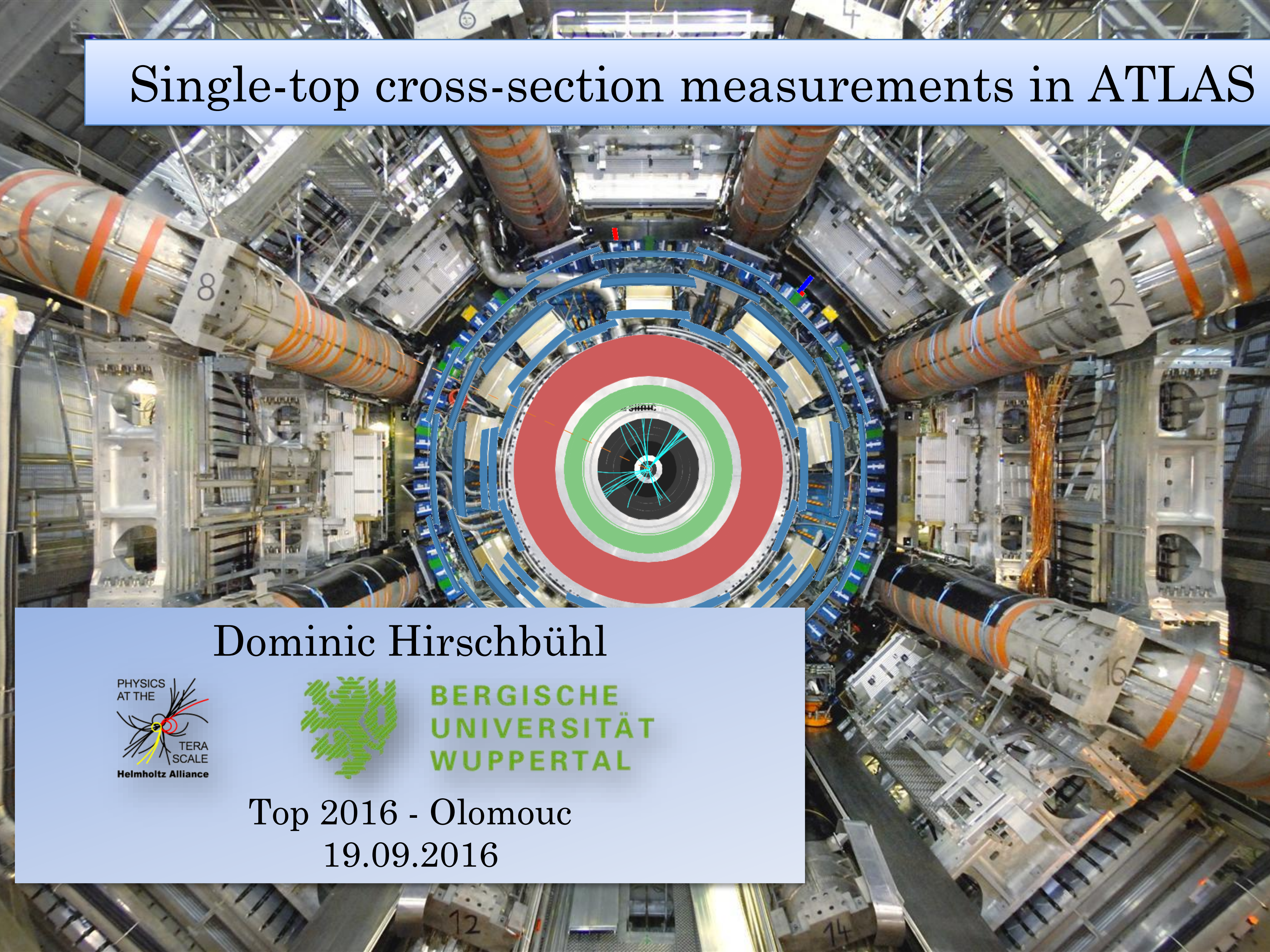


Single-top cross-section measurements in ATLAS

Dominic Hirschbühl

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

BERGISCHE
UNIVERSITÄT
WUPPERTAL

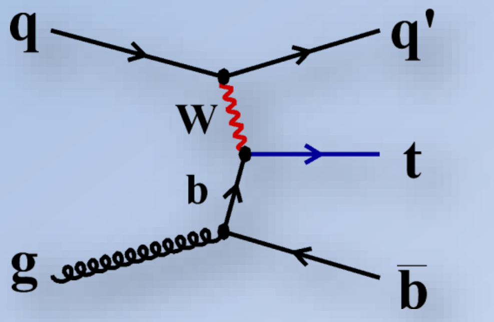
Top 2016 - Olomouc
19.09.2016

Single top quark production

tq - cross sections

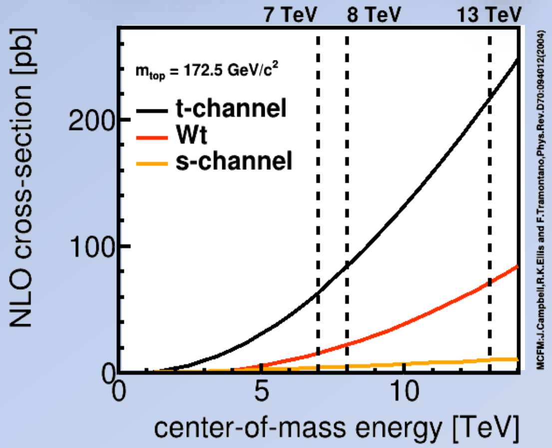
7 TeV	PRD 90, 112006 (2014)
8 TeV	Paper in preparation
13 TeV	arxiv: 1609.03920

t – channel (tq)



tq - properties

See talk from
Javier Jimenez Pena tomorrow

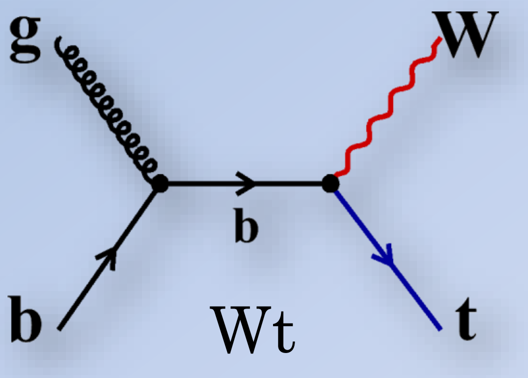


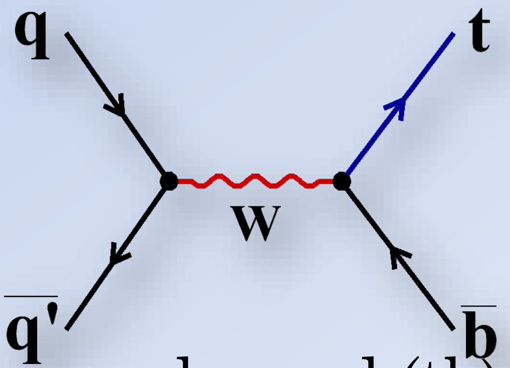
Wt - cross sections

7 TeV	ATLAS-CONF-2011-104
8 TeV	JHEP01(2016)064
13 TeV	ATLAS-CONF-2016-065

tb - cross sections

7 TeV	ATLAS-CONF-2011-118
8 TeV	PLB (2016), 228-246



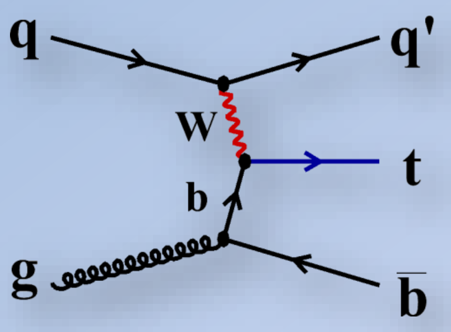


s – channel (tb)

Interesting measurements

The cross-section ratio top-quark/top-antiquark production is sensitive to the u/d-quark ratio in the **PDF** sets.

t – channel (tq)



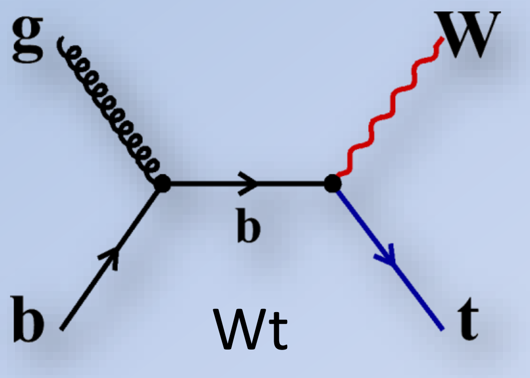
Test of **MC generators** using unfolded distributions

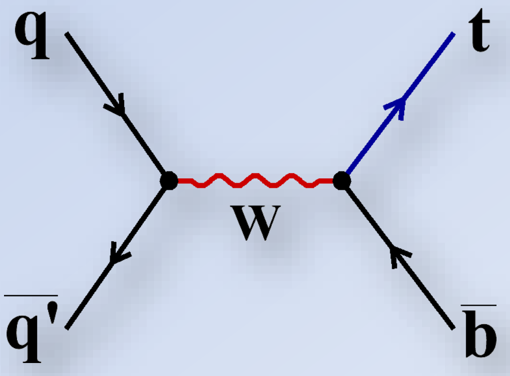
Indirect measurement of the top-quark mass

Test of the **b-quark PDF**

$$|V_{tb}^{obs}| = \sqrt{\frac{\sigma^{obs}}{\sigma^{theo}}}$$

Looking for signs of new pyhsics





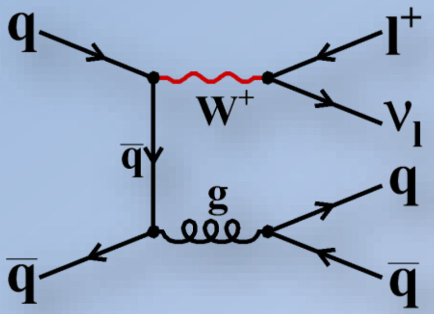
s – channel (tb)

Background processes

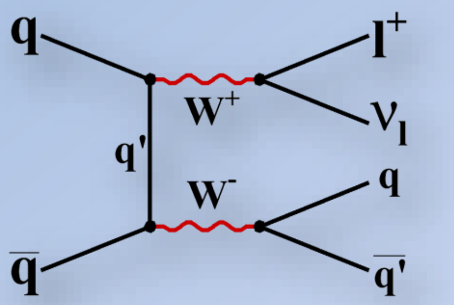
Event signature

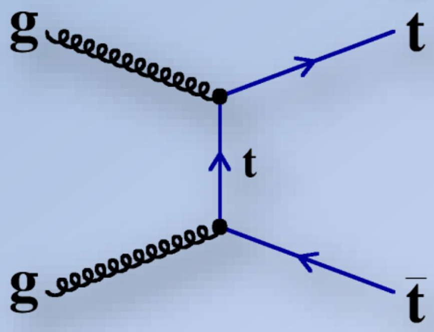
- One **top quark**, decaying leptonically plus **one** addiontal
- **light jet** (t-channel), or **b-quark jet** (s-channel), or **W boson** (Wt)

W/Z + jets



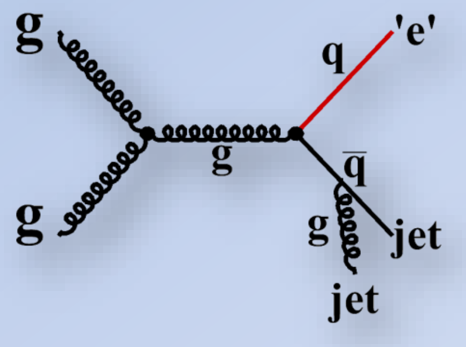
WW/WZ/ZZ





$t\bar{t}$ pair production

Dilepton veto (t- & s-channel)

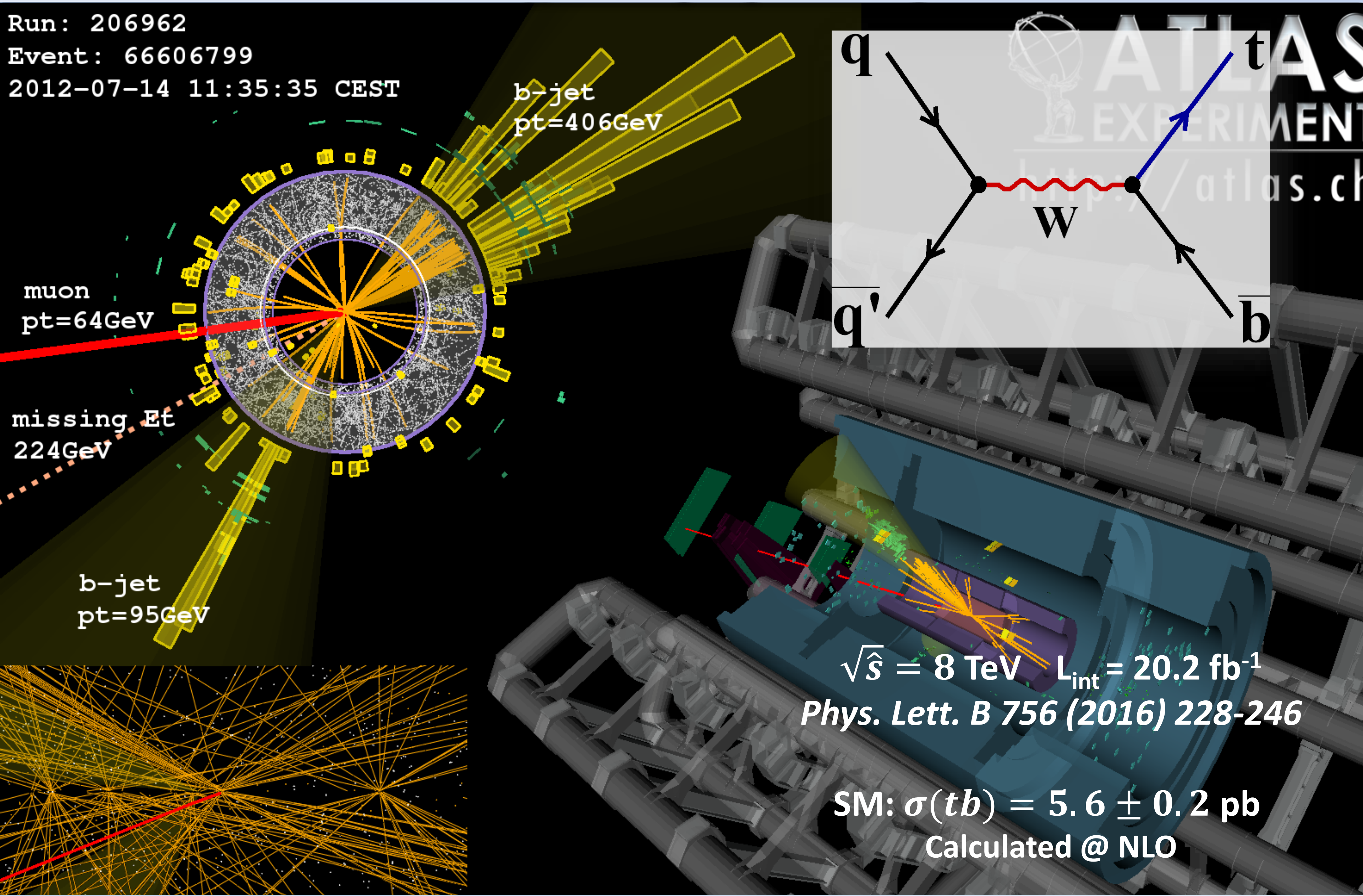


Multijet production
("fake" leptons)

Multijet veto

- Lepton selection (electron / muon):
  - Exactly one / two isolated lepton
- Jets
  - Anti-k_t algorithm R=0.4,
  - One or two central ones
  - t-channel:
    including forward jets $|\eta| < 4.5$
  - One or two b-tags
- Missing transverse momentum
  - No additional lepton
    → reduction of $t\bar{t}$ events

s-channel single top quark production



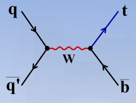
$\sqrt{\hat{s}} = 8$ TeV $L_{int} = 20.2$ fb^{-1}

Phys. Lett. B 756 (2016) 228-246

SM: $\sigma(tb) = 5.6 \pm 0.2$ pb

Calculated @ NLO

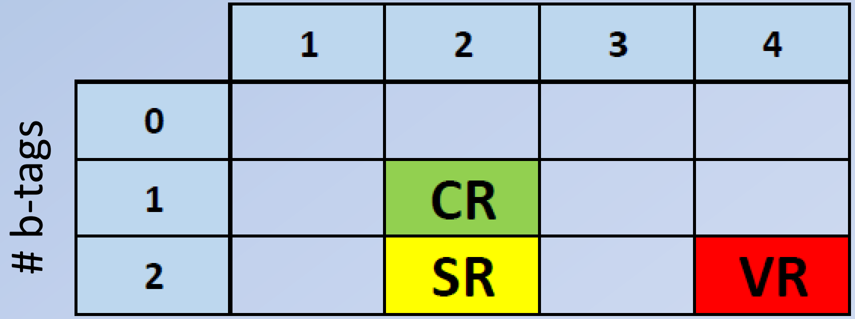
Event yield / analysis strategy



Process	Pre-fit
Single-top s-channel	610
Single-top t-channel	1230
Assoc. W production	370
$t\bar{t}$ production	8200
W+jets	2600
Z+jets & diboson	290
Multi-jet	600
Total expectation	13 980

S/B ≈ 5.4%

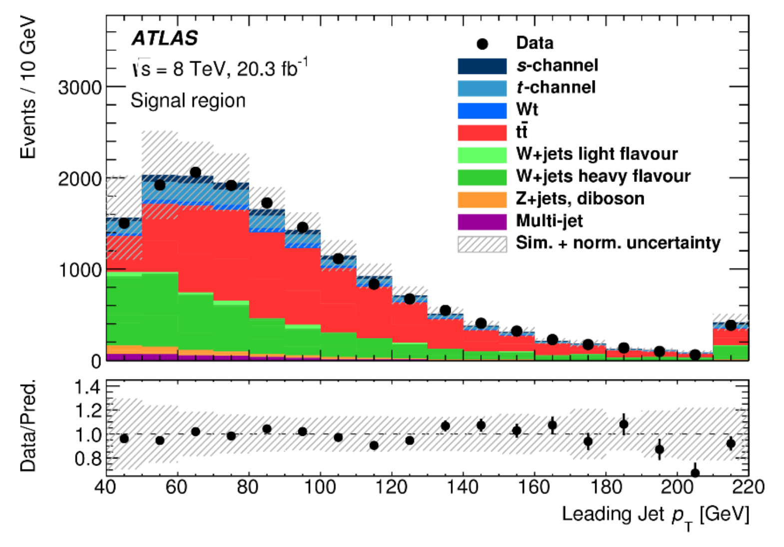
Analysis strategy:

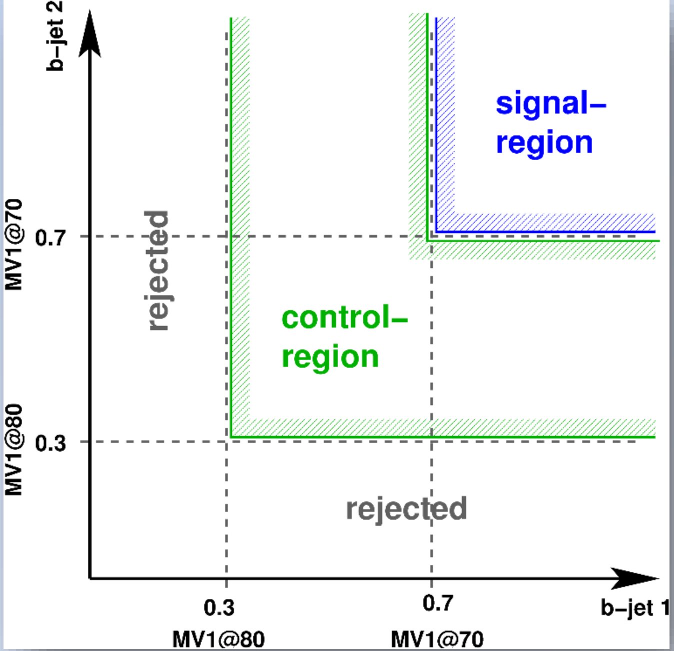


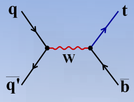
jets

b-tags

	1	2	3	4
0				
1		CR		
2		SR		VR







Matrix element method

Integration over part of the phase space Φ_4

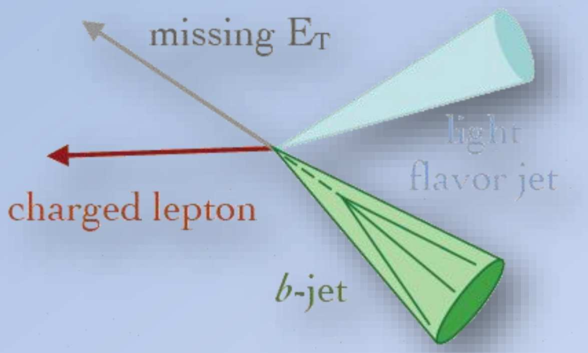
Parton distribution functions

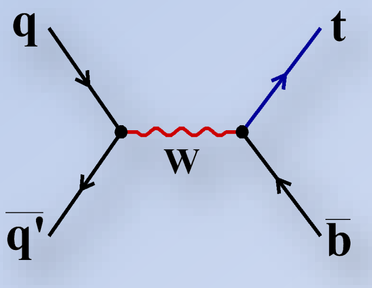
$$P(p_l^\mu, p_{j1}^\mu, p_{j2}^\mu) = \frac{1}{\sigma}\int d\rho_{j1}\, d\rho_{j2}\, dp_\nu^z \sum_{comb} \phi_4 \,|M(p_i^\mu)|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} W_{jet}(E_{jet}, E_{part})$$

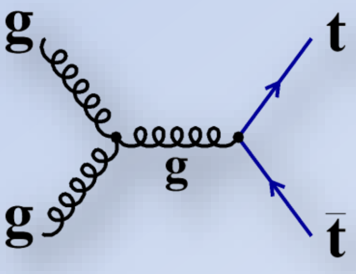
Input: lepton and jet-vectors

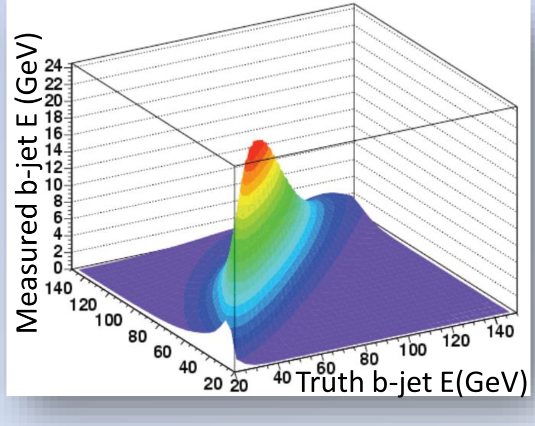
Leading order matrix elements

Probability of measuring a jet energy E_j if E_p was produced.

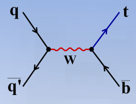




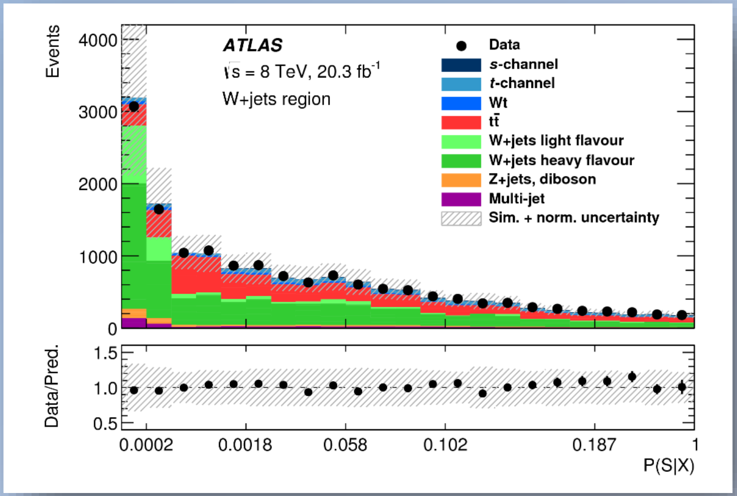


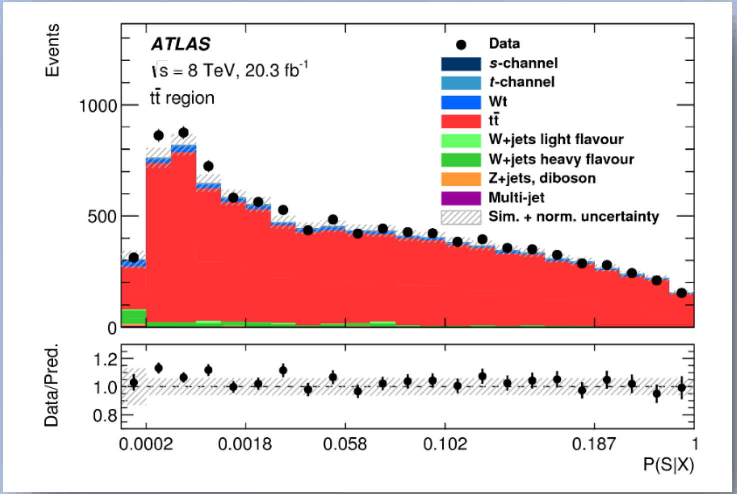


s-channel single top quark production

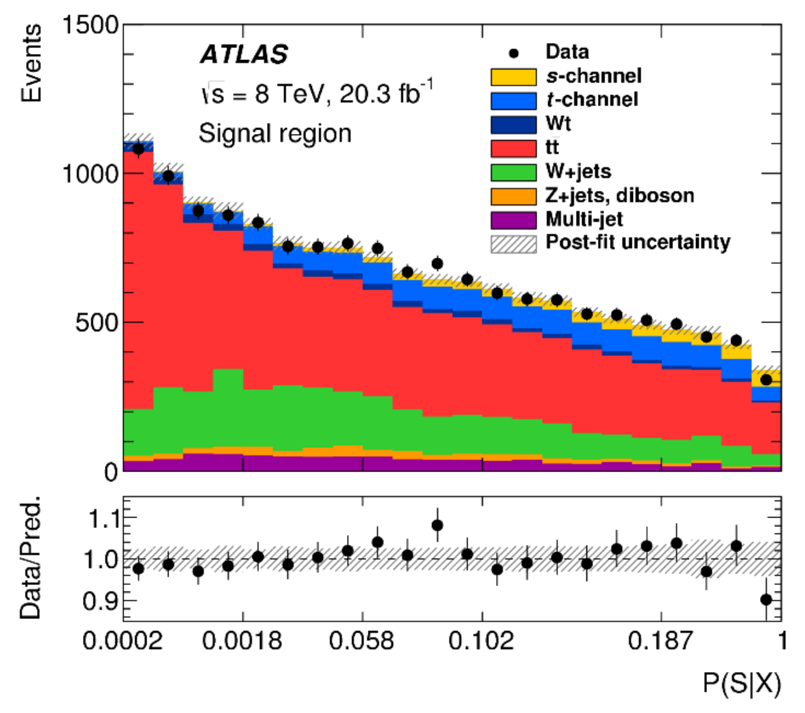


Combining all processes together to one discriminate:

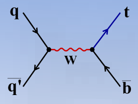


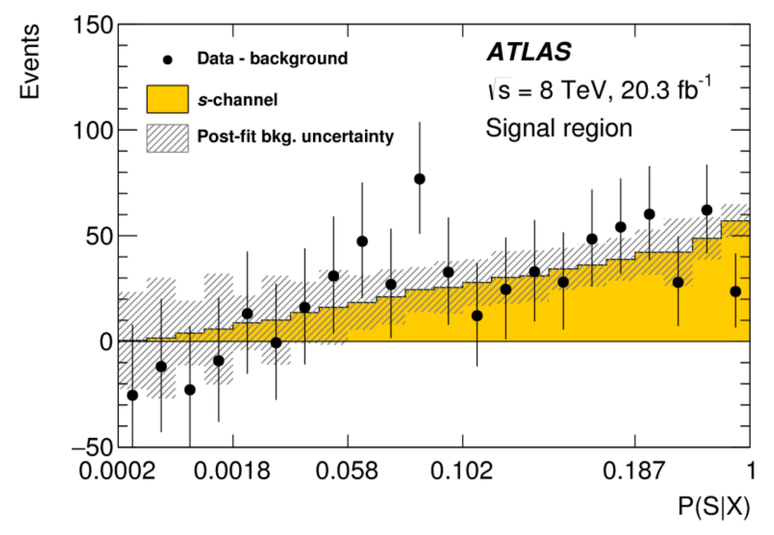


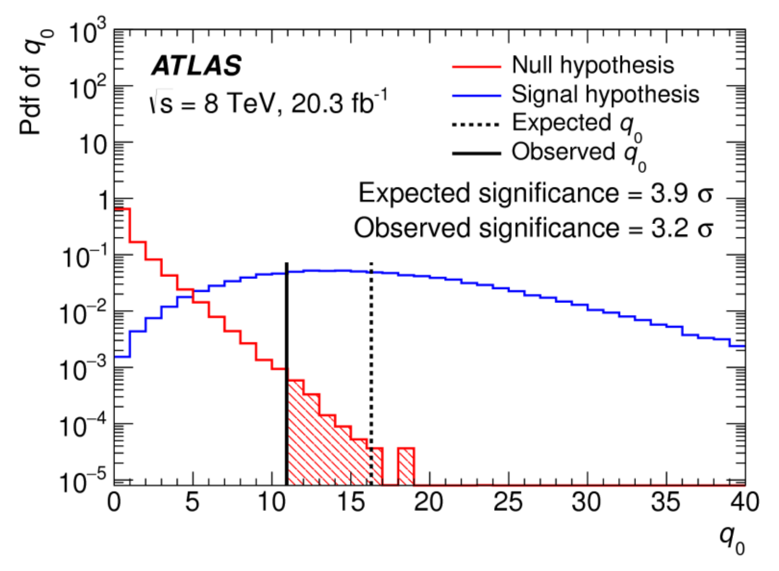
$$P(S|X) = \frac{\sum_i \alpha_{S_i}\mathcal{P}(X|S_i)}{\sum_i \alpha_{S_i}\mathcal{P}(X|S_i) + \sum_j \alpha_{B_j}\mathcal{P}(X|B_j)}$$



s-channel single top quark production

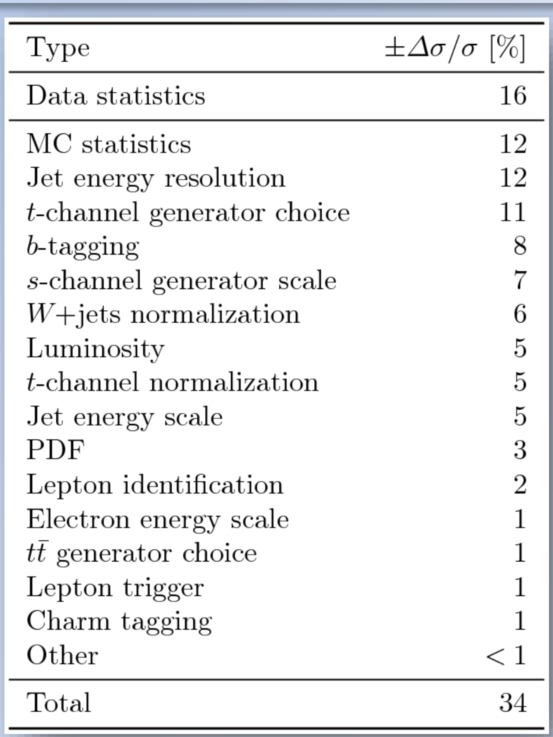






Signal extraction:

Profile maximum likelihood fit



Type	$\pm\Delta\sigma/\sigma$ [%]
Data statistics	16
MC statistics	12
Jet energy resolution	12
t-channel generator choice	11
b-tagging	8
s-channel generator scale	7
W+jets normalization	6
Luminosity	5
t-channel normalization	5
Jet energy scale	5
PDF	3
Lepton identification	2
Electron energy scale	1
$t\bar{t}$ generator choice	1
Lepton trigger	1
Charm tagging	1
Other	< 1
Total	34

Measured cross section:

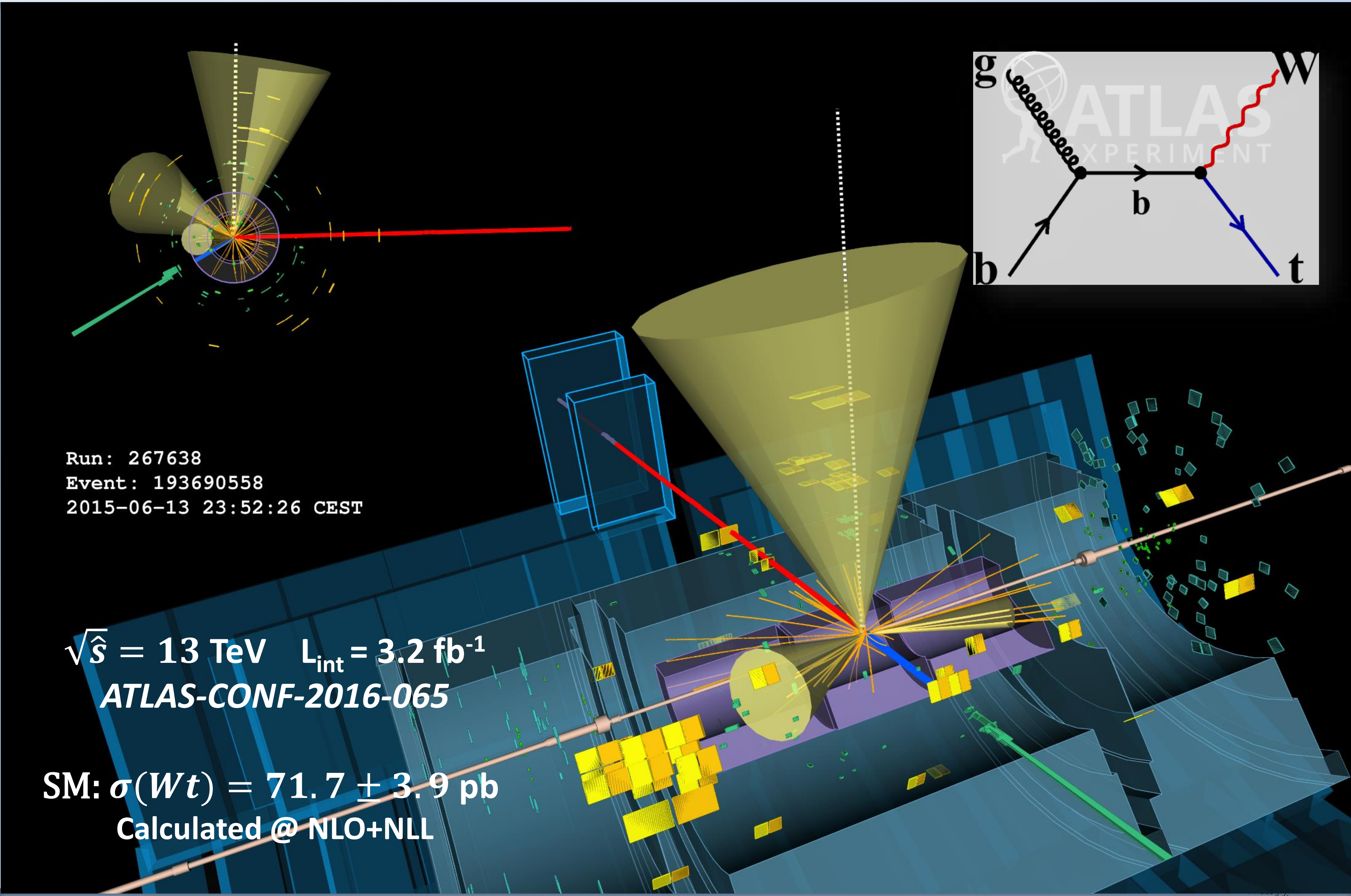
$\sigma(tb) = 4.8 \pm 0.8\ (\text{stat})^{1.6}_{-1.3}(\text{syst})\ \text{pb}$

SM: $\sigma = 5.2 \pm 0.2\ \text{pb}$

Significance: 3.2 σ

Phys. Lett. B 756 (2016) 228-246

Wt production



$\sqrt{\hat{s}} = 13$ TeV $L_{int} = 3.2\ fb^{-1}$

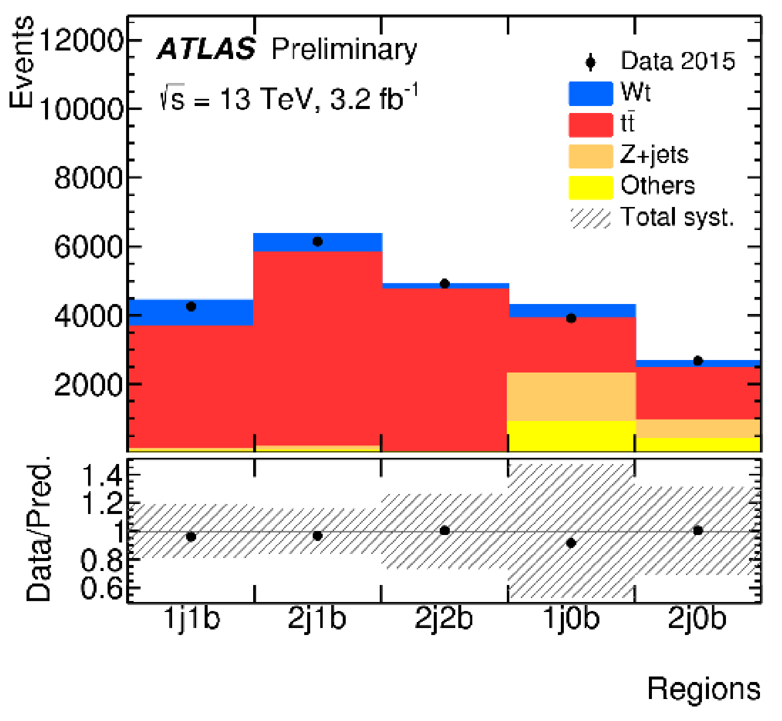
ATLAS-CONF-2016-065

SM: $\sigma(Wt) = 71.7 \pm 3.9$ pb

Calculated @ NLO+NLL

Event selection / Analysis strategy

Di-lepton channel



1j1b: S/B ≈ 25%

2j1b: S/B ≈ 10%

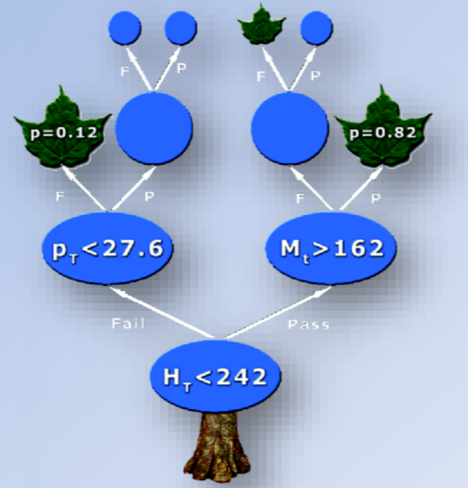
Analysis strategy:

jets

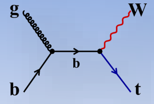
b-tags

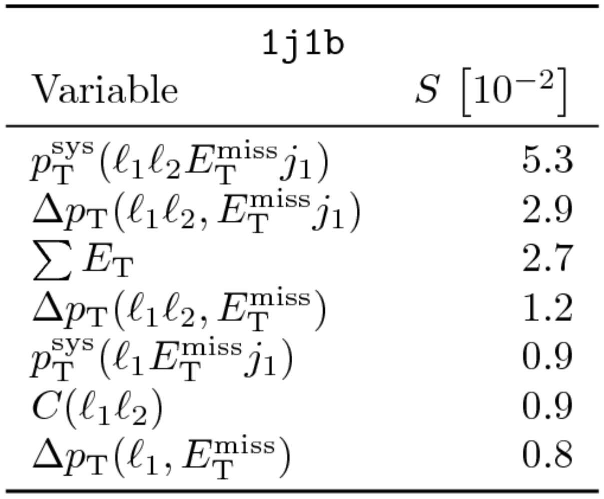
	1	2	3	4
0	VR	VR		
1	SR	SR		
2		CR		

In order to separate Wt and $t\bar{t}$ BDTs are used in the two signal regions



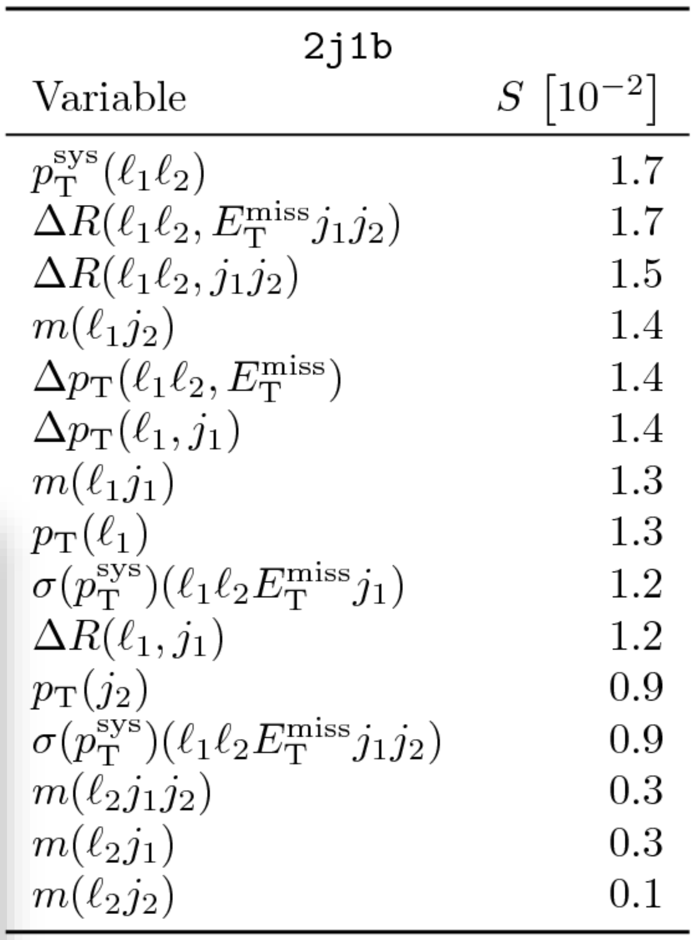
Boosted decision tree





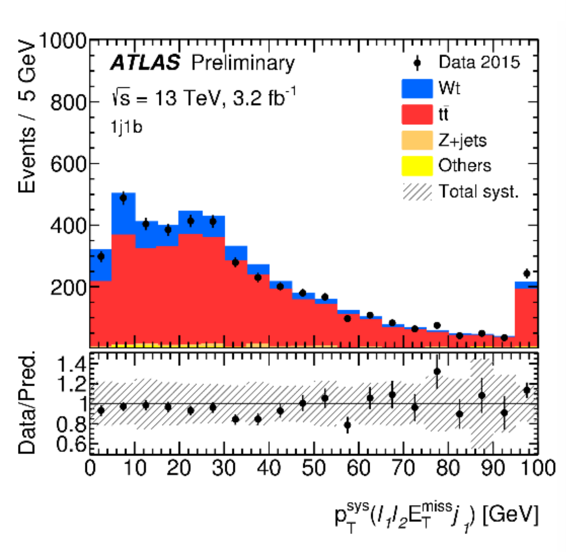
1j1b

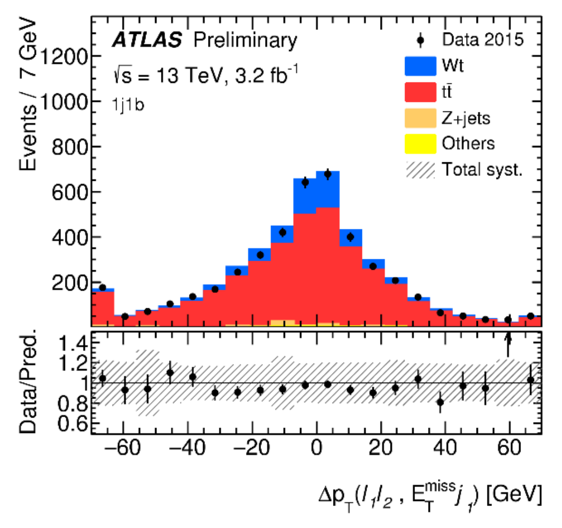
Variable	S $[10^{-2}]$
$p_{\mathrm{T}}^{\mathrm{sys}}(\ell_1\ell_2E_{\mathrm{T}}^{\mathrm{miss}}j_1)$	5.3
$\Delta p_{\mathrm{T}}(\ell_1\ell_2, E_{\mathrm{T}}^{\mathrm{miss}}j_1)$	2.9
$\sum E_{\mathrm{T}}$	2.7
$\Delta p_{\mathrm{T}}(\ell_1\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$	1.2
$p_{\mathrm{T}}^{\mathrm{sys}}(\ell_1E_{\mathrm{T}}^{\mathrm{miss}}j_1)$	0.9
$C(\ell_1\ell_2)$	0.9
$\Delta p_{\mathrm{T}}(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}})$	0.8



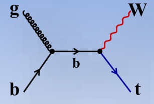
2j1b

Variable	S $[10^{-2}]$
$p_{\mathrm{T}}^{\mathrm{sys}}(\ell_1\ell_2)$	1.7
$\Delta R(\ell_1\ell_2, E_{\mathrm{T}}^{\mathrm{miss}}j_1j_2)$	1.7
$\Delta R(\ell_1\ell_2, j_1j_2)$	1.5
$m(\ell_1j_2)$	1.4
$\Delta p_{\mathrm{T}}(\ell_1\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$	1.4
$\Delta p_{\mathrm{T}}(\ell_1, j_1)$	1.4
$m(\ell_1j_1)$	1.3
$p_{\mathrm{T}}(\ell_1)$	1.3
$\sigma(p_{\mathrm{T}}^{\mathrm{sys}})(\ell_1\ell_2E_{\mathrm{T}}^{\mathrm{miss}}j_1)$	1.2
$\Delta R(\ell_1, j_1)$	1.2
$p_{\mathrm{T}}(j_2)$	0.9
$\sigma(p_{\mathrm{T}}^{\mathrm{sys}})(\ell_1\ell_2E_{\mathrm{T}}^{\mathrm{miss}}j_1j_2)$	0.9
$m(\ell_2j_1j_2)$	0.3
$m(\ell_2j_1)$	0.3
$m(\ell_2j_2)$	0.1



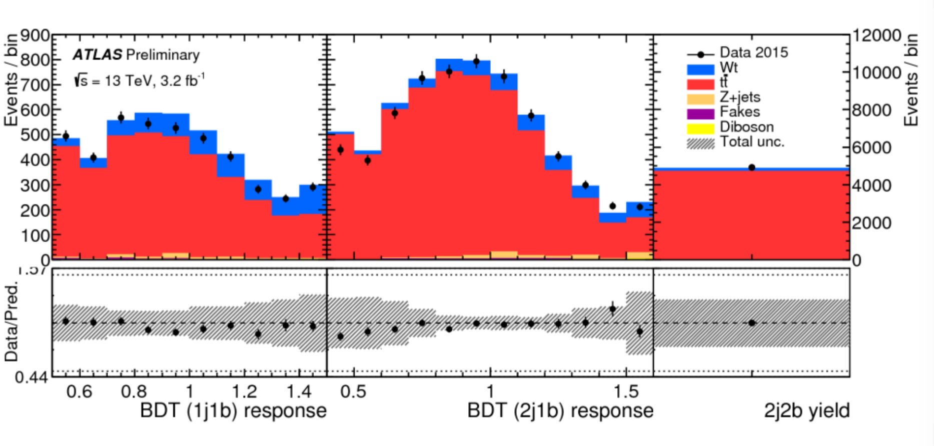


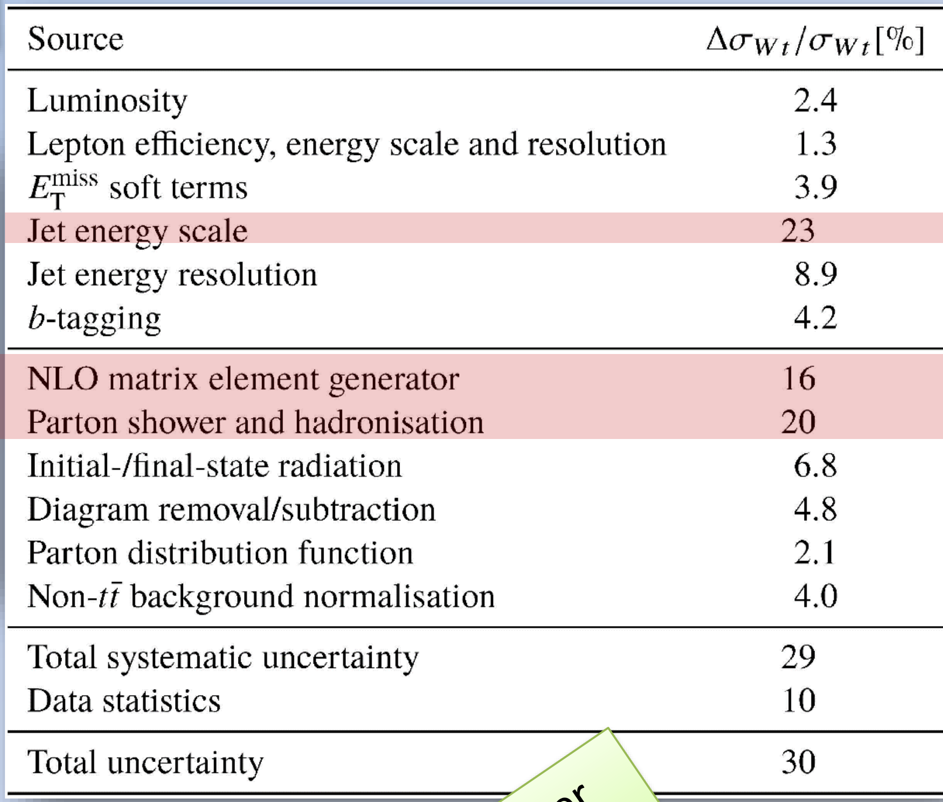
Wt-channel single top quark production



Signal extraction:

Profile maximum likelihood fit





Source	$\Delta\sigma_{Wt}/\sigma_{Wt}[\%]$
Luminosity	2.4
Lepton efficiency, energy scale and resolution	1.3
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft terms	3.9
Jet energy scale	23
Jet energy resolution	8.9
b-tagging	4.2
NLO matrix element generator	16
Parton shower and hadronisation	20
Initial-/final-state radiation	6.8
Diagram removal/subtraction	4.8
Parton distribution function	2.1
Non-$t\bar{t}$ background normalisation	4.0
Total systematic uncertainty	29
Data statistics	10
Total uncertainty	30

Measured cross section:

$\sigma(Wt) = 94 \pm 10\,(\text{stat}){}^{28}_{-23}(\text{syst})$ pb

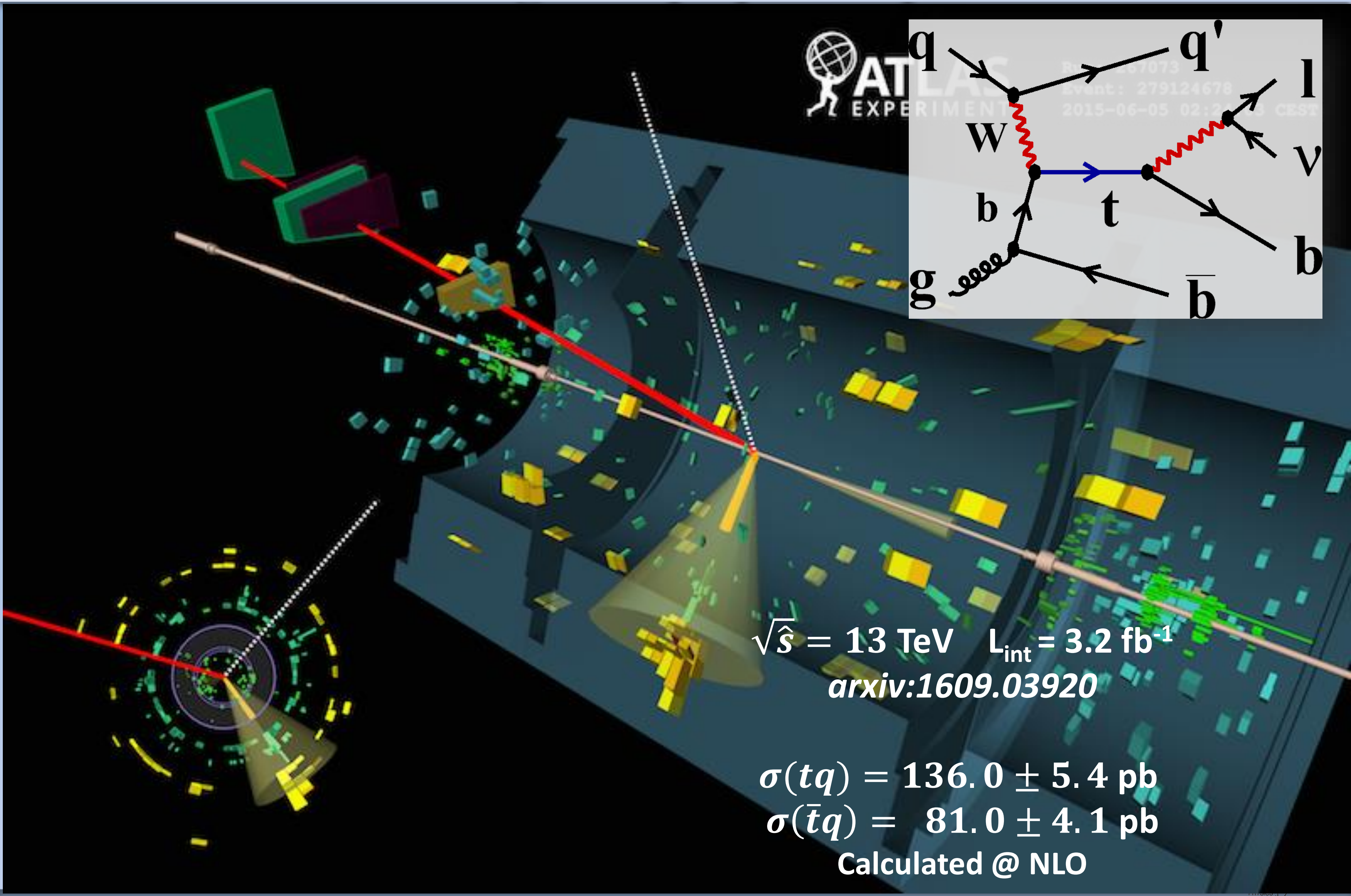
SM: $\sigma = 71.1 \pm 3.9$ pb

Significance: 4.5 σ

ATLAS-CONF-2016-065

More details in poster from Irina Cioara

t-channel single top quark production



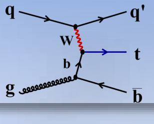
$\sqrt{\hat{s}} = 13$ TeV $L_{int} = 3.2\ \text{fb}^{-1}$

arxiv:1609.03920

$$\sigma(tq) = 136.0 \pm 5.4\ \text{pb}$$
$$\sigma(\bar{t}q) = 81.0 \pm 4.1\ \text{pb}$$

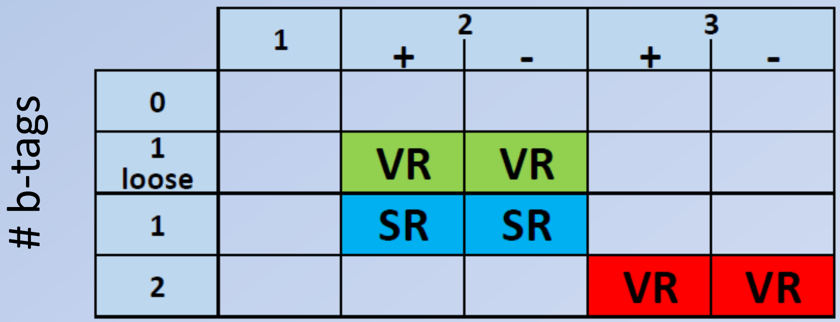
Calculated @ NLO

Event yield



Process	ℓ^+ channel	ℓ^- channel
tq	4 200 ± 170	8 ± 3
$\bar{t}q$	5 ± 2	2 710 ± 140
$t\bar{t}$	13 100 ± 790	13 100 ± 790
Wt	1 640 ± 110	1 640 ± 110
$t\bar{b}$+$\bar{t}b$	298 ± 25	199 ± 18
W^++jets	10 500 ± 2 200	<1
W^-+jets	<1	8 730 ± 1 800
Z, VV+jets	1 530 ± 320	1 410 ± 300
Multijets	2 400 ± 1 200	2 400 ± 1 200
Total expected	33 600 ± 2 600	30 200 ± 2 300
Data observed	34 459	31 056

Analysis strategy:



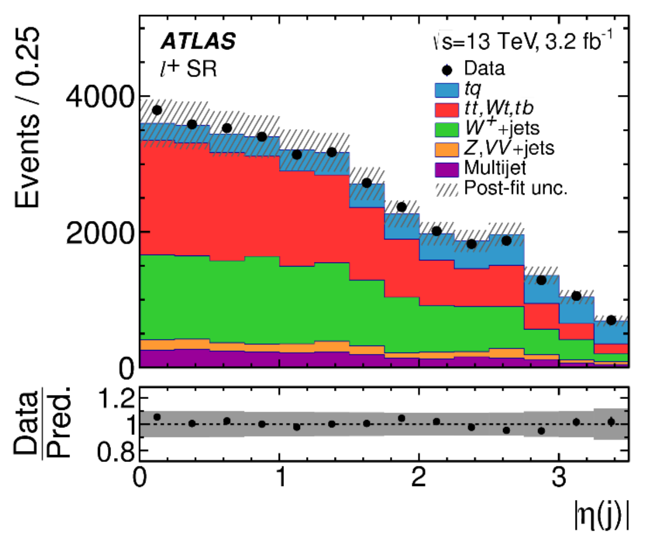
jets

# b-tags	1	2		3	
		+	-	+	-
0					
1 loose		VR	VR		
1		SR	SR		
2				VR	VR

Separated into + and – lepton charge!

+ channel: S/B ≈ 14%

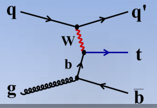
- channel: S/B ≈ 10%

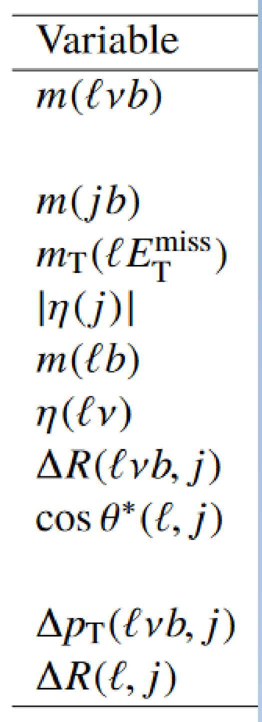


→ Use neural network to:

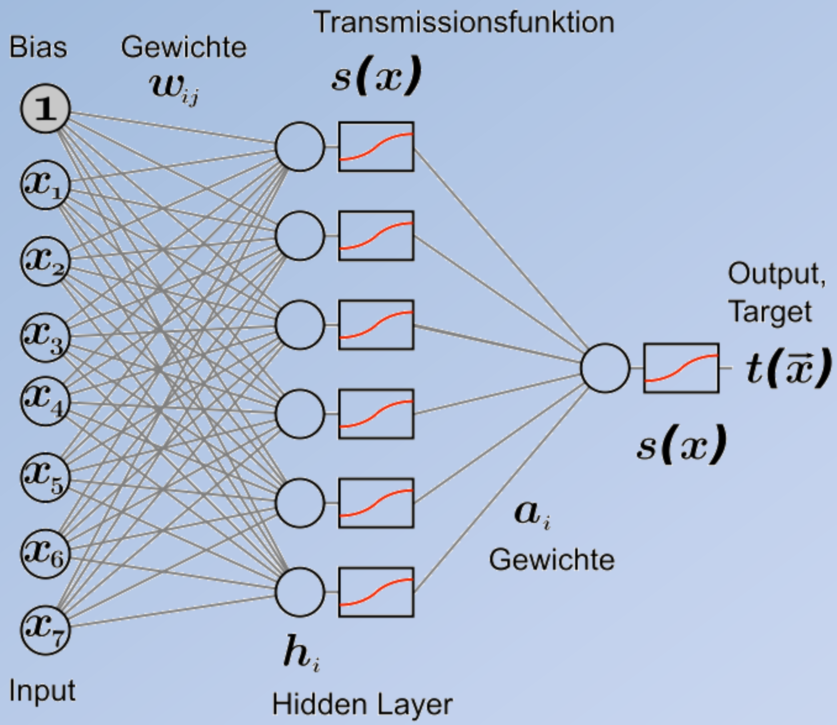
- Improve S/B
- Averaging out systematic shape effects

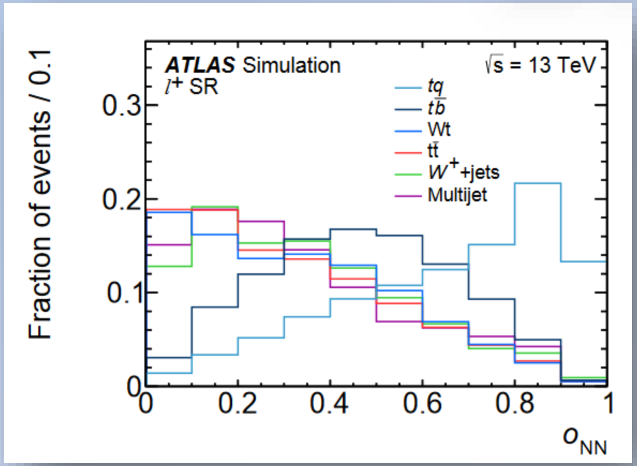
Neural network

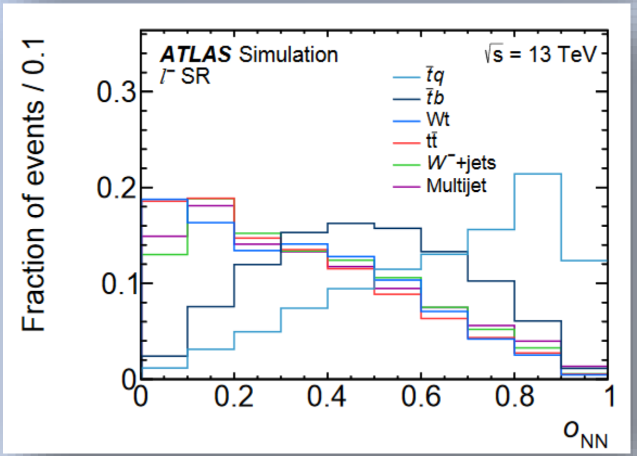




Variable
$m(\ell\nu b)$
$m(jb)$
$m_{\mathrm{T}}(\ell E_{\mathrm{T}}^{\mathrm{miss}})$
$\lvert\eta(j)\rvert$
$m(\ell b)$
$\eta(\ell\nu)$
$\Delta R(\ell\nu b, j)$
$\cos\theta^*(\ell, j)$
$\Delta p_{\mathrm{T}}(\ell\nu b, j)$
$\Delta R(\ell, j)$







Choice of the variables:

- Good data/MC agreement
- Good separation power

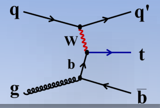
Typical training parameters

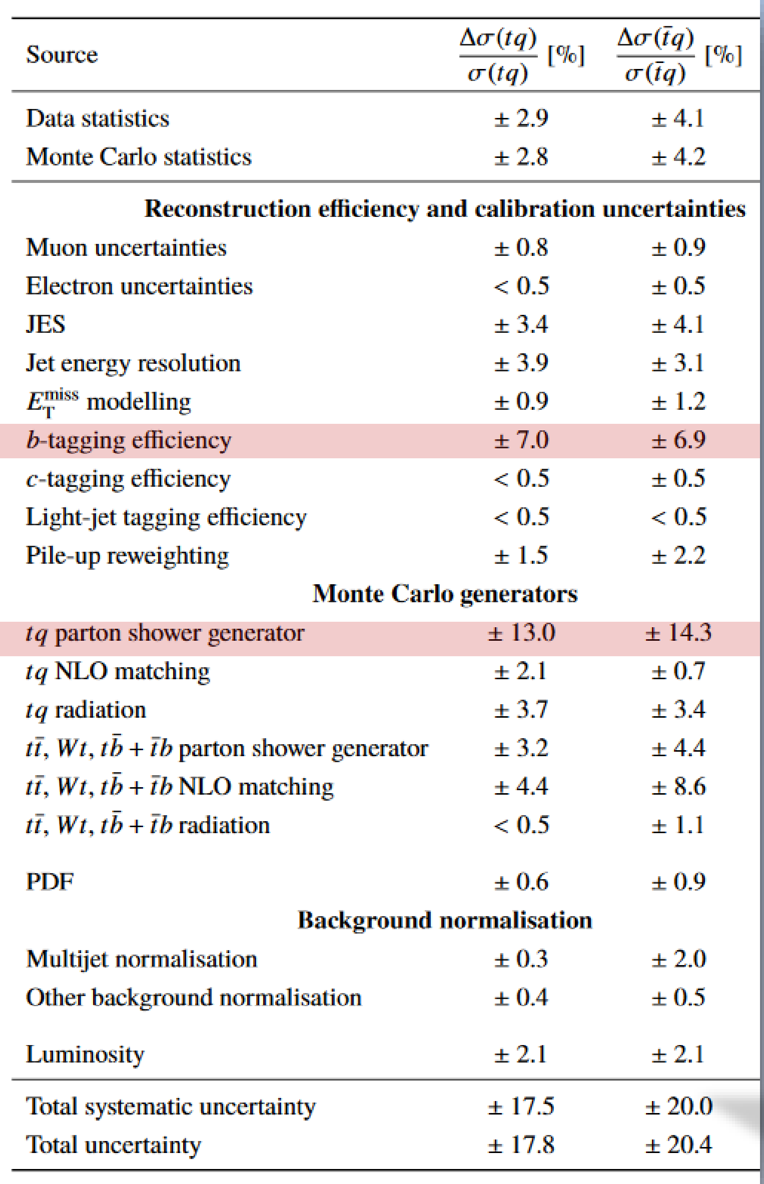
- 50% signal / 50% background
- Only top and W+jets samples used

Validation of the networks

- Overtraining test, Application in validation regions

Inclusive cross section



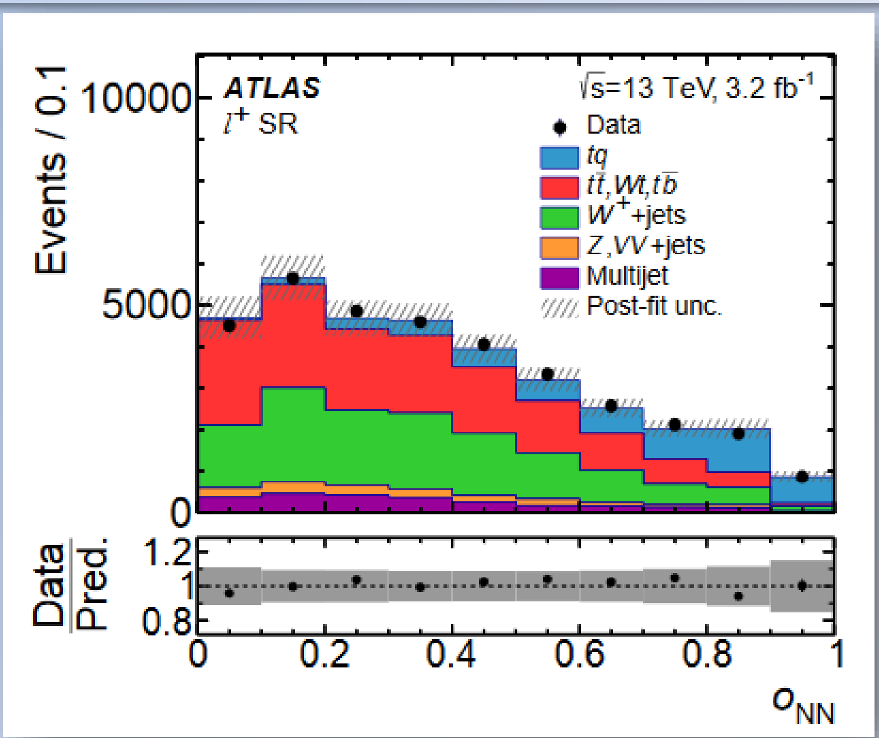


Source	$\frac{\Delta\sigma(tq)}{\sigma(tq)}$ [%]	$\frac{\Delta\sigma(\bar{t}q)}{\sigma(\bar{t}q)}$ [%]
Data statistics	± 2.9	± 4.1
Monte Carlo statistics	± 2.8	± 4.2
Reconstruction efficiency and calibration uncertainties		
Muon uncertainties	± 0.8	± 0.9
Electron uncertainties	< 0.5	± 0.5
JES	± 3.4	± 4.1
Jet energy resolution	± 3.9	± 3.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	± 0.9	± 1.2
b-tagging efficiency	± 7.0	± 6.9
c-tagging efficiency	< 0.5	± 0.5
Light-jet tagging efficiency	< 0.5	< 0.5
Pile-up reweighting	± 1.5	± 2.2
Monte Carlo generators		
tq parton shower generator	± 13.0	± 14.3
tq NLO matching	± 2.1	± 0.7
tq radiation	± 3.7	± 3.4
$t\bar{t}$, Wt, $t\bar{b}+\bar{t}b$ parton shower generator	± 3.2	± 4.4
$t\bar{t}$, Wt, $t\bar{b}+\bar{t}b$ NLO matching	± 4.4	± 8.6
$t\bar{t}$, Wt, $t\bar{b}+\bar{t}b$ radiation	< 0.5	± 1.1
PDF	± 0.6	± 0.9
Background normalisation		
Multijet normalisation	± 0.3	± 2.0
Other background normalisation	± 0.4	± 0.5
Luminosity	± 2.1	± 2.1
Total systematic uncertainty	± 17.5	± 20.0
Total uncertainty	± 17.8	± 20.4

Signal extraction:

Maximum likelihood fit

Systematics evaluated using pseudo experiments



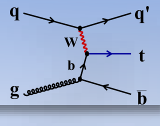
Measured cross section:

$$\sigma(tq) = 156 \pm 5(\text{stat}) \pm 27(\text{syst}) \pm 3\ (\text{lumi})\ \text{pb}$$

$$\sigma(\bar{t}q) = \ 91 \pm 4(\text{stat}) \pm 18(\text{syst}) \pm 2\ (\text{lumi})\ \text{pb}$$

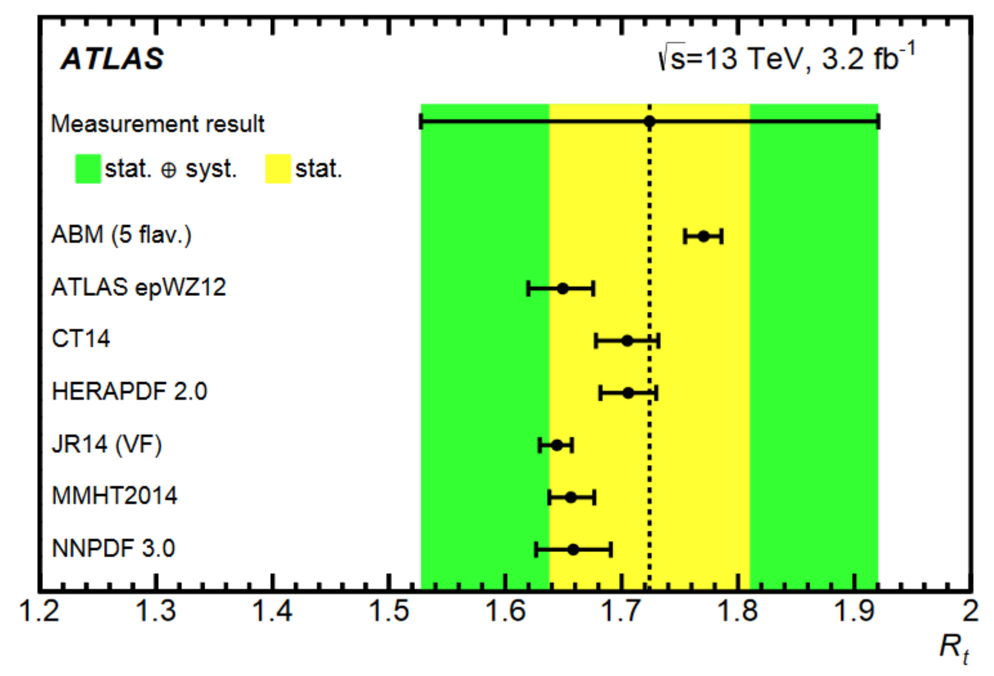
arxiv:1609.03920

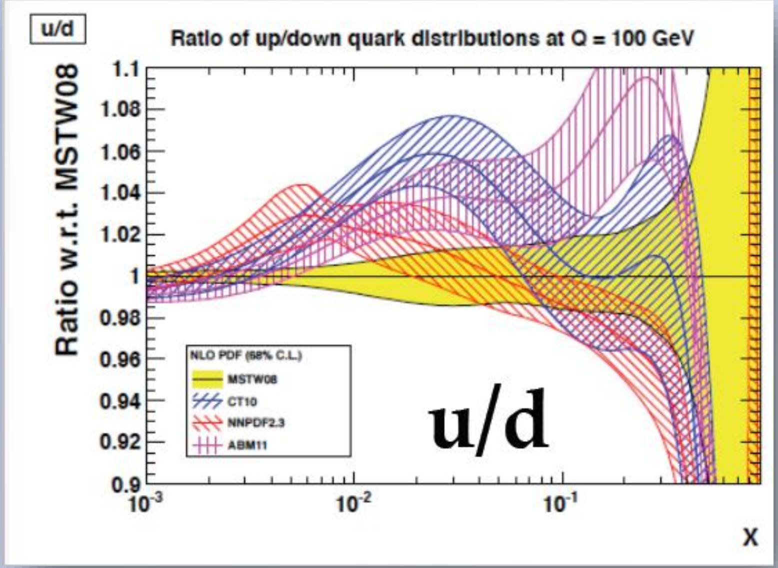
Cross section ratio



The charge of the top quark is connected to the type of the incoming light-flavour quark

→ top-quark/top-antiquark production is sensitive to d/u-quark ratio : $R_t = \sigma(t) / \sigma(\bar{t})$



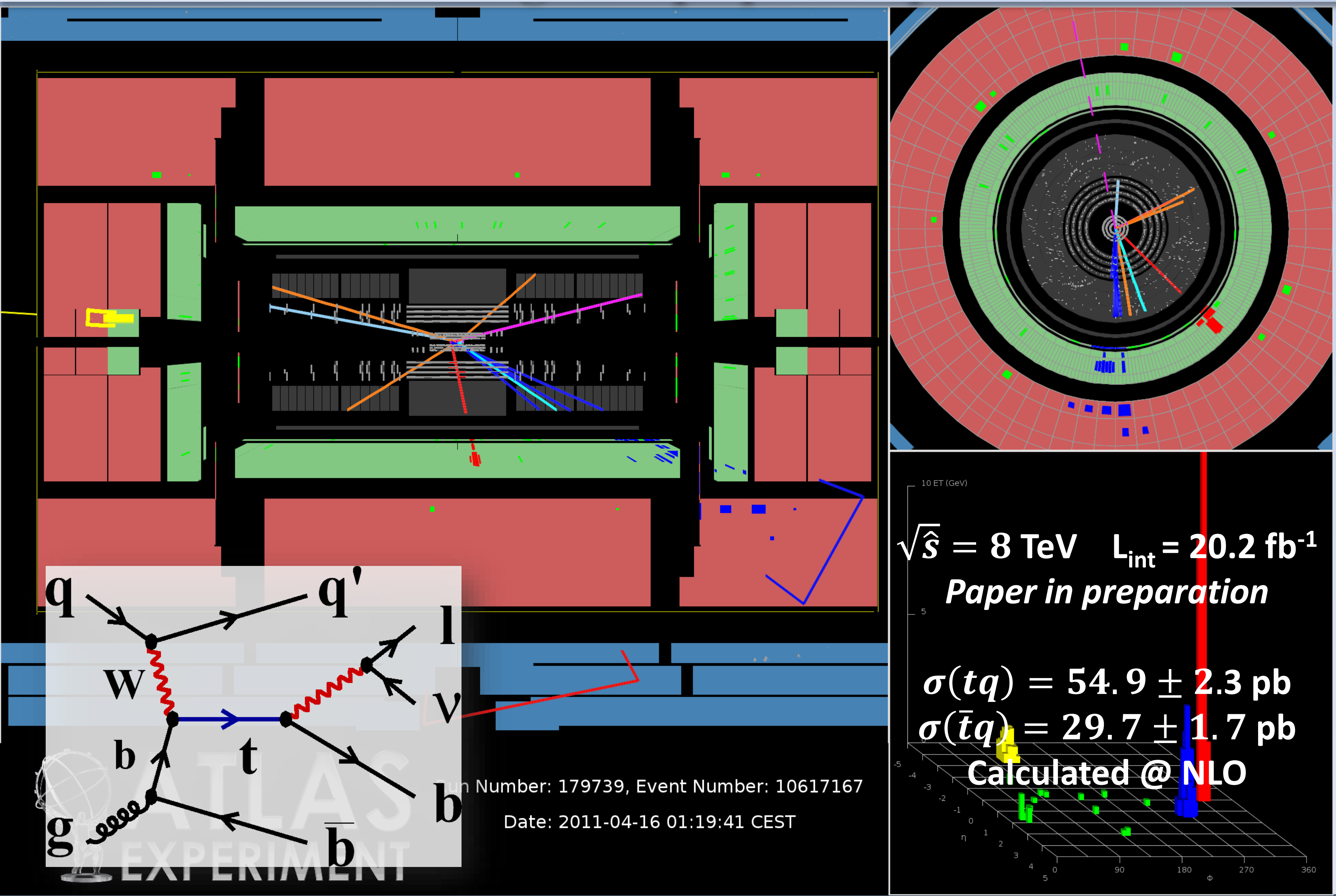


Measured ratio:

$$R_t = 1.72 \pm 0.09\ (\text{stat}) \pm 0.18\ (\text{syst})$$

arxiv:1609.03920

t-channel single top quark production



$\sqrt{\hat{s}}$ = 8 TeV L_{int} = 20.2 fb^{-1}

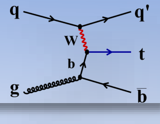
Paper in preparation

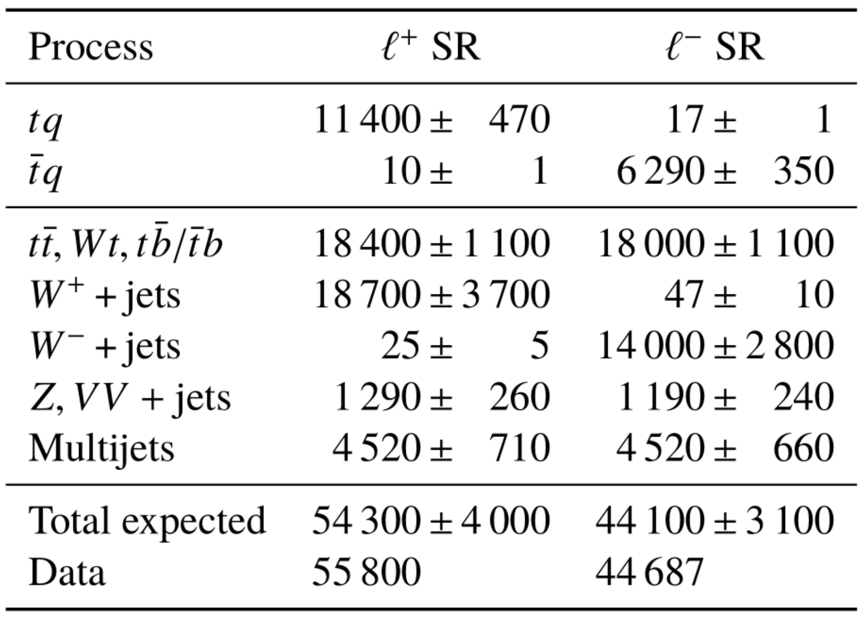
$$\sigma(tq) = 54.9 \pm 2.3 \text{ pb}$$

$$\sigma(\bar{t}q) = 29.7 \pm 1.7 \text{ pb}$$

Calculated @ NLO

Event yield / analysis strategy





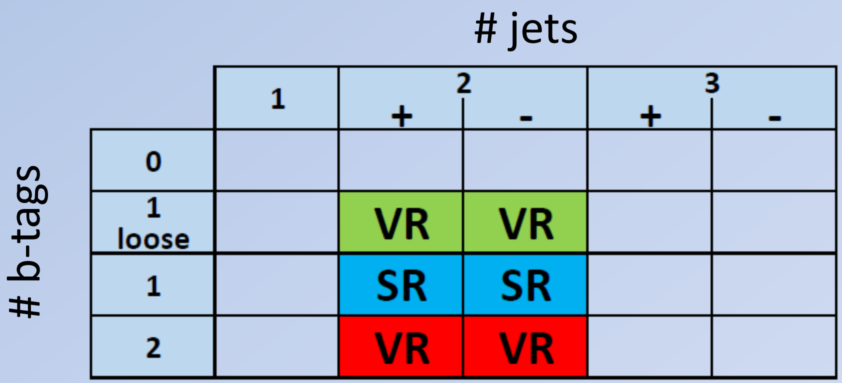
Process	ℓ^+ SR	ℓ^- SR
tq	11 400 ± 470	17 ± 1
$\bar{t}q$	10 ± 1	6 290 ± 350
$t\bar{t}, Wt, t\bar{b}/\bar{t}b$	18 400 ± 1 100	18 000 ± 1 100
W^+ + jets	18 700 ± 3 700	47 ± 10
W^- + jets	25 ± 5	14 000 ± 2 800
Z, VV + jets	1 290 ± 260	1 190 ± 240
Multijets	4 520 ± 710	4 520 ± 660
Total expected	54 300 ± 4 000	44 100 ± 3 100
Data	55 800	44 687

+ channel: S/B ≈ 26%

- channel: S/B ≈ 17%

Measurement is done in a fiducial phase space close to the experimental one

Analysis strategy:

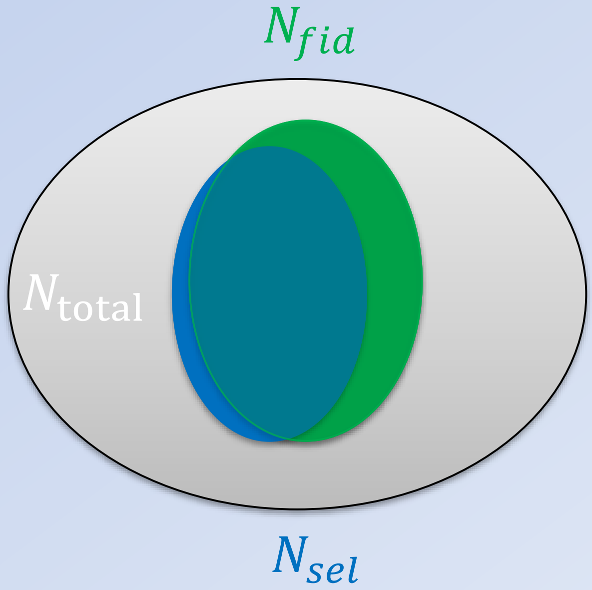


jets

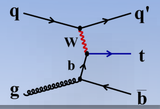
b-tags

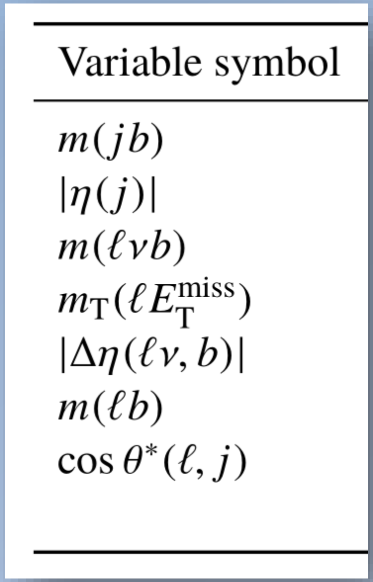
	1	2		3	
		+	-	+	-
0					
1 loose		VR	VR		
1		SR	SR		
2		VR	VR		

Separated into + and – lepton charge!

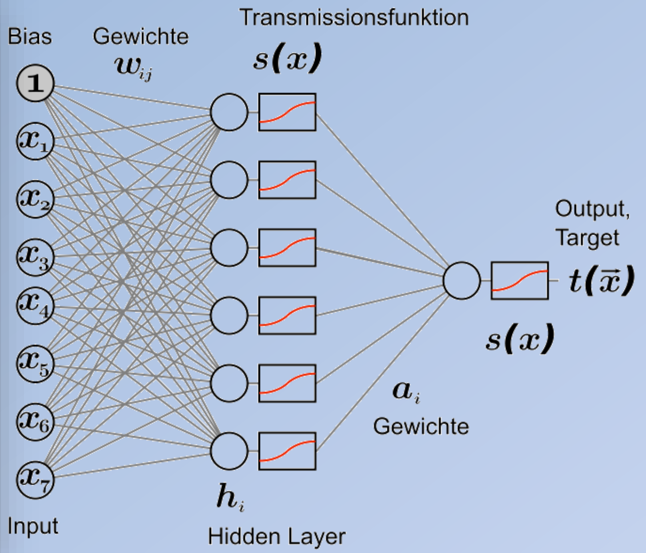


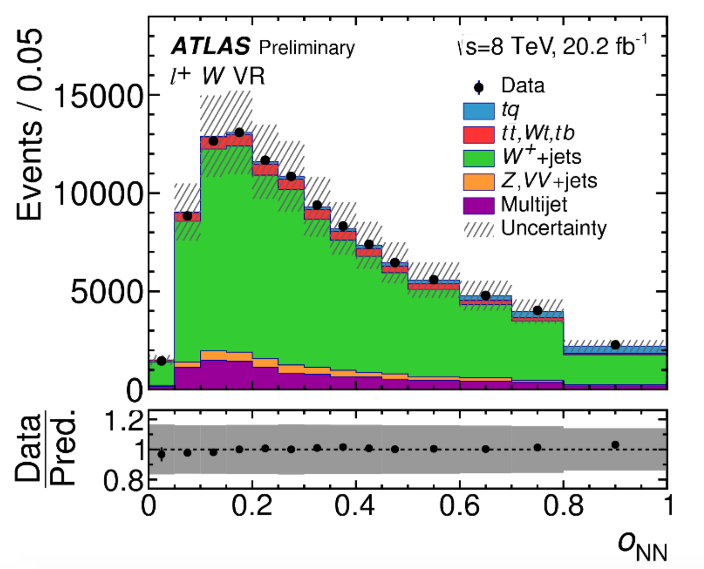
Multivariate Analyses

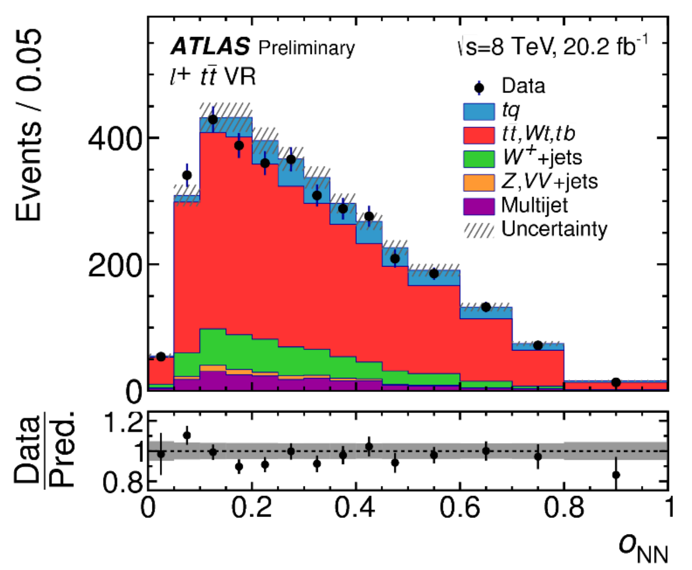




Variable symbol
$m(jb)$
$\|\eta(j)\|$
$m(\ell\nu b)$
$m_{\mathrm{T}}(\ell E_{\mathrm{T}}^{\mathrm{miss}})$
$\|\Delta\eta(\ell\nu, b)\|$
$m(\ell b)$
$\cos\theta^{*}(\ell, j)$







Choice of the variables:

- Good data/MC agreement
- Intensive study to reduce number of input variables, while keeping sensitivity

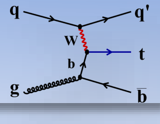
Typical training parameters

- 50% signal / 50% background

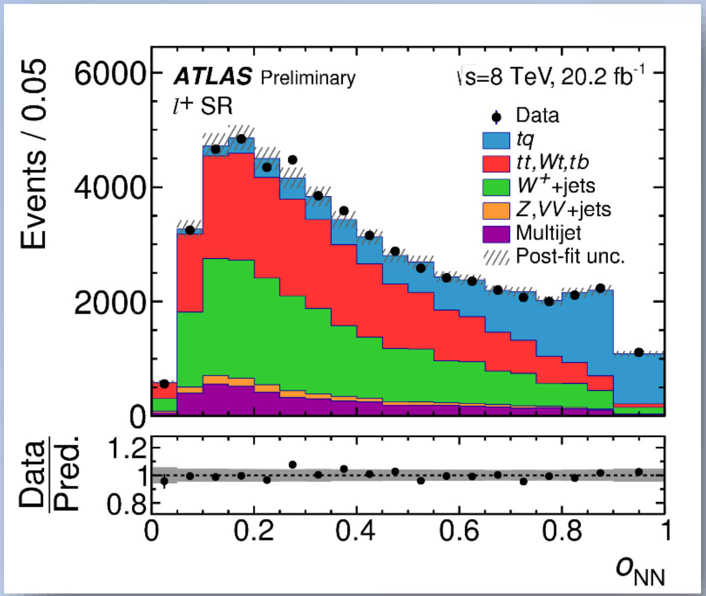
Validation of the networks

- Overtraining test,
  Application in validation regions

Fiducial cross section result



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



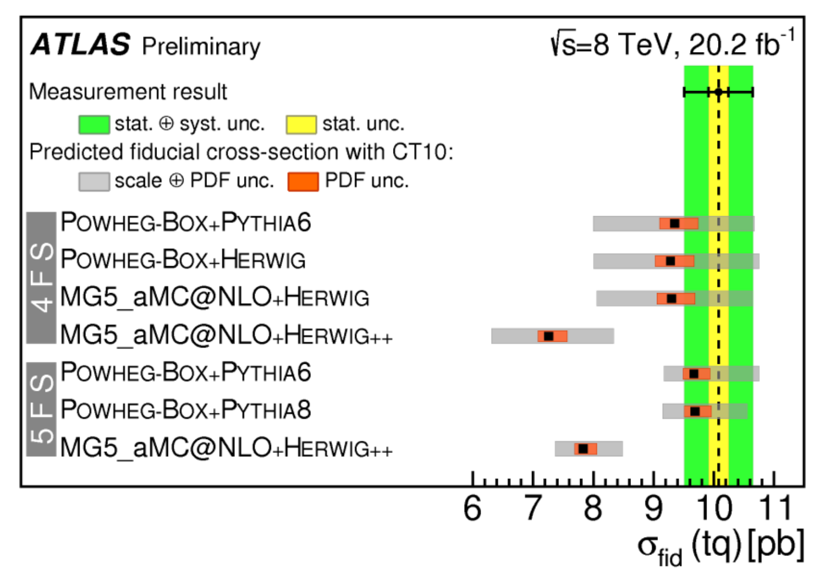
Several uncertainties are reduced for the fiducial cross-section w.r.t the total cross-section

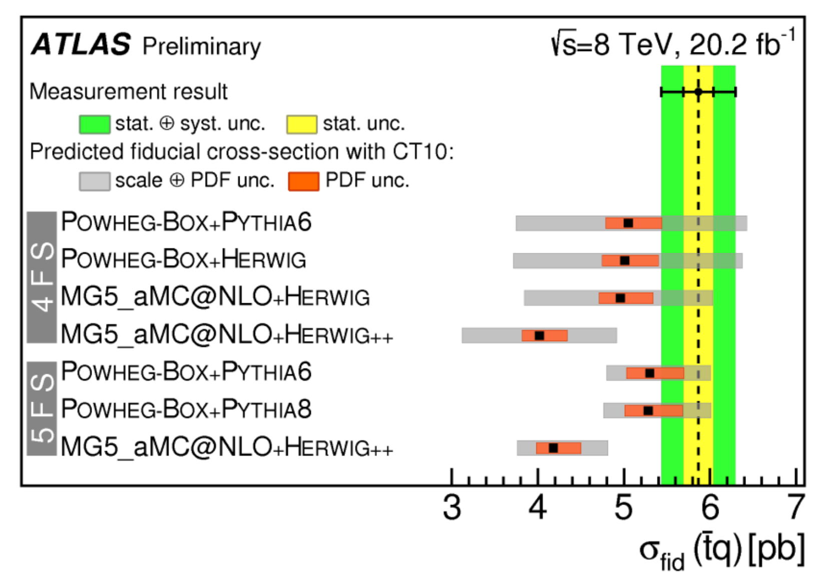
Total uncertainty:

tq : 5.8% !

$\bar{t}q$: 7.8%

Comparisons with different MC generators





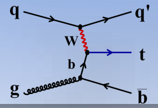
Predictions calculated using:

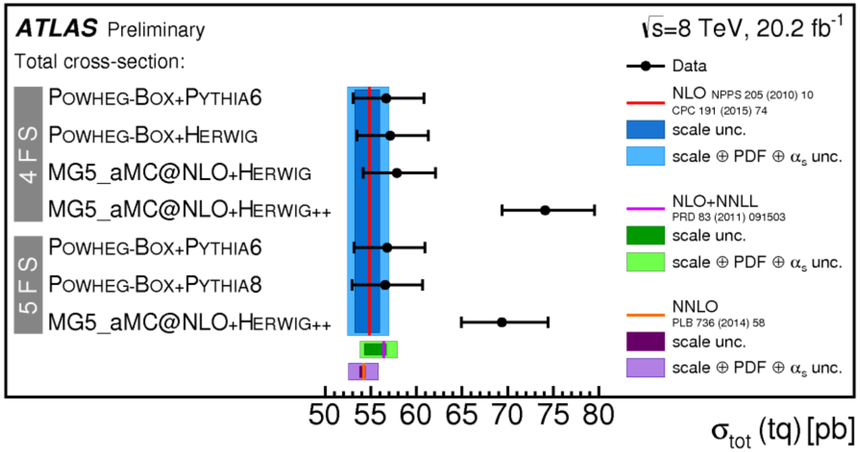
$$\sigma_{fid} = A_{fid} \cdot \sigma_{total}$$

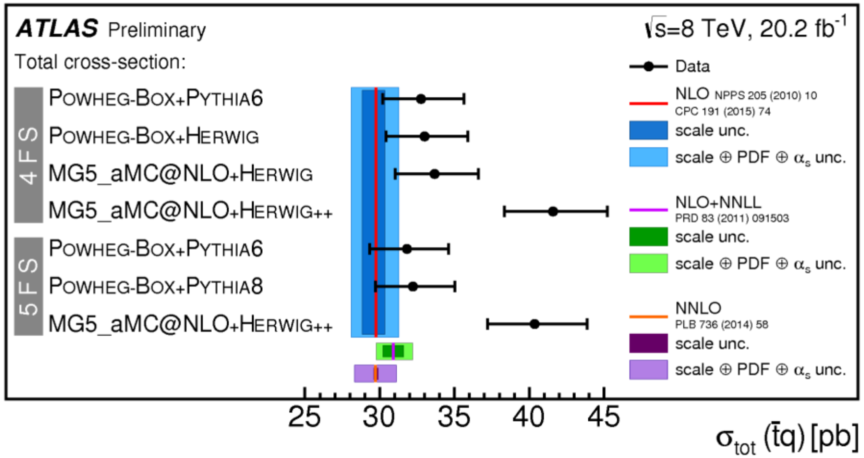
σ_{total}: taken from MC generators

- 5FS gives in general slighty higher predictions
- scale uncertainty on 4FS calculations is larger than on 5FS ones
- Herwig++ has too soft jets → lower acceptance

Extrapolated cross section







Measured cross section extrapolated to full phase space is calculated with:

$$\sigma_{tot} = \frac{1}{A_{fid}} \cdot \sigma_{fid}^{meas}$$

Taking into account in a correlated way theory uncertainties on A_{fid}

Measured extrapolated cross section using Powheg+Pythia6:

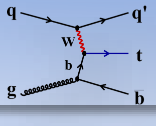
$\sigma_{tot}(tq) = 56.7 \pm 0.9(\text{stat}) \pm 2.7(\text{exp}) \pm 3.0(\text{theo}) \pm 1.1\ (\text{lumi})$ pb

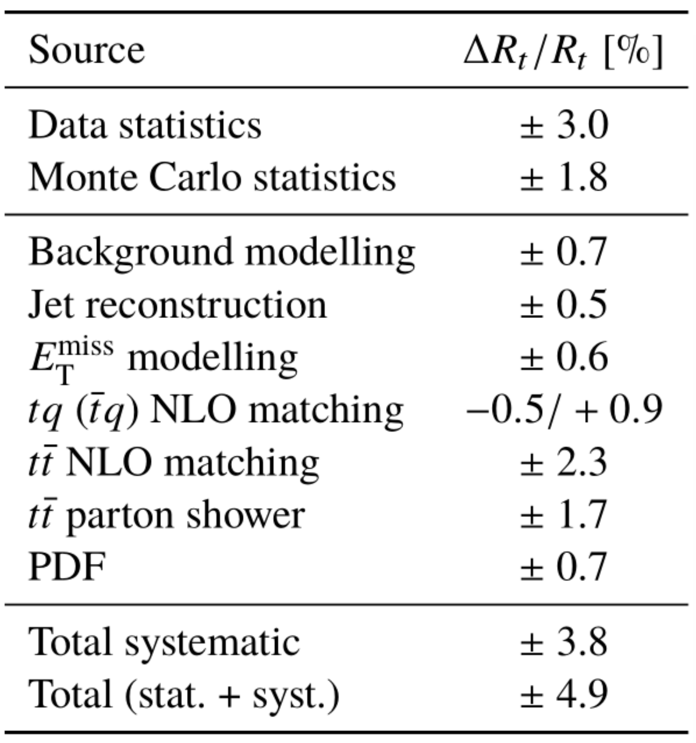
1.6% 4.8% 5.3% 1.9%

$\sigma_{tot}(\bar{t}q) = 32.8 \pm 0.8(\text{stat}) \pm 2.2(\text{exp}) \pm 1.7(\text{theo}) \pm 0.6\ (\text{lumi})$ pb

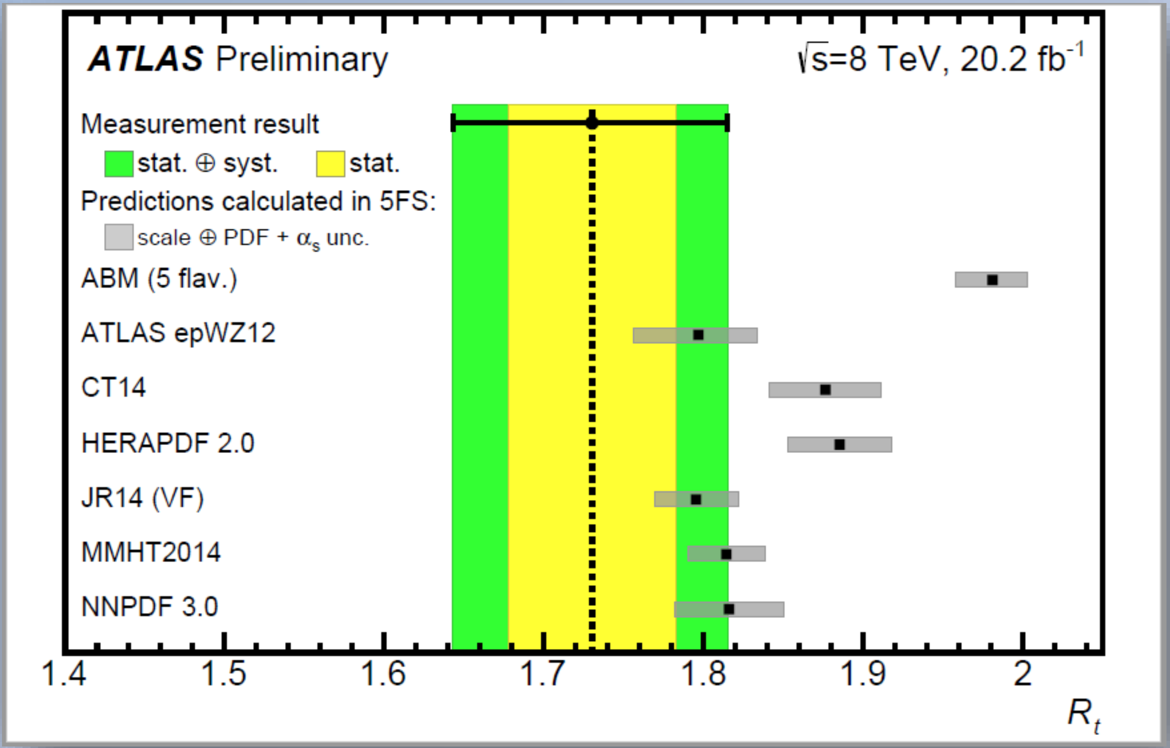
2.4% 6.7% 5.2% 1.9%

Cross section ratio





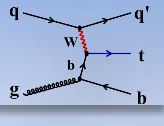
Source	$\Delta R_t / R_t$ [%]
Data statistics	± 3.0
Monte Carlo statistics	± 1.8
Background modelling	± 0.7
Jet reconstruction	± 0.5
E_T^{miss} modelling	± 0.6
tq ($\bar{t}q$) NLO matching	$-0.5/+0.9$
$t\bar{t}$ NLO matching	± 2.3
$t\bar{t}$ parton shower	± 1.7
PDF	± 0.7
Total systematic	± 3.8
Total (stat. + syst.)	± 4.9

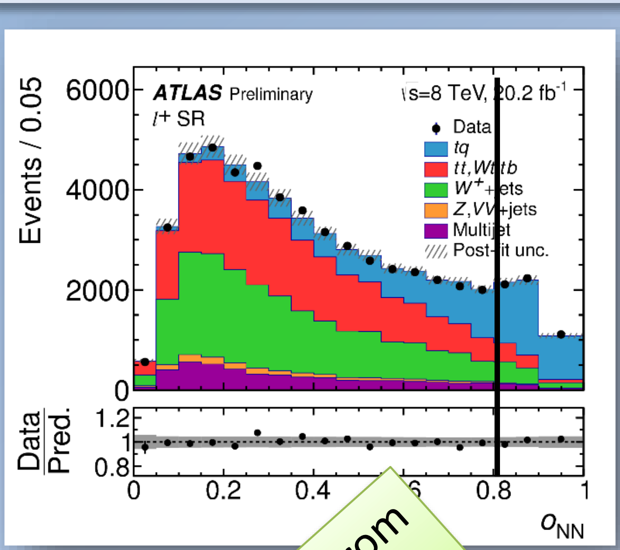


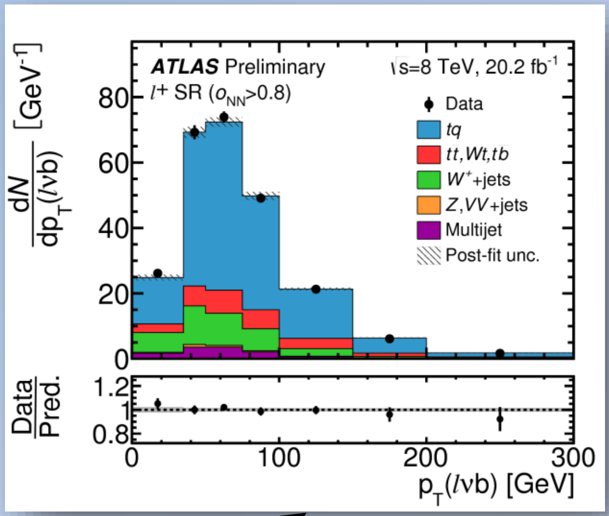
Using the extrapolated cross section:

$$R_t = 1.73 \pm 0.05\ (\text{stat}) \pm 0.07\ (\text{syst})$$

Differential cross sections







Chosen binning

- Resolution
- Statistics
- Migration matrix
- Structure in measured distributions

Cut on $o_{NN} > 0.8$

More details in the talk from Pienpen Seema in the YSF

correct for events that pass fid. but not reco.

respond matrix

number of observed events

$$d\hat{\sigma}_k = \frac{1}{\boxed{L_{int}}} \cdot \boxed{C_k^{\text{ptcl!reco}}} \cdot \sum_j \boxed{M_{jk}^{-1}} \cdot \boxed{C_j^{\text{reco!ptcl}}} \cdot \left(\boxed{N_j^{\text{data}}} - \boxed{\hat{B}^j}\right)$$

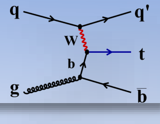
Particle level

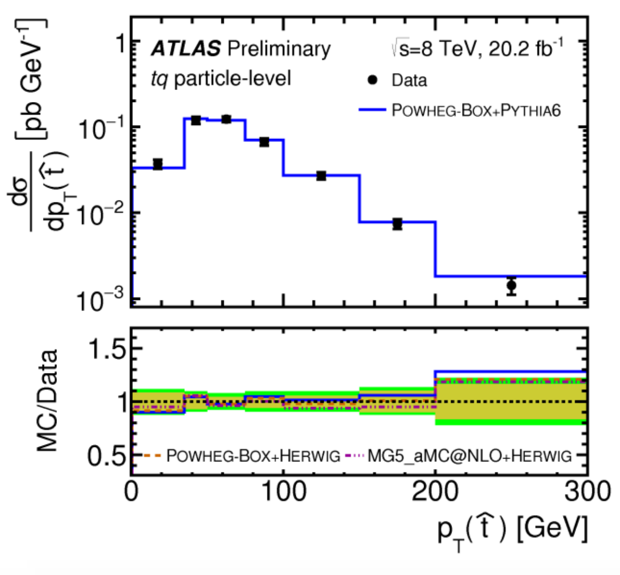
integrated luminosity

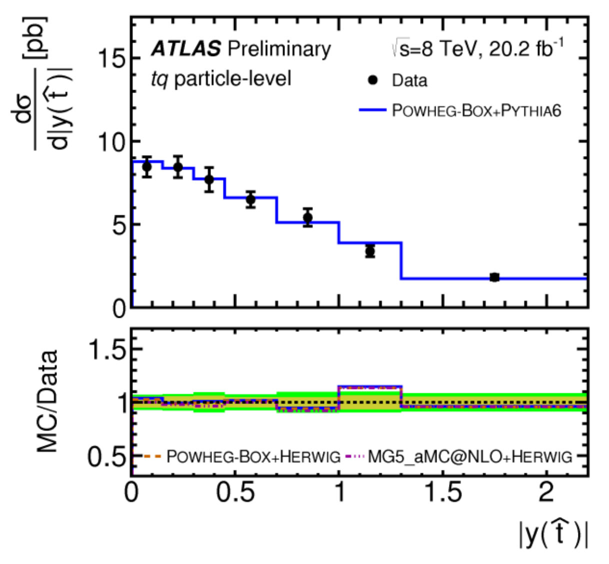
correct for events that pass reco. but not fid.

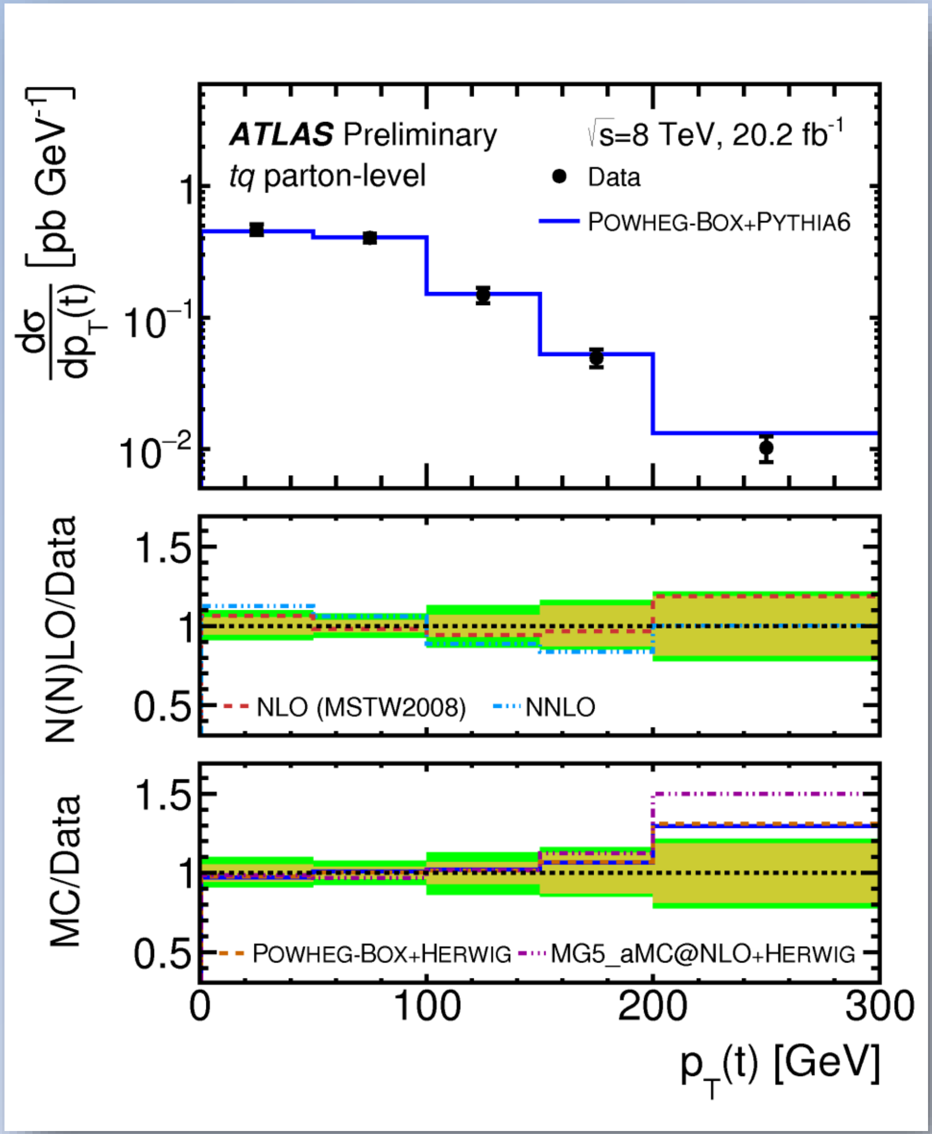
number of background events

Differential cross sections

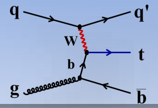


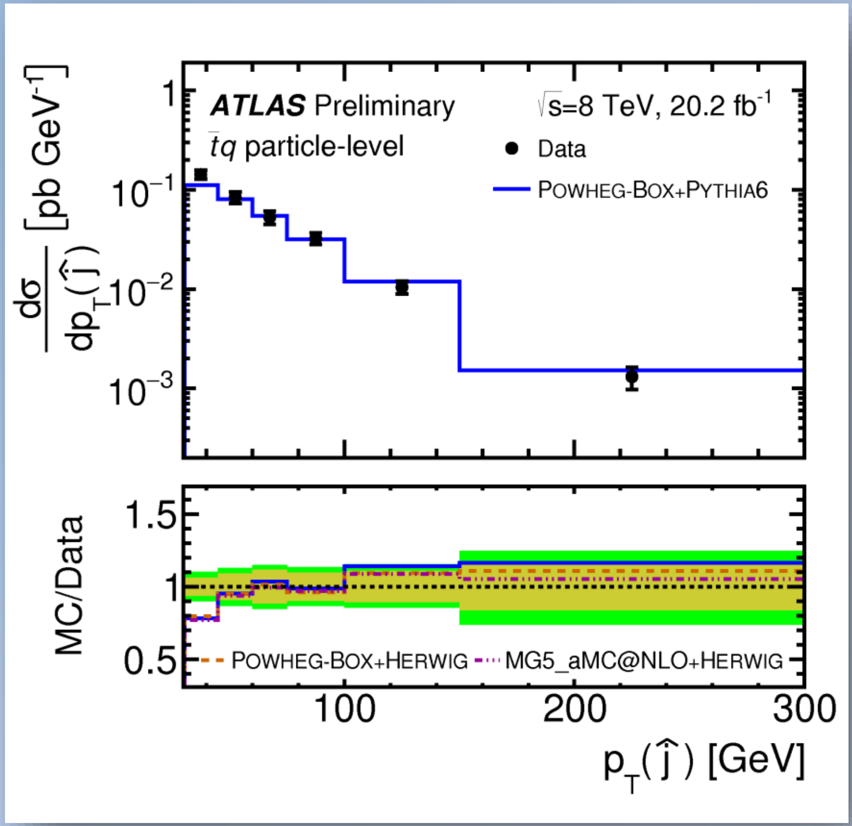


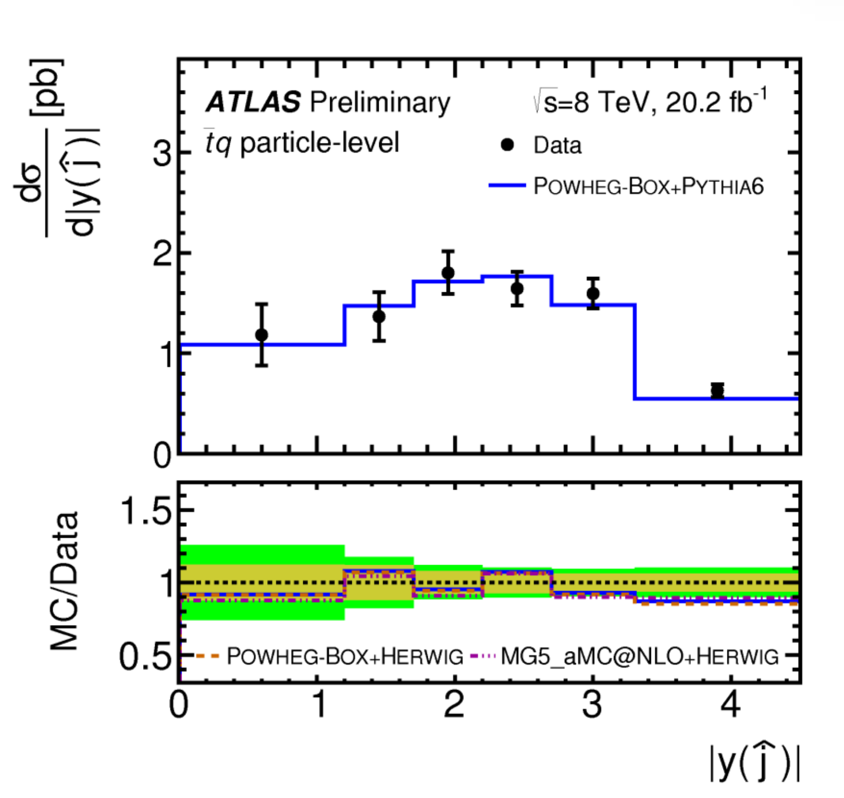


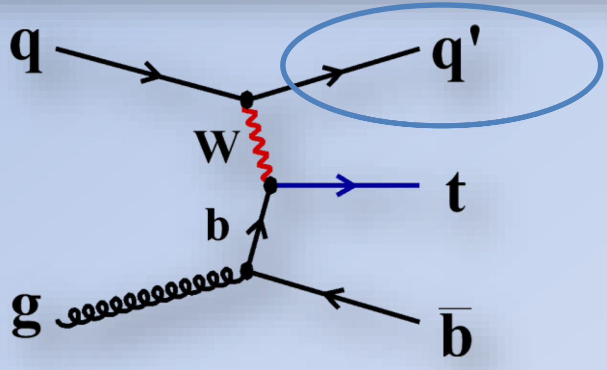


Differential cross section



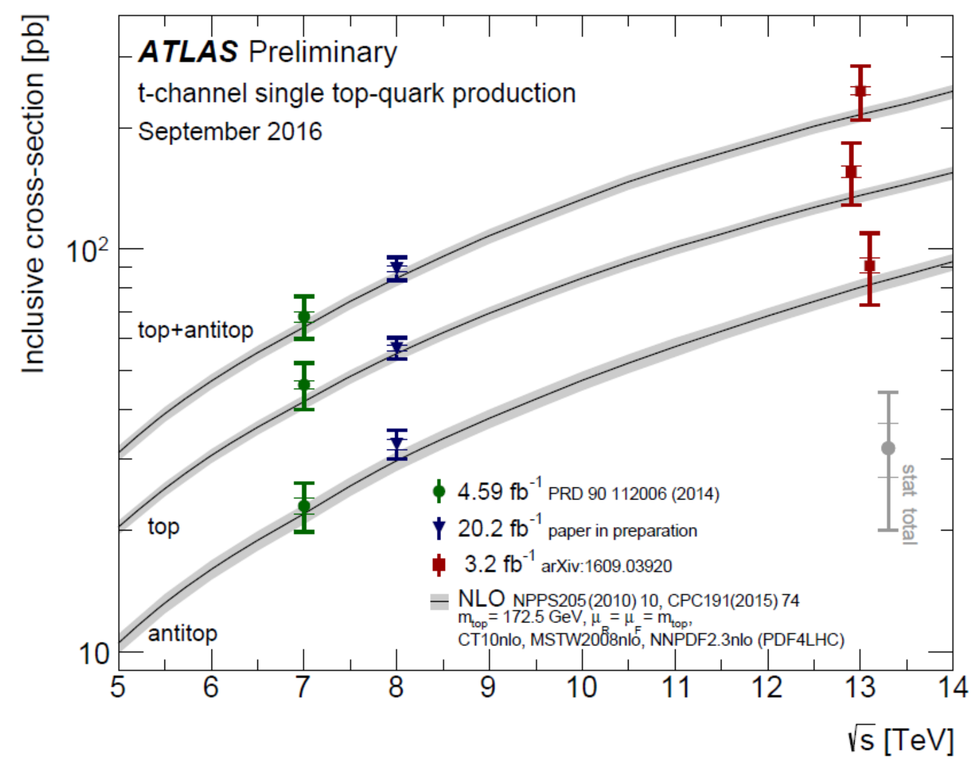


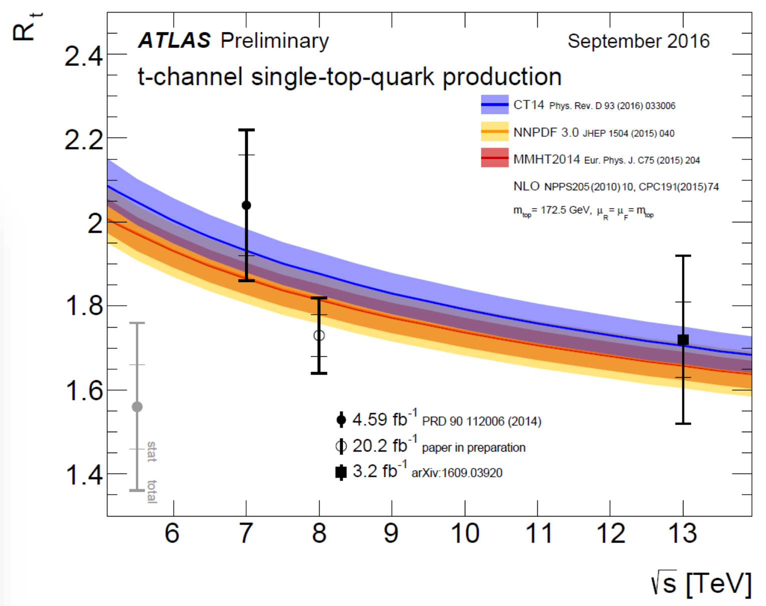


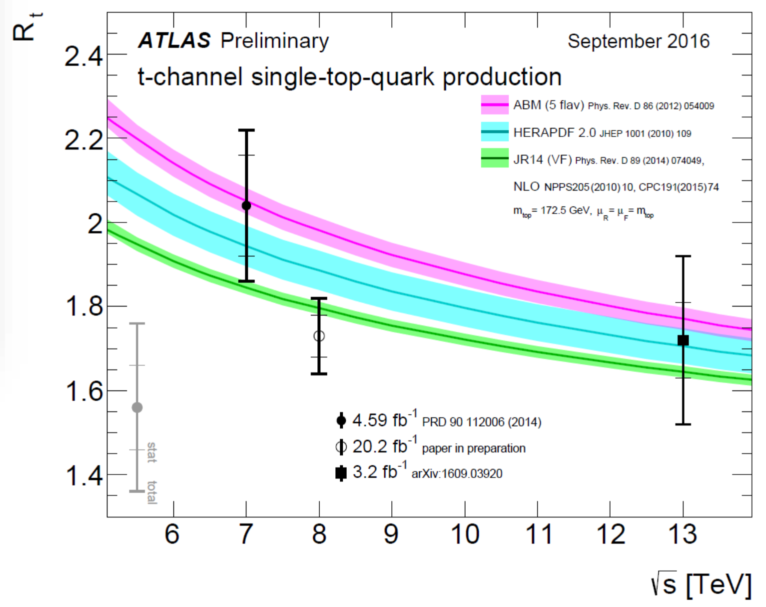


- Use different NN - without $|\eta(j)|$
- Predictions are harder than the data
- Similar behaviour found also in absolute XS

t-channel Summary



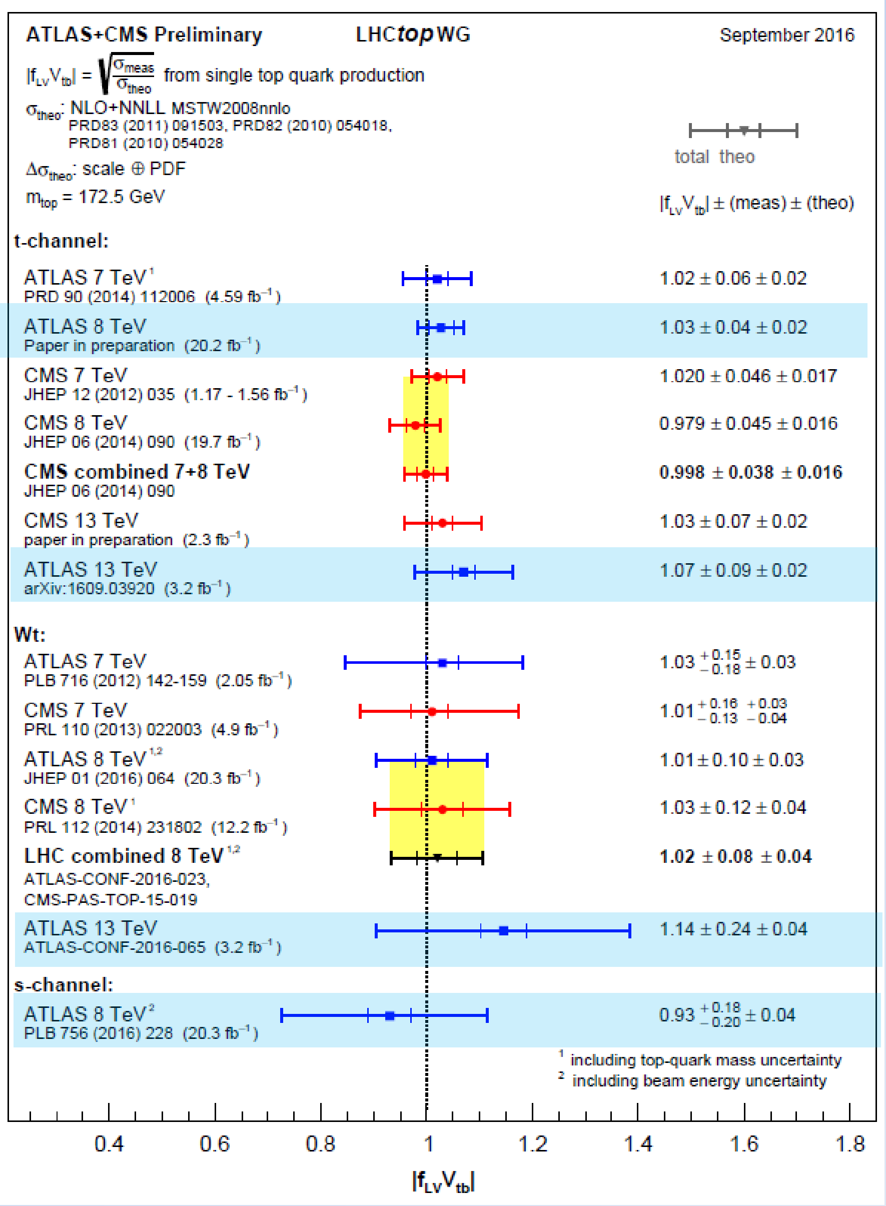




Determination of $|V_{tb}|$

Cross section is proportional to $|V_{tb}|^2$

- In the Standard Model with 3 quark generations one expects $|V_{tb}| \sim 1$ (unitarity):
- $$|V_{tb}^{\text{obs}}| = \sqrt{\frac{\sigma^{\text{obs}}}{\sigma^{\text{theo}}}}$$



Assumptions for the extraction:

- Independence of 3 quark generations
- Left-handed weak interaction
- Top quark decays only into b quarks:

  $(|V_{td}|, |V_{ts}| \ll |V_{tb}|)$

Can be done with all three single top processes

Highest precision for t-channel:

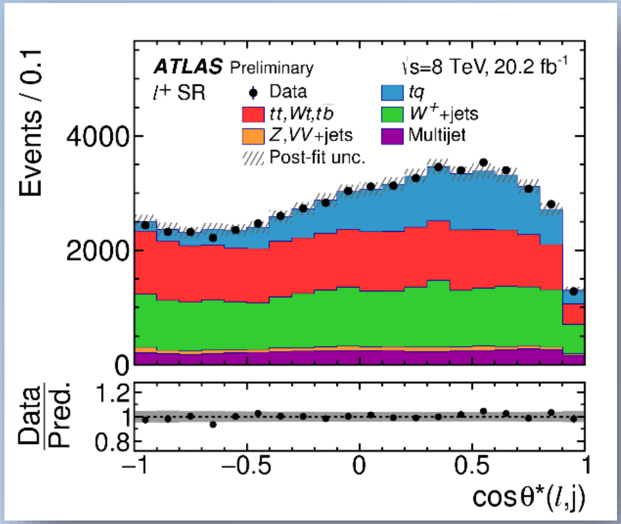
$\sim 4\%$

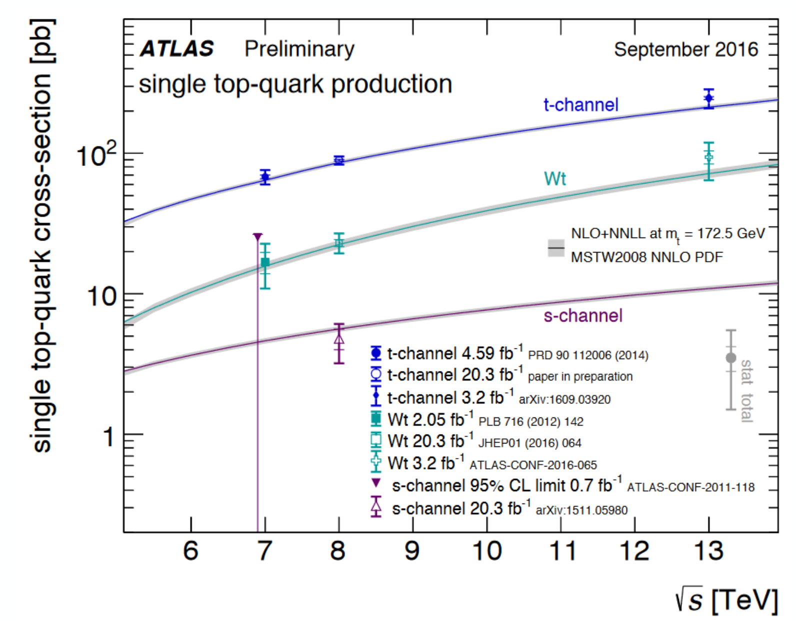
Summary

Have shown first results with the 2015 dataset @ 13 TeV for t-channel and Wt
→ no surprises, main systematic: generator modelling

Comprehensive measurement in the t-channel @ 8 TeV

- Fiducial cross section
- Cross section extrapolated to the full phase space
- Cross section ratio
- Differential cross sections for top p_T, top rapidity, and the first time also for the forward light jet





Evidence for s-channel production @ 8 TeV

- Explored matrix element technique