Highlights of top cross section measurements in ATLAS

Marino Romano
(INFN – Bologna)
On behalf of the ATLAS Collaboration

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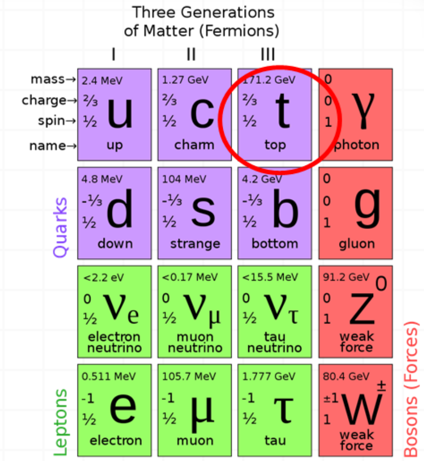
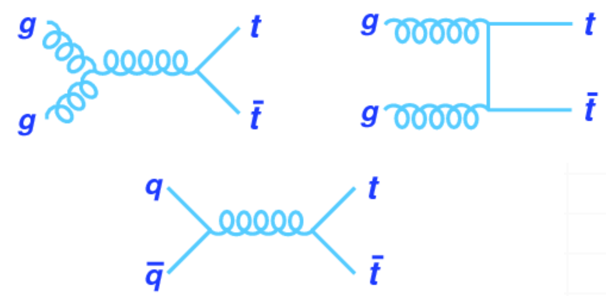
Introduction



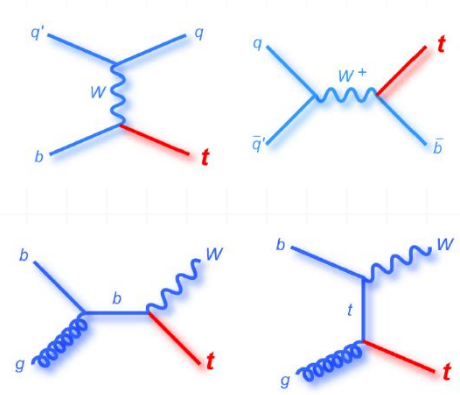
- Top quark basics:
  - Mass: 173.0 ± 0.4 GeV (Particle Data Group, PRD 98, 030001 (2018))
  - Decays: charged current weak decays in $t \rightarrow Wb$
- Why study top quark physics?
  - Yukawa coupling with the Higgs ~1→Important role in the EWSB
  - Life-time shorter than hadronization time →Unique possibility to study a 'bare' quark
  - Precise tests of the Standard Model and verification of pQCD
  - Important background for rare and interesting SM process like 4t and ttH
  - Privileged window to search for new physics
- Large number of results produced by the ATLAS experiment, today will focus on a selection of latest measurements:
  - Differential top pair cross in association with jets and in association with heavy flavor
  - ATLAS + CMS combination of single top cross section and $|f_{LV}V_{tb}|$ measurements

Top production and decay

- Top pair production at the LHC governed by strong interaction
  - Gluon-gluon fusion (~90%)
  - Quark-antiquark annihilation



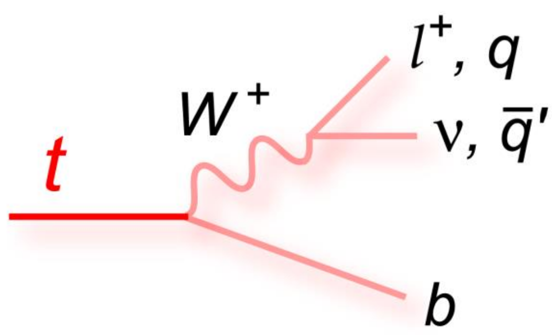
- Single top production via EW interaction:
  - Exchange of a virtual *W* boson in the *s* and *t* channels
    - *t* channel production dominates at LHC
  - Production in association of a real *W* boson



Top production and decay

Decays

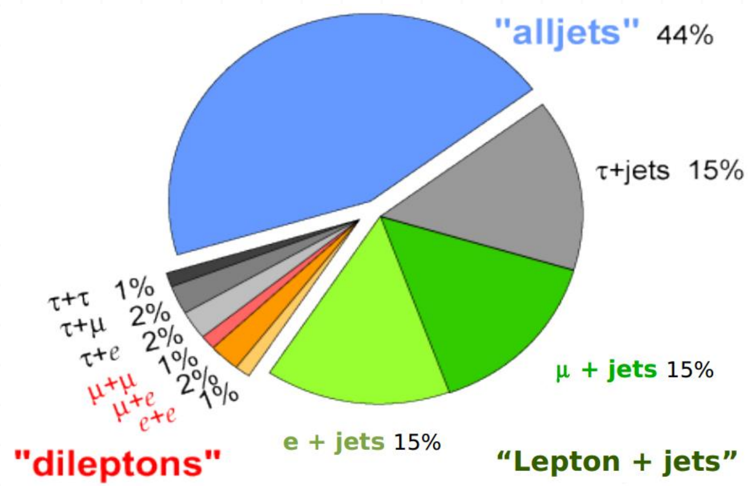
- $t \rightarrow Wb(\sim 100\%)$



$W \rightarrow l\nu_l \sim 33\%$

$W \rightarrow q\overline{q}' \sim 66\%$

Top pair final states

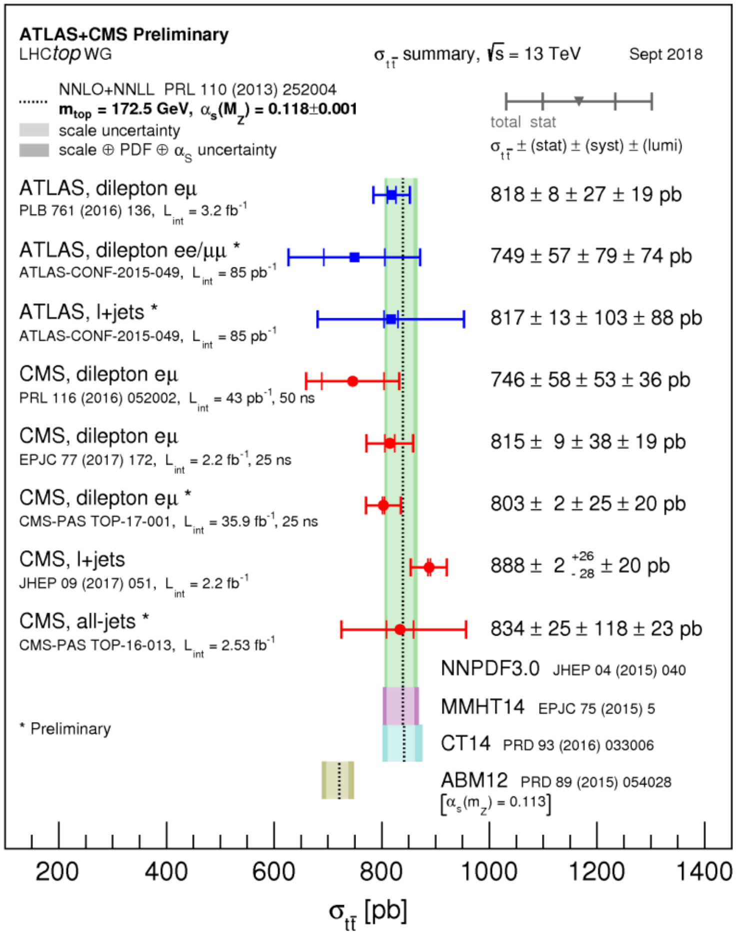


Dilepton: cleanest signature, but lower statistics

Alljets (or all hadronic): higher statistics but large uncertainty due to multijet background. Allows full $t\bar{t}$ kinematic reconstruction

Lepton+jets (or single lepton): compromise between statistics and background contamination

Top quark pair inclusive cross section at 13 TeV: summary



Wide range of measurements by ATLAS and CMS in different decay channels

Good agreeement of all measurements with SM predictions

Experimental uncertainties already comparable with theoretical ones

Measurements in eμ and lepton+jets channels are outstanding

Overall comparable precision between the two experiments

Common limitation: uncertainty on integrated luminosity (2.3% for both experiments)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/

Differential cross section measurements

Total $\sigma_{t\bar{t}}$ measurements show very good agreement with the SM, but:

- New physics phenomena can still affect the shape of $\frac{d\sigma_{t\bar{t}}}{dX}$
- Top production can still be not well modelled in *corners* of the phase space

Phase space definitions:

- Particle-level: extrapolate measurement in a fiducial region
  - Observables based on "stable" particles ($\tau > 0.3 \cdot 10^{-10}$s)
  - Less affected by modeling/extrapolation uncertainties
  - Used for MC comparison/tuning (RIVET)
- Parton-level: extrapolate measurement to full top pair production phase space
  - Observables defined using the top quarks after the final state radiation
  - Can be compared with theoretical higher order calculations

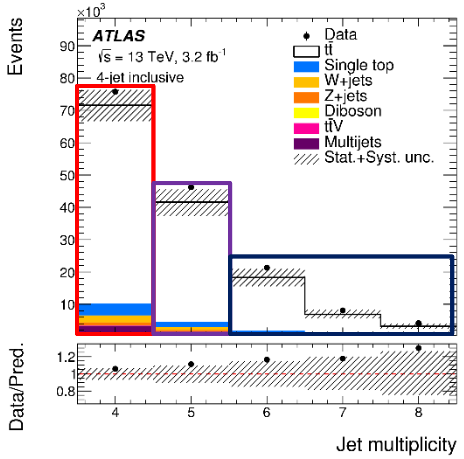
$t\bar{t}$+jets differential cross section

JHEP 10 (2018) 159

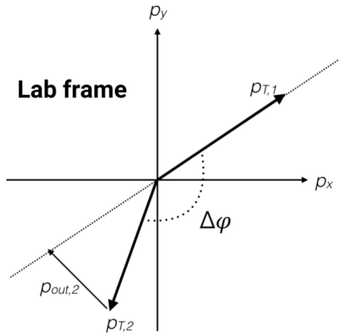
$\sqrt{s} = 13$ TeV, $L = 3.2$ fb^{-1}

Lepton+jets

- The effect of gluon radiation on the tt kinematics is checked by measuring differential cross-sections for a given number of jets in the event (4, 5 and ≥ 6)
  - Extension of the differential cross section measurement with any number of jets (Eur. Phys. J. C 78 (2018) 487)



- Analysis strategy:
  - Events selected in the lepton(e/μ) channel
  - $t\bar{t}$ kinematic variables corrected for the limited detector resolution via unfolding methods and extrapolated to the *fiducial* phase space
  - Measured the absolute and normalized differential cross section as a function of $t\bar{t}$ kinematic variables
    - $p_T^{t\bar{t}}, p_T^{t,had}$:transverse momentum of the top quark pair system and the hadronically decaying top
    - $\left|p_{out}^{t\bar{t}}\right| = \left|\vec{p}_T^{\,t,had} \cdot \frac{\vec{p}_T^{\,t,lep} \times \hat{z}}{\left|\vec{p}_T^{\,t,lep} \times \hat{z}\right|}\right|$: out-of-plane transverse momentum, sensitive to radiation and used in MC tuning



$t\bar{t}$+jets differential cross section

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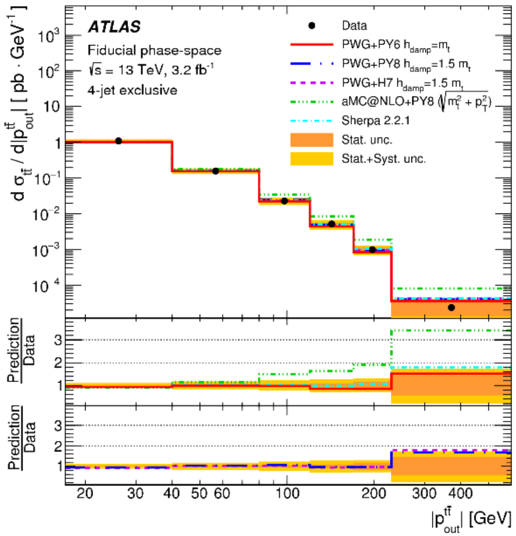
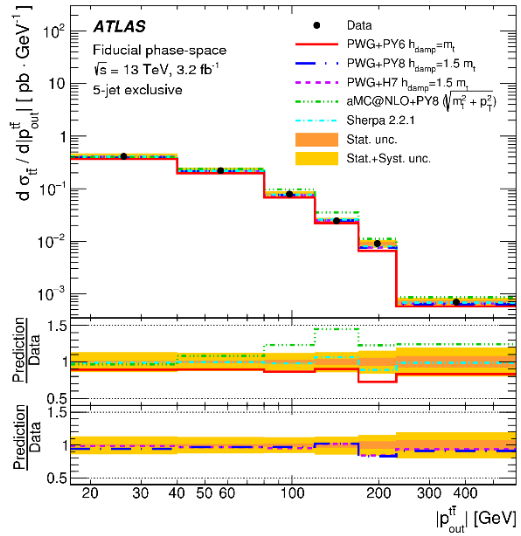
$\sqrt{s} = 13$ TeV, $L = 3.2$ fb^{-1}

Lepton+jets

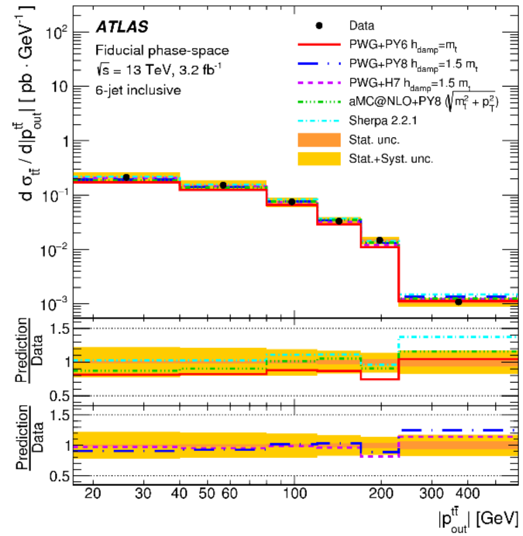
- Measurement limited by systematic uncertainties: signal modelling, jet energy scale and resolution and b-tagging efficiency



$N_{jet} = 4$



$N_{jet} = 5$



$N_{jet} \geq 6$

$\frac{d\sigma}{d|p_{out}^{t\bar{t}}|}$: Significant mismodelling by aMC@NLO+Pythia8 in the 4- and 5- jet multiplicity regions

$t\bar{t}$+jets differential cross section

JHEP 10 (2018) 159

$\sqrt{s} = 13$ TeV, $L = 3.2$ fb^{-1}

Lepton+jets

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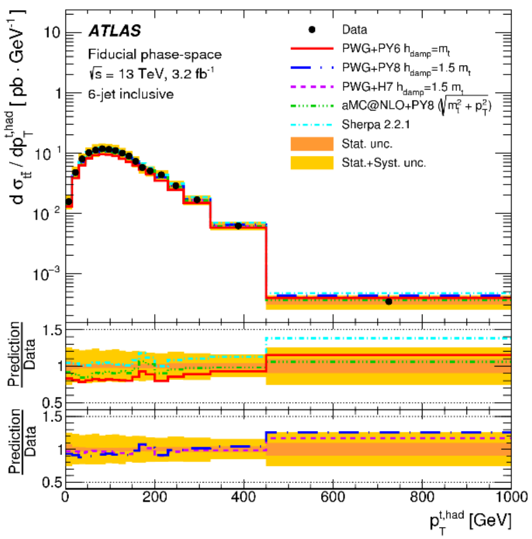

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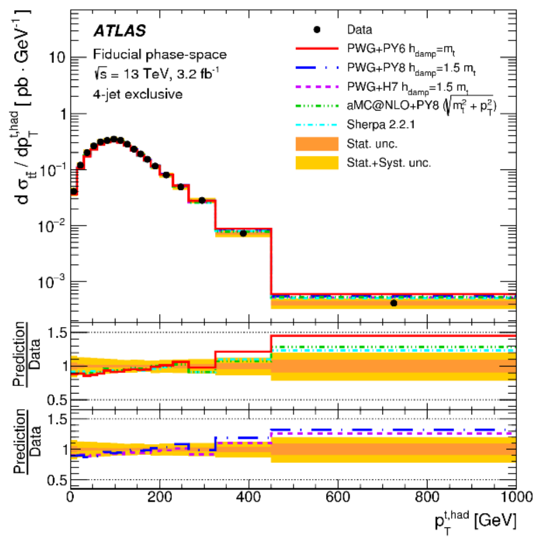

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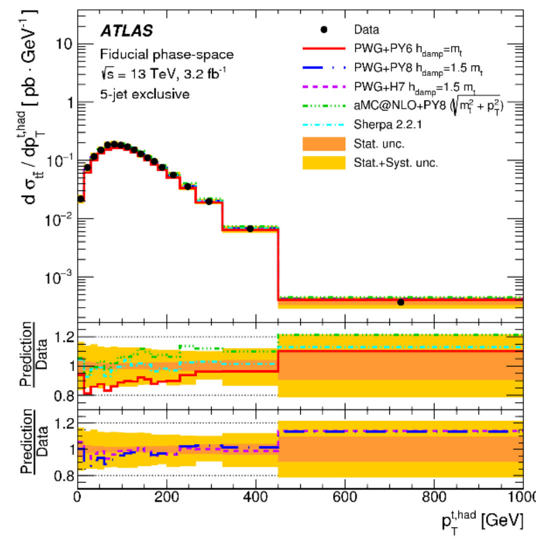
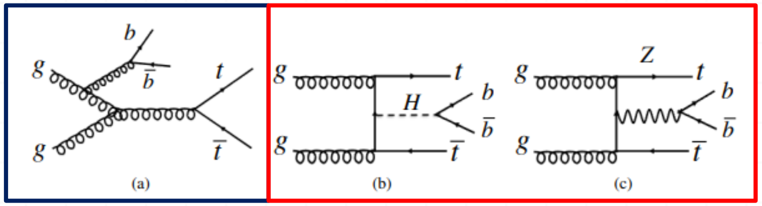


$N_{jet} \geq 6$

$\boldsymbol{d\sigma/dp_T^{t_{had}}}$:

Mismodelling enhanced in the intermediate jet multiplicity region

$t\bar{t}$+HF differential cross section



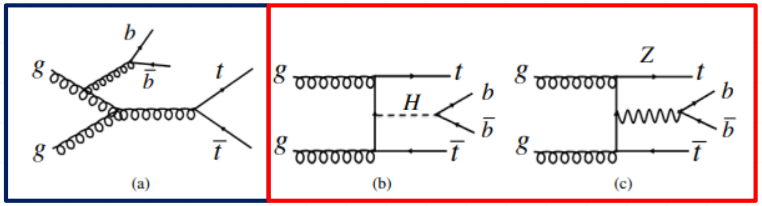
arXiv:1811.12113 [hep-ex]

$\sqrt{s} = 13$ TeV, $L = 36.1$ fb^{-1}

Lepton+jets and dilepton (eμ)

- Motivations:
  - Predictions for the $t\bar{t}$+HF process affected by higher uncertainties due to the non-negligible m_b
  - Important background for $t\bar{t}H(H \to b\bar{b})$ production
- **Inclusive** cross-sections of the production of top pairs with three and four b-jets as well as *normalized* **differential** cross-sections as a function of global event and of b-jet properties
  - Differential cross-sections presented for events with at least three b-jets in the eμ channel and with at least four b-jets in the lepton + jets channel
    - As a function of H_T, H_T^{had}, p_T of each b-jet, b-jet multiplicity, ΔR_{bb}, m_{bb} and $p_{T,bb}$
  - No attempt to identify the origin of the b-jets
  - $t\bar{t}H$ and $t\bar{t}Z$ contributions included in the signal definition

$t\bar{t}$+HF differential cross section

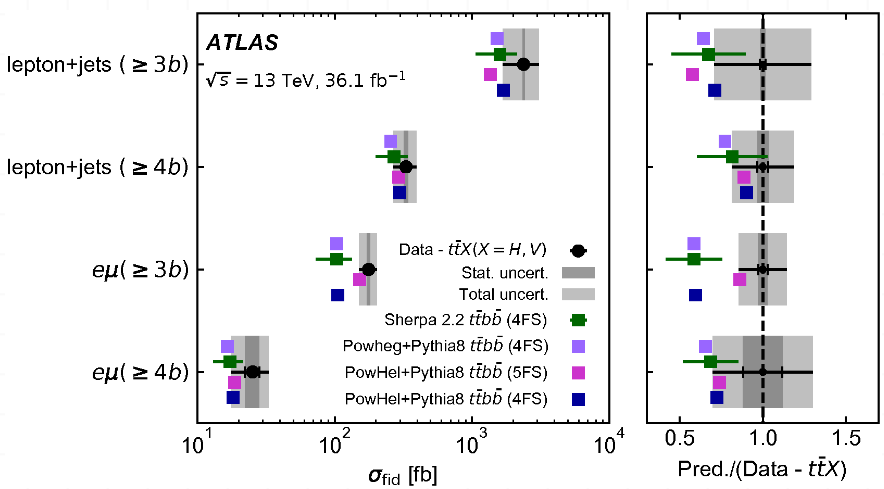


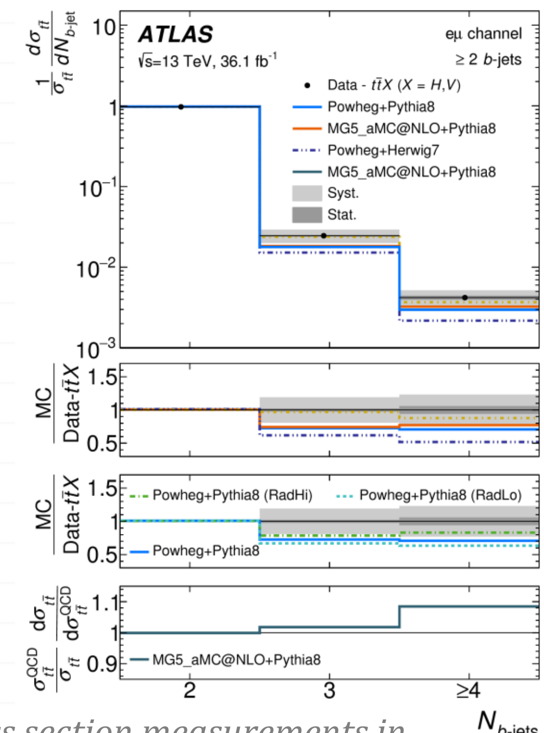
arXiv:1811.12113 [hep-ex]

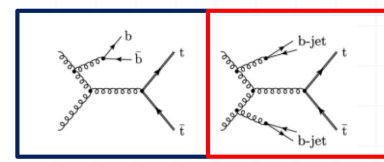
$\sqrt{s} = 13$ TeV, $L = 36.1$ fb^{-1}

Lepton+jets and dilepton

- Final *particle* level measurement extracted to the *fiducial* phase space
  - $t\bar{t}H$ and $t\bar{t}Z$ predictions subtracted from the final measurement
  - *Normalized* measurement more precise than the *absolute* →cancellation of correlated systematics
  - Precision limited by data statistics, generator uncertainties, jet energy scale and resolution
  - Comparisons with NLO+PS predictions employing 4- and 5- flavor schemes, produced using the $t\bar{t}$ and $t\bar{t}b\bar{b}$ matrix elements

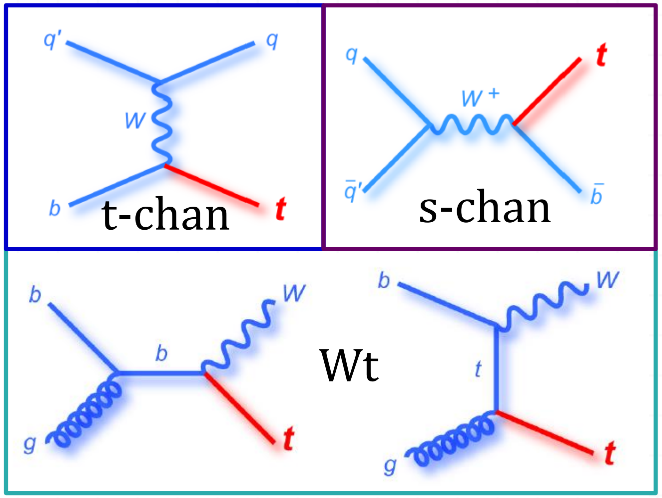






MC predictions where additional b-jets are dominantly produced by the parton shower predict too few events

Single top quark cross section

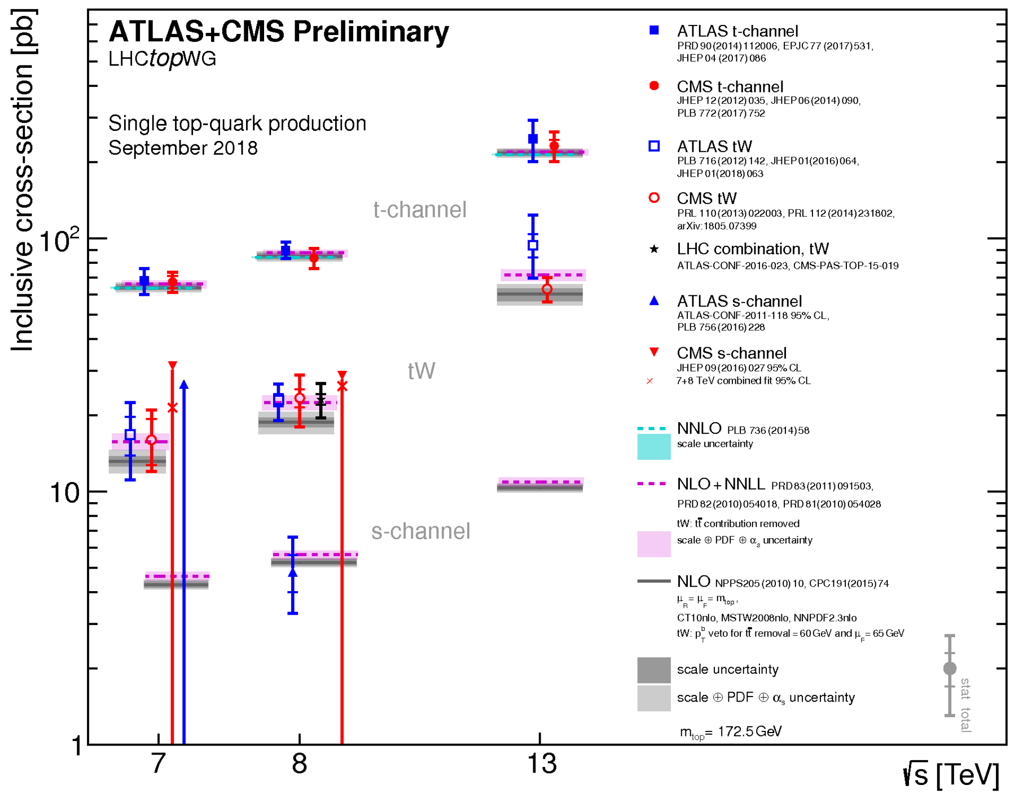


Dominant production modes well measured at 7, 8 and 13 TeV

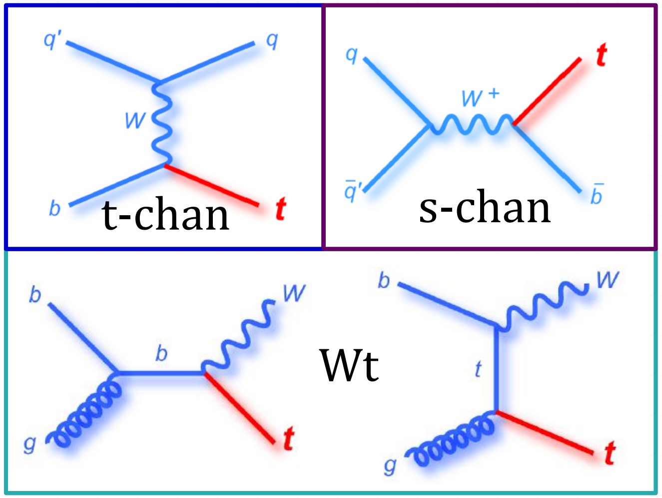
$> 3\sigma$ evidence for the s-chan mode at 8 TeV

Cross section summary

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/



Single top quark cross section



Dominant production modes well measured at 7, 8 and 13 TeV

> 3σ evidence for the s-chan mode at 8 TeV

First LHC combination for all the production channels with Run 1 data

Cross section summary

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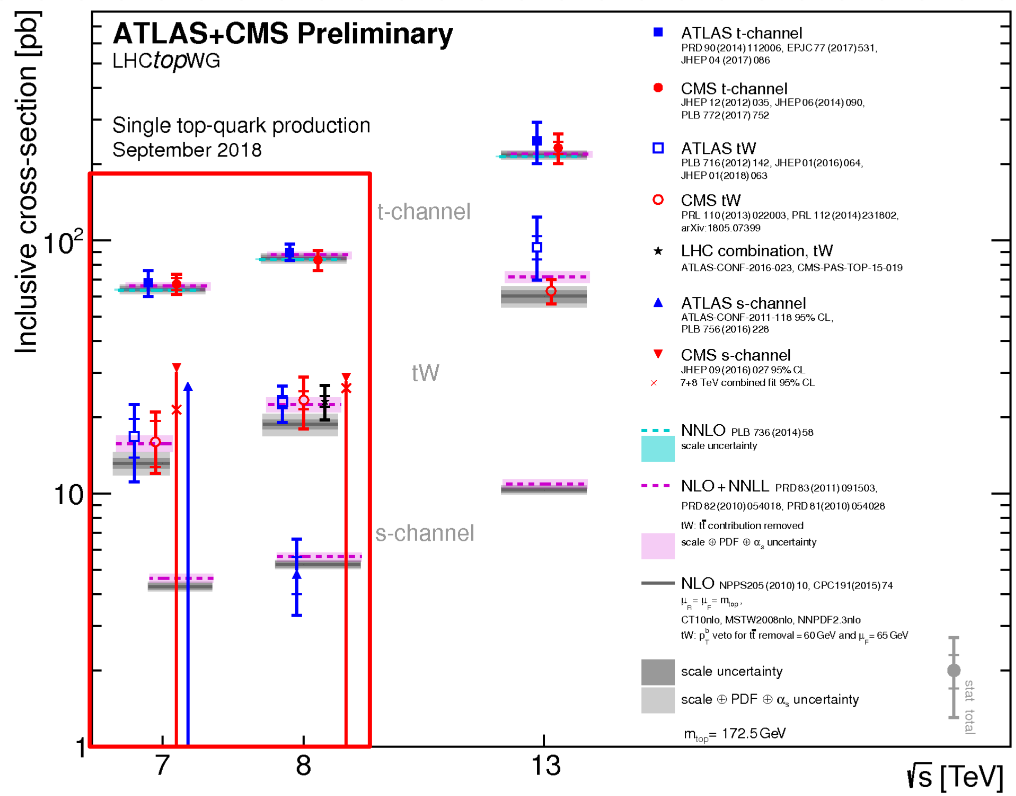
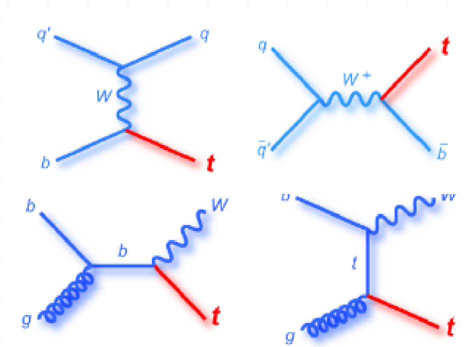


ATLAS + CMS combination of single top cross section and $|f_{LV}V_{tb}|$

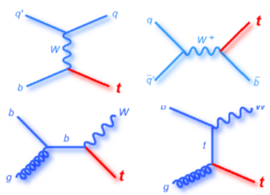
TOPQ-2017-16

$\sqrt{s} = 7$ and 8 TeV

- Single top cross sections are measured separately for the different production channels
  - Only the evidence of s-channel production at 8 TeV considered
- The left-handed vector coupling at the tWb production vertex extracted from all single top-quark cross-section measurements: $|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{meas}}{\sigma_{th}}}$
  - In the SM, the tWb coupling is given by the CKM matrix element V_{tb}
  - f_{LV} contains non-SM contributions



ATLAS + CMS combination of single top cross section and $|f_{LV}V_{tb}|$

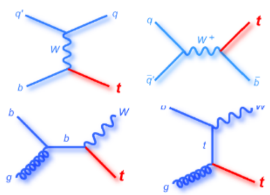


TOPQ-2017-16

$\sqrt{s}$ = 7 and 8 TeV

- Combination done with the iterative BLUE (Best Linear Unbiased Estimate) method
  - Accounting for uncertainties and correlations of the measured and theoretical cross sections
  - Iterates until convergence: central value and total uncertainty change by less than 1% compared to the previous iteration
- Correlations for σ_{meas}
  - All modelling uncertainties fully correlated
  - Experimental uncertainties fully uncorrelated between ATLAS and CMS and 7 and 8 TeV
  - Luminosity uncertainty 30% correlated
- Correlations for σ_{th}:
  - Scale uncertainties uncorrelated for different precisions (NLO vs NLO+NNLL)
  - PDF taken as 50% correlated (each pair of production channel has one parton in common)
  - m_t and E_{beam} are fully correlated

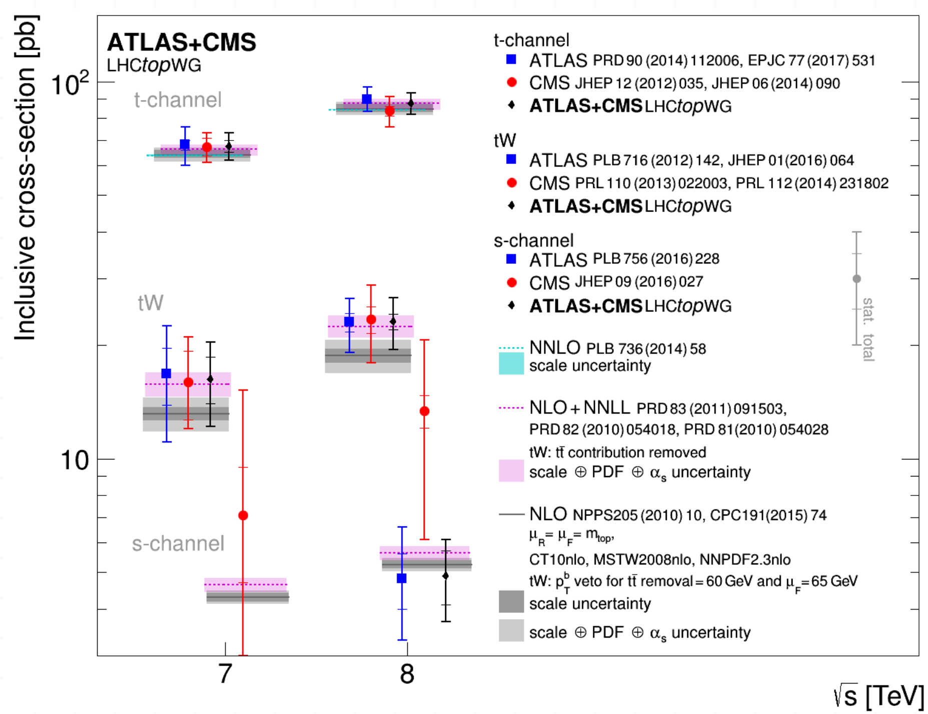
ATLAS + CMS combination of single top cross section and $|f_{LV}V_{tb}|$



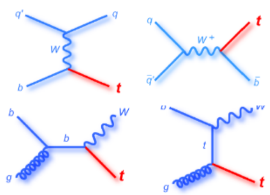
TOPQ-2017-16

$\sqrt{s} = 7$ and 8 TeV

Single top-quark cross-section measurements performed by ATLAS and CMS, and combined result compared with the NLO (*t* and *s*-channel), NLO+NNLL (*tW*) and NNLO (*t*-chan) predictions



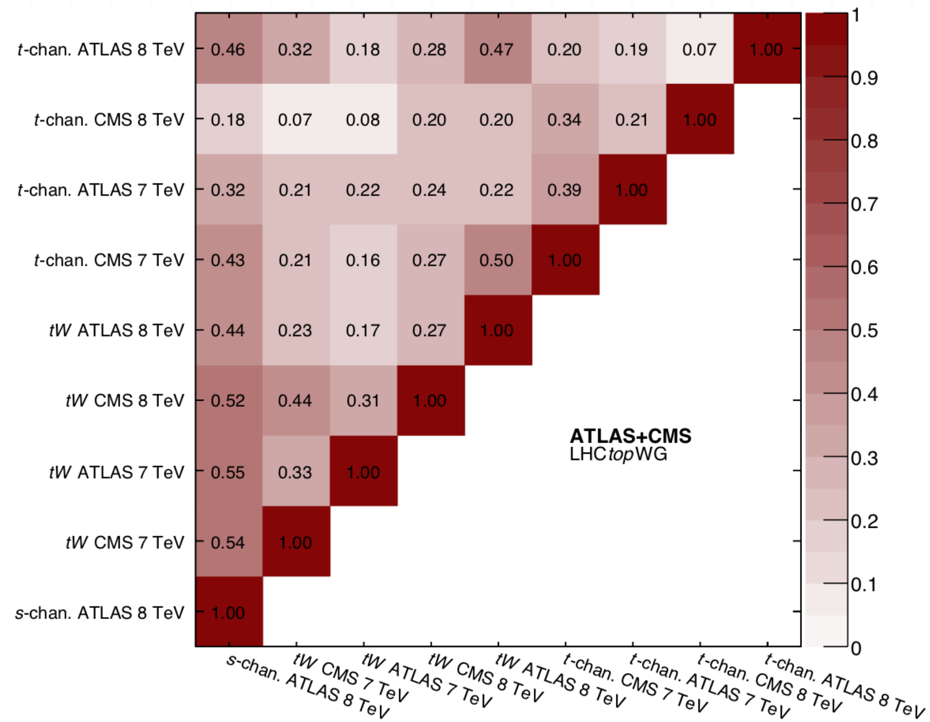
ATLAS + CMS combination of single top cross section and $|f_{LV}V_{tb}|$



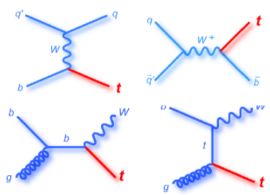
TOPQ-2017-16

$\sqrt{s} = 7$ and 8 TeV

- Combination performed also for $|f_{LV}V_{tb}|^2$ (linear with the cross section)
  - All production modes are combined besides the CMS s-channel measurement
  - Uncertainties on σ_{meas} and σ_{th} are propagated to $|f_{LV}V_{tb}|^2$



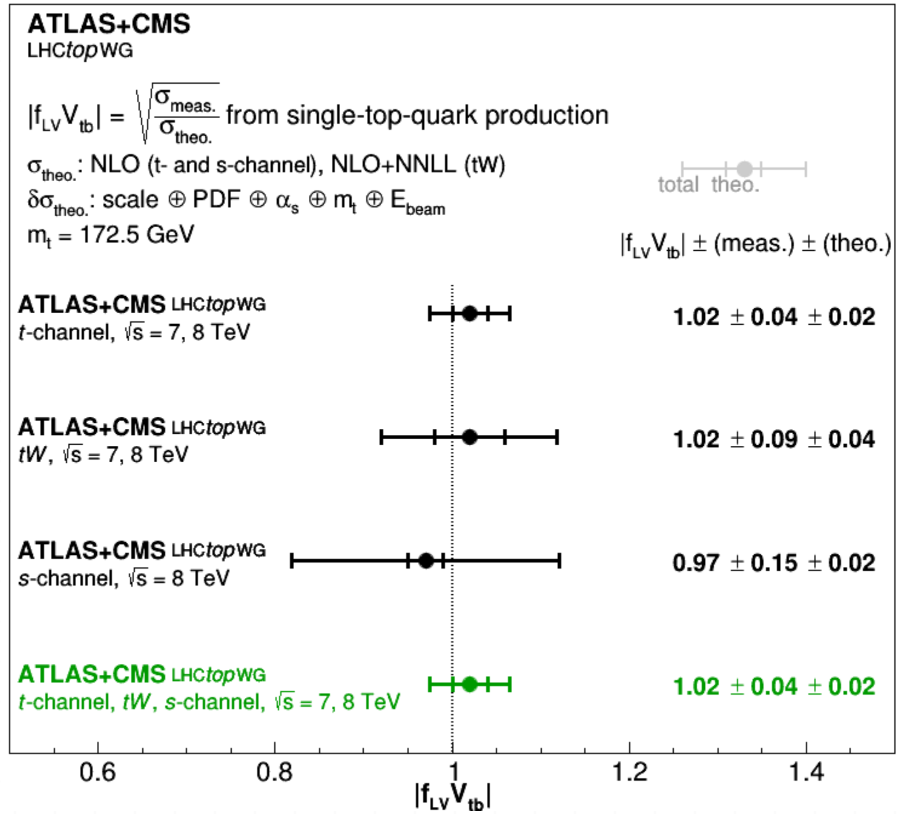
ATLAS + CMS combination of single top cross section and $|f_{LV}V_{tb}|$



TOPQ-2017-16

$\sqrt{s} = 7$ and 8 TeV

- Summary plot for the $|f_{LV}V_{tb}|$ combinations from the Run I cross-section measurements:
  - As expected, t-channel provides the largest contribution.
- Total uncertainty: 4.3%
  - 30% improvement wrt the Tevatron combination PRL 115, 152003 (2015)



Summary

- Top quark measurements have provided stringent tests of SM
- Top quark pair production
  - Total cross section measured in many channels, uncertainties already competitive with the theoretical predictions
  - Differential cross-sections for $t\bar{t}$ production in association of light[1] and heavy flavor[2] jets measured for several observables, reconstructed in different channels
  - Overall good modeling of tt production provided by NLO generators
  - Signal modeling among the largest sources of systematic uncertainties
- LHC Run-I combination of single top-quark cross-sections and $|f_{LV}V_{tb}|^2$ measurements[3]
  - Combination of the cross-section per production mode.
  - Combination of $|f_{LV}V_{tb}|^2$ from **all** production modes
- Stay tuned for measurements with full Run II dataset , expect $36\text{fb}^{-1} \rightarrow \sim 140\text{fb}^{-1}$
  - Opens up access to rarer and rarer processes
  - Potential to extend differential measurements to more dimensions, additional final states
  - Improved signal modelling thanks to early Run II results will reduce the uncertainties

(1) JHEP 10 (2018) 159
(2) arXiv:1811.12113 [hep-ex]
(3) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2017-16/

Backup

$t\bar{t}$+jets differential cross section

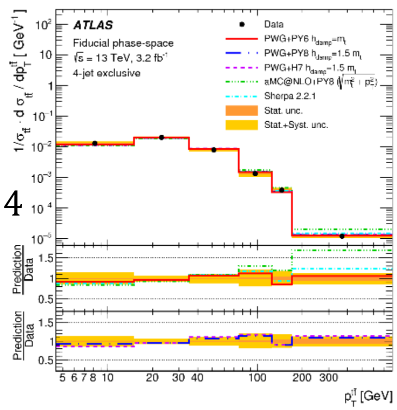
JHEP 10 (2018) 159

$\sqrt{s} = 13$ TeV, $L = 3.2$ fb^{-1}

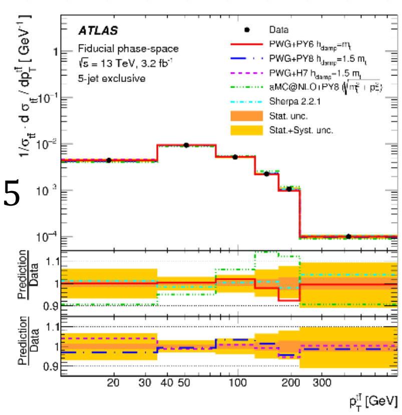
Lepton+jets

- Measurement limited by systematic uncertainties: signal modelling, jet energy scale and resolution and b-tagging efficiency
  - Strong reduction in the uncertainty on b-tagging when measuring *normalized* differential cross section

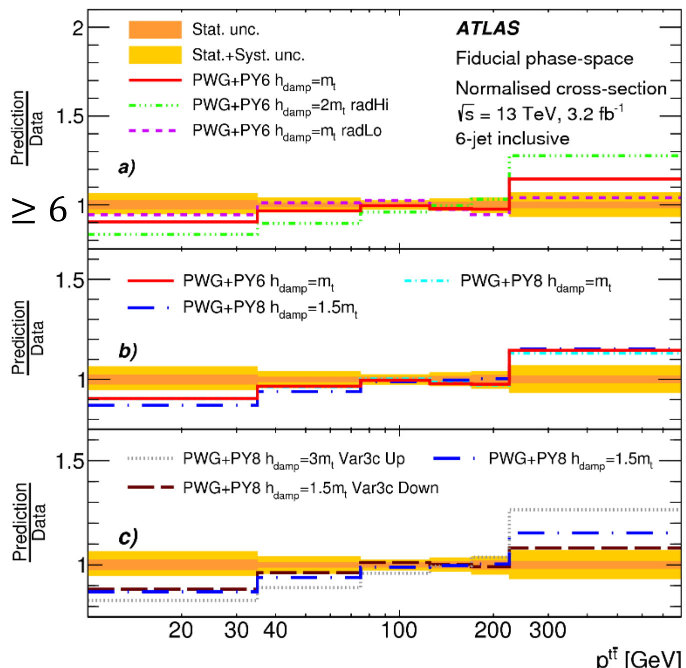
$N_{jet} = 4$



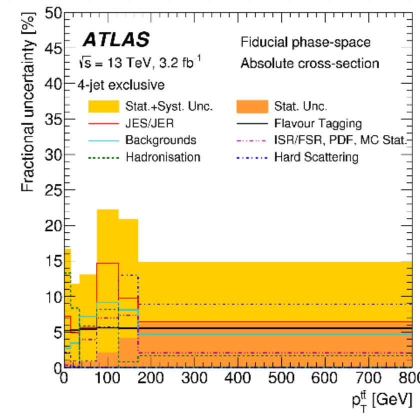
$N_{jet} = 5$

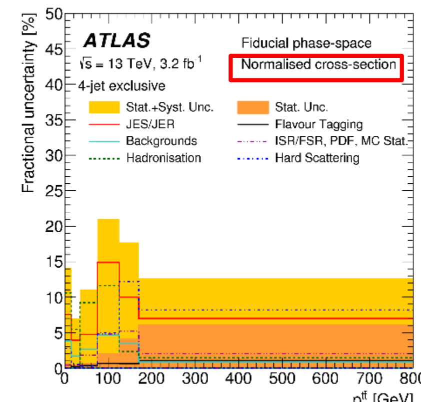


$N_{jet} \geq 6$



$\frac{1}{\sigma}\frac{d\sigma}{dp_T^{tt}}$: Mismodelling enhanced in the high jet multiplicity region





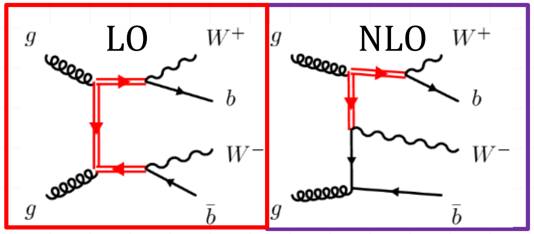
Interference between tW and $t\bar{t}$

PRL 121 (2018) 152002

$\sqrt{s} = 13$ TeV, $L = 36.1$ fb^{-1}

Dilepton

- tW diagrams beyond the leading order interfere with $t\bar{t}$
  - Size of the interference dependent on the phase space
  - Can be important for searches



- Both process are factorized in standard calculations (narrow width approx.)

$$|A_{tW}|^2 = |A_{tWb}|^2 + |A_{t\bar{t}}|^2 + 2Re\{A^*_{tWb}A_{t\bar{t}}\}$$

- Different methods to handle the interference at NLO
  - Diagram removal (DR) removes all the $t\bar{t}$ diagram contributions: $|A_{tW}|^2_{DR} = |A_{tWb}|^2$
  - Diagram removal 2 (DR2) removes the LO $t\bar{t}$ term but keep the interference:

$$|A_{tW}|^2_{DR2} = |A_{tWb}|^2 + 2Re\{A^*_{tWb}A_{t\bar{t}}\}$$

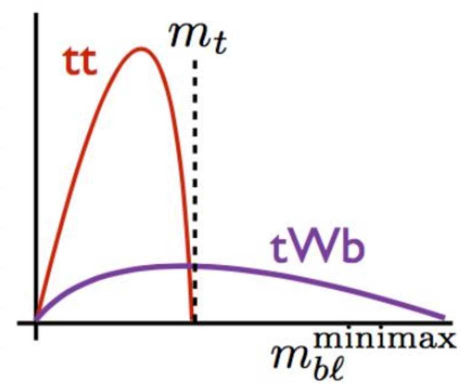
  - Diagram subtraction (DS) cancels the resonant $t\bar{t}$ contribution with a local subtraction term: $|A_{tW}|^2_{DS} = |A_{tWb} + A_{t\bar{t}}|^2 - C_{2t}$
  - $WbWb(lvblvb)$ implemented in PowHeg (no narrow width approx.): interference automatically handled

DR: JHEP07(2008)029
DR2: EPJC77(2017)34
DS: JHEP07(2008)029
$WbWb$: EPJC76(2016)691

Interference between tW and $t\bar{t}$

PRL 121 (2018) 152002
$\sqrt{s} = 13$ TeV, $L = 36.1$ fb^{-1}
Dilepton

- Interference investigated using differential cross section as a function of a variabile sensitive to its effects **(m_{bW})**
  - For $t\bar{t}$ production $m_{bW} \sim m_t$ (two bW pairs from top)
  - For tWb there is only one bW pair from top
- $WWbb$ (dilepton) taken as signal
  - Lepton taken as a proxy for the W: $m_{bW} \rightarrow m_{bl}$

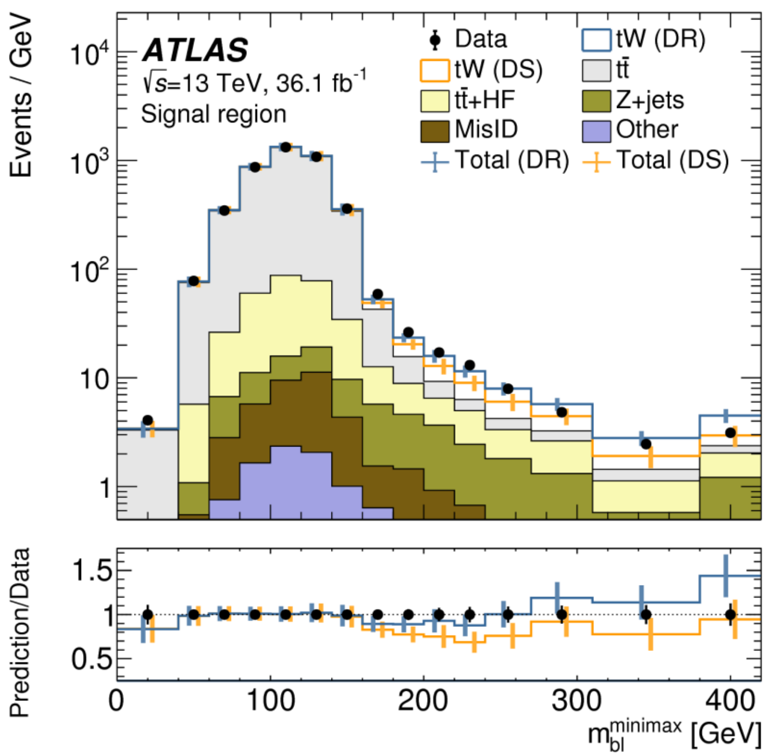


- Lepton-b pairing ambiguity solved with the *minimax* procedure: $m_{bl}^{minimax} = \min\{\max(m_{b_1 l_1}, m_{b_2 l_2}), \max(m_{b_1 l_2}, m_{b_2 l_1})\}$
  - Double resonant $t\bar{t}$ populates the $m_{bl}^{minimax} < m_t$ region
  - Single resonant Wtb populates the whole range
  - Interference effects significant at high $m_{bl}^{minimax}$

Interference between tW and $t\bar{t}$

PRL 121 (2018) 152002
$\sqrt{s} = 13$ TeV, $L = 36.1$ fb^{-1}
Dilepton

- *Normalized* differential cross section measured in the fiducial phase space from the reconstructed discriminant distribution
  - Showing the different interference schemes
  - Tails enriched of *Wt* events
- Measurement limited by the modelling uncertainties
  - $t\bar{t} + tWb$: total cross section and MC parameters
  - $t\bar{t}$ + HF: PowhegPythia6 and Sherpa predictions
  - Main detector uncertainties: JES and b-tagging



Interference between tW and $t\bar{t}$

PRL 121 (2018) 152002
$\sqrt{s} = 13$ TeV, $L = 36.1$ fb^{-1}
Dilepton

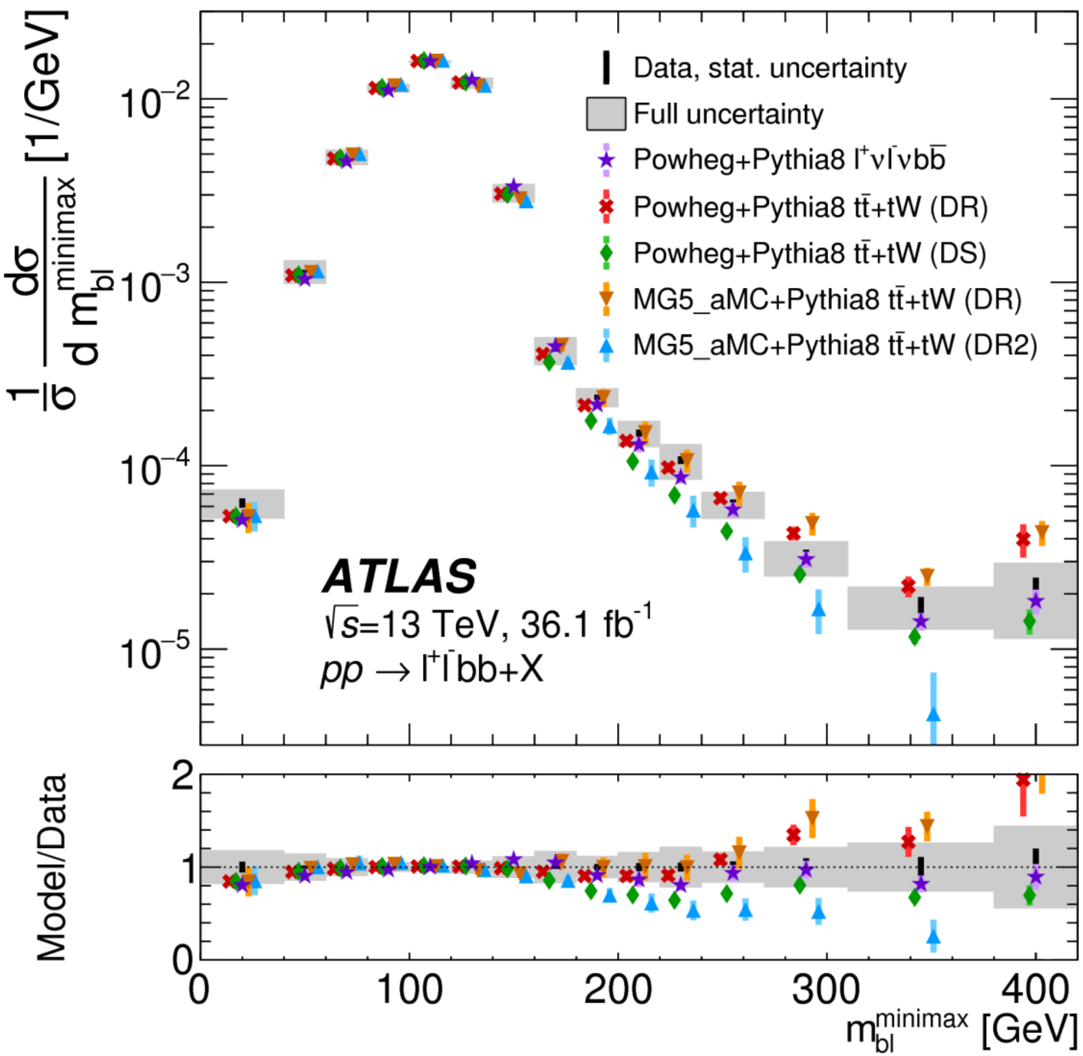
$m_{lb}^{minimax}$ distribution clearly sensitive to the $t\bar{t}/tWb$ interference

The core ($t\bar{t}$ dominated) distribution well described by all the predictions

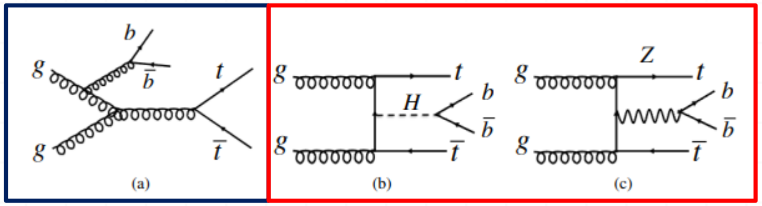
Good agreement for $l\nu l\nu bb$ in the full range

Mismodelling in the tails by MG5_aMC+Pythia8 predictions (with opposite behavior)

As expected, PWG+py8 DS and DR diverge at in tails
- Consistent with the data within 2σ



$t\bar{t}$+HF differential cross section

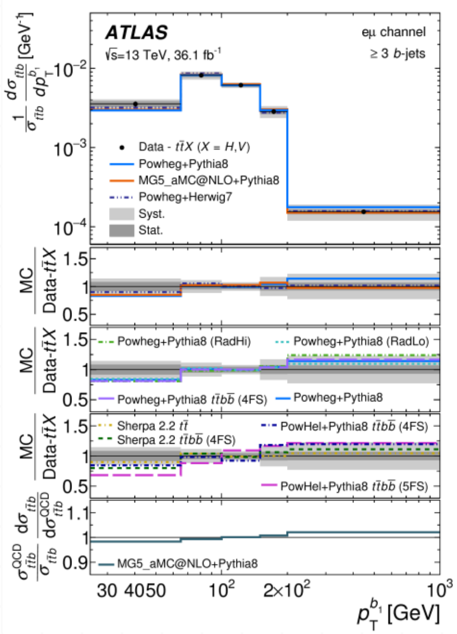


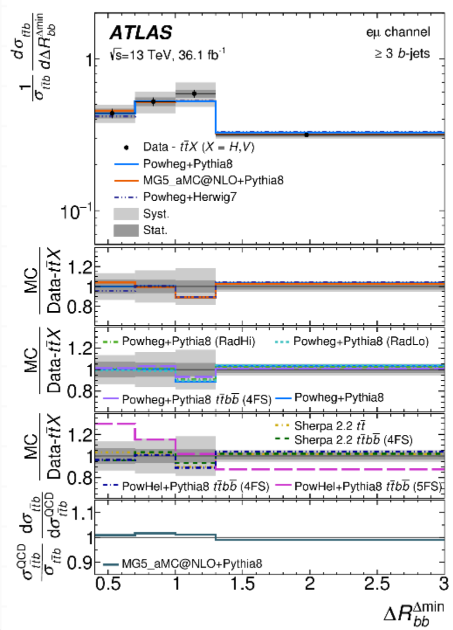
arXiv:1811.12113 [hep-ex]

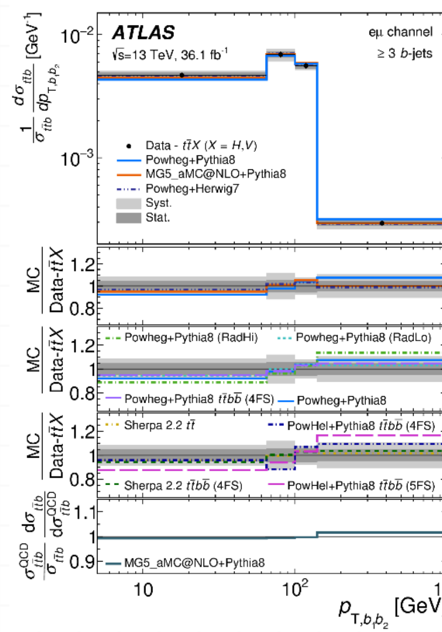
$\sqrt{s}$ = 13 TeV, L = 36.1 fb^{-1}

Lepton+jets and dilepton

- Final *particle* level measurement extracted via unfolding procedure and extrapolated to the *fiducial* phase space
  - $t\bar{t}H$ and $t\bar{t}Z$ predictions subtracted from the final measurement
  - *Normalized* measurement more precise than the *absolute* →cancellation of correlated systematics
  - Precision limited by data statistics, generator uncertainties, jet energy scale and resolution
  - Comparisons with NLO+PS predictions employing 4- and 5- flavor schemes, produced using the $t\bar{t}$ and $t\bar{t}b\bar{b}$ matrix elements







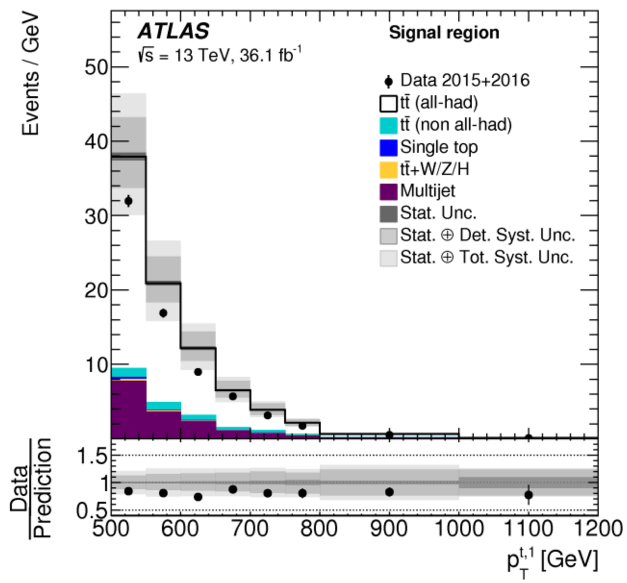
$t\bar{t}$ differential cross section in the boosted topology

PRD 98 (2018) 012003

$\sqrt{s} = 13$ TeV, $L = 36.1$ fb^{-1}

All hadronic

- Full $t\bar{t}$ kinematic reconstruction possible only in the all hadronic final state
  - Usually high uncertainties due to contamination from the multijet background
  - Final state with many (≥ 6) jets → High combinatorial background
- Boosted topology can alleviate these issues
  - Multijet background is reduced in the high pt regimes
  - Top candidates defined as single large-R jets →no combinatorial ambiguity
  - Allow measurements at kinematic frontier: very high top pT



$t\bar{t}$ (all-hadronic)	3250 ± 470
$t\bar{t}$ (non-all-hadronic)	200 ± 40
Single-top-quark	24 ± 12
$t\bar{t}$+$W/Z/H$	33 ± 10
Multijet events	810 ± 50
Prediction	4320 ± 530
Data (36.1 fb^{-1})	3541

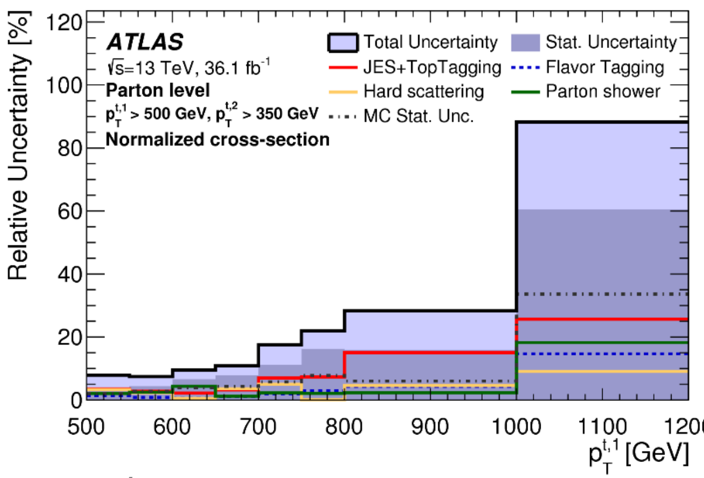
$t\bar{t}$ differential cross section in the boosted topology

PRD 98 (2018) 012003

$\sqrt{s} = 13$ TeV, $L = 36.1$ fb^{-1}

All hadronic

- Differential cross section at *parton* and *particle* level as a function of the leading and subleading top kinematics and event variables
- Top candidate:
  - Large-R ($R = 1$) jet with $p_T > 500/350$ GeV
  - Top tagging with jet substructure variables: m_{jet} and N-subjettiness ratio τ_{32}
  - Same definition applied at particle level (using stable particles)
- Backgrounds:
  - QCD multijets: (dominant) estimated from data (ABCD method)
  - non-allhadronic $t\bar{t}$, single top, $t\bar{t} + H/V$: from simulation
- Measurement limited by the statistical, large-R jet energy scale/top tagging and the signal modelling uncertainties



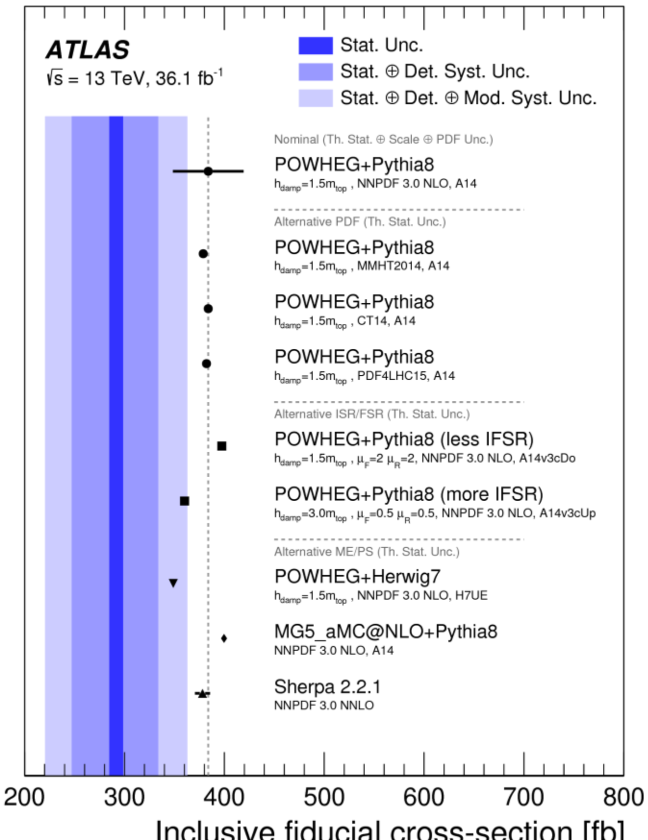
$t\bar{t}$ differential cross section in the boosted topology

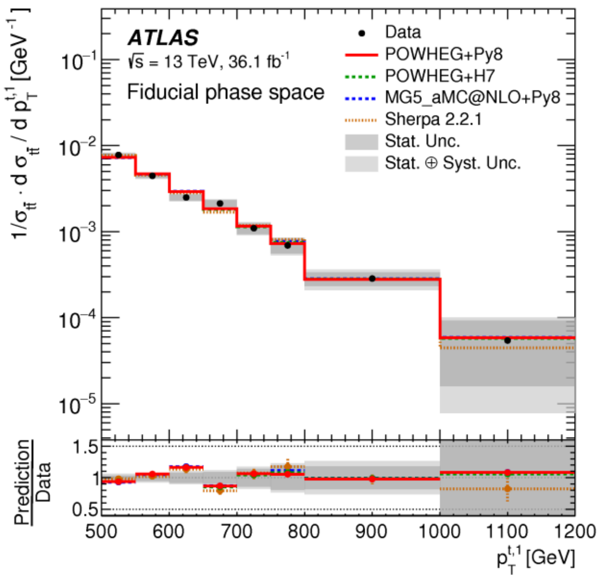
PRD 98 (2018) 012003

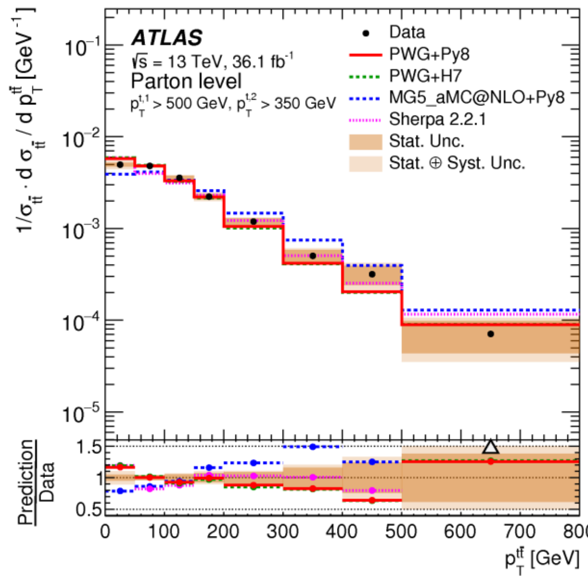
$\sqrt{s} = 13$ TeV, $L = 36.1$ fb^{-1}

All hadronic

- Predicted total fiducial cross section overestimates the measurement
  - Large uncertainties, not statistically significant







- Reasonable agreement between measurement and predictions for the normalized differential cross section
  - Largest discrepancy with respect to the aMC@NLO+Pythia8 modelling of the p_T of the $t\bar{t}$ pair

Summary

(1) JHEP 10 (2018) 159
(2) arXiv:1811.12113 [hep-ex]
(3) ATLAS-PUB-XXX
(4) PRL 121 (2018) 152002

- Top quark measurements have provided stringent tests of SM
- Top quark pair production
  - Total cross section measured in many channels, uncertainties already competitive with the theoretical predictions
  - Differential cross-sections for $t\bar{t}$ production in association of light(1) and heavy flavor(2) jets measured for several observables, reconstructed in different channels
  - Overall good modeling of tt production provided by NLO generators
  - Signal modeling among the largest sources of systematic uncertainties
- LHC Run-I combination of single top-quark cross-sections and $|f_{LV}V_{tb}|^2$ measurements(3)
  - Combination of the cross-section per production mode.
  - Combination of $|f_{LV}V_{tb}|^2$from **all** production modes
- If (3) not approved: First investigation of the $t\bar{t} + Wtb$ interference(4)
  - *lvlvbb* shows the best agreement in the whole discriminant range
  - DR/DS behave very differently in the sensitive range, but within 2sigma from the data
- No top quark measurements with full Run II dataset public yet, expect $36\text{fb}^{-1} \rightarrow \sim 140\text{fb}^{-1}$
  - Opens up access to rarer and rarer processes
  - Potential to extend differential measurements to more dimensions, additional final states
  - Improved signal modelling thanks to early Run II results will reduce the uncertainties