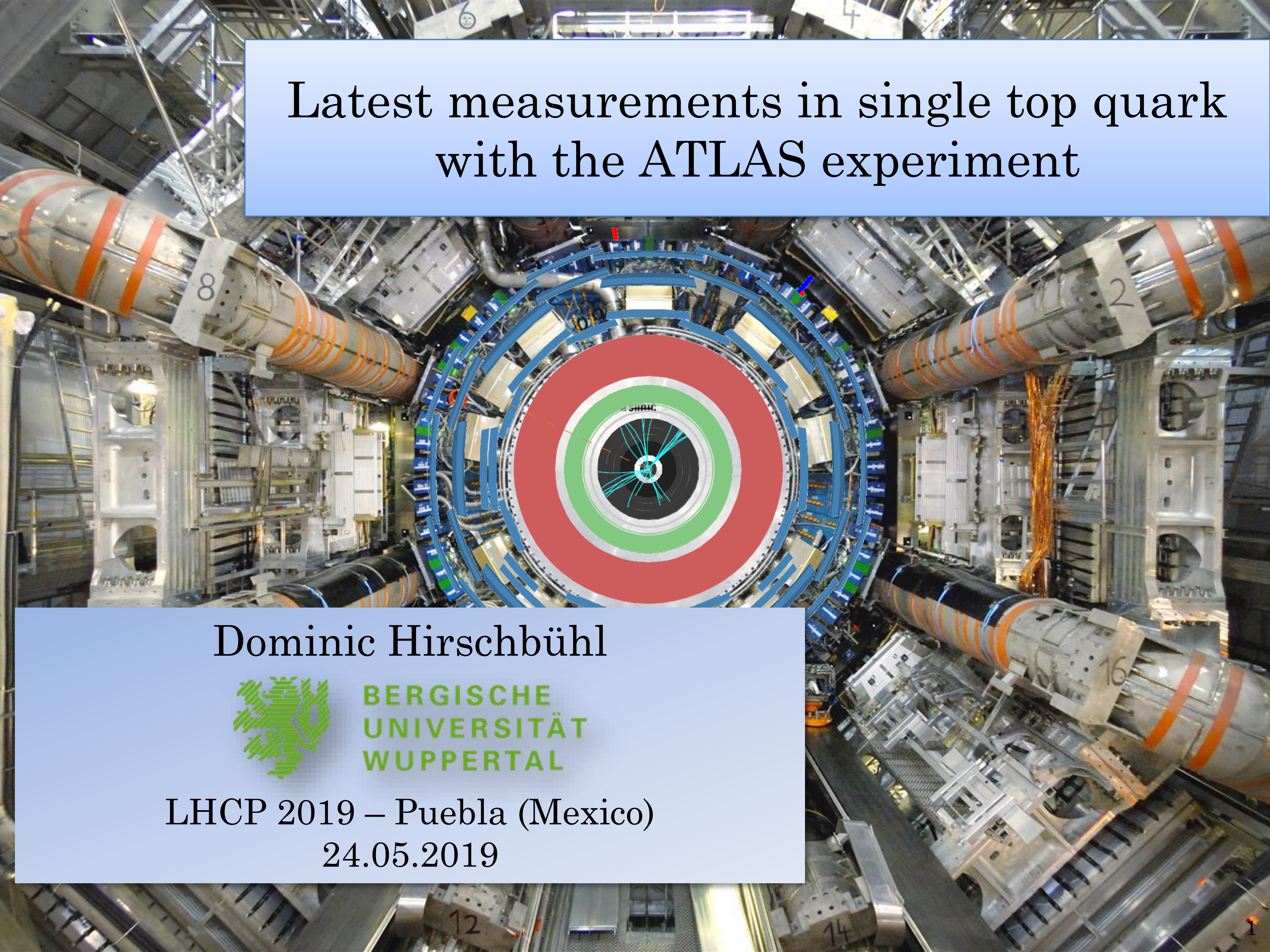

Latest measurements in single top quark with the ATLAS experiment

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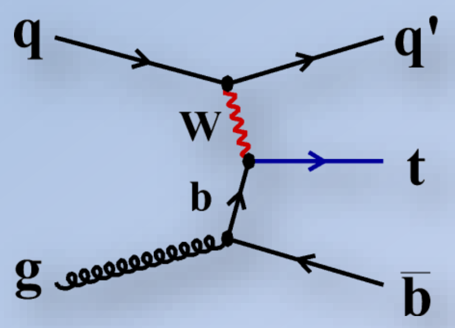
BERGISCHE UNIVERSITÄT WUPPERTAL

LHCP 2019 – Puebla (Mexico)
24.05.2019

Single top quark production

t – channel (tq)

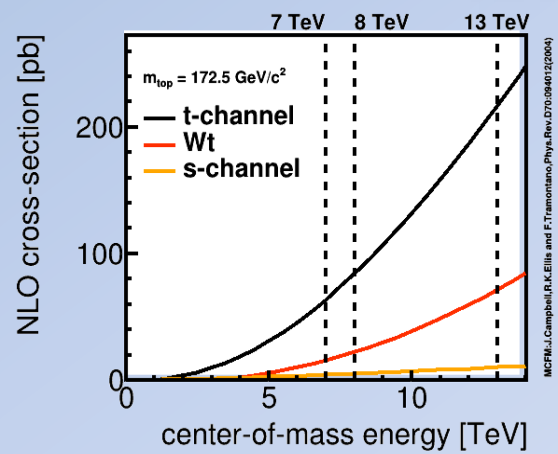


m_t=172.5 GeV

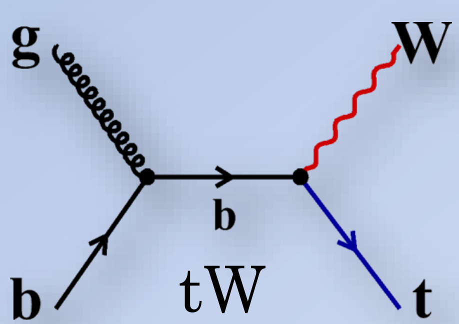
tq - cross sections	
7 TeV	63.9 ± 2.9 pb
8 TeV	84.7 ± 3.8 pb
13 TeV	217 ± 9 pb

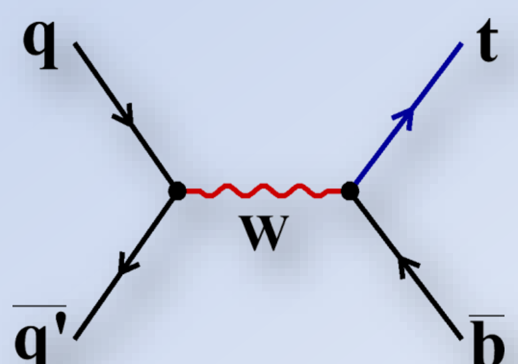
tW - cross sections	
7 TeV	15.7 ± 1.1 pb
8 TeV	22.4 ± 1.5 pb
13 TeV	71.7 ± 3.8 pb

Phys.Rev.D82 (2010) 054018,2010
at NLO + NNLL resummation



tb - cross sections	
7 TeV	4.3 ± 0.2 pb
8 TeV	5.2 ± 0.2 pb
13 TeV	10.3 ± 0.4 pb



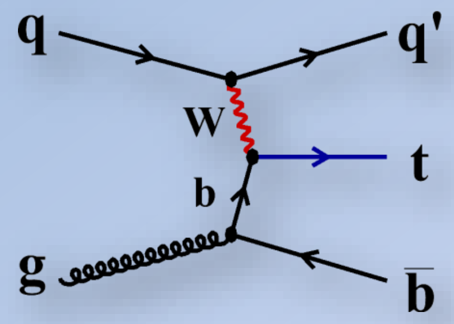


s – channel (tb)

Single top quark production

tq - cross sections	
7 TeV	63.9 ± 2.9 pb
8 TeV	84.7 ± 3.8 pb
13 TeV	217 ± 9 pb

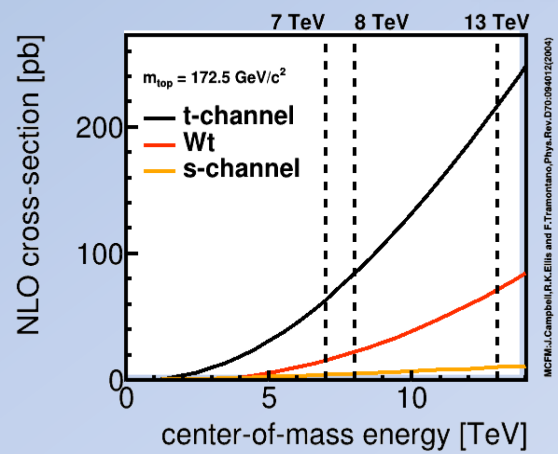
t – channel (tq)



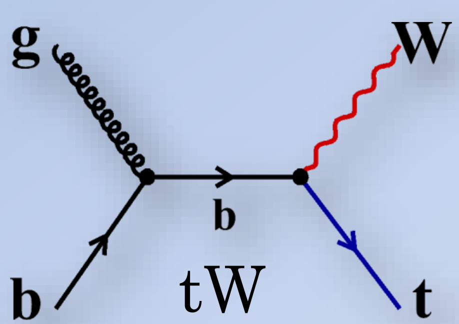
m_t=172.5 GeV

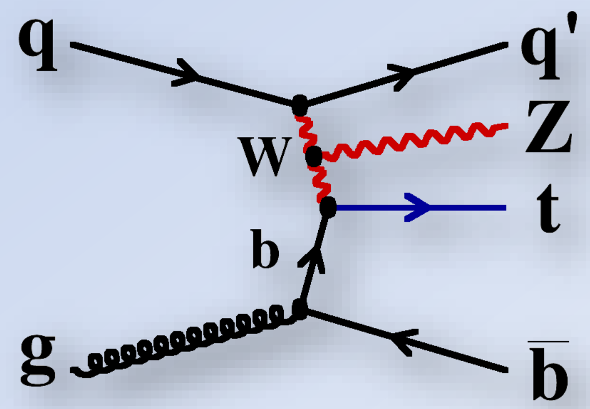
tW - cross sections	
7 TeV	15.7 ± 1.1 pb
8 TeV	22.4 ± 1.5 pb
13 TeV	71.7 ± 3.8 pb

Phys.Rev.D82 (2010) 054018,2010
at NLO + NNLL resummation

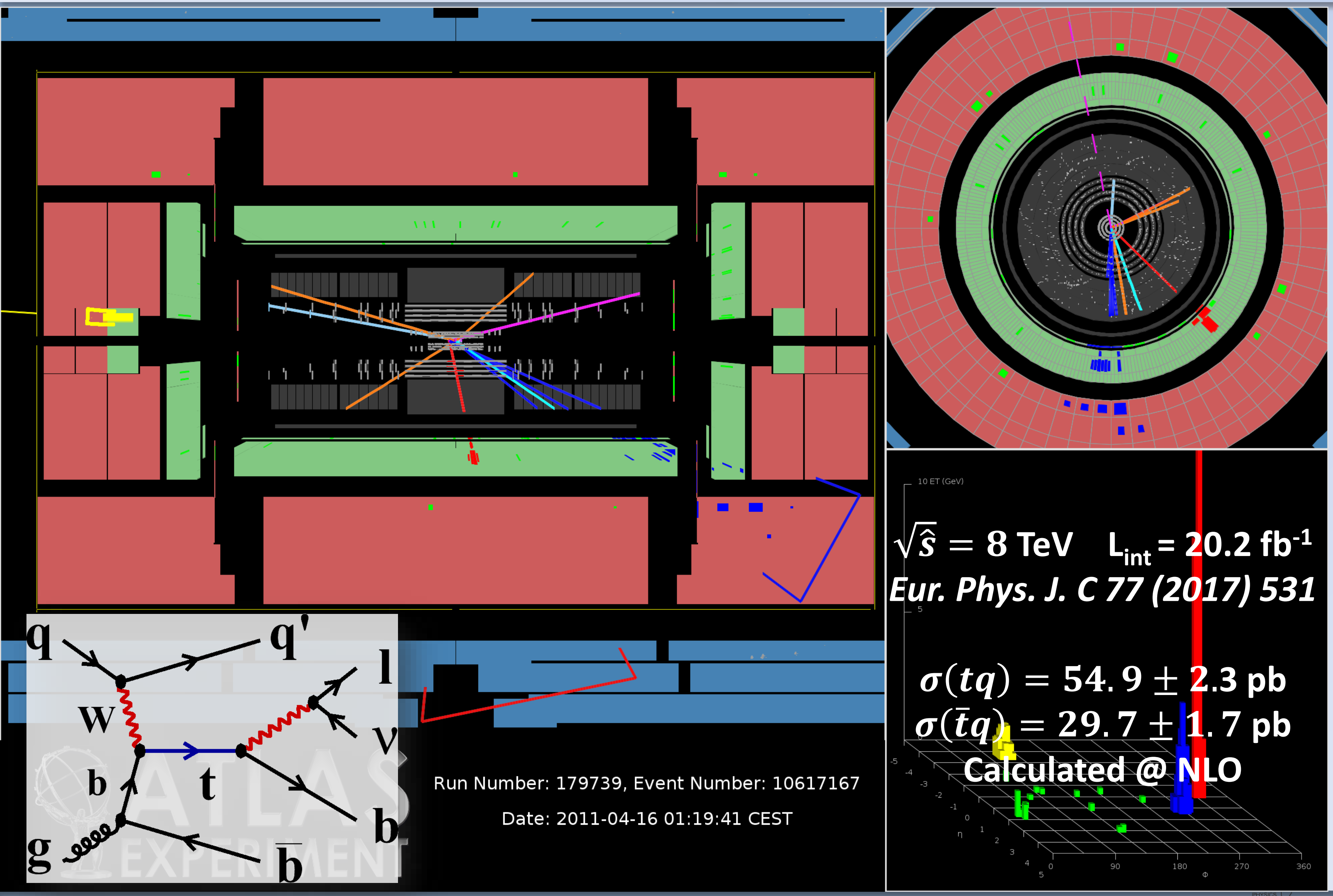


tZj - cross sections	
13 TeV	0.80 ± 0.6 pb





t-channel @ 8 TeV



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

Eur. Phys. J. C 77 (2017) 531

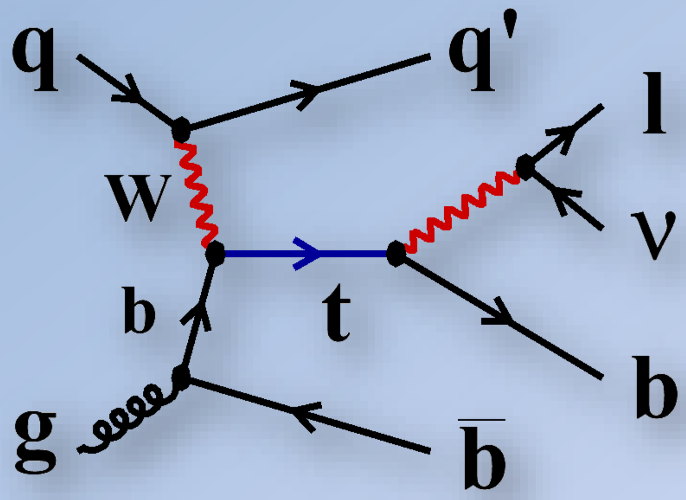
$\sigma(tq) = 54.9 \pm 2.3$ pb

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

Calculated @ NLO

Why study t-channel single top?

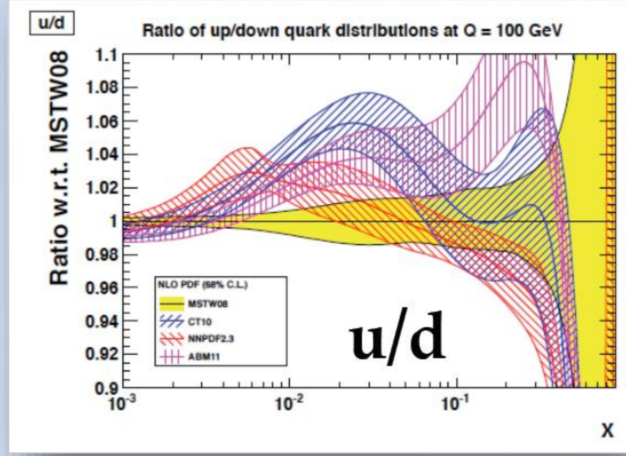
Cross section $\propto |V_{tb}^2|$
→ test of the unitarity of the CKM Matrix



Test of the V-A structure of the Wtb vertex, e.g. using the top polarisation or W helicity

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

Test of the b-quark PDF



Measurement of the top quark mass

- different color structure
- different energy scale

Multivariate Analyses

Selection:

- Exactly one isolted lepton (e/μ)
- Two jets, including **forward** ($|\eta| < 4.5$) calorimeters!
- Identification of b-quark jets (including sufficient c-quark suppression)
- Missing transverse momentum
- Multijet veto

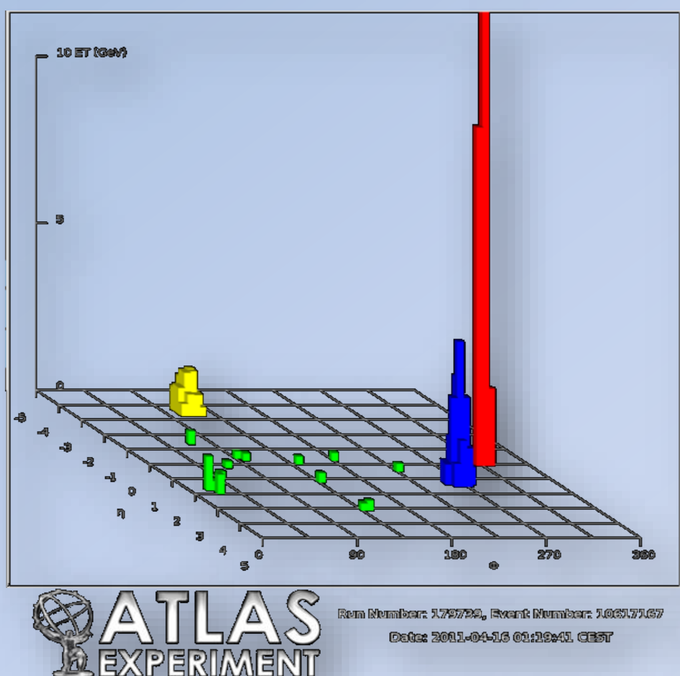
\# jets

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

Separated into + and – lepton charge!

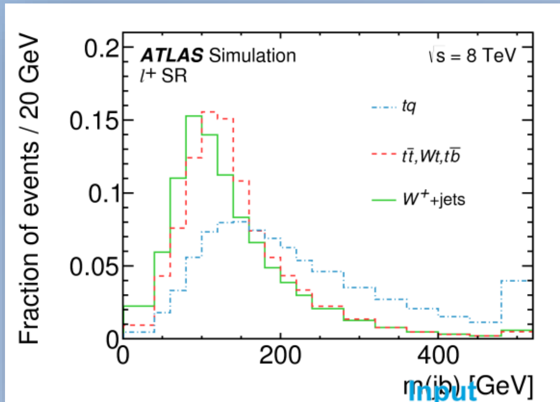
\+ channel: S/B ≈ 26%

\- channel: S/B ≈ 17%

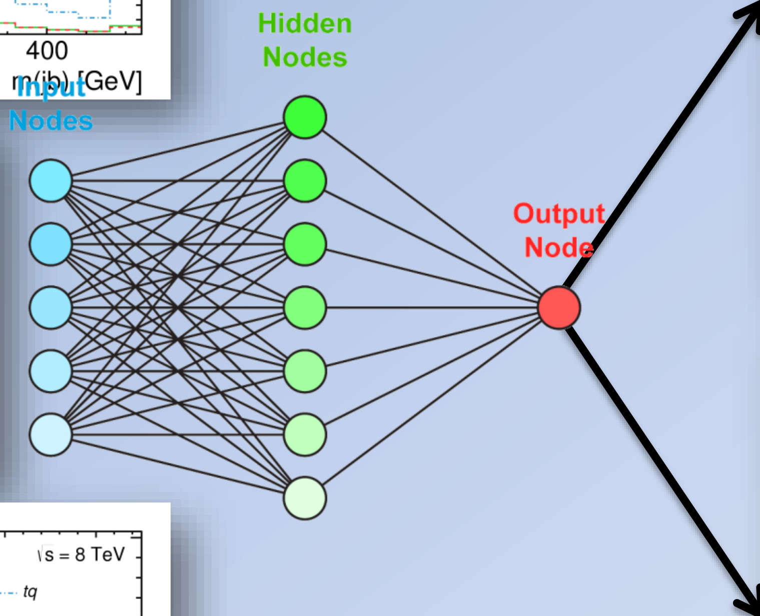


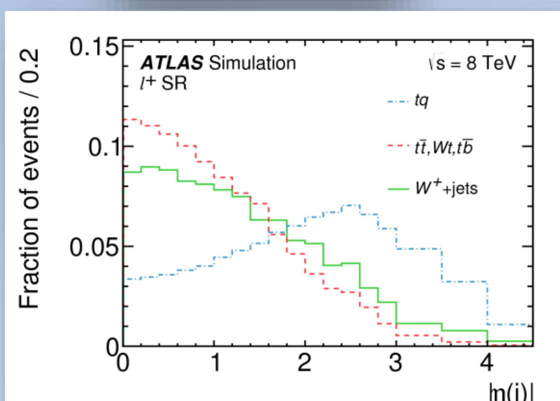
Process	ℓ^+ SR	ℓ^- SR
tq	11 400 ± 470	17 ± 1
$\bar{t}q$	10 ± 1	6 290 ± 350
$t\bar{t}, Wt, t\bar{b}/\bar{t}b$	18 400 ± 1 100	18 000 ± 1 100
W^+ + jets	18 700 ± 3 700	47 ± 10
W^- + jets	25 ± 5	14 000 ± 2 800
Z, VV + jets	1 290 ± 260	1 190 ± 240
Multijets	4 520 ± 710	4 520 ± 660
Total expected	54 300 ±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

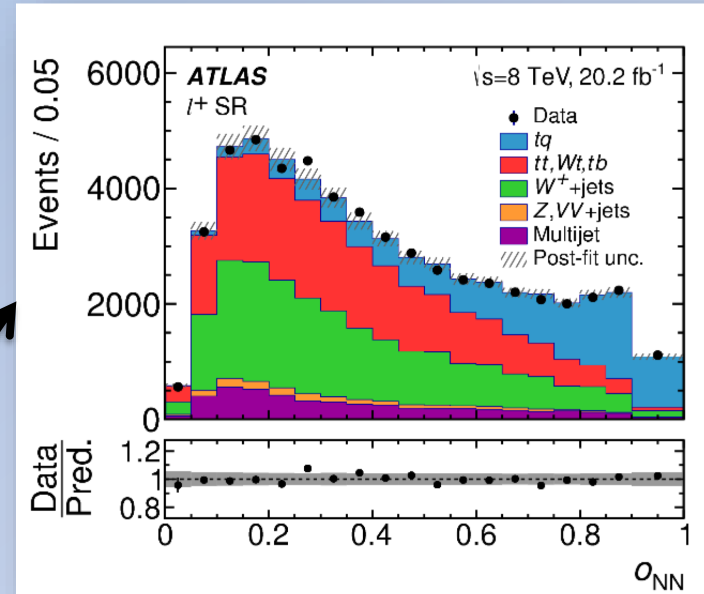
Multivariate Analyses

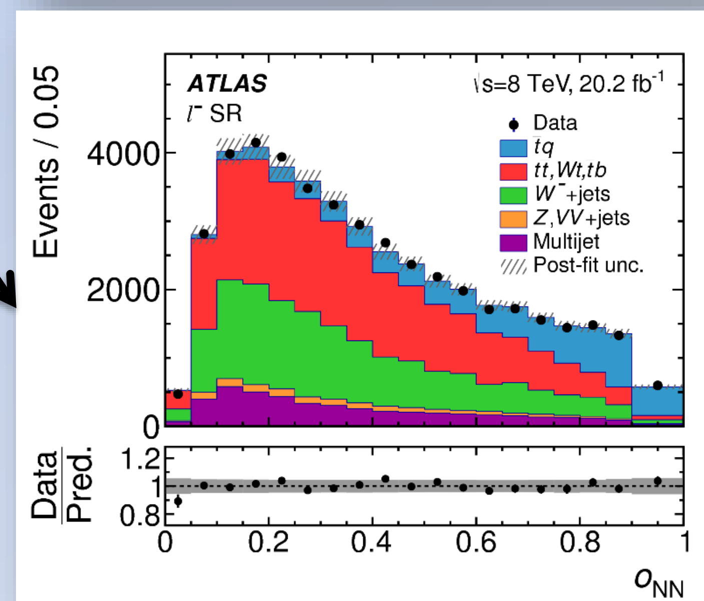


$m(jb)$
$|\eta(j)|$
$m(\ell\nu b)$
$m_{\mathrm{T}}(\ell E_{\mathrm{T}}^{\mathrm{miss}})$
$|\Delta\eta(\ell\nu, b)|$
$m(\ell b)$
$\cos\theta^{*}(\ell, j)$



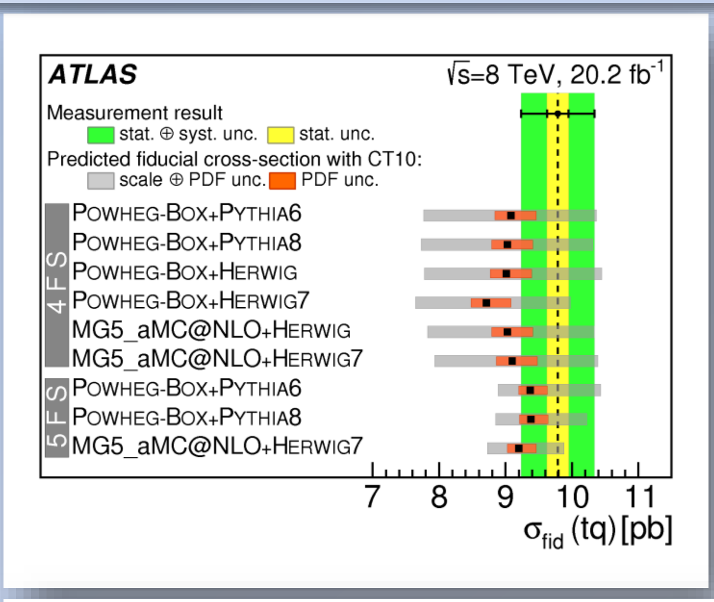


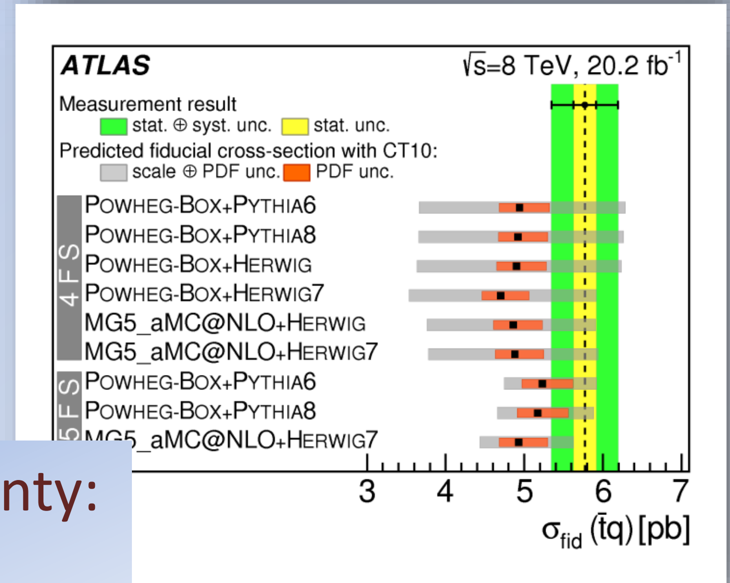




Fiducial cross section result

Source	$\Delta\sigma_{fid}(tq)$ / $\sigma_{fid}(tq)$ [%]	$\Delta\sigma_{fid}(\bar{t}q)$ / $\sigma_{fid}(\bar{t}q)$ [%]
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_{T}^{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





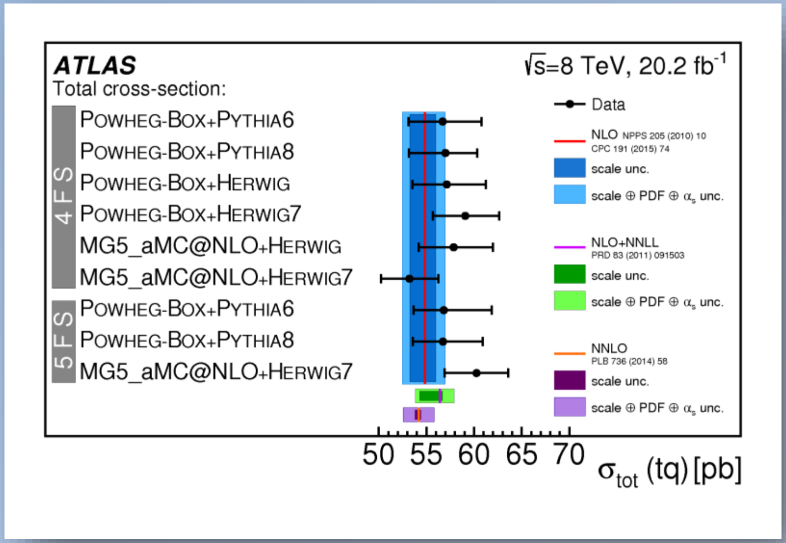
Several uncertainties are reduced for the fiducial cross-section w.r.t the total cross-section

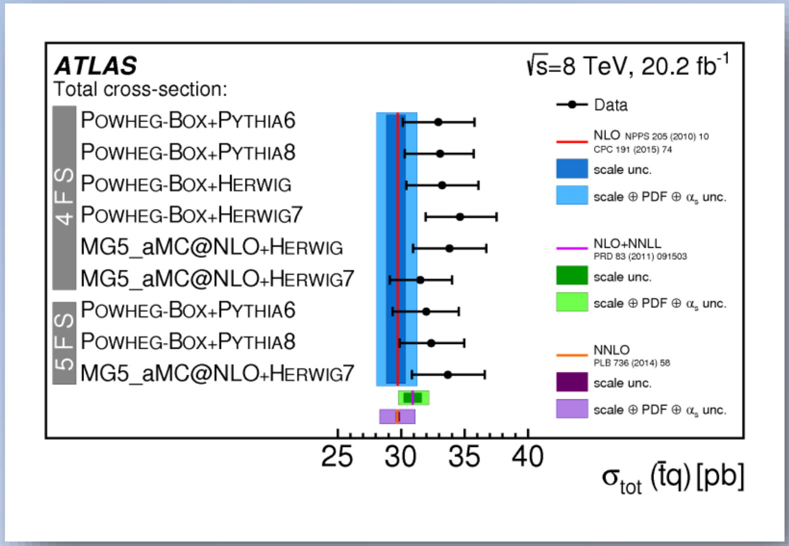
Total uncertainty:

tq : 5.8% !

$\bar{t}q$: 7.8%

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:

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

1.6% 4.8% 5.3% 1.9%

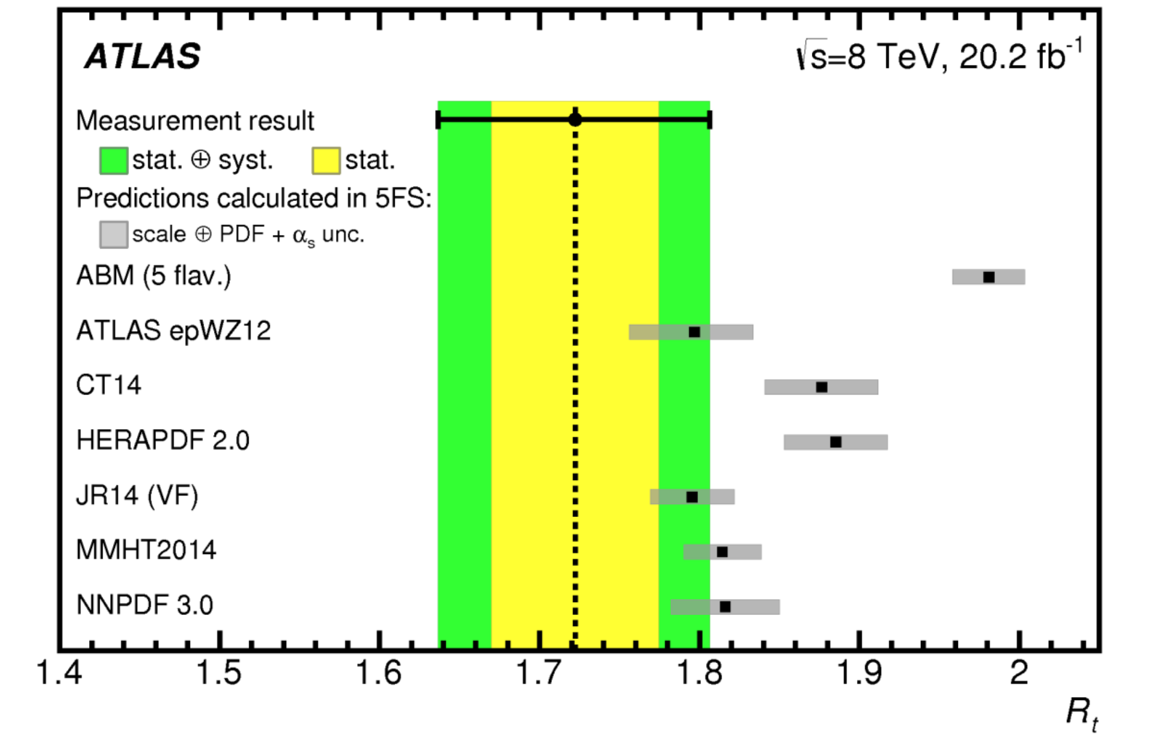
$$\sigma_{tot}(\bar{t}q) = 32.8 \pm 0.8(\text{stat}) \pm 2.2(\text{exp}) \pm 1.7(\text{theo}) \pm 0.6\ (\text{lumi})\ \text{pb}$$

2.4% 6.7% 5.2% 1.9%

Cross section ratio

$$R_t = \sigma(t) / \sigma(\bar{t})$$

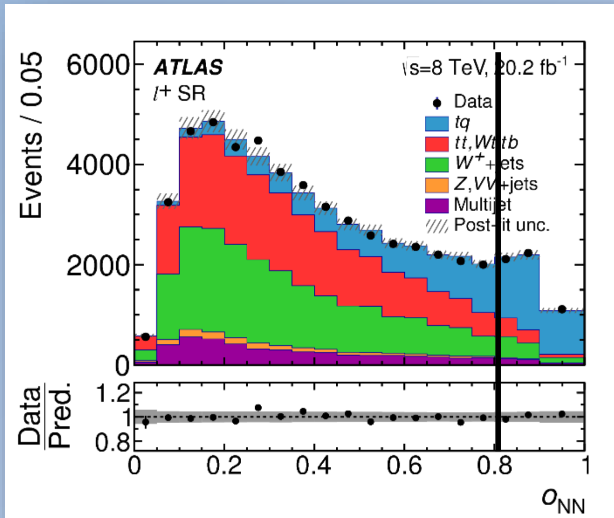
Source	$\Delta R_t / R_t$ [%]
Data statistics	± 3.0
Monte Carlo statistics	± 1.8
Background modelling	± 0.7
Jet reconstruction	± 0.5
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	± 0.6
tq ($\bar{t}q$) NLO matching	−0.5/ + 0.9
$t\bar{t}$ NLO matching	± 2.3
$t\bar{t}$ parton shower	± 1.7
PDF	± 0.7
Total systematic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

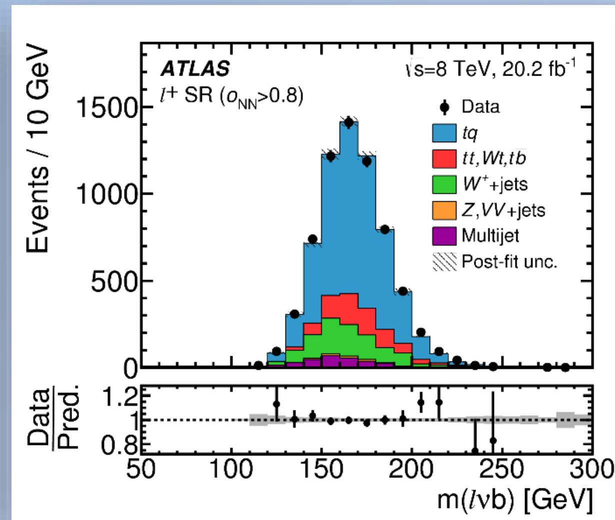


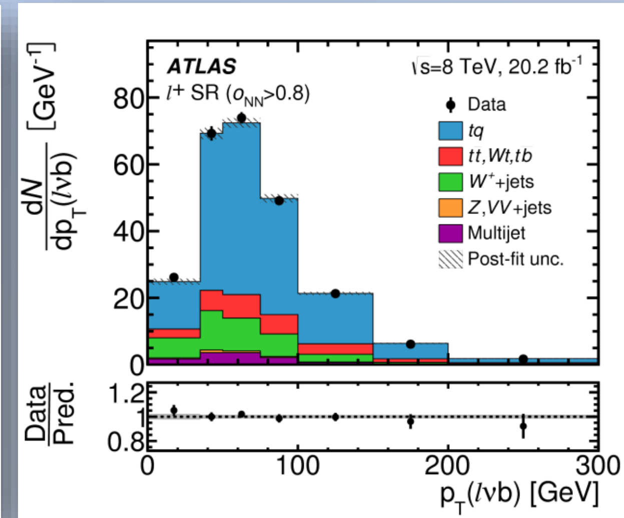
Using the extrapolated cross section:

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

Differential cross sections







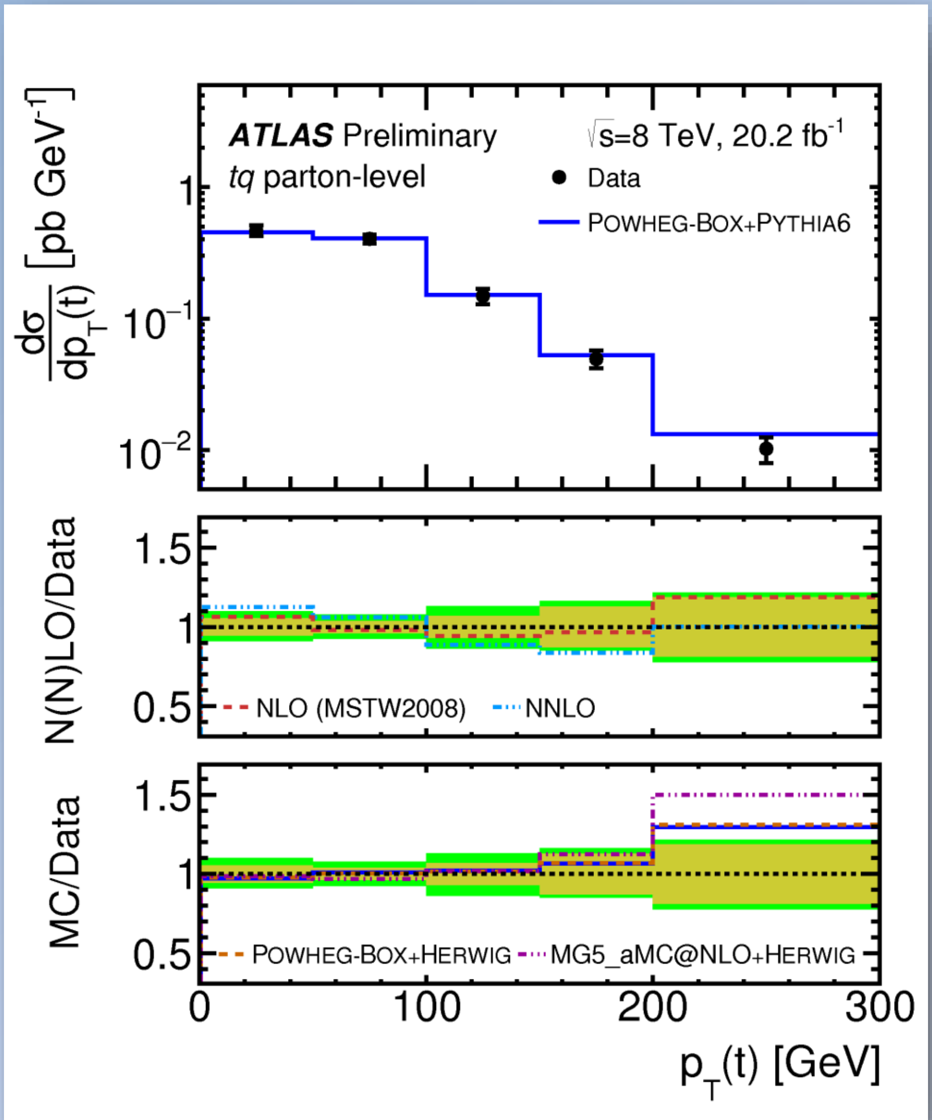
Cut on $o_{NN} > 0.8$

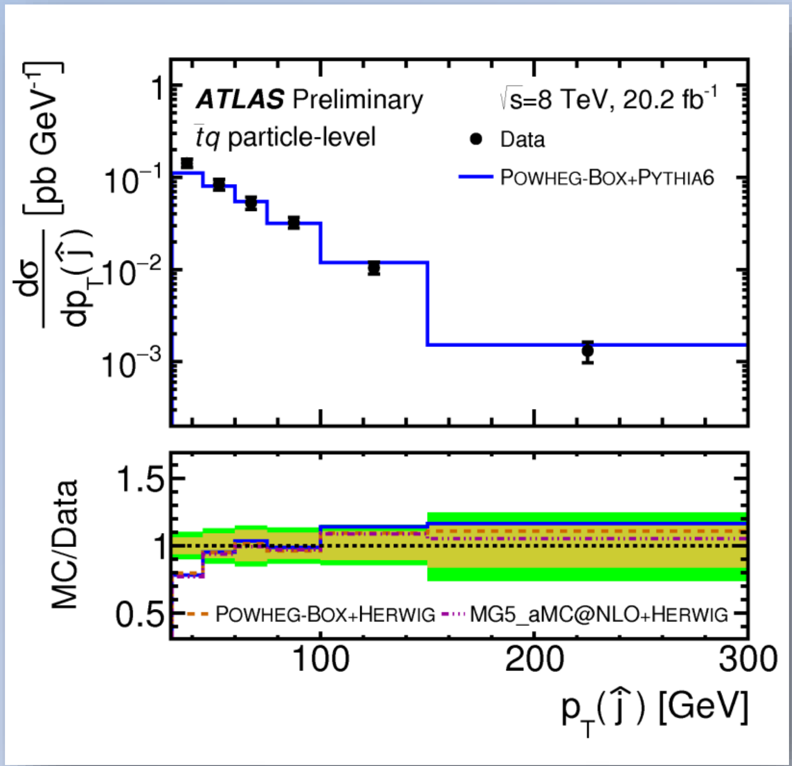
Process	ℓ^+ SR ($O_{NN} > 0.8$)	ℓ^- SR ($O_{NN} > 0.8$)
tq	4470 ± 180	5 ± 0
$\bar{t}q$	3 ± 0	2270 ± 130
$t\bar{t}, Wt, t\bar{b}/\bar{t}b$	754 ± 45	753 ± 45
$W^+ + $jets	960 ± 190	1 ± 0
$W^- + $jets	1 ± 0	610 ± 120
$Z, VV + $jets	52 ± 10	60 ± 12
Multijet	291 ± 46	267 ± 39
Total estimated	6540 ± 270	3960 ± 190
Data	6567	4007

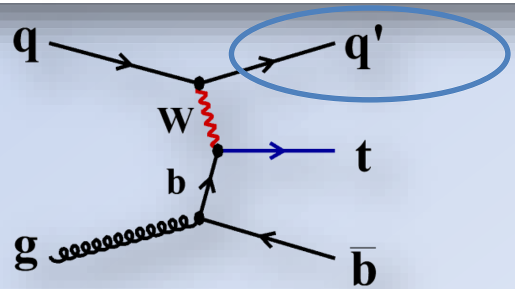
+ channel: S/B ≈ 2.2

- channel: S/B ≈ 1.34

Differential cross sections

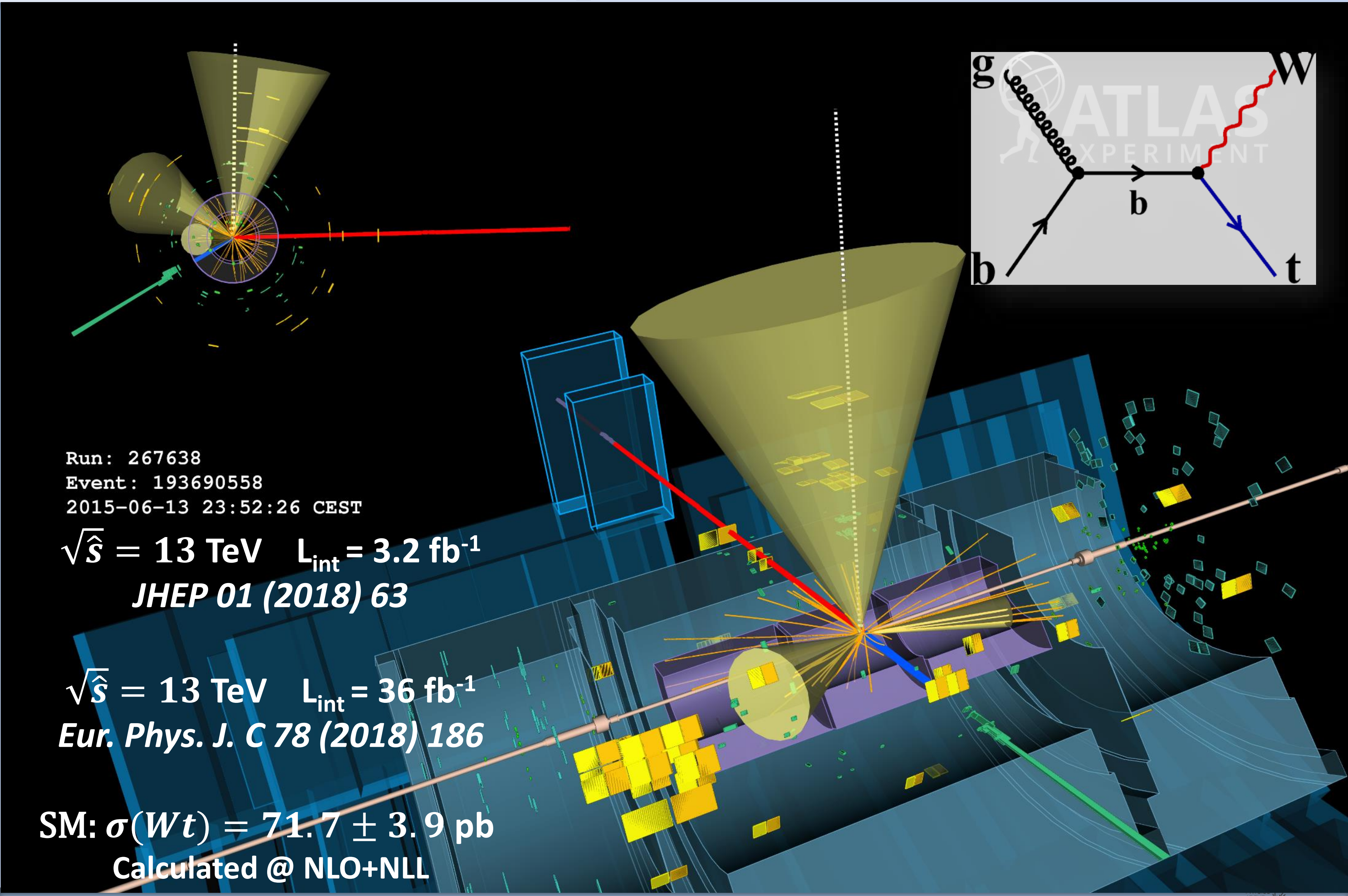






- Use different NN - without $|\eta(j)|$
- Predictions are harder than the data

tW production



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

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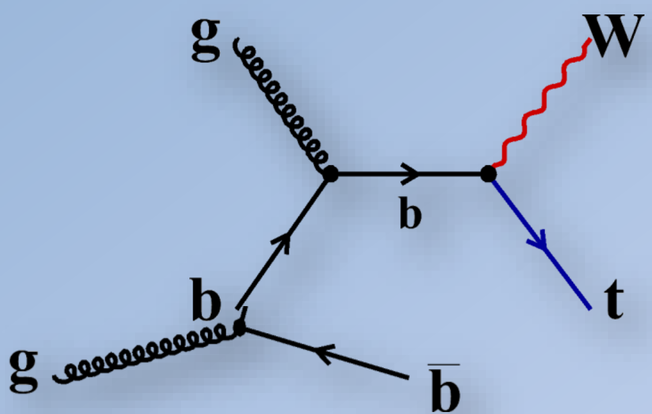
$\sqrt{\hat{s}} = 13$ TeV $L_{int} = 36\ fb^{-1}$

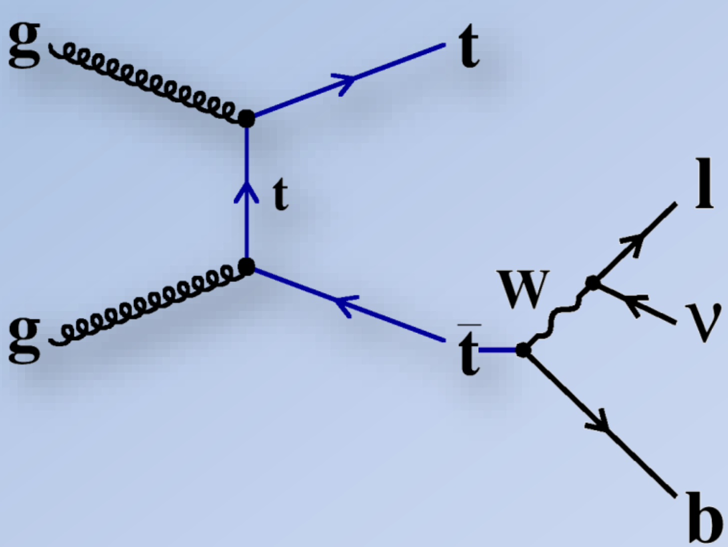
Eur. Phys. J. C 78 (2018) 186

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

Calculated @ NLO+NLL

Signal modelling – Traditional approach





NLO: interference between both processes

$$\mathcal{M}_{\rm tot} = \mathcal{M}_{\rm sr} + \mathcal{M}_{\rm dr}\,,$$
$$|\mathcal{M}_{\rm tot}|^2 = |\mathcal{M}_{\rm sr}|^2 + 2{\rm Re}(\mathcal{M}_{\rm sr}\cdot\mathcal{M}_{\rm dr}^*) + |\mathcal{M}_{\rm dr}|^2.$$

Different methods to define Wt @ NLO

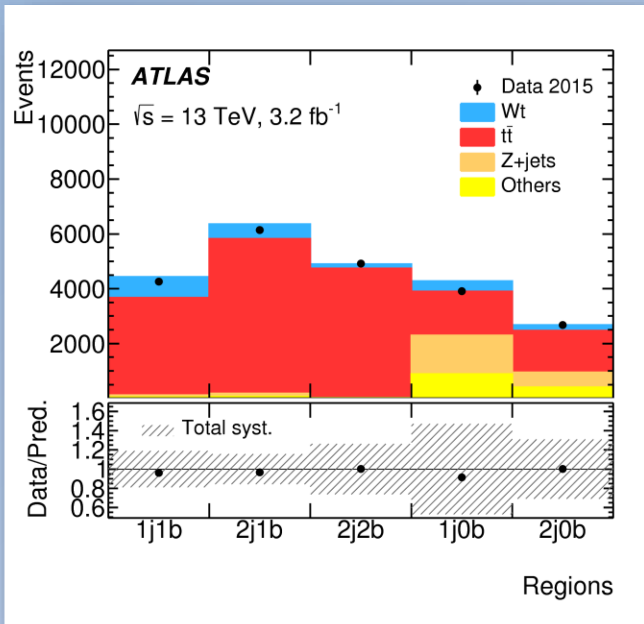
Diagram removal:
Remove all double resonant diagrams on amplitude level ($M_{dr} = 0$)

Diagram removal 2:
Remove all double resonant diagrams on amplitude level squared ($|M_{dr}|^2 = 0$)

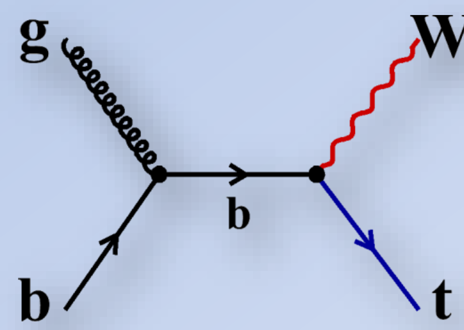
Diagram subtraction:
Modifies the NLO cross-section with subtraction terms to cancel locally the $t\bar{t}$ contribution

Wt production

Selection: Exactly two leptons



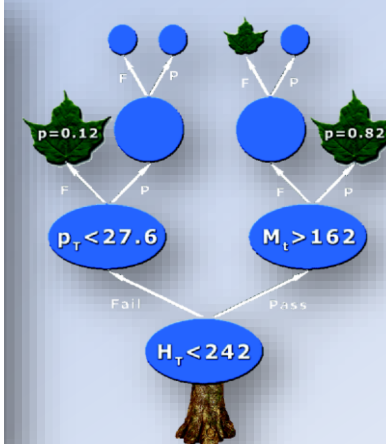
# b-tags \ # jets	1	2
0	VR	VR
1	SR	SR
2		CR



	1j1b		2j1b		2j2b	
Observed events	4254		6138		4912	
Expected total events	4430	± 780	6350	± 810	4900	± 1200
Exp. Wt events	760	± 140	526	± 87	164	± 45
Exp. $t\bar{t}$ events	3550	± 700	5640	± 820	4700	± 1200
Exp. Z + jets events	74	± 37	118	± 59	7.5	± 7.4
Exp. fake events	25	± 25	37	± 36	14	± 14
Exp. diboson events	23.7	± 6.0	24.9	± 6.3	0.91	± 0.23

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

Variable (1j1b)	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

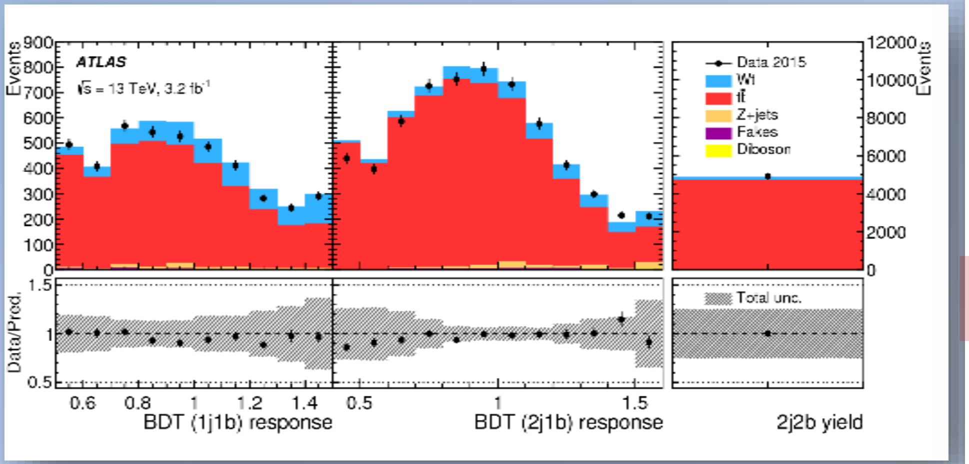


1j1b: S/B ≈ 25%

2j1b: S/B ≈ 10%

Wt production

Signal extraction:
Profile maximum likelihood fit



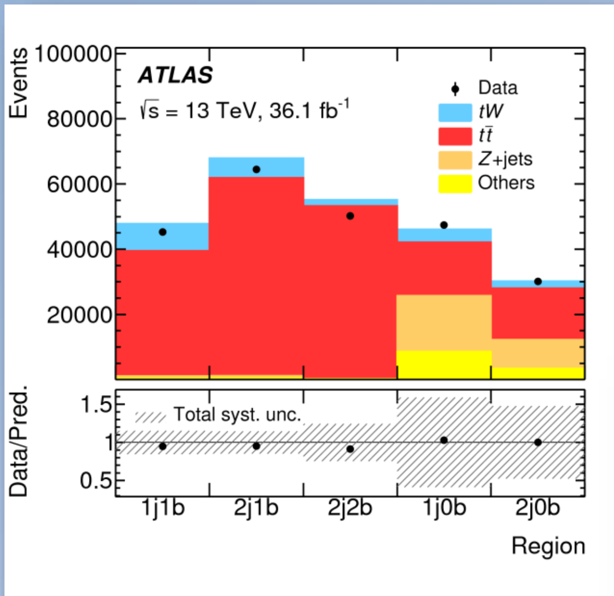
Source	$\Delta\sigma_{Wt}/\sigma_{Wt}[\%]$
Jet energy scale	21
Jet energy resolution	8.6
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft terms	5.3
b-tagging	4.3
Luminosity	2.3
Lepton efficiency, energy scale and resolution	1.3
NLO matrix element generator	18
Parton shower and hadronisation	7.1
Initial-/final-state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

Measured cross section:

$\sigma(Wt) = 94 \pm 10\ (\mathrm{stat})^{28}_{-22}(\mathrm{syst})\ \mathrm{pb}$

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

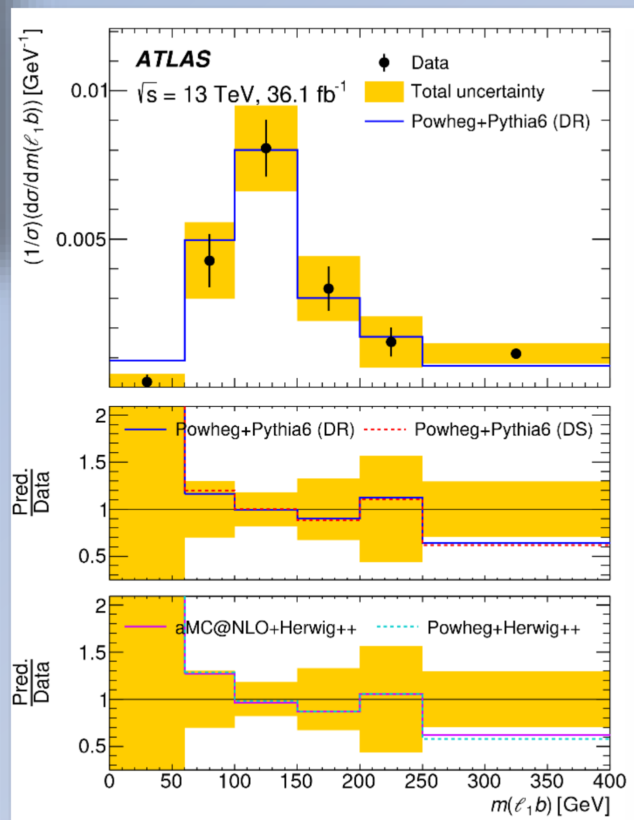
Differential cross sections

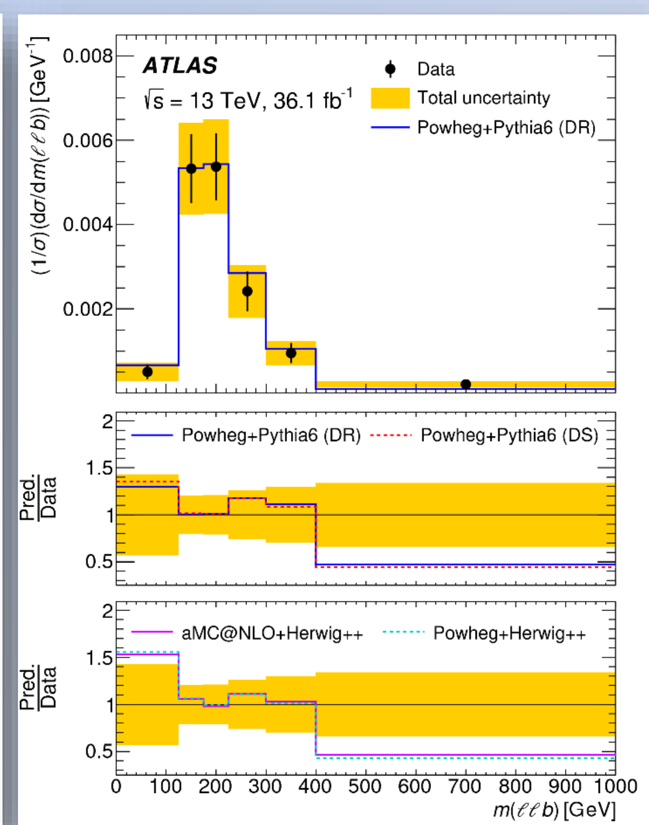


Measured in a fiducial phase space defined by the presence of two charged leptons and exactly one jet identified as containing b-hadrons.

Dominant uncertainties Data statistics, signal modelling, and $t\bar{t}$ background modelling.

Good agreement with predictions from several MC event generators.

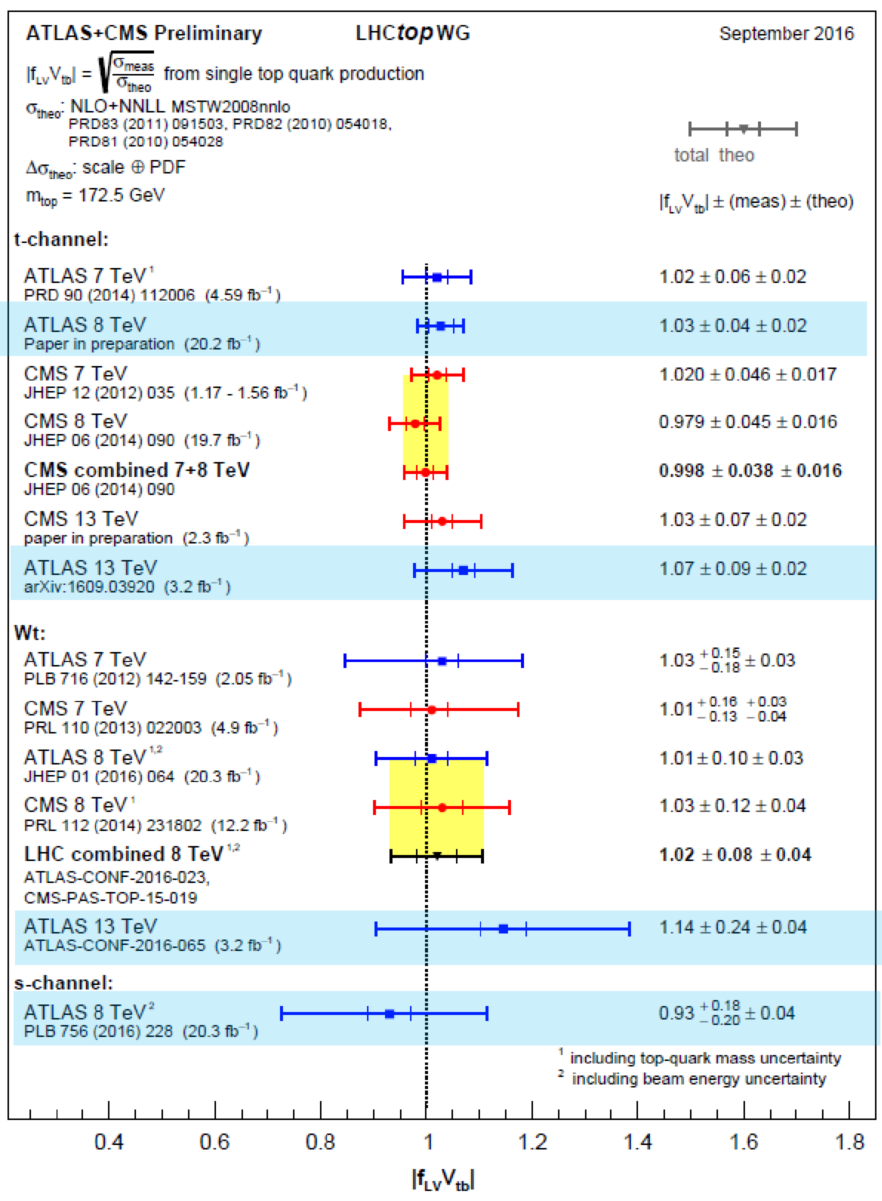




Determination of $|V_{tb}|$

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

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



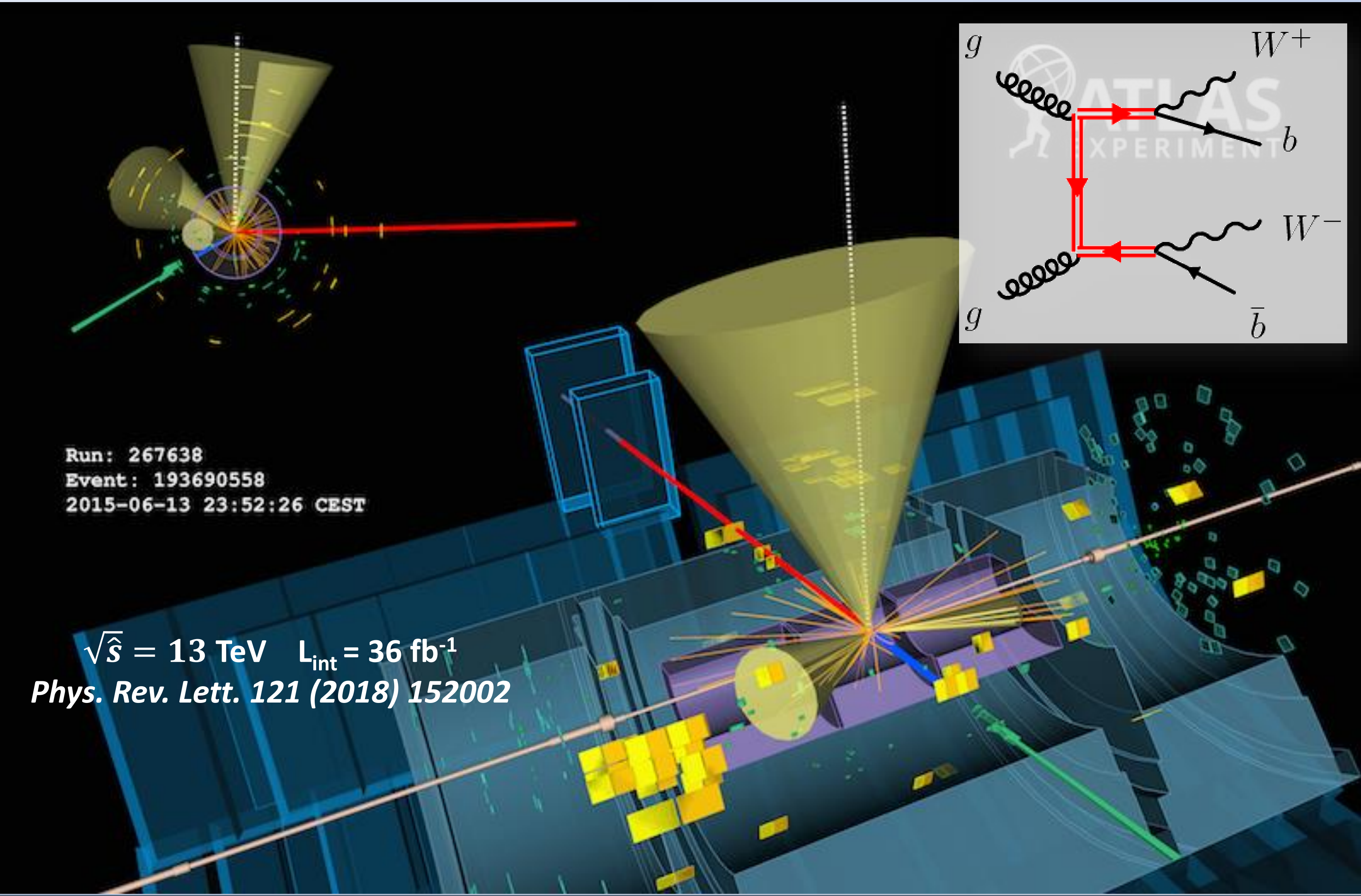
Assumptions for the extraction:

- 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: $\sim 5\%$

WbWb production



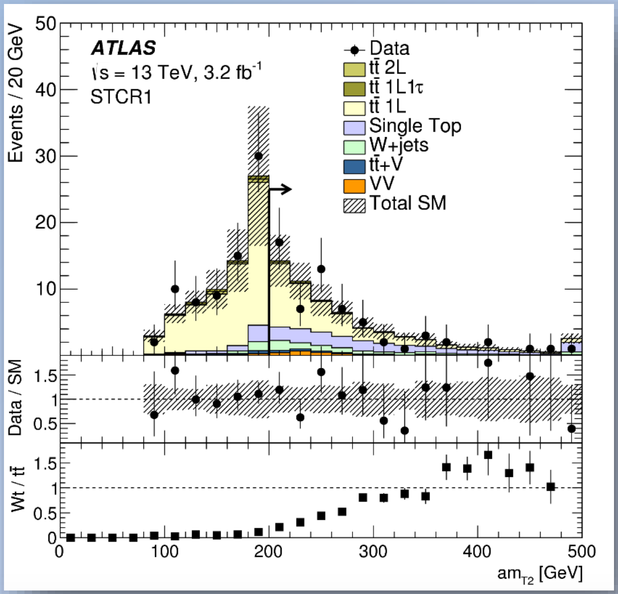
$\sqrt{\hat{s}} = 13$ TeV $L_{int} = 36\ fb^{-1}$

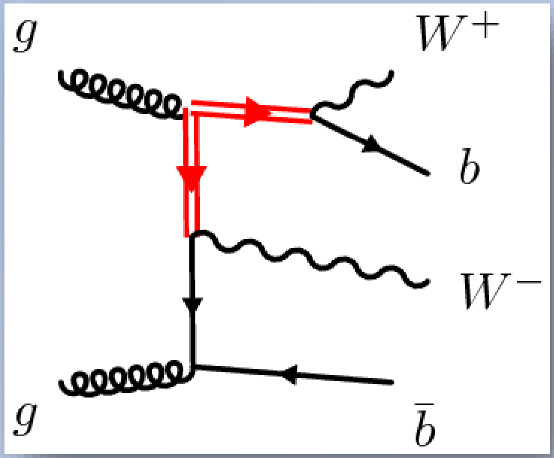
Phys. Rev. Lett. 121 (2018) 152002

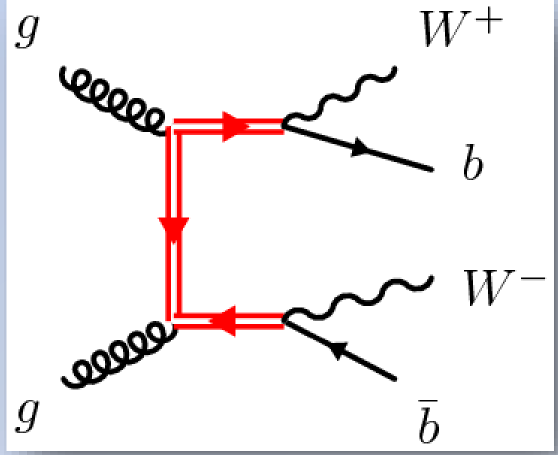
Offshell $t\bar{t}$ production

- For direct searches Wt more or less well-defined
- Analysis typically done in non-resonant phase spaces
- SUSY searches do explore interference regions

Solution: WbWb @ NLO







Single-Top Uncertainties in Signal Regions

source	SR1	SR2	SR3
	Uncertainties on TF to SR [%]		
Radiation	3.66 ± 0.15	5.14 ± 0.23	5.76 ± 0.31
Had/Frag	-5.39 ± 0.45	-8.49 ± 0.78	-13.9 ± 1.49
Interference	-37.3 ± 3.97	-48.8 ± 5.58	-56.2 ± 7.58
Total	38	49	57

Offshell $t\bar{t}$ production

Selection:

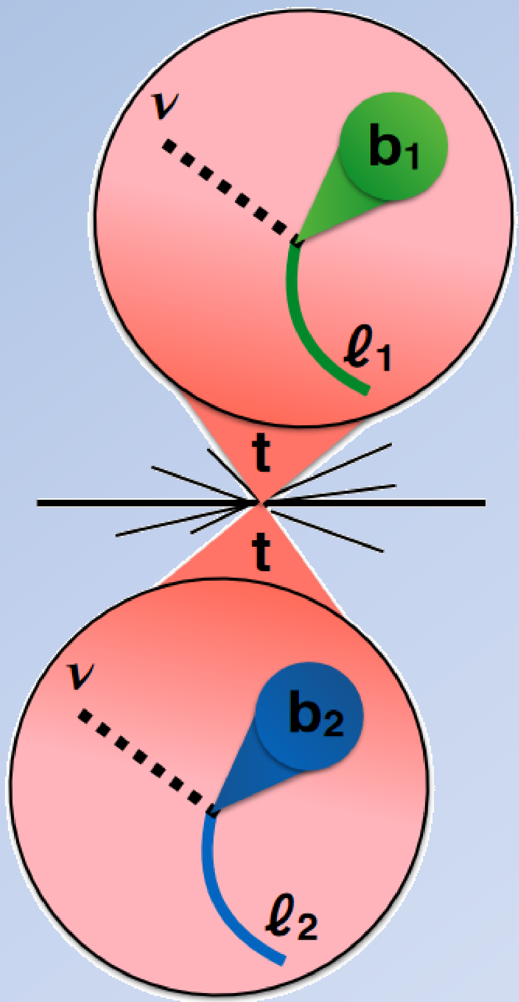
- One electron
- One muon,
- Exactly 2 b-tagged jets

Sensitive observable: →

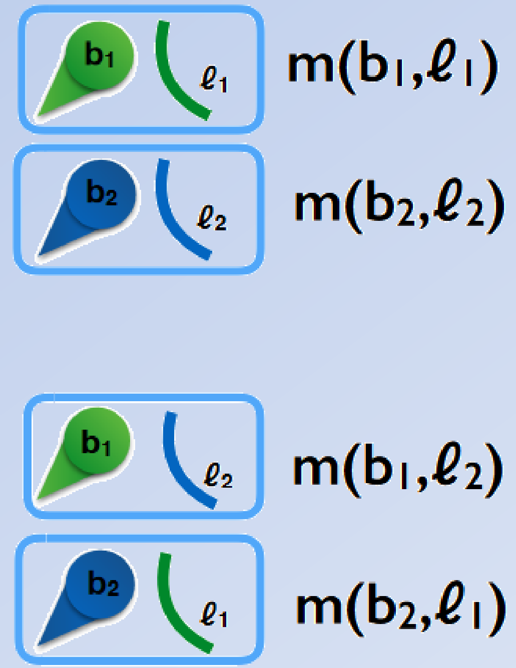
At parton level for $t\bar{t}$:

$$m_{bl}^{minimax} < \sqrt{m_t^2 - m_W^2}$$

→ high $m_{bl}^{minimax}$ has high tWb fraction

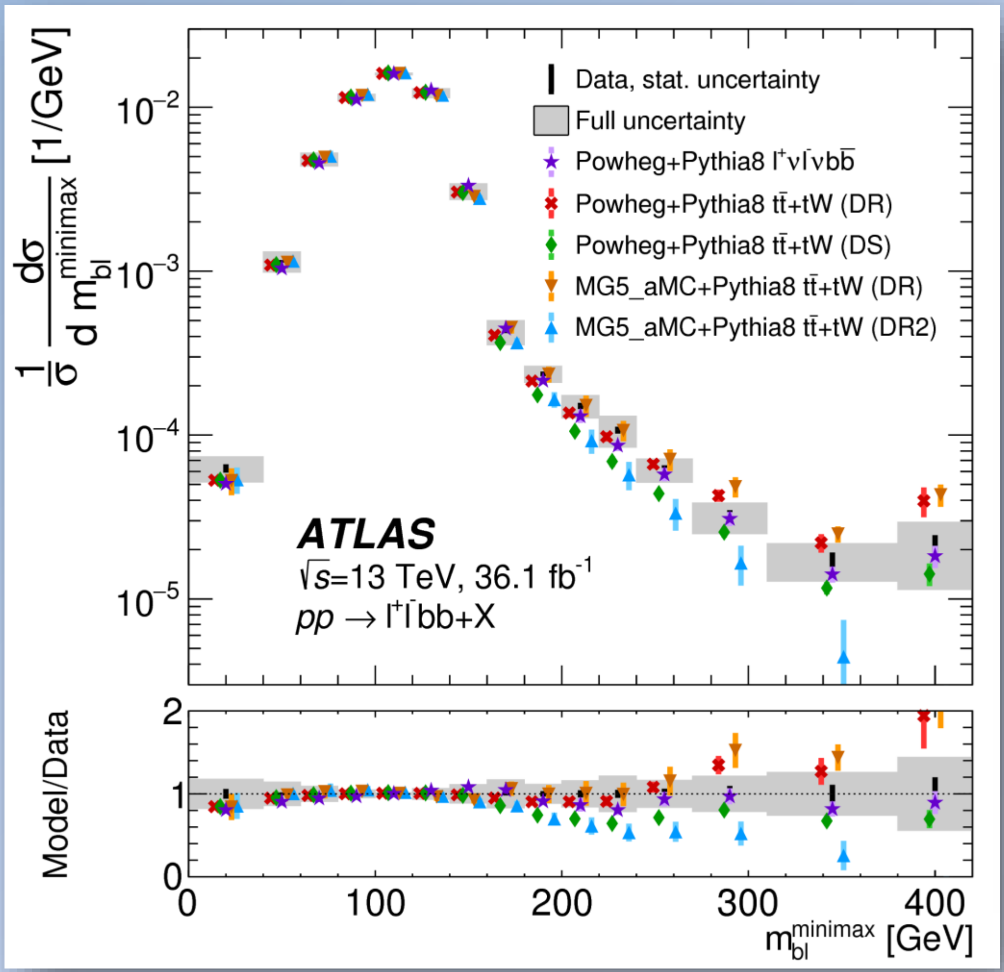


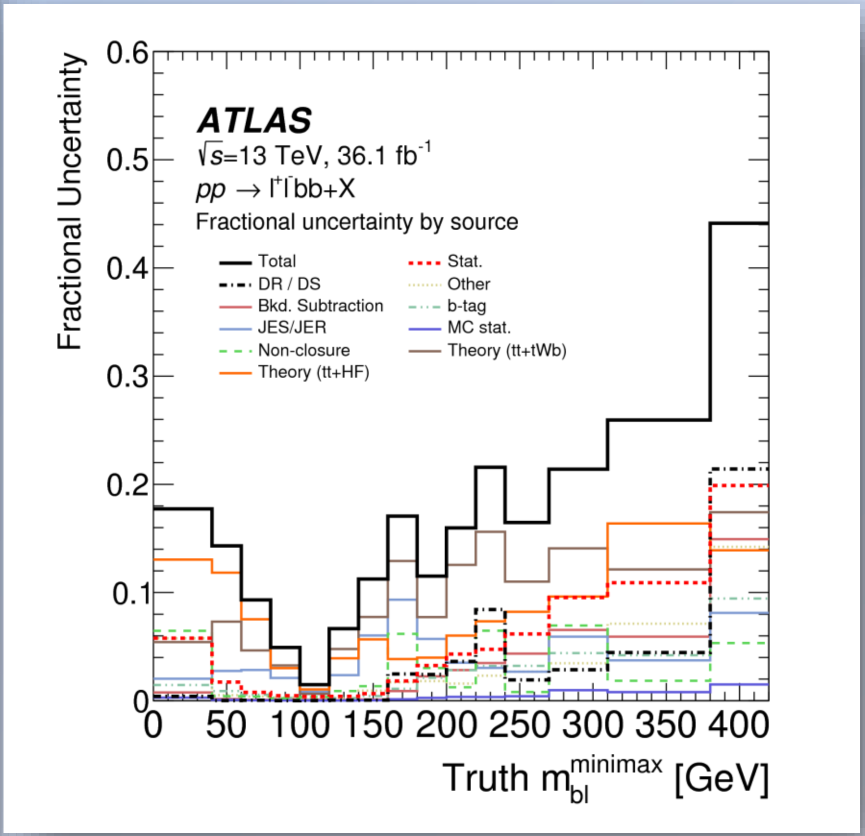
Two ways of pairing:



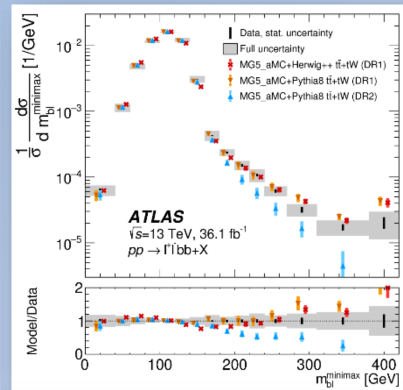
$$\boldsymbol{m_{bl}^{minimax} = \min\{\max\{m_{b_1}l_1, m_{b_2}l_2), \max(m_{b_1}l_2, m_{b_2}l_1)\}}$$

Offshell $t\bar{t}$ production



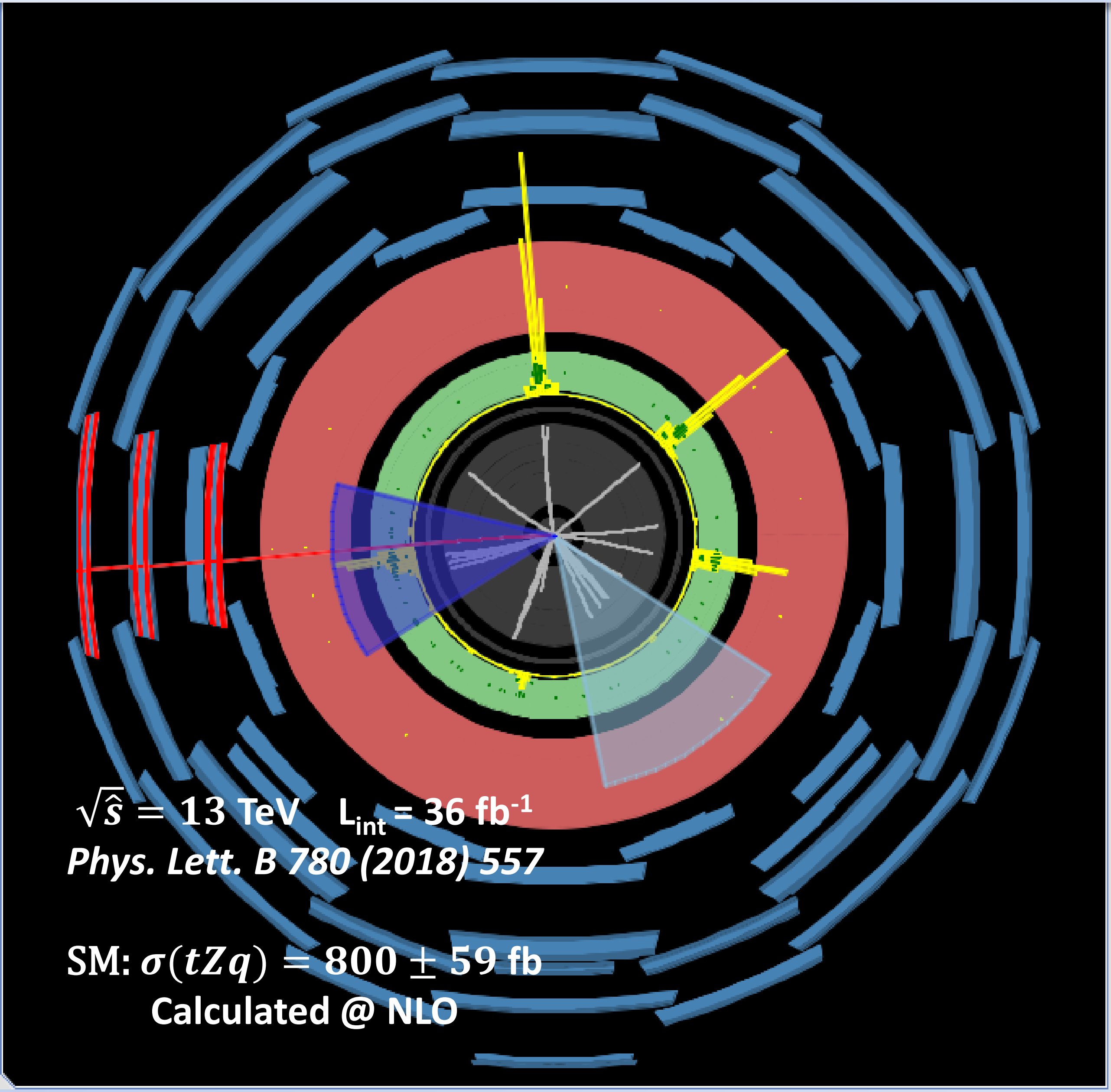


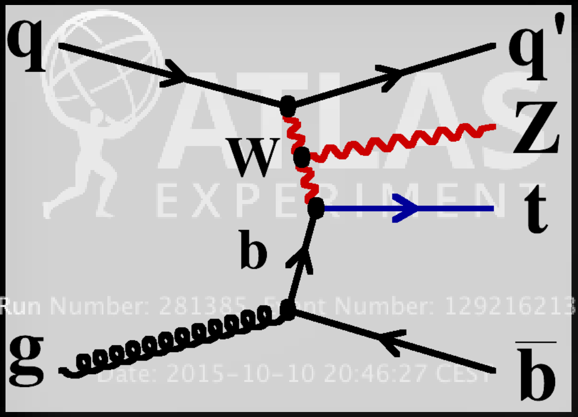
Offshell $t\bar{t}$ production

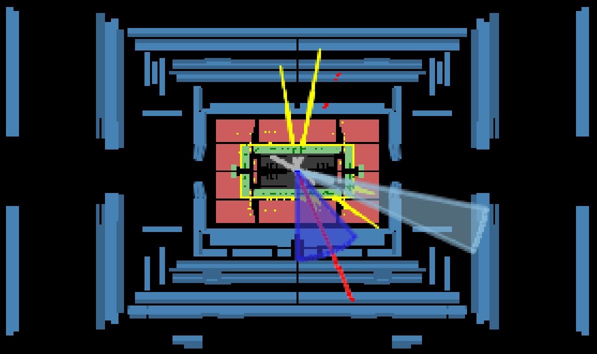


Model	Full Distribution		$m_{b\ell}^{\text{minimax}} > 160$ GeV	
	χ^2 / nDOF	p-value	χ^2 / nDOF	p-value
Powheg+Pythia8 $t\bar{t} + tW$ (DR)	10 / 14	0.71	8.5 / 8	0.40
Powheg+Pythia8 $t\bar{t} + tW$ (DS)	10 / 14	0.77	6.6 / 8	0.56
Powheg+Pythia8 $\ell^+\nu\ell^-\nu bb$	5.9 / 14	0.92	2.0 / 8	0.95
MG5_aMC+Pythia8 $t\bar{t} + tW$ (DR1)	26 / 14	0.14	13 / 8	0.17
MG5_aMC+Pythia8 $t\bar{t} + tW$ (DR2)	36 / 14	0.02	20 / 8	0.08
Powheg+Herwig++ $t\bar{t} + tW$ (DR)	26 / 14	0.07	7.3 / 8	0.48
MG5_aMC+Herwig++ $t\bar{t} + tW$ (DR)	30 / 14	0.04	11 / 8	0.23
Powheg+Pythia6 $t\bar{t} + tW$ (DR)	14 / 14	0.49	11 / 8	0.23
Powheg+Pythia6 $t\bar{t} + tW$ (DS)	14 / 14	0.49	10 / 8	0.32
MG5_aMC+Pythia8 (LO) $WWbb$	12 / 14	0.68	8.2 / 8	0.42
MG5_aMC+Pythia8 (LO) $WWbb$, no int.	28 / 14	0.05	22 / 8	0.005

tZq production







tZq analysis

Event selection:

- 2 jets, 1 b-tag
- 3 isolated leptons, 2 forming Z mass
- Validate background predictions in data ($t\bar{t}$ + nonprompt enriched and WZ enriched regions)

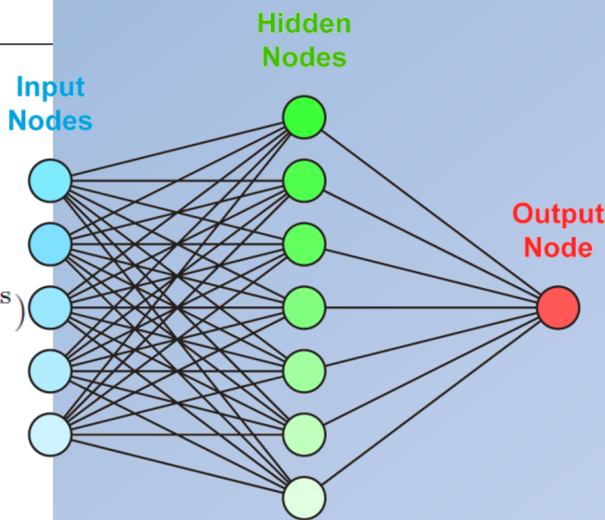
Common selections			
Exactly 3 leptons with $\|\eta\| < 2.5$ and $p_T > 15$ GeV $p_T(\ell_1) > 28$ GeV, $p_T(\ell_2) > 25$ GeV, $p_T(\ell_3) > 15$ GeV $p_T(\text{jet}) > 30$ GeV $m_T(\ell_W, \nu) > 20$ GeV			
SR	Diboson VR / CR	$t\bar{t}$ VR	$t\bar{t}$ CR
≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSDF pair
$\|m_{\ell\ell} - m_Z\| < 10$ GeV	$\|m_{\ell\ell} - m_Z\| < 10$ GeV	$\|m_{\ell\ell} - m_Z\| > 10$ GeV	No OSSF pair
2 jets, $\|\eta\| < 4.5$	1 jet, $\|\eta\| < 4.5$	2 jets, $\|\eta\| < 4.5$	2 jets, $\|\eta\| < 4.5$
1 b-jet, $\|\eta\| < 2.5$	—	1 b-jet, $\|\eta\| < 2.5$	1 b-jet, $\|\eta\| < 2.5$
—	VR/CR: $m_T(\ell_W, \nu) > 20/60$ GeV	—	—

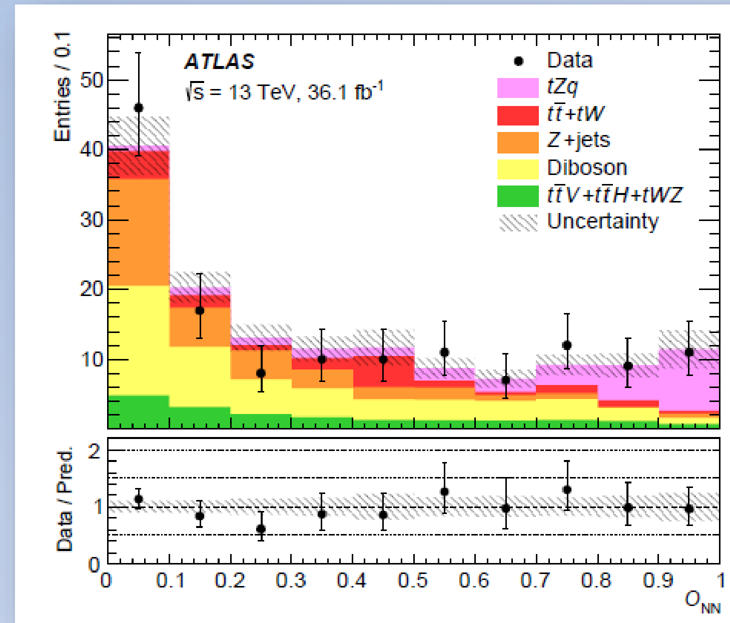
Channel	Number of events	
	Asimov dataset	Data
tZq	35 ± 9	26 ± 8
$t\bar{t} + tW$	18 ± 7	17 ± 7
Z + jets	37 ± 11	34 ± 11
Diboson	53 ± 13	48 ± 12
$t\bar{t}V + t\bar{t}H + tWZ$	20 ± 3	19 ± 3
Total	163 ± 12	143 ± 11

S/B ≈ 27%

tZq analysis

Variable
$\|\eta(j)\|$
$p_T(j)$
m_t
$p_T(\ell^W)$
$\Delta R(j, Z)$
$m_T(\ell, E_T^{miss})$
$p_T(t)$
$p_T(b)$
$p_T(Z)$
$\|\eta(\ell^W)\|$





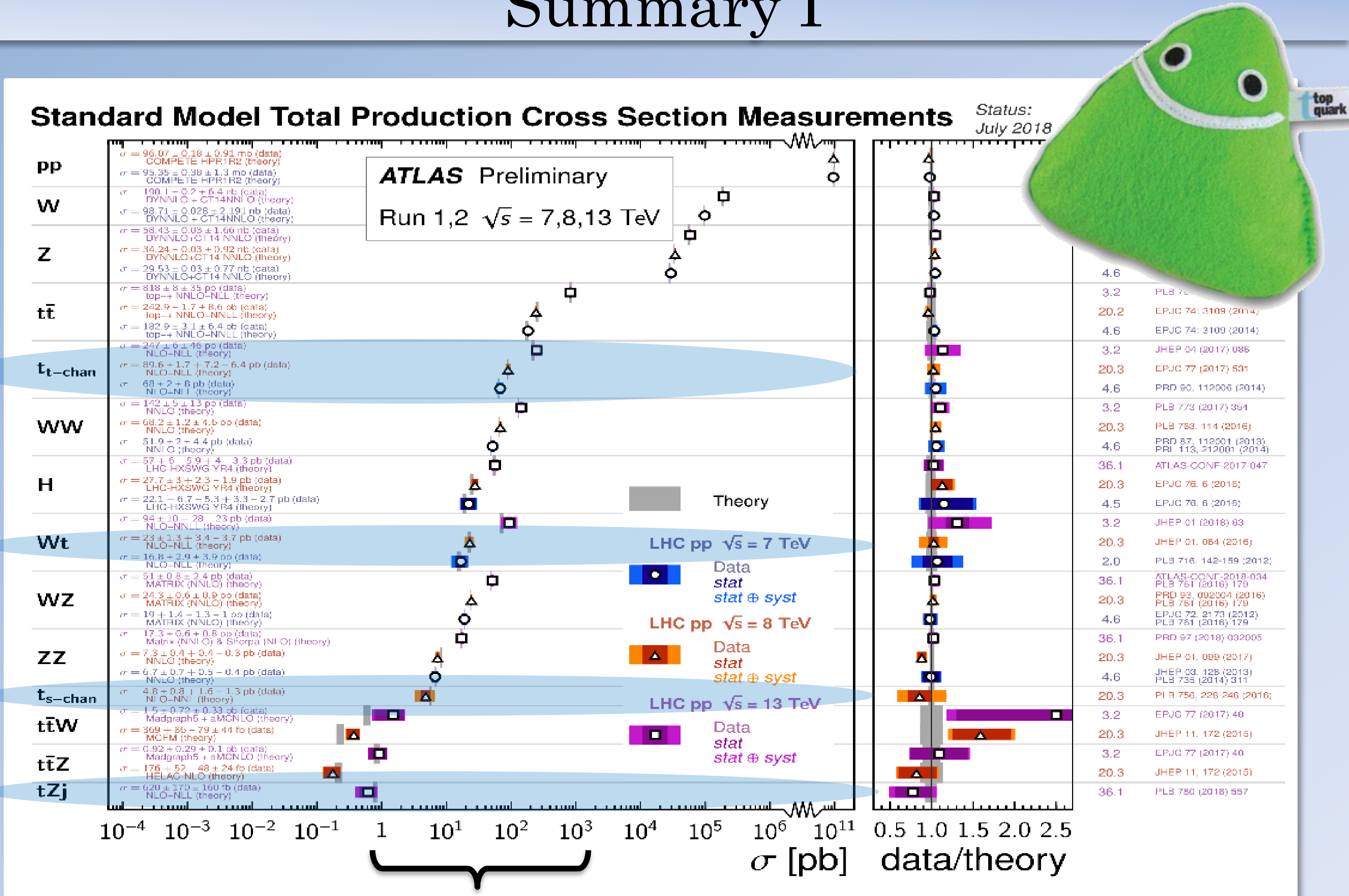
Source	Uncertainty [%]
tZq radiation	±10.8
Jets	±4.6
b-tagging	±2.9
MC statistics	±2.8
tZq PDF	±2.2
Luminosity	±2.1
Leptons	±2.1
E_T^{miss}	±0.3

Measured cross section:

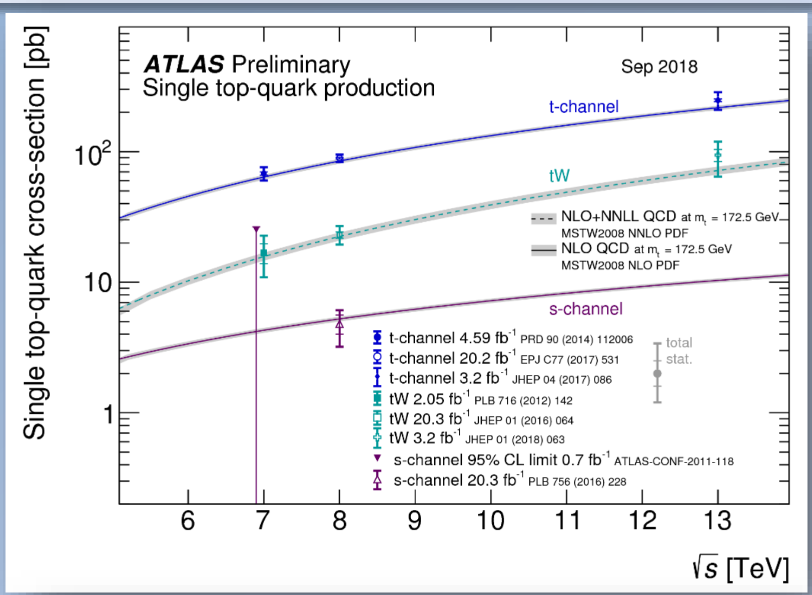
$\sigma(tZ) = 600 \pm 170\ \text{(stat)} \quad \pm 140\text{(syst) fb}$

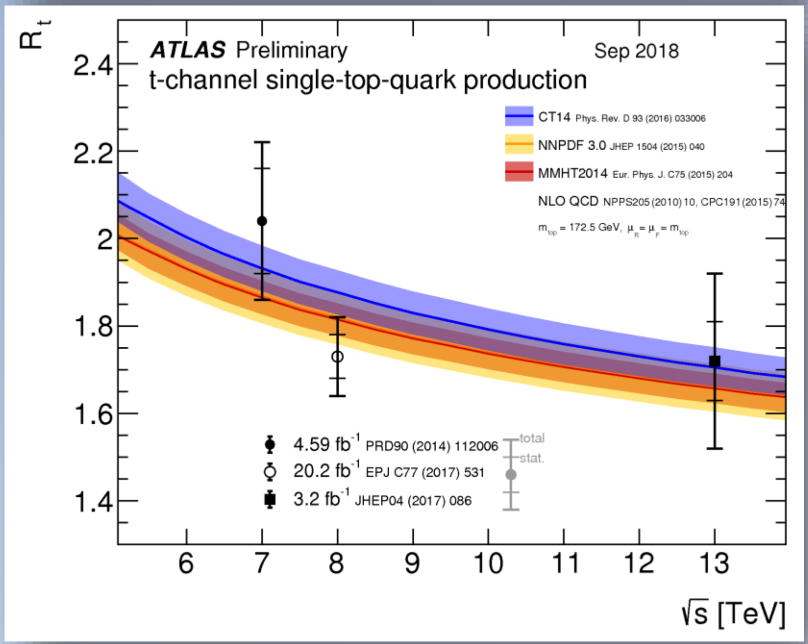
Significance: 4.2 σ

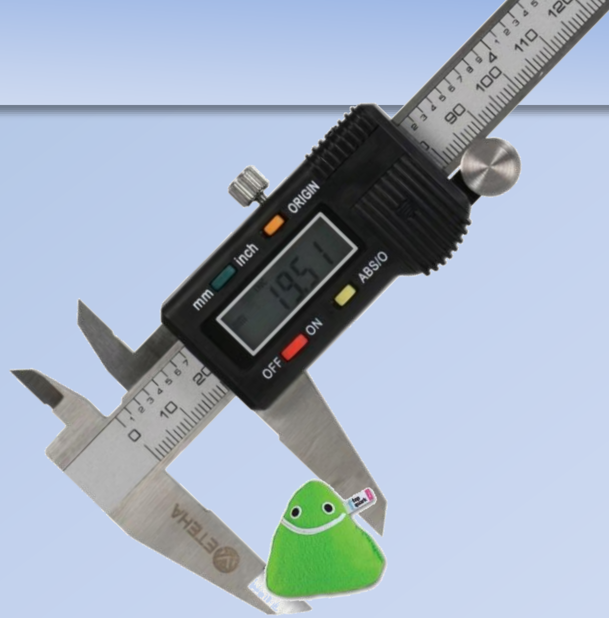
Summary I


Standard Model Total Production Cross Section Measurements
Status: July 2018
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
pp
W
Z
tt̄
tt−chan
WW
H
Wt
WZ
ZZ
ts−chan
tt̄W
tt̄Z
tZj
Theory
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
σ [pb]
data/theory

Summary II







- Single top production measurements entered he precision measurment era.
- Differential cross section for main channels are available
- New rare processes started to be investiagted (and discovered)