ATLAS + CMS TOP CROSS SECTIONS

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On behalf of the ATLAS and CMS collaborations.

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WHY MEASURE $\bar{t}t$ & SINGLE TOP CROSS SECTIONS?

- Test QCD over a wide range of Q^2
- Constrain:
  - parton distribution functions in the proton (and heavy nuclei).
  - α_s and the top quark pole mass.
  - four-quark interactions at the $\bar{t}t$ and single top production vertices.
  - EFT parameters of the Wtb and $g\bar{t}t$ vertices in global fits.
  - supersymmetric models and other models of new physics.

7 AND 8 TEV $\bar{t}t$ CROSS SECTION

- Measurements using $e^{\pm}\mu^{\pm}$ using dilepton events from ATLAS, CMS at 8 TeV are the most precise.
- ATLAS/CMS combination achieves 25%(28%) reduction of uncertainty at 7 (8) TeV.
- Theory predictions depend on α_s and the PDF's

PDF set	$\sigma_{t\bar{t}}$ ($\sqrt{s}$ = 7 TeV) [pb]	$\sigma_{t\bar{t}}$ ($\sqrt{s}$ = 8 TeV) [pb]	$R_{8/7}$
CT14	$181.7^{+10.6}_{-10.3}$	$258.9^{+13.8}_{-14.3}$	$1.425^{+0.007}_{-0.008}$
MMHT14	$181.2^{+9.6}_{-10.3}$	$258.1^{+12.8}_{-14.1}$	$1.424^{+0.005}_{-0.004}$
NNPDF3.1_a	$178.8^{+7.8}_{-8.8}$	$255.3^{+10.6}_{-12.2}$	$1.428^{+0.005}_{-0.004}$

- Double-tag method:

$$N_1 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b\left(1 - C_b\epsilon_b\right) + N_1^{bkg}$$

$$N_2 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{bkg}$$

$N_{1,2}$ event count, 1 or 2 b tags.
$\mathcal{L}$ luminosity
$\epsilon_{e\mu}$ selection efficiency
ϵ_b b-tag efficiency
$N_{1,2}^{bkg}$ event count, bkg
C_b: see JHEP 07 (2023) 213

Nuisance parameters

$$\mathbf{C} = \begin{pmatrix} U & \kappa^T \\ \kappa^T & M \end{pmatrix}$$

Cross sections

➔ Extract $\sigma_{t\bar{t}}$ and ϵ_b.
➔ ATLAS varying the nuisance parameters in Eur. Phys. J **74** (2014)3109
➔ CMS profiling over nuisance parameters in JHEP 08 (2016) 029

SYSTEMATIC UNCERTAINTIES

Total uncertainties comparable beween ATLAS/CMS.

Both dominated by Luminosity uncertainty.

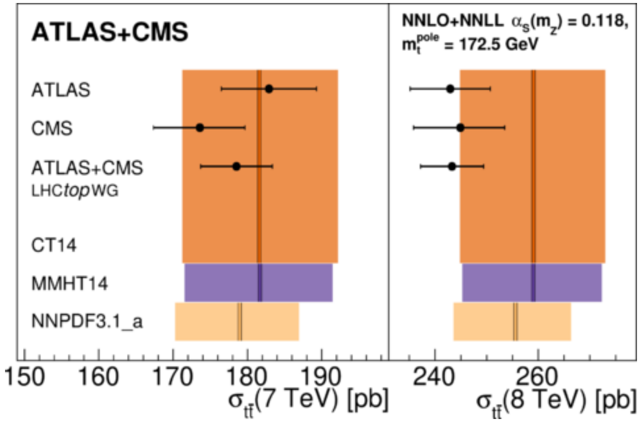
CMS	Uncertainty [%]	
Source	7 TeV	8 TeV
Trigger	1.3	1.2
Lepton (mis-)ID/isolation	1.5	1.5
Lepton energy scale	0.2	0.1
JES total	0.8	0.9
Jet energy resolution	0.1	0.1
b-jet ID	0.5	0.5
b-jet mis-ID	0.2	0.1
Pile-up	0.3	0.3
tW background	1.0	0.6
Drell–Yan background	1.4	1.3
Non-$e\mu$ $t\bar{t}$	0.1	0.1
$t\bar{t}V$ background	0.1	0.1
Diboson background	0.2	0.6
W+jets/QCD background	0.1	0.2
$t\bar{t}$ scale choice	0.3	0.6
ME/PS matching	0.1	0.1
ME generator	0.4	0.5
Hadronisation (JES)	0.7	0.7
Top-quark p_T modelling	0.3	0.4
Colour reconnection	0.1	0.2
Underlying event	0.1	0.1
PDF	0.2	0.3
Integrated luminosity	2.2	2.6
Statistical	1.2	0.6
$t\bar{t}$ scale choice (extrapolation)	$^{+0.1}_{-0.4}$	$^{+0.2}_{-0.1}$
ME/PS matching (extrapolation)	$^{+0.1}_{-0.1}$	$^{+0.3}_{-0.3}$
Top-quark p_T (extrapolation)	$^{+0.5}_{-0.3}$	$^{+0.6}_{-0.3}$
PDF (extrapolation)	$^{+0.1}_{-0.1}$	$^{+0.1}_{-0.1}$
Total uncertainty	$^{+3.6}_{-3.5}$	$^{+3.7}_{-3.5}$

ATLAS	Merged uncertainty [%]	
Source	7 TeV	8 TeV
Trigger	0.2	0.2
Lepton (mis-)ID/isolation	0.9	0.8
Lepton energy scale	0.3	0.5
JES flavour composition/specific response	0.2	0.4
JES modelling	0.04	0.2
JES central/forward balance	0.03	0.1
JES pile-up	0.03	0.2
Other JES	0.03	0.2
Jet energy resolution	0.3	0.5
b-jet ID	0.4	0.4
b-jet mis-ID	0.02	0.02
tW background	0.8	0.8
Drell–Yan background	0.05	0.02
Diboson background	0.1	0.1
$t\bar{t}$ scale choice	0.3	0.3
$t\bar{t}$ generator modelling	1.4	1.2
PDF	1.0	1.1
Integrated luminosity	2.0	2.1
Statistical	1.7	0.7
Total uncertainty	**3.5**	**3.2**

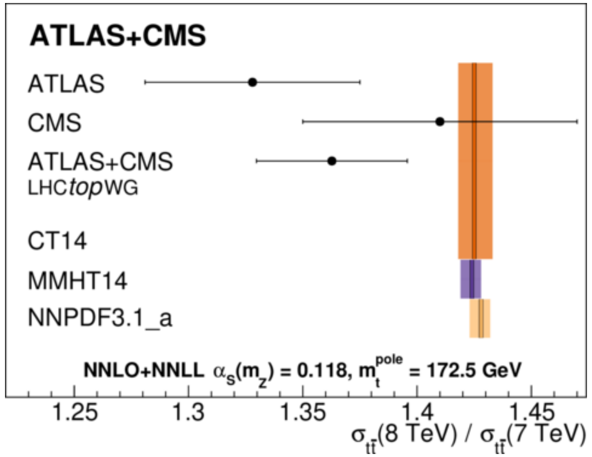
COMBINED RESULTS

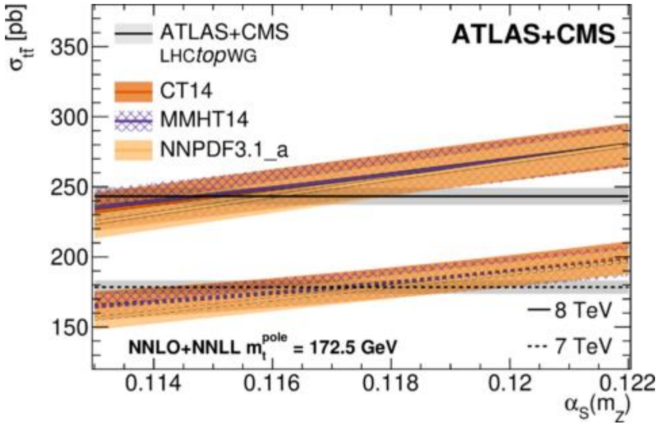
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 7\ \text{TeV}) = 178.5 \pm 4.7\ \text{pb}$$
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 8\ \text{TeV}) = 243.3^{+6.0}_{-5.9}\ \text{pb},$$

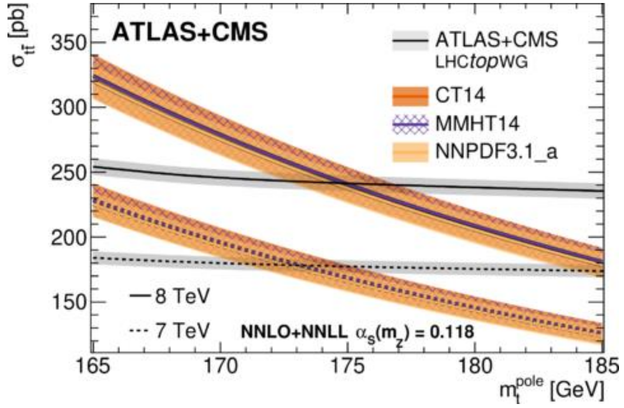
Correlation: $\rho = 41\%$

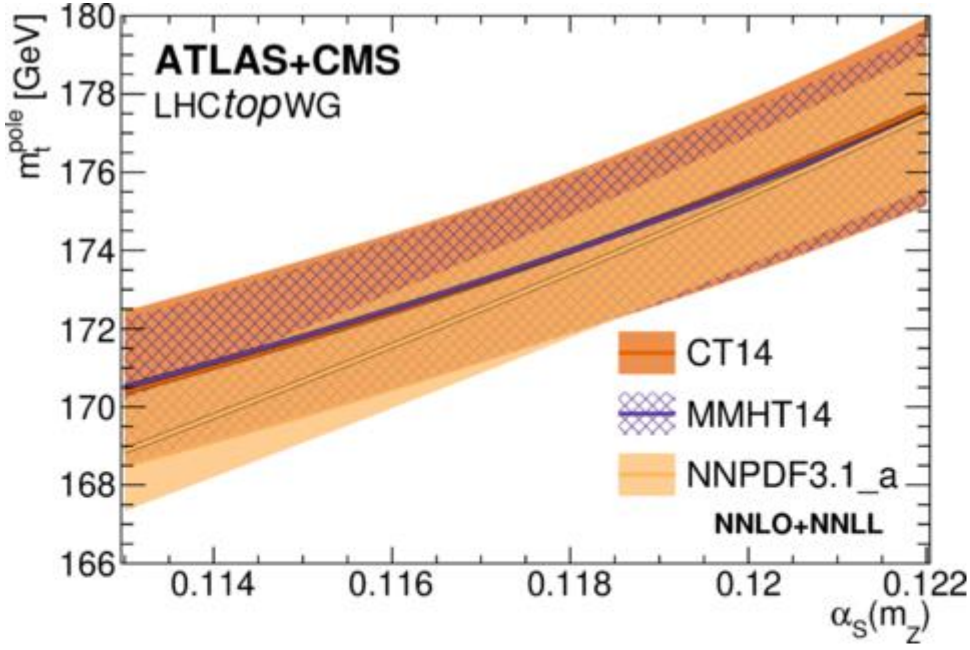


$$R_{8/7} = 1.363 \pm 0.015\ (\text{stat.}) \pm 0.028\ (\text{syst.}),$$





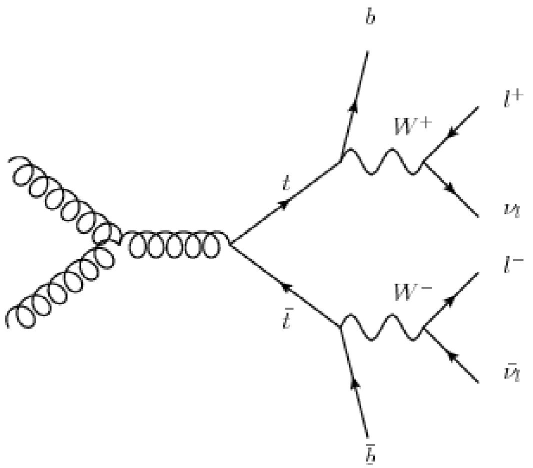


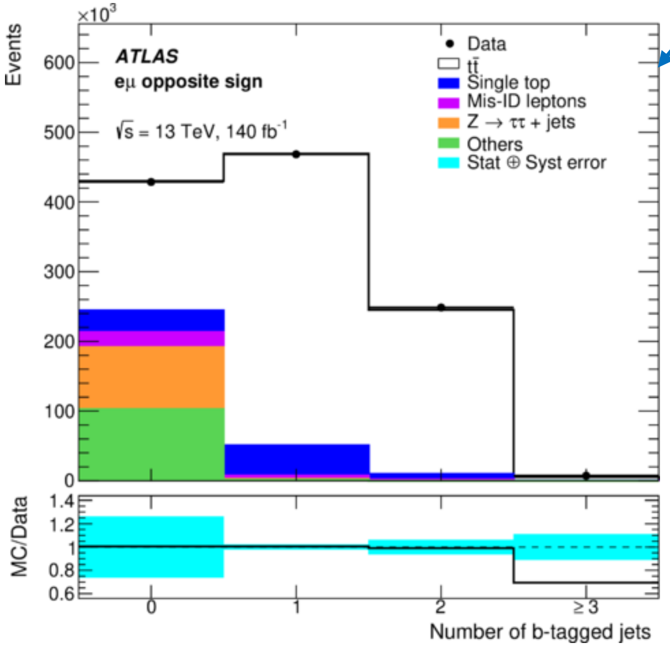


PDF set	m_t^{pole} ($\alpha_s = 0.118 \pm 0.001$)	$\alpha_s(m_Z)$ ($m_t = 172.5 \pm 1.0$ GeV)
CT14	$174.0^{+2.3}_{-2.3}$ GeV	$0.1161^{+0.0030}_{-0.0033}$
MMHT2014	$174.0^{+2.1}_{-2.3}$ GeV	$0.1160^{+0.0031}_{-0.0030}$
NNPDF3.1_a	$173.4^{+1.8}_{-2.0}$ GeV	$0.1170^{+0.0021}_{-0.0018}$

$t\bar{t}$ CROSS SECTION, 13 TEV, $e^{\pm}\mu^{\mp}$ EVENTS

ATLAS EXPERIMENT



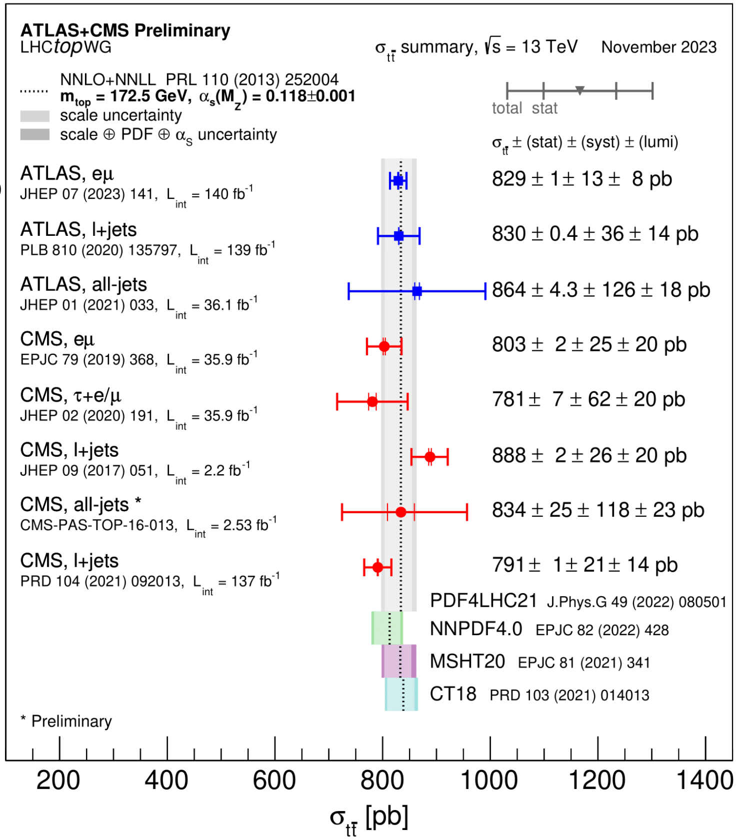


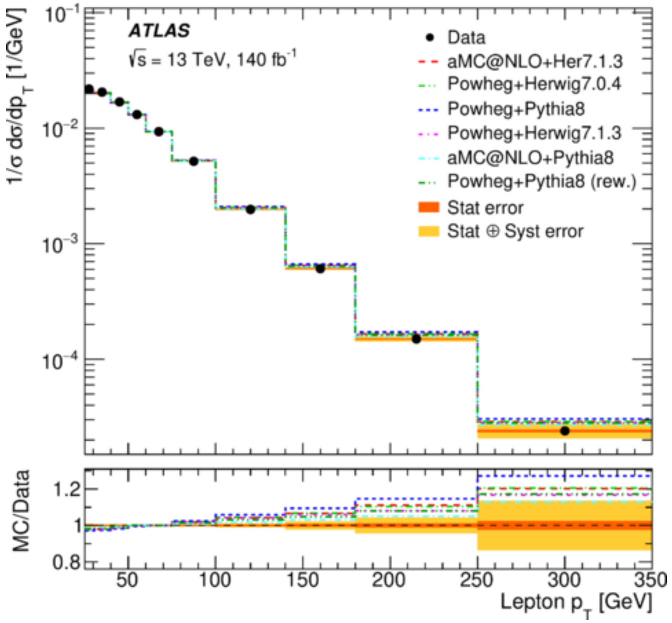
- Event selection:
  - Isolated electron, muon, and at least one b-tagged jet.
  - The plot shows the number of b-tagged jets.
  - Opposite sign $e\mu$ pairs in the second two bins of this distribution constitute the signal.
    - Backgrounds from single top, $Z \to \tau^+\tau^-$, multijets
    - Background levels are 11% and 4% in these bins.
  - Improvement of luminosity using Van der Meer scans
  - ATLAS Run 2: $\Delta\mathcal{L}/\mathcal{L}$ =0.83%
  - CMS 2016: $\Delta\mathcal{L}/\mathcal{L}$ =1.2%

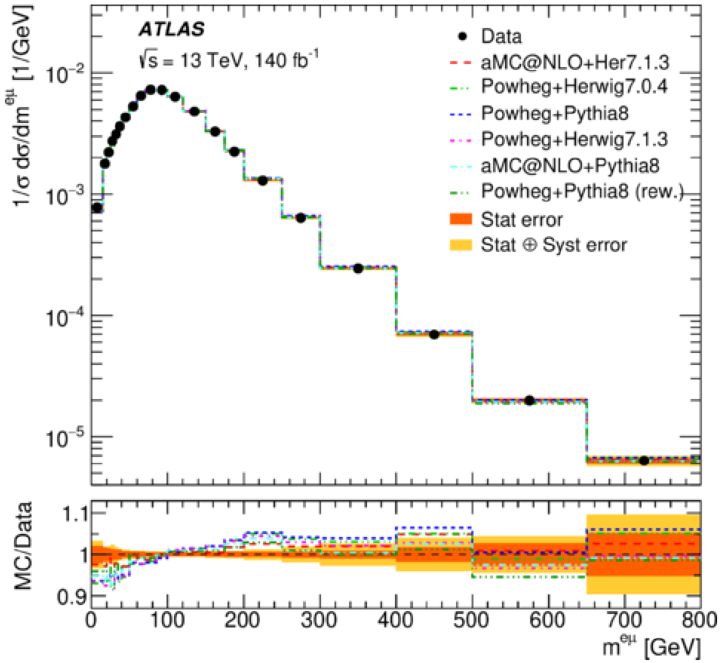
Source of uncertainty	$\Delta\sigma^{\text{fid}}_{t\bar{t}}/\sigma^{\text{fid}}_{t\bar{t}}$ [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics	0.15	0.15
MC statistics	0.04	0.04
Matrix element	0.12	0.16
h_{damp} variation	0.01	0.01
Parton shower	0.08	0.22
$t\bar{t}$ + heavy flavour	0.34	0.34
Top p_T reweighting	0.19	0.58
Parton distribution functions	0.04	0.43
Initial-state radiation	0.11	0.37
Final-state radiation	0.29	0.35
Electron energy scale	0.10	0.10
Electron efficiency	0.37	0.37
Electron isolation (in situ)	0.51	0.51
Muon momentum scale	0.13	0.13
Muon reconstruction efficiency	0.35	0.35
Muon isolation (in situ)	0.33	0.33
Lepton trigger efficiency	0.05	0.05
Vertex association efficiency	0.03	0.03
Jet energy scale & resolution	0.10	0.10
b-tagging efficiency	0.07	0.07
$t\bar{t}/Wt$ interference	0.37	0.37
Wt cross-section	0.52	0.52
Diboson background	0.34	0.34
$t\bar{t}V$ and $t\bar{t}H$	0.03	0.03
Z+jets background	0.05	0.05
Misidentified leptons	0.32	0.32
Beam energy	0.23	0.23
Luminosity	0.93	0.93
Total uncertainty	1.6	1.8

RESULTS $e^{\pm}\mu^{\mp}$ EVENTS

- Fiducial cross section and inclusive cross sections at $\sqrt{s}$= 13 TeV
  - $\sigma_{t\bar{t}}^{fid} = 10.53 \pm 0.02(\mathbf{stat}) \pm 0.13(\mathrm{syst}) \pm 0.10(\mathrm{lumi}) \pm 0.02\ (\mathrm{beam})\ \mathbf{pb}$
  - $\sigma_{\bar{t}t} = 829 \pm 1(\mathbf{stat}) \pm 13(\mathrm{syst}) \pm 8(\mathrm{lumi}) \pm 2\ (\mathrm{beam})\ \mathbf{pb}$
  - This is the most precise measurement at 13 TeV



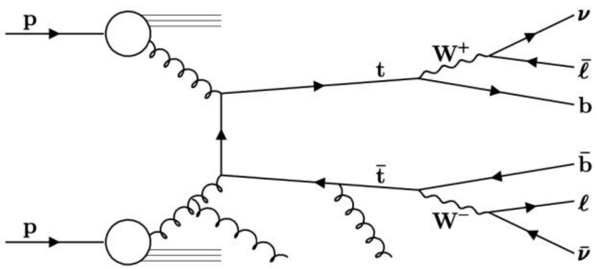


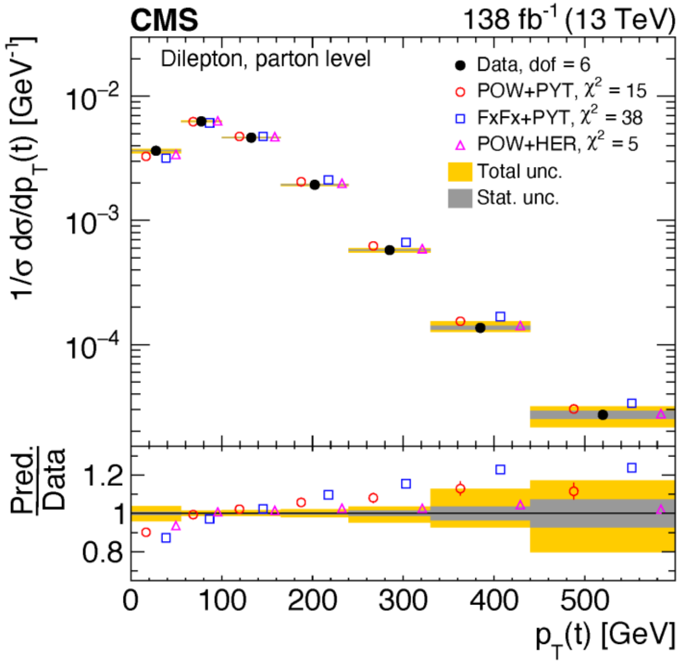


- Normalized differential particle-level cross sections in the variables $p_T^{\ell}, |\eta^{l}|, m^{e\mu}, p_T^{e\mu}, |y^{e\mu}|$, $E^e + E^{\mu}, p_T^e + p_T^{\mu}$, and $|\Delta\phi^{e\mu}|$.
- Typical precision of 1%
- *No single generator describes all distributions with prob > 1%.*

JHEP 07 (2023) 141	$t\bar{t}$ XS, dileption, differential	13 TeV	140 fb^{-1}

DIFFERENTIAL DISTRIBUTIONS IN DILEPTON EVENTS WITH ADDITIONAL JETS





More than 250 single and double differential cross sections are reported on at particle and parton level.

Tabulated data available in HEPData.

Observable is	Predicted at NLO to be
p_T of t and $\bar{t}$ quarks	harder than
rapidity of t and $\bar{t}$ quarks	more central than
mass of $t\bar{t}$ system	consistent with
rapidity of $t\bar{t}$ system	consistent with
p_T of $t\bar{t}$ system	inconsistent with
	the data

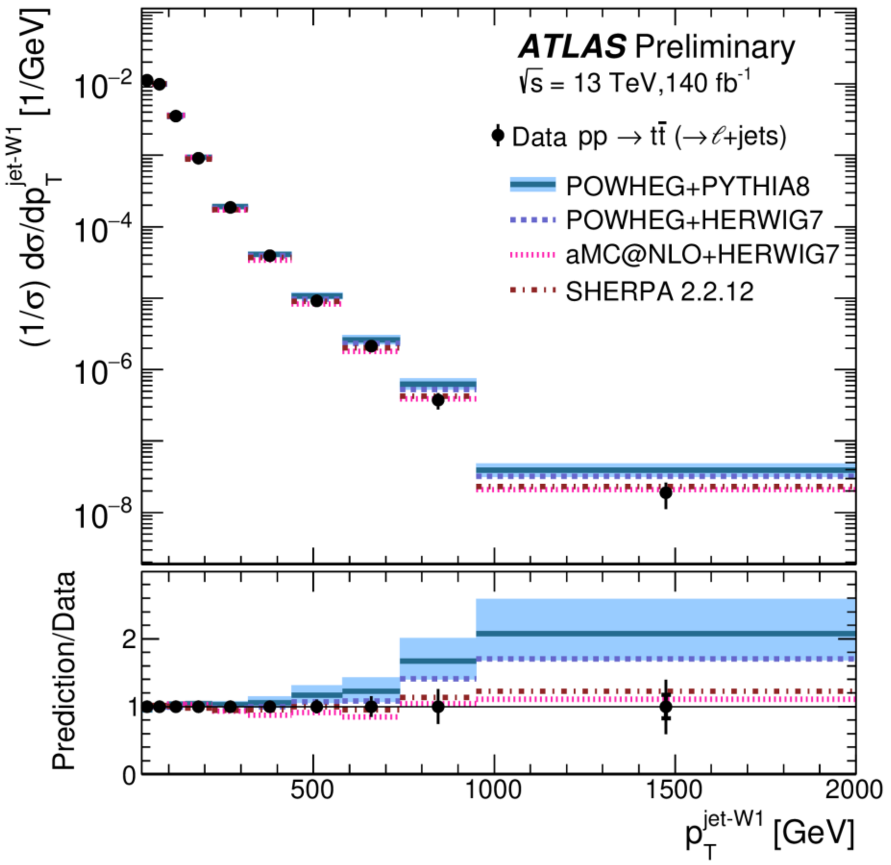
Cross section variables	p-values of χ^2 (in %) POW+PYT (w. unc.)	FxFx+PYT	POW+HER
$p_T(t)$	2 (10)	<1	51
$p_T(\bar{t})$	5 (16)	<1	41
$y(t)$	<1 (2)	<1	1
$y(\bar{t})$	<1 (<1)	<1	<1
$p_T(t\bar{t})$	<1 (32)	<1	<1
$y(t\bar{t})$	51 (74)	7	73
$m(t\bar{t})$	56 (77)	30	70
$\|\Delta\phi(t,\bar{t})\|$	82 (97)	15	7
$\|y(t)\| - \|y(\bar{t})\|$	3 (22)	<1	6
$p_T(t)/m(t\bar{t})$	<1 (<1)	<1	3
$p_T(t\bar{t})/m(t\bar{t})$	3 (62)	<1	<1
$\log(\xi_1)$	9 (26)	3	15
$\log(\xi_2)$	24 (54)	<1	51

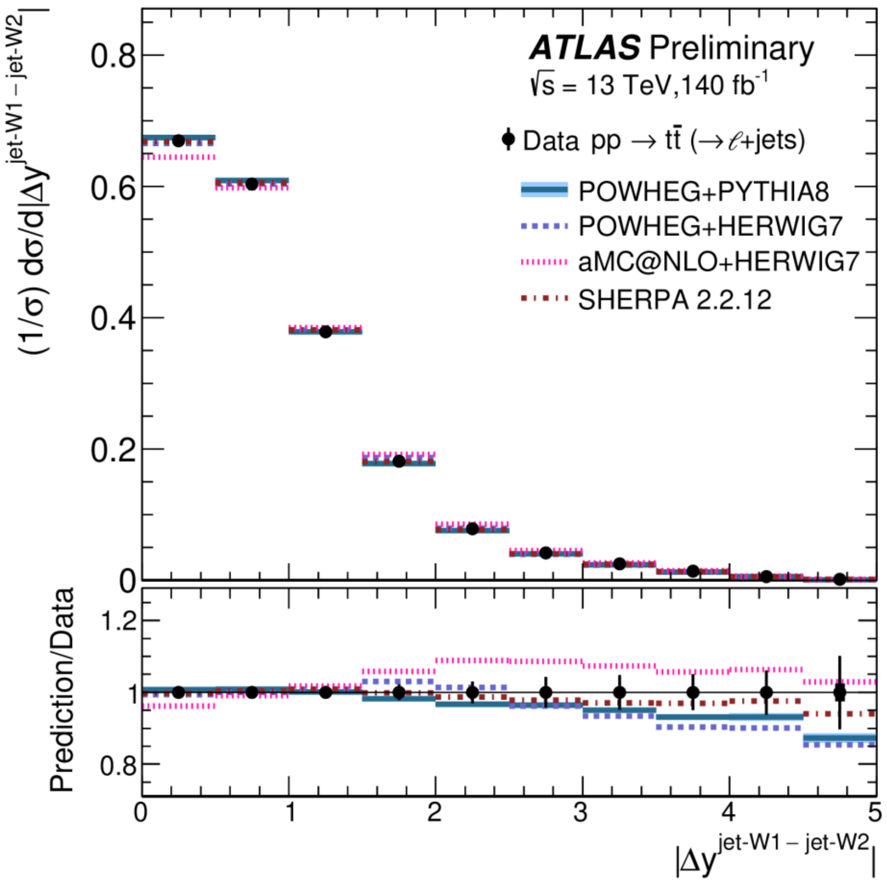
$t\bar{t}$ DIFFERENTIAL CROSS SECTIONS, LEPTON+ JETS

- The lepton+jets channel allows full reconstruction of production and decay kinematics.
- Various approaches to "going differential" in $t\bar{t}$ production.
  - Find the magic variable with sensitivity to parameter(s) of interest.
  - Carry out multi-differential analyses.
  - Slice the kinematics in multiple ways.
- **CMS** (`Phys. Rev D 104 092013`) **and ATLAS** (`ATLAS-CONF-2023-068`, plots on following slides) measure differential cross sections in $t\bar{t}$ events at 13 TeV.
- CMS: more that 250 figures showing differential distributions at the particle and parton level, compared to NLO and NNLO calculations. Also in HEPData.
- ATLAS compares kinematic quantities at particle level,
  - Focusing on jet variables,
  - In inclusive $t\bar{t}$ events
  - $t\bar{t}$ events with 1 extra jet
  - $t\bar{t}$ events with 2 extra jets
  - …to NLO and NNLO [PRL 127 (2021) 062001] calculations.

`ATLAS-CONF-2023-068`

Normalized differential distributions, jets from W boson decay on the hadronic side, $t\bar{t}$ inclusive events compared to NLO simulation

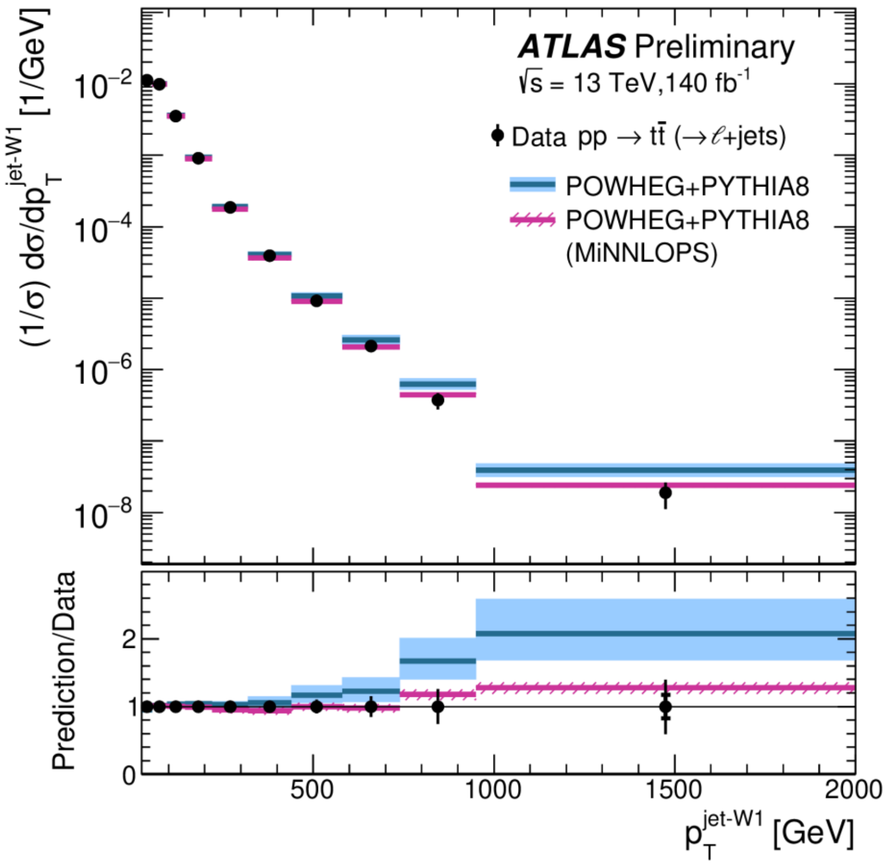


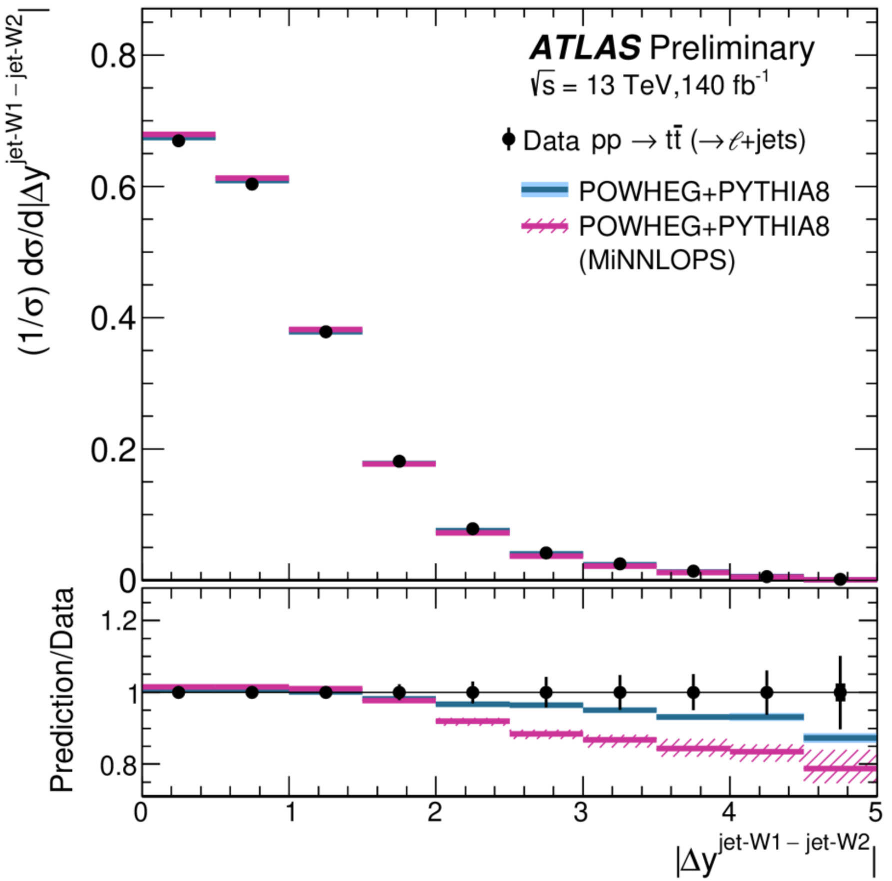


- Example: transverse momentum up to 1.5 TeV, leading jet from W decay.
- Varies over five orders of magnitude.
- Only SHERPA gives a good description above 500 GeV

- Example: rapidity difference Δy between leading and subleading jet from W decay

Normalized differential distributions, jets from W boson decay on the hadronic side, $t\bar{t}$ inclusive events compared to NLO and NNLO simulation

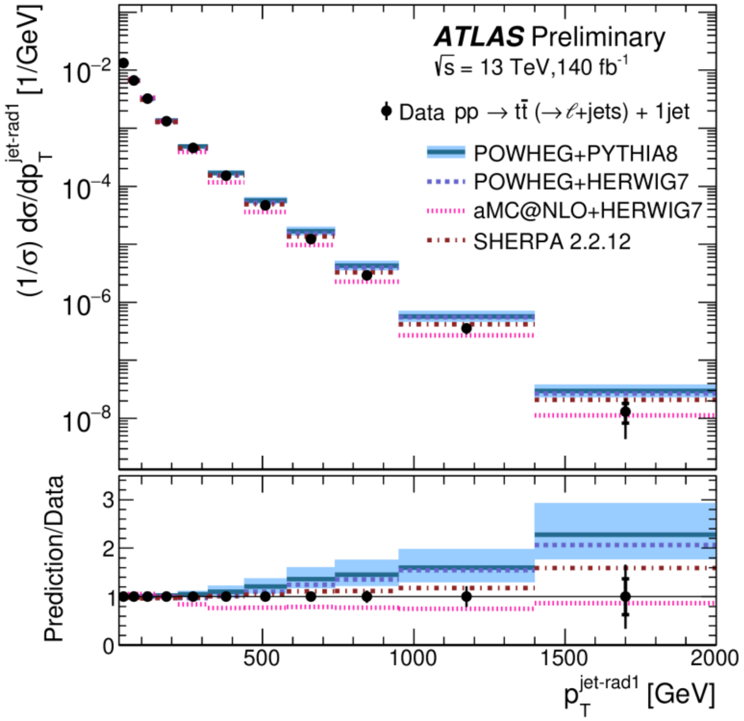


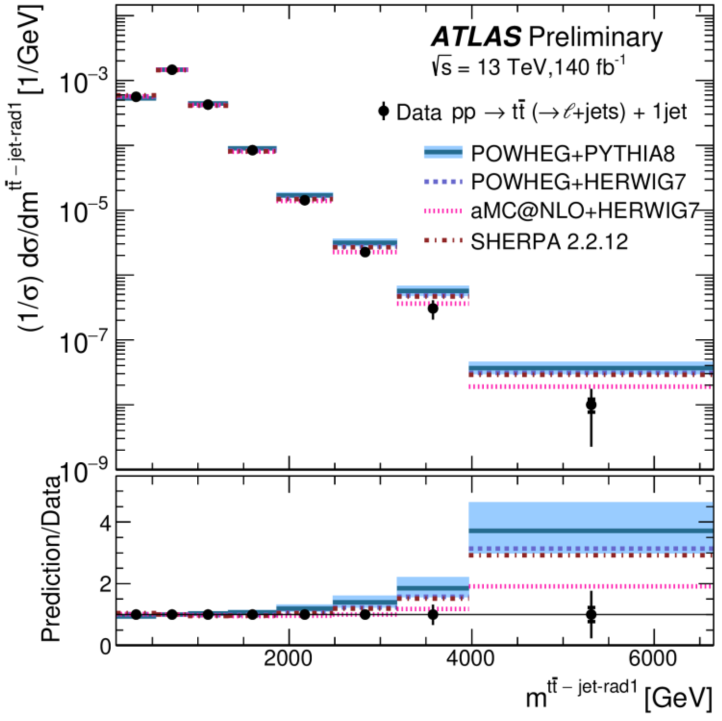


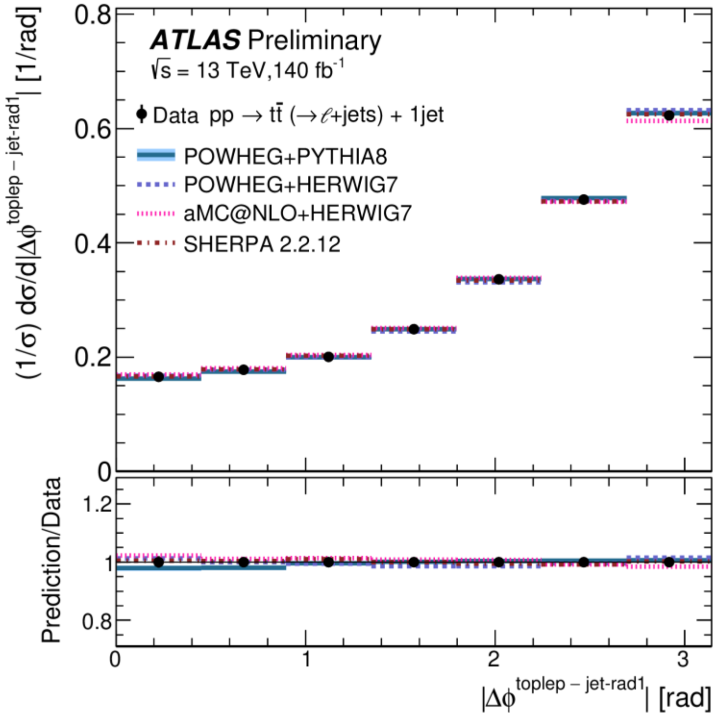
- NNLO gives a more precise prediction and better agreement with the data..

- However shows discrepancy with the Δy distribution.

Normalized differential distributions, extra gluon jet, $t\bar{t}$ + 1 jet events compared to NLO simulation





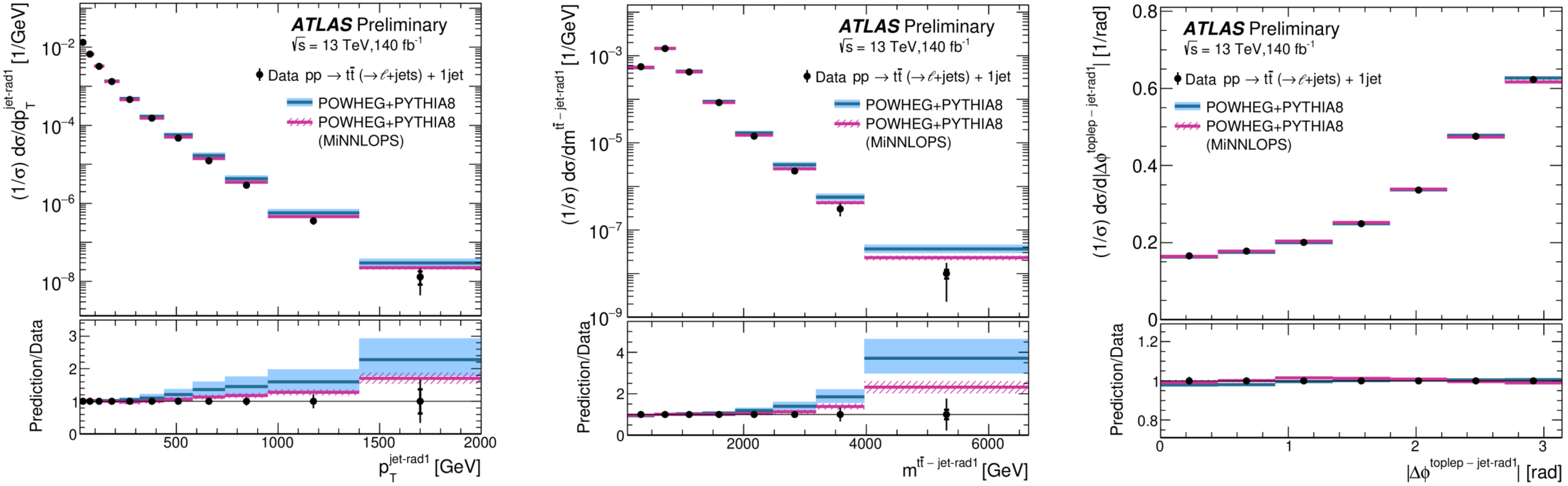


- Example: transverse momentum up radiated jet.
- Varies over six orders of magnitude.
- POWHEG+PYTHIA8 gives poor description above 500 GeV

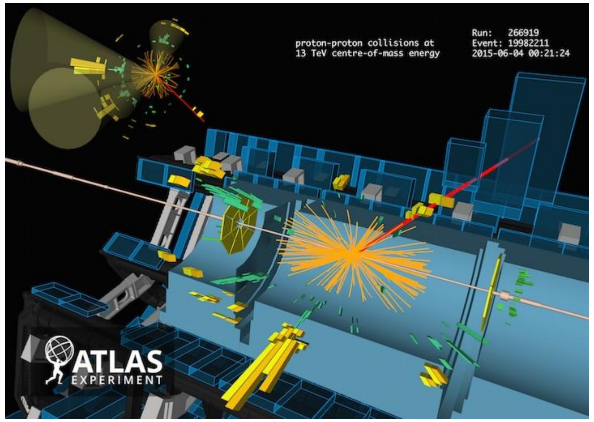
- Example: mass of the (top + jet) system
- Varies over five orders of magnitude

- Example: difference in azimuth $\Delta\phi$ between lepton from W and radiated jet.

Normalized differential distributions, extra gluon jet, $t\bar{t}$ +1 jet events compared to NLO and NNLO simulation



- NNLO gives a more precise prediction and better agreement with the data..
- And one learns that gluon radiation tends to arise far from the lepton from W decay



RUN 3: $\sqrt{s}$=13.6 TEV

ATLAS EXPERIMENT

- Run 3 $\sigma(t\bar{t})$ at $\sqrt{s}$=13.6 TeV is the highest energy measurement of top quark pair production cross section.
- Theory expectation: increase of 12% in the cross section between 13 and 13.6 TeV.

$\sigma(t\bar{t}) = 850 \pm 3(\text{stat}) \pm 18(\text{syst}) \pm 20(\text{lumi})$ pb. (ATLAS)
$\sigma(t\bar{t}) = 881 \pm 23(\text{stat, syst}) \pm 20(\text{lumi})$ pb. (CMS, 1.21 fb^{-1})

Cf. Theory: $\sigma(t\bar{t}) = 924^{+32}_{-40}$ pb

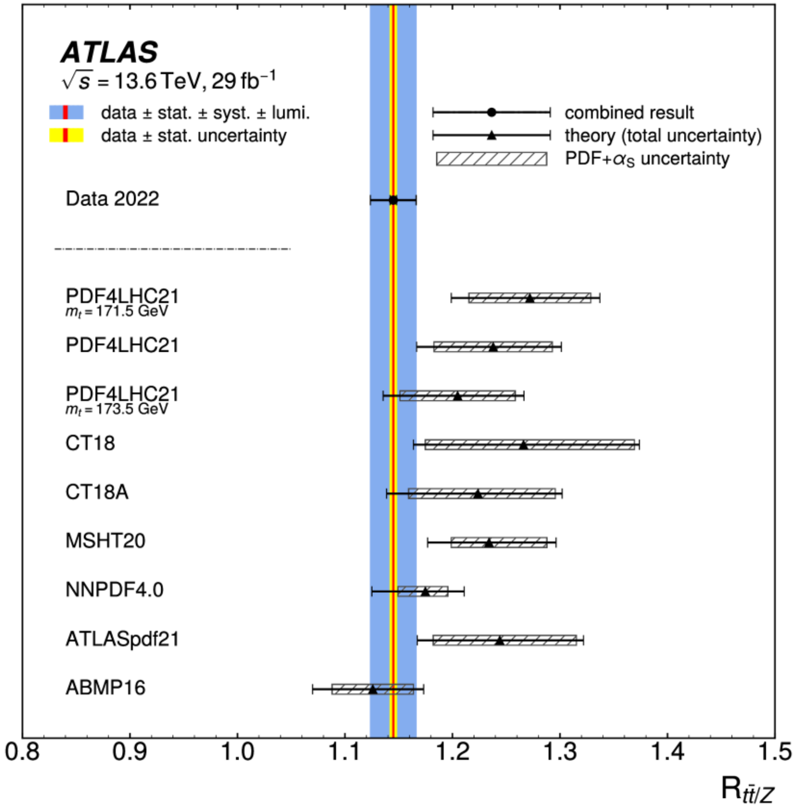
The very precise $e^{\pm}\mu^{\mp}$ channel is used, the usual double-counting technique applied.

Also the ratio $\sigma(t\bar{t})/\sigma(Z)$ is measured, in which systematic uncertainties due to luminosity measurement cancel.

$$R_{t\bar{t}/Z} = 1.145 \pm 0.03(\text{stat}) \pm 0.021(\text{syst}) \pm 0.002(\text{lumi})$$

Cf. Theory: $R_{t\bar{t}/Z} = 1.238^{+0.063}_{-0.071}$

Category		Uncertainty [%]		
		$\sigma_{t\bar{t}}$	$\sigma^{\text{fid.}}_{Z\to\ell\ell}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ parton shower/hadronisation	0.9	< 0.2	0.9
	$t\bar{t}$ scale variations	0.4	< 0.2	0.4
	$t\bar{t}$ normalisation	-	< 0.2	-
	Top quark p_T reweighting	0.6	< 0.2	0.6
Z	Z scale variations	< 0.2	0.4	0.3
Bkg.	Single top modelling	0.6	< 0.2	0.6
	Diboson modelling	< 0.2	< 0.2	0.2
	$t\bar{t}V$ modelling	< 0.2	< 0.2	< 0.2
	Fake and non-prompt leptons	0.6	< 0.2	0.6
Lept.	Electron reconstruction	1.2	1.0	0.4
	Muon reconstruction	1.4	1.4	0.3
	Lepton trigger	0.4	0.4	0.4
Jets/tagging	Jet reconstruction	0.4	-	0.4
	Flavour tagging	0.4	-	0.3
	PDFs	0.5	< 0.2	0.5
	Pileup	0.7	0.8	< 0.2
	Luminosity	2.3	2.2	0.3
	Systematic uncertainty	3.2	2.8	1.8
	Statistical uncertainty	0.3	0.02	0.3
	Total uncertainty	3.2	2.8	1.9



RUN 2: $\sqrt{s}$=5.02 TEV

- 302 pb^{-1} of data at $\sqrt{s}$= 5 TeV was collected during Run 2.
- $q\bar{q}$ initiated events are 25% of the cross section (Cf. 11% at $\sqrt{s}$ = 13 TeV)
- Expected cross section (NNLO+NNLL) $\sigma_{t\bar{t}} = 69.5^{+2.9}_{-3.1}$ pb
- This is a *low statistics* measurement; using only $e^{\pm}\mu^{\mp}$ events CMS selected:➔

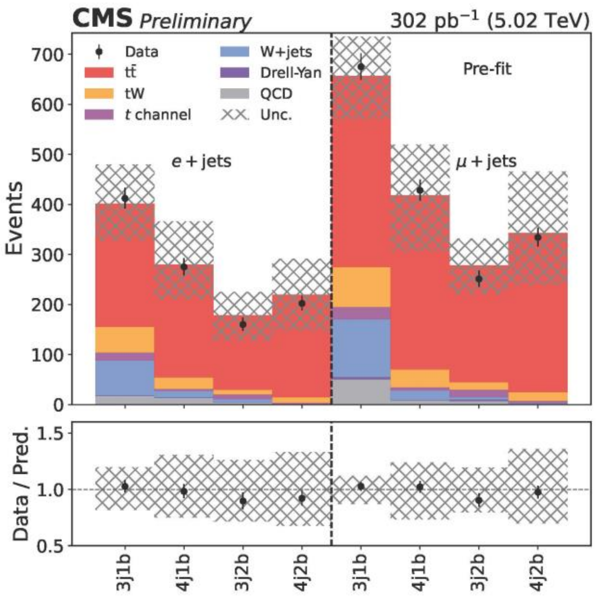
Process	Event yield
tW	8 ± 2
Nonprompt leptons	2 ± 1
DY	10 ± 4
VV	4 ± 1
Total background	24 ± 4
$t\bar{t}$	187 ± 9
Data	194

JHEP 04 (2022) 144

New cross section measurement at 5 TeV from CMS:

* uses lepton+jets (CMS-PAS-TOP-23-005)

* combines with $e^{\pm}\mu^{\mp}$ (JHEP 04 (2022) 144)

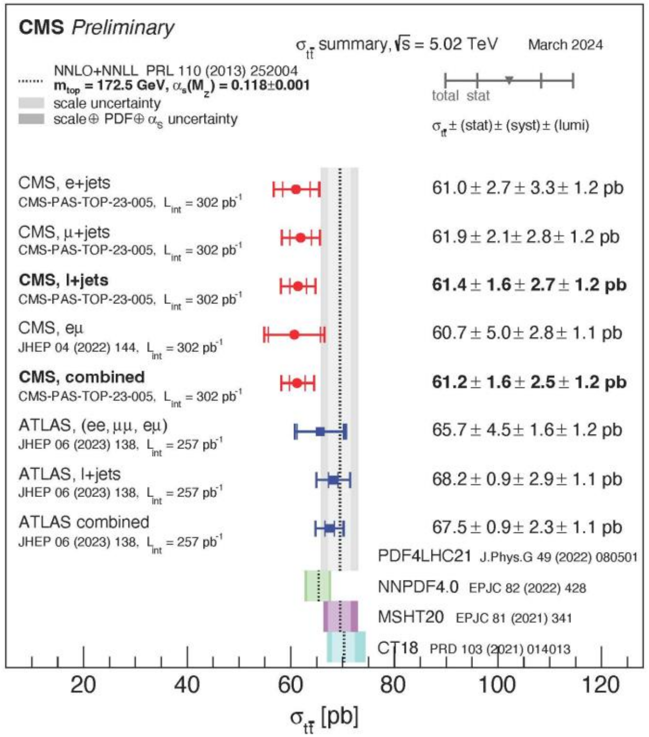


Lepton+jets (CMS-PAS-TOP-23-005)

$$\sigma(t\bar{t}) = 61.4 \pm 1.6(\text{stat})^{+2.7}_{-2.6}(\text{syst}) \pm 1.2(\text{lumi})\ \text{pb}$$

Combined with $e^{\pm}\mu^{\mp}$ from JHEP 04 (2022) 144

$$\sigma(t\bar{t}) = 61.2^{+1.6}_{-1.5}(\text{stat})^{+2.6}_{-2.3}(\text{syst}) \pm 1.2(\text{lumi})\ \text{pb}$$



CMS-PAS-TOP-23-005	$t\bar{t}$ XS	5.02 TeV	0.302 fb^{-1}

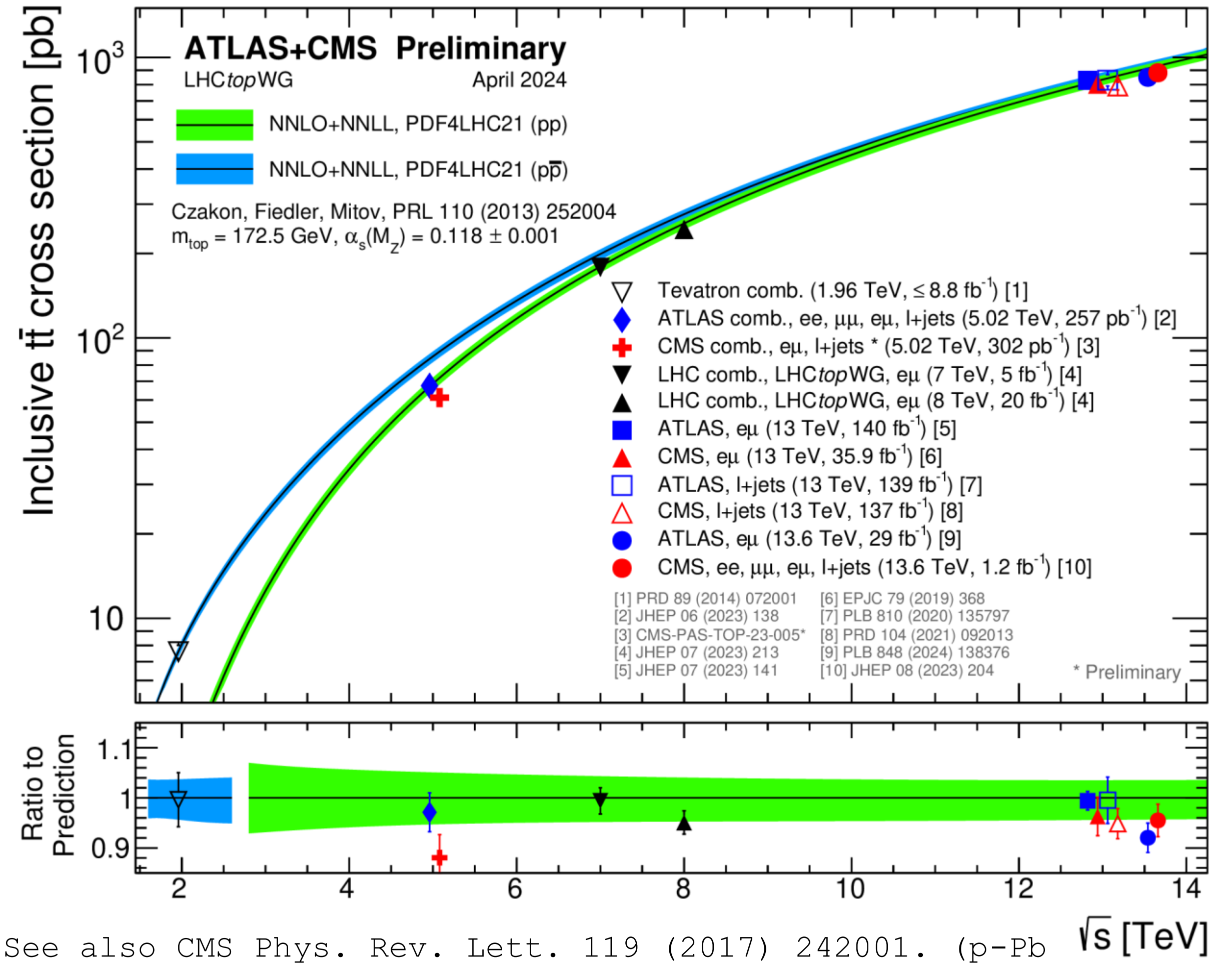
SUMMARY $\sigma(t\bar{t})$ VS. $\sqrt{s}$

ATLAS and CMS both provide measurements at 5, 7, 8, 13, and 13.6 TeV.

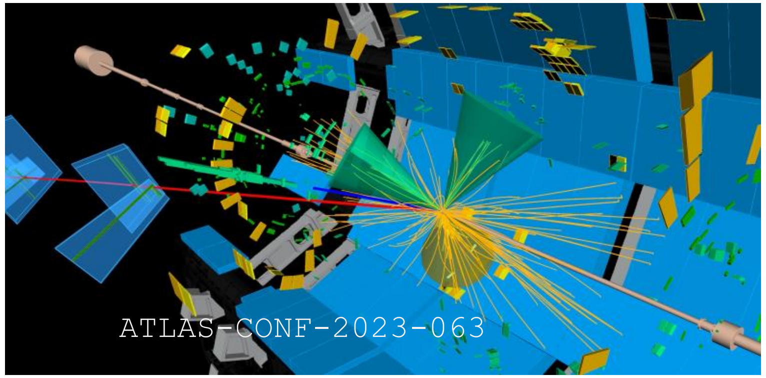
LHC Top working group combinations are published at 7 and 8 TeV

All measurements in agreement with the standard model. (The ATLAS measurement at 13.6 TeV is low by 1.5 sigma; CMS measurement at 5.02 by about 1.8 sigma).

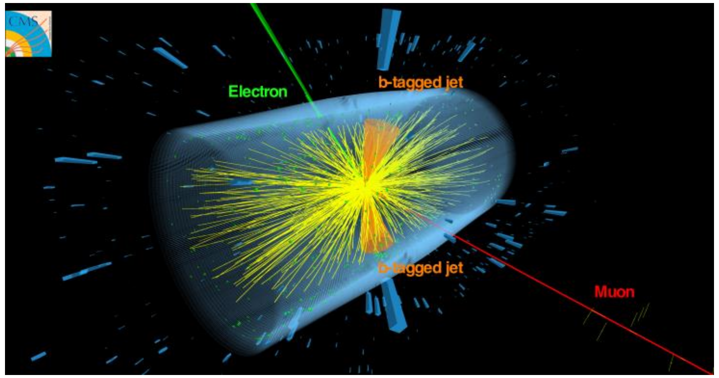
Also noteworthy: measurement of $\sigma(t\bar{t})$ in p-Pb collisions at $\sqrt{s}$=8.16 TeV (both experiments).



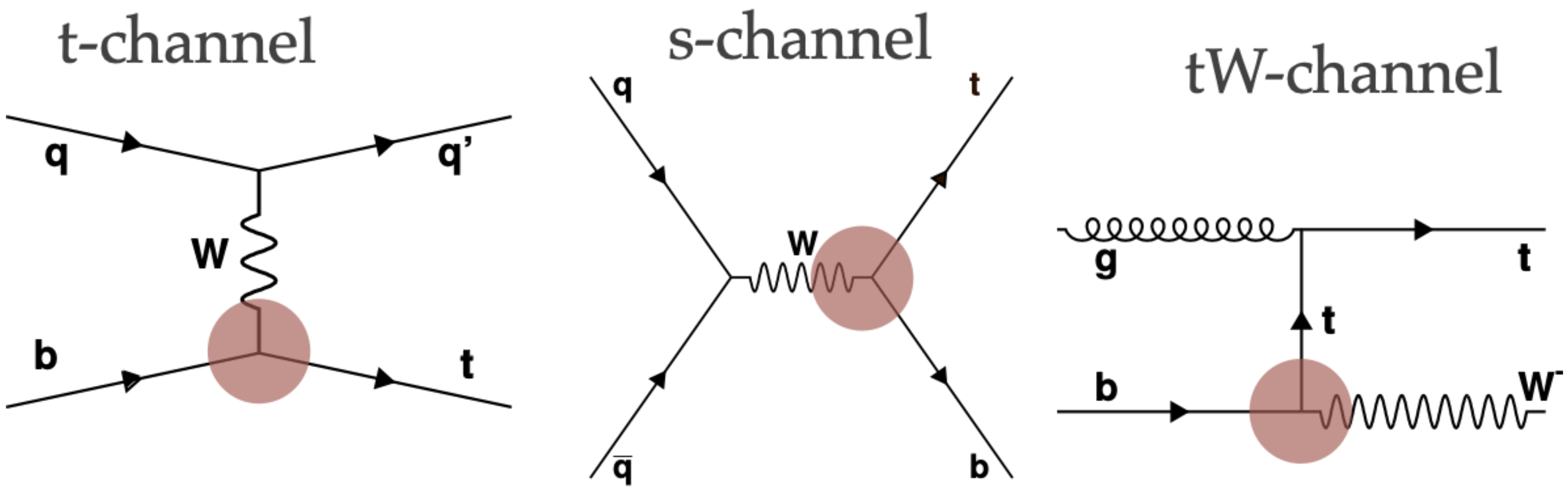
See also CMS Phys. Rev. Lett. 119 (2017) 242001. (p-Pb collisions)



And note that CMS has observed top quark pair production in Pb-Pb collisions! Phys Rev. Lett. 119 (2017) 242001



ELECTROWEAK PRODUCTION OF SINGLE TOP QUARKS



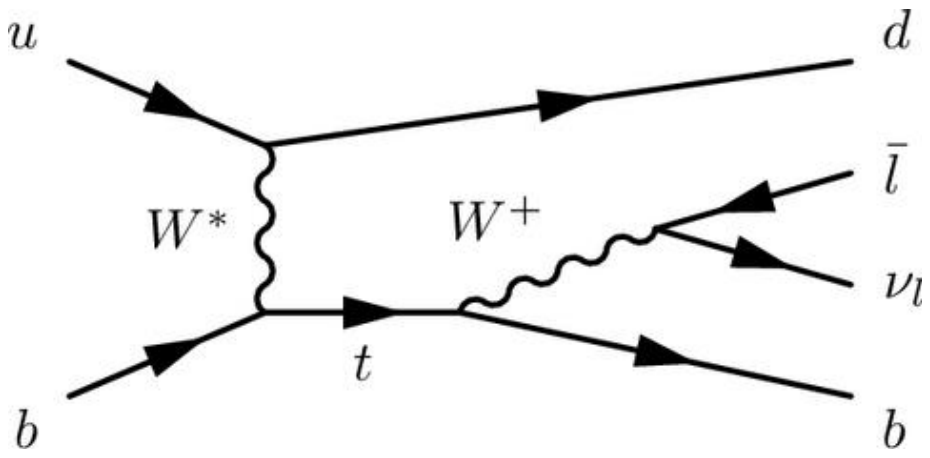
- The production and decay is via the Wtb vertex
- Sensitive to V_{tb}

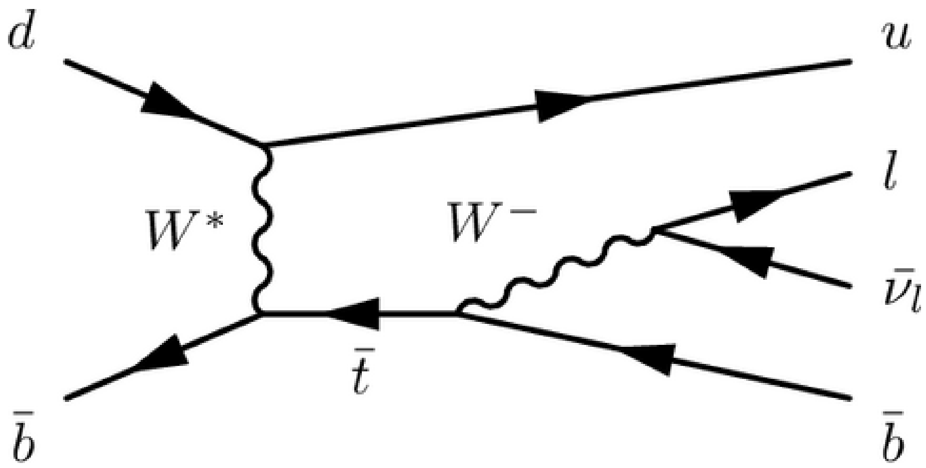
At 13 TeV:

- Cross section for *t*-channel production is 25% that of $t\bar{t}$
- for *tW* production is 10% that of $t\bar{t}$
- for *s*-channel production, 1.2% that of $t\bar{t}$

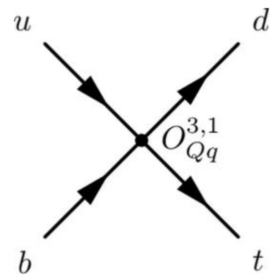
- Signals are noisier than for $t\bar{t}$, imposing data-driven estimation of W+jets, $t\bar{t}$ backgrounds

SINGLE-TOP T-CHANNEL PRODUCTION





- t-channel production from up and down quarks leads to more top than antitop in this channel.
- This depends on the u/d quark fractions in the proton
- Wtb vertex mediates both the production and decay process
- Four quark interactions or extra Higgs couplings can also be lurking
- They are parameterized in EFT coefficients $C_{Qq}^{3,1}$ and $C_{\phi Q}^{3}$



t-CHANNEL CROSS SECTION @ 13 TEV

2 signal regions by lepton charge.

2 control regions defined by inverting the $E_T^{miss} > 30$ cut for:
- Electrons in Barrel
- Electrons in Endcap

Event counts in these regions considered in fit.

2 control regions defined by inverting angular cut between jet and muon for:
- Muons

$\Delta\phi(\mu, p_T^{miss})$ considered in fit.

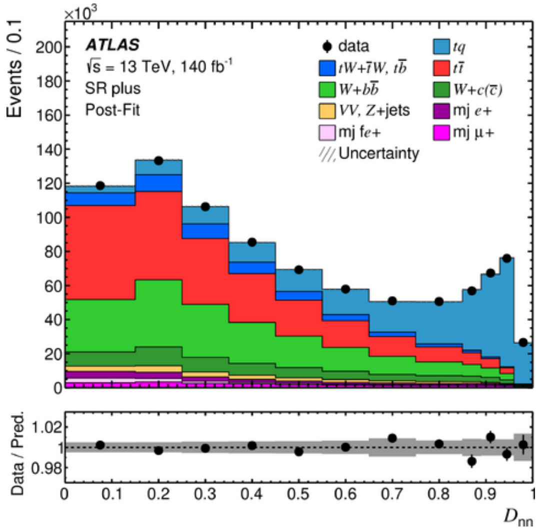
$$\sigma(tq) = 137 \pm 8 \text{ pb}$$

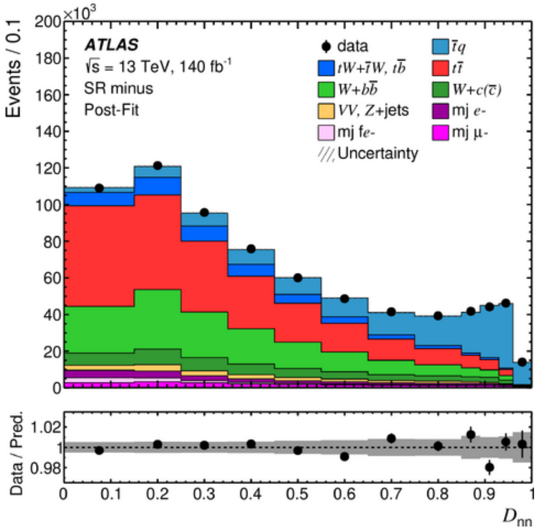
$$\sigma(\bar{t}q) = 84^{+6}_{-5} \text{ pb}$$

$$R_t = 1.636^{+0.036}_{-0.034}$$

$$f_{LV}|V_{tb}| = 1.015 \pm 0.031$$

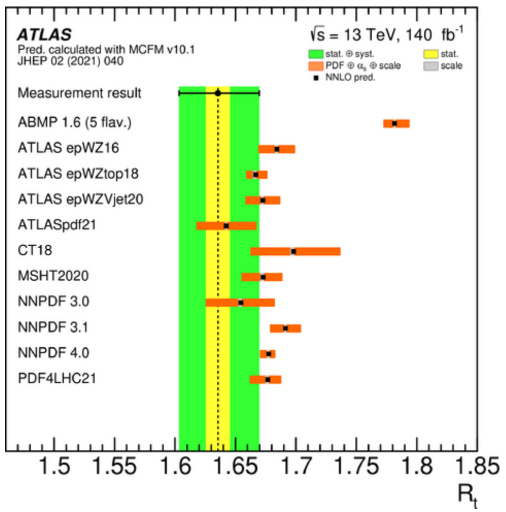
(improved precision of 30%, relative to Run 1 ATLAS+CMS in JHEP 05 (2019) 088)



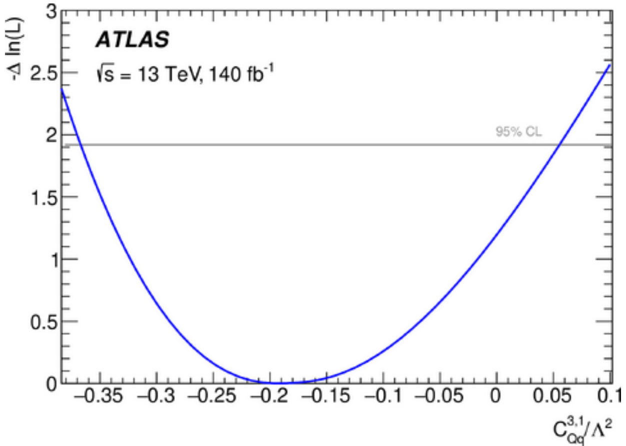


INTERPRETATION

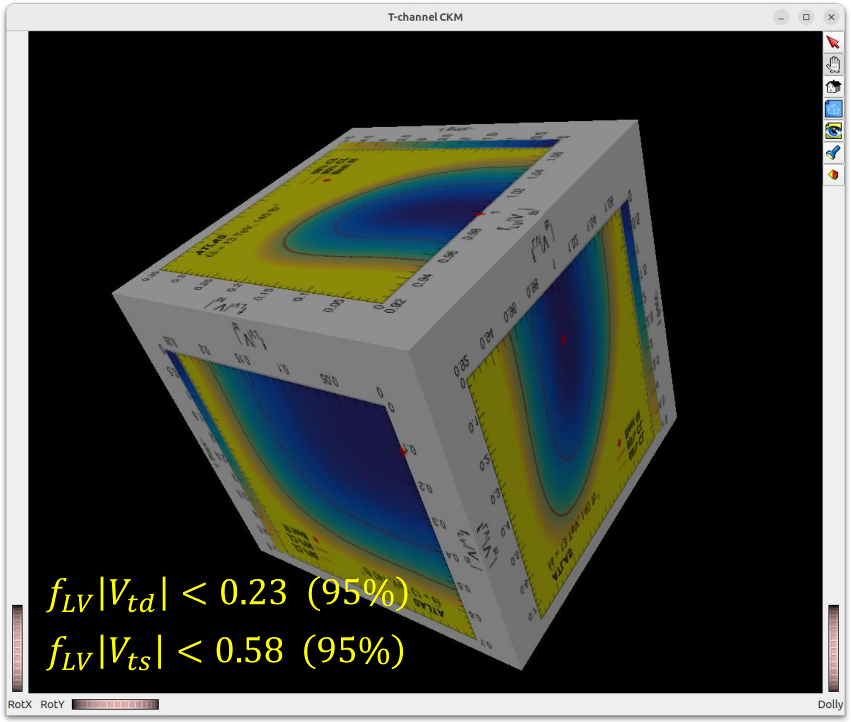
Constrain PDF's (u/d ratio in proton)



set limits on four-quark operator C_{Qq}



Constrain CKM matrix elements V_{ts}, V_{td}, V_{tb}

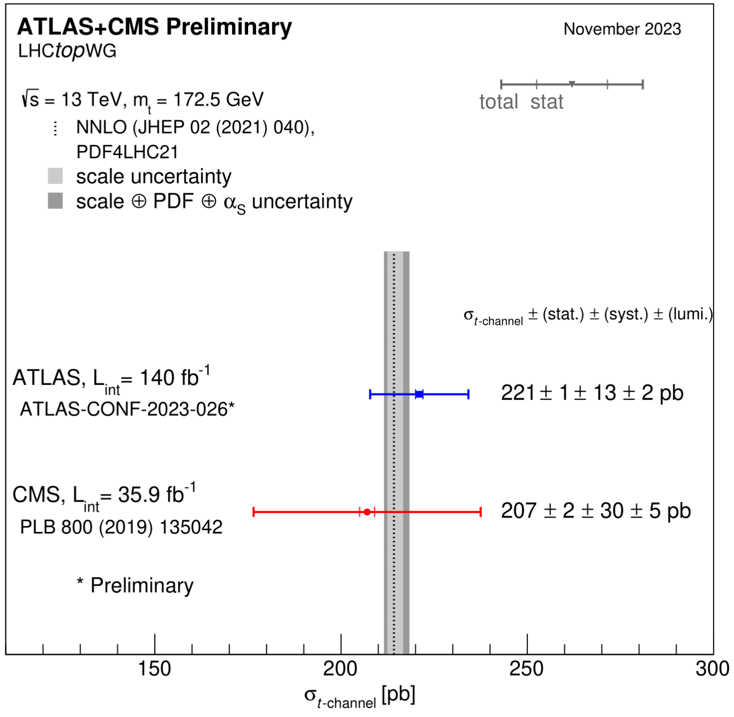


Limits on EFT coefficients

$$-0.37 < C_{Qq}^{3,1} < 0.06$$

$$-0.87 < C_{\phi Q}^{3} < 1.42$$

Summary, ATLAS & CMS measurement of t-channel production

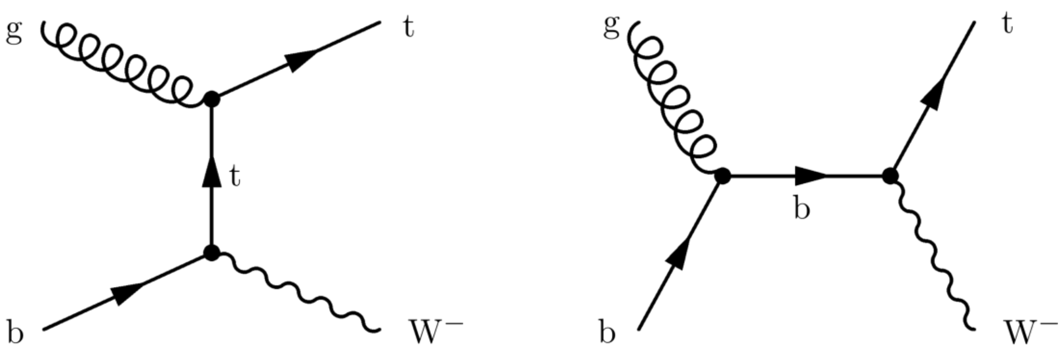


[LHC top working group summary plots]

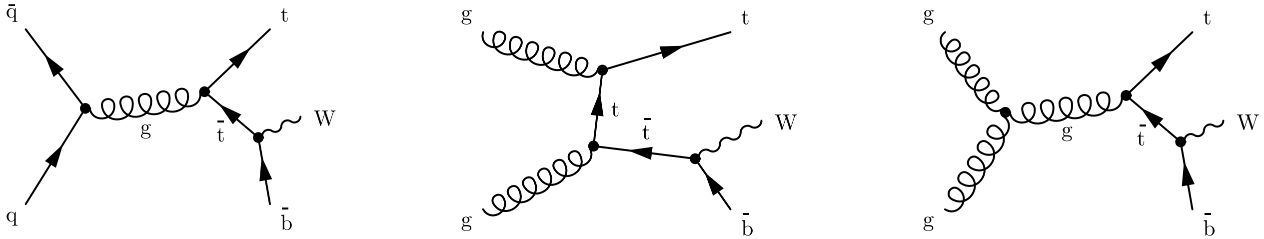
arXiv:2403.02126	*t*-channel XS	13	140

SINGLE TOP PRODUCTION, tW CHANNEL

JHEP 07 (2023) 046



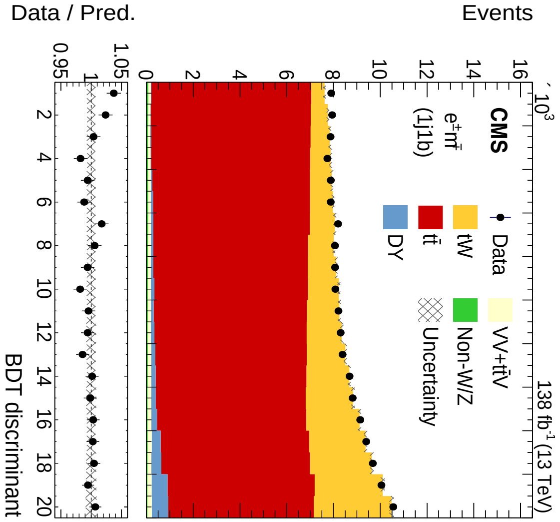
- tW channel is not observed at the Tevatron
- Both strong and weak processes are involved.
- $\bar{t}t$ production interferes with the signal; two schemes may be employed to remove the effect:
  - Diagram removal (DR)
  - Diagram subtraction (DS)
- *Alternately, study the $\bar{b}b\bar{\nu}\nu\ell^+\ell^-$ final state with all interference effects accounted for.*

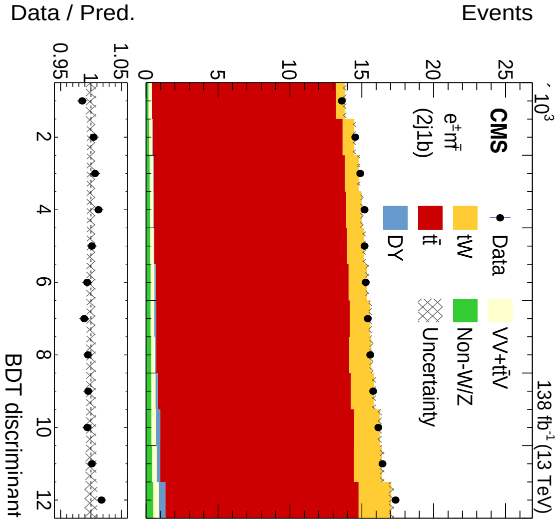


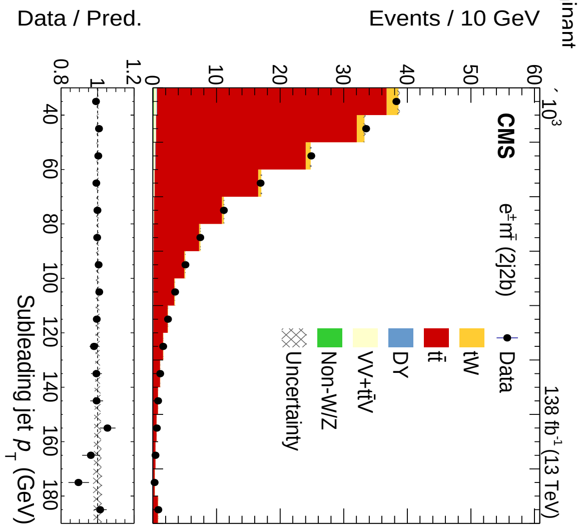
(Diagrams which are/ interfere with with $\bar{t}t$ production)

tW CHANNEL IN CMS 13 TEV

- 138 fb^{-1} of data in Run II used
- Dilepton $e^{\pm}\mu^{\mp}$ events are used
- Three regions defined
  - 1 jet, 1 b-tagged jet with significant signal fraction
  - 2 jets, 1 b-tagged jet with significant signal fraction
  - 2 jets, 2 b-tagged jets with little signal, constrains the $\bar{t}t$ background.



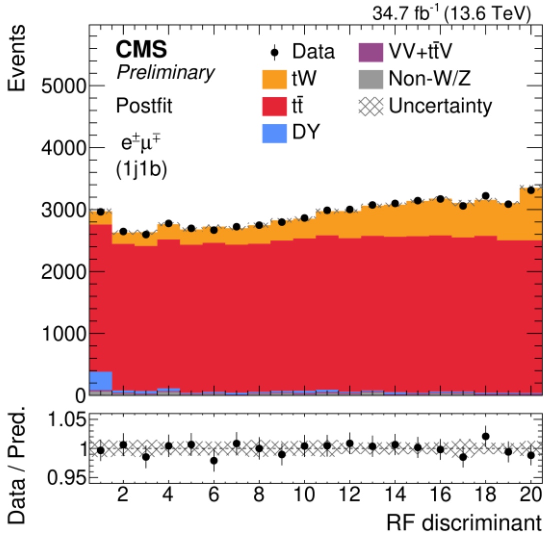


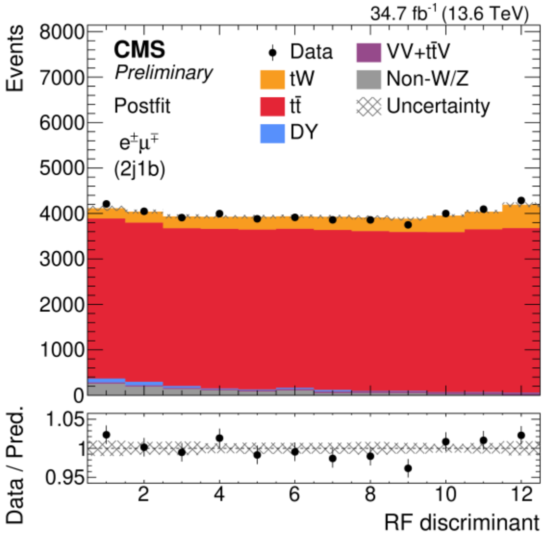


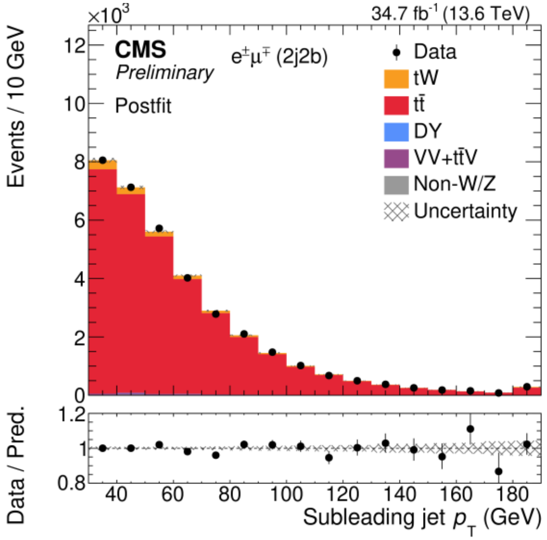
The three distributions on this page are input to a maximum log likelihood fit.

tW CHANNEL IN CMS 13.6 TEV

- 34.7 fb^{-1} of data in Run 3 used
- Dilepton $e^{\pm}\mu^{\mp}$ events are used
- Three regions defined
  - 1 jet, 1 b-tagged jet with significant signal fraction
  - 2 jets, 1 b-tagged jet with significant signal fraction
  - 2 jets, 2 b-tagged jets with little signal, constrains the $\bar{t}t$ background.

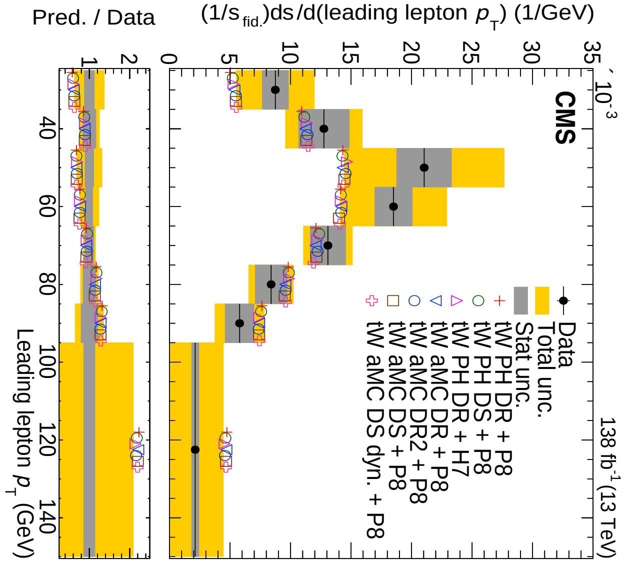


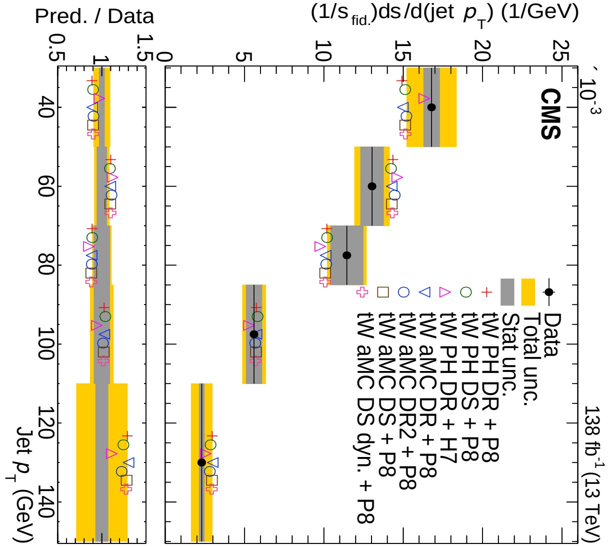


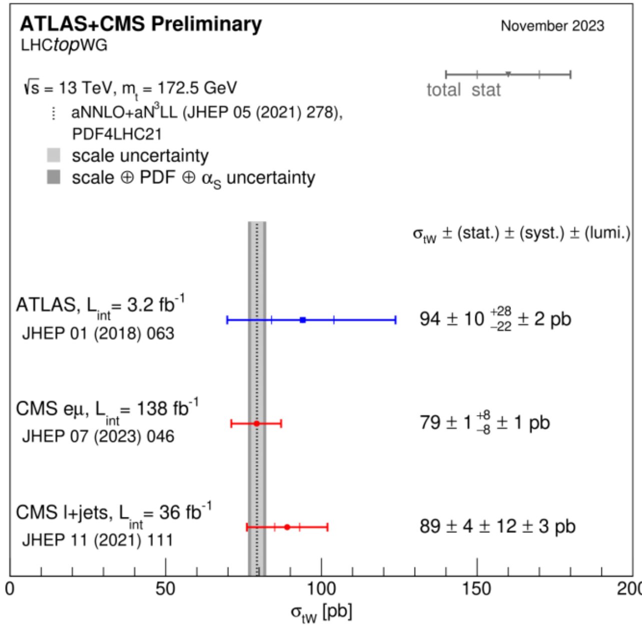


The three distributions on this page are input to a maximum log likelihood fit.

tW ASSOCIATED PRODUCTION AT $\sqrt{s} = 13$ TEV







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

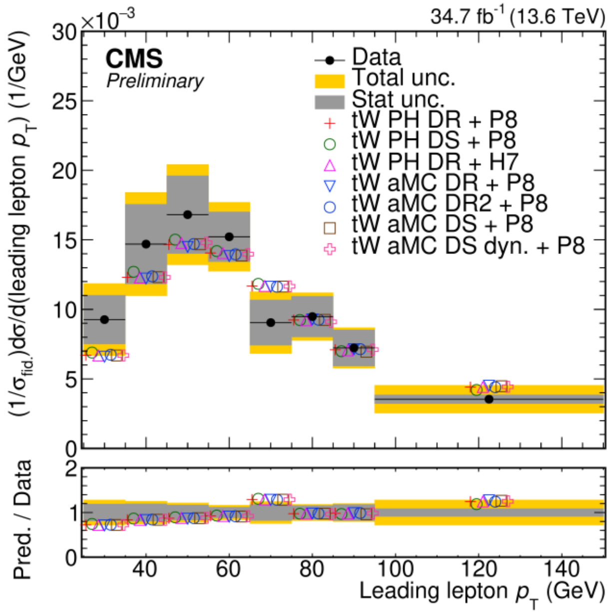
Cf. Theory $\sigma(tW) = 71.7 \pm 1.8(\text{scale}) \pm 3.4\ (\alpha_S, \text{PDF})$ pb [aNNLO+aN³LL]

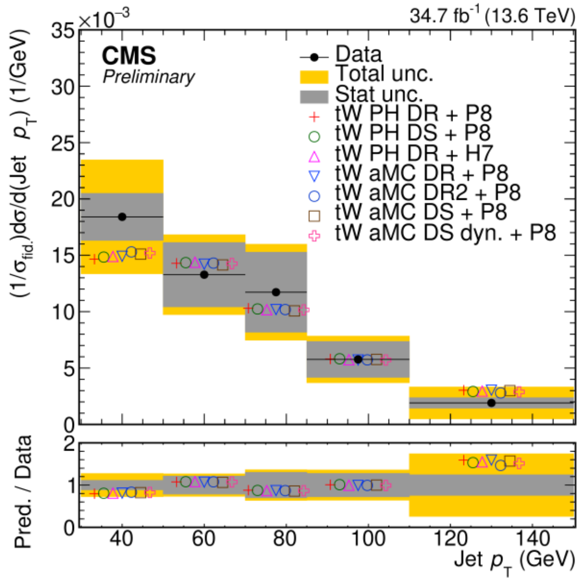
P-values for differential distributions:

Variable	PH DR + P8	PH DS + P8	PH DR + H7
Leading lepton p_T	0.02	0.01	0.03
Jet p_T	0.14	0.27	0.01
$\Delta\varphi(e^{\pm},\mu^{\mp})/\pi$	0.26	0.29	0.32
$p_z(e^{\pm},\mu^{\mp},j)$	0.70	0.77	0.82
$m_T(e^{\pm},\mu^{\mp},j,\vec{p}_T^{\,miss})$	0.54	0.60	0.59
$m(e^{\pm},\mu^{\mp},j)$	0.03	0.02	0.28

JHEP 07 (2023) 046 | tW XS | 13 TeV | 138 fb^{-1}

tW ASSOCIATED PRODUCTION AT $\sqrt{s} = 13.6$ TEV





$\sigma(tW) = 84.1 \pm 2.1(\mathrm{stat})^{+9.8}_{-10.2}(\mathrm{syst}) \pm 3.3(\mathrm{lumi})$ pb

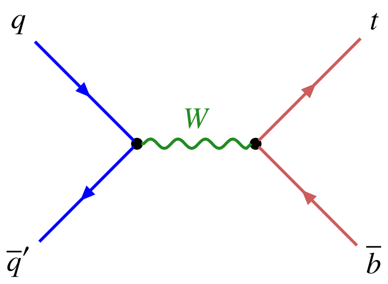
Cf. Theory $\sigma(tW) = 87.9^{+2.0}_{-1.9}(\mathrm{scale}) \pm 2.4\ (\alpha_S, \mathrm{PDF})$ pb [aNNLO+aN³LL]

P-values for differential distributions:

Variable	PH DR + P8	PH DS + P8	PH DR + H7
Leading lepton p_T	0.96	0.98	0.96
Jet p_T	0.96	0.97	0.97
$\Delta\varphi(e^{\pm}, \mu^{\mp})/\pi$	0.94	0.94	0.93
$p_z(e^{\pm}, \mu^{\mp}, j)$	0.96	0.96	0.96
$m_T(e^{\pm}, \mu^{\mp}, j, \vec{p}_T^{\mathrm{miss}})$	0.78	0.75	0.79
$m(e^{\pm}, \mu^{\mp}, j)$	0.95	0.93	0.95

CMS-PAS-TOP-23-008 | tW XS | 13.6 TeV | 34.7 fb^{-1}

S-CHANNEL ELECTROWEAK PRODUCTION



- Low expected cross section at LHC ($\sigma^{SM} = 10.32^{+0.40}_{-0.36}$ pb @ 13 TeV)
  - Anomalies could indicate W', b' or H^+ production or modified couplings
- But favorable conditions at the Tevatron led to observation in 2014 [Phys. Rev. Lett. **112** (2014) 231803]
- Previously measured at $\sqrt{s}$=7 TeV(CMS), 8 TeV (CMS, ATLAS)

ATLAS EXPERIMENT

- At 13 TeV, ATLAS measures the cross section using the lepton+jets final state
  - Main backgrounds are $\bar{t}t$ and W+jets
  - A Matrix Element based discriminant is used to separate signal (based on calculable probability densities)
  - Normalization of the W+jets background and $t\bar{t}$ background is determined from control regions.

CROSS SECTION MEASUREMENT:

Discriminent is based on likelihood for process H_{proc} ∈{signal, $\bar{t}t$, W+jets}, conditional on final state particle kinematic quantities X, those being p_T and η

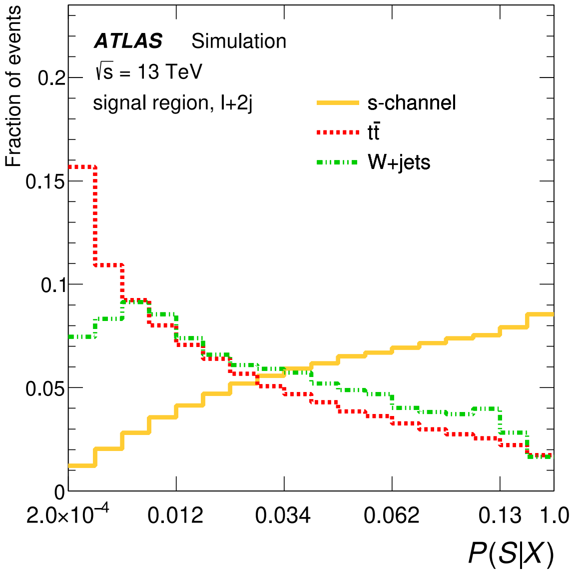
$$\mathcal{P}(X \mid H_{\text{proc}}) = \int \mathrm{d}\Phi \, \frac{1}{\sigma_{H_{\text{proc}}}} \frac{\mathrm{d}\sigma_{H_{\text{proc}}}}{\mathrm{d}\Phi} T_{H_{\text{proc}}}(X \mid \Phi) \, .$$

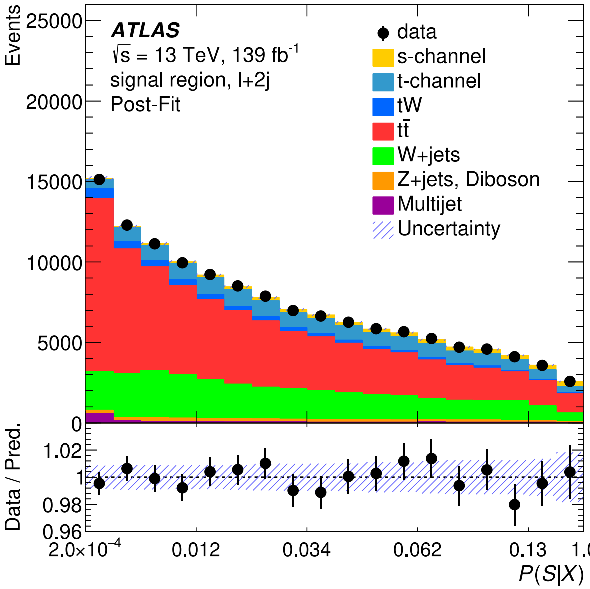
Parton-level cross sections $d\sigma/d\Theta$ from analytic calculation.
Transfer functions T from simulation
Computed for signal, top and W+jets backgrounds.
The likelihood ratio is used as the discriminant, $P(S|X)$

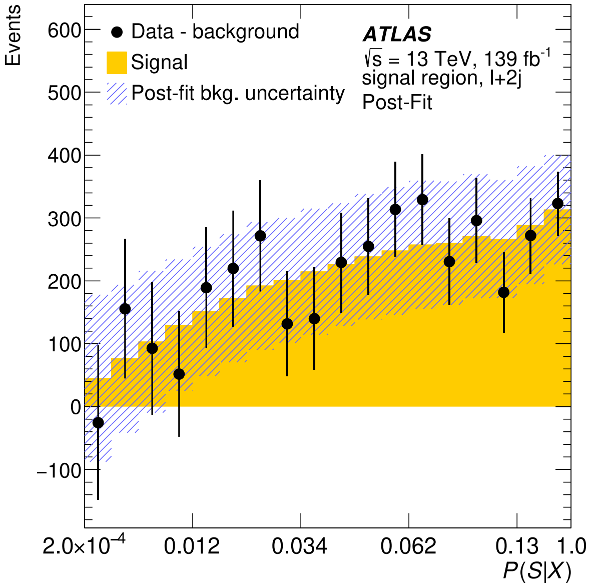
$$\sigma = 8.2^{+3.5}_{-2.9}\ \text{pb}$$

Cf. NLO Prediction

$$\sigma = 10.32^{+0.40}_{-0.36}\ \text{pb}$$

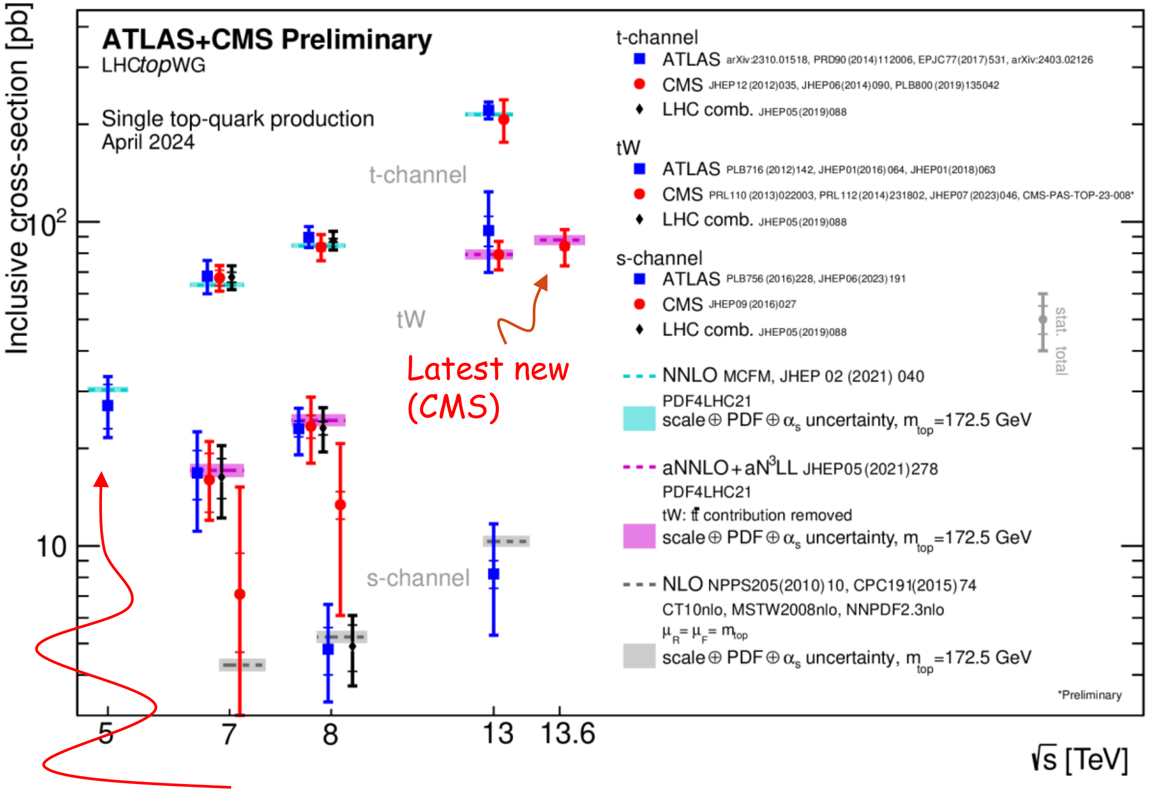


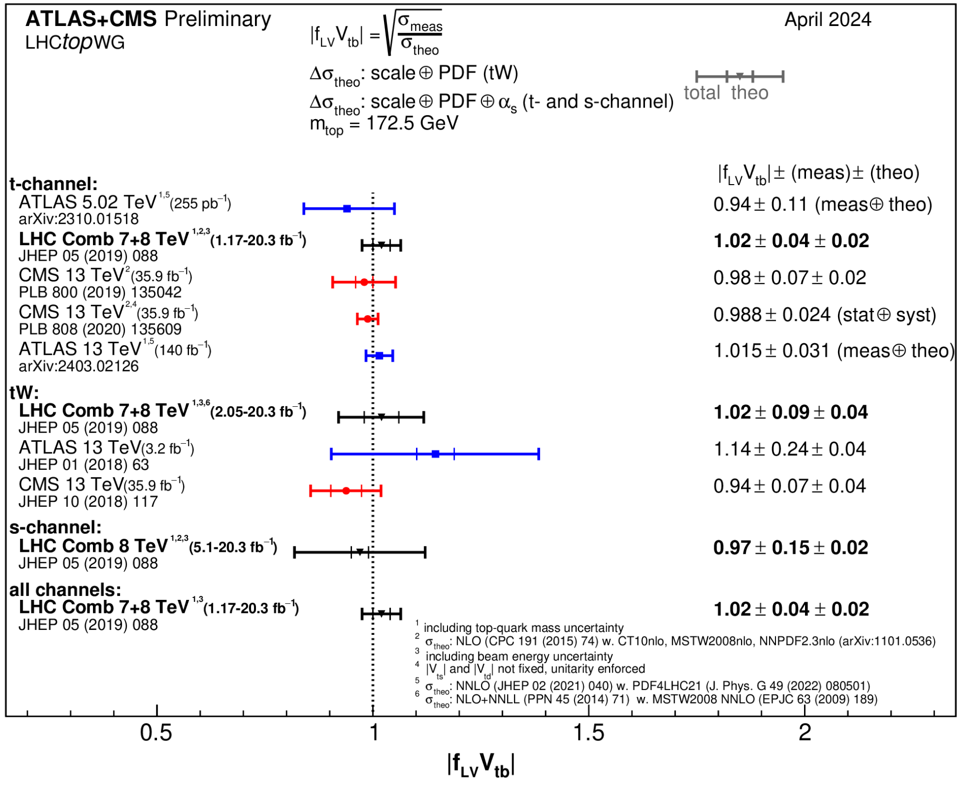




SUMMARY OF SINGLE TOP QUARK PRODUCTION CROSS SECTIONS

[LHC top working group summary plots](#)
and ATL-PHYS-PUB-2024-006





New point from ATLAS@ 5 TeV, `arXiv:2310.01518`

CONCLUSIONS

- Cross section measurements of $t\bar{t}$ and single top t, tW, and s-channel production have been carried out at 5, 7, 8, 13, and 13.6 GeV in pp collisions and also p-Pb collisions at 8 TeV.
- These measurements are in agreement with the standard model.
  - Uncertainties of less than 2% have been obtained, thanks to improvements in lumi measurement.
  - Dominant uncertainty is still luminosity, whose error has reached sub-percent level.
  - Differential measurements indicate softer p_T distributions than NNLO predictions
- The most common interpretation of these results is in terms of $\alpha_s(M_Z)$, the top quark pole mass m_T^{pole}, and PDF parameters (for strong production of $t\bar{t}$).
- Single top production measures $|f_{LV}V_{tb}|$ (for electroweak production of single top), with further interpretation in terms of EFT coefficients, CKM matrix elements, four-quark interactions.
- Top production cross sections in $p-Pb$ collisions are described in `ATLAS-CONF-2023-063` and in `Phys. Rev. Lett. 119 (2017) 242001`

TABLE OF CONTENTS

BACKUP

DIGRESSION ON LUMINOSITY MEASUREMENT

- ATLAS uses LUCID II detector,
  - charge-integrating Cerenkov light detector 17m from IP
  - active material is the quartz fibers and the quartz photomultiplier windows.
  - Gain monitored with ^{207}Bi sources for stability of relative luminosity measurement
  - The Run 2 Luminosity error is 0.83%. Cf. 1.9% (8 TeV)

- CMS uses HF
  - Hadronic Forward Calorimeter
  - Steel w/ quartz fibers.
- And Pixel detector, Pixel Luminosity Telescope, and Fast Beam Condtions Monitor.
- Run 2 Luminosity of 1.2% precision achieved (Cf. 1.9% at 8 TeV)
- However stability issues, and beam-beam interactions may increase this to over 2%.

- Absolute luminosity determined through *Vandermeer scans* at low lumi.

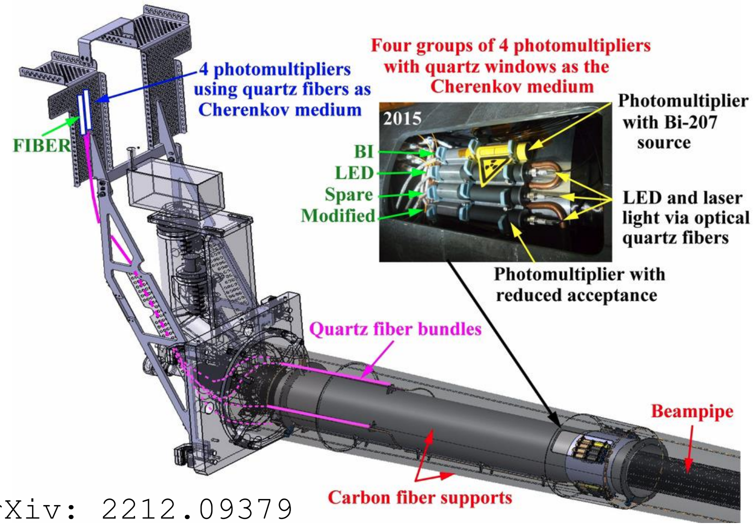
40 Mhz

from beam instrumentation

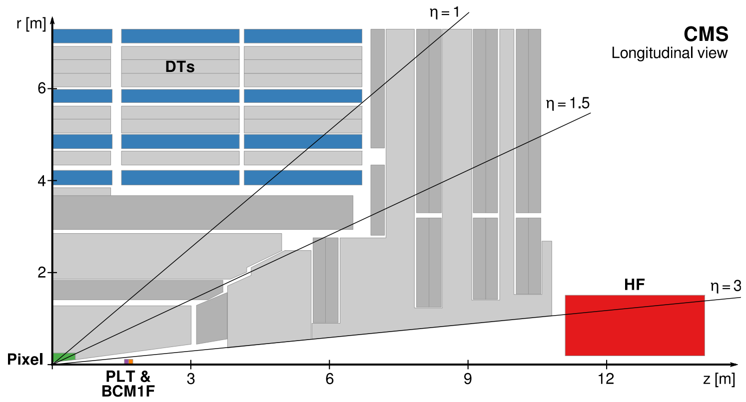
$$\mathcal{L}_b = \frac{f n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

Convolved Beam sizes

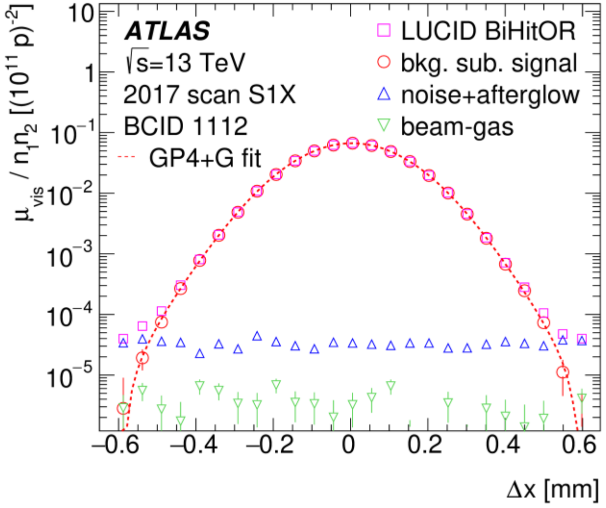
From VDM scan

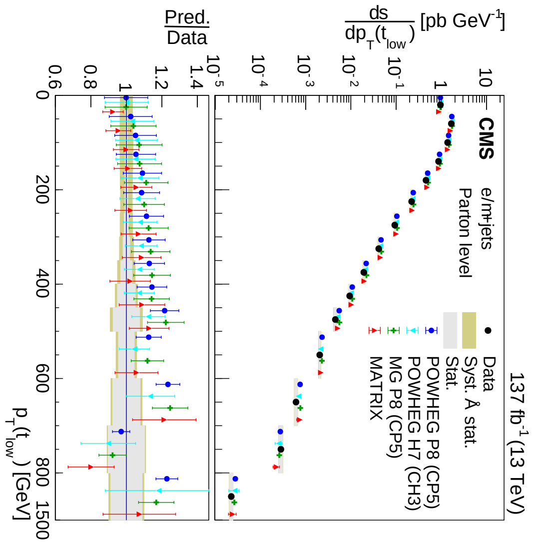


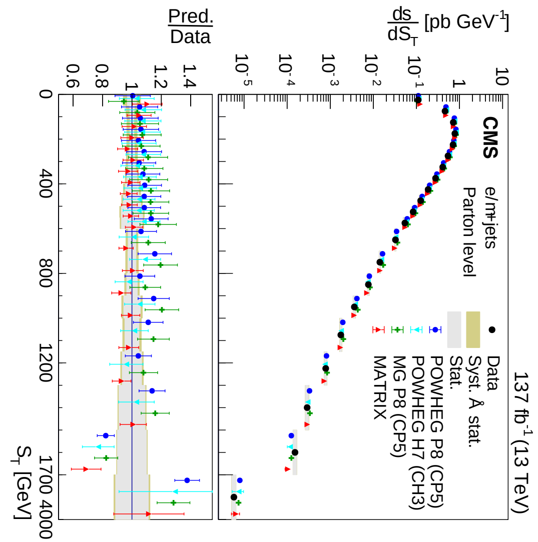
arXiv: 2212.09379



Eur Phys. J. C. 81 (2021) 800

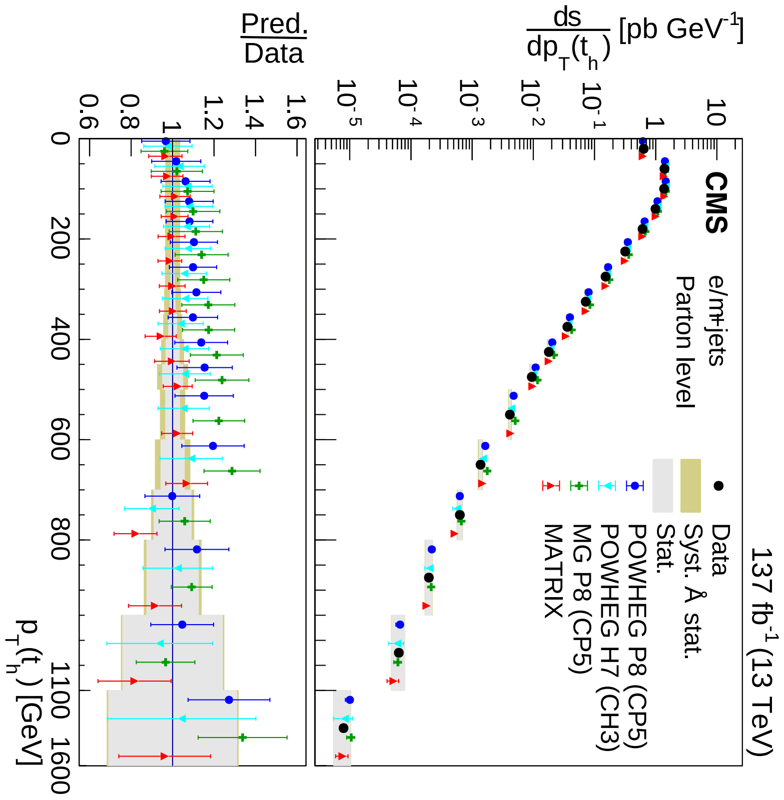


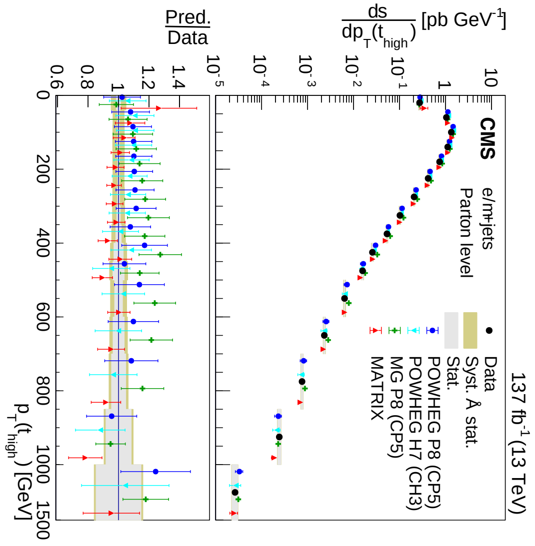


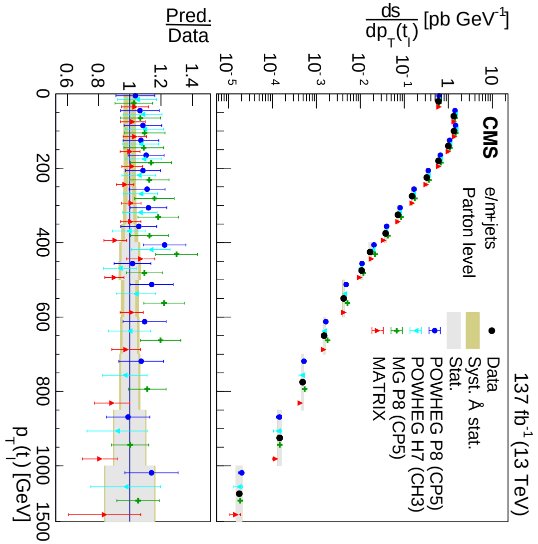


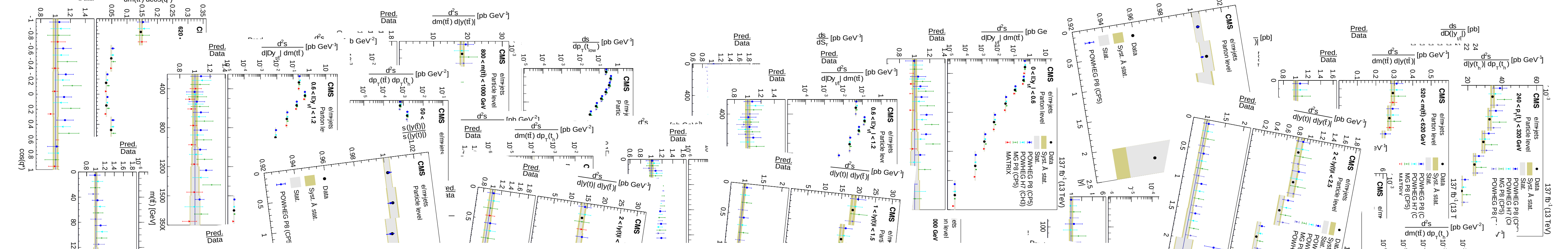
Differential and double-differential cross sections in lepton+jets mode.

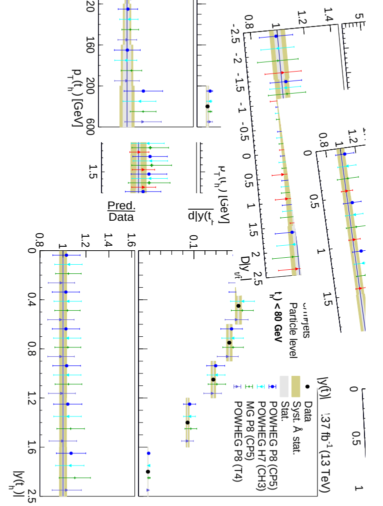
Parton level comparisons include POWHEG (NLO) and MATRIX (NNLO) w / significantly smaller errors.



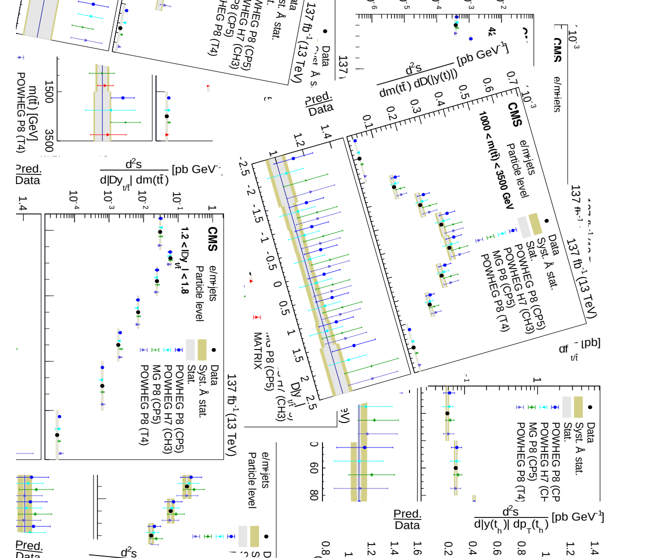


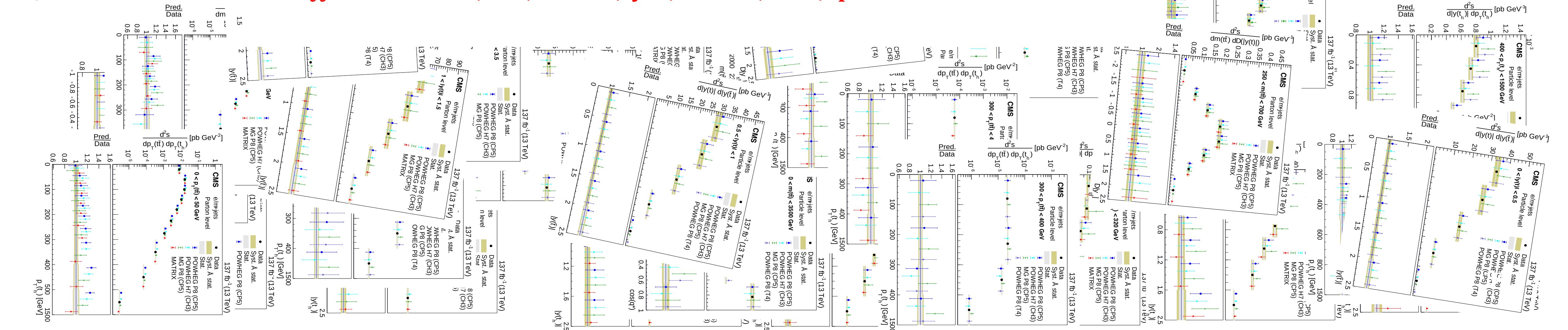






- Most distributions agree with
  - Powheg+Pythia
  - Powheg+Herwig
  - MG5_aMC@NLO+Pythia
- Top Quark p_T distributions softer than most NLO predictions
- Jet multiplicies and related observables are not well predicted by Powheg+Herwig and MG5_aMC@NLO+Pythia
- Tabulated data available in HEPData
- $\sigma_{t\bar{t}} = 791 \pm 1(\text{stat}) \pm 21(\text{syst}) \pm 14(\text{lumi})\ \text{pb}$





WHAT CAN BE DONE WITH THIS WEALTH OF INFORMATION?

Lepton+jets mode, 35.9 fb^{-1} of data at 13 TeV.

Eur. Phys. J. C. 80 (2020) 658

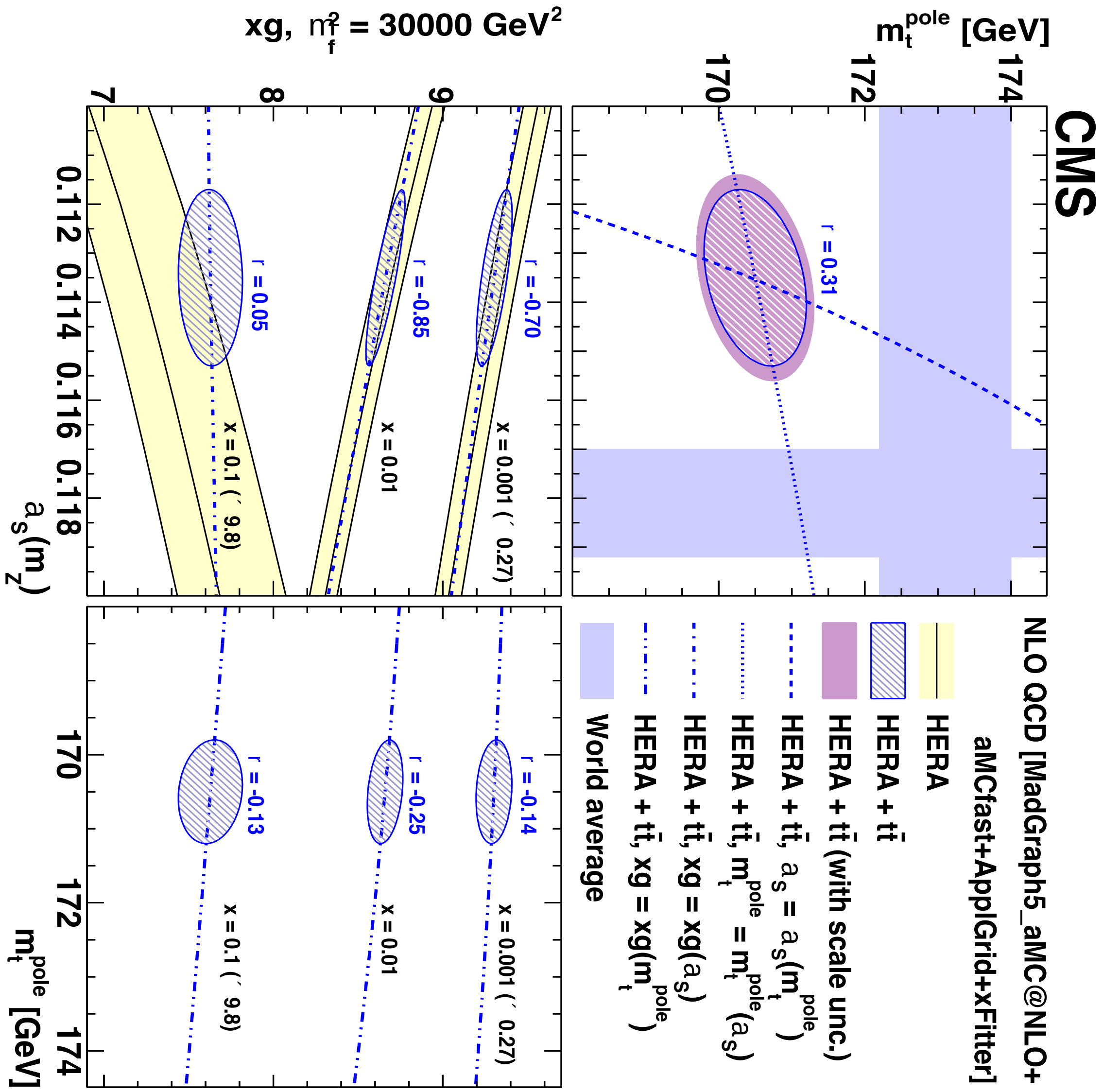
Double and triple-differential cross sections are analyzed.

From the triple-differential cross section in the variables $M(t\bar{t}), y(t\bar{t})$, and N_{jets} CMS determines

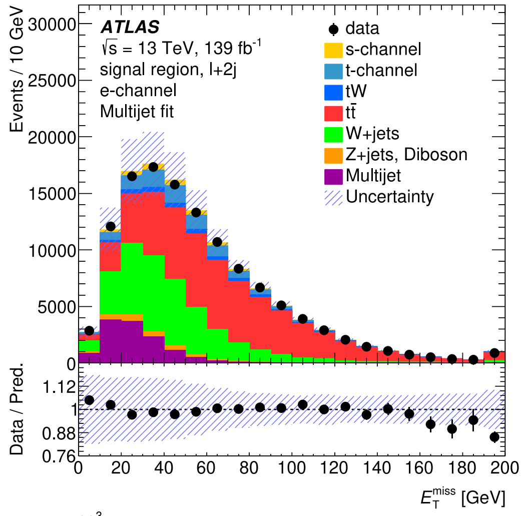
- $\alpha_s(M_Z) = 0.1135^{+0.0021}_{-0.0017}$
- $m_t^{pole} = 170.5 \pm 0.8$ GeV

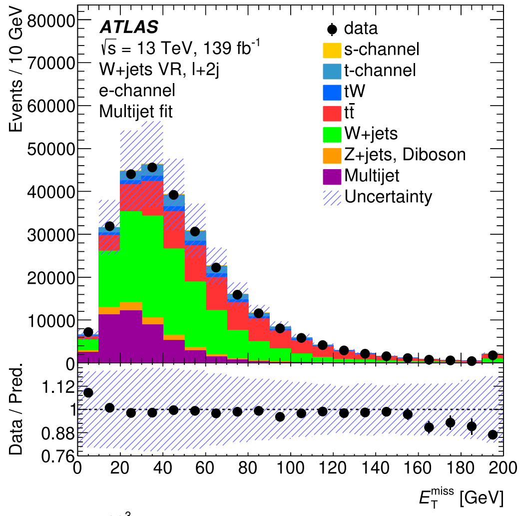
High precision extractions

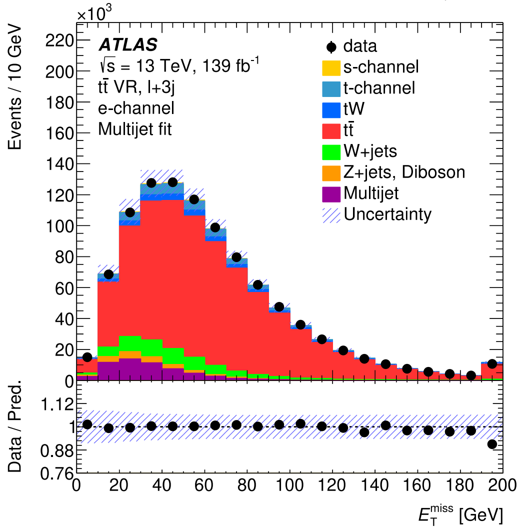
In CMS's Phys. Rev. D 104 (2021) 092013 (previous page) , such interpretations are left to the theoretical community.

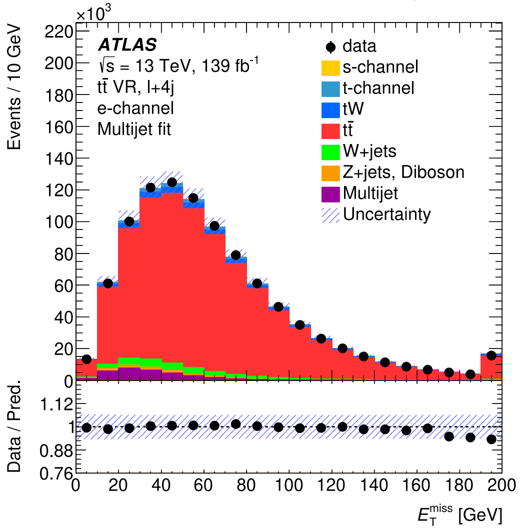


MULTIJET BACKGROUND DETERMINATION









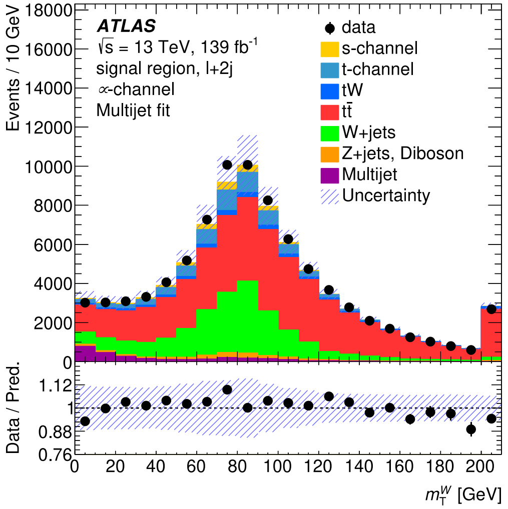
Multijet backgrounds estimated using

- "jet-electron" MC-based method for electrons.
- "anti—muon" data-based method for muons.

- Fits to E_T^{miss} (electron) or m_T^W (muon) used to set normalization.

← Shown for all four regions for electrons

Shown for signal region only for muons →



- Most bkg is removed by cuts.