Top quark measurements at $\sqrt{s} = 5.02$ TeV by the CMS experiment

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Valencia

CMS

CERN

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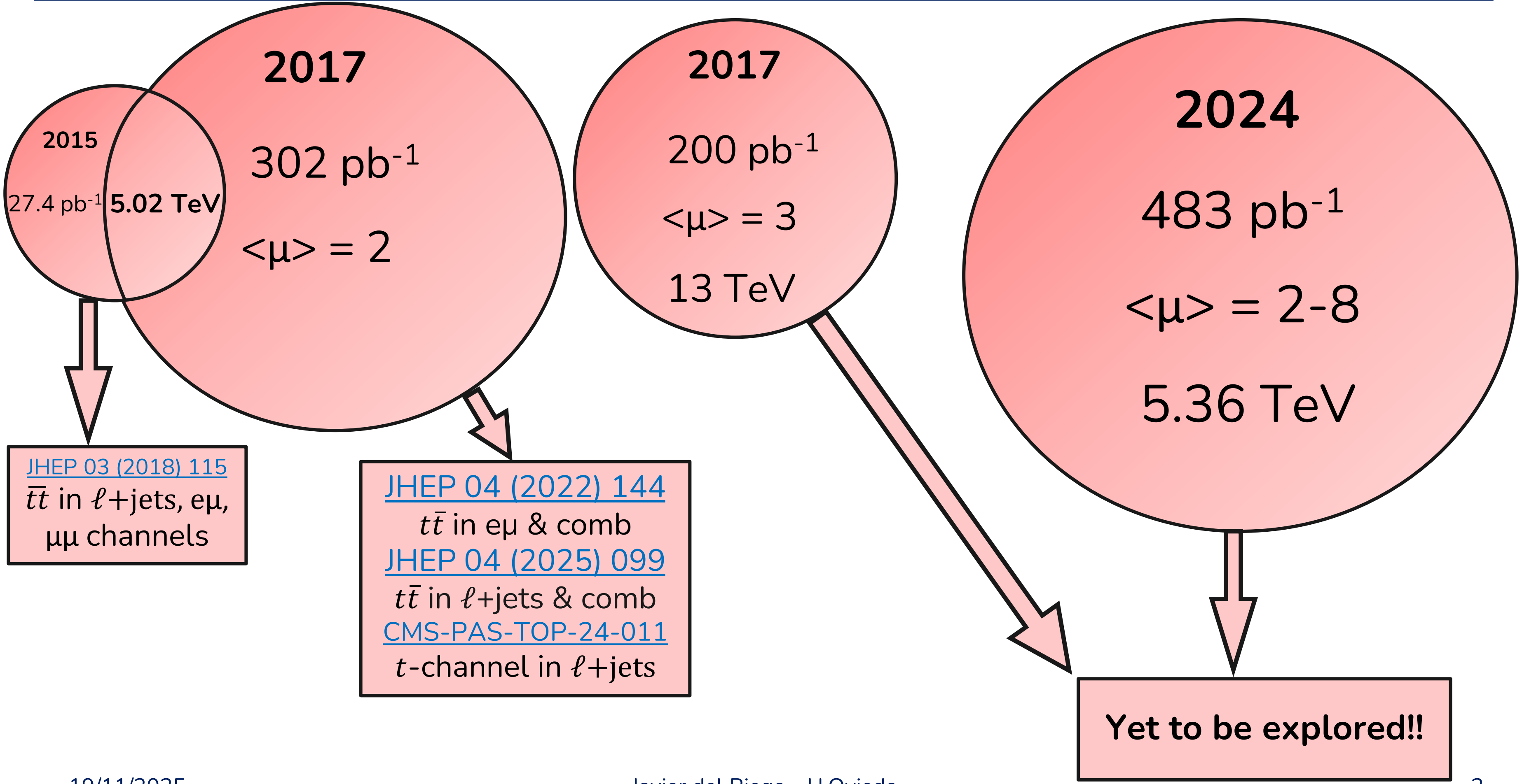
Top production at low pile up (CMS)



Top production at low pile up (CMS)

2015

27.4 pb^{-1} 5.02 TeV

2017

302 pb^{-1}

<μ> = 2

2017

200 pb^{-1}

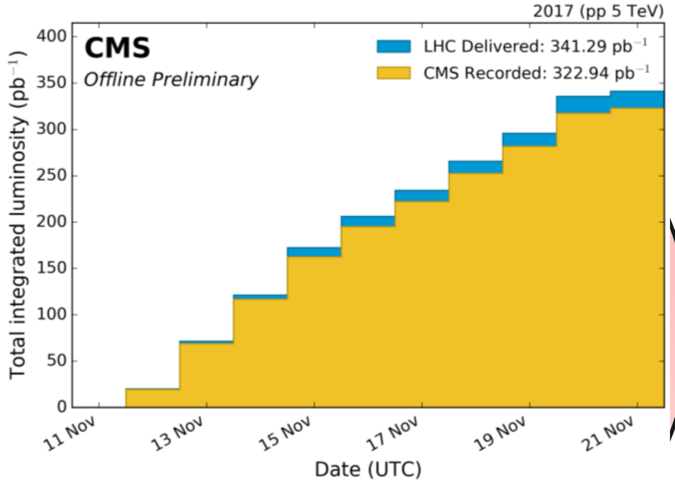
<μ> = 3

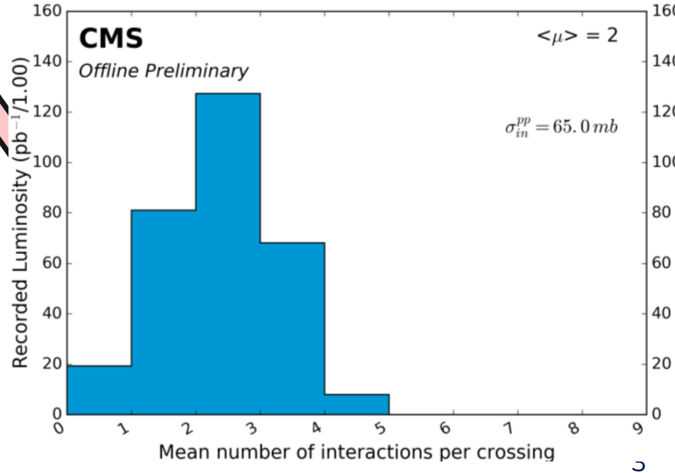
13 TeV

JHEP 05 (2018) 115
$t\bar{t}$ in ℓ+jets, eμ, μμ channels

JHEP 04 (2022) 144
$t\bar{t}$ in eμ & comb

JHEP 04 (2025) 099
$t\bar{t}$ in ℓ+jets & comb
CMS-PAS-TOP-24-011
t-channel in ℓ+jets





Overview

- **Low pileup** runs offer very good opportunities for measurements at the LHC. Important as **reference** for **heavy ion** analyses, but also as SM **stress tests**

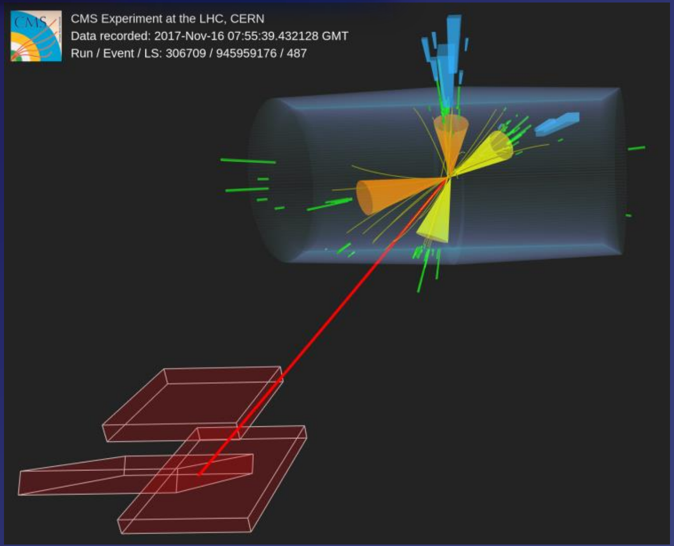
- Their clean environment allow for **very precise measurements** with low luminosity. Especially with **dedicated object studies**.

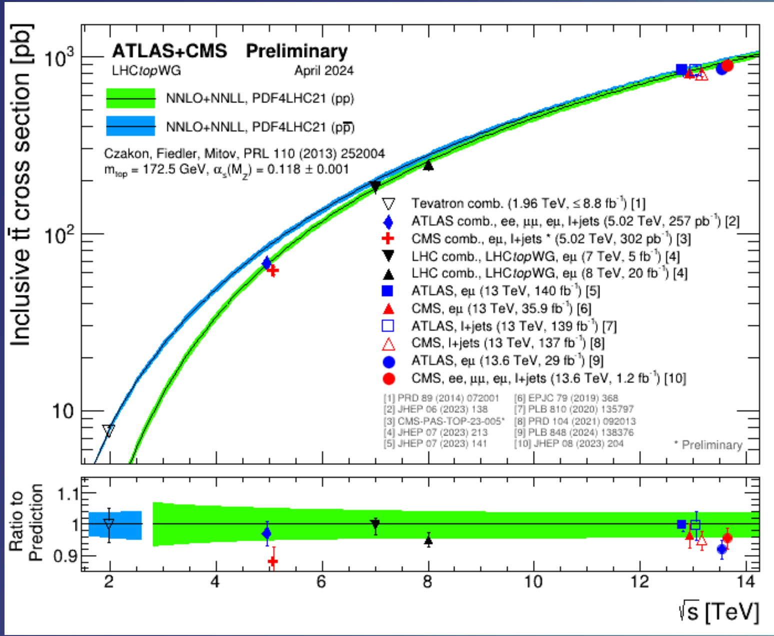
- This talk covers **recent** measurements by the **CMS experiment**, in the **top sector** and using a dataset of **302 pb^{-1}** from **2017**, at $\sqrt{s} = 5.02$ **TeV** and mean PU of 2 int./crossing

  - $t\bar{t}$ measurement (JHEP 04 (2025) 099)
    - Most precise CMS measurement of $\bar{t}t$ at that energy
    - Published in JHEP last April

- t-channel measurement (CMS-PAS-TOP-24-011)
  - First CMS measurement of t-channel at that energy
  - To be submitted soon to journal

$t\bar{t}$ measurement





Motivation

Goal: measure the $t\bar{t}$ **cross section at 5.02 TeV** in the semileptonic final state with the 2017 data 302 pb^{-1}

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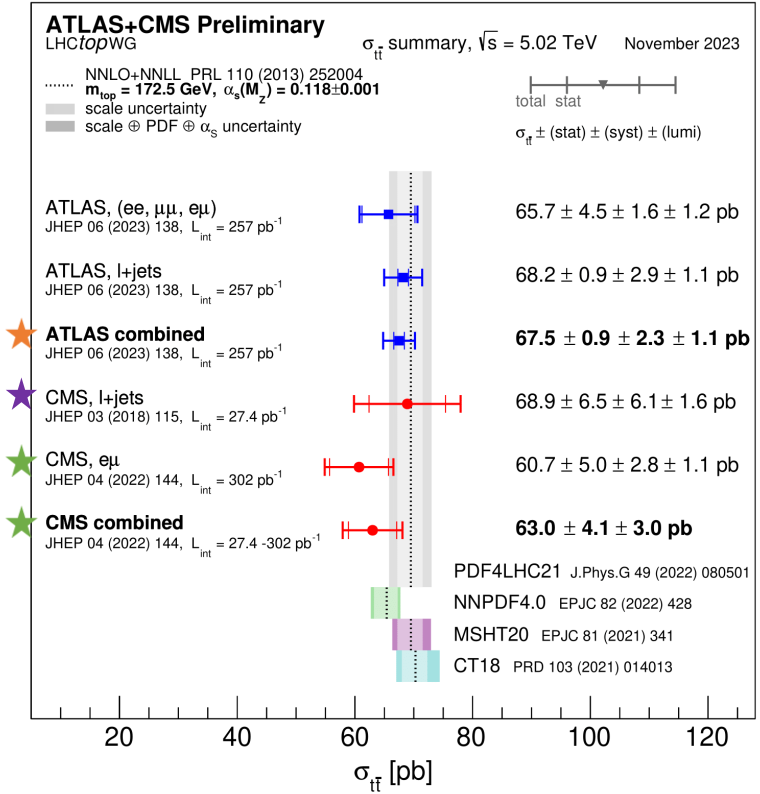
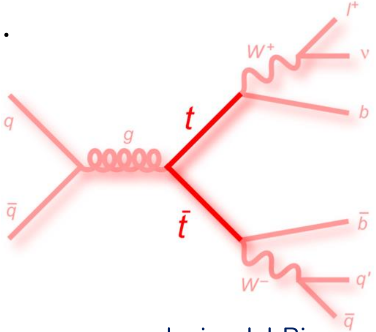
- **Previous measurements** overview:
  - [JHEP 03 (2018) 115](#) : 27 pb^{-1} (2015 data). Statistically dominated. Total uncertainty: 12%.
  - [JHEP 04 (2022) 144](#) : 302 pb^{-1}. Uncertainty still dominated by statistics. **Combined with ℓ+jets from 2015**. Total uncertainty: 8%.
  - [JHEP 06 (2023) 138](#) (ATLAS): Combination **dilepton+single lepton** using the 2017 dataset. Uncertainty: 4%.

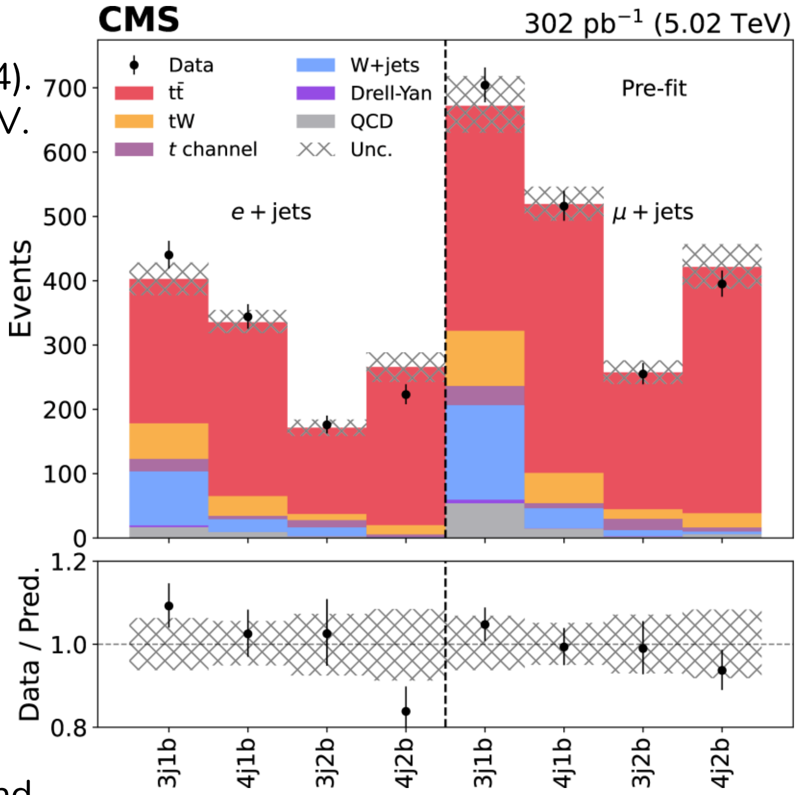


- This analysis combines ℓ+jets with dilepton final states



Event Selection

- **Exactly 1 lepton (electron or muon)** ($p_T > 20$ GeV, $|\eta| < 2.4$). Veto on sub-leading lepton of opposite flavour, $p_T > 10$ GeV.
- **At least 3 jets** ($p_T > 25$ GeV, $|\eta| < 2.4$).
- **MET > 30 GeV.**
- Events are further categorized into **8 categories** depending on the **number of jets and b-tagged jets, and the lepton flavour** (electron or muon). Among those:
  - All are signal-dominated
  - $\ell + 3j \geq 2b$ and $\ell + 4j \geq 2b$ are purest in signal (89% of total MC)
  - $\ell + 3j1b$ provide the greatest contribution from tW and W+jets backgrounds (12% and 18% of total MC)



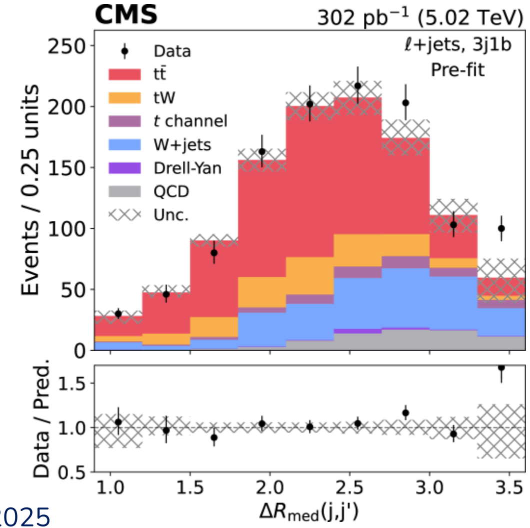
- **4 main backgrounds: Single top** (**tW + t-channel**), **W+jets**, **QCD multijets** (cut in **MET > 30GeV** to suppress it, estimated from data) and **Drell-Yan.**

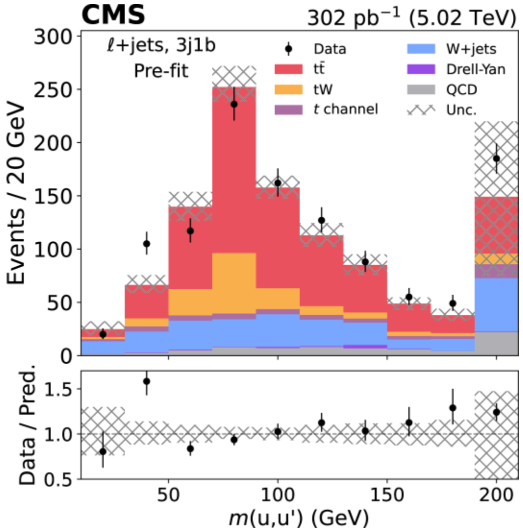
Analysis Strategy

- Different observables were tested: m_T , m(j,j’), ΔR(j, j’), m(b,ℓ)…
- Finally, **median(ΔR(j, j’))** shape is used in the fits in every region expect the **3j1b category**, where an **MVA** is trained to further separate $t\bar{t}$ from W+jets.

Analysis Strategy

- Different observables were tested: m_T , m(j,j'), ΔR(j, j'), m(b,ℓ)...
- Finally, **median(ΔR(j, j'))** shape is used in the fits in every region expect the **3j1b category**, where an **MVA** is trained to further separate $t\bar{t}$ from W+jets.
- **MVA details:**
  - Model: random forest trained with Sklearn. 500 trees with max depth 6.
  - Signal: $t\bar{t}$ sample. Background: W+jets sample.
  - Division of samples: 70% for train and 30% for test
  - 8 input variables: median ΔR(j, j'), m(u,u'), ΔR(u,u'), min m(j,j'), m(b,ℓ), H_T, ΔR(b,ℓ), $j_0 p_t$.





Uncertainties

- **Experimental**
  - Lepton efficiencies
  - Trigger efficiencies
  - B-tagging: light (udsg) and heavy (bc).
  - L1 Prefiring
  - JEC and JER (13 sources)
  - Unclustered energy.
  - Stat. unc. from limited size of the MC samples

Dedicated samples

- **$\bar{t}t$ modelling**
  - ISR/FSR: vary PS scales by 2, 0.5 factors
  - Underlying event: vary CP5 tuning → Normalization
  - ME/PS matching: vary h_{damp} of Powheg
  - ME scales: μ_F and μ_R scales by factors of 0.5 and 2
  - PDFs and α_S: 100+2 sources

ΔR/MVA shape

Nj/Nb shape

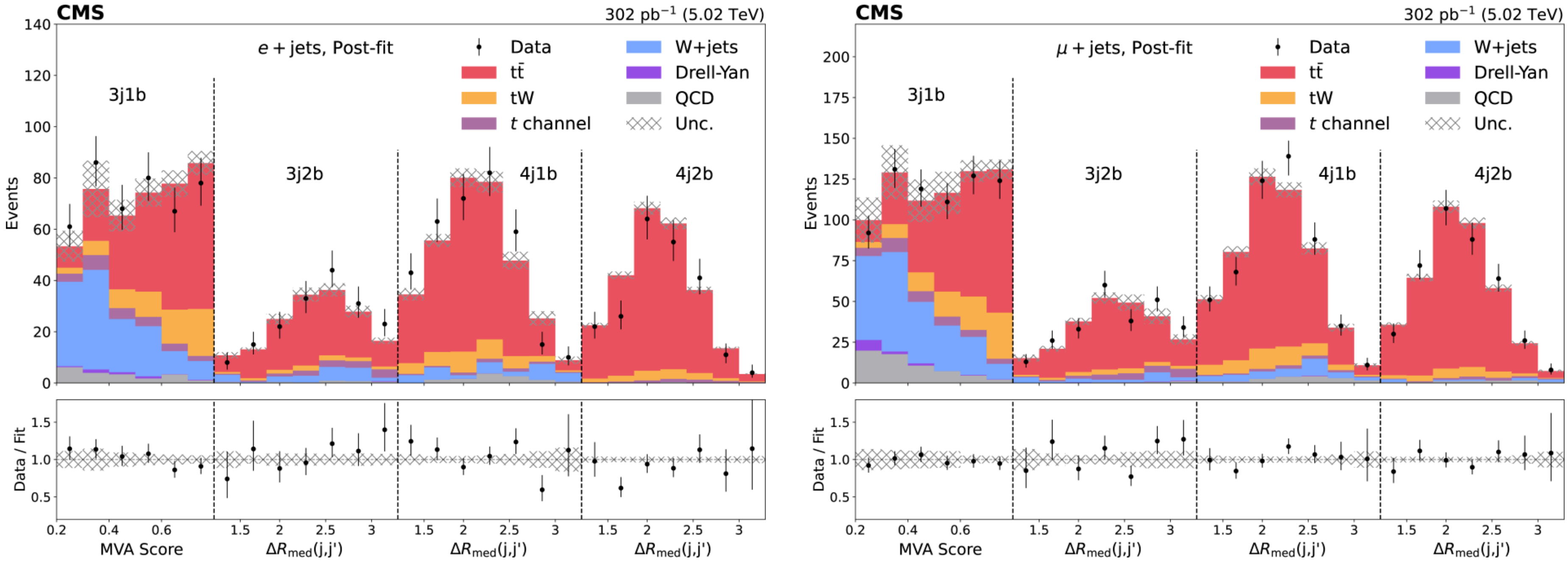
- **Normalization**
  - Background normalization -> QCD: stat+30% norm, DY: 30%, W+Jets: 20%, tW: 5.6%, t channel: 10%
  - Luminosity: 1.9%

Cross Section Measurement

- Final distribution of 27 bins x 2 (e/μ) = 54 bins:

  median(ΔR(j, j')) + MVA Score (3j1b category)

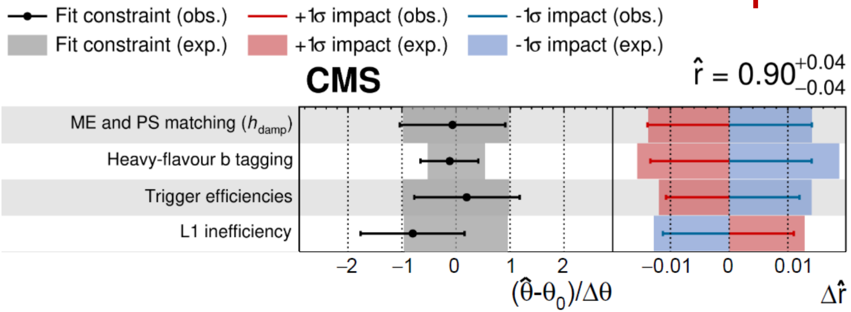
- A maximum-likelihood fit is done simultaneously to the distributions.



Observed Results

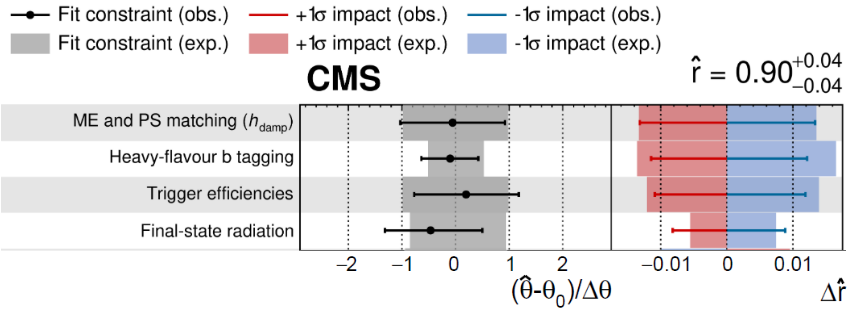
SM prediction: $\sigma_{t\bar{t}}^{SM} = 69.5^{+2.0}_{-2.3}\,(scales) \pm 2.9\,(PDFs + \alpha_S)\; pb$ LHCTopWG recomm.

ℓ+jets result



$$\sigma_{t\bar{t}} = 62.5 \pm 1.6\,(stat)^{+2.6}_{-2.5}(syst) \pm 1.2\,(lumi)\; pb$$

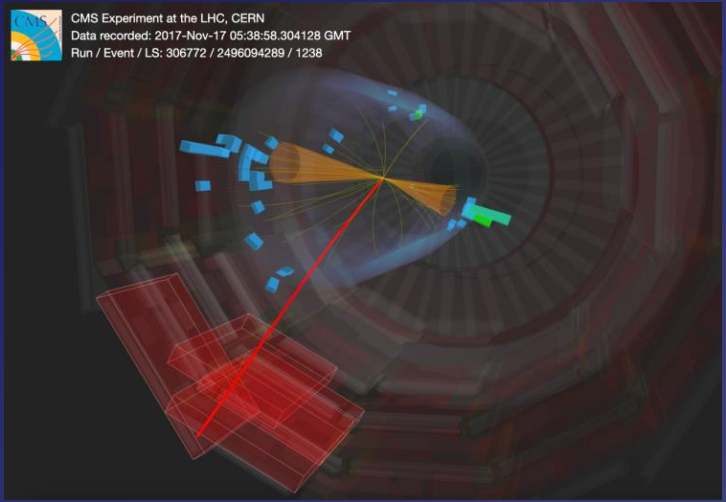
Comb. with dilep result

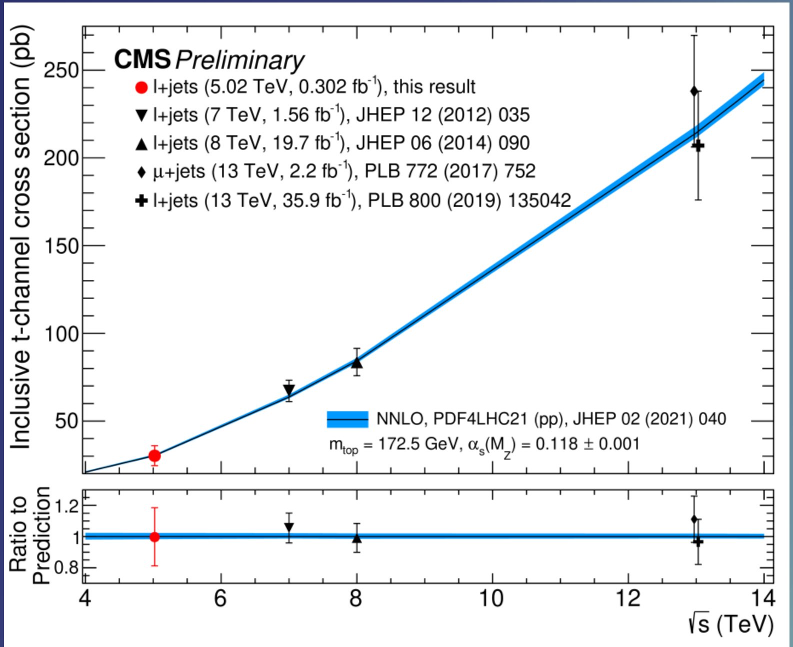


$$\sigma_{t\bar{t}} = 62.3 \pm 1.5\,(stat) \pm 2.4\,(syst) \pm 1.2\,(lumi)\; pb$$

5.5% unc -> 4.9% unc

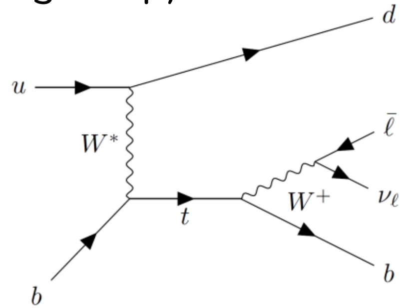
t- channel measurement





Motivation

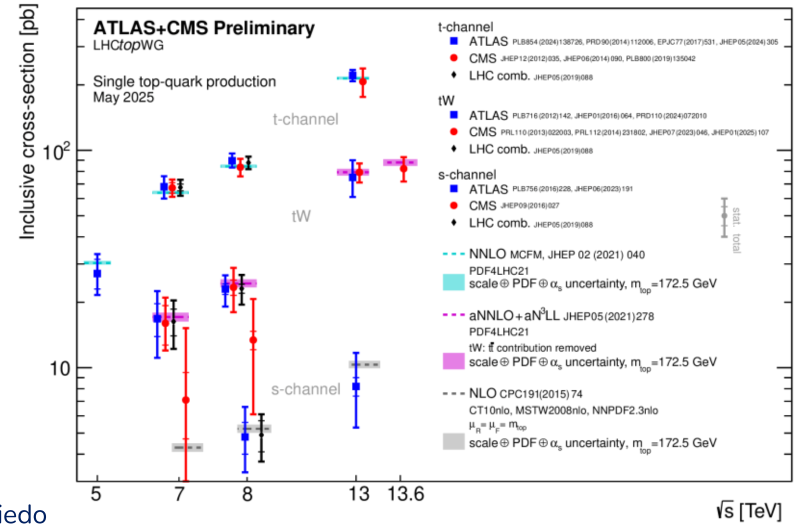
- t-channel is **dominant** single top quark production process (70% of single top).



- **Measured** at the **LHC** at different centre-of-mass energies by CMS and ATLAS:
  - 7 TeV: JHEP 12 (2012) 035 , Phys. Rev. D 90, 112006
  - 8 TeV: JHEP 06 (2014) 090 , Eur. Phys. J. C 77 (2017) 531
  - 13 TeV: Eur. Phys. J. C 80, 370 (2020) , JHEP 05 (2024) 305

- ATLAS measured it at 5.02 TeV in 2023 Phys. Lett. B 854 (2024) 138726 with a precision of 22%.

- CMS has never measured it at 5.02.



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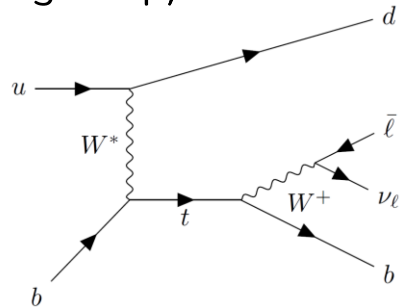

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2024) 305

Target of this part of the talk!

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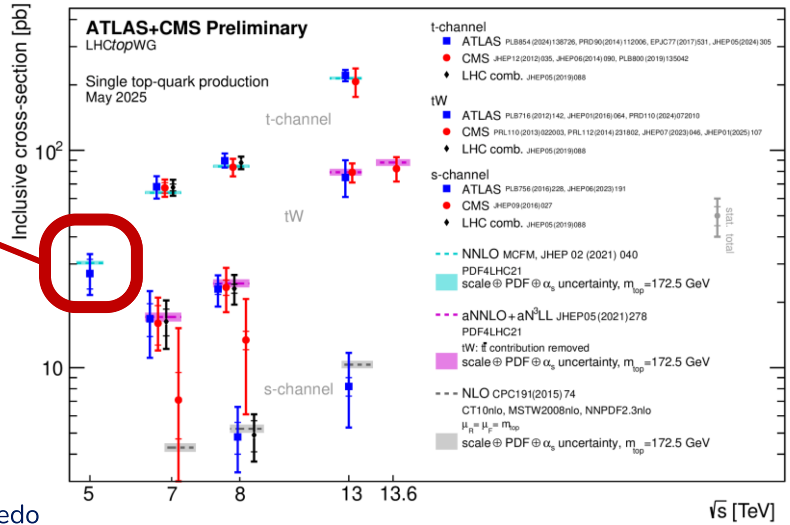


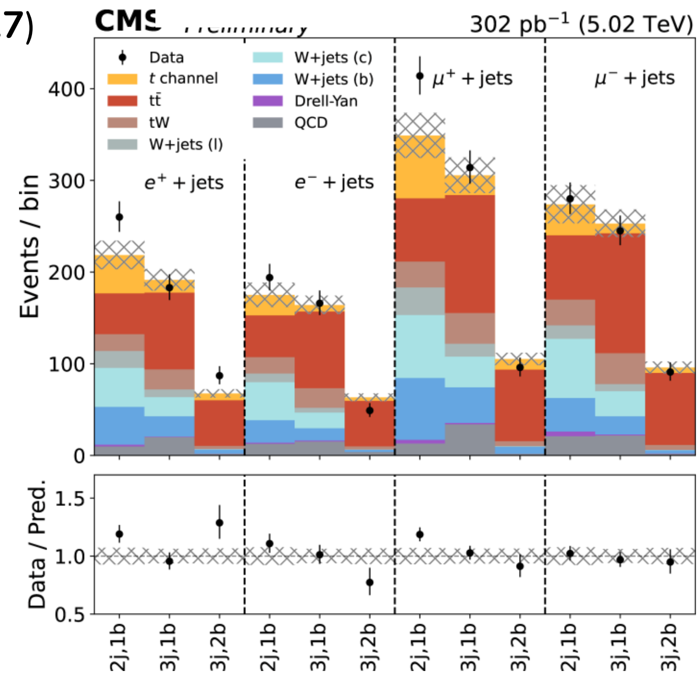
Event Selection

- **Same** objects as previous result but **jet |η|** coverage (up to **4.7**)

	1 b-tag jet	2 b-tag jets
2 jets	**Signal Region**	X
3 jets	**$t\bar{t}$ Control Region**	**$t\bar{t}$ Control Region**

× lepton flavour & charge

→ **12 categories**



Common to all:

- Exactly 1 lepton (e or mu)
- MET > 30 GeV
- MtW > 50 GeV
- $H_T{}'$ > 170 GeV (MET + jet p_T +lep p_T)

- t channel: 16%
- W+ b jets: 17%
- W + c jets: 21%
- $t\bar{t}$: 23%
- W+ light jets: 7%
- tW: 9%
- Drell-Yan: 2%
- QCD: data-driven 5%

Analysis Strategy

- Targeting the measurements of $\sigma(tq+\bar{t}q)$, $\sigma(tq)$, $\sigma(\bar{t}q)$ and $\mathcal{R}_{t-ch}$

- ML fits done to **MVA score/leading untagged jet's η** distributions in the ℓ+2j1b/3jNb categories of the analysis

- Three independent ML fits done
  - Single POI for extracting $\sigma(tq+\bar{t}q)$
  - 2 POIs for extracting $\sigma(tq)$, $\sigma(\bar{t}q)$
  - 2 POIs for extracting $\sigma(tq+\bar{t}q)$, $\mathcal{R}_{t-ch}$

Analysis Strategy

- Targeting the measurements of $\sigma(tq + \bar{t}q)$, $\sigma(tq)$, $\sigma(\bar{t}q)$ and $\mathcal{R}_{t-ch}$

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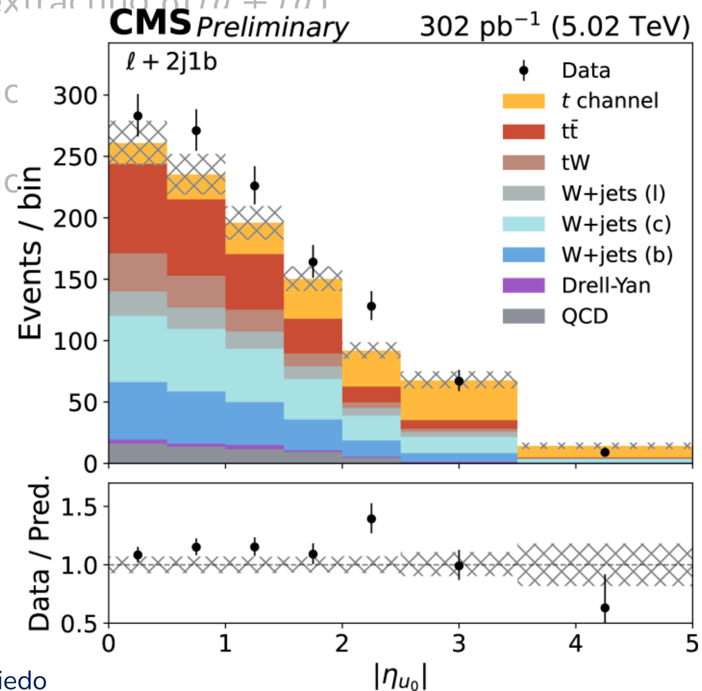
  - 2 POIs for extrac
  - 2 POIs for extrac

- **MVA details:**
  - Model: random forest trained with Sklearn.
  - Signal: t-channel. Background: W+jets & $t\bar{t}$
  - 13 input variables: $|\eta_{u0}|$, $|\Delta\eta(u_0, b_0)|$, m_T^W, m_{top},...



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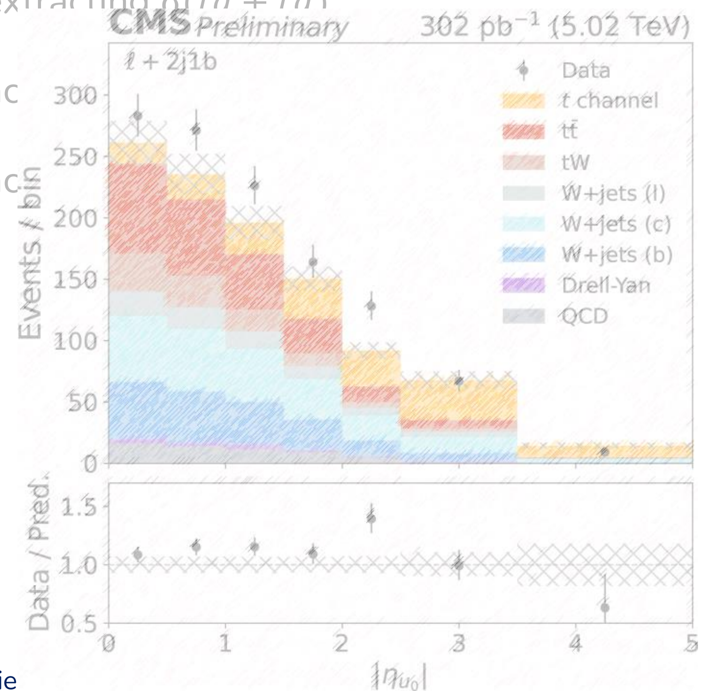
- Similar uncertainty treatment as $t\bar{t}$ analysis

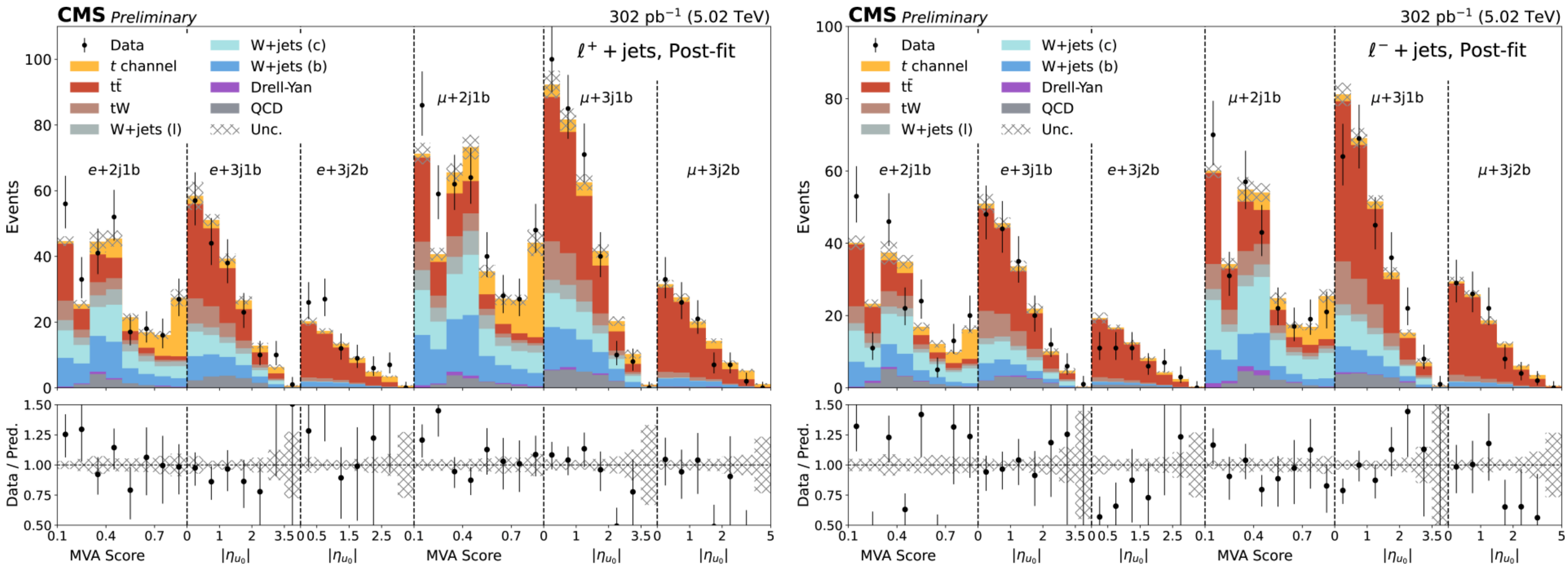


Fitted distributions

Post-fit

- Final distribution of 44 bins x 2 (ℓ^+/ ℓ^-) = 88 bins:
  MVA score (ℓ+2j1b)+ **leading untagged jet's η** (ℓ+3jMb)

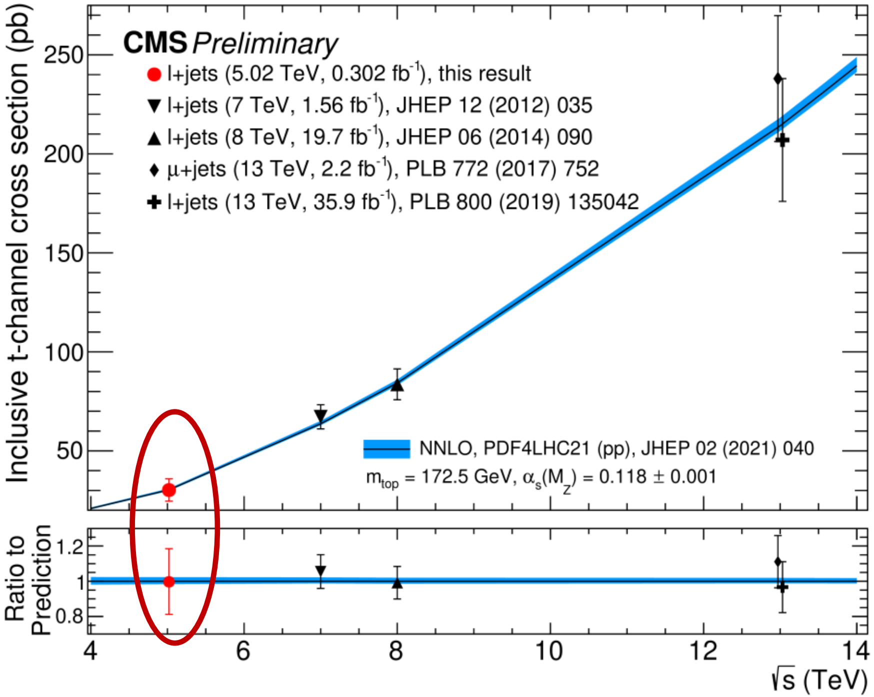
- 3 maximum-likelihood fits simultaneously to the distributions.



Observed Results: $\sigma(tq + \bar{t}q)$

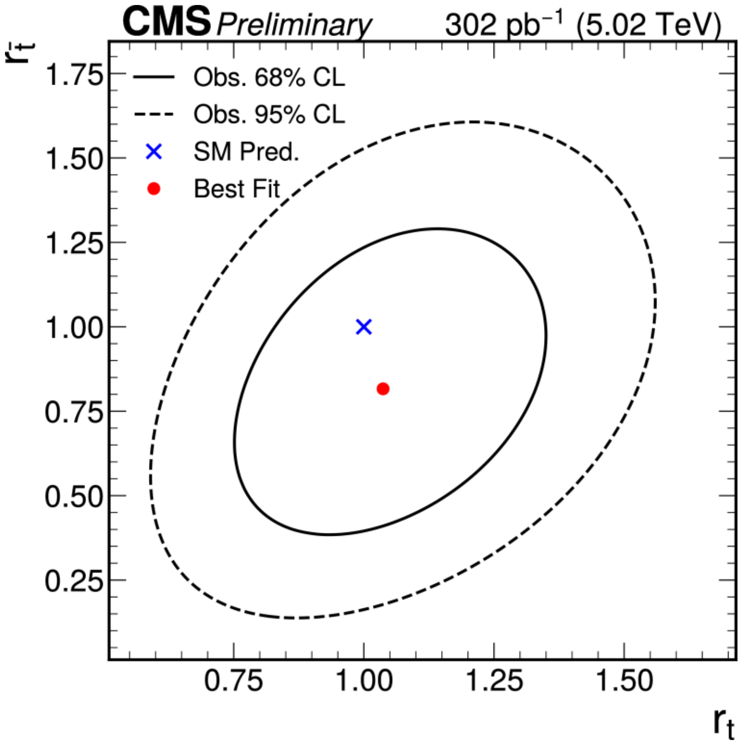
- Measured $\boxed{\sigma(tq + \bar{t}q) = 30.2^{+3.7}_{-3.6}\,(stat)^{+4.4}_{-4.2}(syst) \pm 0.6\,(lumi)\,pb}$

$\sigma(tq + \bar{t}q)^{SM} = 30.3^{+0.4}_{-0.3}\,(scales)^{+0.6}_{-0.4}\,(PDFs + \alpha_S)\,pb$ (NNLO, ref.)



- Good **agreement** with SM.
- **Systematically** dominated measurement (14% vs 12% statistical) for a total of 19%.
- **Leading uncertainties**: b tagging scale factors & W+c jets normalization.

Observed Results: $\sigma(tq), \sigma(\bar{t}q), \mathcal{R}_{t-ch}$ Pred. at NNLO (ref.)



- Measured $\sigma(tq)$:

$$\boxed{\sigma(tq) = 21.1^{+3.0}_{-2.8}\,(stat)\,^{+2.8}_{-2.7}(syst) \pm 0.4\,(lumi)\,pb}$$

$$\sigma(tq)^{SM} = 20.3^{+0.3}_{-0.2}\,(scales)^{+0.4}_{-0.3}\,(PDFs + \alpha_S)\,pb$$

- Measured $\sigma(\bar{t}q)$:

$$\boxed{\sigma(\bar{t}q) = 8.2^{+2.4}_{-2.3}\,(stat)\,^{+1.9}_{-1.8}(syst) \pm 0.2\,(lumi)\,pb}$$

$$\sigma(\bar{t}q)^{SM} = 10.0 \pm 0.1\,(scales)^{+0.3}_{-0.2}\,(PDFs + \alpha_S)\,pb$$

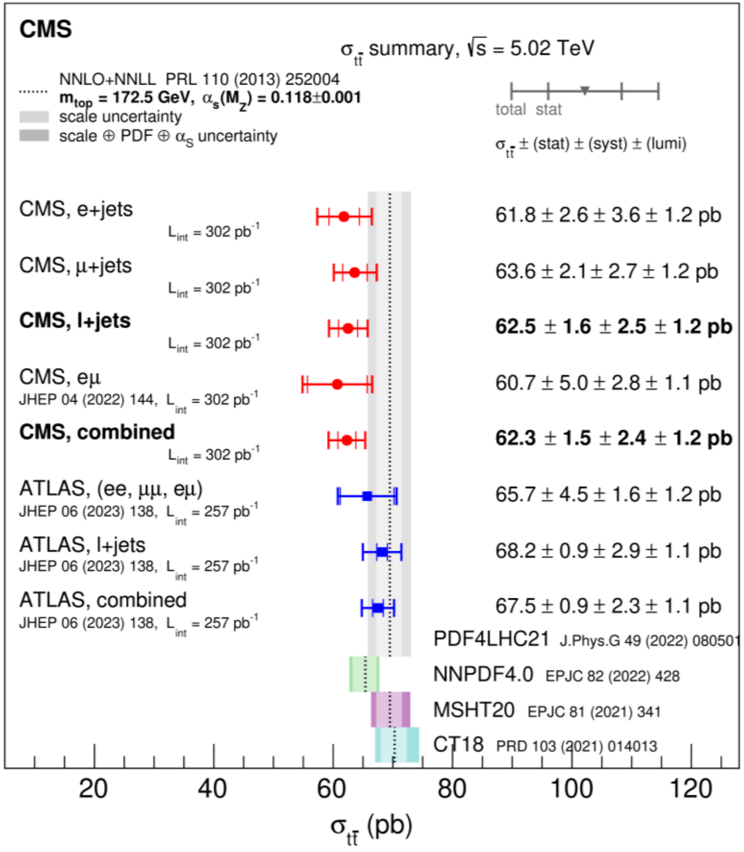
- Measured $\boxed{\mathcal{R}_{t-ch} = 2.6^{+1.1}_{-0.7}\,(stat)\,^{+0.7}_{-0.2}(syst)}$

$$\mathcal{R}_{t-ch}^{SM} = 2.03^{+0.4}_{-0.5}\,(scales + PDFs + \alpha_S)$$

Summary

Summary

- Measurements at 'not usual' CM energies serve as stress tests of theoretical predictions.
- Precision can be achieved due to cleaner scenarios in low pileup pp reference runs.
- Most precise CMS result for the $t\bar{t}$ inclusive cross section at 5.02 TeV! Means great improvement with respect to previous results:
  - previous ℓ+jets CMS result ([JHEP 03 (2018) 115]()): **13% → 5.5%.**
  - previous dilepton & ℓ+jets CMS result ([JHEP 04 (2022) 144]()): **8.4% → 4.9%.**
- Result consistent with SM prediction:



Summary

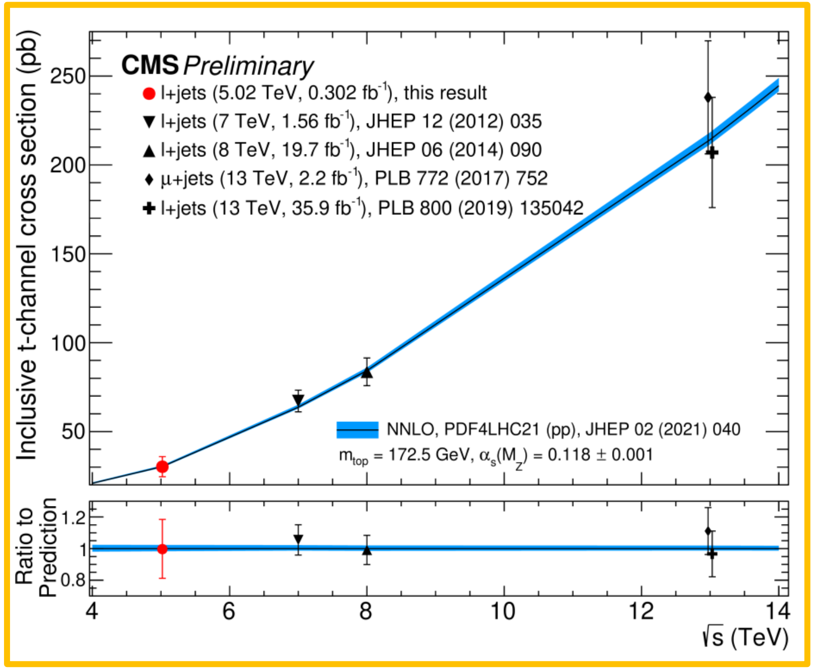
- First CMS results for the **t-channel** process at 5.02 TeV, complementing the ones performed by ATLAS ([Phys. Lett. B 854 (2024)](#)).

- Measurements on $\sigma(tq+\bar{t}q)$, $\sigma(tq)$, $\sigma(\bar{t}q)$ and $\mathcal{R}_{t-ch}$

- Results:

  - $\sigma(tq+\bar{t}q) = 30.2^{+3.7}_{-3.6}\,(stat)^{+4.4}_{-4.2}(syst) \pm 0.6\,(lumi)\,pb$
  - $\sigma(tq) = 21.1^{+3.0}_{-2.8}\,(stat)\,^{+2.8}_{-2.7}(syst) \pm 0.4\,(lumi)\,pb$
  - $\sigma(\bar{t}q) = 8.2^{+2.4}_{-2.3}\,(stat)\,^{+1.9}_{-1.8}(syst) \pm 0.2\,(lumi)\,pb$
  - $\mathcal{R}_{t-ch} = 2.6^{+1.1}_{-0.7}\,(stat)\,^{+0.7}_{-0.2}(syst)$

- Cross section measured with a **19% systematically** dominated **precision**



- Results consistent with SM prediction:

Every piece of data collected at the LHC is worth it!

Thanks for the attention!

Any question?

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SAMPLES/CORRECTIONS

- **DATA:**
  - **2017** data, for an integrated luminosity of **302 pb^{-1}**
  - Usage of **single-lepton** triggers
  - Mean number of pp interactions per bunch crossing ≈ **2 -> low PU.**

- **MC:**

Process	Generator + Parton Shower	Cross section, σ_{norm} (pb)	Order of σ_{norm} approximation
t channel	POWHEG + PYTHIA 8	30.3 ± 0.6	NNLO [13]
$t\bar{t}$	POWHEG + PYTHIA 8	69.5 ± 3.6	NNLO + NNLL [47,48]
tW	POWHEG + PYTHIA 8	6.54 ± 0.36	Approximate NNLO [44]
W+jets	MADGRAPH5_aMC@NLO + PYTHIA 8	$21\,160 \pm 330$	NNLO [QCD] + NLO [EW] [45]
DY	MADGRAPH5_aMC@NLO + PYTHIA 8	$3\,647 \pm 63$	NNLO [QCD] + NLO [EW] [45]

- **Corrections:**
  - **Lepton** (e and μ), **Trigger, B-tag SFs + JECs.**

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Summary of previous results

		Stat.	Syst.	Lumi	Total
Dilep 2015	CMS	24.7%	5.2%	2.6%	25%
Semilep 2015	CMS	9.4%	8.8%	2.3%	13.1%
Comb. dilep+semilep 2015	CMS	8.8%	8%	2.3%	12.1%
Semilep 2017	CMS	2.6%	4.4%	1.9%	5.5%
	ATLAS	1.3%	4.3%	1.6%	4.5%
Dilep 2017	CMS	8.2%	4.6%	1.9%	9.6%
	ATLAS	6.8%	2.5%	1.8%	7.5%
Comb. dilep 2017 + semilep 2015	CMS	6.5%	4.7%		8.4%
Comb. dilep + semilep 2017	CMS	2.4%	4.1%	1.9%	5.1%
	ATLAS	1.3%	3.4%	1.6%	3.9%

Comparison with ATLAS result

- **Uncertainties in l+jets analysis:**

: 1.3 (stat) +- 4.3 (syst) +- 1.6 (lumi) %

CMS: 2.6 (stat) +- 4.4 (syst) +- 1.9 (lumi) %

	$\ell+2j\ \geq 1b$	$\ell+3j\ 1b$	$\ell+3j\ 2b$	$\ell+\geq 4j\ 1b$	$\ell+4j\ 2b$	$\ell+\geq 5j\ 2b$
$t\bar{t}$	194 ± 27	310 ± 33	199 ± 24	690 ± 60	318 ± 32	380 ± 60
Single top	195 ± 22	98 ± 12	38 ± 5	67 ± 9	22 ± 4	15.9 ± 2.7
W+jets	1700 ± 400	690 ± 210	58 ± 23	350 ± 120	30 ± 14	19 ± 10
Other bkg.	110 ± 40	55 ± 23	7.2 ± 3.0	29 ± 12	3.5 ± 1.5	3.7 ± 1.7
Misidentified leptons	250 ± 130	110 ± 60	10 ± 5	60 ± 30	6 ± 3	8 ± 5
Total	2500 ± 400	1260 ± 210	312 ± 34	1200 ± 160	380 ± 40	430 ± 70
Data	2411	1214	293	1135	375	444

Data: 5872 **Bkg: 3991**

$$\%\,stat. = \frac{\sqrt{data}}{data - bkg}$$

Bkg=0

1.3%

4.1%

CMS

Yields	$\ell+3j1b$	$\ell+\geq 4j1b$	$\ell+3j\geq 2b$	$\ell+\geq 4j\geq 2b$
tt	627.6	573.4	381.8	522.3
tW	131.4	59.5	24.1	28.7
tchan	40.3	9.2	25.1	7.9
DY	5.3	0.2	3.0	0.0
WJets	185.9	33.6	11.5	1.0
QCD	67.5	22.2	10.6	2.0
total	1058.0	698.2	456.2	562.0
data	1087.0	703.0	411.0	536.0

Data: 2737 **Bkg: 669.3**

$$\%\,stat. = \frac{\sqrt{data}}{data - bkg}$$

Bkg=0

1.9%

2.6%

QCD Estimation

- Splitted in two parts: normalization & shape

1) Define a control region: “non-iso”

We invert the lepton MVA cut or the isolation requirements to obtain a region enriched in QCD events.

2) Define orthogonal region using low-MET events: MET < 25 GeV

Assuming that the reconstruction of a QCD lepton does not depend on MET, we compute the fake rate from the control region to our signal region using low-MET events.

Fake rate

3) Difference factor

Compute difference data-MC in CR (yields per category) → Yield

1) Usage of QCD MC to estimate a unique shape → Shape

Sum of all categories and removal of MET, m_T^W, H'_T selection to get statistics.

$$N^{\mathrm{SR}}_{\mathrm{QCD}} = \frac{N^{\mathrm{CR,incl}}_{\mathrm{QCD,MC}}(\mathrm{bin})}{N^{\mathrm{CR,incl}}_{\mathrm{QCD,MC}}(\mathrm{yields})} \underbrace{\left(N^{\mathrm{CR}}_{\mathrm{obs}} - N^{\mathrm{CR}}_{\mathrm{MC}}\right)_{\mathrm{yields}}} \times \underbrace{\frac{N^{\mathrm{SR}}_{\mathrm{obs,\ low\ p_T^{miss}}} - N^{\mathrm{SR}}_{\mathrm{MC,\ low\ p_T^{miss}}}}{N^{\mathrm{CR}}_{\mathrm{obs,\ low\ p_T^{miss}}} - N^{\mathrm{CR}}_{\mathrm{MC,\ low\ p_T^{miss}}}}}$$

Uncertainty differences

Nuisance	tt	t-channel
ISR	Single nuisance	2 decorrelated nuisances (t-tbar)
Btag	B-tag b,c / b-tag usdg	B-tagging / mistagging
W+jets	Decorrelated per NjMb	Decorrelated in heavy/light
QCD	Single norm per all, no shape uncertainty	Norm decorrelated in l_flav+NjMb, shape uncertainty built
UE	Single norm for all regions	Shape per region
Hdamp	Norm per NjMb	Shape per region + decorrelated (t-tbar)
Scales	Envelope	2 nuisances
t-channel/tt	t-channel: 10%	tt: 5%

Lowess method

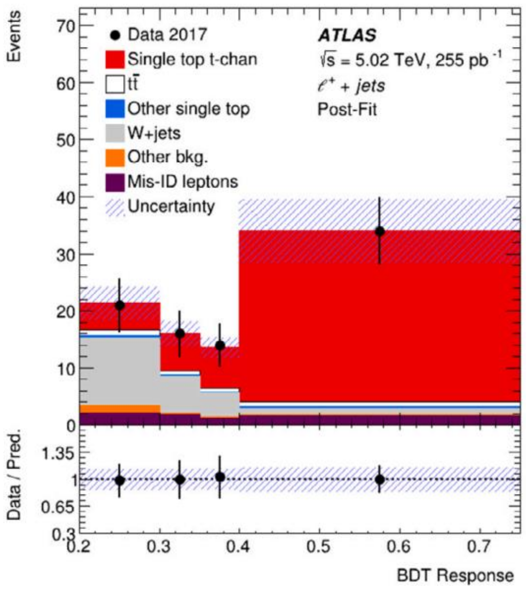
t-channel comparison with ATLAS

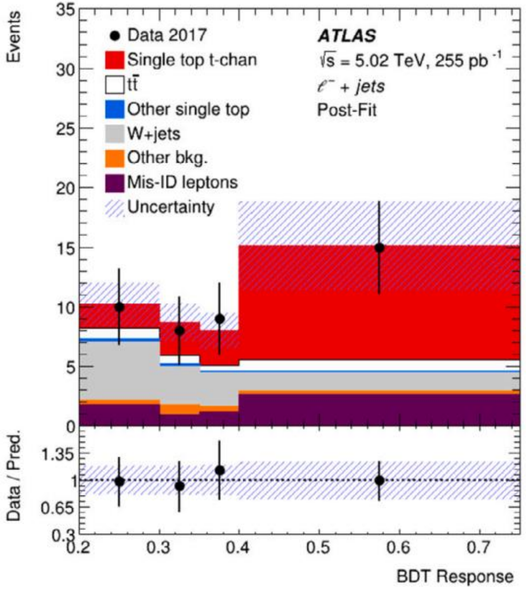
- $\boldsymbol{\sigma(tq + \bar{t}q)}$: Total $^{+23\%}_{-20\%}$
- $\mathcal{R}_{t-ch}$: Total $^{+65\%}_{-32\%}$
- $\boldsymbol{\sigma(tq)}$: Total $^{+25\%}_{-19\%}$
- $\boldsymbol{\sigma(\bar{t}q)}$: Total $^{+60\%}_{-36\%}$

ATLAS (obs)

- $\boldsymbol{\sigma(tq + \bar{t}q)}$: Total 19%
- $\mathcal{R}_{t-ch}$: Total $^{+54\%}_{-27\%}$
- $\boldsymbol{\sigma(tq)}$: Total 20%
- $\boldsymbol{\sigma(\bar{t}q)}$: Total 39%

CMS (obs)





t-channel comparison with ATLAS

CMS

Source	Impact (%)
Trigger efficiencies	2.2
b tagging	4.0
L1 inefficiency	3.8
Mistagging	0.6
Jet energy resolution	1.0
Jet energy scales	9.1
Electron efficiencies	0.5
Muon efficiencies	0.5
tW normalization	0.4
tt normalization	0.3
W+ heavy jets normalization	7.6
W+ light jets normalization	3.1
QCD normalization	1.6
QCD shape	1.9
ISR/FSR	2.5
t chan PDFs	0.1
tbar PDFs	0.0
Scales (μ_R, μ_F)	-
ME PS matching	0.2
Underlying Event	0.4
MC statistical	1.2
Statistical Uncertainty	12.1
Total	18.6

ATLAS

Category	$\delta\sigma(tq+\bar{t}q)/\sigma(tq+\bar{t}q)[\%]$	$\delta R_t/R_t[\%]$
Single-top quark signal modelling	8.6	4.1
Parton distribution functions	0.5	0.8
Misidentified leptons background	6.3	11.1
$W+\geq 1b$ jets modelling	3.9	4.4
$W+\geq 1c$ jets modelling	2.7	3.4
Z+jets normalisation	1.1	2.1
$t\bar{t}$ modelling	0.8	1.2
Single-top quark background modelling	0.6	2.1
$W+\geq 1$ light jets modelling	0.3	0.4
Diboson normalisation	0.1	0.3
Jet energy resolution	4.6	7.8
$\sqrt{s}=5.02$ TeV JES correction	4.4	5.1
Jet energy scale	4.0	5.3
Flavour tagging	2.0	1.3
Electron reconstruction	1.4	0.5
Muon reconstruction	1.3	0.7
Integrated luminosity	1.3	0.4
E_T^{miss}	0.6	2.4
Jet-vertex tagging	0.07	0.05
Simulation's statistical uncertainty	2.3	6.5
Data's statistical uncertainty	16	38
Total systematic uncertainty	15	18
Total uncertainty	21	42

Results by ATLAS