Measurements of single top quark production processes with the ATLAS and CMS experiments

Laura Pintucci on behalf of Atlas and CMS collaborations

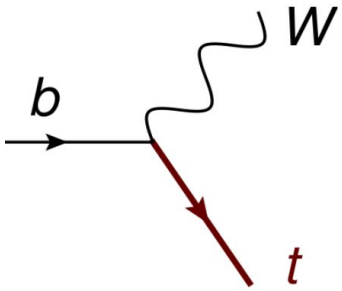
Introduction

Single Top production

Top quark produced at hadron colliders via:

- strong interaction → top quark pair
- EW interaction → **single top** quark or antiquark, has much smaller signal wrt top pair production

SM single top production is a charged-current EW process with a *Wtb* vertex



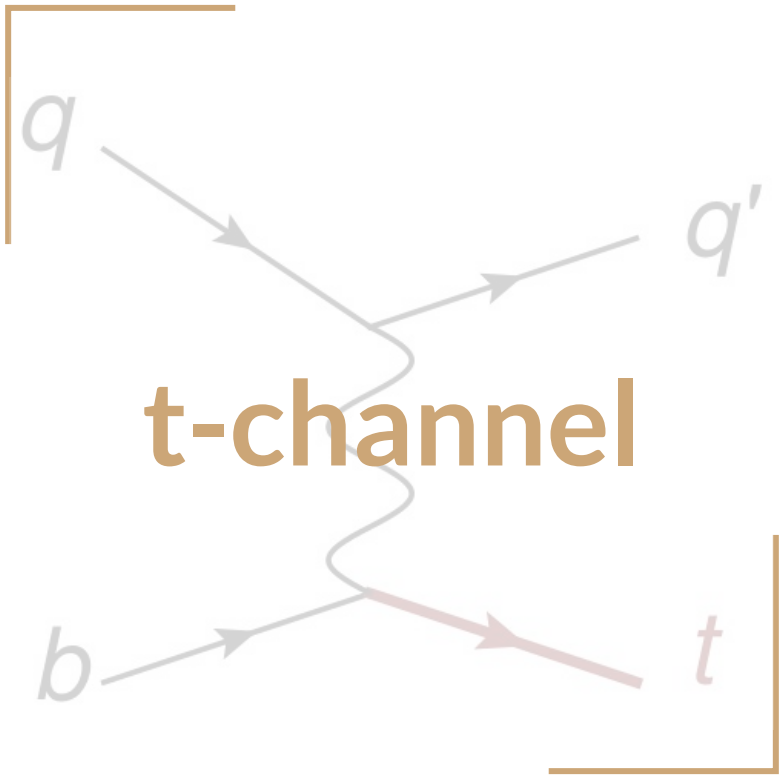
Three main modes:

- *t*-channel
- *s*-channel
- *W* associated production (*tW*)

Some properties:

- ➔ production cross-section $\sigma_t \propto V_{tb}^2$ CKM matrix element;
- ➔ Precise measurements of σ_t, as well as charge asymmetry measurement (top vs antitop), can have impact on PDF constraints;
- ➔ top quarks produced polarized → almost 100% degree of polarization in *t*- and *s*-channel.

Overview of ATLAS and CMS Run 2 single top measurement



t-channel

Differential cross sections and charge ratios at 13 TeV with 35.9 fb^{-1}

Measurement of differential cross sections and charge ratios for t-channel single top quark production in proton–proton collisions at √s = 13 TeV

Event Selection:

- 1 isolated *e* or *μ*
- 2/3 jets
- 0/1/2 *b*-tag jets

Signal Yield Estimation:

Fit to $m_T(W)$,$BDT_{t\text{-}chan}$,$BDT_{tt/tW}$ in the 2j1b reg and $m_T(W)$ in the 3j2b region, each reg splitted by e/μ and their charge

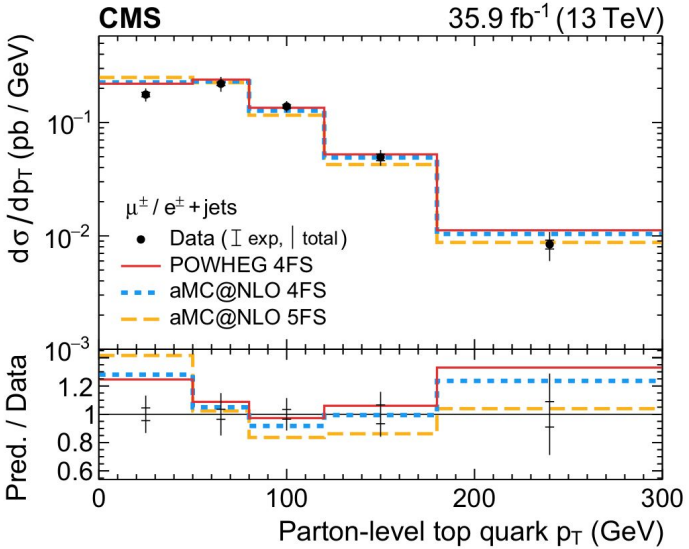
Differential Cross-Sections

Unfolding at parton and particle level

➔ good agreement with prediction of 4F scheme (with Powheg/MG5@NLO+Pythia), 5F scheme (with MG5@NLO+Pythia) does not agree as well for *t* and *W* p_T

➔ **differential charge ratio** in agreement with prediction from all 3 PDF sets considered

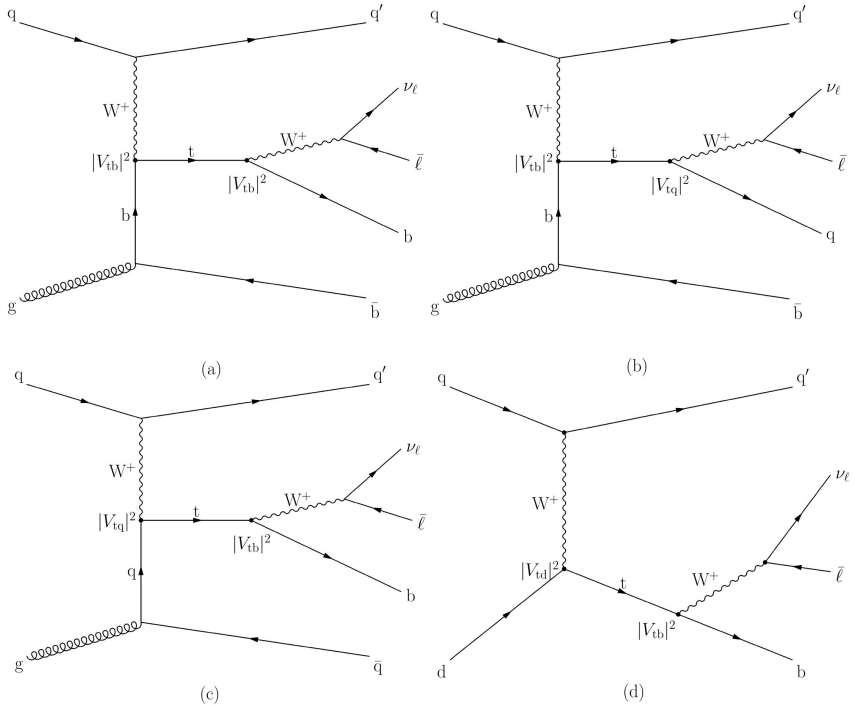
Spin asymmetry from $d\sigma/d\theta_p$ distribution good agreement with SM



Eur. Phys. J. C 80, 370 (2020)

CKM matrix elements in t-channel at 13 TeV with 35.9 fb^{-1}

Measurement of CKM matrix elements in single top quark t-channel production in proton-proton collisions at √s = 13 TeV



Objective: Measure $|V_{tb}|$, $|V_{ts}|$and $|V_{td}|$with *t*-channel

Event Selection:

1 isolated *e* or *μ* +$m_T(W)$ > 50 GeV

- 2j1b enriched in ST_{bb}→BDT train ST_{bb}vs top pair, *W*+jets
- 3j1b enriched in ST_{bq}, ST_{qb}→ BDT train ST_{qb}vs ST_{bb}, top pair, *W*+jets
- 3j2b enriched in ST_{bb} → BDT train ST_{bb} vs top pair prod.

Maximum LH fit to the three BDT discriminants

CKM element measured:

➔ SM unitarity **constrain**, 95% CL $|V_{tb}|>0.970$ and $|V_{ts}|^2+|V_{td}|^2<0.057$

➔ 2 BSM scenarios **unconstrained**

$|V_{tb}| = 0.988 \pm 0.024$, and $|V_{ts}|^2+|V_{td}|^2=0.06\pm0.06$

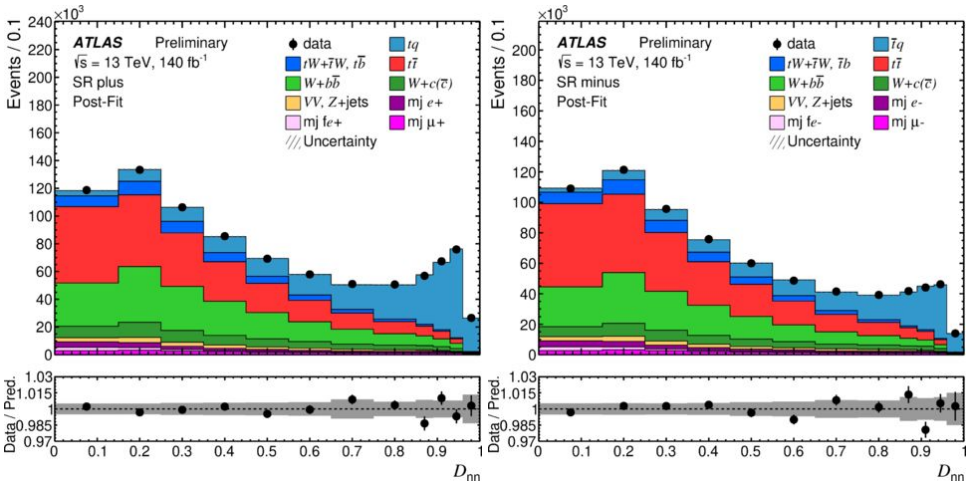
Phys. Lett. B 808 (2020) 135609

Measurement of t-channel production at 13 TeV with 140 fb^{-1}

Measurement of t-channel production of single top quarks and antiquarks in pp collisions at 13 TeV using the full ATLAS Run 2 dataset

Event Selection:

- **1** isolated ***e* or *μ*** (p_T>28 GeV, |η|<2.5)
- **2 jets** (p_T>30 GeV, |η|<4.5)
- **1 *b*-tag** jet (|η|<2.5, *b*-tag eff 60%)
- Selection on
  - E_T^{miss}, $m_T(W)$ and $p_T(l)$ to **reduce multijet** bkg
  - m(*lb*) to **avoid bad modelling** of *t* decays



2 SRs defined based on **lepton charge**

NN to separate signal → trained on inclusive region

- 17 input kinematic variables of reconstructed object, *W* and *t* (m(*jb*), n(*j*) highest ranked)
- NeuroBayes package with symmetric sigmoid activation function

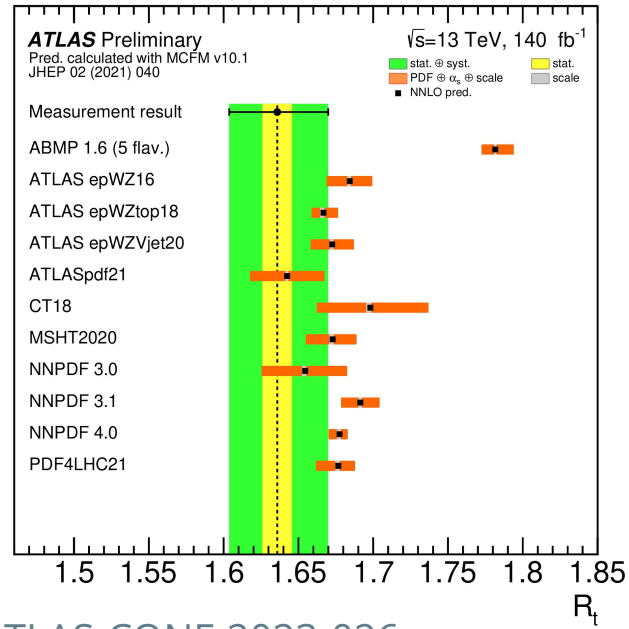
NEW!

ATLAS-CONF-2023-026

Measurement of t-channel production at 13 TeV with 140 fb^{-1}

Measurement of t-channel production of single top quarks and antiquarks in pp collisions at 13 TeV using the full ATLAS Run 2 dataset

Profile Likelihood (LH) fit extract total *t*-channel cross-section, top quark, and antiquark cross-sections, and their ratio R_t.



	σ_t[pb]	$\sigma_{\bar{t}}$ [pb]	σ_{t-chan} [pb]	$R_t = \sigma_t/\sigma_{\bar{t}}$
Measured	137 ± 8	84^{+6}_{-5}	221 ± 13	$1.636^{+0.036}_{-0.034}$
Predicted	134.2 ± 2.2	80.0 ± 1.6	214.2 ± 3.4	$1.677^{+0.010}_{-0.014}$

Results in good agreement with NNLO predictions

Highest impact **systematic uncertainties** on cross-section

- top quark modelling (matching scale, PS, FSR)
- JES and *b*-tagging

Highest impact **systematic uncertainties** on ratio

- *W*+*c* cross-section
- top quark parton shower (PS), PDFs

NEW!

[ATLAS-CONF-2023-026]

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EFT interpretations

Dim-6 operators in EFT to parametrize new physics

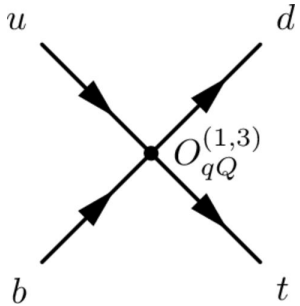
- study of the 4 fermion operator $O_{q,Q}^{(1,3)}$
- Maximum LH scan of $C_{q,Q}^{(1,3)}$:
  95% CL is $-0.25 < C_{q,Q}^{(1,3)} < 0.12$

Assuming that $|V_{ts}|$, $|V_{td}| \ll |V_{tb}|$ and t always decays in Wb

$$f_{LV} \cdot V_{tb} = 1.016 \pm 0.031$$

or restricting $V_{tb} \in [0,1]$ and $f_{LV}=1$

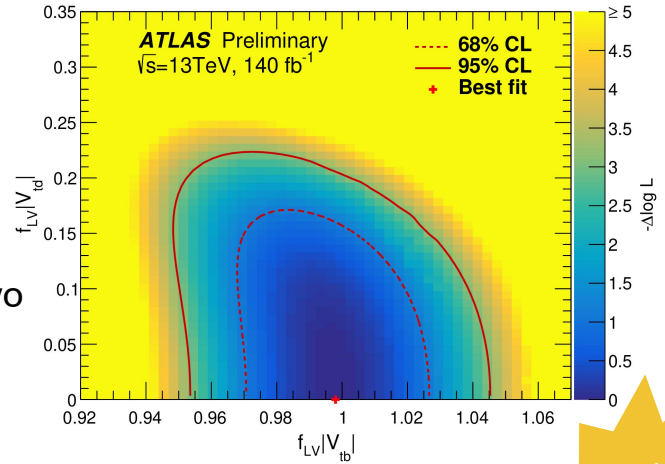
$$|V_{tb}| > 0.95 \text{ at } 95\%\text{CL}$$



Generalised CKM interpretation: no $|V_{ts}|$,$|V_{td}| \ll |V_{tb}|$ constrain

- *Wtq* vertex with $q \in \{d,s,b\}$ both in production and decay

Setup:
set 1 CKM element to 0, 2D scan on the others two parameters



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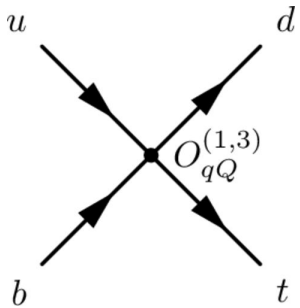

Generalised CKM interpretation: constrain

- *Wtq* vertex with $q \in \{d,s,b\}$ both in p… decay

See YSF talk by Joshua!

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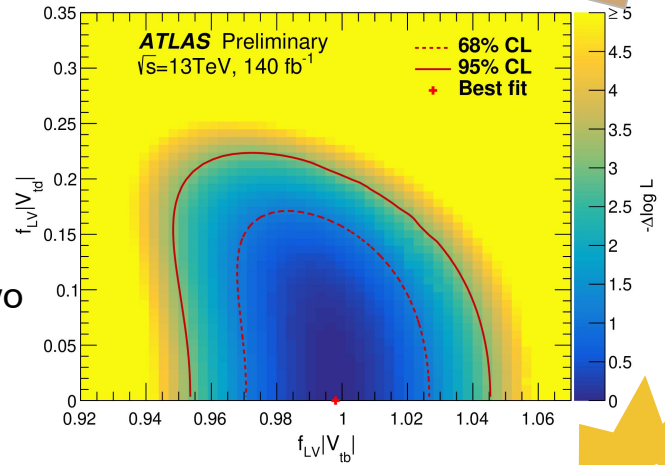
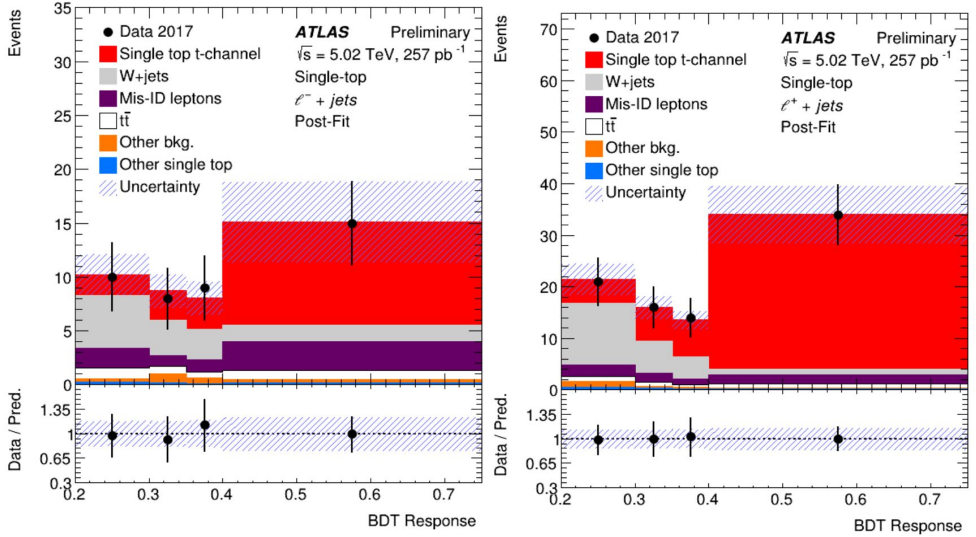


NEW!

ATLAS-CONF-2023-026

Measurement of t-channel production at 5.02 TeV with 257 pb^{-1}

Measurement of t-channel single-top-quark production in pp collisions at √s = 5.02 TeV with the ATLAS detector



Data with low pile-up <μ>=2

2 SRs defined based on **lepton charge**

BDT with XGBoost package trained on inclusive regions

- 9 input variables and 3 fold cross-validation

Event Selection:

- **1** isolated ***e*** or ***μ*** (p_T>18 GeV)
- Exactly **2 jets** (p_T> 23 GeV, |η| < 4.0)
  - **1 *b*-tag** jet (|η| < 2.5, *b*-tagging eff. 60%)
  - **1 *untag*** jet (1.5<|η|<4.0)
  - Δη(*b*,*j*) > 1.5 to reduce top pair bkg
- Selection on:
  - m_T^W, E_T^{miss}, $m_T^W+E_T^{miss}$ to **reduce mis-ID bkg**
  - H_T, m(*l*,*b*), m(*W*), m(*t*) to **increase signal purity**

NEW!

ATLAS-CONF-2023-033

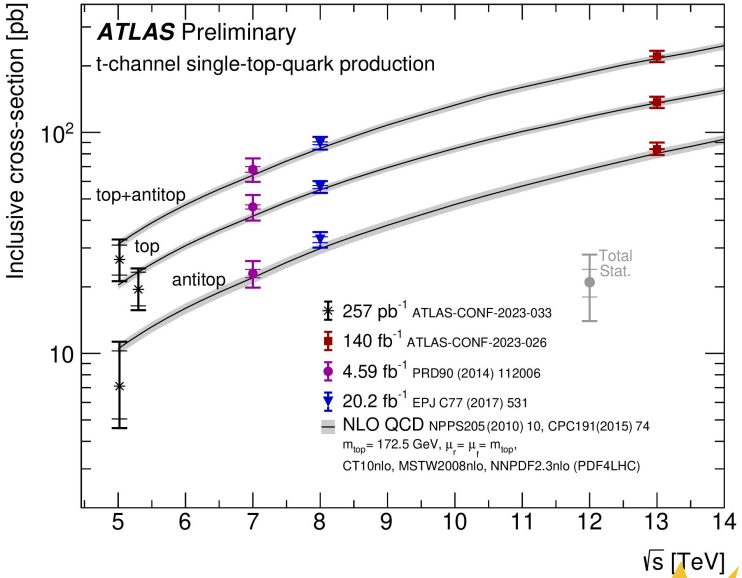
Measurement t-channel production at 5.02 TeV with 257 pb^{-1}

Measurement of t-channel single-top-quark production in pp collisions at √s = 5.02 TeV with the ATLAS detector

Profile **Maximum LH fit** to extract single top, and anti-top cross-sections, their ratio and the total *t*-channel cross-section.

Results:

Variable	Predicted	Measured
R_t	$2.03^{+0.06}_{-0.07}$	$2.74^{+1.44}_{-0.83}(\text{stat.})\ ^{+1.04}_{-0.29}(\text{syst.})$
σ_{t-chan}	$30.3^{+0.5}_{-0.5}$ pb	$26.6^{+4.3}_{-4.0}(\text{stat.})\ ^{+4.4}_{-3.6}(\text{syst.})$ pb
σ_t	$20.3^{+0.5}_{-0.4}$ pb	$19.5^{+3.8}_{-3.1}(\text{stat.})\ ^{+2.9}_{-2.2}(\text{syst.})$ pb
$\sigma_{\bar{t}}$	$10.0^{+0.2}_{-0.3}$ pb	$7.1^{+3.2}_{-2.1}(\text{stat.})\ ^{+2.8}_{-1.5}(\text{syst.})$ pb



Process observed at 5.02 TeV with a significance of 6.1σ

Cross-section measurement uncertainties → **similar** impact from **statistical** and **systematic uncertainties**

Ratio measurement uncertainty is dominated by **statistical uncertainty**

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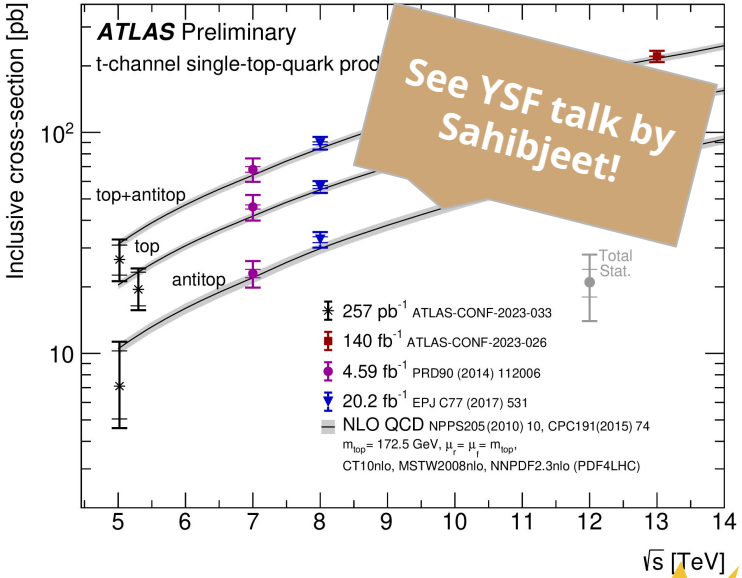

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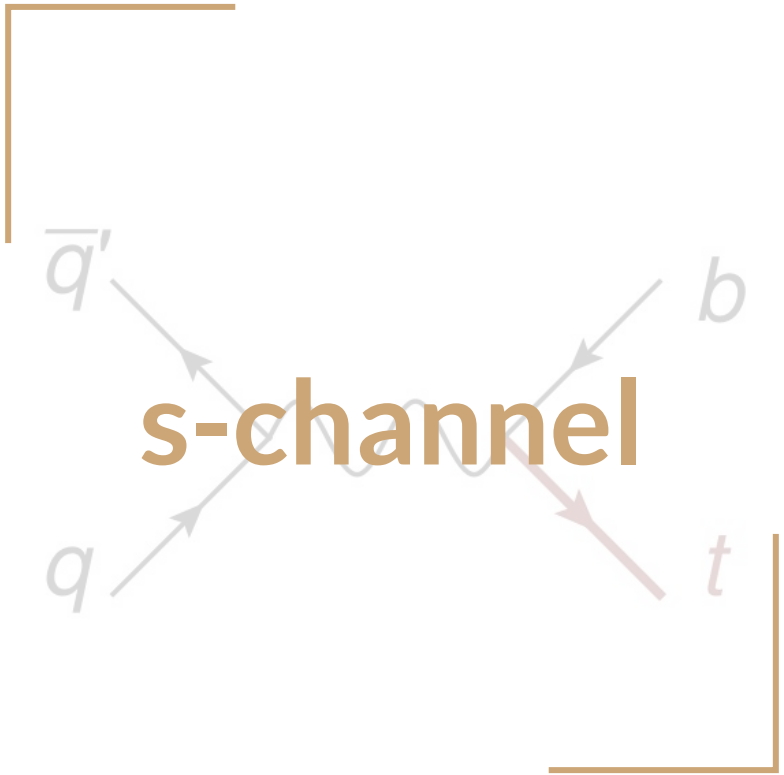
NEW!

ATLAS-CONF-2023-033



s-channel

Measurement s-channel production at 13 TeV with 139 fb^{-1}

Measurement of single top-quark production in the s-channel in proton–proton collisions at √s = 13 TeV with the ATLAS detector

Event Selection: 1 *e/μ* + E_T^{miss}>35GeV, m_T^W>30GeV to reduce *W*+jet bkg + at least 2 *b*-tag jets

- Define SR (exactly 2 *b*-tag jets) + 1 VR for W+jets + 2 VR for top pair production

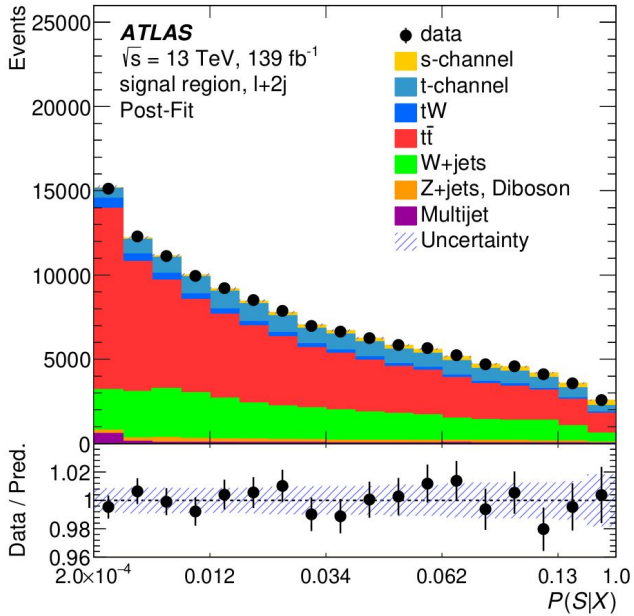
Matrix Element Method to separate sig vs bkg: per-event LH calculation that final state *X* is of process $H_{proc} \rightarrow P(X|H_{proc})$

- use Bayes' theorem to obtain a discriminant

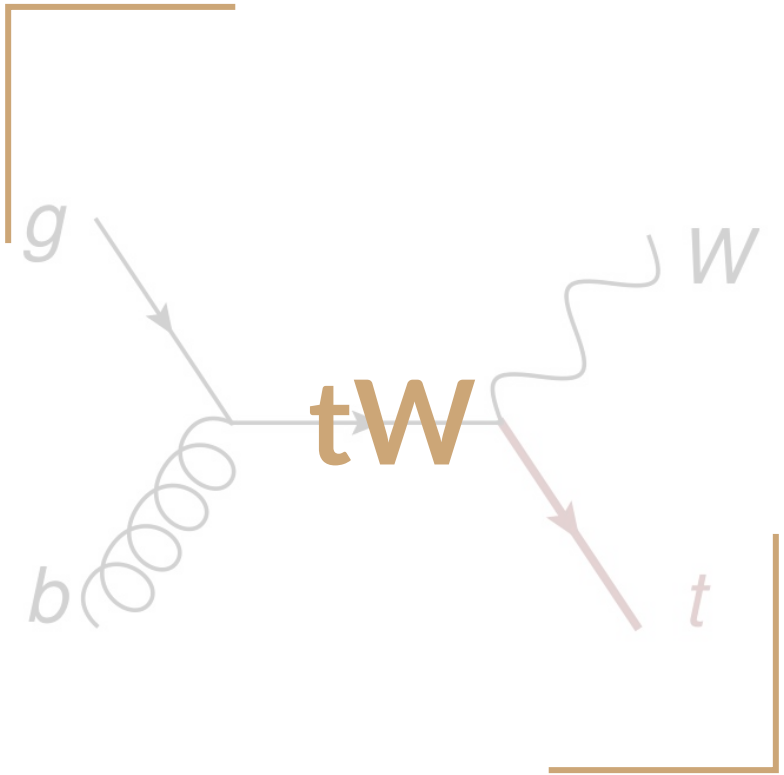
Highest impact **systematics**: top pair prod. normalisation and modelling, *s*-channel modelling, JER, JES, and MC statistics

Results:
3.3(3.9)σ observed(expected) significance

σ_{obs}[pb]	σ_{SM} [pb]
$8.2^{+3.5}_{-2.9}$	10.3 ± 0.4

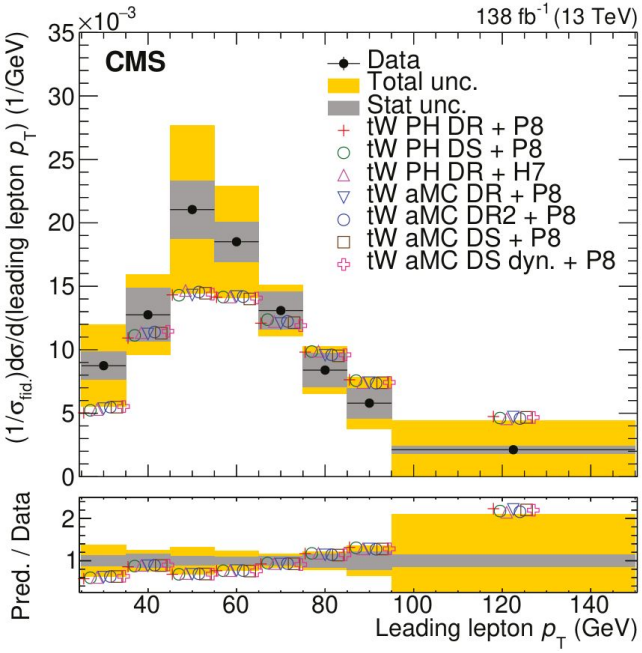


JHEP 06 (2023) 191


g
W
tW
b
t

Inclusive and differential tW at 13 TeV with 138 fb^{-1}

Measurement of inclusive and differential cross sections for single top quark production in association with a W boson in proton-proton collisions at √s = 13 TeV



Event Selection:

- 1 $e^{\pm}$ + 1 $\mu^{\mp}$ (leading p_T>25GeV)
- $m(e\mu)$>20GeV

Inclusive regions: 1j1b, 2j1b, 2j2b

Differential region: 1j1b + no loose jet

Differential measurement:

Max LH fit to extract signal and unfold to particle level +normalise to σ_{fid}+Asimov data for closure and performance

Inclusive measurement:

Use BDT to separate *tW* vs top pair prod. in:

- 1j1b, 2j1b

Use 2j2b as CR for top pair production

Fit to BDT discriminants + subleading jet p_T in CR to constraint JES unc.

Results: $\sigma_{tW} = 79.2 \pm 0.9(\text{stat})^{+7.7}_{-8.0}(\text{syst}) \pm 1.2(\text{lumi})$ pb

Differential distributions good agreement, leading $l^{\pm}$ p_T and $\Delta\varphi(e,\mu)$ slight disagreement. All DR, DS method have similar compatibility.

JHEP 07 (2023) 046

Observation of tW in single-lepton channel at 13 TeV with 36 fb^{-1}

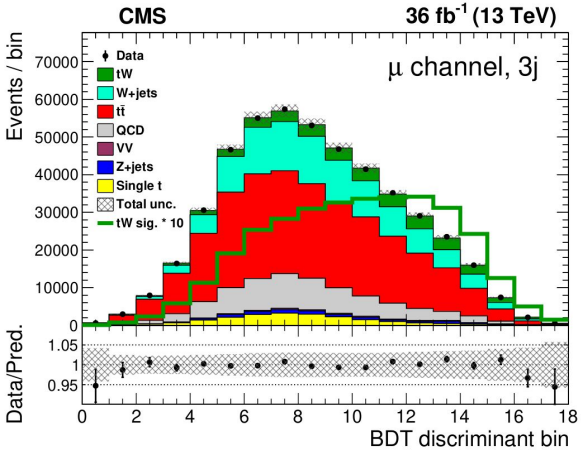
Observation of tW production in the single-lepton channel in pp collisions at √s = 13 TeV

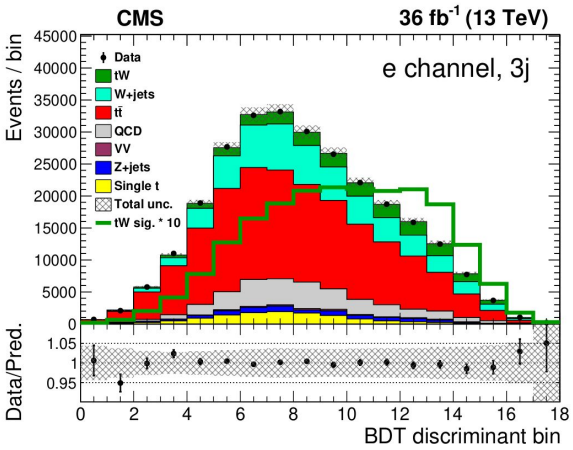
Event Selection:

1 *e*/*μ* + ≥ 2jets + 1 *b*-tag jet

Number of jets:

- SR: 3jets
- CR for W+jets and multijet bkgs: 2 jets
- CR for top pair bkg: 4jets





W+jet bkg normalisation and multijet bkg from data

JHEP 11 (2021) 111

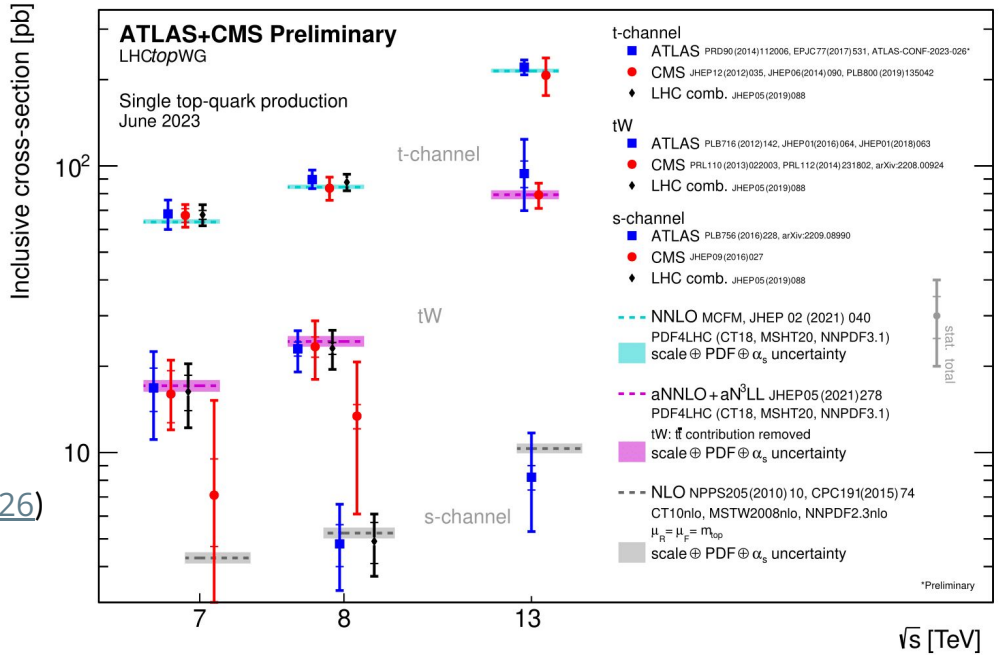
Signal Extraction: 2 BDTs (with *e* or *μ*) trained with *tW* vs top pair production → distributions used for Maximum LH fit

Results:

$\sigma_{tW} = 89 \pm 4(\text{stat}) \pm 12(\text{syst})\text{pb}$ compatible with SM prediction at NNLO and N^{3}LO

Summary

Summary



Overview of single top results

- **Relative uncertainties on inclusive measurements:**
  - $\sigma_{t\text{-}chan} \rightarrow 5.9\%$, $R_t \rightarrow 2.2\%$ (ATLAS-CONF-2023-026)
  - $\sigma_{s\text{-}chan} \rightarrow +42\%\ -35\%$ (JHEP 06, (2023), 191), $\sigma_{s\text{-}chan} \rightarrow 30\%$ (JHEP 05, (2019), 88)
  - $\sigma_{tW} \rightarrow 10\%$ (JHEP 07 (2023) 046)

- **Leading Uncertainties:**
  - signal modelling, jet (JES, JER), bkg modelling → *t*-channel
  - top pair modelling, signal modelling and jet (JER, JES) → *s*-channel
  - bkg normalization (multijet, W+jet), jet (JES), signal modelling → *tW* mode

Summary

Overview of Run2 results on single top production cross-section

- ***t*-channel**
  - New *t*-channel results from ATLAS at 13 TeV and 5 TeV
  - Inclusive and differential cross-section measurements
- ***s*-channel**
  - ATLAS measurement with full Run2 data with evidence of the process
- ***tW* mode**
  - CMS observation and measurement in dileptonic and semi-leptonic channels

Good agreement is found **with SM** predictions

BACKUP

Summary

Overview of single top results

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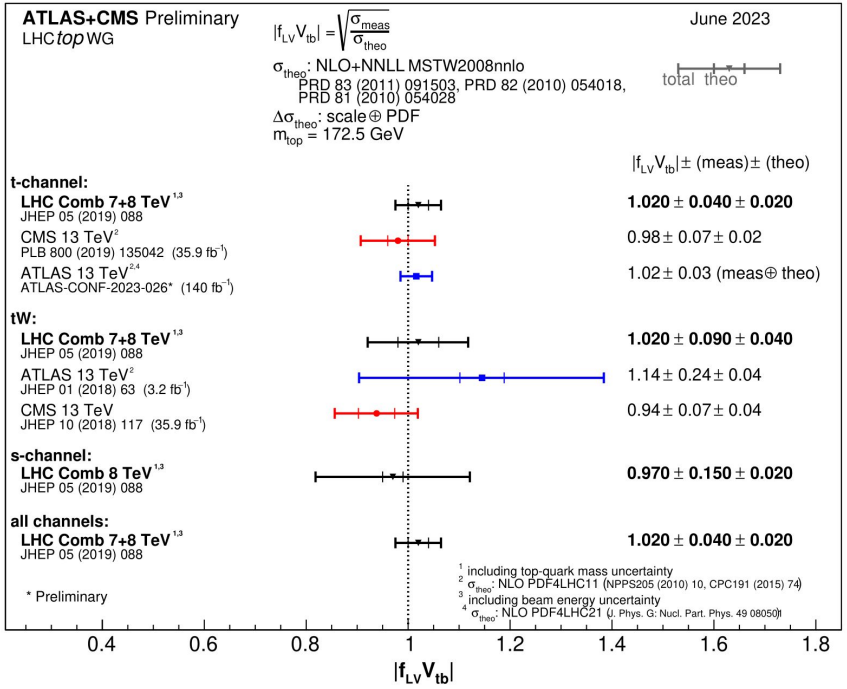

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  - signal modelling, jet (JES, JER), bkg modelling → *t*-channel
  - top pair modelling, signal modelling and jet (JER, JES) → *s*-channel
  - bkg normalization (multijet, W+jet), jet (JES), singal modelling → *tW* mode

ATLAS and CMS Run 1 single top measurements combination

ATLAS+CMS combination of single top with Run 1 data

Combinations of single-top-quark production cross-section measurements and $|f_{LV}V_{tb}|$ determinations at $\sqrt{s}$ = 7 and 8 TeV with the ATLAS and CMS experiments

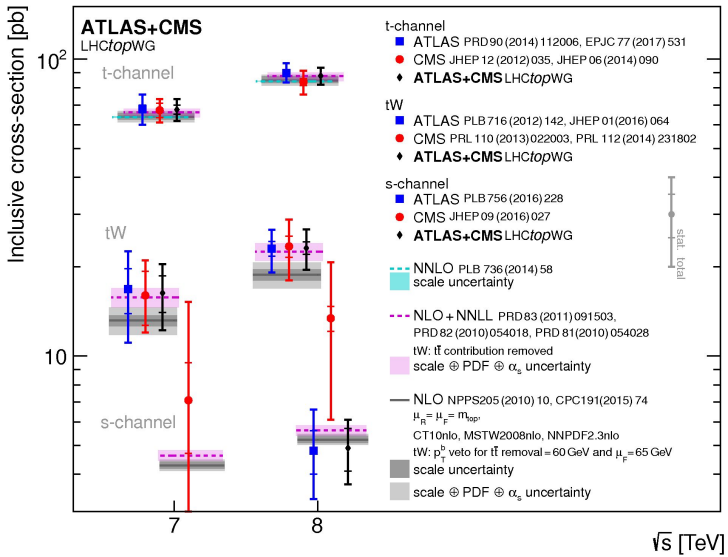
Similar approaches for Atlas and CMS measurements:

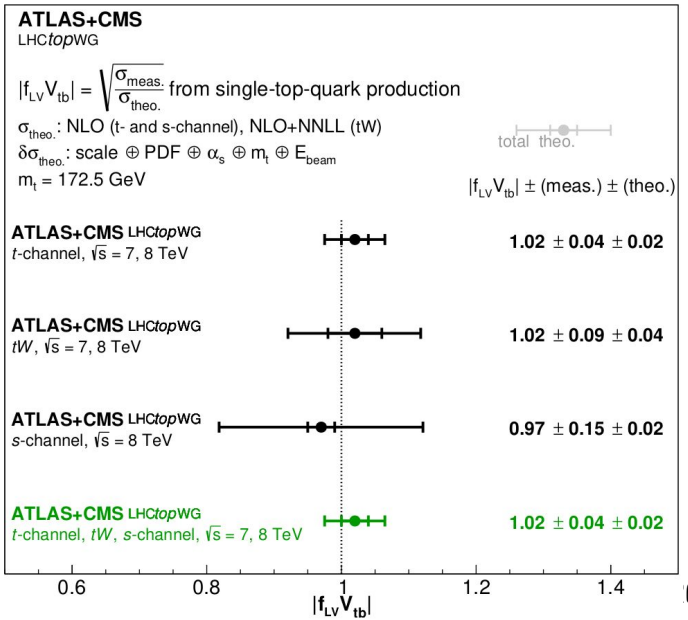
- select ≥1 *e*/μ and ≥1 jet
- use MVA to separate sig vs bkg (BDT, NN, MEM)
- binned Maximum Likelihood (LH) fit to measure cross-section

Considered value of m_t = 172.5 GeV for all measurements

Combination strategy: BLUE method

All combined measurements are **consistent** with their **SM predictions**



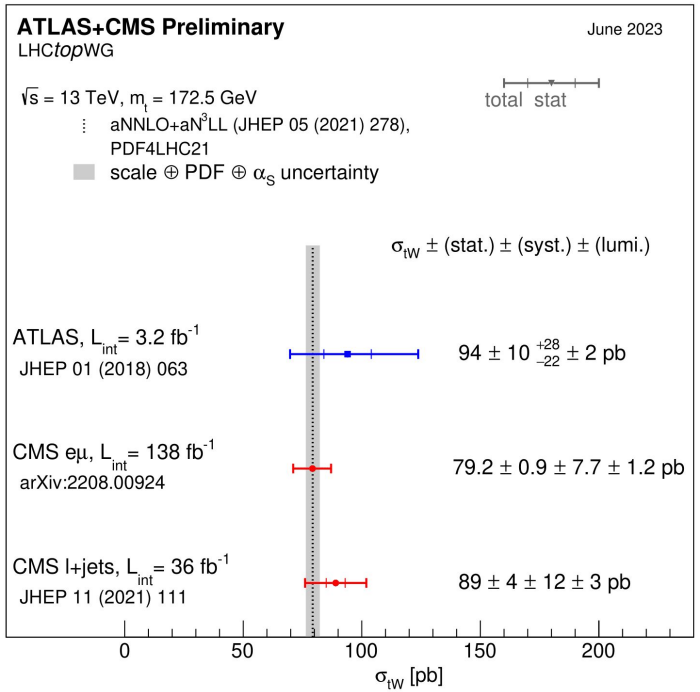


JHEP05, 2019, 88

s-channel and tW

s-channel SM prediction at NLO

$$\sigma_{s-channel} = 10.32\ ^{+0.29}_{-0.24}(\text{scale}) \pm 0.27(\text{PDF} + \alpha_s)\ ^{+0.23}_{-0.22}(\text{m}_{top})\ \text{pb}$$



tW NNLO prediction

$$\sigma_{\text{tW}}^{\text{SM}} = 71.7 \pm 1.8\ (scale) \pm 3.4\ (\text{PDF})\ \text{pb}$$

tW N^{3}LO prediction

$$\sigma_{\text{tW}}^{\text{SM}} = 79.5\ ^{1.9}_{1.8}\ (scale)\ ^{2.0}_{1.4}\ (\text{PDF})\ \text{pb}$$

t-channel

CMS analyses:

- *Measurement of differential cross sections and charge ratios for t-channel single top quark production in proton–proton collisions at √s = 13 TeV* (Eur. Phys. J. C 80, 370 (2020))
- *Measurement of CKM matrix elements in single top quark t-channel production in proton-proton collisions at √s = 13 TeV* (Phys. Lett. B 808 (2020) 135609)

ATLAS analyses:

- *Measurement of t-channel production of single top quarks and antiquarks in pp collisions at 13 TeV using the full ATLAS Run 2 dataset* (ATLAS-CONF-2023-026)
- *Measurement of t-channel single-top-quark production in pp collisions at √s = 5.02 TeV with the ATLAS detector* (ATLAS-CONF-2023-033)