet
MC stat.
dN/dE_T^miss [1/GeV]
Data-Pred./Pred.
E_T^miss [GeV]

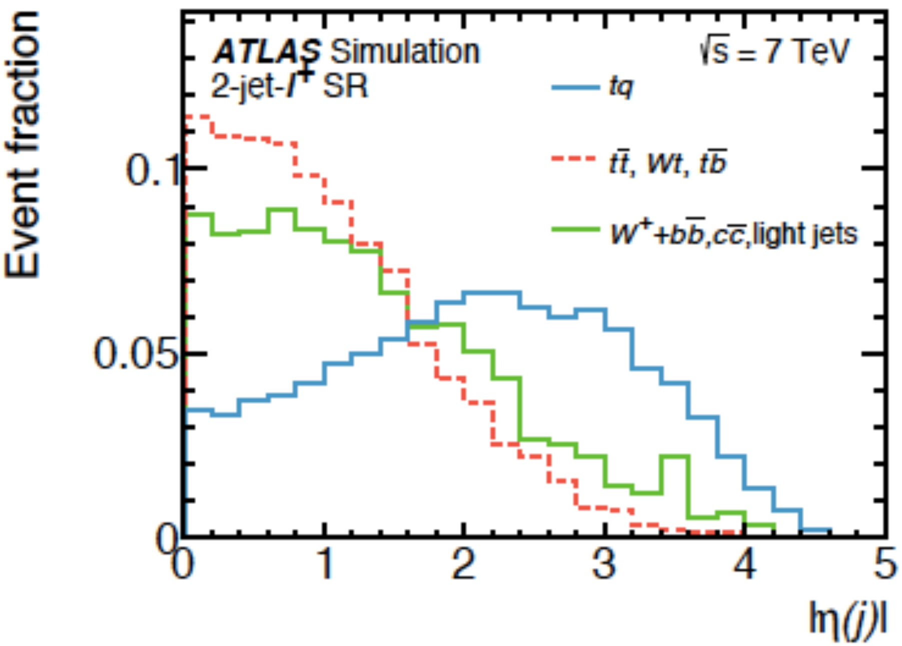
Event yield

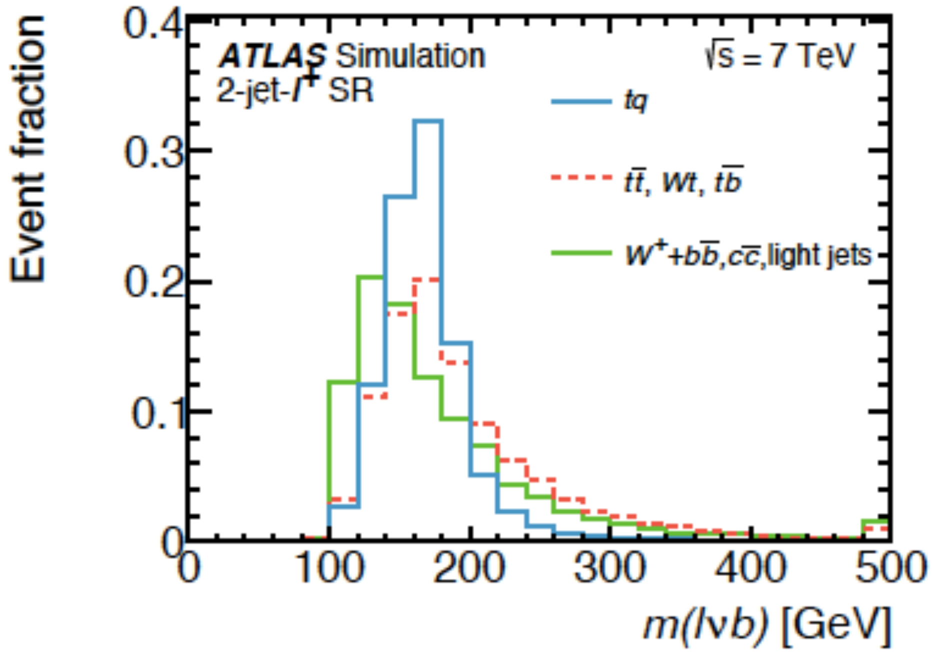
	2-jet channels		3-jet channels		
	ℓ^+	ℓ^-	ℓ^+	ℓ^-	2-tag
tq	2550 ± 220	3.6 ± 0.3	845 ± 74	1.2 ± 0.1	309 ± 26
$\bar{t}q$	1.5 ± 0.1	1390 ± 120	0.52 ± 0.05	435 ± 38	162 ± 14
$t\bar{t}, Wt, t\bar{b}, \bar{t}b$	5250 ± 530	5130 ± 510	8200 ± 820	8180 ± 820	5850 ± 580
W^++$b\bar{b}$,$c\bar{c}$,light jets	5700 ± 2500	16.3 ± 8.2	2400 ± 1200	11.5 ± 5.7	200 ± 100
W^-+$b\bar{b}$,$c\bar{c}$,light jets	9.2 ± 4.6	3400 ± 1700	4.1 ± 2.0	1470 ± 740	137 ± 68
W+c	1460 ± 350	1620 ± 390	388 ± 93	430 ± 100	6.5 ± 1.6
Z+jets, diboson	370 ± 220	310 ± 180	190 ± 120	180 ± 110	22 ± 13
Multijet	750 ± 340	740 ± 370	320 ± 160	440 ± 220	21 ± 11
Total expectation	16100 ± 2600	12600 ± 2000	12400 ± 1500	11100 ± 1100	6710 ± 610
Data	16198	12837	12460	10819	6403

Input variables

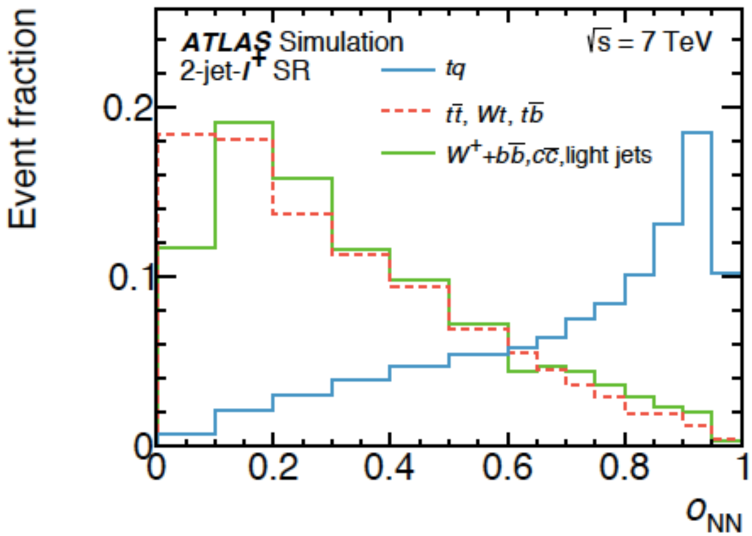
Variables used in the 2-jet channels and the 3-jet channels	
$m(\ell\nu b)$	The invariant mass of the reconstructed top quark.
$m_{\mathrm{T}}(\ell E_{\mathrm{T}}^{\mathrm{miss}})$	The transverse mass of the lepton–$E_{\mathrm{T}}^{\mathrm{miss}}$ system, as defined in Eq. (1).
$\eta(\ell\nu)$	The pseudorapidity of the system of the lepton and the reconstructed neutrino.
$m(\ell b)$	The invariant mass of the charged lepton and the b-tagged jet.
H_{T}	The scalar sum of the transverse momenta of the jets, the charged lepton, and the $E_{\mathrm{T}}^{\mathrm{miss}}$.
Variables used in the 2-jet channels only	
$m(jb)$	The invariant mass of the untagged jet and the b-tagged jet.
$\lvert\eta(j)\rvert$	The absolute value of the pseudorapidity of the untagged jet.
$\Delta R(\ell, j)$	ΔR between the charged lepton and the untagged jet.
$\Delta R(\ell\nu b, j)$	ΔR between the reconstructed top quark and the untagged jet.
$\lvert\eta(b)\rvert$	The absolute value of the pseudorapidity of the b-tagged jet.
$\lvert\Delta p_{\mathrm{T}}(\ell, j)\rvert$	The absolute value of the difference between the transverse momentum of the charged lepton and the untagged jet.
$\lvert\Delta p_{\mathrm{T}}(\ell\nu b, j)\rvert$	The absolute value of the difference between the transverse momentum of the reconstructed top quark and the untagged jet.
$E_{\mathrm{T}}^{\mathrm{miss}}$	The missing transverse momentum.
Variables used in the 3-jet channels only	
$\lvert\Delta y(j_1, j_2)\rvert$	The absolute value of the rapidity difference of the leading and 2nd leading jets.
$m(j_2 j_3)$	The invariant mass of the 2nd leading jet and the 3rd leading jet.
$\cos\theta(\ell, j)_{\ell\nu b\,\mathrm{r.f.}}$	The cosine of the angle θ between the charged lepton and the leading untagged jet in the rest frame of the reconstructed top quark.
$\Sigma\eta(j_i)$	The sum of the pseudorapidities of all jets in the event.
$m(j_1 j_2)$	The invariant mass of the two leading jets.
$p_{\mathrm{T}}(\ell\nu b)$	The transverse momentum of the reconstructed top quark.

Examples of discriminating variables

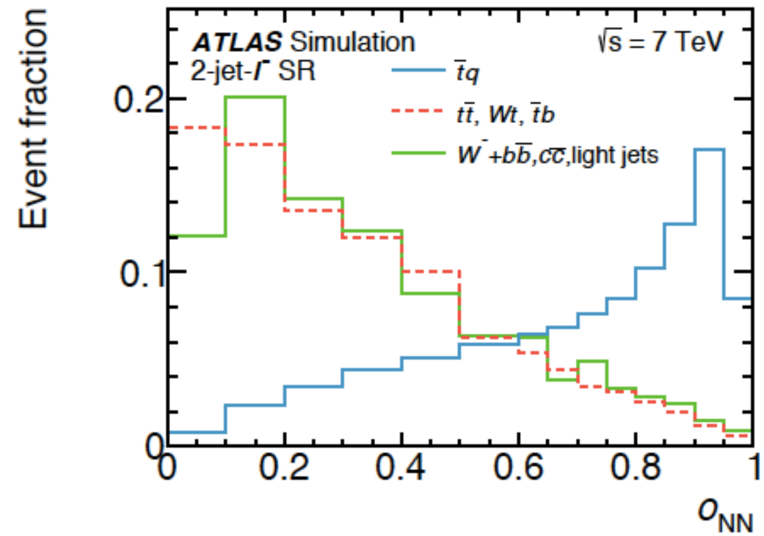




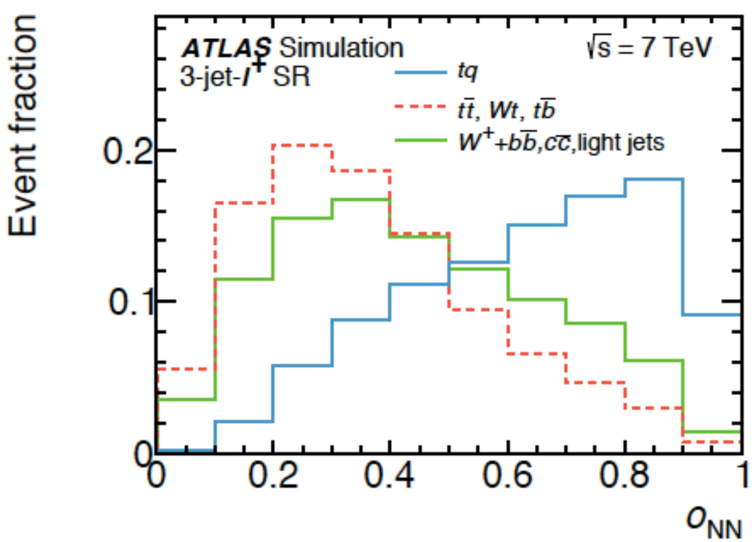
NN discriminant shapes



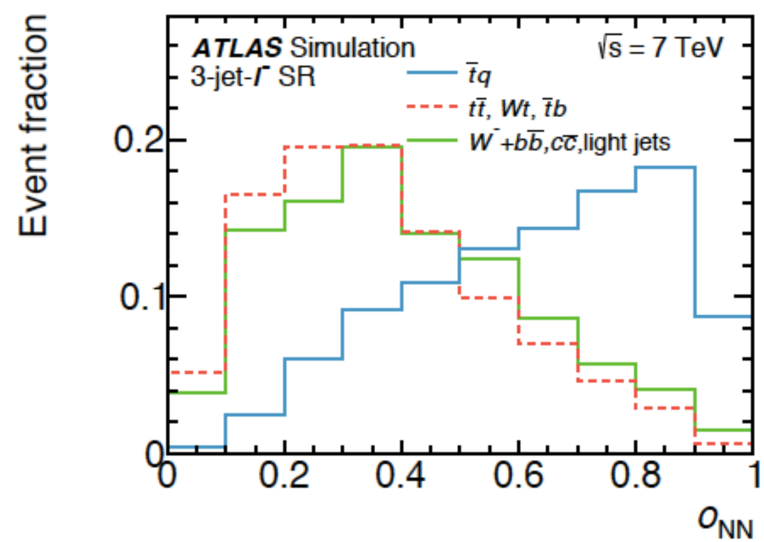
(a)



(b)

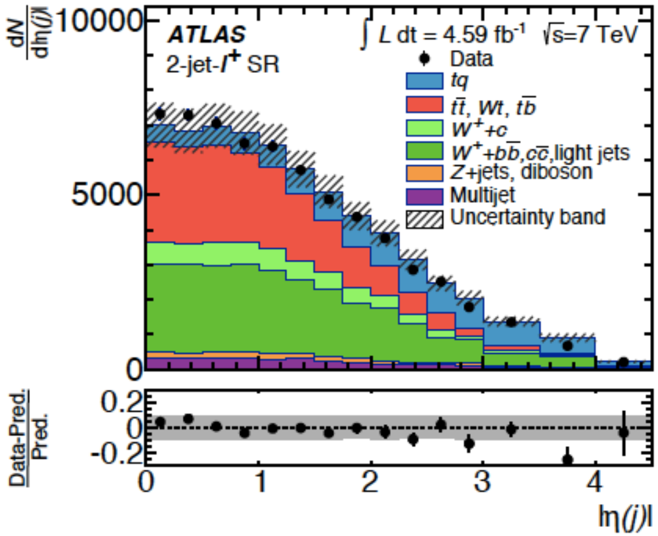


(c)

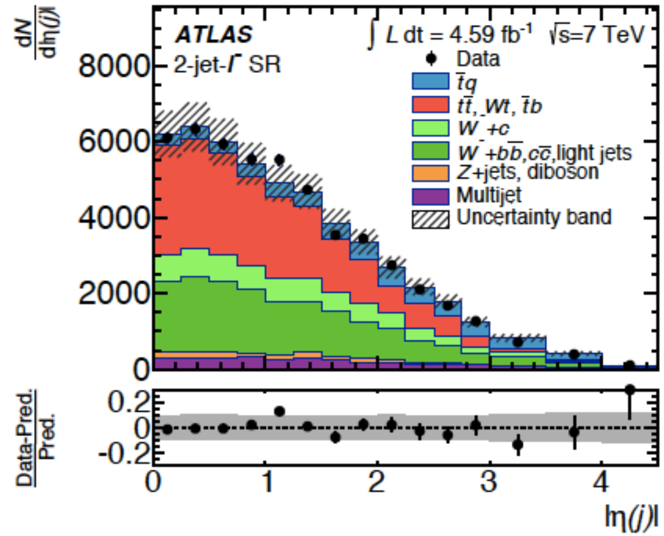


(d)

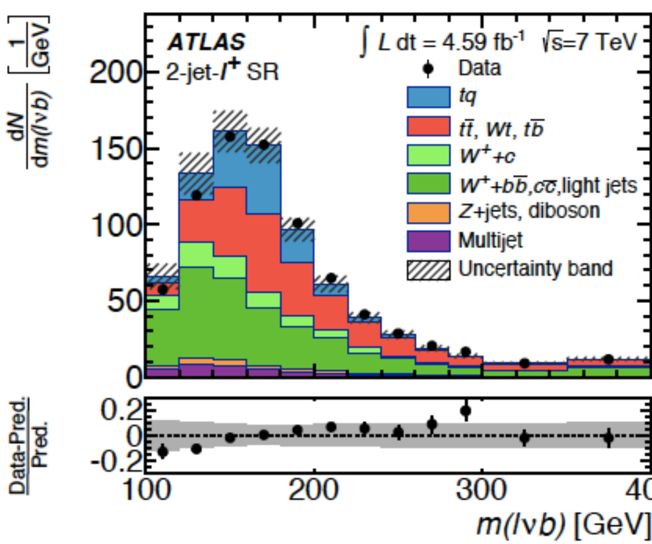
Post-fit input variables



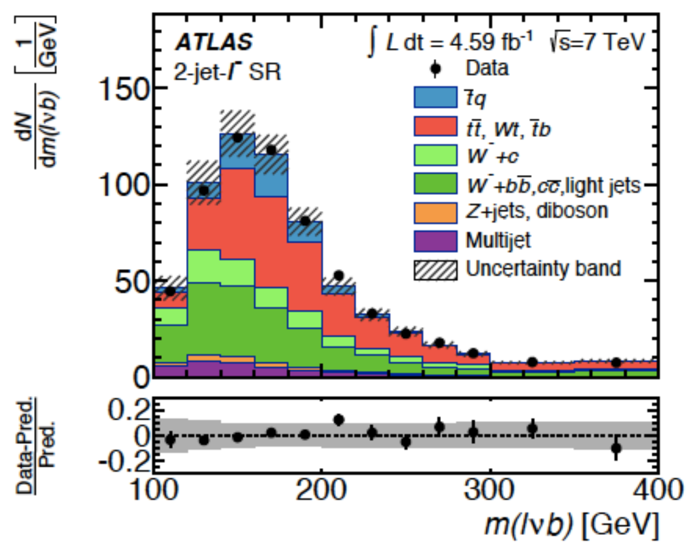
(a)



(b)

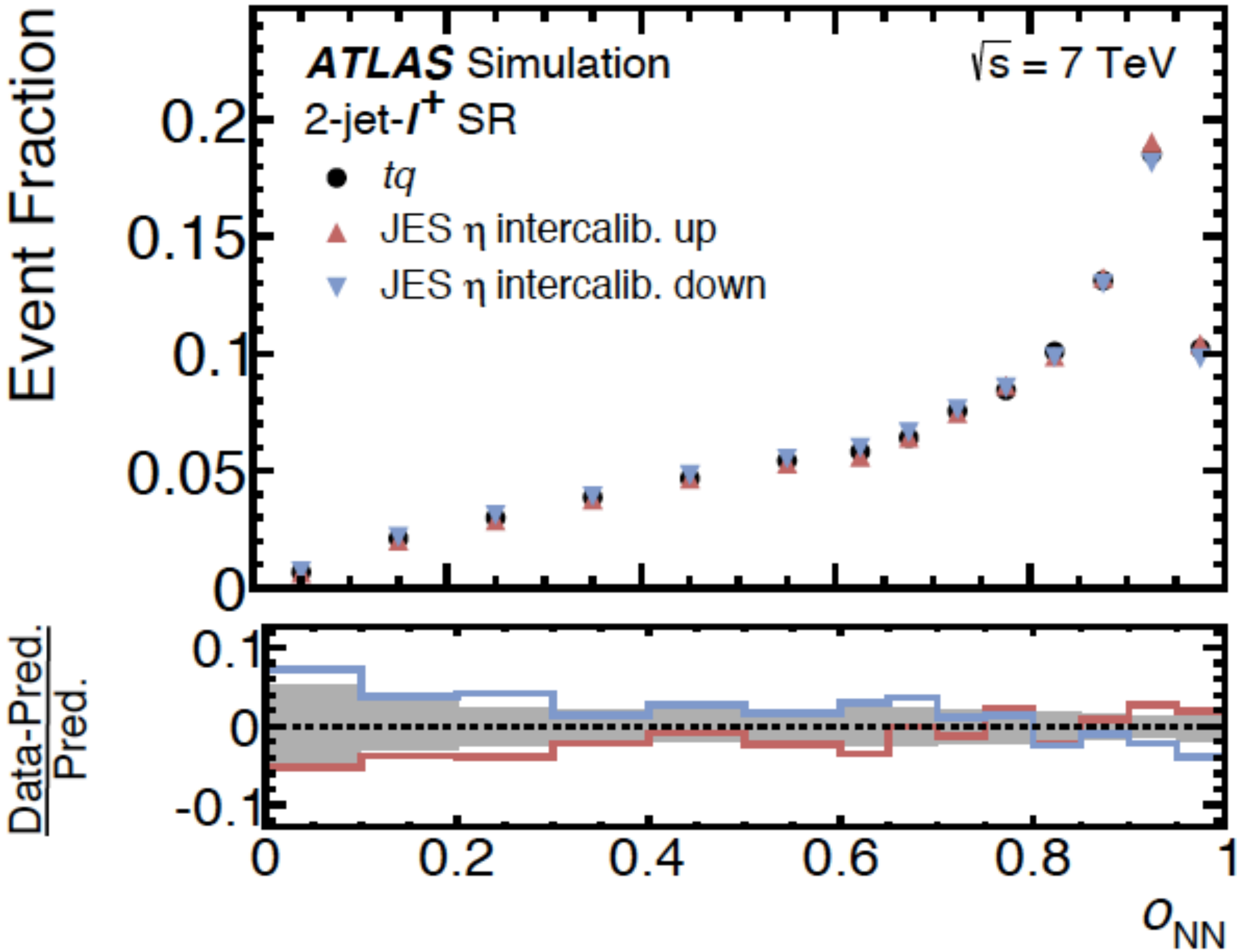


(c)



(d)

Shape uncertainties



Systematic uncertainties 1

Source	$\Delta\sigma(tq)/\sigma(tq)$ [%]	$\Delta\sigma(\bar{t}q)/\sigma(\bar{t}q)$ [%]	$\Delta R_t/R_t$ [%]	$\Delta\sigma(tq+\bar{t}q)/\sigma(tq+\bar{t}q)$ [%]
Data statistical	±3.1	±5.4	±6.2	±2.7
Monte Carlo statistical	±1.9	±3.2	±3.6	±1.9
Multijet normalization	±1.1	±2.0	±1.6	±1.4
Other background normalization	±1.1	±2.8	±1.9	±1.6
JES detector	±1.6	±1.4	< 1	±1.4
JES statistical	< 1	< 1	< 1	< 1
JES physics modeling	< 1	< 1	< 1	< 1
JES η intercalibration	±6.9	±8.4	±1.8	±7.3
JES mixed detector and modeling	< 1	< 1	< 1	< 1
JES close-by jets	< 1	< 1	< 1	< 1
JES pile-up	< 1	< 1	< 1	< 1
JES flavor composition	±1.4	±1.4	±1.2	±1.6
JES flavor response	< 1	< 1	±1.0	< 1
b-JES	< 1	< 1	< 1	< 1
Jet energy resolution	±2.1	±1.6	±1.0	±1.9
Jet vertex fraction	< 1	< 1	< 1	< 1
b-tagging efficiency	±3.8	±4.1	< 1	±3.9
c-tagging efficiency	< 1	±1.4	< 1	< 1
Mistag efficiency	< 1	< 1	< 1	< 1
$b/\bar{b}$ acceptance	±1.0	< 1	< 1	−−
E_T^{miss} modeling	±2.3	±3.4	±1.6	±2.6
Lepton uncertainties	±2.8	±3.0	±1.0	±2.8

Systematic uncertainties 2

Source	$\Delta\sigma(tq)/\sigma(tq)$ [%]	$\Delta\sigma(\bar{t}q)/\sigma(\bar{t}q)$ [%]	$\Delta R_t/R_t$ [%]	$\Delta\sigma(tq+\bar{t}q)/\sigma(tq+\bar{t}q)$ [%]
PDF	± 3.2	± 5.8	± 2.5	± 3.2
W+jets shape variation	< 1	< 1	< 1	< 1
tq generator + parton shower	± 1.9	± 1.6	< 1	± 1.9
tq scale variations	± 2.6	± 3.0	< 1	± 2.6
$t\bar{t}$ generator + parton shower	< 1	± 2.1	± 1.6	< 1
$t\bar{t}$ ISR / FSR	< 1	< 1	± 1.0	< 1
Luminosity	± 1.8	± 1.8	± 0.5	± 1.8
Total systematic	± 12.0	± 14.9	± 6.1	± 12.1
Total	± 12.4	± 15.9	± 8.7	± 12.4

Top mass dependence

$$\sigma_t = \sigma_t(172.5\ \mathrm{GeV}) + p_1 \cdot \Delta m_t + p_2 \cdot \Delta m_t^2$$

	p1 [pb/GeV]	p2 [pb/ GeV^2]
$\sigma(tq+\bar{t}q)$	–0.46	–0.06
$\sigma(tq)$	–0.27	–0.04
$\sigma(\bar{t}q)$	–0.19	–0.02