Single top-quark production at ATLAS and CMS

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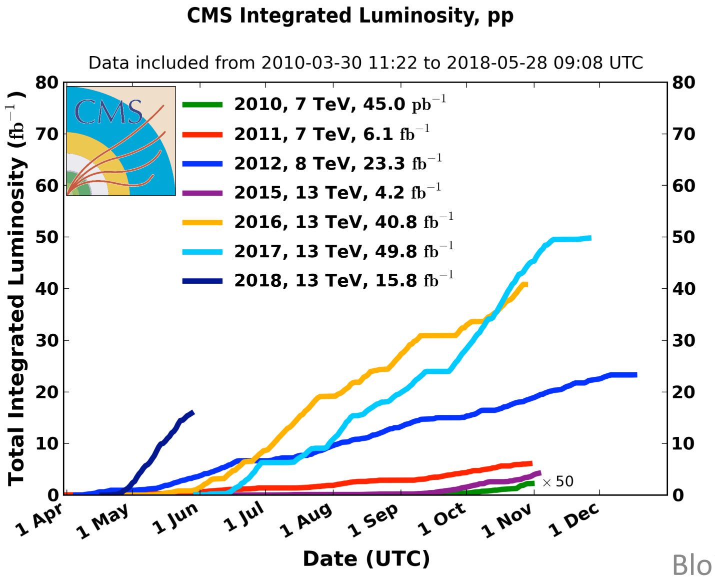
on behalf of the ATLAS and CMS collaborations
Blois, 3-8 Jun 2018

Single top-quark production @ the LHC

- The top-quark is the **most massive** known fundamental particle (m_t=173.3± 0.8 GeV) (arXiv:1403.4427), relatively young particle (discovery in 1995 at the Tevatron).
- Unique among quarks, it decays before hadronization starts → Possibility to study a **bare quark**.
- Important to **test SM**, **tune MC** and constrain **PDF**s
- Access to CKM element $|V_{tb}|$ through ***Wtb* vertex**.
- Principal **background source** to many new physics channels in HEP.
- **Gate for new physics**, it has a strong coupling with many exotic particles in Beyond SM theories.

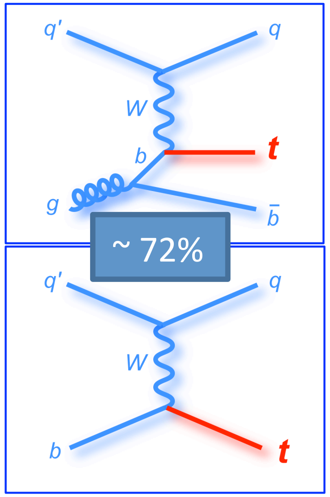


- Large integrated luminosity accumulated by experiments.
- Excellent detector performance.
- **LHC is a top-quark factory**
- Single top-quark measurements enter the precision domain.
- Investigation of rare decays.

Single top-quark production @ the LHC

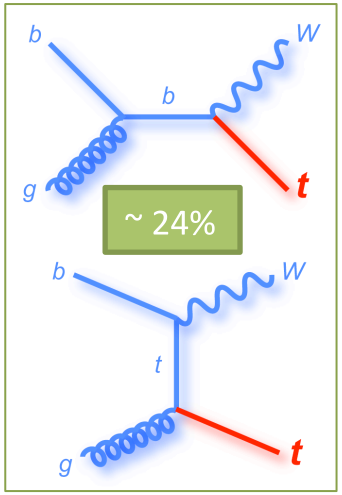
Three single top-quark production channels through weak interaction:

t-channel



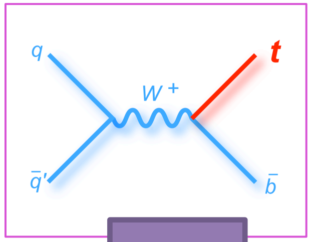
~ 72%

tW-channel



~ 24%

s-channel



~ 4%

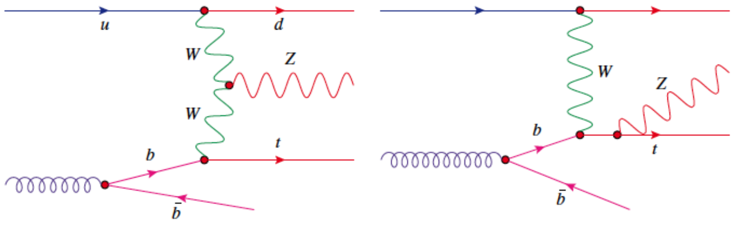
Important to measure all the 3 channels for their different sensibility to *Wbt* vertex.

@ 13 TeV

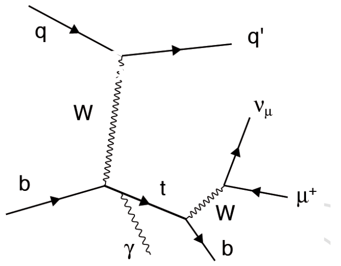
With the increase of energy and luminosity, the ability to study process with very low cross-section ("rare SM processes") at LHC became possible.

tZq-channel

~ 0,02%



tγq-channel



Outline

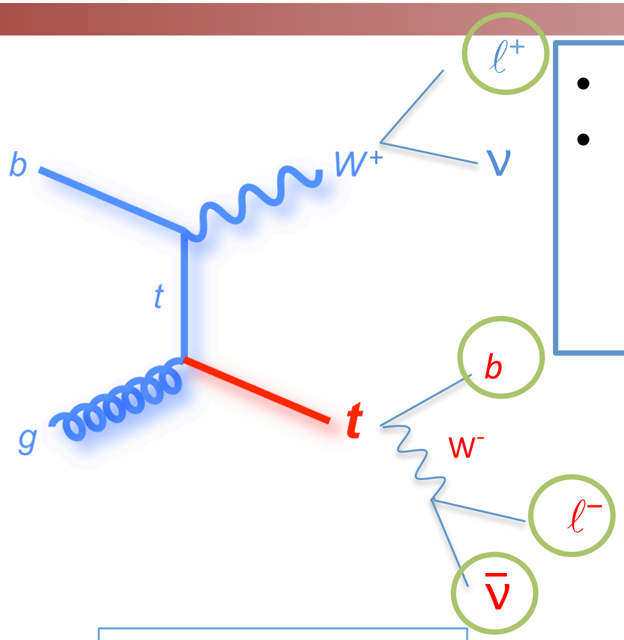
Only the newest single top-quark results by ATLAS and CMS will be covered here

ATLAS	***t*-channel**	***tW*-channel**	***s*-channel**	***tZq*-channel**	***tγq*-channel**
7 TeV	PRD 90, 1120006 (2014)	ATLAS-CONF-2011-204	ATLAS-CONF-2011-118		
8 TeV	EP. J. C77 (2017) 531 JHEP 12 (2017) 017 (anomalous couplings) JHEP 04 (2017) 124: (polarisation)	JHEP 01(2016)064	PLB 756 (2016) 228		
13 TeV	JHEP 04(2017)086	JHEP 01 (2018) 63 EPJ. C 78 (2018) 186 (diff) Paper in preparation *($tW/t\bar{t}$* interference)		PLB 780 (2018) 557	

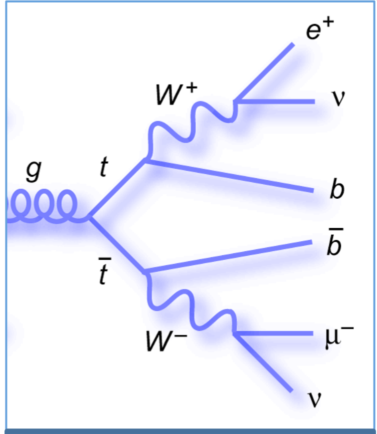
CMS	***t*-channel**	***tW*-channle**	***s*-channel**	***tZq*-channel**	***tγq*-channel**
7 TeV	JHEP 12(2012)035	PRL 110(2013)0022003	JHEP 09(2016)027		
8 TeV	CMS-TOP-15-007 CMS-TOP-14-014 (diff) JHEP 04 (2016) 073 (polarisation)	PRL 112(2014)231803	CMS-TOP-13-009	JHEP 07(2017)003	
13TeV	CMS-TOP-16-003 (diff) PLB 772(2017)752	arXiv:1805.07399 (submited to JHEP)		PLB7 79(2018) 358	CMS-TOP-17-016

Inclusive *tW*-channel @ 13TeV

arXiv:1805.07399

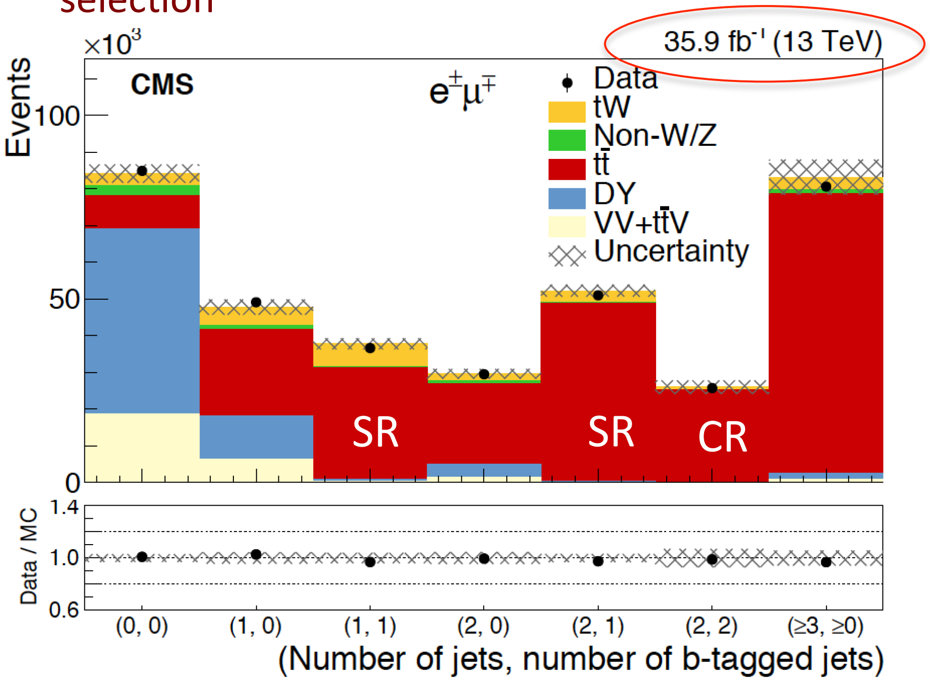


- Second largest single top-quark production channel at LHC.
- Studied decay mode:
  - 2 isolated high p_T Opposite Sign leptons (OS).
  - 1 *b*-tagged jet.
  - E_T^{miss}.



Main Background

Event categorization based on (*n-jet,n-btag*) after dileptonic selection



SR: dominant background $t\bar{t}$ events

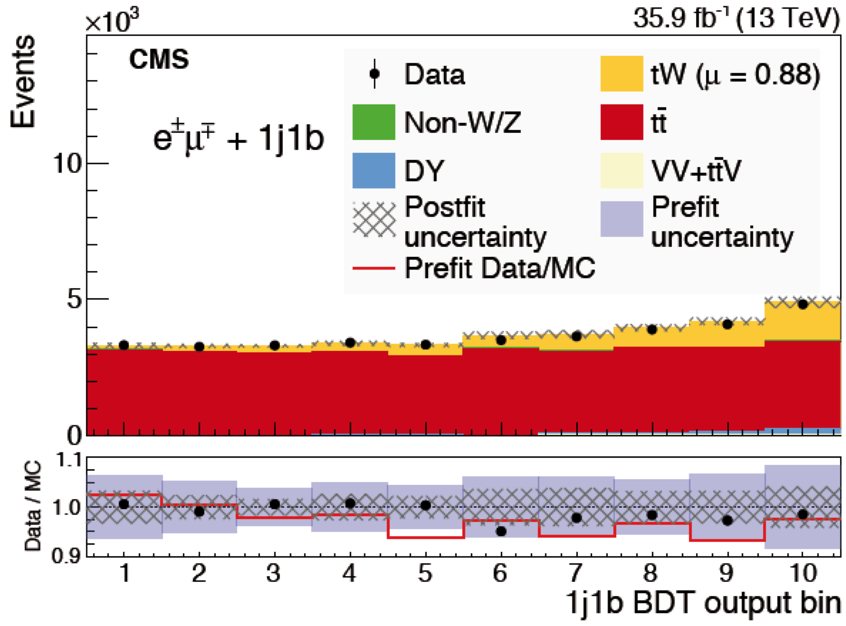
CR: Enriched in $t\bar{t}$ events

Inclusive *tW*-channel @ 13TeV

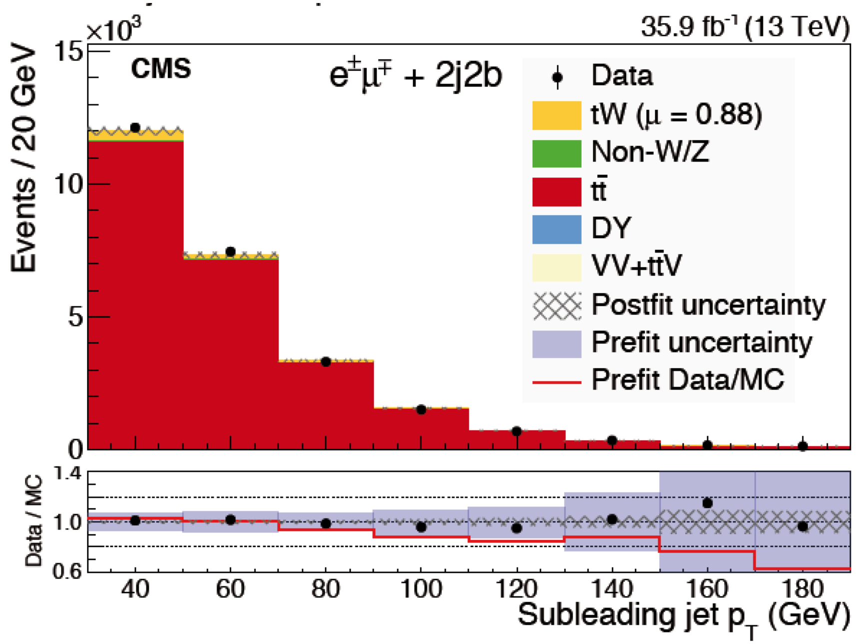
arXiv:1805.07399

- Boosted Decision Tree BDT to separate *tW* form *tt̄* background.
- Binned maximum likelihood fit to extract the cross-section.

Simultaneous fit to the BDT output, in SR: (***1****jet*,***1b***-*tag*) and (***2****jets*,***1b***-*tag*).



The CR (***2****jets*,***2b***-*tag*) is used to constrain the main sources of background using the distribution of the p_T of the subleading jet.



Inclusive *tW*-channel @ 13TeV

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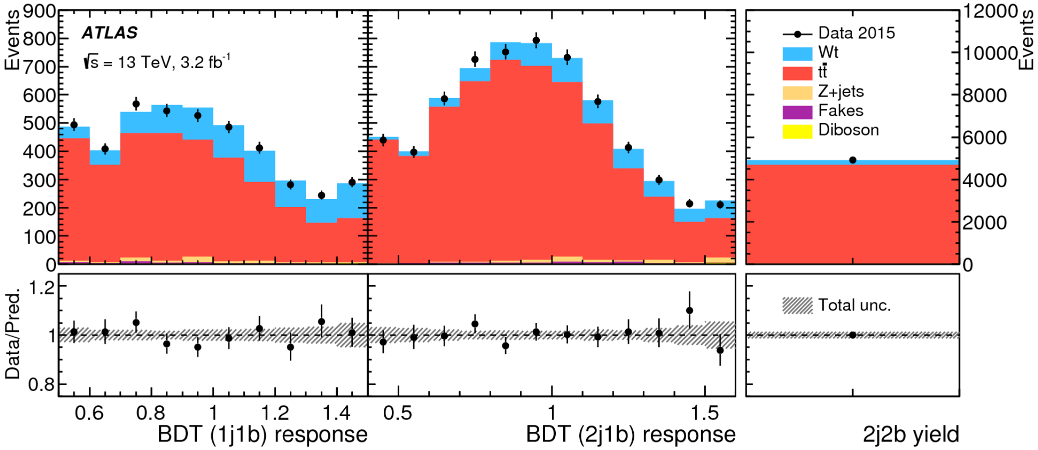
ATLAS has followed a similar strategy using 3.2 *fb*$^{-1}$ (2015).



Main sources of systematic uncertainty:

CMS

- Lepton efficiency and Jet energy scale.
- tt̄ μ_R, μ_F scale variations and tt̄ normalization

ATLAS

- Jet-energy-scale and Jet energy resolution.
- NLO ME generator choice.

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arXiv:1805.07399

$$\sigma_{CMS} = 63.1 \pm 1.8(stat.) \pm 6.4(syst.) \pm 2.1(lumi.)\,pb \qquad 10\%$$

$$\sigma_{ATLAS} = 94 \pm 10(stat.)\;{}^{+28}_{-22}(syst.) \pm 2(lumi.)\,pb \qquad 29\%$$

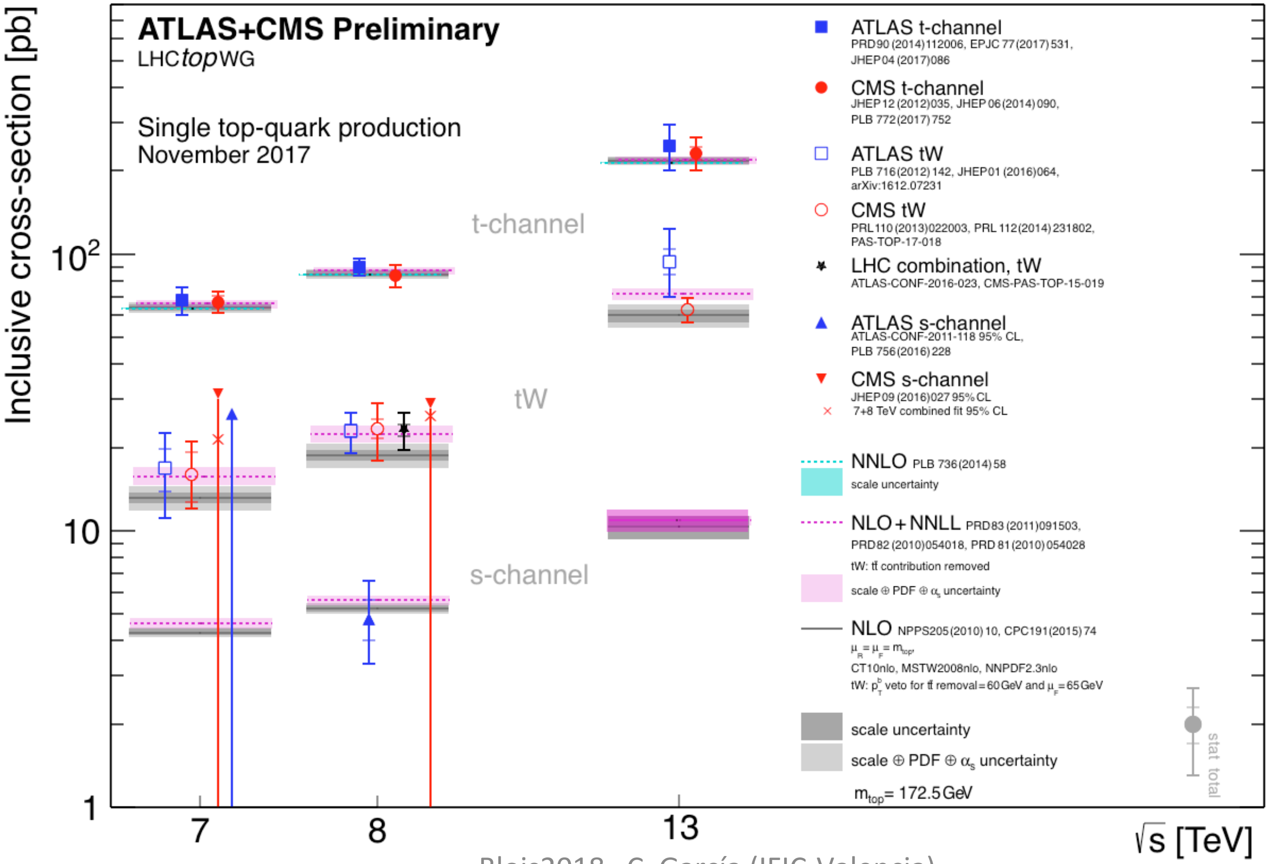
$$\sigma_{Theory} = 71.7 \pm 1.8(scale) \pm 3.4(PDF)\,pb \quad (*) \qquad 5\%$$

Both measurements consistent with the SM prediction

(∗) (N. Kidinakis, arXiv:1506.04072)

Summary of single top-quark cross-sections

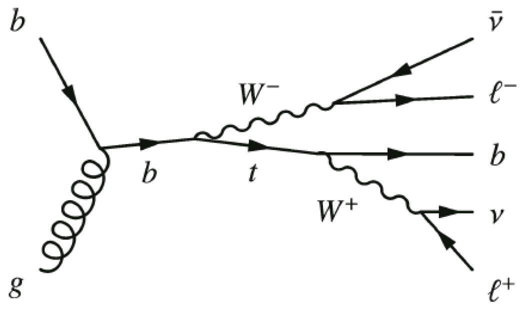
- ATLAS and CMS measurement of the single top-quark production cross-sections in various channels as a function of the center-of-mass energy.
- The measurements are compared to theoretical calculations based on:
  NLO QCD, NLO QCD complemented with NNLL resummation and NNLO QCD (t-channel only).

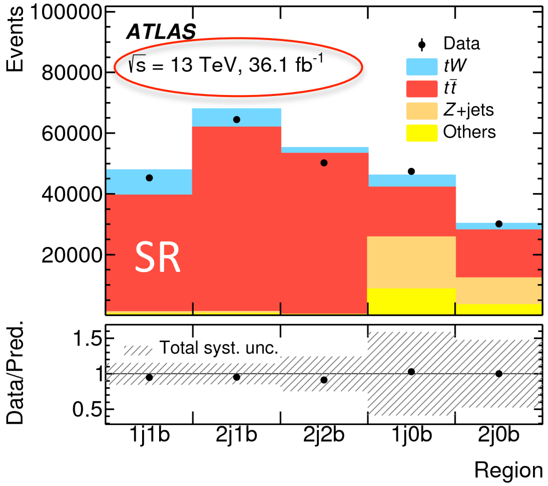


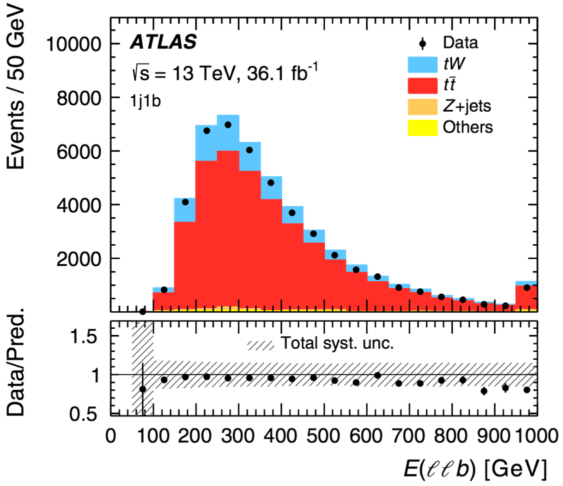
Differential *tW*-channel @13 TeV

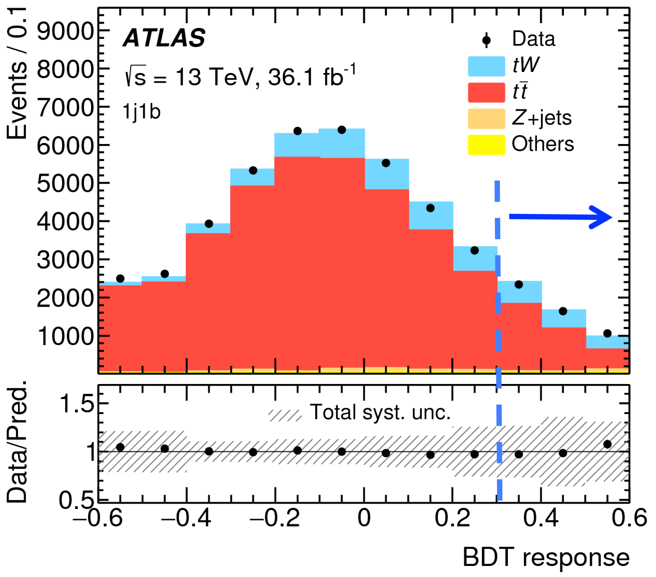
EPJ. C 78 (2018) 186

- **First measurement of the *tW* differential cross-section.**
- SR: (***1jet,1b**-tag*) + cut on BDT output score to increase S/B.
- Measured as a function of particle-level observables related with kinematic properties of *tW* and sensitive to differences in the theoretical modelling:
  - $E(b)$ → probe the top-quark production.
  - $m(l_1 b)$, $m(l_2 b)$ → probe the top-quark decay (angular correlations due to spin correlations).
  - $E(llb)$, $m_T(ll\nu\nu b)$, $m(llb)$ → prove the *tW* system.



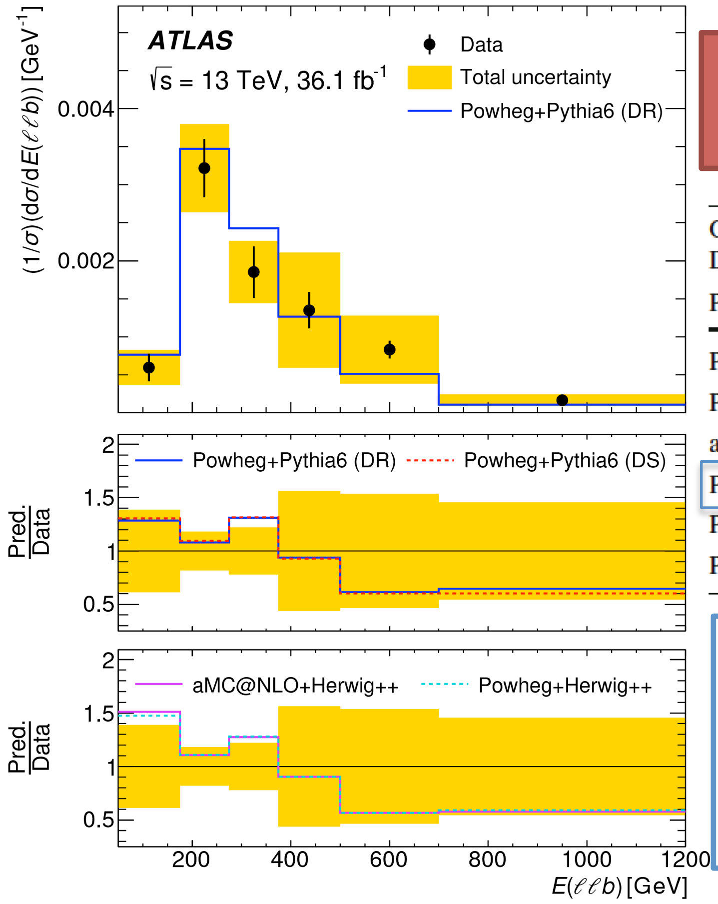






Differential *tW*-channel @13 TeV

EPJ. C 78 (2018) 186



Main uncertainties cancel when normalise to the cross-section

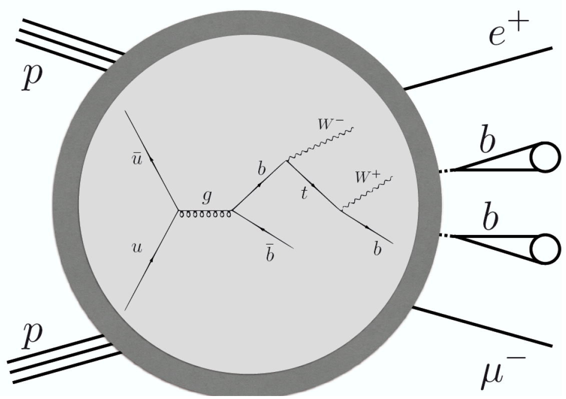
Largest uncertainties come from the data statistics and $t\bar{t}$ and *tW* modelling

Observable	$E(b)$		$m(\ell_1 b)$		$m(\ell_2 b)$		$E(\ell\ell b)$		$m_T(\ell\ell\nu\nu b)$		$m(\ell\ell b)$	
Degrees of freedom	4		5		3		5		3		5	
Prediction	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p
POWHEG+PYTHIA 6 (DR)	4.8	0.31	5.7	0.34	2.6	0.45	8.1	0.15	2.0	0.56	4.0	0.55
POWHEG+PYTHIA 6 (DS)	5.0	0.29	6.1	0.30	2.6	0.46	9.1	0.11	2.4	0.49	4.4	0.50
aMC@NLO+Herwig++	5.6	0.23	5.4	0.37	2.4	0.49	8.7	0.12	1.8	0.61	3.6	0.61
POWHEG+Herwig++	6.2	0.18	8.1	0.15	2.3	0.52	11.0	0.05	2.0	0.57	5.2	0.40
POWHEG+PYTHIA 6 radHi	4.8	0.30	5.3	0.38	2.5	0.48	7.9	0.16	1.9	0.60	3.7	0.60
POWHEG+PYTHIA 6 radLo	5.0	0.29	5.8	0.33	2.6	0.45	8.4	0.14	2.1	0.56	4.0	0.55

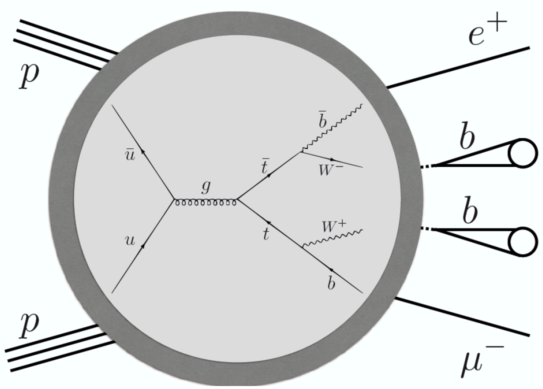
- Reasonable agreement with MC prediction within uncertainties.
- Slightly harder *E(ℓℓb)* spectrum in data.
- Powheg+Herwig++ deviate slightly more from data.

Quantum interference *tWb*/*tt̄*

As measurements and searches increase their sensitivity, they began **to prove regions of phase space that are not well described by separable leading order matrix element calculations**, that is the case of ***tWb* production** .



tWb (one resonance)



tt̄ (two resonances)

Same final state:
- Two opposite sign leptons
- 2 *b*-tagged jets
- Missing Energy

Due to their identical final states, processes with ONE or TWO timelike top-quark propagators interfere.

NEW

Quantum interference *tWb*/*tt̄*

The **cross-section for WWbb** will be proportional to

$$\sim |\mathcal{A}_{t\bar{t}}|^2 + |\mathcal{A}_{tWb}|^2 + 2\mathrm{Re}\{\mathcal{A}^*_{t\bar{t}}\mathcal{A}_{tWb}\}$$

Interference effects are estimated by comparing ad-hoc prescriptions :

Diagram Removal (DR) :
Wtb prediction $\sim |\mathcal{A}_{tWb}|^2$
arXiv:0805.3067

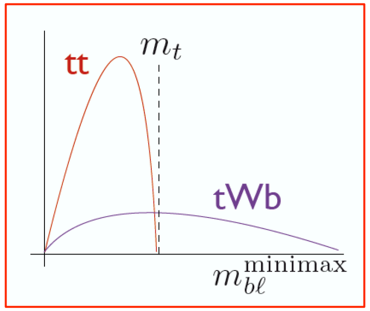
arXiv:0805.3067
Diagram Subtraction (DS): *Wbt* takes entire expression, minus a gauge invariant –term (**φ**) that cancels tt̄ "on average".
tWb prediction $\sim |\mathcal{A}_{t\bar{t}}|^2 + |\mathcal{A}_{tWb}|^2 + 2\mathrm{Re}\{\mathcal{A}^*_{t\bar{t}}\mathcal{A}_{tWb}\} - \varphi$

Diagram Removal 2 (DR2):
Wtb prediction
$\sim |\mathcal{A}_{tWb}|^2 + 2\mathrm{Re}\{\mathcal{A}^*_{t\bar{t}}\mathcal{A}_{tWb}\}$
arXiv:1207.1071, arXiv:1607.05862

Recently, a generator of $\ell^+\nu\ell^-\nu bb$ process was implemented in Powheg (fixed-order calculations with the full NLO + matched to PS) with an inclusive treatment → interference is "automatically" included. arXiv:1607.04538

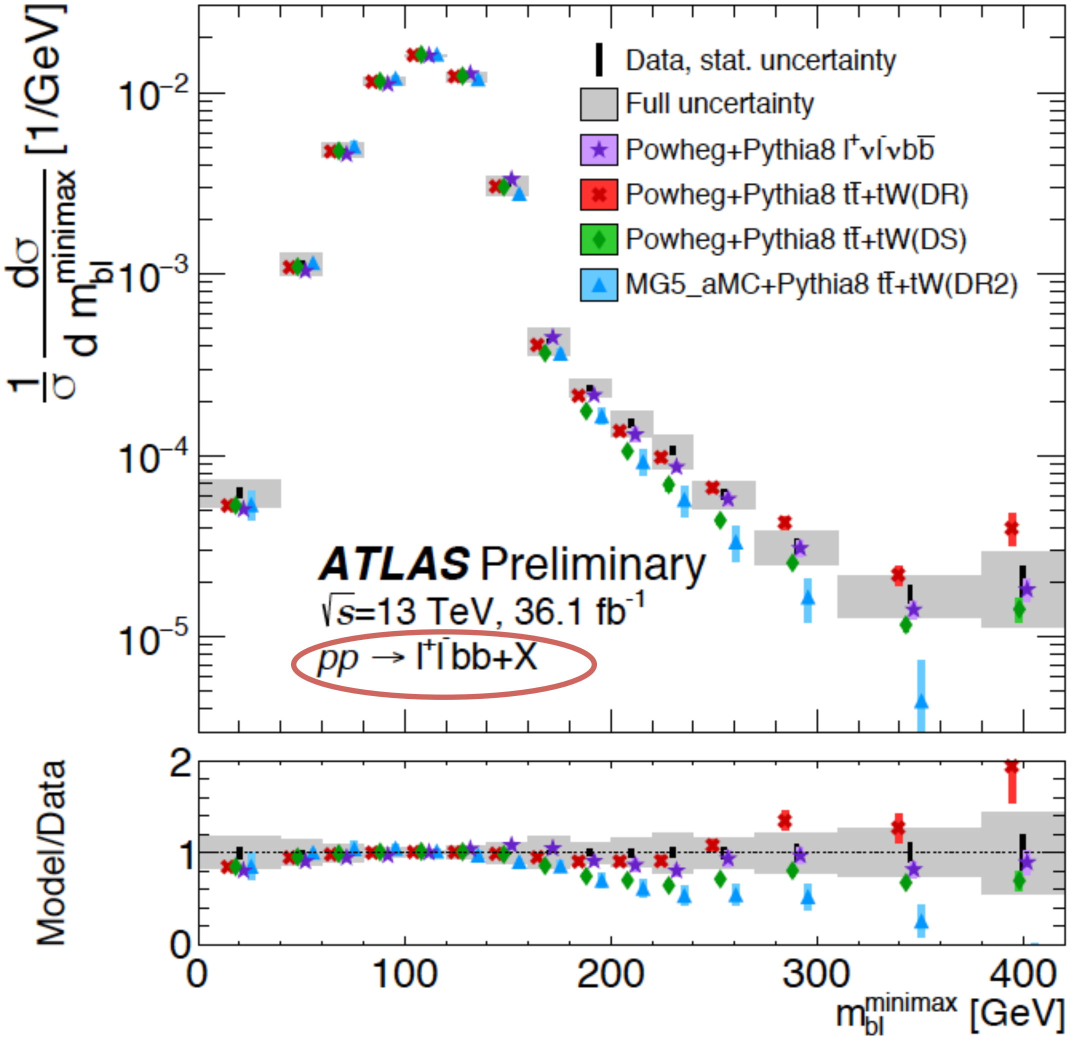
$$m_{b\ell}^{\mathrm{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

tt̄ at LO: $m_{b\ell}^{\mathrm{minimax}} < \sqrt{m_t^2 - m_W^2}$ (kinematic endpoint)



Quantum interferences $tWb/t\bar{t}$

NEW



Powheg+Pythia8 $\ell^+\nu\ell^-\nu bb$ (explicitly includes interference) describes the data across the full spectrum.

Powheg+Pythia8 $t\bar{t}+tW$ with different strategies for the interference are considered:

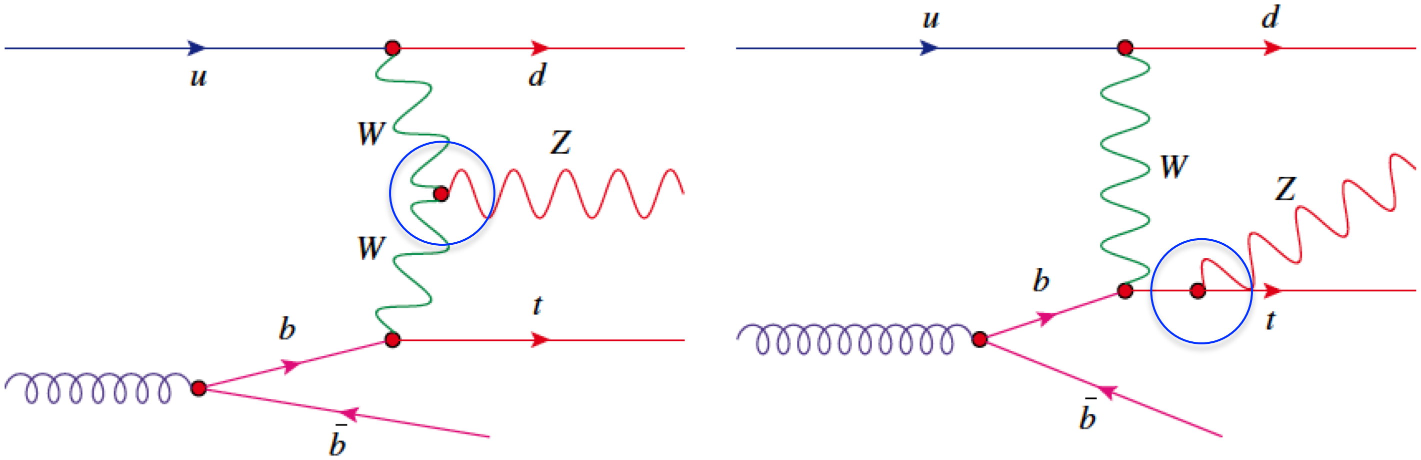
- In the tail ($m_{b\ell}^{\mathrm{minimax}} \gtrsim m_t$) **DR** and **DS** predictions diverge, but they are consistent with data at ∽2σ level .
- **DR2** describes well the data up to top-quark mass but deviates significantly for above.

Main uncertainties:

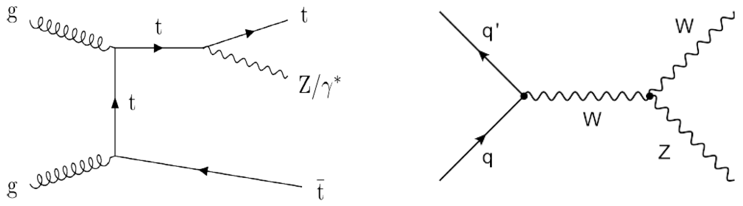
Top modelling ($t\bar{t}$,tW, $t\bar{t}$+HF)

Jet-energy-scale, b-tagging efficiency

tZq-channel



- **Rare process**: 2 orders of magnitude smaller that *tW* channel.
- Sensitive to ***tZ* coupling** and **triple gauge boson *WWZ* coupling**.
- **Possible deviation may indicate physics beyond the SM** (FCNC, anomalous coupling).
- Trilepton final state:
    - 3 isolated high p_T leptons.
    - 1 *b*-tagged jet.
    - 1 forward jet.
    - E_T^{miss}.
- Main background from *ttV*, *WZ* and non-prompt lepton production.



tZq-channel @ 13TeV

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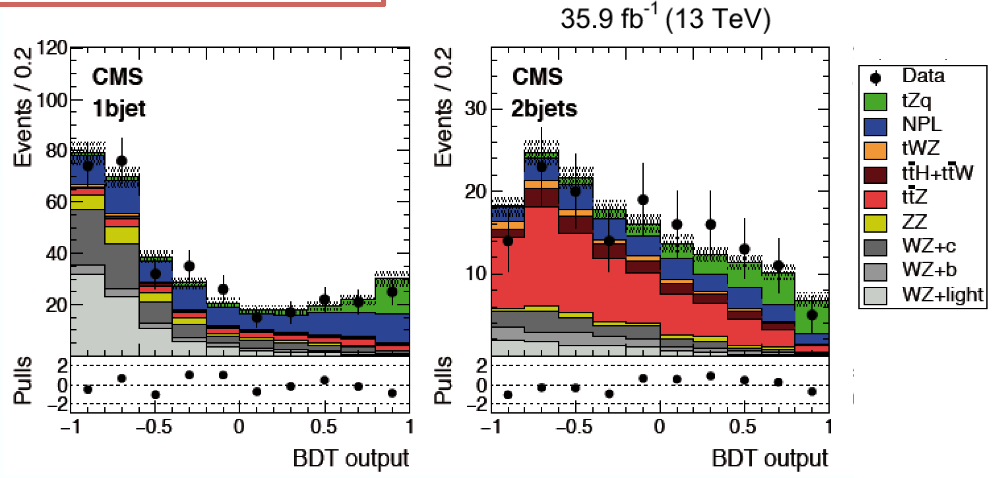
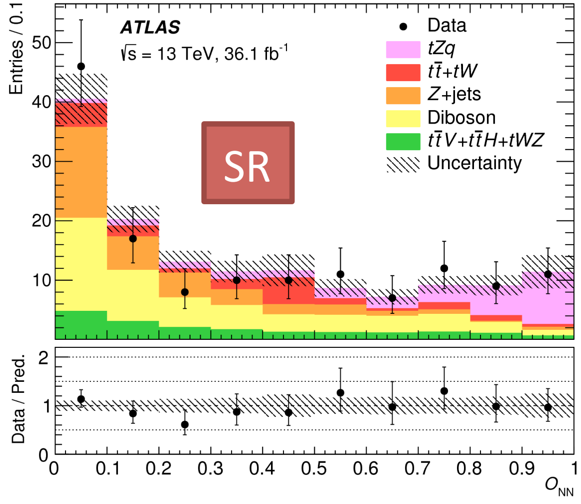
Two BDT based in observable for the ***1b-taged jet*** and ***2b-tagged jets*** regions are used to enhance S/B + a weight for the hypothesis (signal, $t\bar{t}Z$ or *WZ)* is included in the input variables (base on MEM).





SR

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Neural Network is used to enhance S/B separation with 10 variables. Training with a mixture of all BG, except *tt* (low statistics).

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tZq-channel@ 13 TeV

$$\begin{aligned} \sigma_{\mathrm{CMS}}(tllq) &= 123^{+33}_{-31}(\mathrm{stat.})^{+29}_{-23}(\mathrm{syst.})\ \mathrm{fb} \quad 3.7(\mathbf{3.1})\sigma\ \mathrm{obs.(exp.)} \\ \sigma_{\mathrm{ATLAS}}(tZq) &= 600 \pm 170(\mathrm{stat.}) \pm 140(\mathrm{syst.})\ \mathrm{fb} \quad 4.2(\mathbf{5.4})\sigma\ \mathrm{obs.(exp.)} \end{aligned}$$

$$\sigma^{\mathrm{SM}}(\mathrm{t}\ell^{+}\ell^{-}\mathrm{q}) = 94.2^{+1.9}_{-1.8}(\mathrm{scale}) \pm 2.5(\mathrm{PDF})\ \mathrm{fb}$$

$$\sigma^{\mathrm{SM}}(\mathrm{tZq}) = 800^{+49}_{-59}\ \mathrm{fb}$$

Main sources of systematic uncertainty

ATLAS:

- Jet-energy-scale.
- PDF and *tZq* μ_R, μ_F scale variations .

CMS:

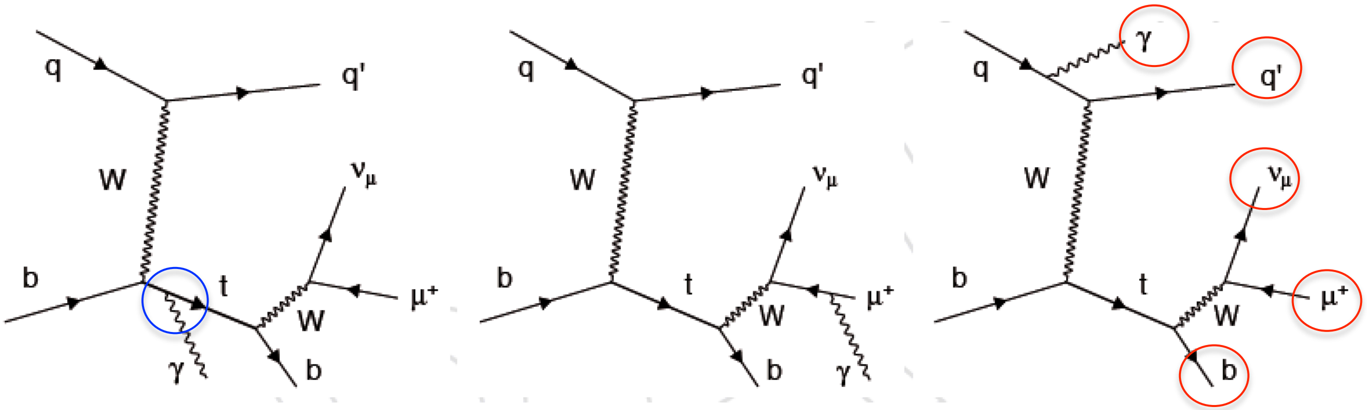
- Background normalization.
- *tZq* μ_R, μ_F scale variations .

- First evidences of *tZq* production from two collaborations.
- Results are consistent with the SM predictions.

tγq-channel @ 13TeV

CMS-TOP-17-016

NEW



- **Rare process**: 2 orders of magnitude smaller that *t*-channel.
- Sensitive **top-quark charge** and **top-quark electric and magnetic dipole moments**.
- **Possible deviation may indicate physics beyond the SM.**
- Final state:
  - 1 isolated high p_T muon.
  - 1 isolated photon.
  - 1 *b*-tagged jet.
  - 1 forward jet
  - $\vec{p}_T^{\,miss}$.

Main background:

- Jet misidentified as photon
  tt, W+jet, *Z*+jet
- Real photon
  tt+*γ*, *Wγ*+jet, *Zγ*+jet

tγq-channel @ 13TeV

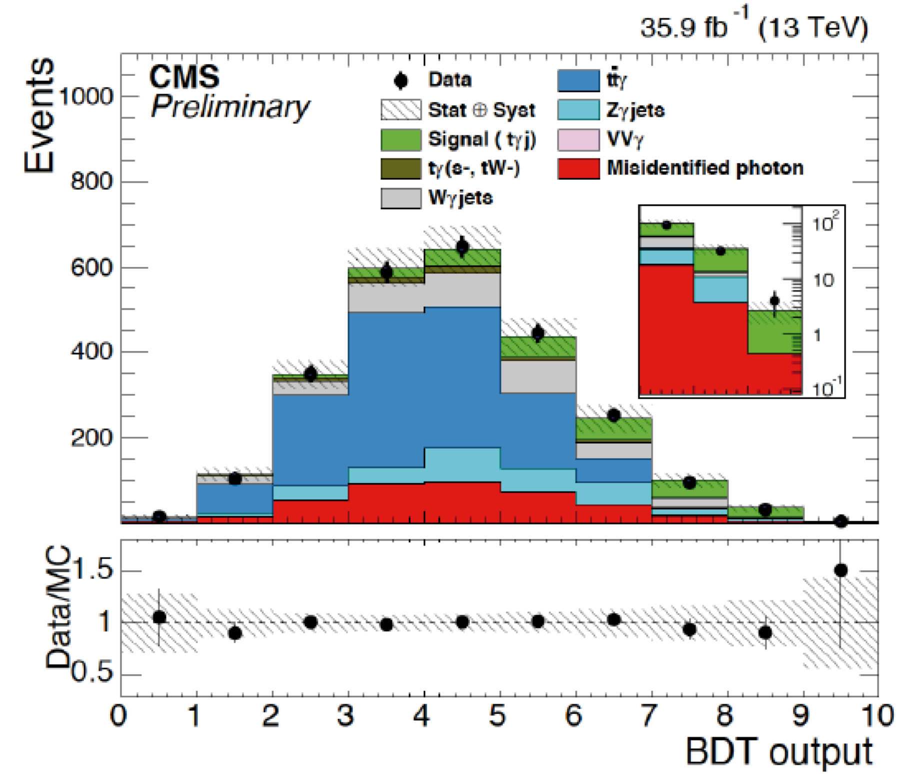
CMS-TOP-17-016

NEW

- Two BDTs are used for :
  - SR (1 *b*-tagged jet) and
  - *CR* (2 *b*-tagged jets) to get *tt+γ* background.
- A binned likelihood to extract:

$$\mathcal{B}(\mathrm{t}\rightarrow \mu\nu\mathrm{b})\sigma(\mathrm{t}\gamma\mathrm{j})$$

First evidence of the single top-quark production in association with a photon in the *t*-channel.



$$\boxed{\mathcal{B}(\mathrm{t}\rightarrow \mu\nu\mathrm{b})\sigma(\mathrm{t}\gamma\mathrm{j}) = 115 \pm 17(\mathrm{stat})^{+33}_{-27}(\mathrm{syst})\ \mathrm{fb}}$$

Corresponding to a significance of 4.4 (3.0)σ obs. (esp.)

In agreement with the SM prediction of $\boxed{81 \pm 4\ \mathrm{fb}}$

Main sources of uncertainty

- Jet energy scale.
- Signal modelling.
- *Zγ*+jets.
- b-tagging.

Conclusions

ATLAS and CMS have measured the single top-quark production cross-sections in various channels for various centre-of-mass energies.

NEW MEASUREMENTS @ 13 TeV

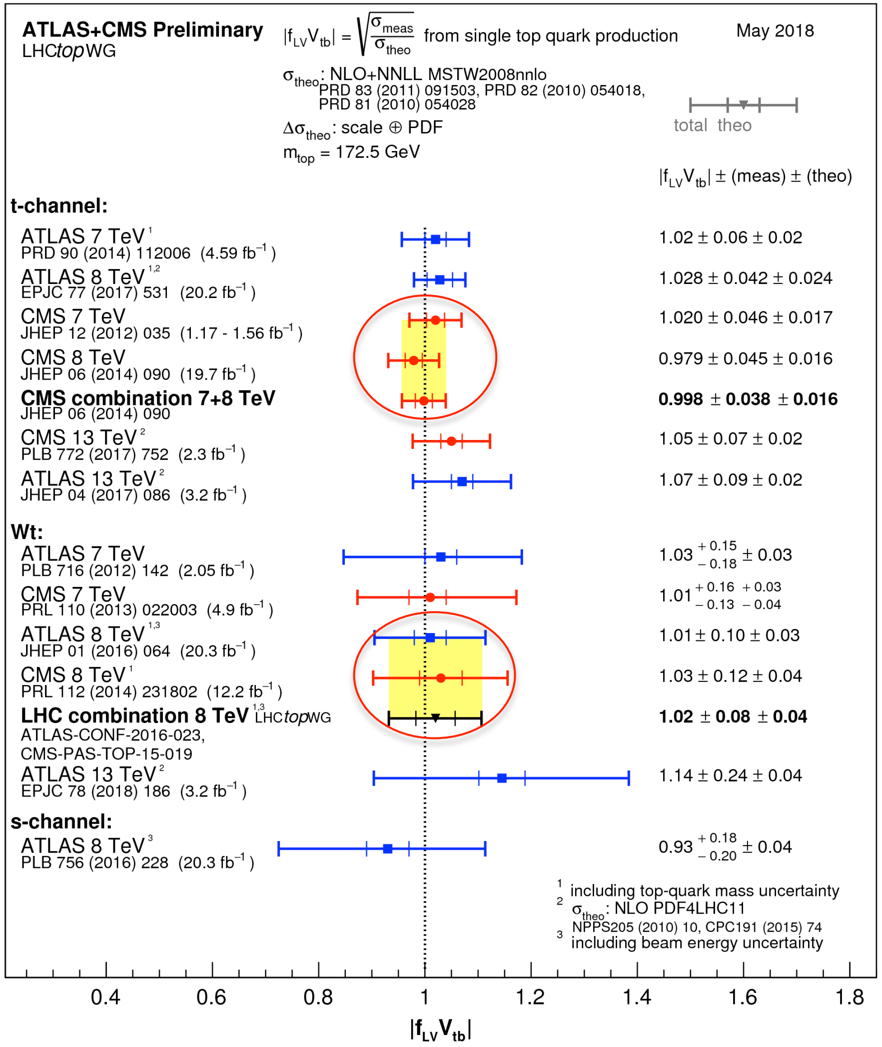
- New result on ***tW*-channel** for inclusive and differential cross-section has been presented.
- ATLAS has developed a novel method to distinguish different for the first time models of the **interference between *tt̄* and *tWb*** process*es*.
- **First evidences of *tZq* production** from the two collaborations.
- **First evidences of *tγq* production** from CMS.
- **All measurements in good agreement (within uncertainties) with the state-of-the-art theoretical predictions.**

BACKUP

Probing *Wtb vertex* from the cross-sections

- The single top-quark production cross-sections are proportional to $|f_{LV} V_{tb}|^2$.
- In the SM, V_{tb} is very close to 1 and f_{LV} value is exactly 1.
- New physics contribution could affect the valour of f_{LV}.

$$f_{LV} V_{tb} = \sqrt{\frac{\sigma_{\text{meas.}}}{\sigma_{\text{theo.}}}}$$



- Measurement is independent of assumptions about the number of quarks generations or about the unitarily of the CKM matrix.
- Assumptions for the extractions:
  - *Wtb* interaction is a SM-like left-handed weak coupling.
  - $|V_{tb}| >> |V_{td}|, |V_{ts}|$, i.e. BR($t \rightarrow Wb$).

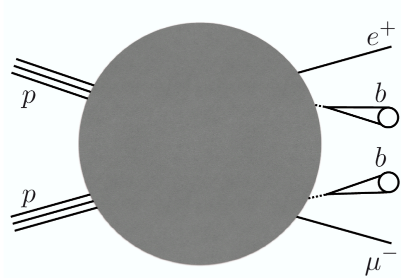
$|f_{LV}V_{tb}|$ results from all three single top-quark production processes are in agreement with the SM predictions.

Quantum interference *tWb*/*tt̄*

Novel method to distinguish different models of the interference between *tt̄* and *tWb*

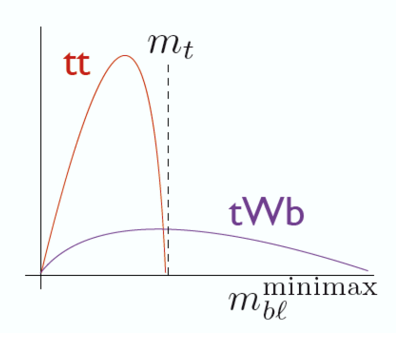
- The **contributions from doubly- and singly-resonant amplitudes** (and hence also their interference) to the combined cross-section **depend on the invariant mass of the *bW*** pairs in the event (m_{bW})
- The lepton is used to proxy the *W*.
- **Differential cross-section** is measured with **respect to the mass of a *b*-jet and a lepton** (m_{bl})
- There is ambiguity in forming this mass, so:

$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$



ttbar at LO: $m_{b\ell}^{\text{minimax}} < \sqrt{m_t^2 - m_W^2}$ (kinematic endpoint)

The region above the kinematic endpoint will be highly enriched in *tWb* .



Quantum interferences *tWb*/*$t\bar{t}$*

Signal *ttbar + tWb*

Events with:

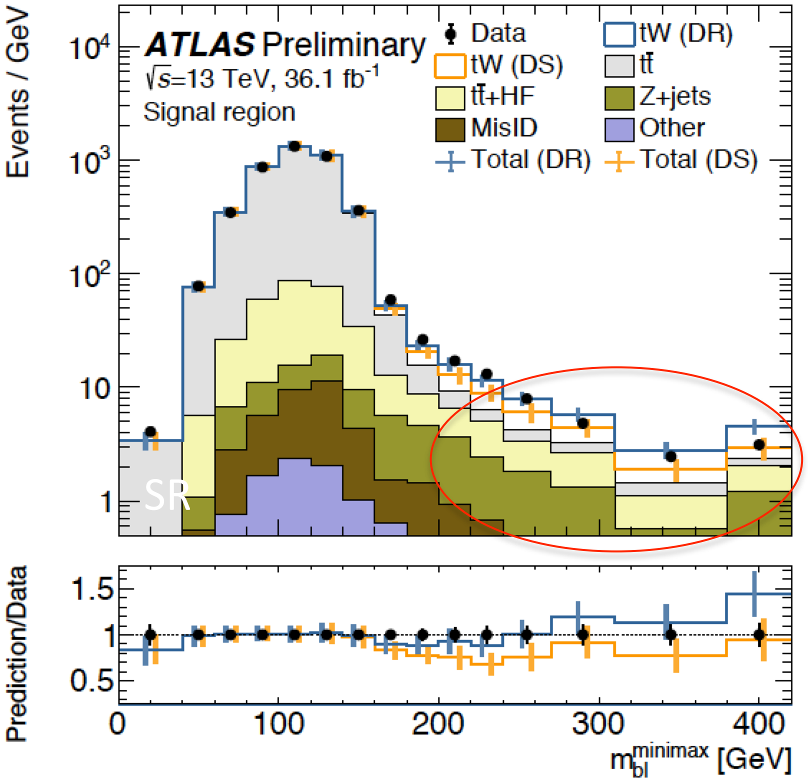
- 2 OS leptons .
- 2*b-tagged jets.*
- E_T^{miss} .

Rejection of low resonances and *Z*+jets:

$$m(ll) < 10GeV$$

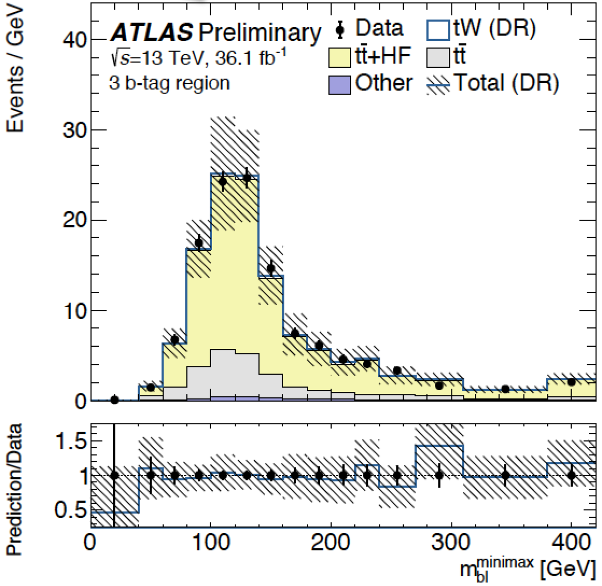
$$|m(ll) - m(Z)| < 15GeV$$

- Dominant BG in the hight mass region is $t\bar{t}$ + Heavy Flavor (HF) with a *b-jet* form *t-quark* not *b*-tagged.
- Evaluated for 3 *b-jet* events (CR), the mass variable is calculated from the 2 *b*-tagged jets with highest p_T.



Predictions given for both **DR and DS** schemes for *tW.*

High purity in *tW* events in the tail of the distributions.



tZq-channel @ 13TeV

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Selected events:

- 3 leptons
- Z candidate
- 1b jets + 1 untagged jet

tZq→ (t→blν)
(Z→l^+l^-) q

SR:

- $|m_{\ell\ell} - m_Z| < 10\ GeV$ (OSSF)
- $m_T(\ell_W, \nu) > 20\ GeV$

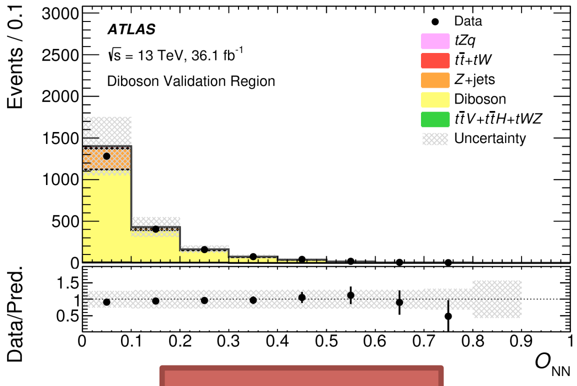
VR to check BG modelling:

- Diboson: 1 jets (0-*btagged j*)
- $t\bar{t}$: $|m_{\ell\ell} - m_Z| > 10\ GeV$

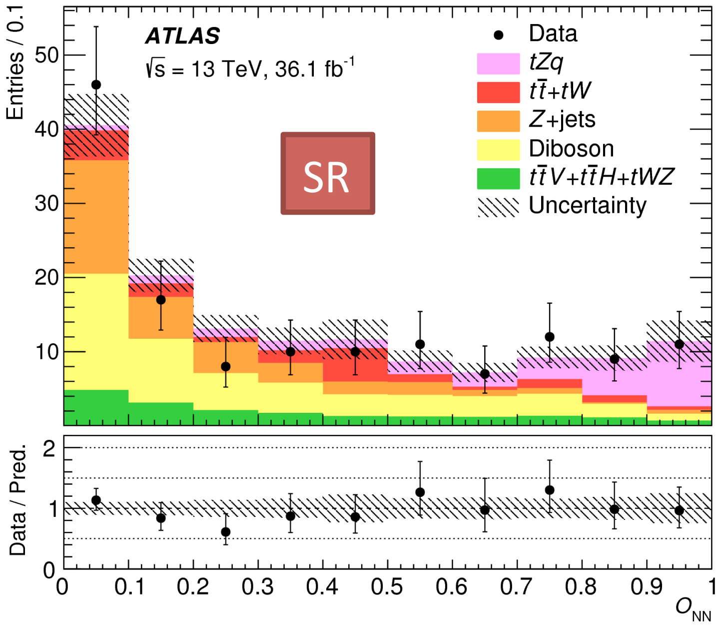
CR to normalize BG:

- Diboson: $m_T(\ell_W, \nu) > 60\ GeV$
- $t\bar{t}$: ≥1 OSDF pair and not OSSF, 1*b-tagged j*

Neural Network is used to enhance S/B separation with 10 variables. Training with a mixture of all BG, except ttbat (low statistics).



Diboson VR



SR

tZq-channel @ 13TeV

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Similar analysis carry out by CMS with regions defined according with the jet and b-jet multiplicities

tZq→ (t→blν)
(Z→l^+l^-) q

tt̄Z→ (t→blν) (t→blν)
(Z→l^+l^-)

WZ→ (W→lν)
(Z→l^+l^-)

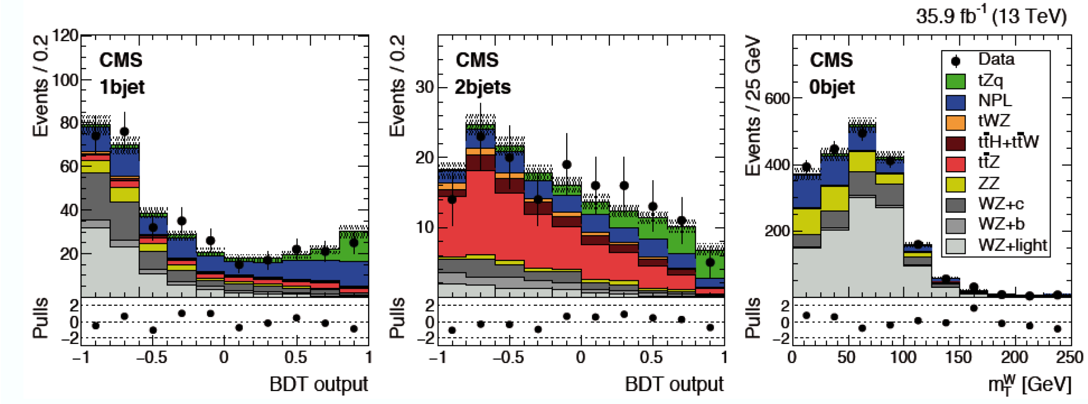
3 leptons + 1bj

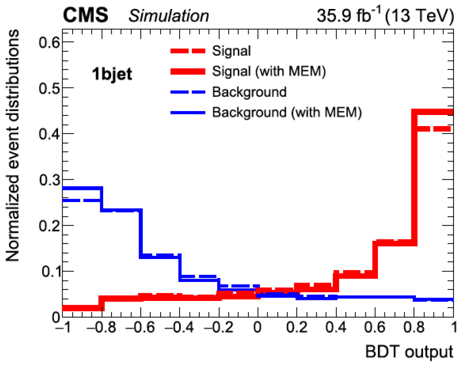
3 leptons + 2bj

3 leptons + 0bj

Two multivariate discriminators (BDT) based in observable for the *1b-jet* and 2*b-jets* regions are used to enhance S/BG.

For each event, a weight for the hypothesis: signal, tt̄*Z* or *WZ,* base on Matrix Element Method (MEM) is included in the input variables.

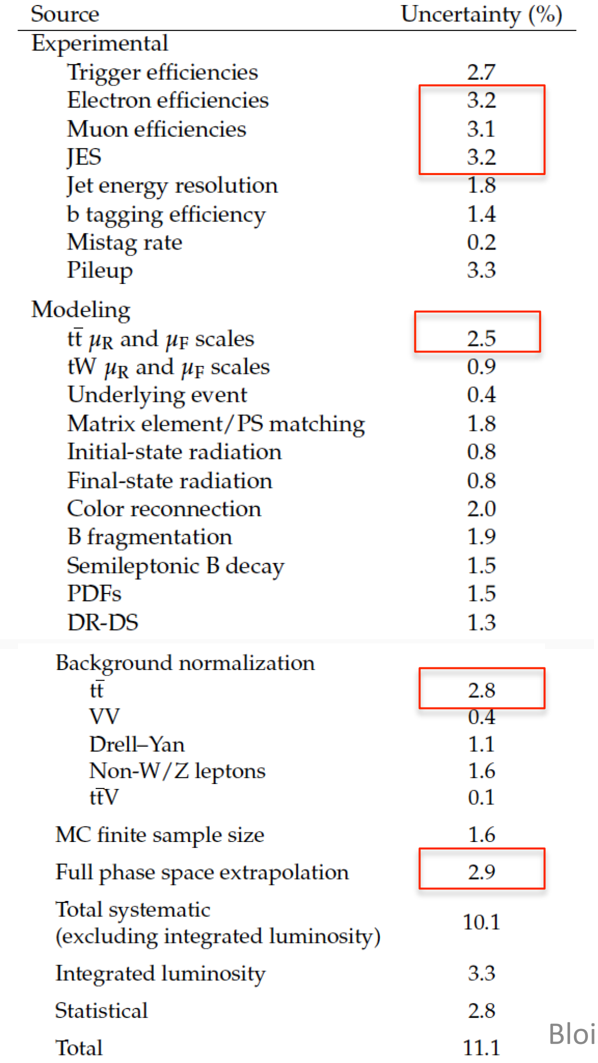




20% improvement in the expected significance using MEM

Inclusive *tW*-channel @ 13TeV

CMS-TOP-17-018



Source	Uncertainty (%)
Experimental	
Trigger efficiencies	2.7
Electron efficiencies	3.2
Muon efficiencies	3.1
JES	3.2
Jet energy resolution	1.8
b tagging efficiency	1.4
Mistag rate	0.2
Pileup	3.3
Modeling	
$t\bar{t}$ μ_R and μ_F scales	2.5
tW μ_R and μ_F scales	0.9
Underlying event	0.4
Matrix element/PS matching	1.8
Initial-state radiation	0.8
Final-state radiation	0.8
Color reconnection	2.0
B fragmentation	1.9
Semileptonic B decay	1.5
PDFs	1.5
DR-DS	1.3
Background normalization	
$t\bar{t}$	2.8
VV	0.4
Drell–Yan	1.1
Non-W/Z leptons	1.6
$t\bar{t}$V	0.1
MC finite sample size	1.6
Full phase space extrapolation	2.9
Total systematic (excluding integrated luminosity)	10.1
Integrated luminosity	3.3
Statistical	2.8
Total	11.1

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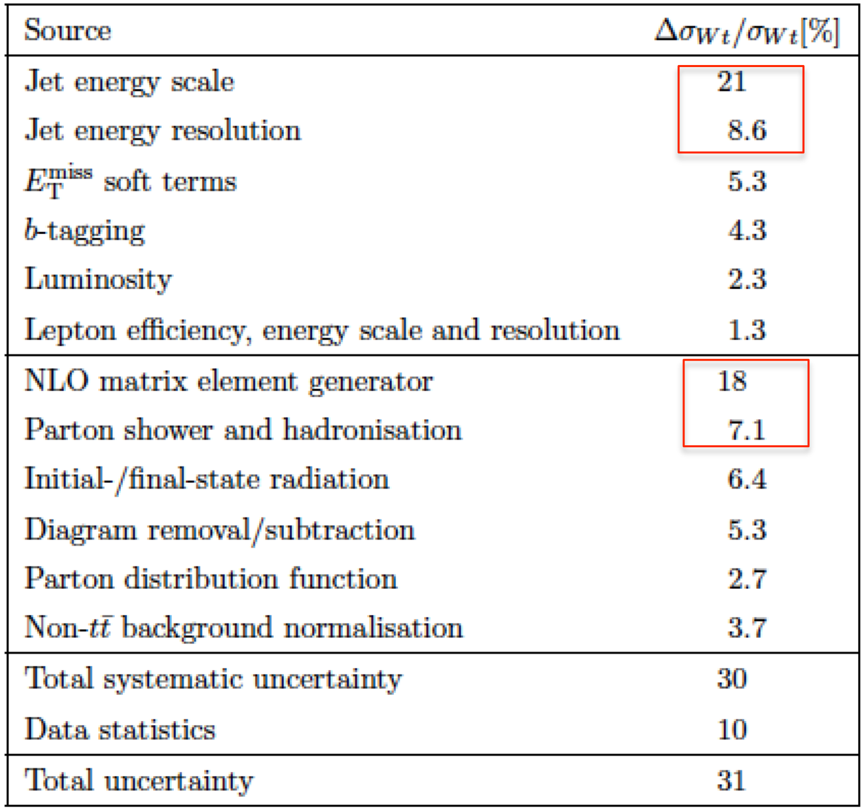

Source	$\Delta\sigma_{Wt}/\sigma_{Wt}[\%]$
Jet energy scale	21
Jet energy resolution	8.6
E_T^{miss} soft terms	5.3
b-tagging	4.3
Luminosity	2.3
Lepton efficiency, energy scale and resolution	1.3
NLO matrix element generator	18
Parton shower and hadronisation	7.1
Initial-/final-state radiation	6.4
Diagram 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 *tW*-channel @13 TeV

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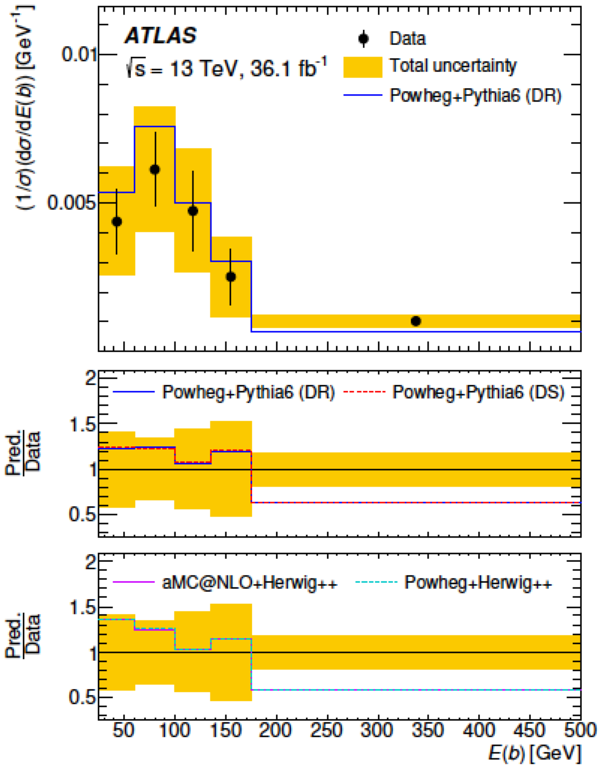
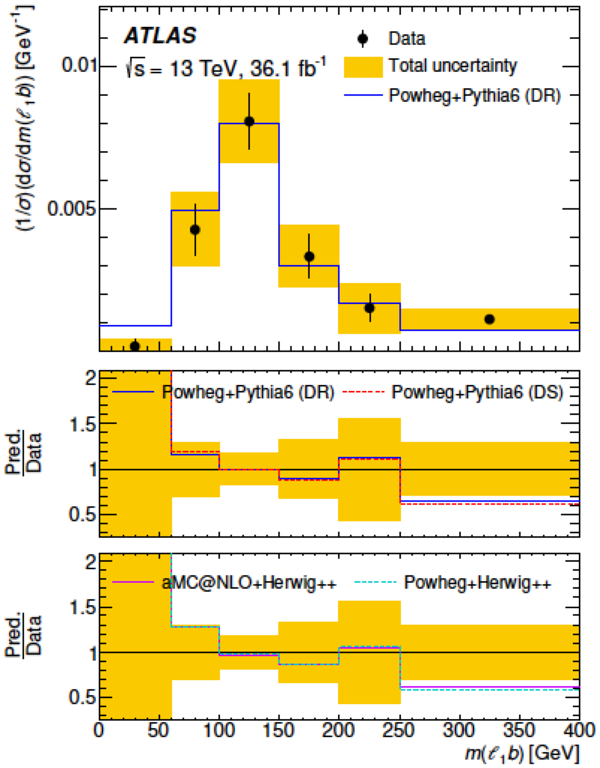
Unfold with iterative Bayesian method

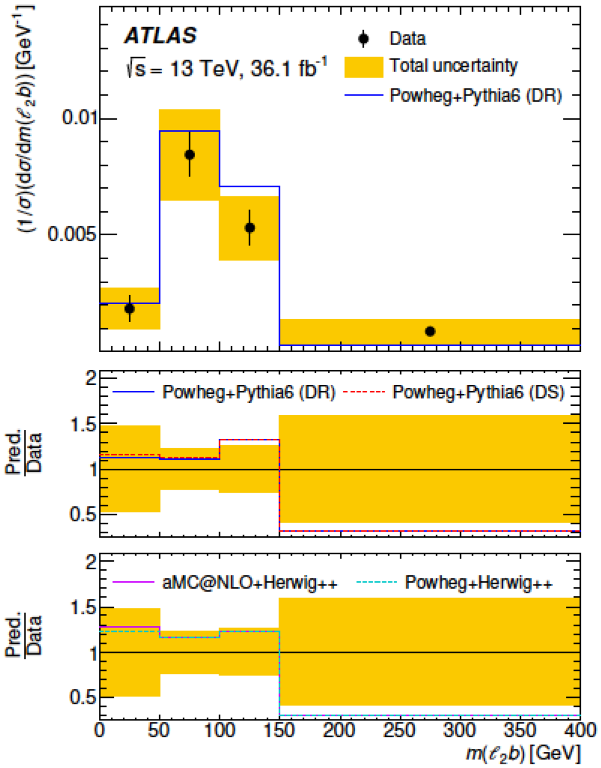
$E(\ell_1\ell_2 b)$



$m_{\mathrm{T}}(\ell_1\ell_2\nu b)$



$m(\ell_1\ell_2 b)$



Differential *tW*-channel @13 TeV

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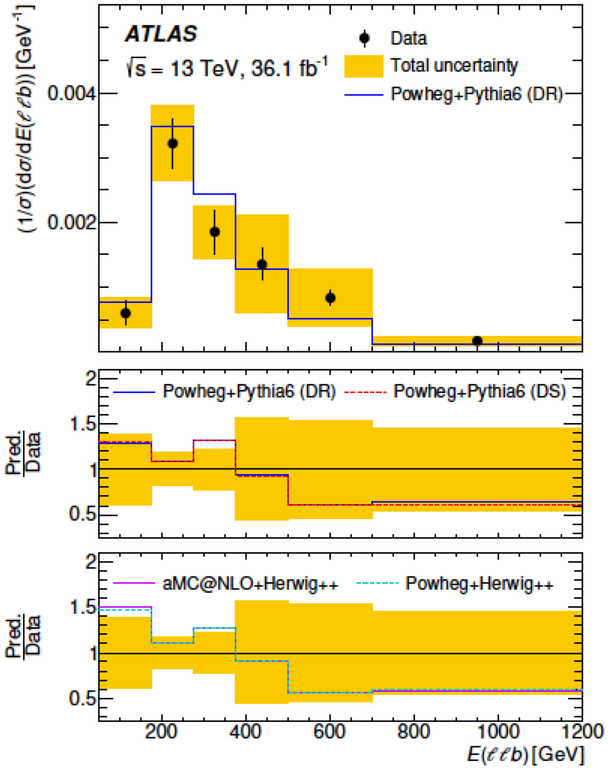
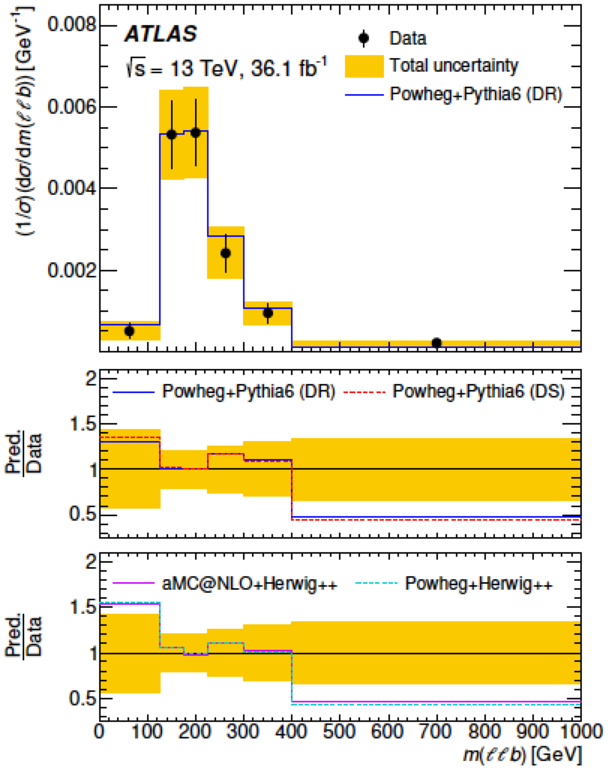
Unfold with iterative Bayesian method

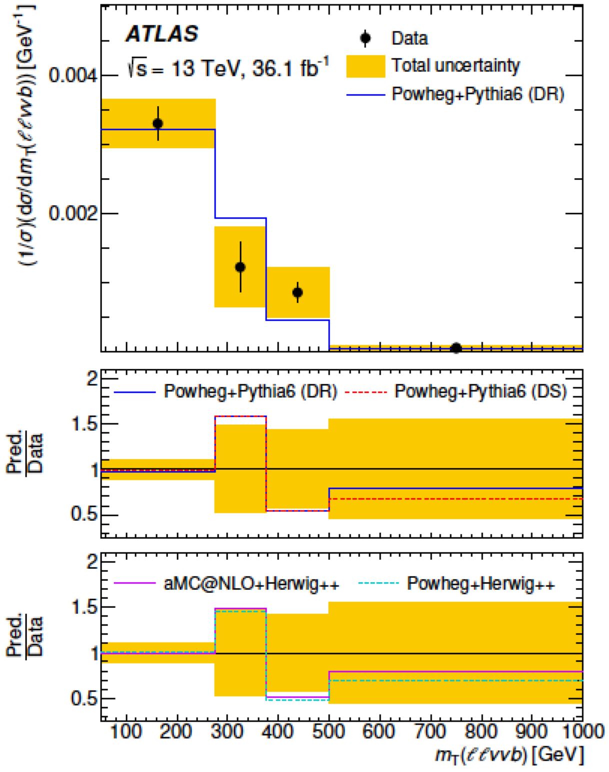
$m(\ell_1 b)$



$m(\ell_2 b)$



$p_{\mathrm{T}}^{\mathrm{sys}}(\ell_1 \ell_2 \nu b)$



Differential *tW*-channel @13 TeV

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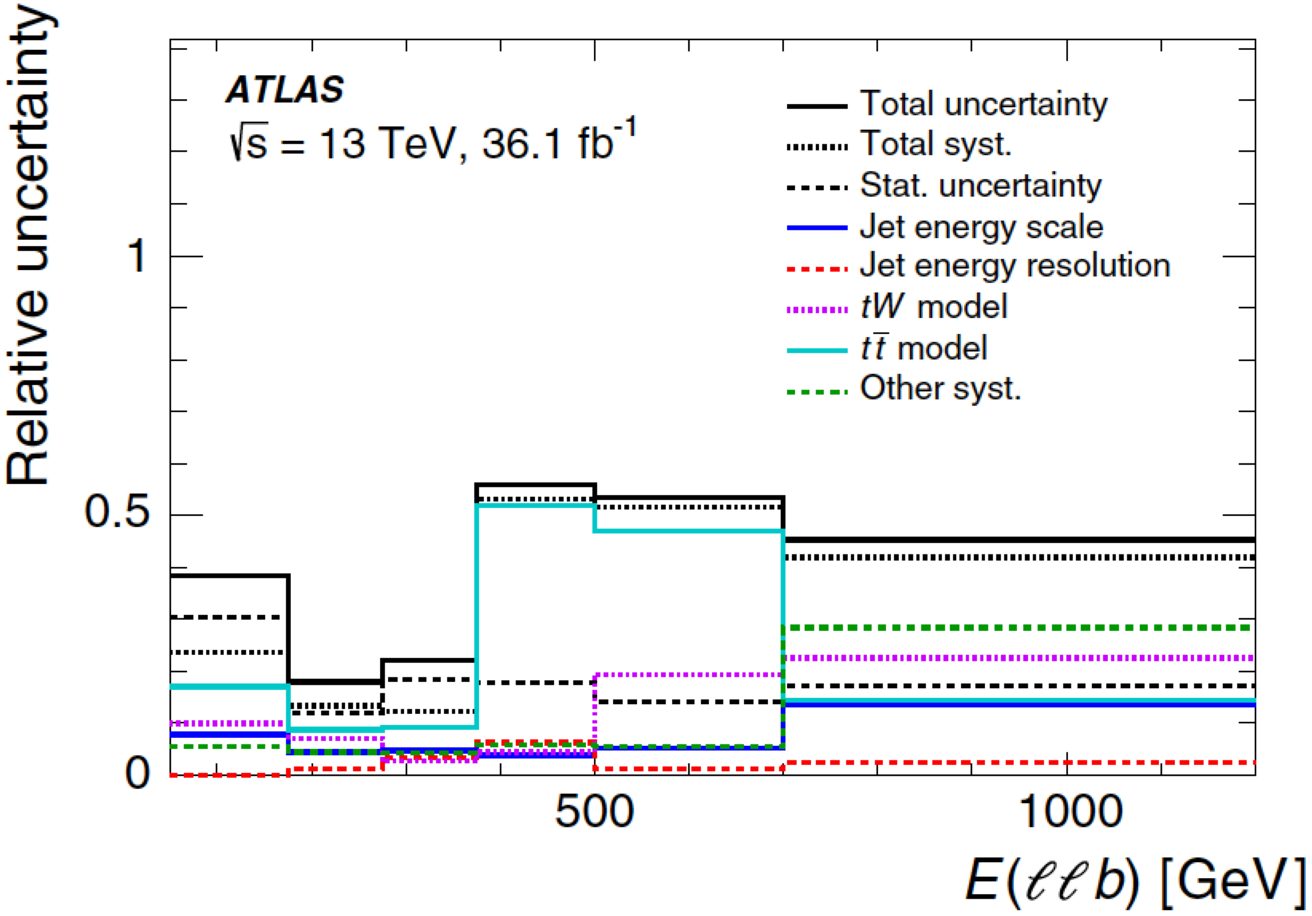
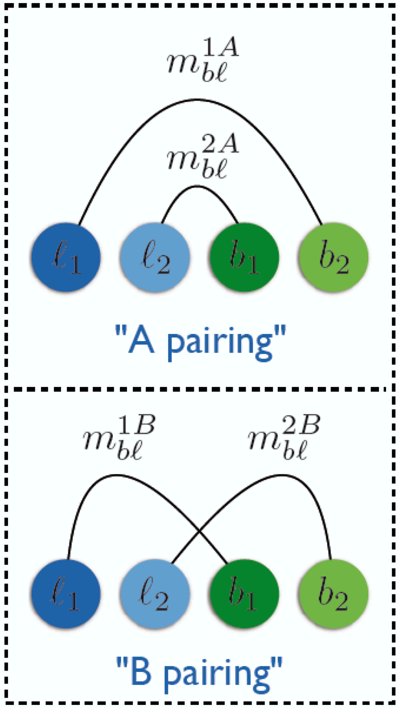


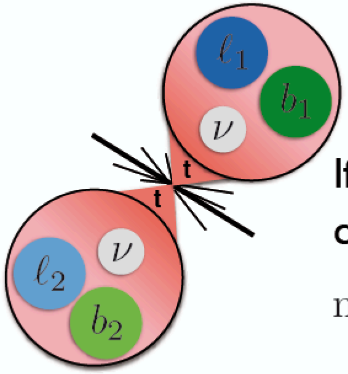
Quantum interferences t*Wb*/tt̄



If the "A pairing" is correct:

Both $m_{b\ell}^{1A} < m_t$ and $m_{b\ell}^{2A} < m_t$

and thus $\max\{m_{b\ell}^{1A}, m_{b\ell}^{2A}\} < m_t$



If the "B pairing" is correct then must have:

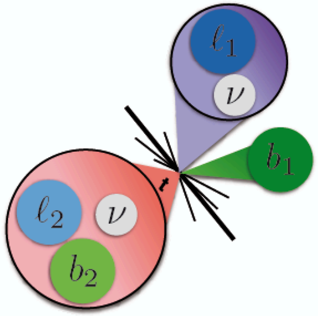
$\max\{m_{b\ell}^{1B}, m_{b\ell}^{2B}\} < m_t$

Consider now tWb events:

If the "A pairing" is correct:

One of $m_{b\ell}^{1A}$ or $m_{b\ell}^{2A}$ must be $< m_t$

But, can have $\max\{m_{b\ell}^{1A}, m_{b\ell}^{2A}\} > m_t$



C. Herwing- LHC Top WG Meeting