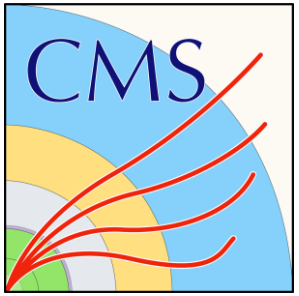
Measurements of single top quark production with the ATLAS and CMS experiments

10th Large Hadron Collider Physics Conference (LHCP 2022)



Björn Wendland

On behalf of the ATLAS and CMS collaborations

17-May-2022

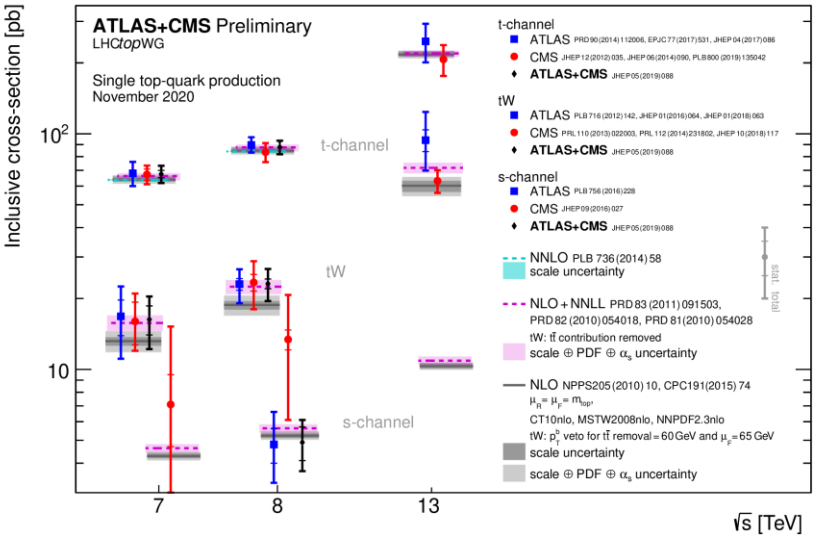
technische universität dortmund

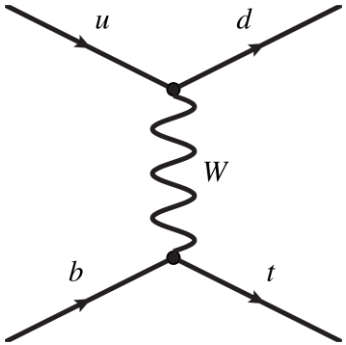
Single top quark production

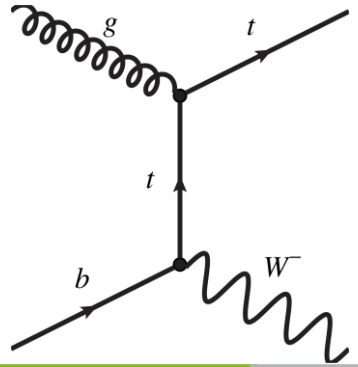
- Single top quark production via *Wtb* vertex
- Direct probe of the V_{tb} CKM matrix element
- Sensitive to PDFs
- Three classical modes:
  - *t*-channel (σ: 217 pb)
  - *tW*-channel (σ: 71.7 pb)
  - *s*-channel (σ: 10.32 pb)

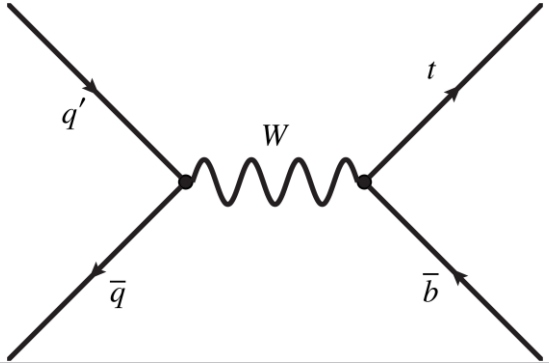
} @13 TeV

- Associated production:
  - Probing top quark couplings to EW bosons
  - Study rare SM processes

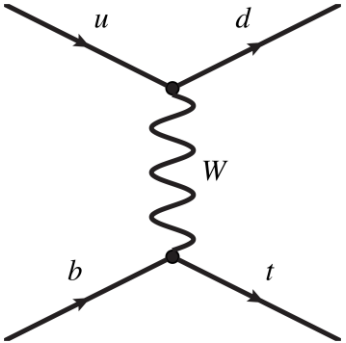




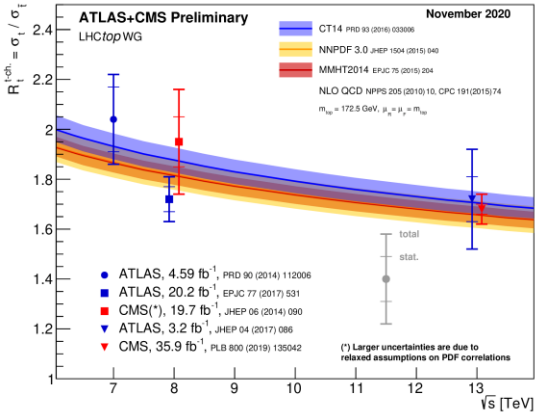




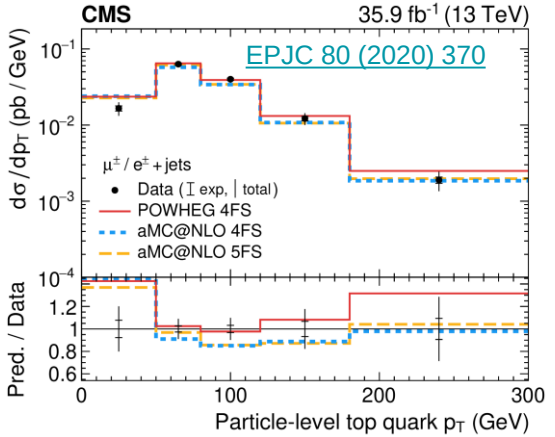
t-channel production

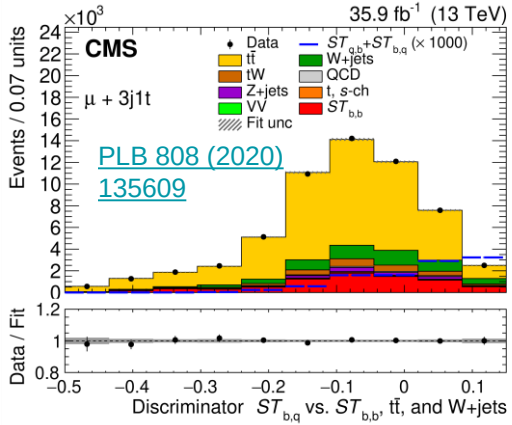


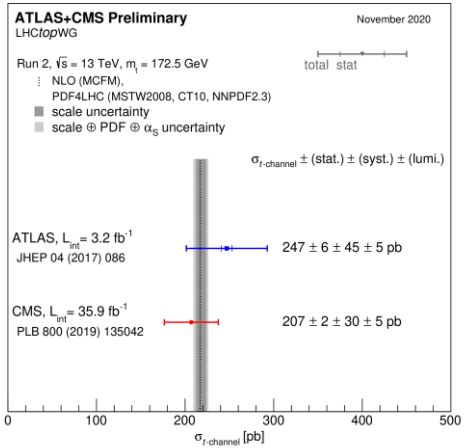
Measurements of *t*-channel production

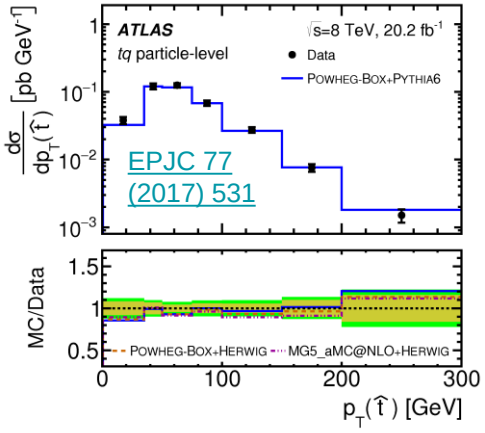


- Workhorse of single top production
- Many results at **7, 8 & 13 TeV** by both collaborations:
  - Fiducial, total, differential σ measurements
  - Measurements of $R_t = \sigma_t/\sigma_{\bar{t}}$
- More recently: model independent approach to measure CKM matrix elements

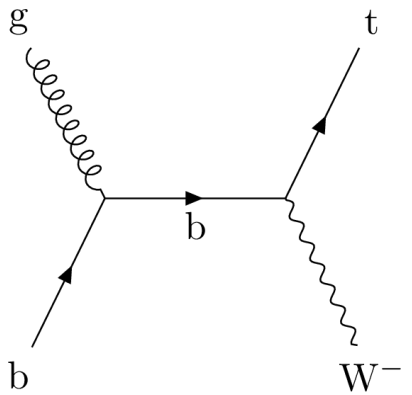




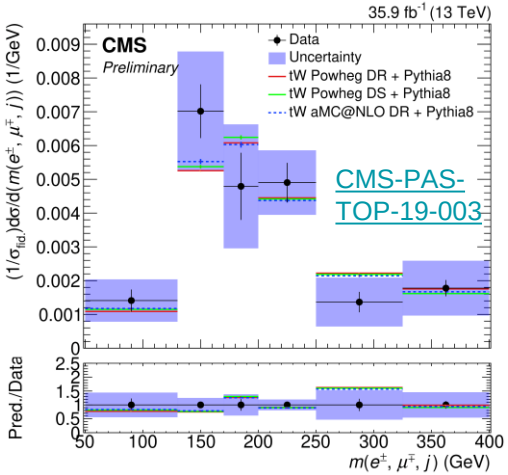


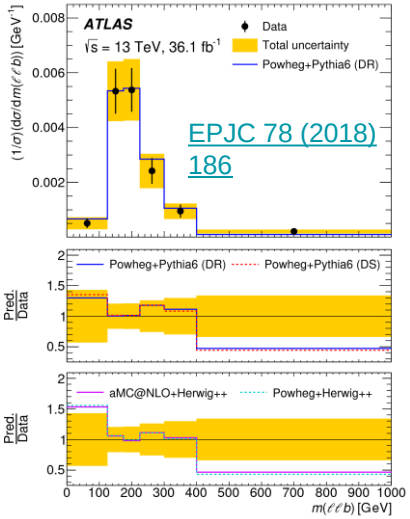


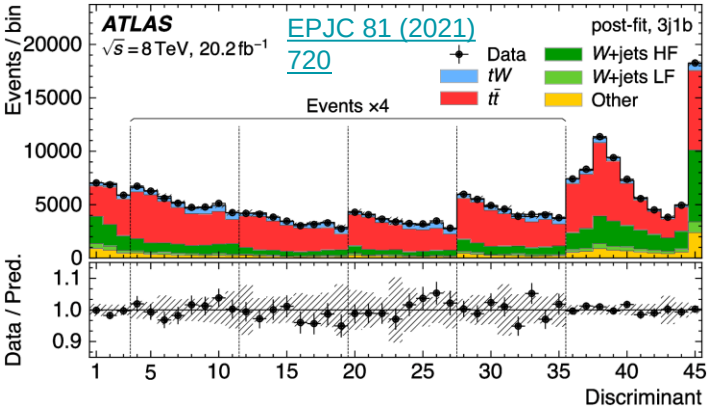
tW-channel production

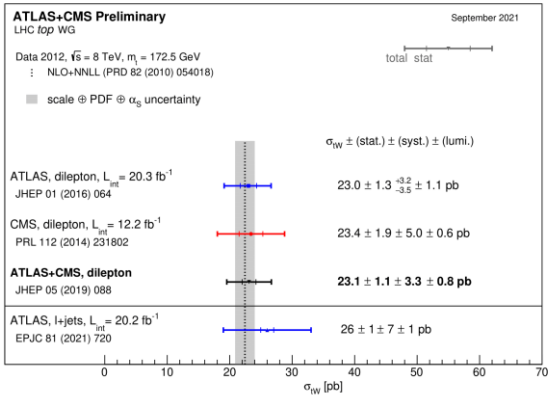


Measurements of *tW* production

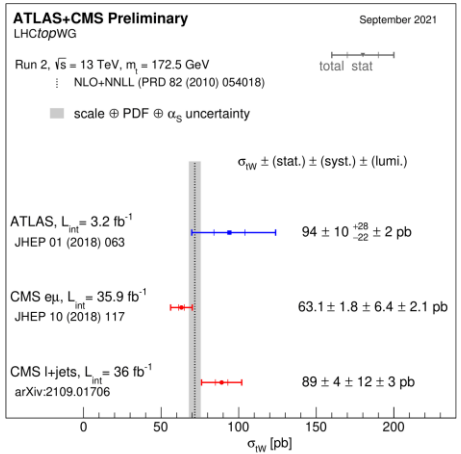




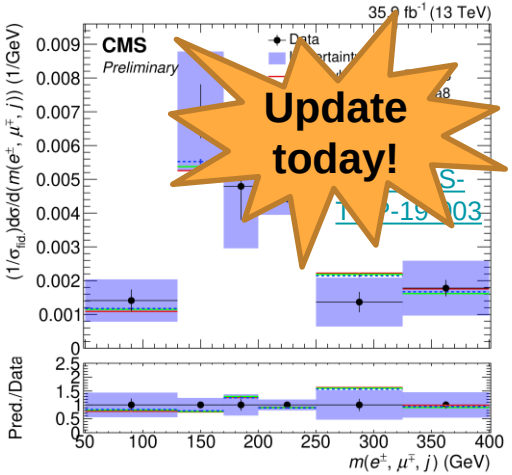


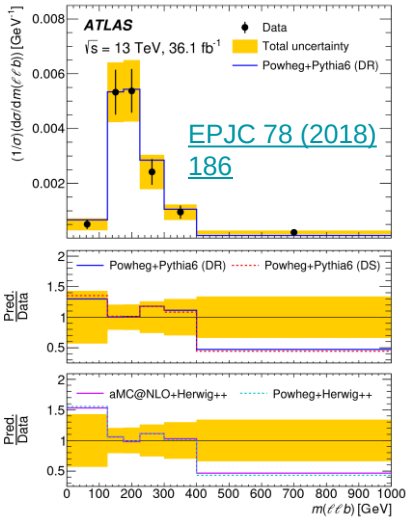


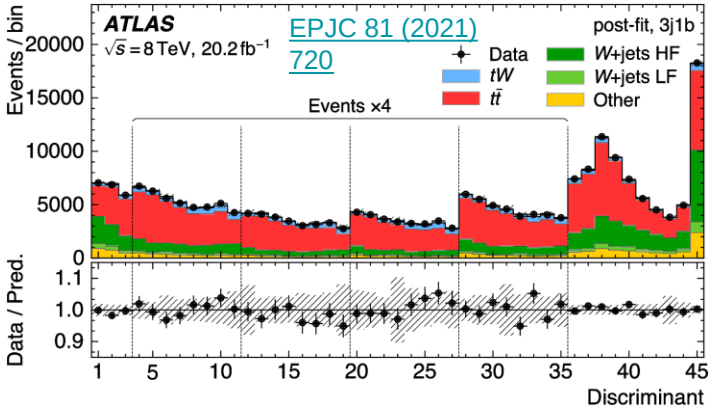
- *tW* production observed and measured inclusively and/or differentially at **7, 8 & 13 TeV in dilepton channel (DL)**
- Most recently also measured in **single lepton (SL)** channel at 8 TeV by ATLAS and **observed!** at 13 TeV by CMS (**today!**)

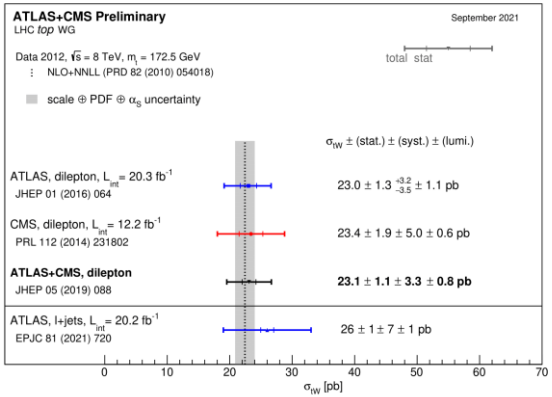


Measurements of *tW* production









- *tW* production observed and measured inclusively and/or differentially at **7, 8 & 13 TeV in dilepton channel (DL)**
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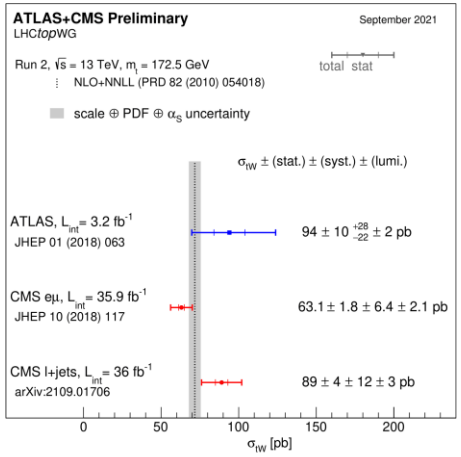
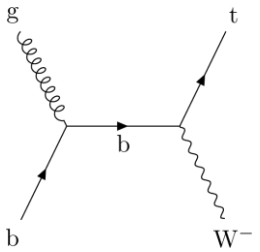
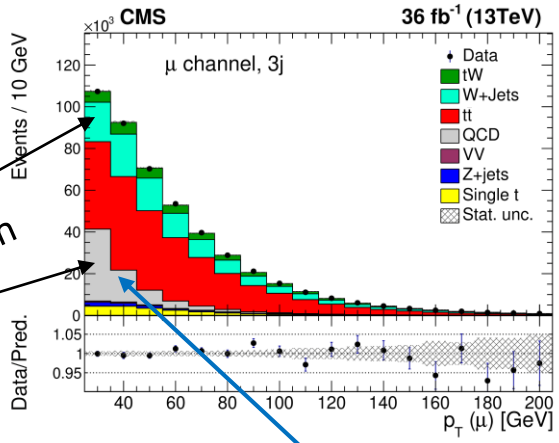


Observation of *tW* production in SL channel

Selection

- Selecting single lepton events:
  - =1e with p_T > 30 GeV & |η| < 1.48 **or** =1μ with p_T > 26 GeV & |η| < 2.1
- Veto events with addtional leptons with: p_T > 20(10) GeV for e(μ) & |η| < 2.4





Normalization

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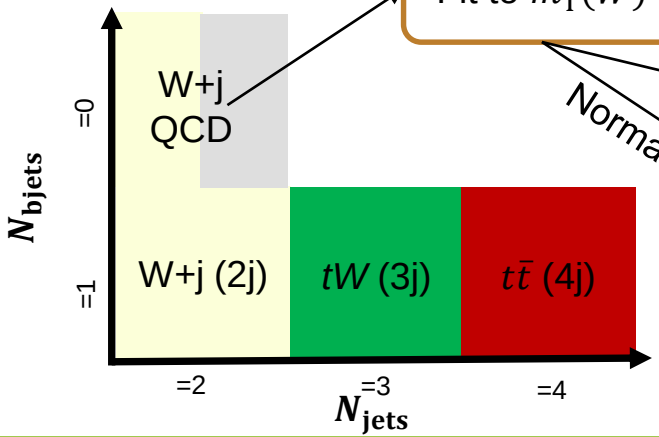
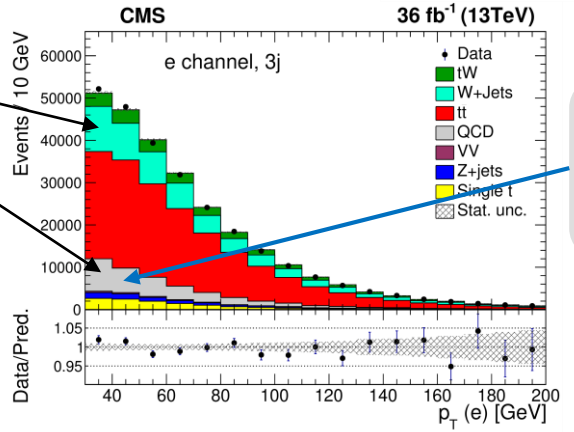
Fit to $m_T(W)$



Normalization



Shape from data-$t\bar{t}$ with non-iso leptons

Results

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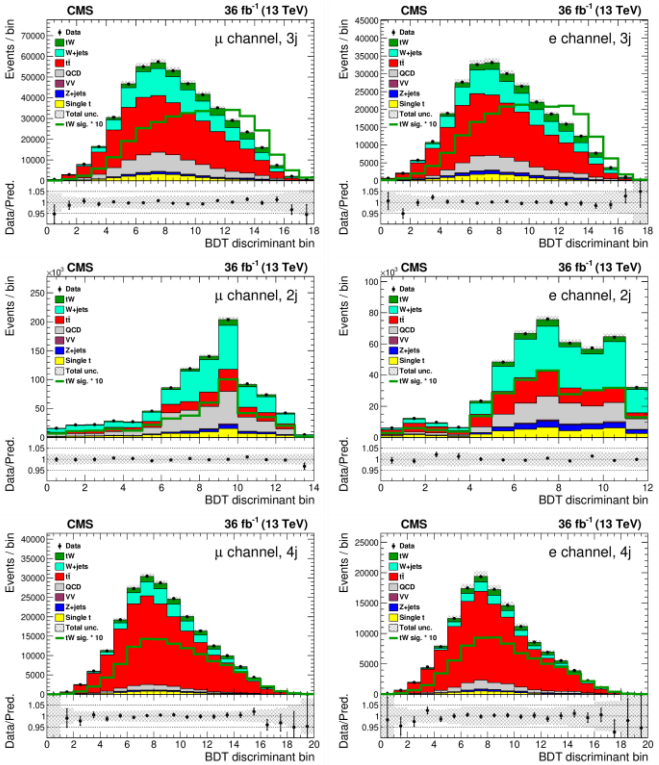
- BDTs for separating *tW* from $t\bar{t}$ events trained separately for e-/μ-channel
- Variables well modelled in simulation offering discriminative power used as input features
- Signal extraction by binned profile likelihood fit to BDT responses
- Result is **systematically dominated**



Source	Relative uncertainty (%)
Experimental	
Jet energy scale	6
b tagging efficiency	4
Luminosity	3
Lepton energy scale	2
Trigger efficiency	1
Jet energy resolution	1
b tagging misidentification rate	<1
Unclustered energy	<1
Pileup	<1
Normalization	
QCD multijet normalization	7
W+jets normalization	6
Z+jets normalization	3
Single t normalization	1
$t\bar{t}$ normalization	1
VV normalization	<1
Theoretical	
h_{damp}	4
Diagram removal/diagram subtraction	3
Underlying event tune	3
Colour reconnection model	1
Parton distribution function	1
Matrix element/parton shower matching	1
Final-state radiation	<1
Initial-state radiation	<1
Total systematic uncertainty	14
Statistical uncertainty	5
Total uncertainty	15

$\sigma_{\mathrm{meas.}} = 89 \pm 4(\mathrm{stat.}) \pm 12(\mathrm{syst.})\mathrm{pb}$

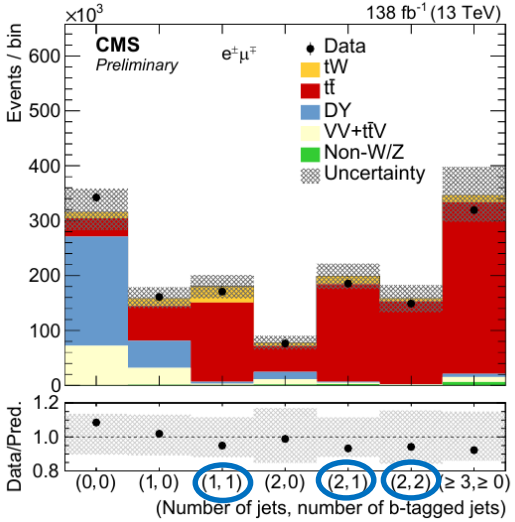
$\sigma_{\mathrm{pred.}} = 71.7 \pm 1.8(\mathrm{scale}) \pm 3.4(\mathrm{PDF})\mathrm{pb}$ NNLO PoS DIS2015 (2015) 170

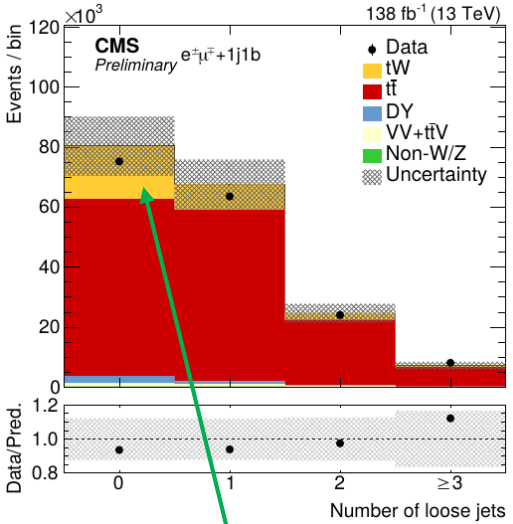
$\sigma_{\mathrm{pred.}} = 79.5^{+1.9}_{-1.8}(\mathrm{scale})^{+2.0}_{-1.4}(\mathrm{PDF})\mathrm{pb}$ N³LO JHEP 05 (2021) 278

Measurements of *tW* production in eμ-channel

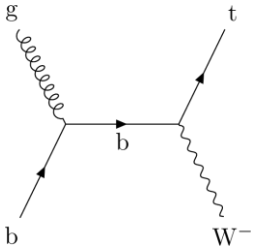
Selection

- Single lepton and dilepton triggers are used
- ≥ 2 leptons (e/μ) with p_T > 20 GeV & |η| < 2.4
- ≥ 1 lepton with p_T > 25 GeV
- Two leading leptons = opposite sign eμ-pair
- $m_{l_i l_j}$ > 20 GeV for all lepton pair combinations
- Jets with p_T > 30 GeV and |η| < 2.4
- Loose jets: 20 GeV < p_T < 30 GeV
- 70% b-tagging WP used





New!



CMS-PAS-TOP-21-010

Inclusive measurement

1j1b+2j1b: sensitive to *tW*

2j2b: controlling $t\bar{t}$ background

Differential measurement
~25% purity

Inclusive measurement

CMS-PAS-TOP-21-010

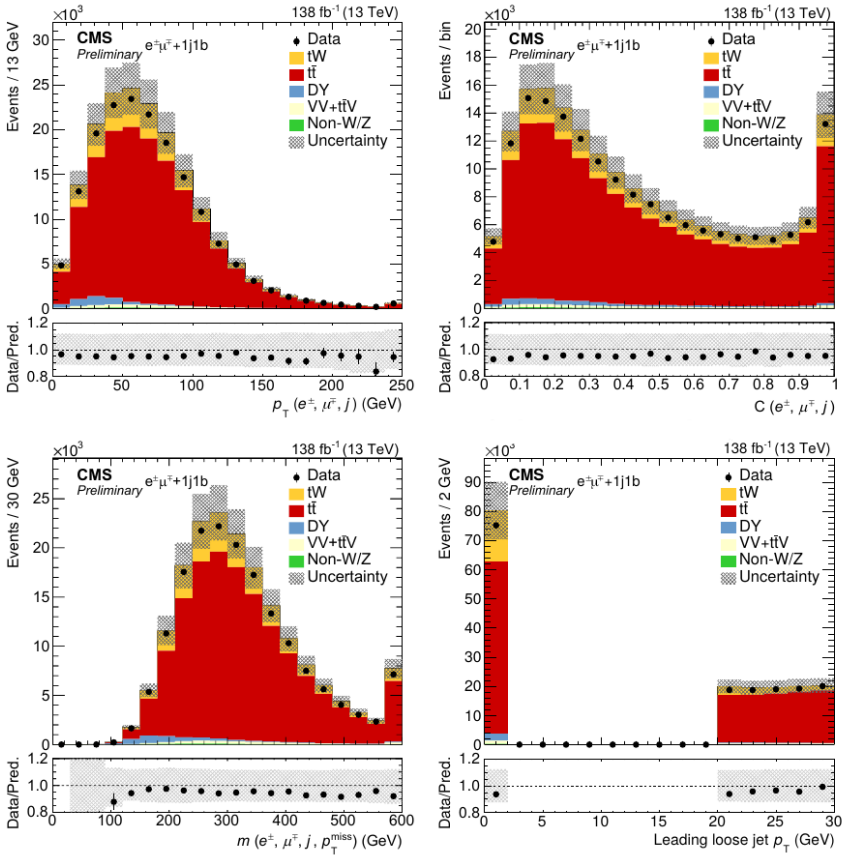
- BDTs for separating *tW* from $t\bar{t}$ events trained separately in 1j1b and 2j1b regions
- Shapes of input features are well modelled

Input in 1j1b

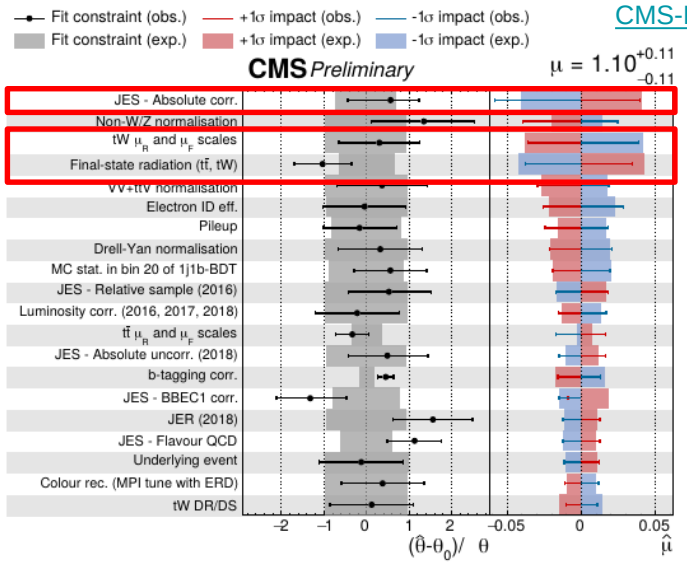
- $p_T(e^{\pm}, \mu^{\mp}, j)$
- Centrality: $C(e^{\pm}, \mu^{\mp}, j) = E_T(e^{\pm}, \mu^{\mp}, j)/E(e^{\pm}, \mu^{\mp}, j)$
- $m(e^{\pm}, \mu^{\mp}, j, p_T^{miss})$
- Leading loose jet p_T: 0 if absent
- Jet p_T
- Presence of loose jet

Input in 2j1b

- $\Delta R(l_1, j_1)$
- $\Delta R(l_{12}, j_{12})$
- Subleading jet p_T

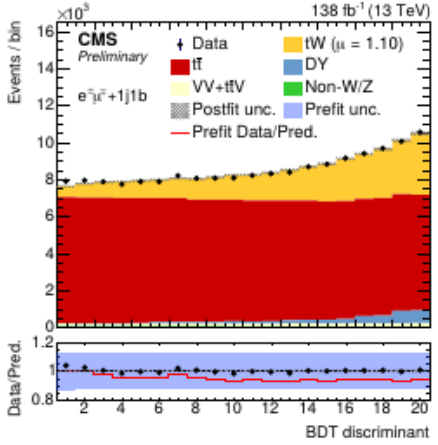


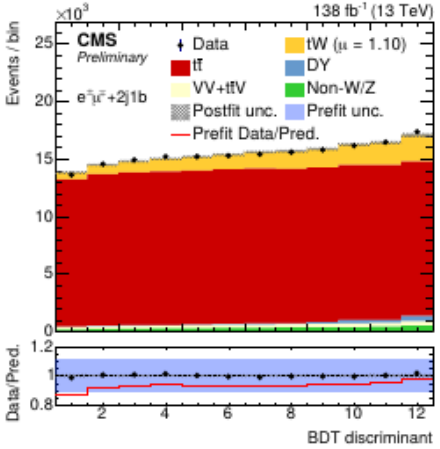
Results of inclusive measurement



Pulls&constraints | **Impact on μ**

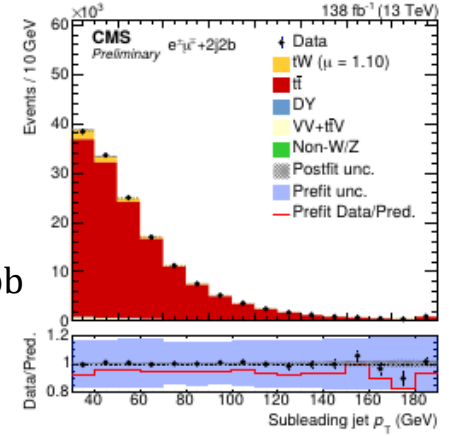
CMS-PAS-TOP-21-010





Signal extraction by binned profile likelihood fit to BDT responses & subleading jet p_T

Result is systematically dominated



Used as **nominal**

$\sigma_{\text{meas.}} = 79.2 \pm 0.8(\text{stat.})^{+7.0}_{-7.2}(\text{syst.}) \pm 1.1(\text{lumi.})\text{pb}$

$\sigma_{\text{pred.}} = 71.7 \pm 1.8(\text{scale}) \pm 3.4(\text{PDF})\text{pb}$ NNLO PoS DIS2015 (2015) 170

$\sigma_{\text{pred.}} = 79.5^{+1.9}_{-1.8}(\text{scale})^{+2.0}_{-1.4}(\text{PDF})\text{pb}$ N³LO JHEP 05 (2021) 278

Differential measurement

CMS-PAS-TOP-21-010

Central information of kinematic properties

Probing top quark p_T modelling

Probing boost of *tW* system

Distributions unfolded to **particle level** using **profile likelihood unfolding**

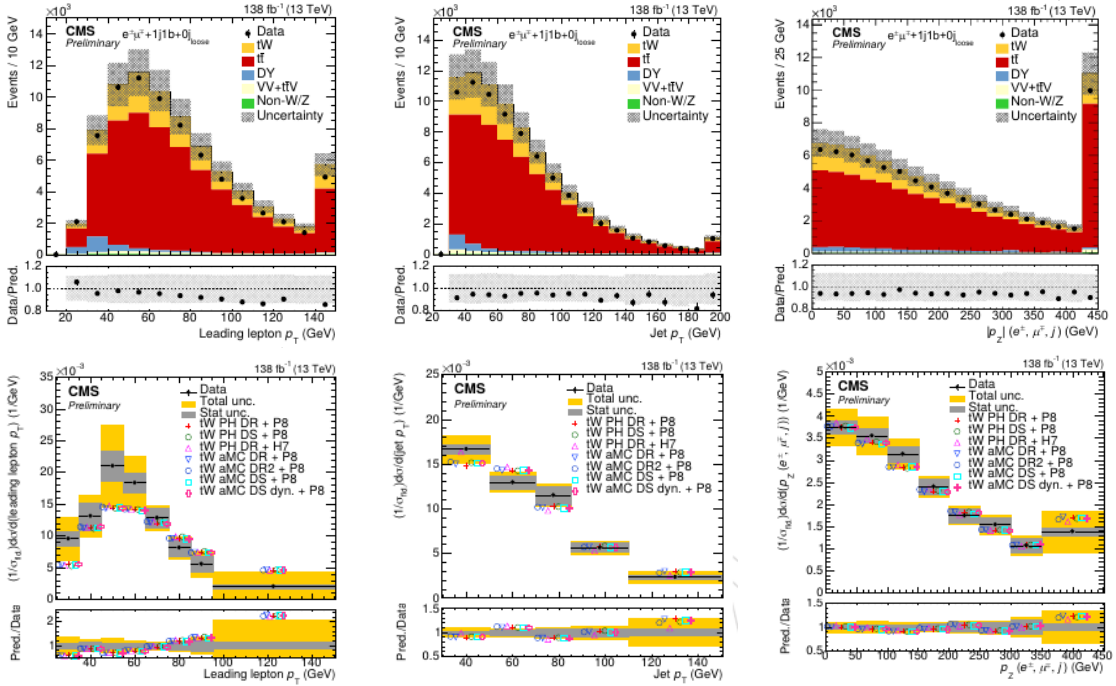
Selection requirements of particle level objects & fiducial phase space definition equivalent to **1j1b+0loose jets**

Uncertainties in range of **10-50%**

Limited by **systematic uncertainties**

Only small differences between **seven!** tested modelling approaches

Little sensitivity to $tW/t\bar{t}$ interference



Differential measurement

CMS-PAS-TOP-21-010

Probing mass/energy properties

Correlations between top&W

Spin-related properties

Distributions unfolded to **particle level** using **profile likelihood unfolding**

Selection requirements of particle level objects & fiducial phase space definition equivalent to **1j1b+0loose jets**

Uncertainties in range of **10-50%**

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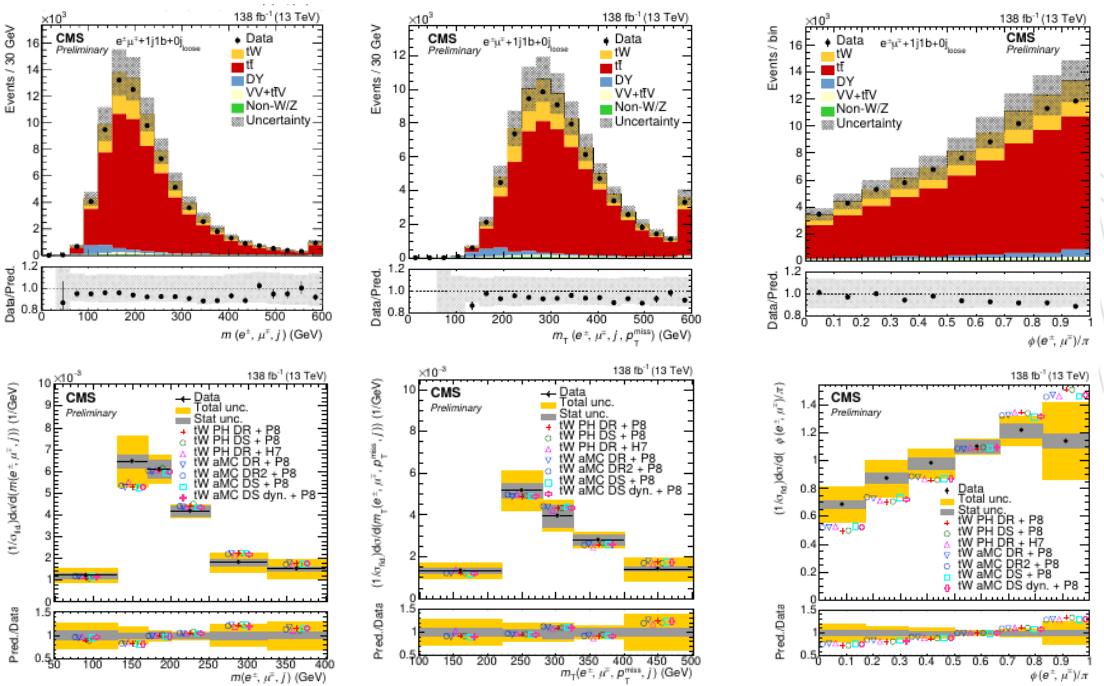
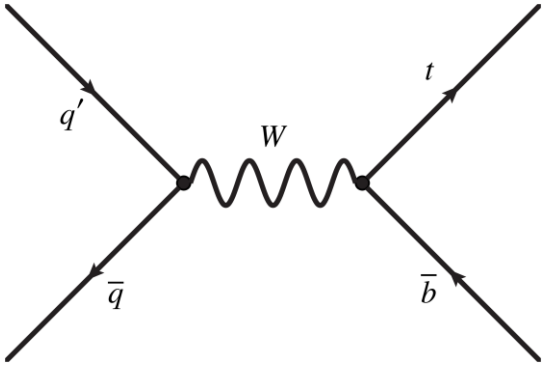


s-channel production



Hunt for s-channel production at LHC

- Only observed at the Tevatron (due to valence antiquarks)
- Smallest cross section of single top production channels
- Single top production channel with least distinctive features
- $t\bar{t}$ cross section grows steeper with $\sqrt{s}$ compared to s-channel (~3/2)
- Swamped by large $t\bar{t}$ and ***W*+jets** background

- Up to now **no 13 TeV results**!
  Presented for **first time today**!

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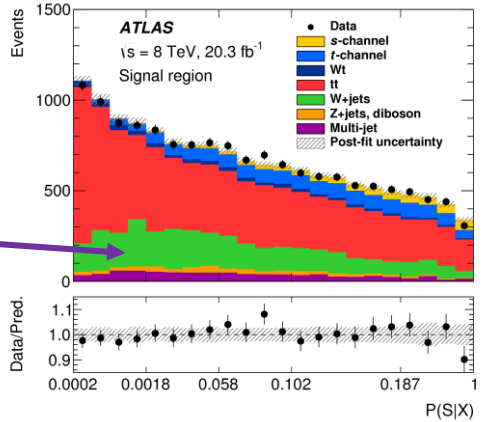
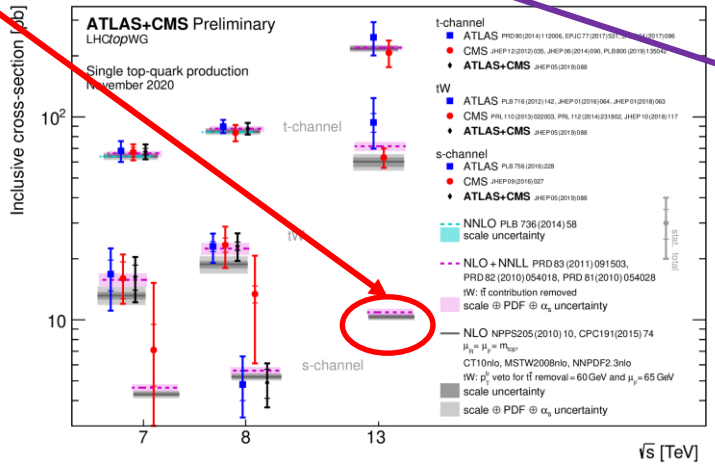


CMS@7 TeV&8 TeV:

- σ(7TeV) = 7.1±8.1 pb
- σ(8TeV) = 13.4±7.3 pb
- Significance:
  2.5(1.1)σ obs.(exp.)

ATLAS@8 TeV:

- $\sigma = 4.8^{+1.8}_{-1.6}$ pb
- Significance:
  3.2(3.9)σ obs.(exp.)



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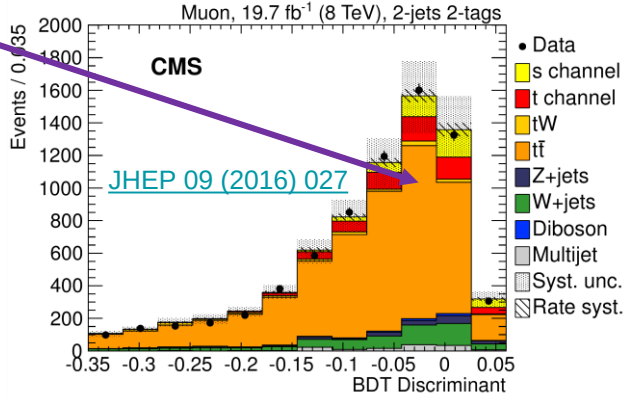
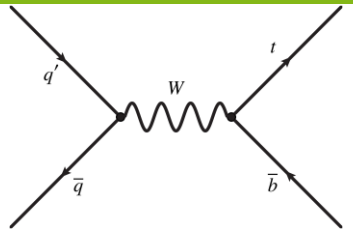


Measurement of s-channel at 13 TeV

Common preselection

- =1e/μ with p_{T} > 30 GeV
- $E_{\mathrm{T}}^{\mathrm{miss}}$ > 35 GeV & $m_{\mathrm{T}}(W)$ > 30 GeV
- =2 jets with p_{T} > 25 GeV & |η| < 2.5



Process	Event yield Pre-fit	Post-fit
s-channel	4 200 ± 710	3 700 ± 1 100
t-channel	13 000 ± 2 000	15 000 ± 2 300
tW	3 680 ± 970	4 250 ± 1 100
$t\bar{t}$	76 000 ± 12 000	70 600 ± 4 200
W+jets	21 500 ± 2 900	32 200 ± 5 000
Z+jets, VV	2 400 ± 1 400	2 900 ± 1 600
Multijet	2 150 ± 650	1 700 ± 540
Total	123 000 ± 17 000	130 310 ± 620
Data	130 310	

Signal Region

- =2 central jets with p_{T} > 30 GeV & ≥1 jet with p_{T} > 40 GeV
- =2 jets passing 77% b-tagging WP
- Veto events with:
  - additional jets with 20 GeV < p_{T} < 30 GeV or |η| > 2.5
  - additional leptons with 10 GeV < p_{T} < 30 GeV

New!

S/B = ~3%
Decreased with respect to 8 TeV
$t\bar{t}$ = 55% (64%)
W+jets = 18% (25%)

$t\bar{t}$ VRs

- =3/4 central jets with p_{T} > 25 GeV
- =2 jets passing 77% b-tagging WP

W+Jets VR

- =2 central jets with p_{T} > 30 GeV
- =2 jets passing 85% b-tagging WP
- ≥1 jet fails 77% b-tagging WP
- Veto events with additional leptons

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Multijet estimation

Jet-electron method

- Jets from dijet sample with high EM energy fraction as electrons passing quality criteria
- b-tagging criteria are dropped

Anti-muon method

- Data with inverted/changed ID requirements

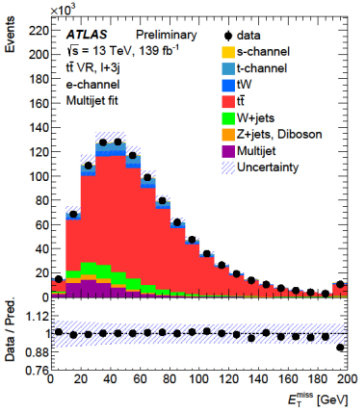
shape

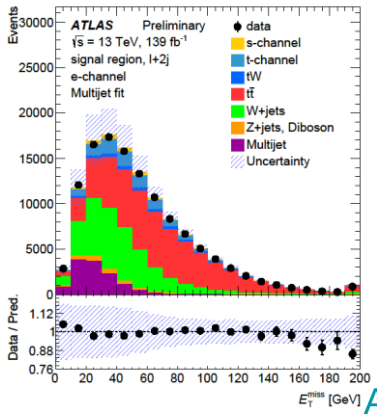
Simultaneous fit to e/μ-channel

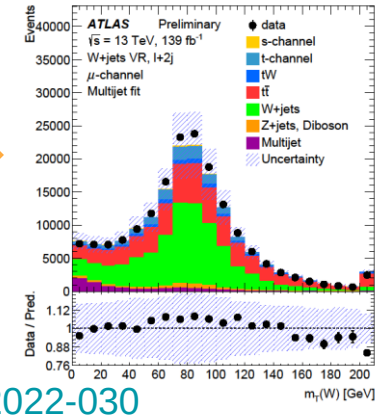
- Fit to $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in e-channel (w/o $E_{\mathrm{T}}^{\mathrm{miss}}$ cut)
- Fit to $m_{\mathrm{T}}(W)$ distribution in μ-channel (w/o $m_{\mathrm{T}}(W)$ cut)

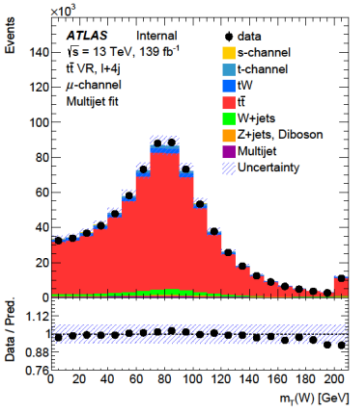
shape

norm









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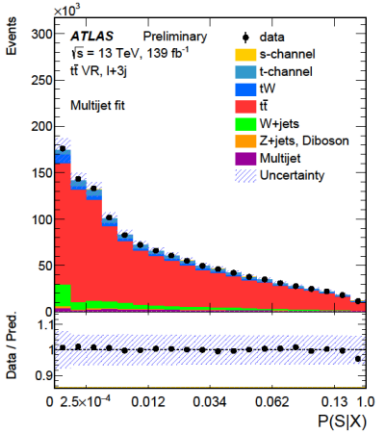
Matrix Element Method

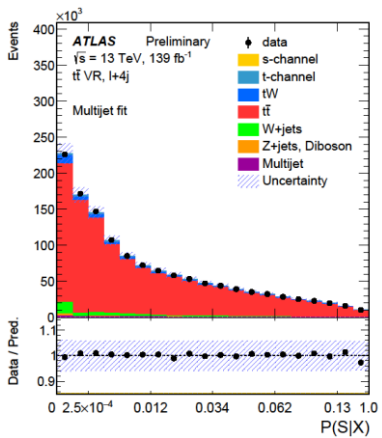
- Build event-by-event likelihood for hypothesis that final state X is obtained from process H_{proc}

$$\mathcal{P}(X \mid H_{\text{proc}}) = \int \mathrm{d}\Phi \frac{1}{\sigma_{H_{\text{proc}}}} \frac{\mathrm{d}\sigma_{H_{\text{proc}}}}{\mathrm{d}\Phi} T_{H_{\text{proc}}}(X \mid \Phi)$$

Normalised fully differential partonic cross section

Transfer functions:
- Detector resolution
- Reconstruction & b-tagging effs
- Reco ⟺ parton permutations





Build MEM discriminant with Bayes theorem

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

8 processes considered (2 S_i+ 6 B_j)

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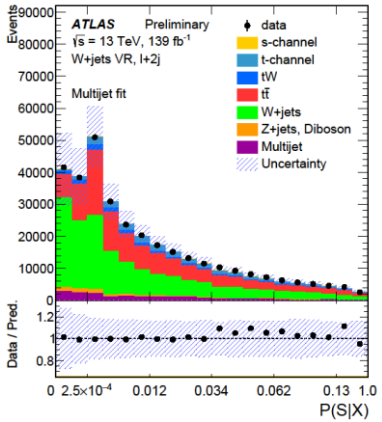


- s-channel with 2/3 final state partons
- t-channel with 3 final state partons
- $t\bar{t}$ single lepton&dilepton
- W+2light/2b/1c+1light partons

Results

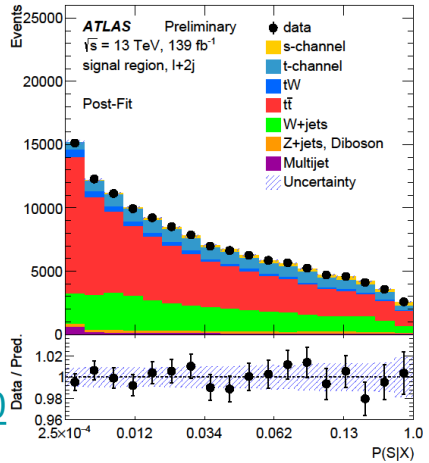
Source	$\Delta\sigma/\sigma$ [%]
$t\bar{t}$ normalisation	$+24/-17$
Jet energy resolution	$+18/-12$
Jet energy scale	$+18/-13$
Other s-channel modelling sources	$+18/-8$
Top-quark processes ISR/FSR	$+13/-11$
MC statistics	$+13/-11$
Other $t\bar{t}$ shape modelling sources	$+12/-10$
Flavour tagging	$+12/-10$
W+jets normalisation	$+11/-8$
Top-quark processes PDFs	$+10/-9$
W+jets μ_R/μ_F shape	$+6/-5$
Other processes normalisation	$+6/-5$
Pileup	$+5/-3$
Other t-channel modelling sources	±5
Luminosity	$+4/-3$
Other tW modelling sources	$+1/-2$
Missing transverse energy	±1
Multijet shape modelling	±1
Other sources	<1
Systematic uncertainties	$+42/-34$
Data statistics	±8
Total	$+42/-35$

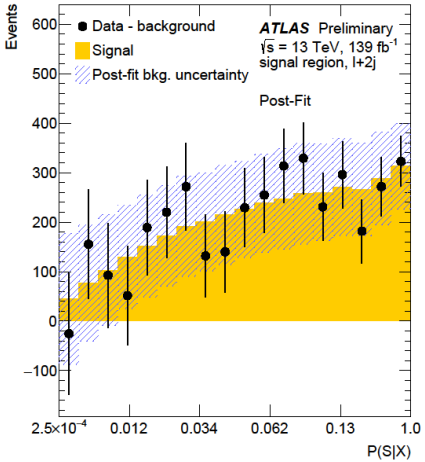
Signal extraction

- Binned profile likelihood fit to signal region
- Normalization of $t\bar{t}$, W+jets & s-channel free floating
- $\sigma_{\text{meas.}} = 8.2 \pm 0.6(\text{stat.})^{+3.4}_{-2.8}(\text{syst.})\text{pb}$ ($\sigma_{\text{pred.}} = 10.32^{+0.40}_{-0.36}\text{pb}$)
- Significance: 3.3(3.9)σ obs.(exp.) [3.2(3.9)σ obs.(exp.) @8TeV]

- Dominated by **systematics**
- **No single culprit**

Data-Background





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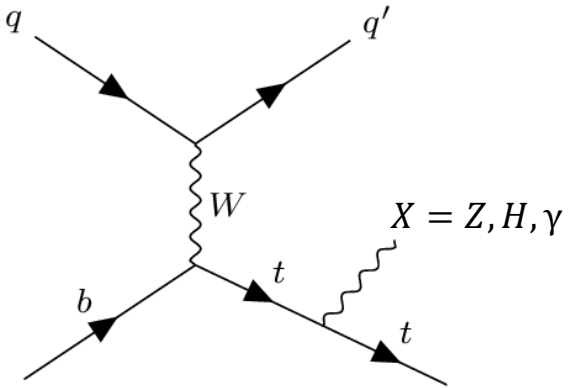
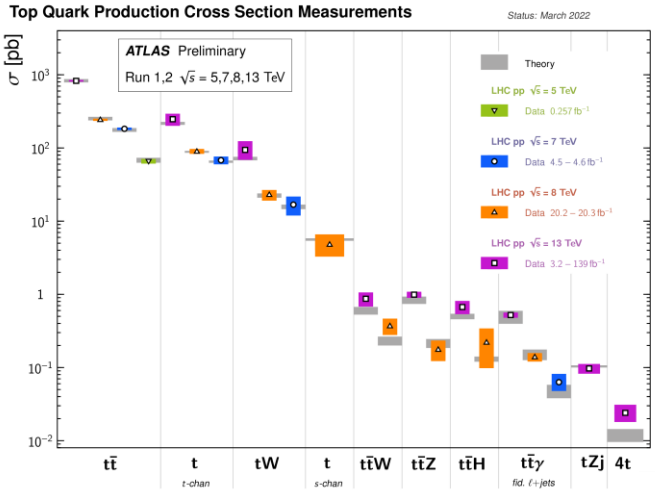
Associated production



$t\bar{t}H/tH$ production:
Talk by Angela Giraldi (CMS)
Talk by Luisa Carvalho (ATLAS)

$t\bar{t}X/tX$ production:
Talk by Carlos Vico Villalba (CMS)
Talk by Kenneth Johns (ATLAS)

Associated single top quark production



- Associated production observed/searched for (mostly) in *t*-channel topology
- Probe the top quark couplings to EW bosons and study rare SM processes
- ***tZq*** observed by both collaborations:
  Measured inclusively by ATLAS & inclusively+differentially by CMS

t-channel prod. with a photon ***(tqγ)***:

- Evidence of 4.4σ reported by CMS with 2016 data using μ-channel
- Observed recently by ATLAS with full Run 2 (**today!**)

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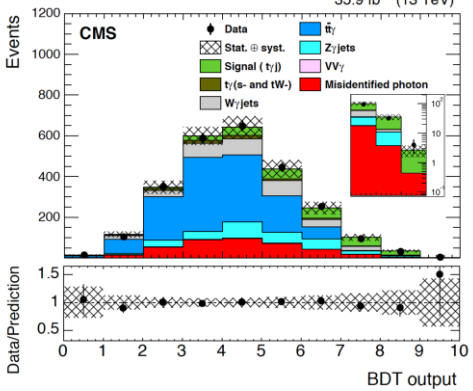

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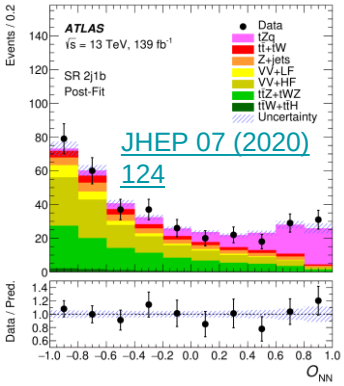

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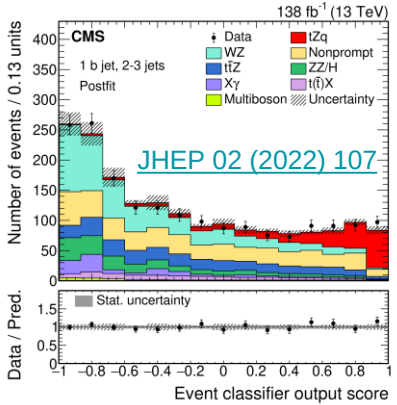
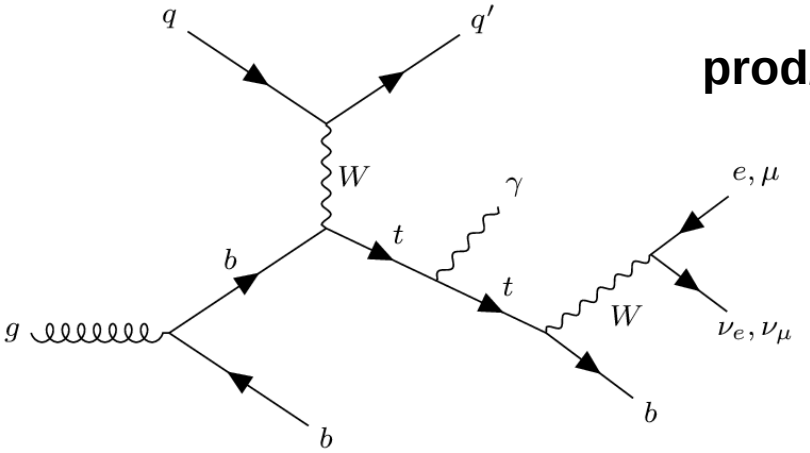


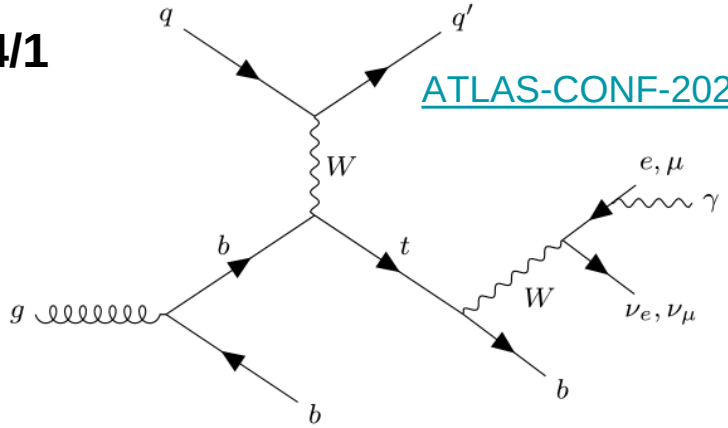
Observation of *tqγ* at 13 TeV

γ in production (*tqγ*)



prod/dec = 4/1

γ in decay (*t(->lvbγ)q)*



ATLAS-CONF-2022-013

- Modelled by aMC@NLO+Pythia8
- Sensitive to **top-photon** coupling
- Parton level fiducial cross section:

$$p_T^{\gamma} > 20\,\text{GeV},\ \Delta R(X,\gamma) > 0.4,\ |\eta^{\gamma(l)}| < 2.37(2.5)$$

$$\sigma_{\text{MC gen}} = 406^{+25}_{-32}\,\text{fb}$$

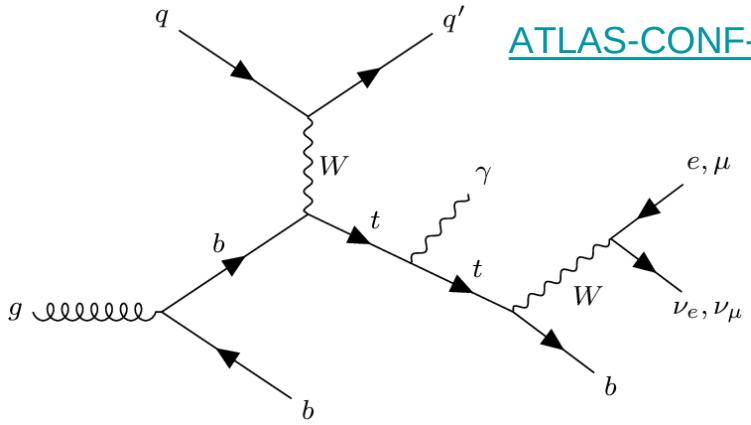
- Inclusive *t*-channel production with Powheg+Pythia8
- Photon radiation modelled by Pythia8
- Selecting events passing radiative decay hypothesis using particle level information:

$$|\Delta(m_{bl\nu\gamma} - m_t)| < |\Delta(m_{bl\nu} - m_t)|$$

or

$$|\Delta(m_{l\nu\gamma} - m_W)| < |\Delta(m_{l\nu} - m_W)|$$

Event selection & categorization

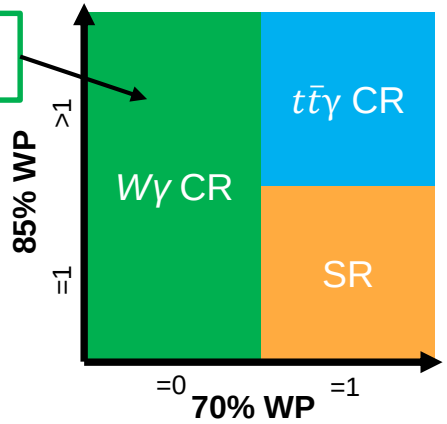


ATLAS-CONF-2022-013

Signal region

- =1 central isolated and well identified e/μ
- ≥1 central, isolated & well identified γ with p_T> 20 GeV
- E_T^{miss} > 30 GeV
- =1 jets passing 70% b-tagging WP
- no additional jets passing 85% b-tagging WP
- Veto 80 GeV < $m_{e\gamma}$ < 100 GeV
- Event categorization in signal region by presence of forward jets with p_T > 25 GeV & |η| > 2.5

As single bin



	≥ 1fj SR	0fj SR
$tq\gamma$	2390 ± 260	2480 ± 320
$t(\to \ell\nu b\gamma)\,q$	360 ± 150	460 ± 240
$t\bar{t}\gamma$ (production)	3100 ± 400	4800 ± 700
$t\bar{t}\gamma$ (radiative decay)	3800 ± 600	9300 ± 1400
$W\gamma$+jets	2500 ± 400	9300 ± 1300
$Z\gamma$+jets	990 ± 310	2800 ± 800
$e \to \gamma$ fake photons	5200 ± 500	10 300 ± 800
$h \to \gamma$ fake photons	1100 ± 400	2700 ± 800
Other prompt γ	1360 ± 350	2600 ± 900
Fake leptons	350 ± 170	900 ± 400
Total	21 250 ± 150	45 720 ± 240
Data	21 227	45 723

Data-driven estimations

Signal and background discrimination

- Neural networks (NN) trained separately in both SRs

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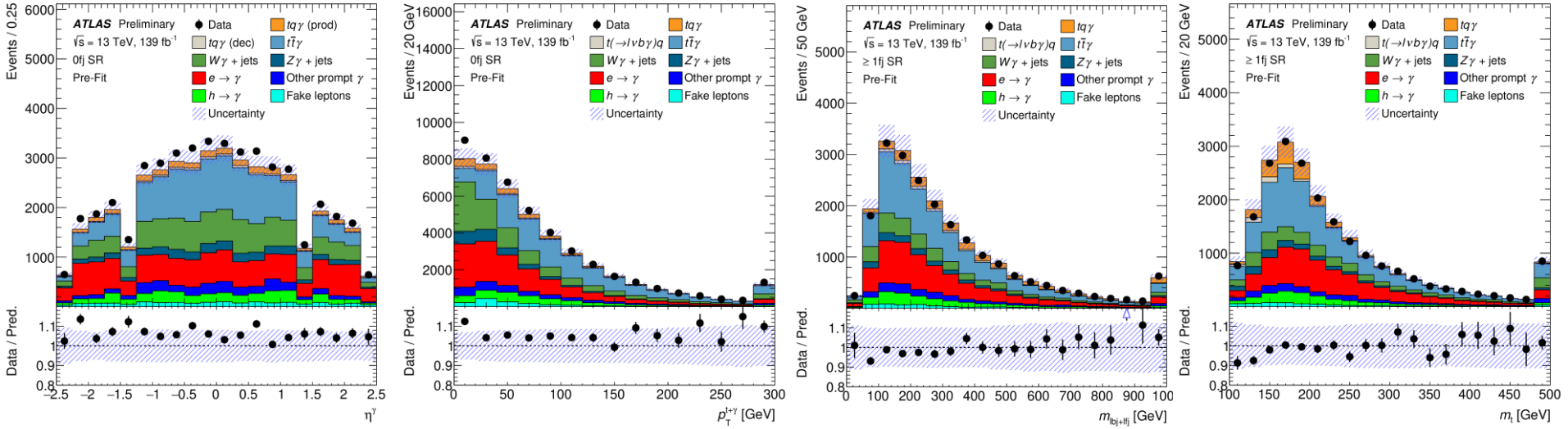
- Input features (12 in 0fj SR, 15 in ≥1fj SR):
  - Four-vector components (p_{T}, η, ϕ) of final state objects & $p_{\mathrm{T}}^{\mathrm{miss}}$ & combinations of these
  - b-tagging properties
- Shapes of input features are well modelled in data



Results

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modelling	±5.6%
Background MC statistics	±3.5%
$t\bar{t}$ modelling	±3.4%
$tq\gamma$ MC statistics	±3.4%
$t(\to \ell\nu b\gamma)\,q$ modelling	±1.9%
Additional background uncertainties	±1.9%
$tq\gamma$ modelling	±1.8%
$t(\to \ell\nu b\gamma)\,q$ MC statistics	±0.3%
Lepton fakes	±2.2%
$h \to \gamma$ photon fakes	±2.2%
$e \to \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.2%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±4.0%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.8%
Total systematic uncertainty	±10.9%

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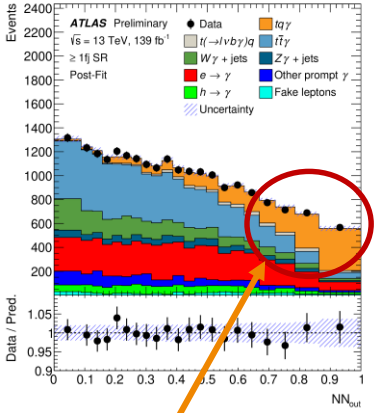
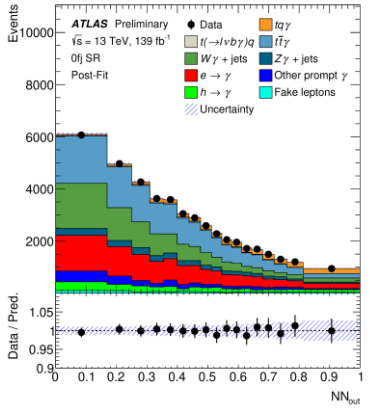
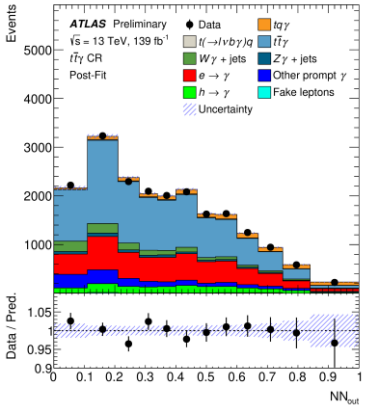


Signal clearly visible





- Binned profile likelihood fit to NN output
- Normalization of $t\bar{t}\gamma$, $W\gamma$+jets, $tq\gamma$ floating

Observation of $tq\gamma$ with 9.1σ (6.7σ exp.)

- Extrapolation to parton level fiducial phase space (**signal = prod**):

$\sigma_{tq\gamma} \times B(t \to l\nu b) = 580 \pm 19(\mathrm{stat.})^{+65}_{-62}(\mathrm{syst.})$ fb $\sigma_{\mathrm{MC\,gen}} = 406^{+25}_{-32}$ fb

  - Useful for comparison to fixed-order calculations & EFT interpretations

- Extrapolation to particle level fiducial phase space (**signal = prod+dec**):

$\sigma_{tq\gamma} \times B(t \to l\nu b) + \sigma_{t(\to l\nu b\gamma)q} = 287 \pm 8(\mathrm{stat.})^{+32}_{-31}(\mathrm{syst.})$ fb $\sigma_{\mathrm{MC\,gen+PS}} = 207^{+26}_{-11}$ fb

Conclusions

- Measurements of *tW* production now also established in single lepton channel
  - Observation reported by CMS at 13 TeV
- New inclusive & differential measurement of *tW* production in eμ-channel from CMS
  - Inclusive cross section measurement reaches precision of 11%
  - Differential cross section measurements at particle level with precisions between 10-50%
- The hunt for *s*-channel production at the LHC continues
  - New ATLAS result at 13 TeV agrees well with SM prediction
  - Significance: 3.3(3.9)σ obs.(exp.)
- ATLAS observed *t*-channel production in association with a photon
  - Parton level fiducial cross section measurement input for comparison with fixed-order calculations & EFT interpretations
- All results are limited by systematic uncertainties