

Top production and decay

9th Edition of the Large Hadron Collider Physics Conference

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on behalf of the ATLAS, CMS & LHCb collaborations

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► Introduction

- Top quark production at the LHC

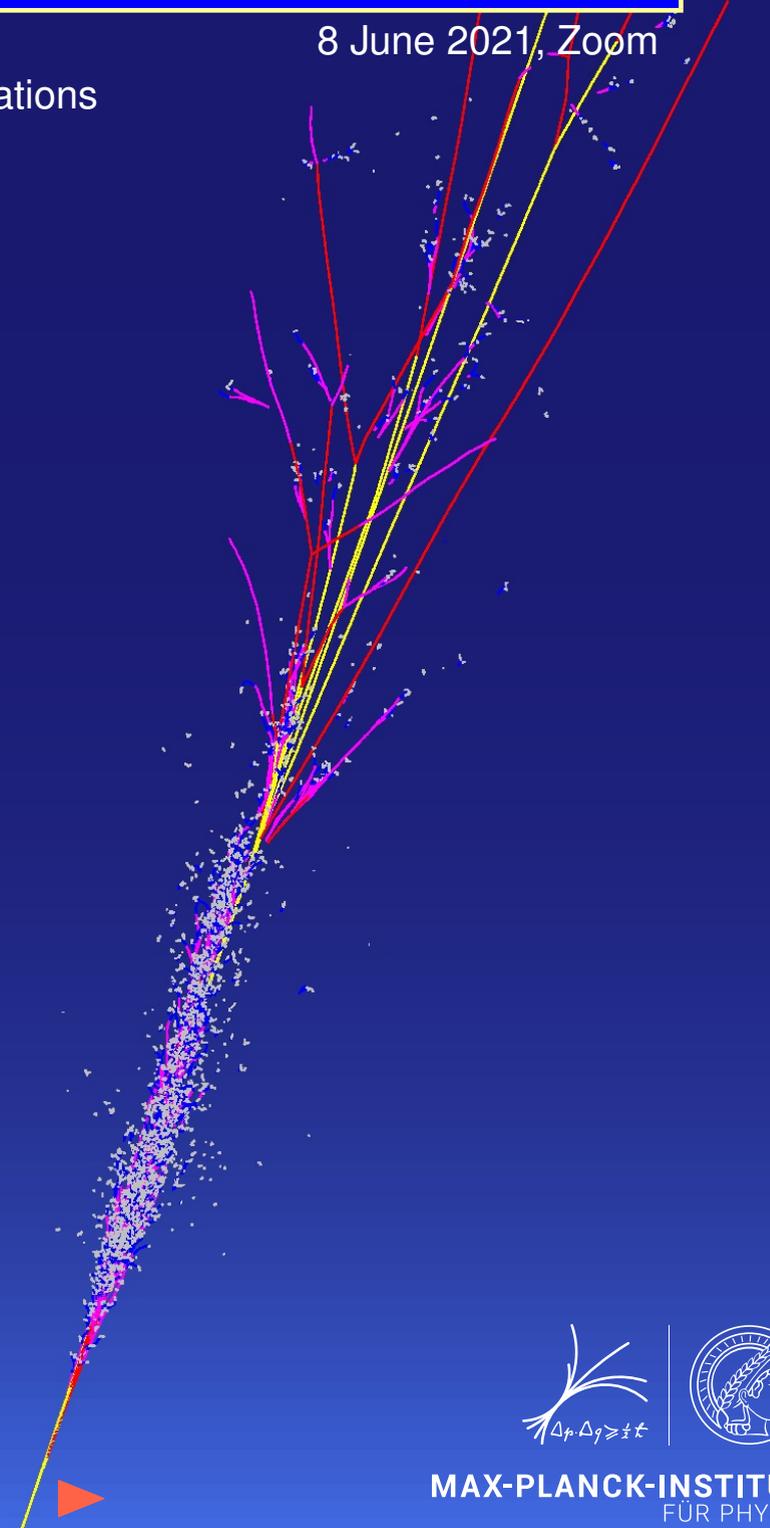
► Cross sections

- Pair production of top quarks
- Single top quark production

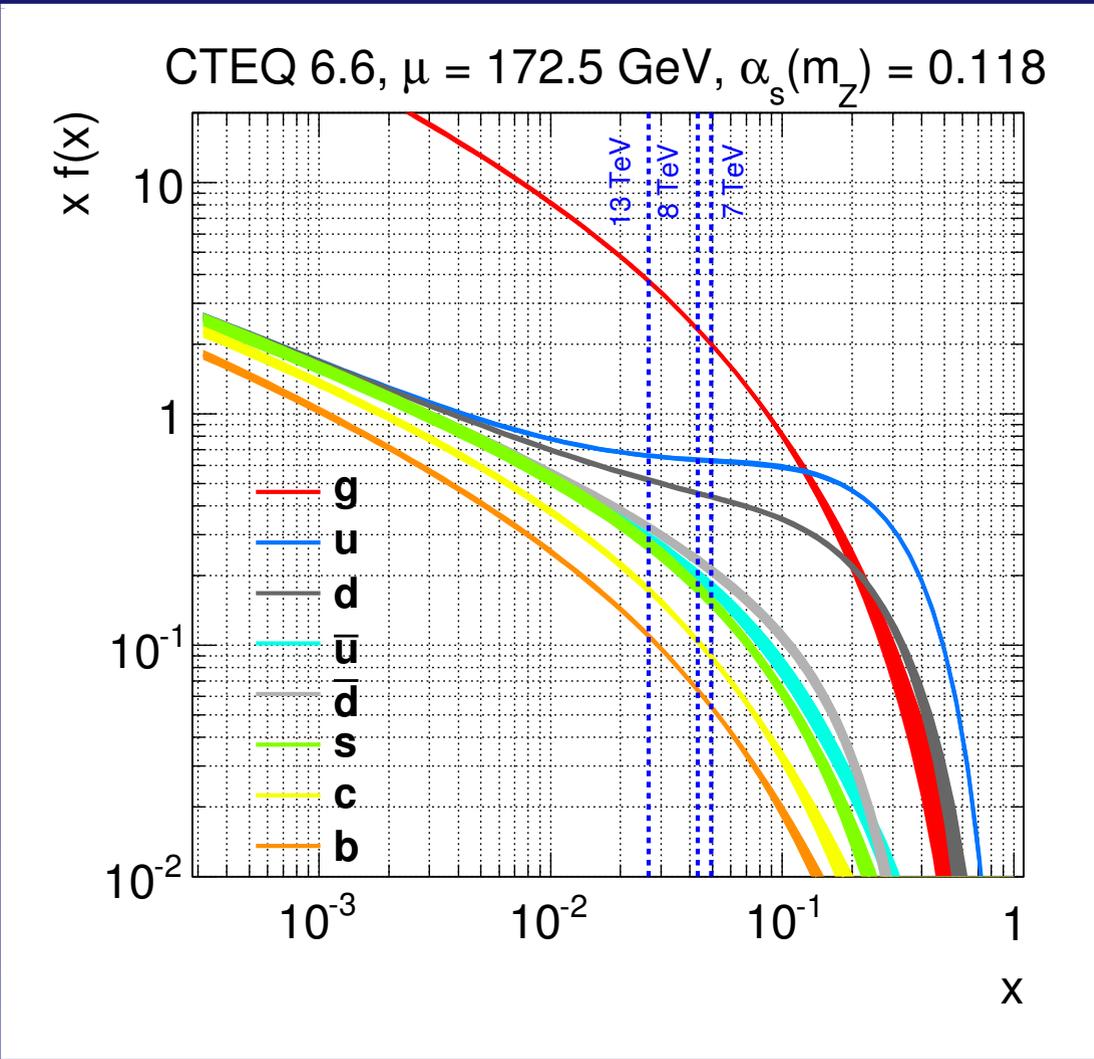
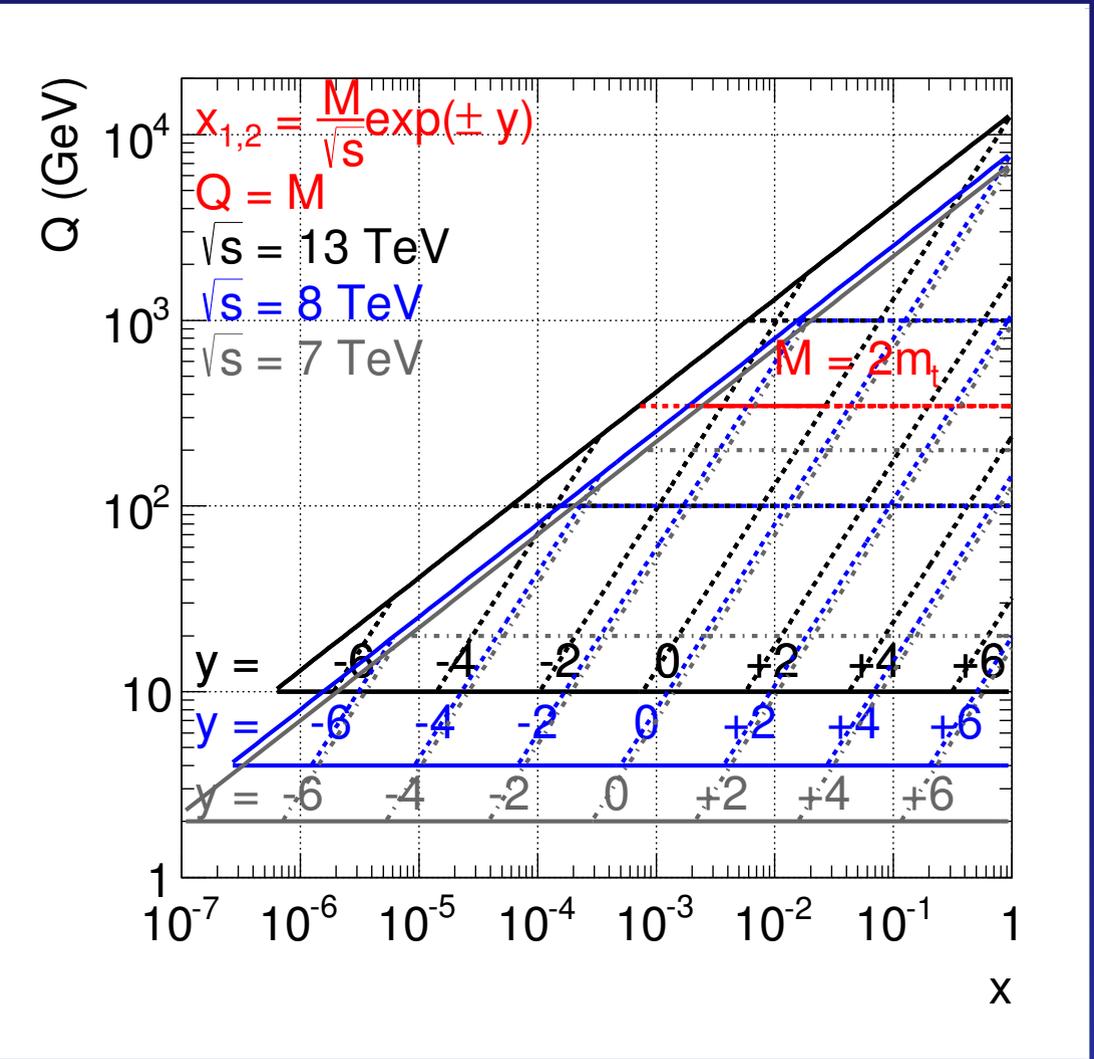
► Top quark properties and tests in top quark decays

- Lepton universality
- W boson helicity
- Test of CP violation
- b fragmentation
- Top quark polarisation
- Top quark mass

► Conclusions



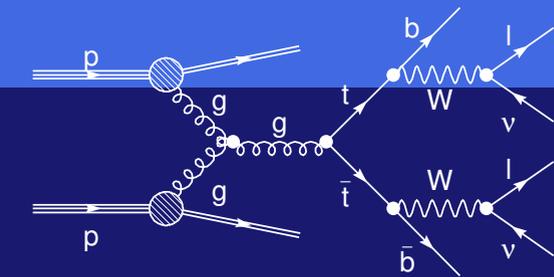
Kinematics at the LHC ▶ $t\bar{t}$ production



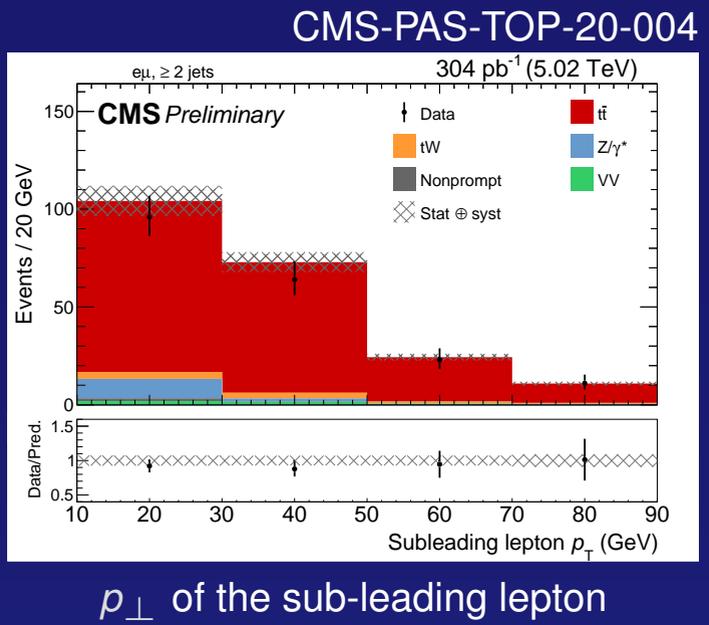
- ▶ Q vs. $x_{1,2}$ for the LHC at 7, 8, and 13 TeV (left)
- ▶ Red curve shows top-pair production as example
- ▶ QCD measurements constrain α_s and PDF's – here CTEQ 6.6 (right)

- ▶ Measuring top-quark production at different \sqrt{s} allows to vary the production mechanism (more gluons at higher \sqrt{s})
- ▶ There is even a small dataset at $\sqrt{s} = 5.02 \text{ TeV}$ where $t\bar{t}$ production has been measured
 - ▶ with $\sim 2.3\times$ higher quark-pair fraction compared to 13 TeV

Cross sections ▶ Pair production of top quarks



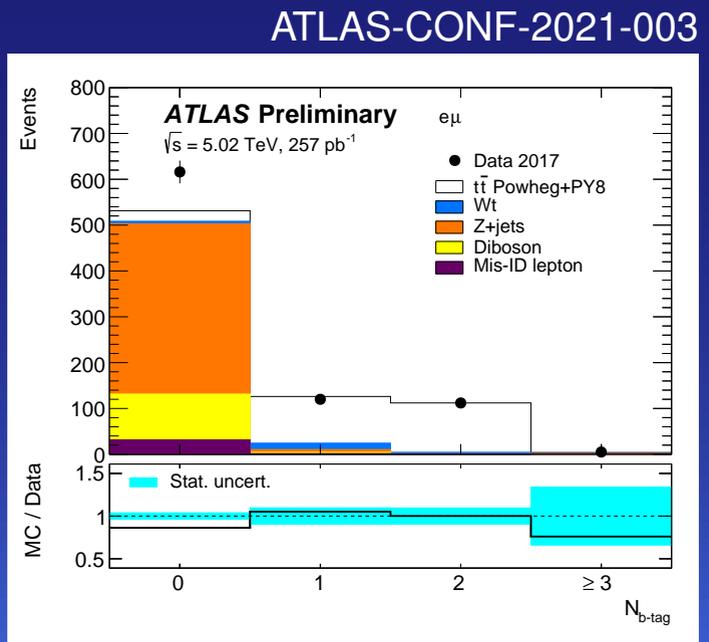
▶ The Di-Lepton channel provides the cleanest sample of $t\bar{t}$ events



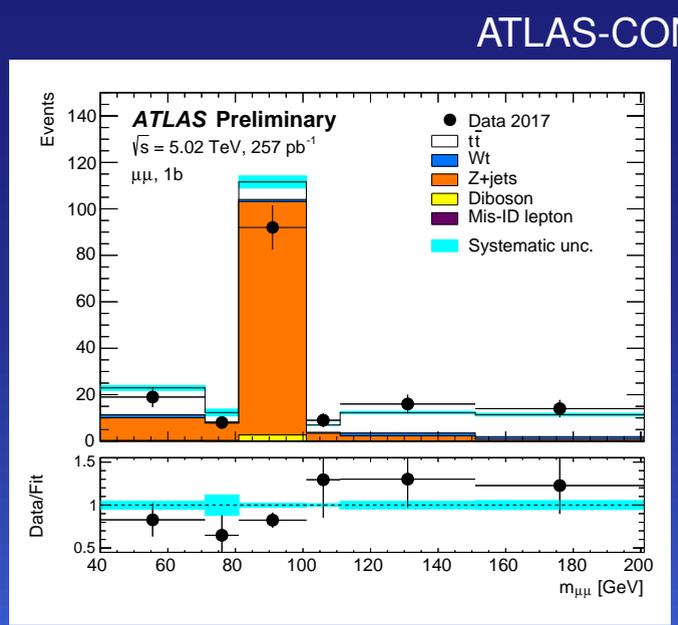
▶ Measurements of $\sigma_{t\bar{t}}$ have been done at 7, 8 and 13 TeV in this channel but most recently the small $\sqrt{s} = 5.02$ TeV pp datasets have been analysed as well by CMS and ATLAS

▶ Event selection for $\sigma_{t\bar{t}}$ @5.02 TeV

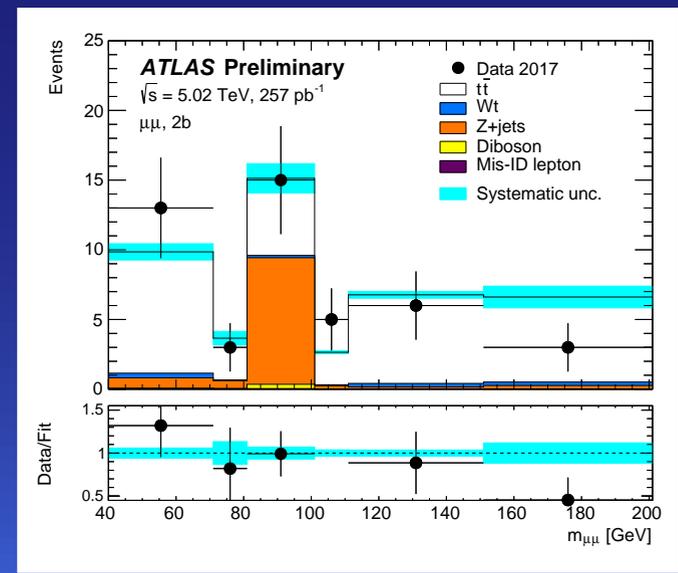
- Exactly two central, isolated and oppositely charged leptons
- Corresponding same-flavour lepton samples used to estimate background
- Keep events with exactly 1 or 2 b-tagged jets (ATLAS) or at least 2 jets (with or without b-tag) (CMS)



Number of b-tagged jets



$m_{\mu\mu}$ for Z + jet bkgd scale for 1 (2) b-tag(s)



Cross sections ▶ Pair production of top quarks

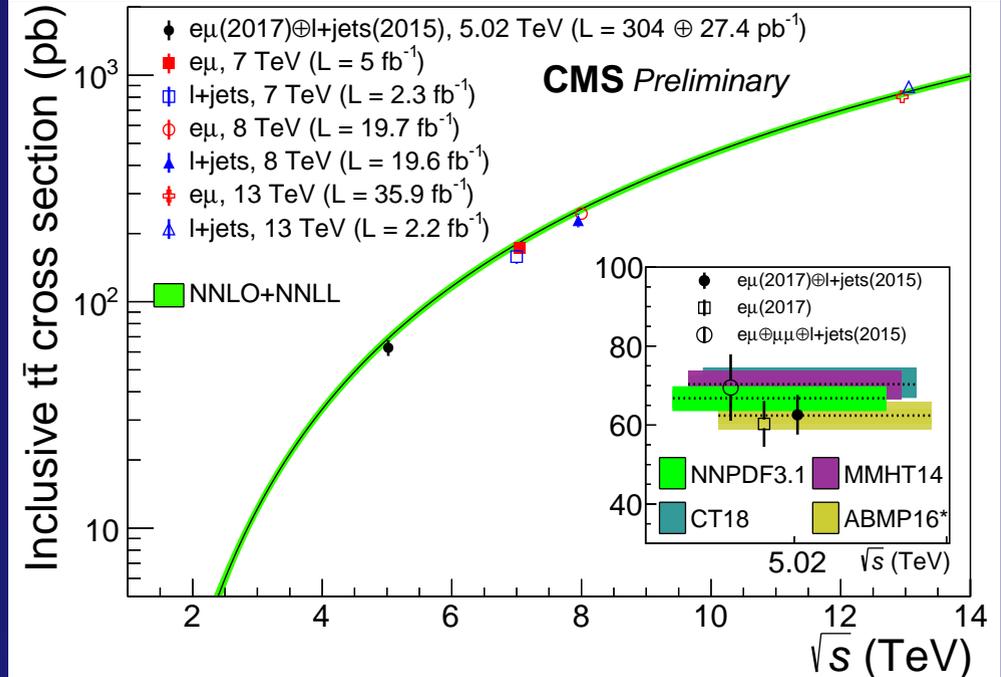
▶ Counting experiment by CMS in $e^\pm \mu^\mp$ -channel

- integrated luminosity: $L = 304 \text{ pb}^{-1}$

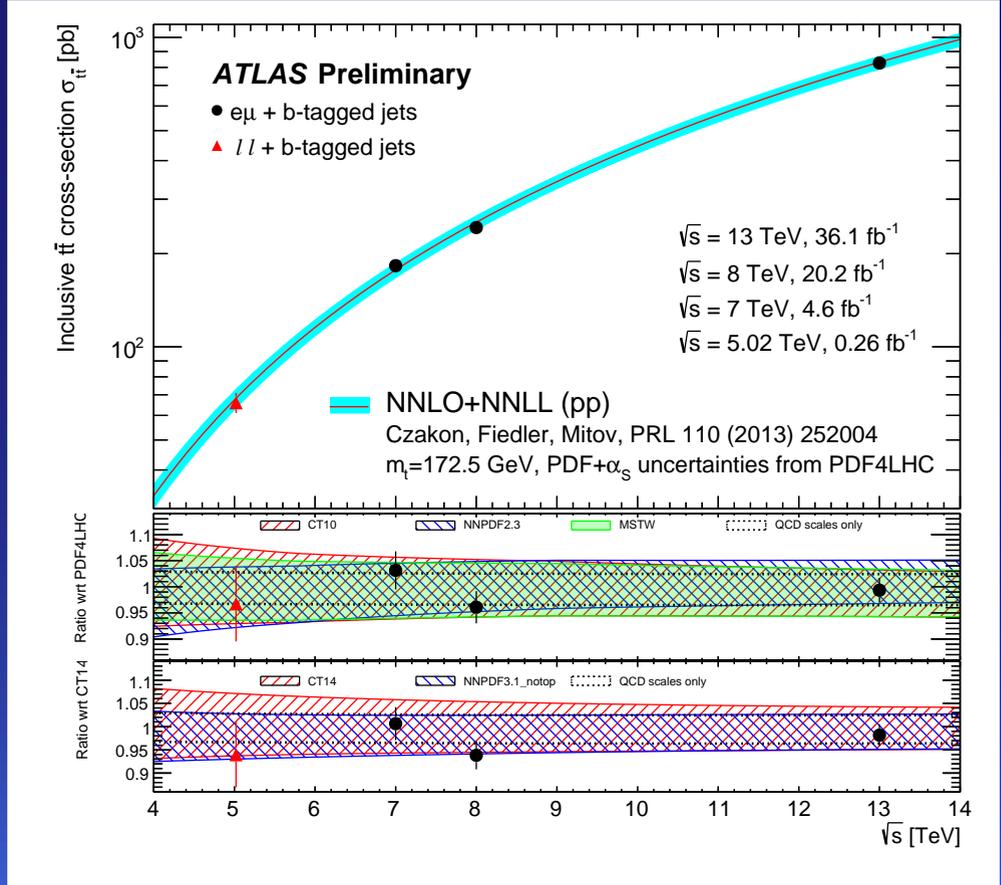
▶ $\sigma_{t\bar{t}}(5.02 \text{ TeV})^{\text{CMS}} = 60.3 \pm 5.0_{\text{stat}} \pm 2.8_{\text{syst}} \pm 0.9_{\text{lumi}} \text{ pb} = 60.3 \pm 5.5_{\text{tot}} \text{ pb}$

- open square in plot: 2017 $e\mu$ -result
- open circle: 2015 result (lepton+jets and di-lepton)
- closed circle: combination 2015 and 2017

CMS-PAS-TOP-20-004



ATLAS-CONF-2021-003



▶ Fit of $\sigma_{t\bar{t}}$ to number of $e\mu$, ee and $\mu\mu$ events with exactly 1 or 2 b-tagged jets in ATLAS

- 6 $m_{\ell\ell} - m_Z$ bins to deplete/enhance background
- integrated luminosity: $L = 257 \text{ pb}^{-1}$

▶ $\sigma_{t\bar{t}}(5.02 \text{ TeV})^{\text{ATLAS}} = 66.0 \pm 4.5_{\text{stat}} \pm 1.6_{\text{syst}} \pm 1.2_{\text{lumi}} \pm 0.2_{\text{beam}} \text{ pb} = 66.0 \pm 4.9_{\text{tot}} \text{ pb}$

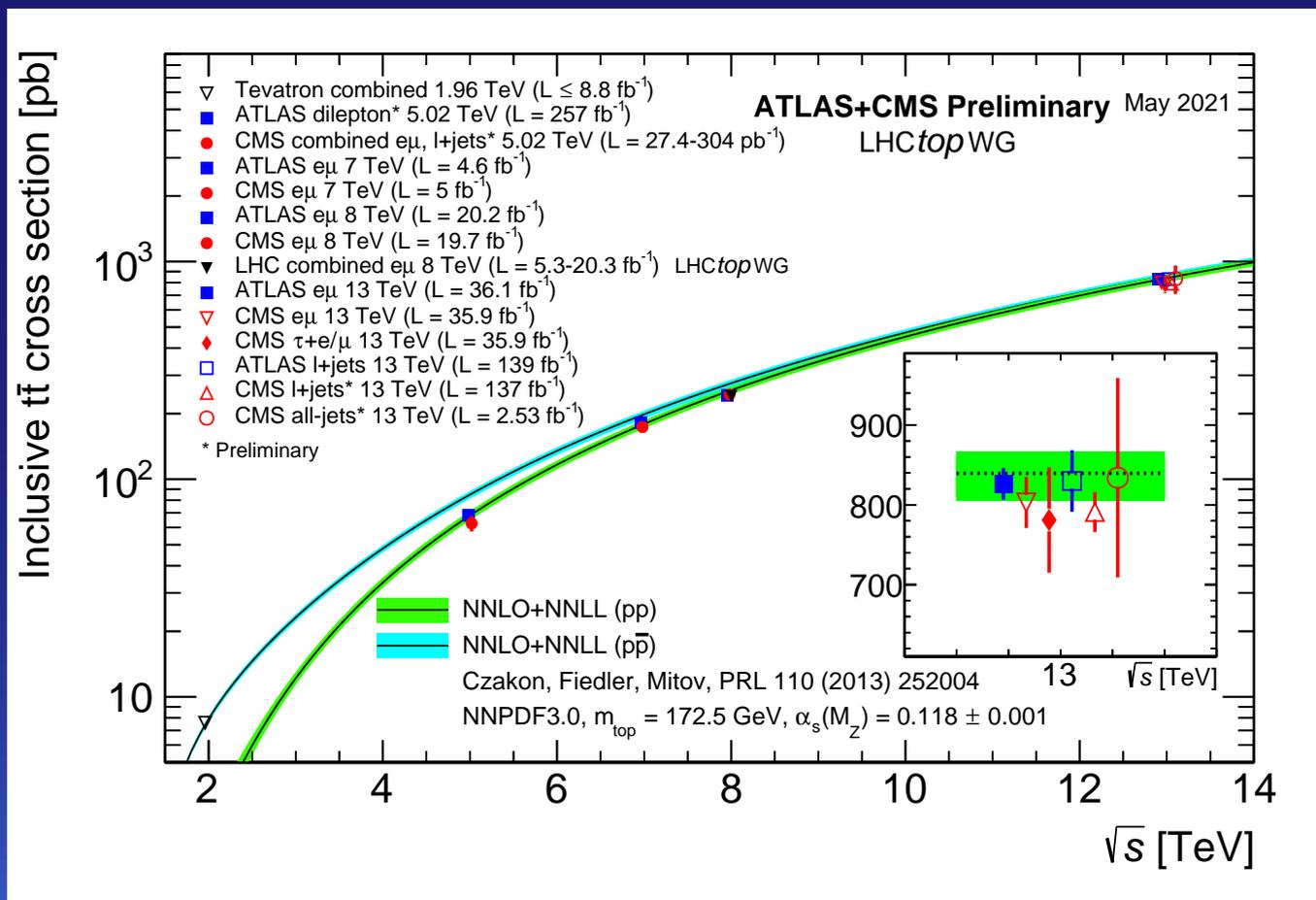
▶ Agreement with all predictions; CMS best described with **ABMP16**; ATLAS with **NNPDF2.3**

$\sigma_{t\bar{t}}$ vs. \sqrt{s}

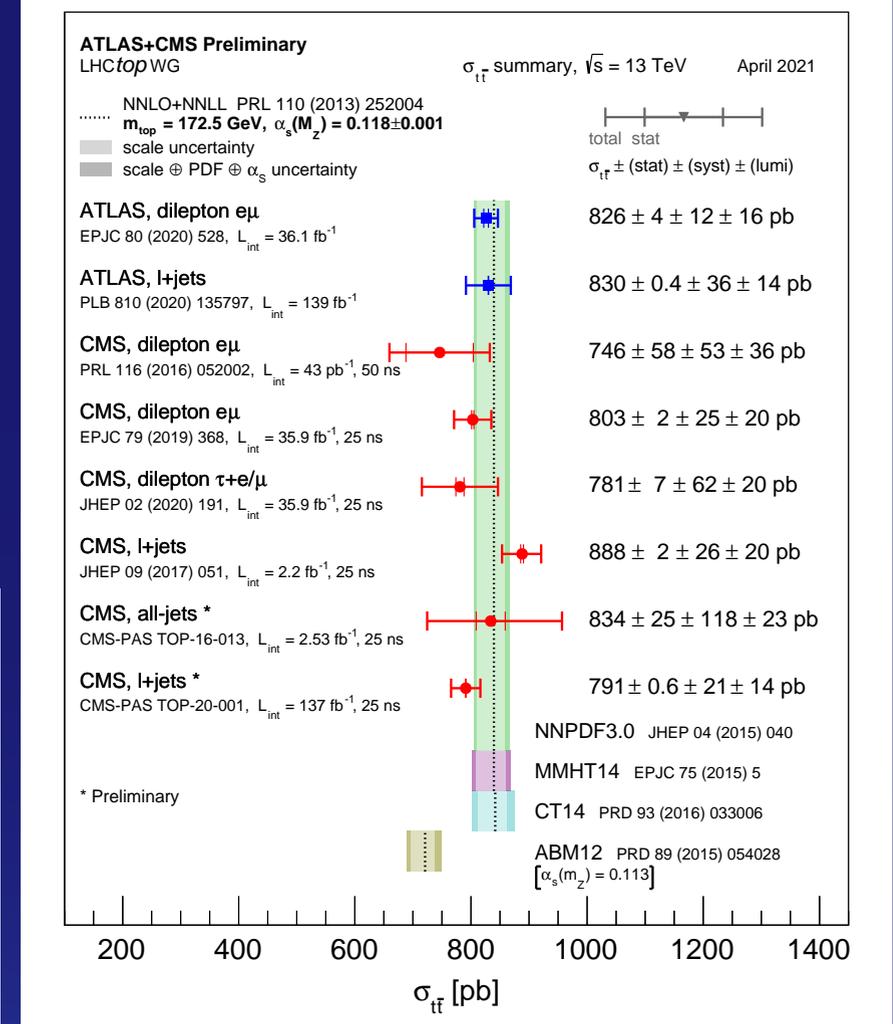
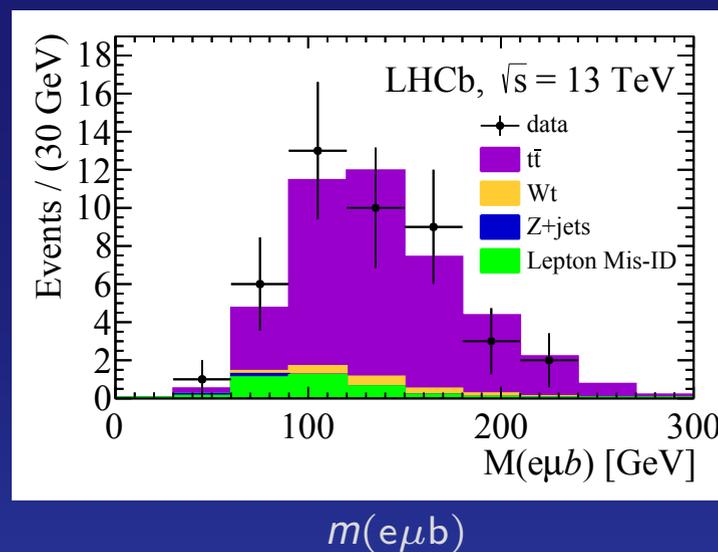
Cross sections ▶ Summary of inclusive $\sigma_{t\bar{t}}$ measurements

- ▶ ATLAS and CMS measured inclusive $\sigma_{t\bar{t}}$ @ $\sqrt{s} = 5.02, 7, 8$ and 13 TeV
- ▶ Comparison to NNLO QCD with NNLL resummation predictions (and Tevatron result for $p\bar{p}$ collisions @ 1.96 TeV) from May 2021 (below)
- ▶ 13 TeV measurements (right)

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots>



arXiv:1803.05188



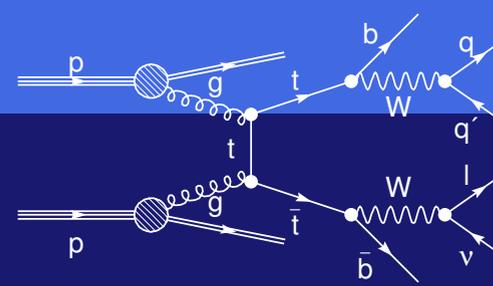
Inclusive $\sigma_{t\bar{t}}$ (13 TeV) measurements: April 2021

- ▶ in agreement with SM expectations

- ▶ LHCb measured forward top-pair production in fiducial phase-space ($\simeq 2.0 < \eta < 4.5$) @ $\sqrt{s} = 8 \text{ TeV}$ (arXiv:1610.08142) and 13 TeV (arXiv:1803.05188):

- $\sigma_{t\bar{t}}(8 \text{ TeV})^{\text{LHCb}} = 0.05^{+0.02}_{-0.01} \text{ stat }^{+0.02}_{-0.01} \text{ syst} \text{ pb}$
- $\sigma_{t\bar{t}}(13 \text{ TeV})^{\text{LHCb}} = 0.126 \pm 0.019_{\text{stat}} \pm 0.016_{\text{syst}} \pm 0.005_{\text{lumi}} \text{ pb}$

Differential cross sections ▶ Pair production of top quarks



CMS-PAS-TOP-20-001

▶ The Lepton+Jets offers best compromise between precision and statistics

▶ Differential and double-differential cross sections in full kinematic range @13 TeV by CMS

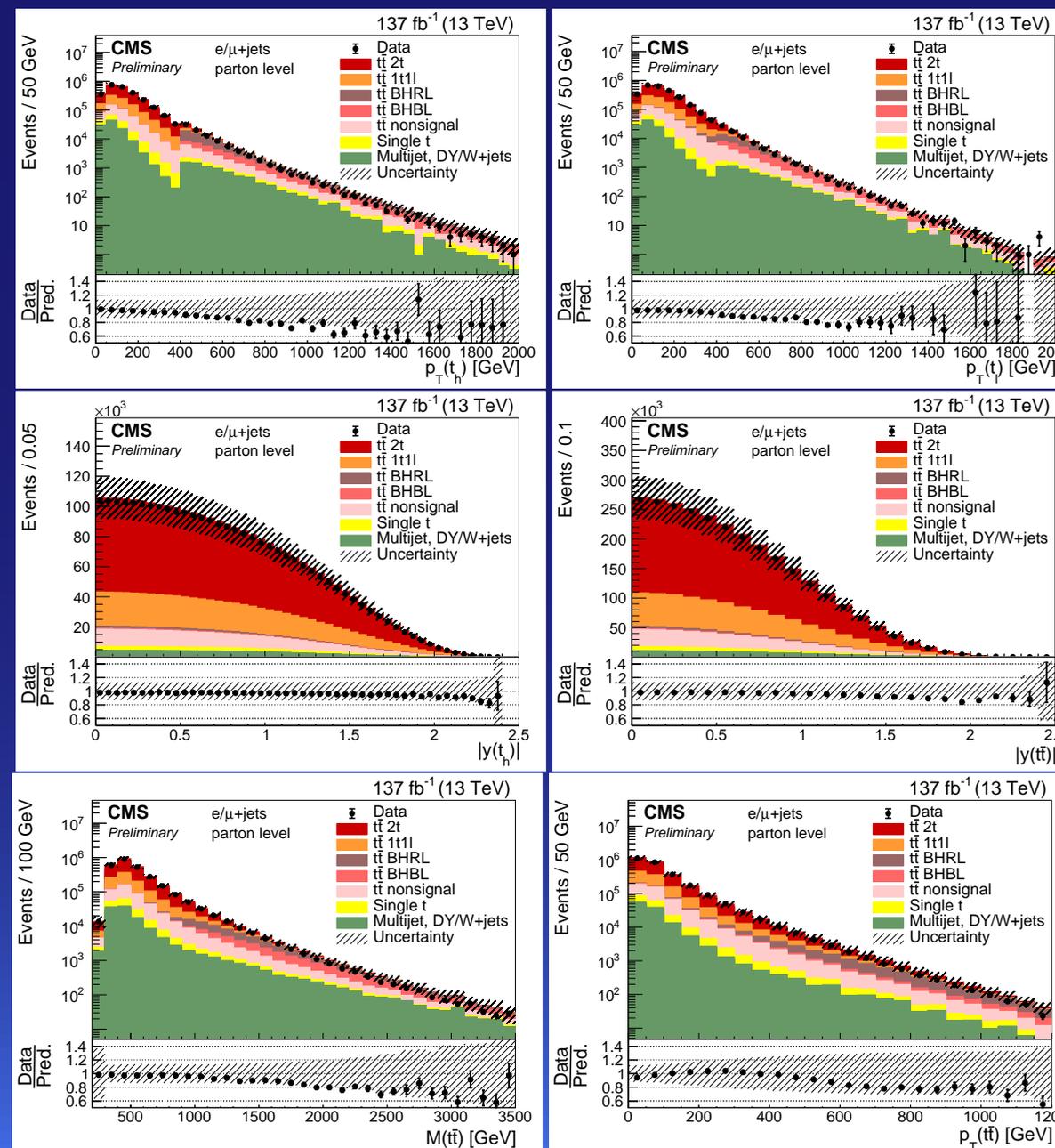
- exactly 1 central, isolated e or μ

▶ 4 event categories based of number of tight (loose) b-tags and resolved or boosted top-quark candidates:

- $2t$: 2 resolved top-candidates with 2 tightly b-tagged jets
- $1t1l$: 2 resolved top-candidates with 1 tight and 1 loose b-tag
- $BHRL$: boosted hadronic top ($p_{\perp} > 400$ GeV) but resolved leptonic top, 1 tight b-tag
- $BHBL$: both top-candidates boosted, 1 loose b-tag on leptonic side

▶ Kinematic quantities on parton-level

- ▶ $p_{\perp}(t_h), p_{\perp}(t_l), |y(t_h)|$
- ▶ $|y(t\bar{t})|, m(t\bar{t}), p_{\perp}(t\bar{t})$



Differential cross sections ► Pair production of top quarks

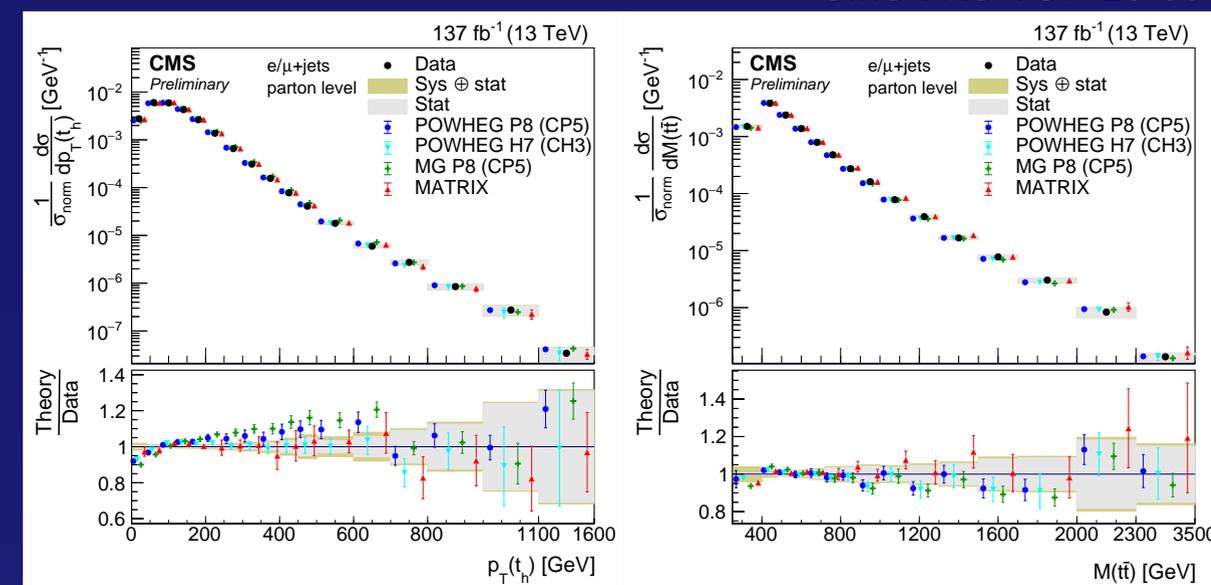
► Unfolding background-subtracted distributions to parton- and particle-level for single- and double-differential cross-section measurements

- **1D**: the 6 kinematic quantities from prev. slide and $p_{\perp}(t_{\text{high}})$, $p_{\perp}(t_{\text{low}})$, $S_{\perp} = p_{\perp}(t_h) + p_{\perp}(t_{\ell})$, $\Delta|y_{t/\bar{t}}|$, $|\Delta y_{t/\bar{t}}|$, $\Delta\phi_{t/\bar{t}}$ and $\cos(\theta^*)$
- **2D**: several combinations of the **1D** observables:
 - $m(t\bar{t})$ vs. $p_{\perp}(t_h)$, $|y(t_h)|$, $\cos(\theta^*)$, $|y(t\bar{t})|$, $\Delta|y_{t/\bar{t}}|$ and $|\Delta y_{t/\bar{t}}|$
 - $p_{\perp}(t_h)$ vs. $|y(t_h)|$ and $p_{\perp}(t\bar{t})$
 - $|y_{\perp}(t)|$ vs. $|y(\bar{t})|$

► Comparison to QCD predictions:

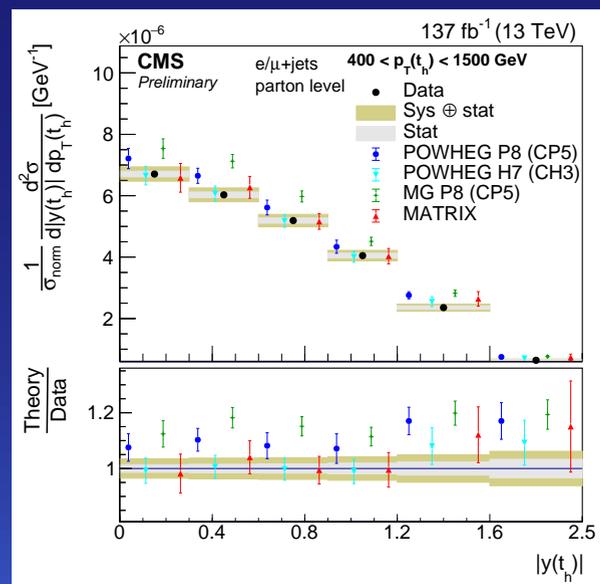
- **POWHEG+PYTHIA**, **POWHEG+HERWIG**, **MG5aMC@NLO+PYTHIA** NLO simulations on parton- and particle-level with parton-showering
- and to NNLO **MATRIX**-calculations on parton-level

CMS-PAS-TOP-20-001

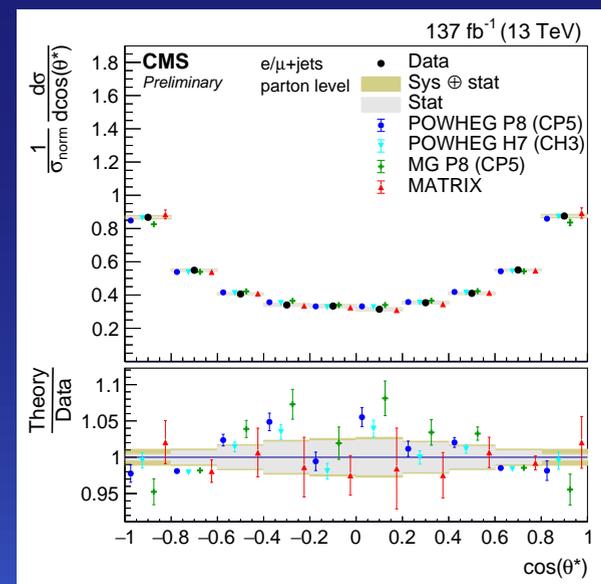


$1/\sigma_{\text{norm}} d\sigma_{t\bar{t}}/d p_{\perp}(t_h)$

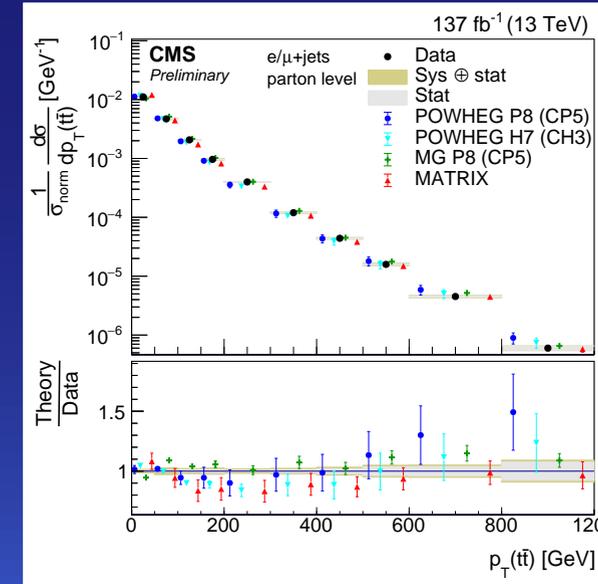
$1/\sigma_{\text{norm}} d\sigma_{t\bar{t}}/d m(t\bar{t})$



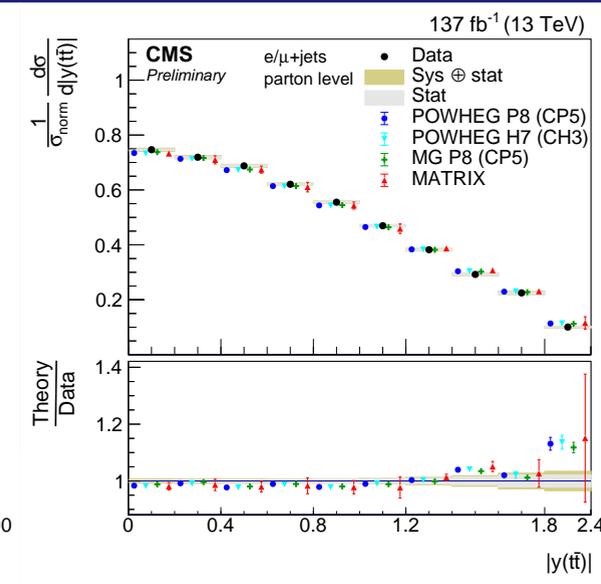
$1/\sigma_{\text{norm}} d^2\sigma_{t\bar{t}}/d|y(t_h)| dp_{\perp}(t_h)$ in high $p_{\perp}(t_h)$ -bin



$1/\sigma_{\text{norm}} d\sigma_{t\bar{t}}/d \cos(\theta^*)$



$1/\sigma_{\text{norm}} d\sigma_{t\bar{t}}/d p_{\perp}(t\bar{t})$

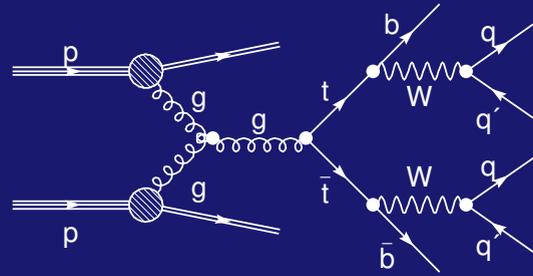


$1/\sigma_{\text{norm}} d\sigma_{t\bar{t}}/d |y(t\bar{t})|$

► Predictions too hard in $p_{\perp}(t)$, o.k. in y , too peaked in $m(t\bar{t})$, deviate at high p_{\perp} , $|y|$, **MATRIX** best

Differential cross sections ▶ Pair production of top quarks

JHEP01(2021)033

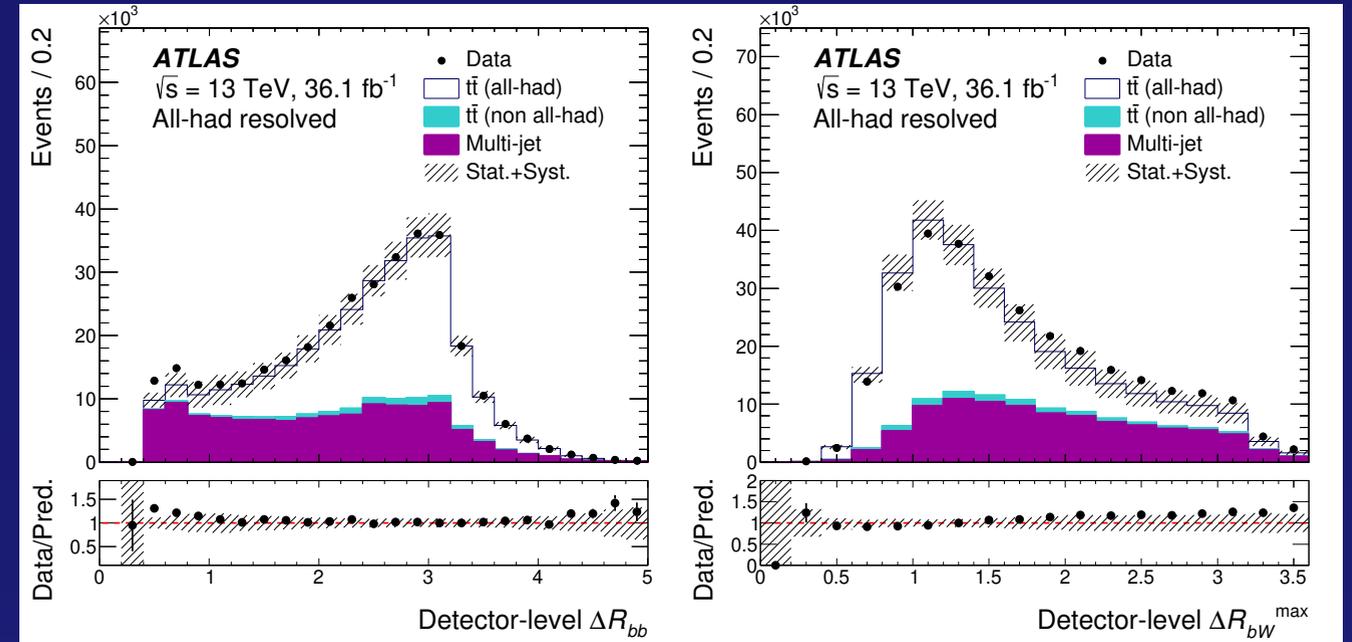


- ▶ The full-hadronic channel provides a fully reconstructed final state of $t\bar{t}$ events but suffers from large QCD multijet background
- ▶ Single- and double-differential cross sections in the full hadronic channel @13 TeV by ATLAS

- 6 central jets with $p_{\perp} > 55$ GeV, no leptons
- 0 or more additional central jets with $p_{\perp} > 25$ GeV
- exactly 2 b-tagged jets
- χ^2 -discriminant to form 2 all-hadronic top-candidates, based on m_W and $\Delta(m_{jjj_1}, m_{jjj_2})$ (but not on m_t)
- N_b -tags and mass-window around m_t to define signal region (D) and background/control regions for data-driven background estimate (ABCD-method)

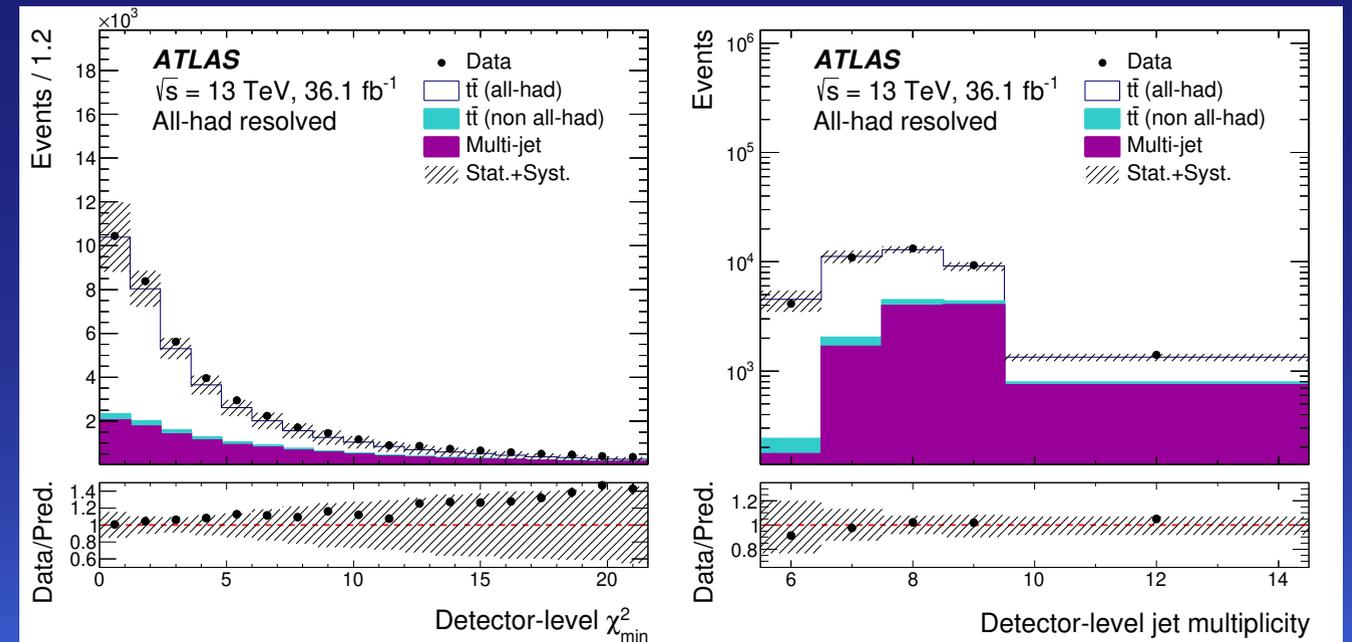
▶ Signal region D :

- 2 b-tags, large separation of b, top-mass window



ΔR_{bb}

ΔR_{bw}^{\max}



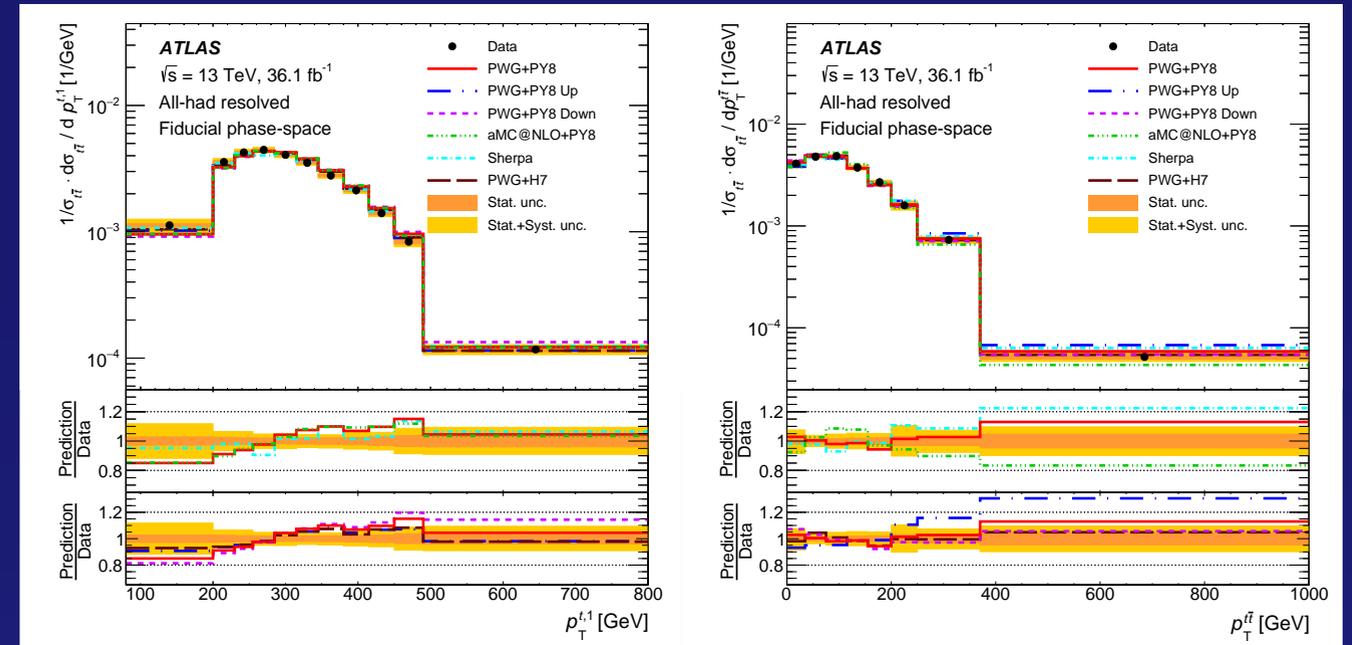
χ^2_{\min}

Jet multiplicity in the signal region

Differential cross sections ▶ Pair production of top quarks

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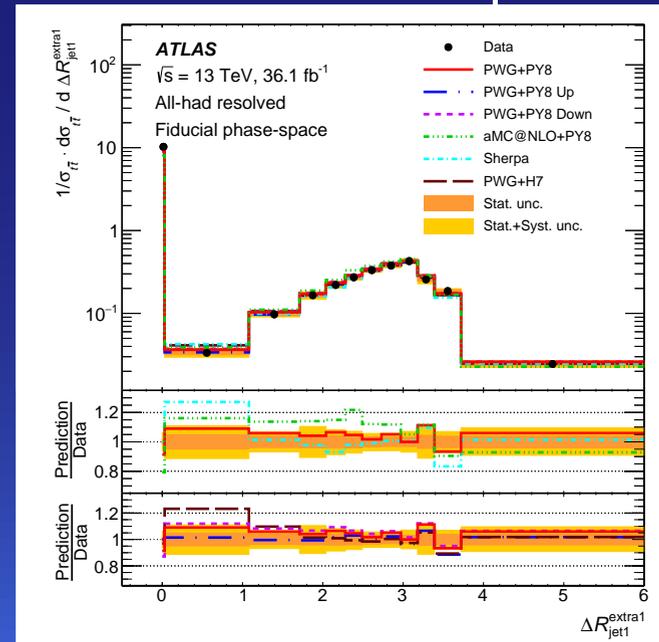
- ▶ Unfolding to particle- and parton-level in 1D and 2D kinematic quantities of t and $t\bar{t}$ systems – and angular distances to additional jet-activity (recoiling against the $t\bar{t}$ -system)
- ▶ Comparison to QCD predictions:
 - POWHEG interfaced with PYTHIA or HERWIG MG5aMC@NLO+PYTHIA and SHERPA NLO simulations on parton- and particle-level with parton-showering
- ▶ similar observation as in lepton+jets channel:
 - ▶ too hard p_{\perp} by all predictions, bump in $m(t\bar{t})$
- ▶ POWHEG+HERWIG describes data best, closely followed by POWHEG+PYTHIA, MG5aMC@NLO+PYTHIA most discrepant



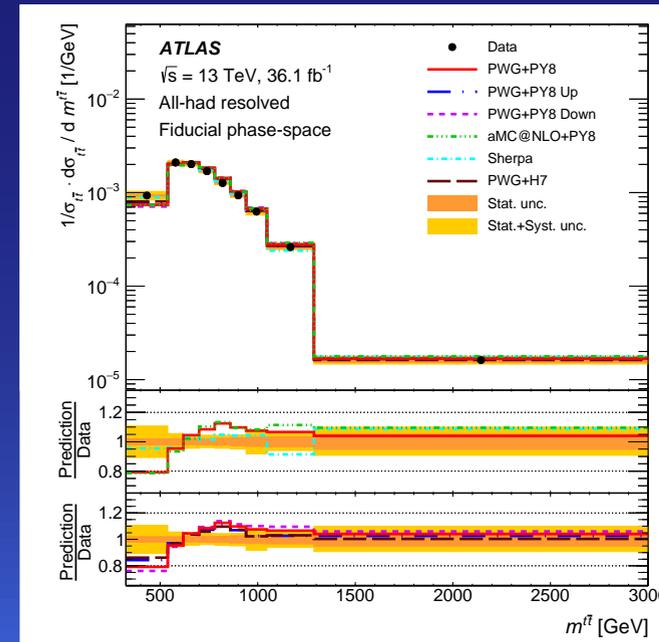
$1/\sigma_{t\bar{t}} d\sigma_{t\bar{t}}/d p_{\perp}(t_1)$

$1/\sigma_{t\bar{t}} d\sigma_{t\bar{t}}/d p_{\perp}(t\bar{t})$

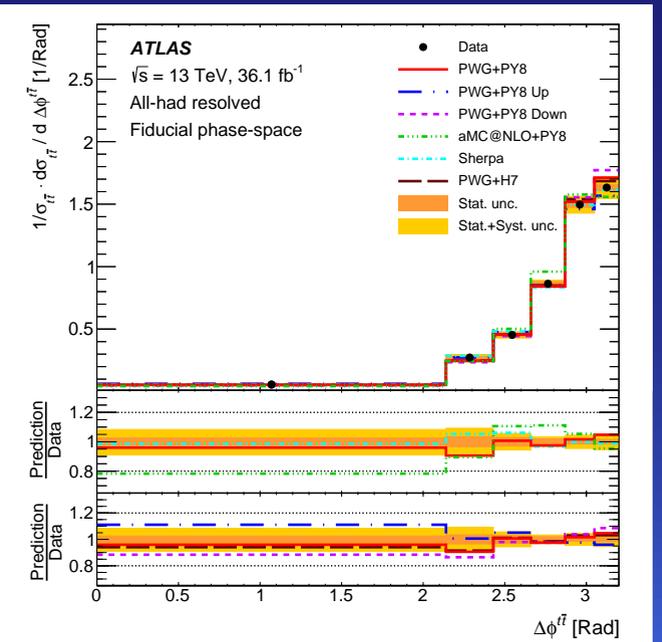
- extra radiation peaks at $\Delta R = 0$:
 - ▶ ISR is dominant source for leading jet
- contribution at $\Delta R \simeq \pi$ when leading jet stems from top-decay:
 - ▶ underestimated by most predictions
- 2D distributions of top and top-pair kinematics in slices of jet-multiplicity poorly modelled by all generators



$1/\sigma_{t\bar{t}} d\sigma_{t\bar{t}}/d \Delta R_{jet1}^{extra}$



$1/\sigma_{t\bar{t}} d\sigma_{t\bar{t}}/d m(t\bar{t})$



$1/\sigma_{t\bar{t}} d\sigma_{t\bar{t}}/d \Delta\phi_{t\bar{t}}$

Cross sections ▶ Single top quark production

- ▶ Total cross section for single top production surprisingly large
 $\simeq 44(36) \%$ of $\sigma_{t\bar{t}}$ @8(13) TeV NLO single-top / NNLO+NNLL $t\bar{t}$ predictions

- Calculations by LHCTopWG with Top++, arXiv:1112.5675 for $t\bar{t}$ and Hathor v2.1, arXiv:1007.1327, arXiv:1406.4403 for single-top

▶ **s-channel**

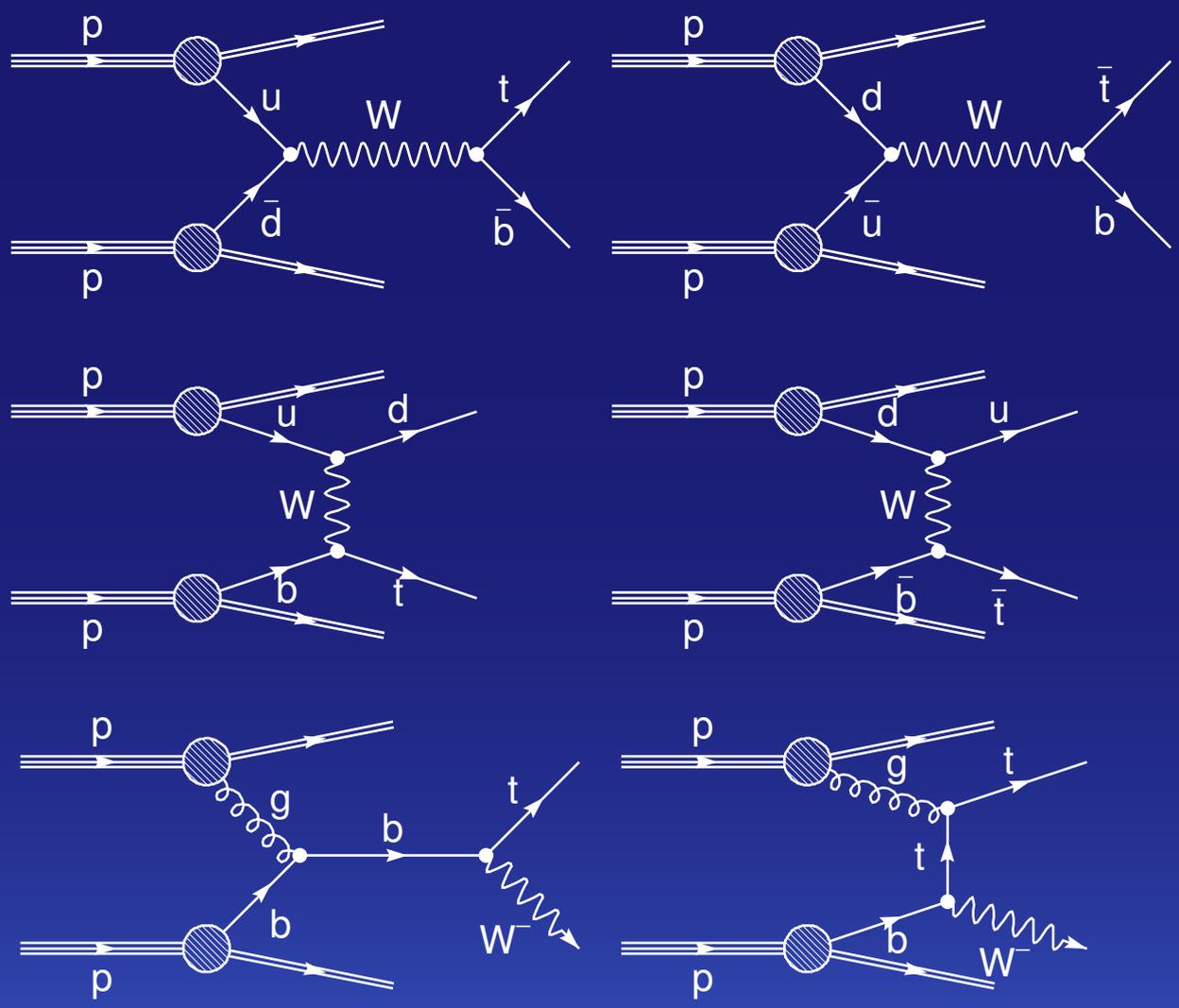
\sqrt{s}	$\sigma_{EWs} / \sigma_{\text{single } t}$
8 TeV	5 %
13 TeV	3 %

▶ **t-channel**

\sqrt{s}	$\sigma_{EWt} / \sigma_{\text{single } t}$
8 TeV	75 %
13 TeV	73 %

▶ **Wt prod.**

\sqrt{s}	$\sigma_{Wt} / \sigma_{\text{single } t}$
8 TeV	20 %
13 TeV	24 %



- ▶ $R_t = \sigma_{EWt}(t) / \sigma_{EWt}(\bar{t})$ sensitive to PDF
 ▶ ratio of valence u to d quark density

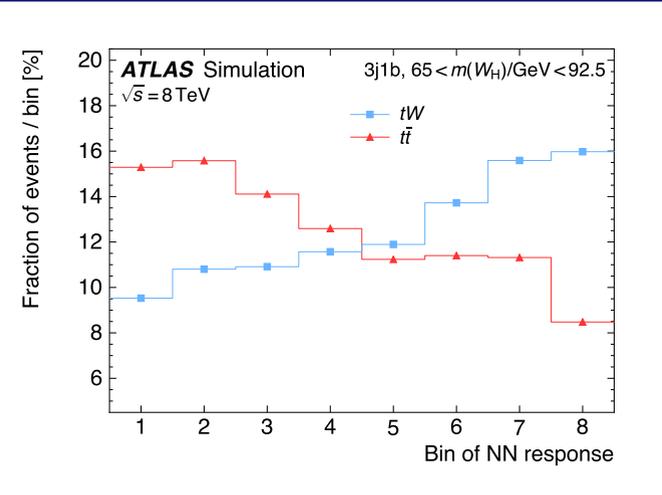
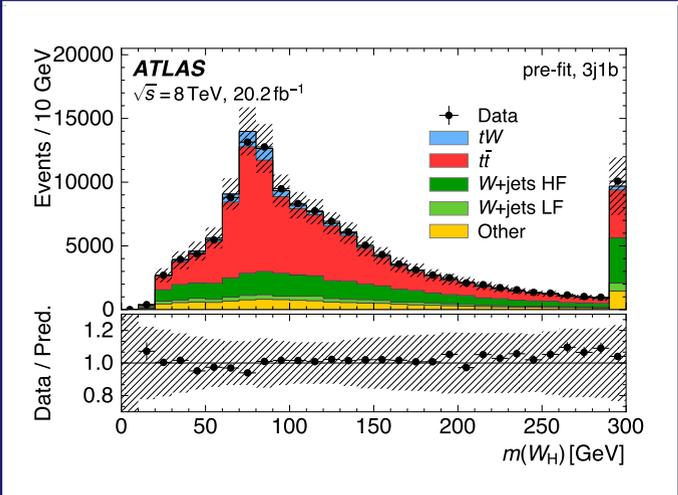
- ▶ BSM physics would lead to deviations from SM expectations for total and differential cross-sections

Cross sections ▶ Single top quark production

▶ Measurement @8 TeV of σ_{Wt} with single lepton+jets final state by ATLAS

- exactly one central μ or e matching trigger
- missing transverse momentum $E_{\perp}^{\text{miss}} > 30$ GeV
- transverse mass of the leptonic W_{ℓ} , $m_{\perp}(W_{\ell}) > 50$ GeV
- 3 central jets, one of them b-tagged forms the signal region (3j1b)
 - ▶ about 5% tW events; 58% $t\bar{t}$
- 4 jets with 2 b-tags (4j2b):
 - ▶ very pure $t\bar{t}$ -dominated background validation region

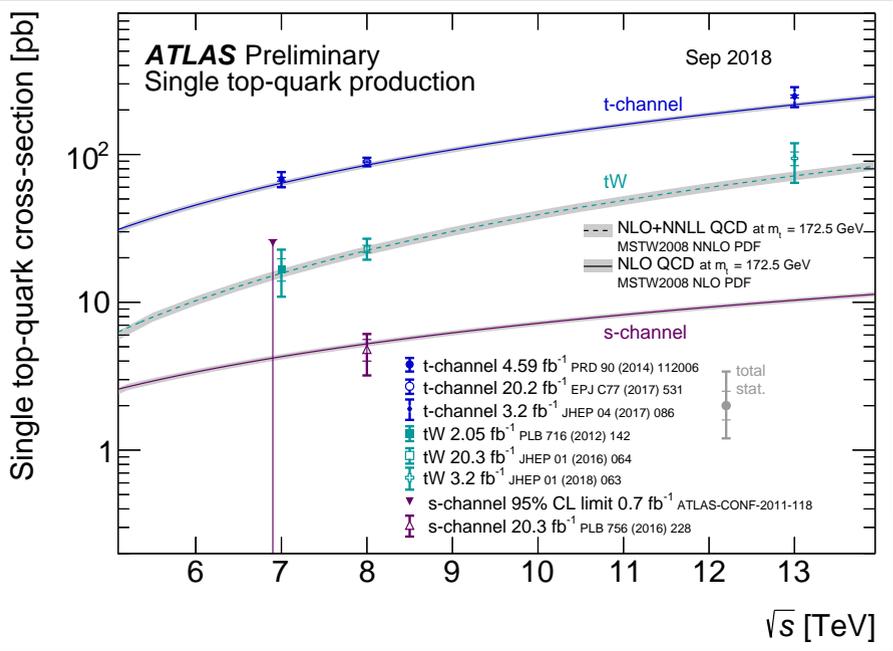
arXiv:2007.01554



pre-fit $m(W_h)$

NN output in the signal region

ATL-PHYS-PUB-2020-029



$\sigma_{EWt}, \sigma_{Wt}, \sigma_{EW_s}$ vs. \sqrt{s}

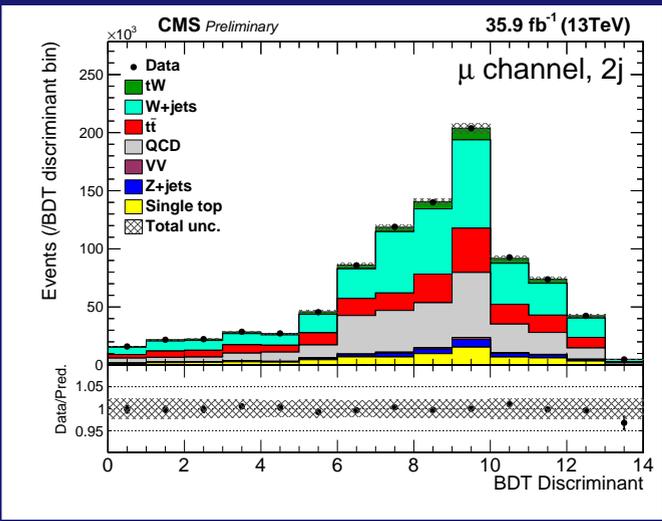
- ▶ use NN to discriminate signal from background
 - NN input: optimised set of 4 kinematic variables of subset of selected objects (but not $m(W_h)$)
- ▶ Likelihood fit to 2D discriminant of $m(W_h)$ and NN output:
 - ▶ $\sigma_{Wt}(8 \text{ TeV})^{\text{ATLAS}} = 26 \pm 7_{\text{tot}} \text{ pb}$
 - Systematic uncertainty dominated by amount of QCD radiation in signal and background events, jet energy scale and b-tagging
- Comparison of all other single top-quark cross sections (left)

Cross sections ▶ Single top quark production

▶ Measurement of σ_{Wt} @13 TeV in the semi-leptonic channel by CMS

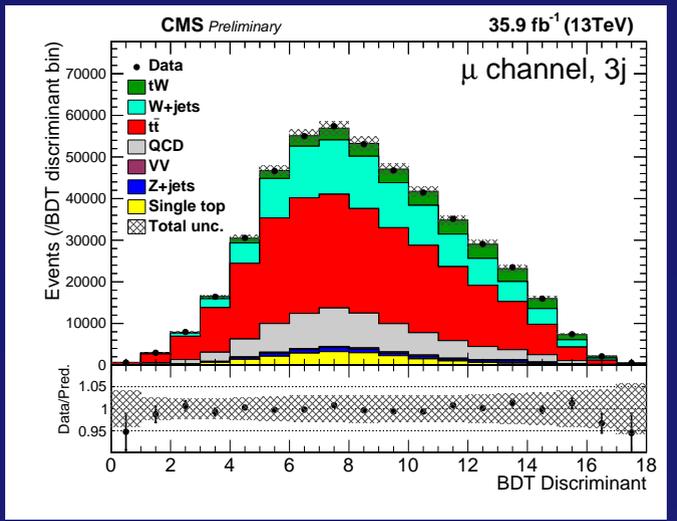
- exactly one central, isolated μ or e matching trigger
- 2-4 central jets exactly one of them b-tagged
- signal region (SR) is defined by 3 jets (3j)
 - ▶ purity is $\simeq 6\%$
- control regions (CR) for 2 jets (2j)
 - ▶ enhances $W + \text{jets}$ and multi-jet background
- and 4 jets (4j)
 - ▶ enhances $t\bar{t}$ background

▶ Data-driven estimate of multi-jet background by inverting lepton isolation



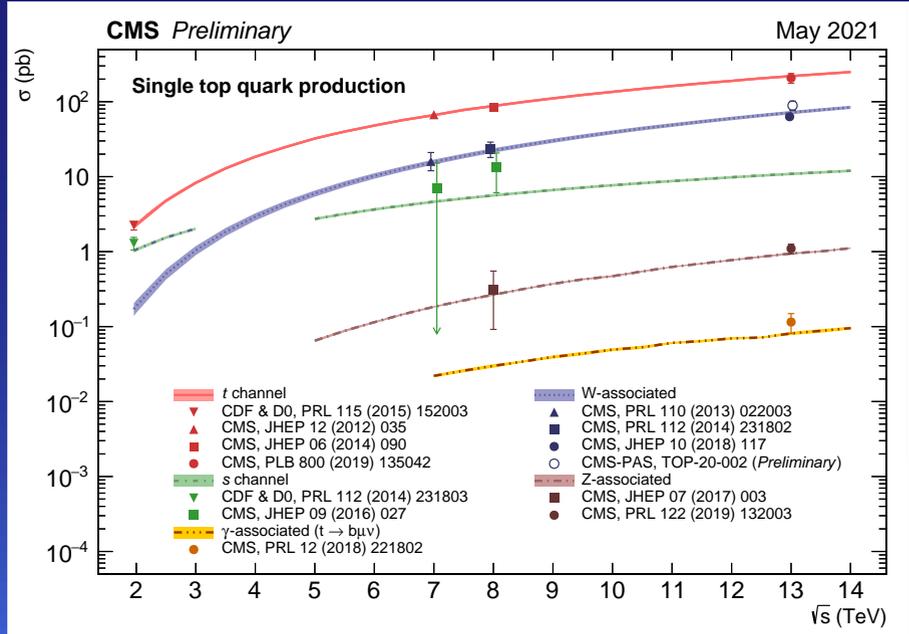
BDT output: 2 jet CR, μ channel

CMS-PAS-TOP-20-002



BDT output: 3 jet SR, μ channel

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures>



$\sigma_{EWt}, \sigma_{Wt}, \sigma_{EWs}, \sigma_{Zt}, \sigma_{\gamma t}$ vs. \sqrt{s}

▶ BDT to discriminate signal from background

- inputs to BDT are 8 kinematic variables based on the selected objects including $m(W_h)$

• Binned likelihood fit on BDT discriminants:

▶ $\sigma_{Wt}(13 \text{ TeV})^{\text{CMS}} = 89 \pm 4_{\text{stat}} \pm 12_{\text{syst}} \text{ pb}$

- systematic uncertainties in multi-jet and $W + \text{jets}$ background normalisation, jet energy scale and $t\bar{t}$ modelling dominate

▶ Comparison of all other single top-quark cross sections (left)

Properties and decays ▶ Tests of lepton universality

▶ Measurement of $R(\tau/\mu) = B(W \rightarrow \tau\nu_\tau)/B(W \rightarrow \mu\nu_\mu)$ in $t\bar{t}$ in the di-lepton channel @13 TeV by ATLAS

arXiv:2007.14040, accepted by Nature

▶ “Tag and probe” approach on di-lepton $t\bar{t}$ events:

- one lepton serves as “tag”
- the μ serves as “probe” to count un-biased
 - ▶ the number of prompt $W \rightarrow \mu\nu_\mu$ decays and
 - ▶ those with an intermediate τ : $W \rightarrow \tau\nu_\tau \rightarrow \mu\nu_\mu\nu_\tau$

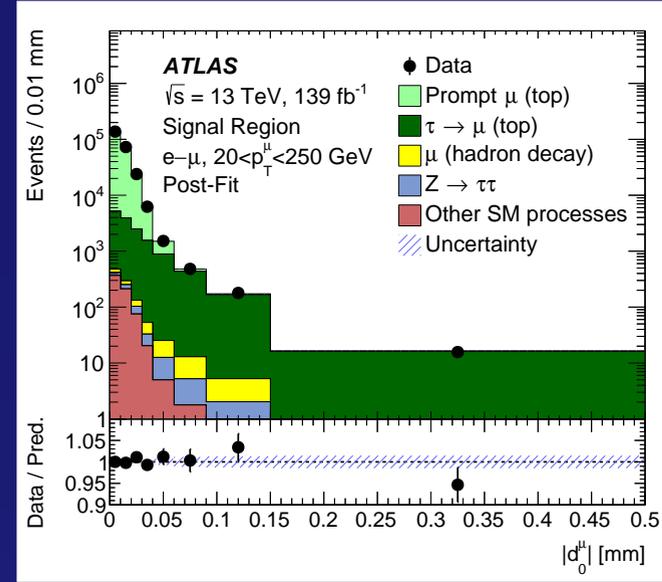
▶ Event selection

- isolated, central μ or e for “tag”
- isolated, $p_\perp > 5$ GeV μ for “probe”
- at least two central b-tagged jets
- $e\mu$ and $\mu\mu$ events with Z-mass veto

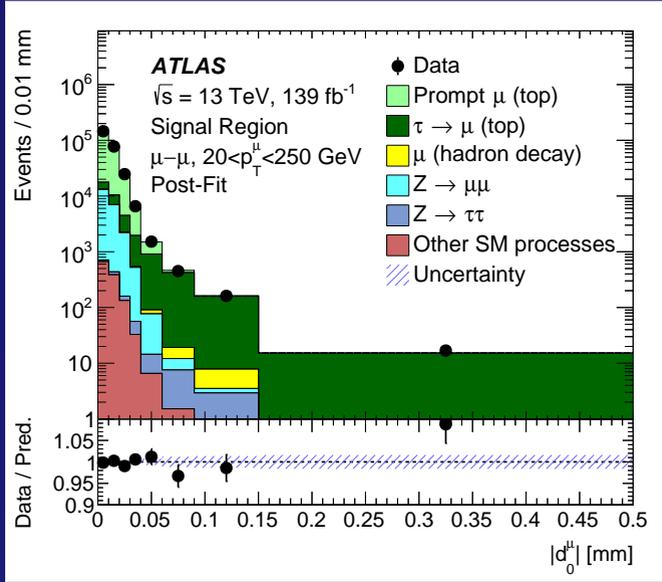
▶ $Z \rightarrow \mu\mu$ calibration sample for transverse impact parameter $|d_0^\mu|$ (defined w.r.t. beam-line)

- 2 μ with same requirements as above but
- Z-mass veto reversed
 - ▶ wider mass-range for control sample to normalise Z-peak
- no requirement on jets

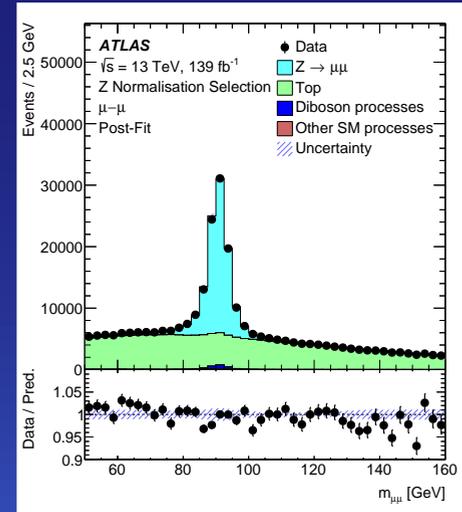
▶ Likelihood fit to templates of $|d_0^\mu|$ from prompt ($Z \rightarrow \mu\mu$) and non-prompt ($\tau \rightarrow \mu\nu_\mu\nu_\tau$ from $t \rightarrow Wb$) muons and fakes



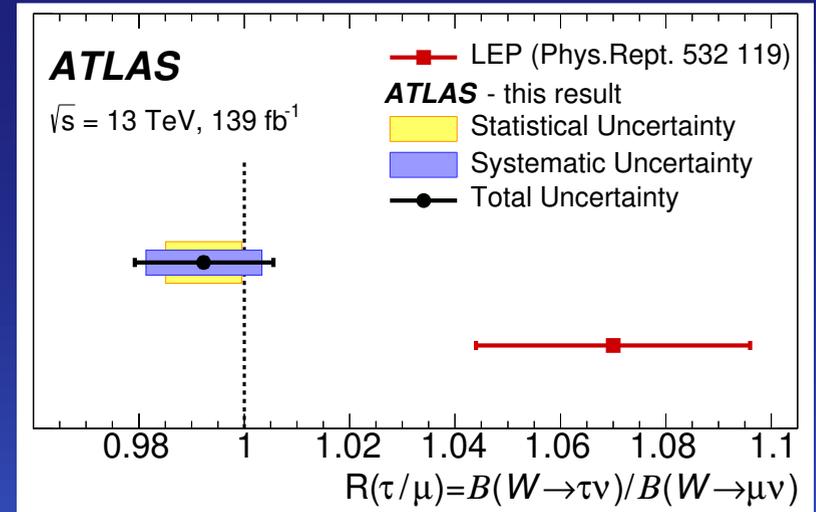
$|d_0^\mu|$ in $e\mu$ -channel



$|d_0^\mu|$ in $\mu\mu$ -channel



$m_{\mu\mu}$ in $Z \rightarrow \mu\mu$ CR



$R(\tau/\nu)$

▶ $R(\tau/\mu) = 0.992 \pm 0.007_{\text{stat}} \pm 0.011_{\text{sys}}$

Properties and decays ▶ W helicity

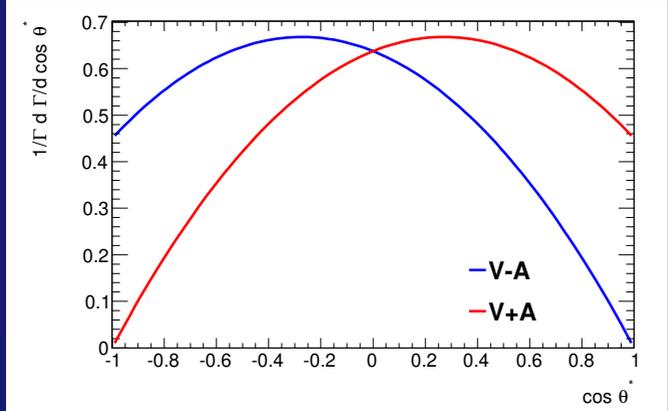
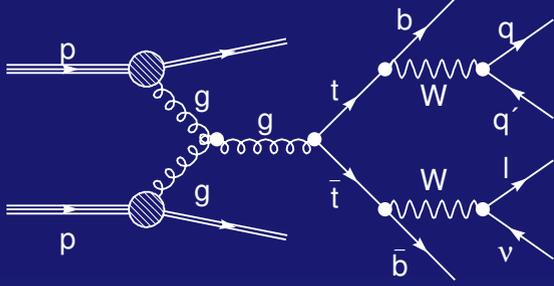
▶ In the SM the t-decay is almost always $t \rightarrow W^+ b$ via a $V - A$ current interaction

- Deviations from expected $V - A$ behaviour indicate new physics
- In general for any combination of V and A:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4} F_0 (1 - \cos^2\theta^*) + \frac{3}{8} F_L (1 - \cos\theta^*)^2 + \frac{3}{8} F_R (1 + \cos\theta^*)^2$$

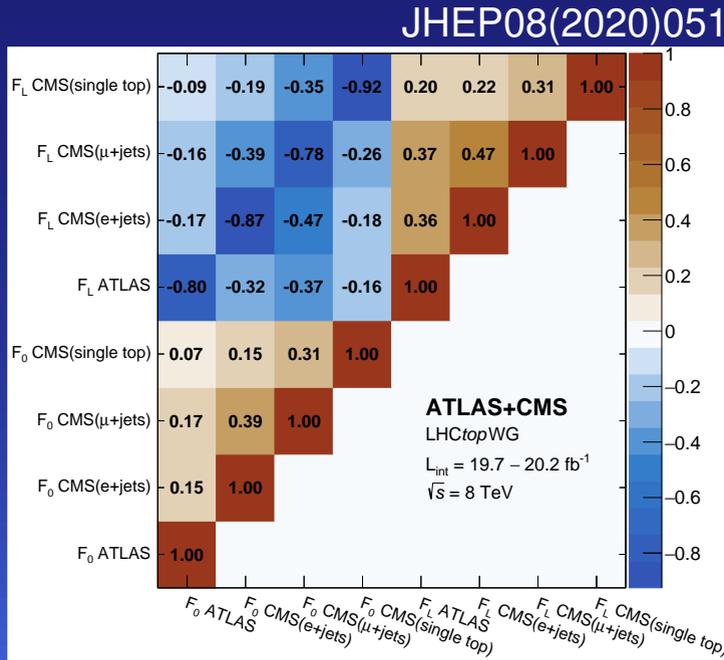
$$F_0 + F_L + F_R = 1, F_0 \simeq \frac{m_t^2}{2m_W^2 + m_t^2 + m_b^2} \simeq 0.7, F_R^{SM} = 0$$

- θ^* is the polar angle in the W rest frame between the $W^{+(-)}$ momentum direction and the $\ell^{+(-)}$ or $\bar{q}(q)$



▶ Combination of 3 measurements of $\cos\theta^*$ -distributions in $t\bar{t}$ lepton+jets events by ATLAS and CMS and 1 such measurement in single t events by CMS, all @8 TeV

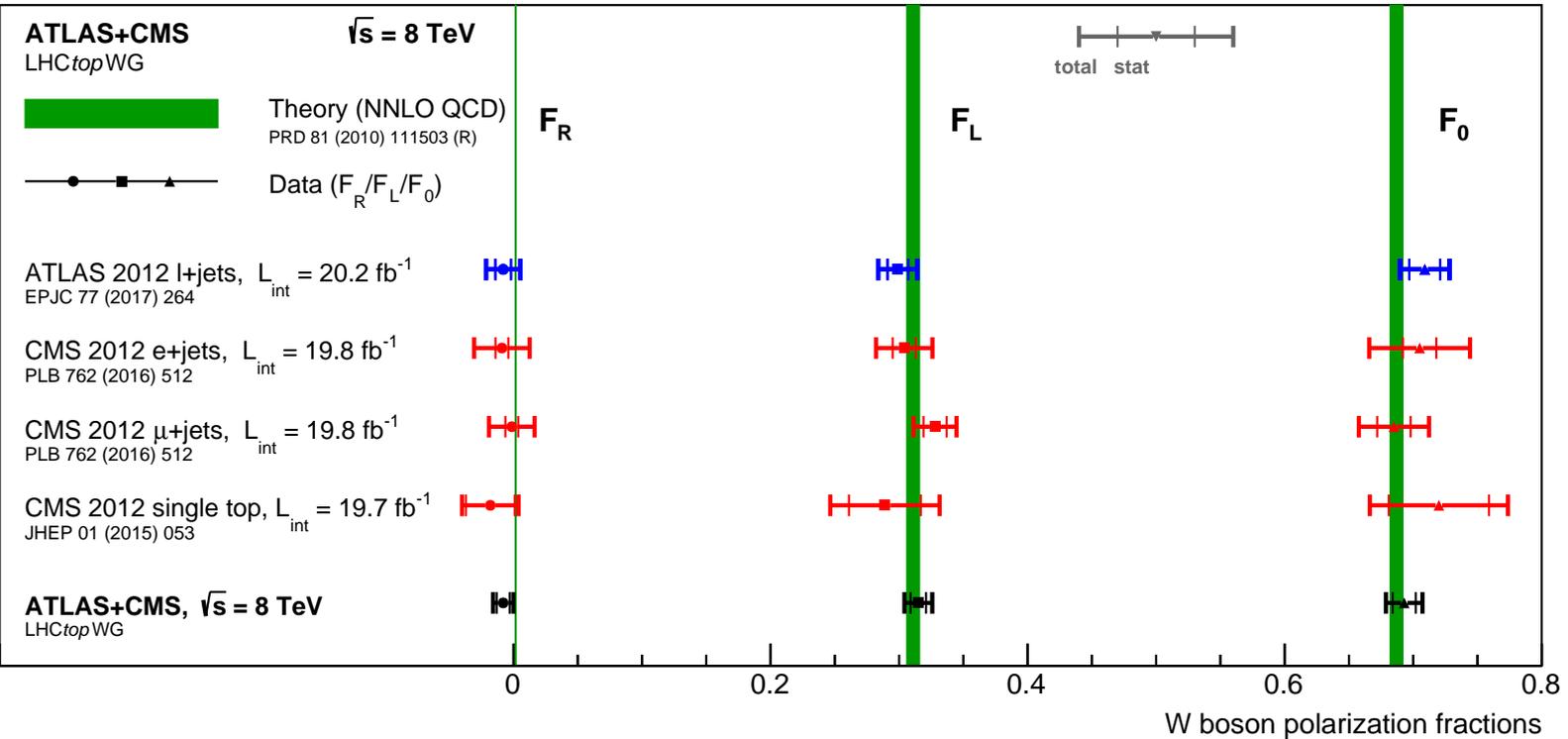
- improving experimental precision ($\simeq 3 - 5\%$ each, compared to $\simeq 2\%$ from theory) motivates the combination of CMS' and ATLAS' results



Correlations

▶ Evaluation of correlations between measurements

- F_0 and F_L typically highly anti-correlated (by unitarity constraint and since $F_R \simeq 0$) within one measurement
- (anti-) correlations between different $t\bar{t}$ measurements around 30 - 40% in magnitude
- CMS single-top measurement correlations to $t\bar{t}$ CMS measurements around 20% in magnitude, smaller to ATLAS



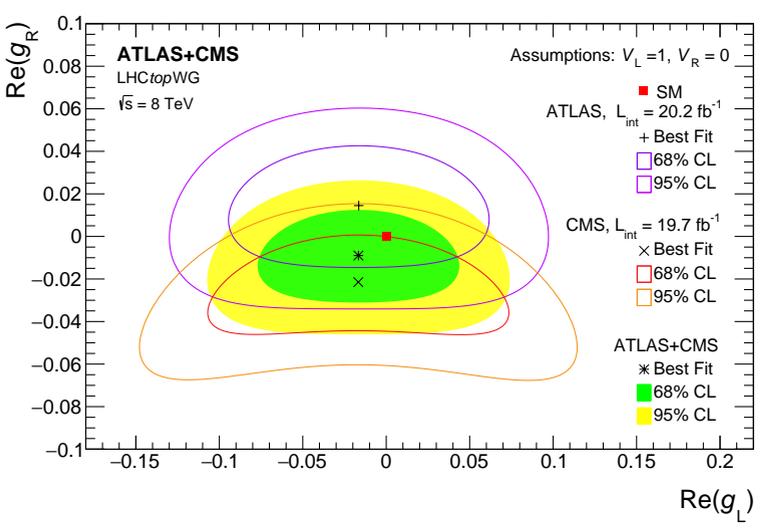
▶ Combined result

- $F_0 = 0.693 \pm 0.009_{\text{stat+bkg}} \pm 0.011_{\text{syst}} (\pm 2.0\%_{\text{tot}})$
- $F_L = 0.315 \pm 0.006_{\text{stat+bkg}} \pm 0.009_{\text{syst}} (\pm 3.5\%_{\text{tot}})$
- with total correlation of $\rho = -85\%$
- from unitarity constraint:
 ▶ $F_R = -0.008 \pm 0.005_{\text{stat+bkg}} \pm 0.006_{\text{syst}}$

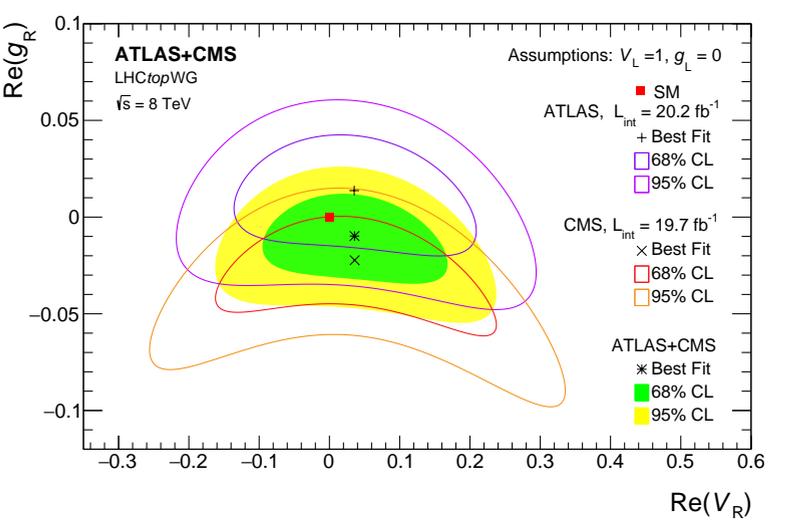
▶ Dominant uncertainties

- statistical uncertainties for data and background estimates
- radiation and scales modelling
- simulation sample size and choice

Individual and combined results



Re(g_R) vs. Re(g_L)



Re(g_R) vs. Re(V_R)

▶ Limits on anomalous couplings

- allow for (BSM) non-zero right-handed vector couplings (V_R) and left- and right-handed tensor couplings (g_L and g_R)
- SM: $V_L \simeq 1$, all others zero
- plots show allowed 68% and 95% CL contours around CMS (+), ATLAS (x) and combined (*) results, compared to SM (■)

Properties and decays ▶ Test of \mathcal{CP} -violation in top production

CMS-PAS-TOP-18-007

▶ Test of \mathcal{CP} -violation in di-leptonic $t\bar{t}$ events @ 13 TeV by CMS

▶ Construct 2 \mathcal{CP} -odd scalars from 4-vectors of reconstructed t and \bar{t} , b and \bar{b} and l^+ , l^-

- $\mathcal{O}_1 = \varepsilon(p(t), p(\bar{t}), p(l^+), p(l^-))$
- $\mathcal{O}_3 = \varepsilon(p(b), p(\bar{b}), p(l^+), p(l^-))$

▶ Count events with positive and negative \mathcal{O}_i

- $A_i = \frac{N(\mathcal{O}_i > 0) - N(\mathcal{O}_i < 0)}{N(\mathcal{O}_i > 0) + N(\mathcal{O}_i < 0)}$

▶ Asymmetries A_i are sensitive to presence of \mathcal{CP} -violating top-production

- e.g. via a Chromo Electric Dipole Moment (CEDM)

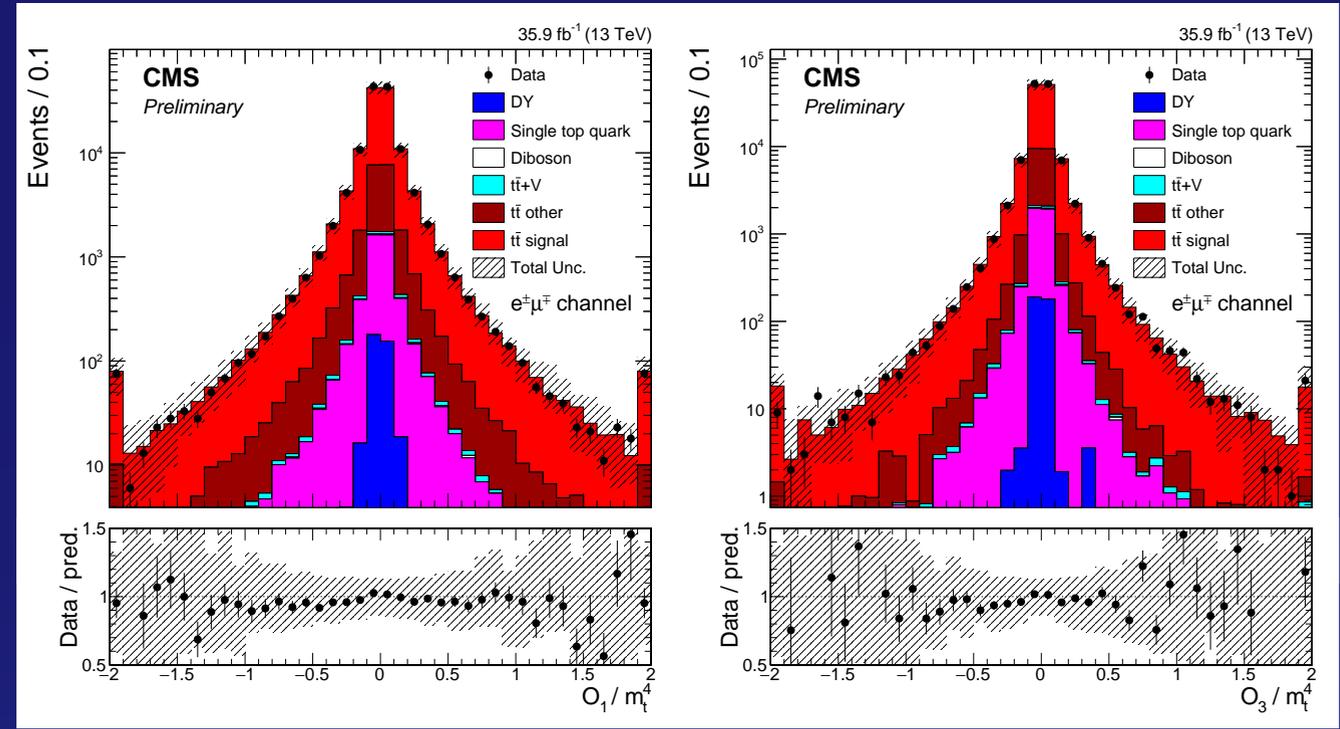
▶ Result from likelihood fit after combining ee , $\mu\mu$ and $e^\pm\mu^\mp$

- $A_1 = (2.4 \pm 2.8) \times 10^{-3}$, $A_3 = (0.4 \pm 2.8) \times 10^{-3}$

▶ Linear relation between A_i and dimensionless CEDM d_{tG}

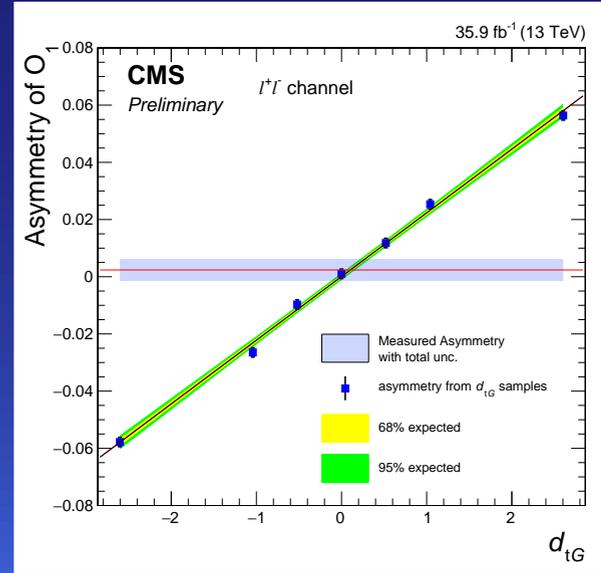
- $\mathcal{O}_1: d_{tG} = 0.10 \pm 0.12_{\text{stat}} \pm 0.12_{\text{syst}}$
- $\mathcal{O}_3: d_{tG} = 0.00 \pm 0.13_{\text{stat}} \pm 0.10_{\text{syst}}$

▶ Compatible with SM prediction

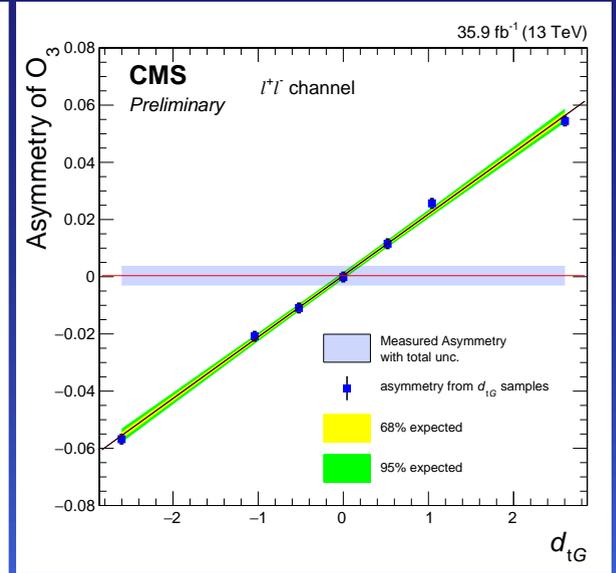


\mathcal{O}_1 in the $e^\pm\mu^\mp$ -channel

\mathcal{O}_3 in the $e^\pm\mu^\mp$ -channel



\mathcal{O}_1 vs. d_{tG}



\mathcal{O}_3 vs. d_{tG}

Properties and decays ▶ b-fragmentation

- ▶ Measurement of b-fragmentation in $t\bar{t}$ events @ 13 TeV by ATLAS and CMS
- ▶ In MC generators b-fragmentation is typically tuned from LEP measurements

- $x_B = E_B / E_{\text{beam}}$ – the fraction of energy carried by a b-hadron over the beam (and b-quark) energy in $e^+e^- \rightarrow b\bar{b}$ events

- ▶ For proton colliders the energy of the fragmenting b-quark is not well defined

- ▶ Use b-quarks from $t\bar{t}$ events instead

- b-jets as proxy for the b-quark
 - ▶ colour-connected to the initial state
 - compare b-hadron momentum (ATLAS) or its c-hadron daughter's momentum (CMS) with that of parent b-jet

- ▶ 2 of the observables studied by ATLAS:

- $z_{\perp,b} = p_{\perp,b}^{\text{chgd}} / p_{\perp,\text{jet}}^{\text{chgd}}$ and $z_{L,b} = \vec{p}_b^{\text{chgd}} \cdot \vec{p}_{\text{jet}}^{\text{chgd}} / |\vec{p}_{\text{jet}}^{\text{chgd}}|^2$, the transverse and longitudinal charged momentum fractions of the b-jet carried by the b-hadron
 - unfolded to particle-level in fiducial phase space

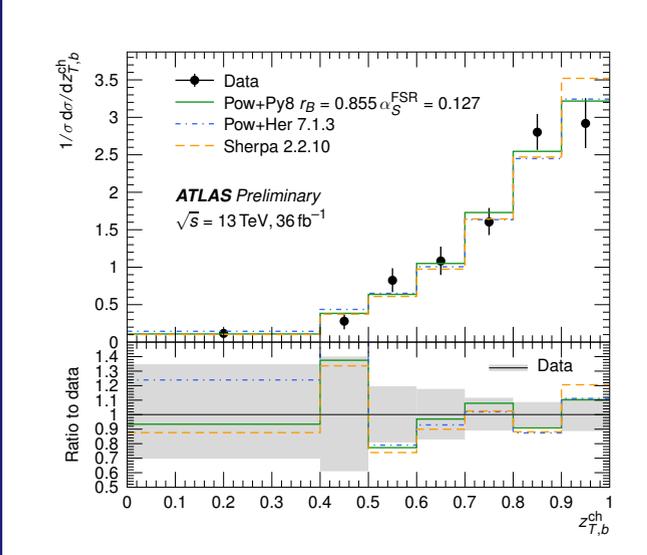
- ▶ Fit of r_b by CMS:

- templates in transverse momentum fraction carried by b-hadron daughters (J/Ψ or D^0) with r_b as template parameter
 - simultaneous fit to J/Ψ , tagged and un-tagged D^0 distributions

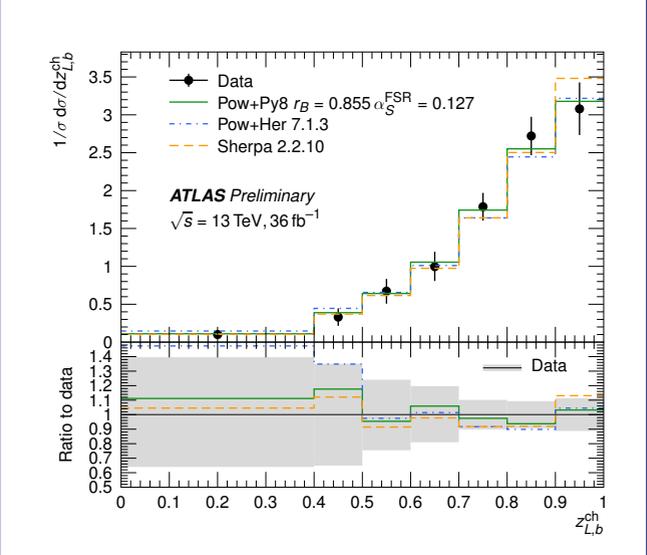
- ▶ $r_b^{\text{CMS}} = 0.858 \pm 0.037_{\text{stat}} \pm 0.031_{\text{syst}}$

- ▶ In agreement with tune to e^+e^- -data

ATLAS-CONF-2020-050

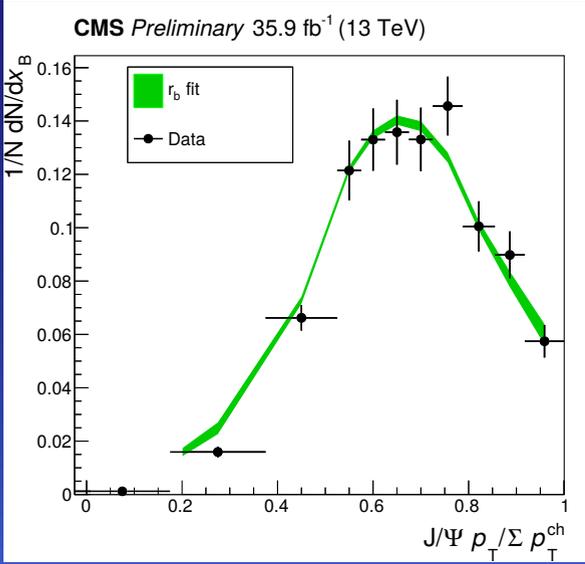


$z_{\perp,b}$

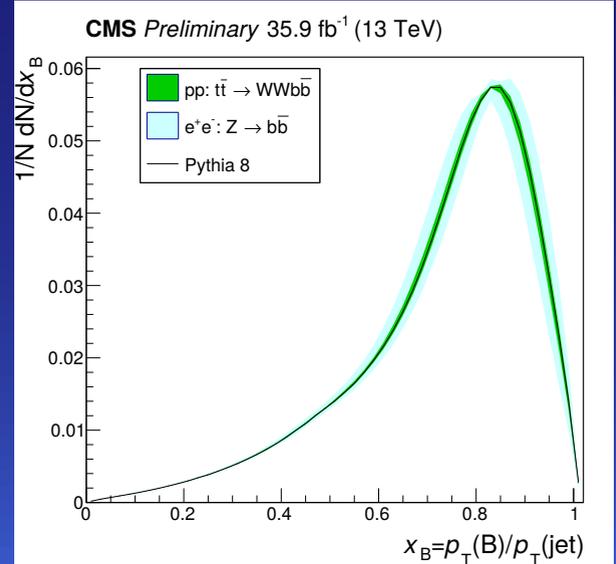


$z_{L,b}$

CMS-PAS-TOP-18-012



$p_{\perp}^{J/\Psi} / p_{\perp,jet}^{\text{chgd}}$



Lund-Bowler b-fragmentation

Properties and decays ▶ Top quark polarisation

▶ Measurement of the polarisation of t and \bar{t} in single-top t -channel events @ 13 TeV by ATLAS

▶ Top quark polarisation

- QCD produces unpolarised top-quarks through $pp \rightarrow t\bar{t}$
- $V - A$ structure of Wtb -vertex leads to fully polarised top-quarks
 - ▶ along (against) the direction of the down-type spectator/incoming quark for top (anti-top)
- different mix of dominant and sub-dominant LO process lead to SM expectation of $+90\%$ for t and -86% for \bar{t} (modified by acceptance)
- define coordinates in t -rest-frame: \hat{z}' : along spectator; \hat{y}' : orthogonal to \hat{z}' and incoming light quark; \hat{x}' : orthogonal to \hat{z}' and \hat{y}'
- ℓ^\pm direction from $t \rightarrow b\ell\nu_\ell$ ($\ell = e, \mu$) as analyser
- $\theta_{\ell i}$, with $i = x', y', z'$ is the polar angle of ℓ w.r.t. axis i

▶ Event selection

- single, isolated, central e or μ
- missing transverse momentum $E_\perp^{\text{miss}} > 35$ GeV; transverse mass of the W_ℓ , $m_\perp(W_\ell) > 60$ GeV
- exactly 2 jets ($|\eta| < 4.5$, $p_\perp > 30$ GeV), exactly one b -tagged ($|\eta| < 2.5$)
- kinematic “cleaning cuts” to enhance t -channel

▶ Polarisation

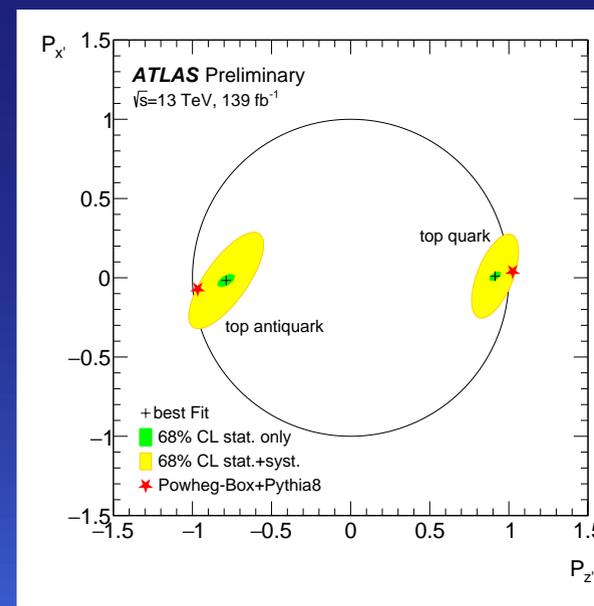
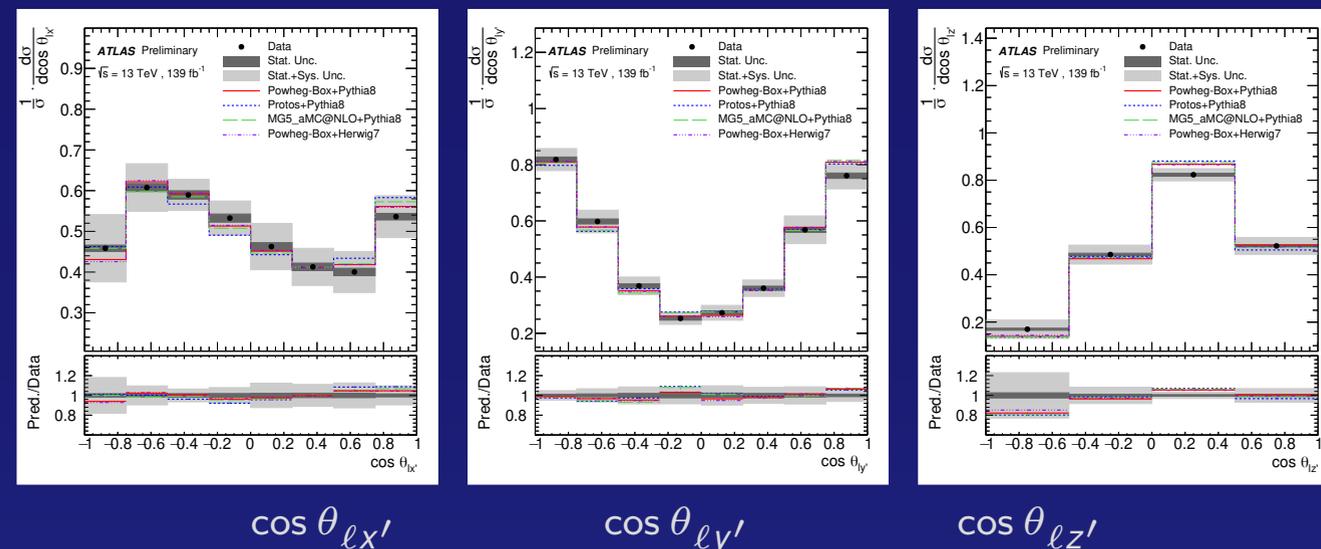
- t : $P_{x'} = 0.01 \pm 0.18$; $P_{y'} = -0.029 \pm 0.027$; $P_{z'} = 0.91 \pm 0.10$
- \bar{t} : $P_{x'} = -0.02 \pm 0.20$; $P_{y'} = -0.007 \pm 0.051$; $P_{z'} = -0.79 \pm 0.16$

▶ Bounds on EFT coefficients

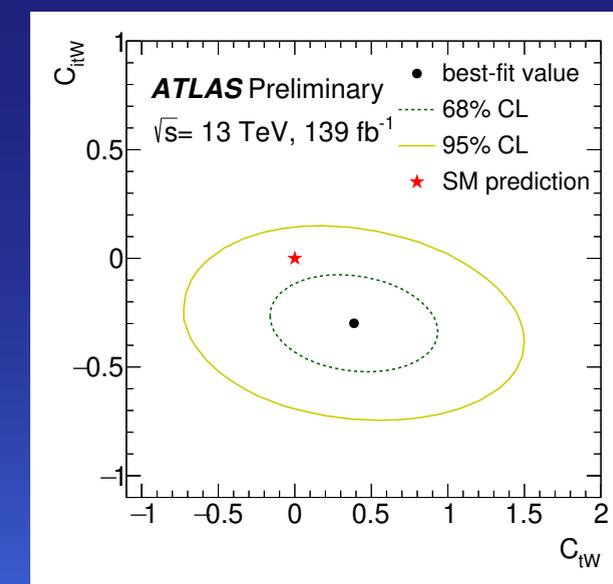
- differential cross-sections constrain Wilson coefficients for \mathcal{O}_{tW} @ 95%CL: $C_{tW} \in [-0.7, 1.5]$; $C_{itW} \in [-0.7, 0.2]$; compatible with SM



ATLAS-CONF-2021-027 (to appear)



Polarisation



EFT coefficients

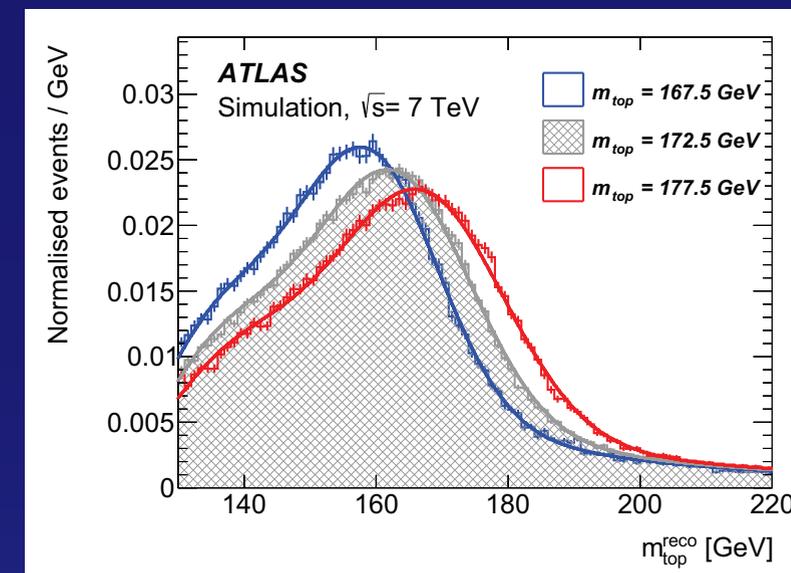
▶ Typical analysis in the case of direct mass measurement

- Reconstruct top candidates in data and MC ▶ often with kinematic fit
- Perform Likelihood fit in one (m_{top}) or more ((b)-Jet Scale Factor (JSF, bJSF), f_{bkgd}) parameters
- Likelihood is based on Templates (ATLAS+CMS) or Ideograms (CMS)

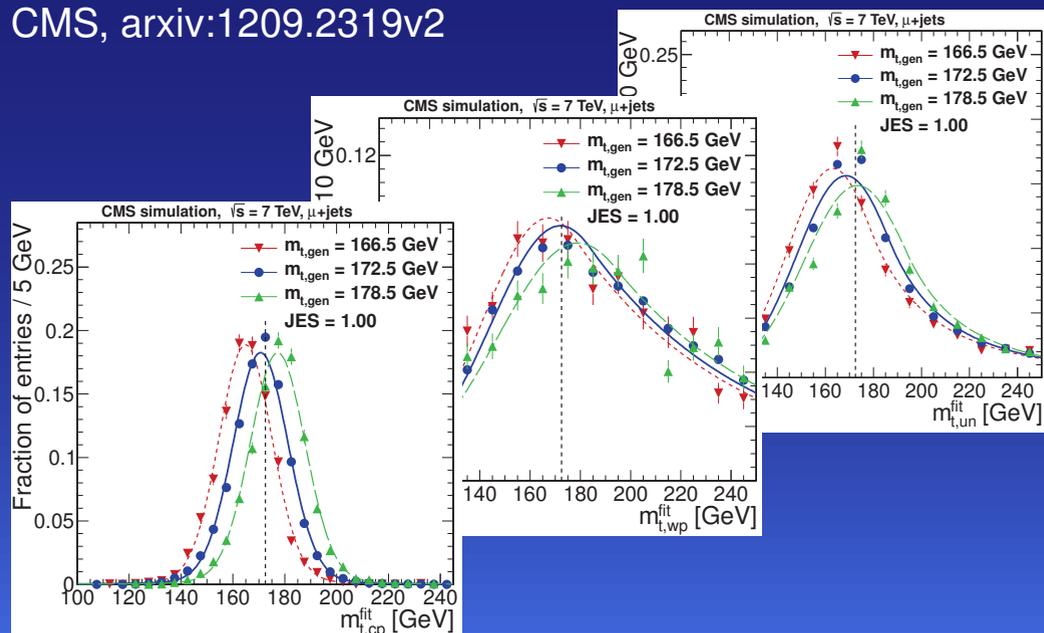
ATLAS, arxiv:1503.05427

▶ Templates (ATLAS+CMS)

- Templates are Probability Density Functions (PDF)s constructed from full simulations in reconstructed quantities (m_{top}^{reco} , kinematic endpoints, ...)
- For many top quark masses (m_{top}^{gen} and optionally (JSF, bJSF))
- Separately for signal ($t\bar{t}$) and background
- Templates are parameterised and the parameters fitted linearly to varied quantities (m_{top}^{gen} , ...)
- Likelihood uses the fitted Template functions



CMS, arxiv:1209.2319v2



▶ Ideograms (CMS)

- Extension of Templates
- PDFs are constructed like above but for more signal categories
- Several permutations of the same event are allowed (weighted with $P_{g.o.f}$)
- PDFs are parameterised and the parameters fitted linearly to m_{top}^{gen} , ... as above
- Likelihood uses the Ideograms with fitted parameterised PDFs

Direct mass measurements ▶ Single t

- ▶ m_{top} from t -channel enhanced single-top sample in lepton+jets events @ 13 TeV by CMS
- ▶ Motivation

- most direct measurements are based on $t\bar{t}$ -events
- single-top probes different colour-reconnection situation

Event Selection

- exactly one central, isolated e (μ)
- jets are considered up to $|\eta| < 4.7$ and with $p_{\perp} > 40$ GeV
- $m_{\perp}(W_{\ell}) > 50$ GeV
- 2 jets with 1 b-tag (2J1T) defines signal region; 2J0T (no b-tag) the bkgd. validation region

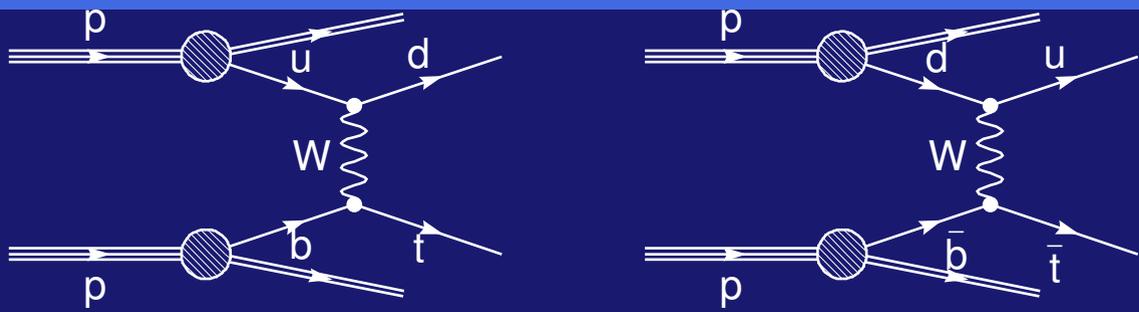
BDT's to enhance t -channel single-top

- in 8 kinematic quantities not correlated with m_t
- other single-top and $t\bar{t}$ from sim.; multi-jet from bkgd. validation sample

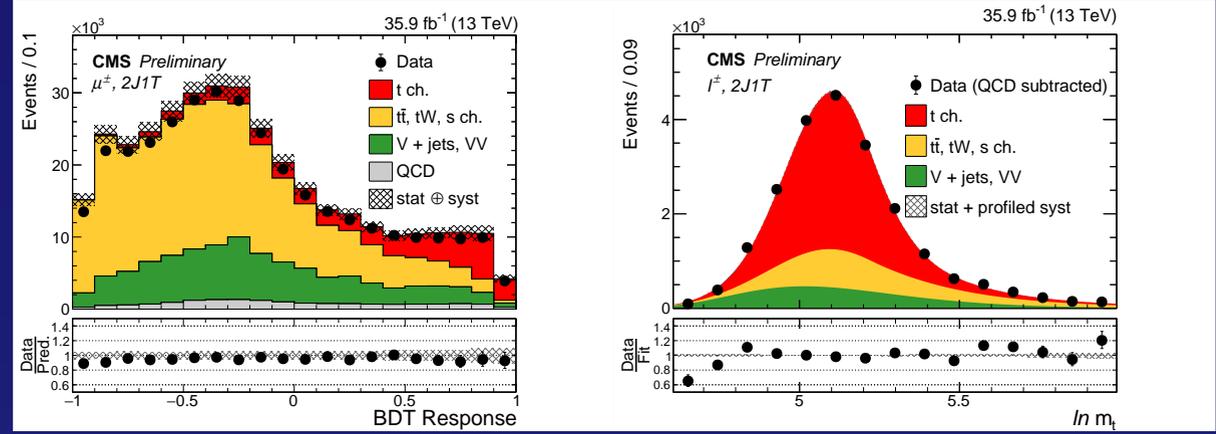
Fit to templates in $\ln m_t$ after cut on BDT

- as alternative to m_t in order to reduce impact of high-mass tail where statistics are low
- lepton-charge combined and separate (to test for $\Delta(m_t, m_{\bar{t}})$)

First sub-GeV precision result in single-top

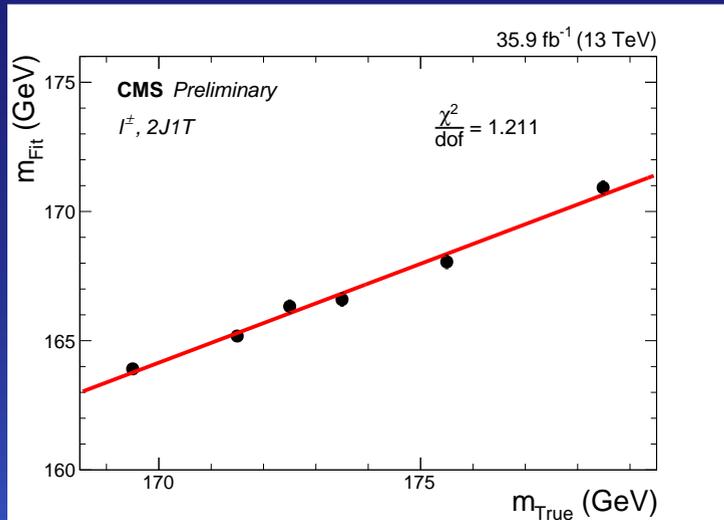


CMS-PAS-TOP-19-009



BDT output

Template fit in $\ln m_t$



mass calibration

$$m_{\text{top}} = 172.13 \pm 0.32_{\text{stat+prof}} \begin{matrix} +0.69 \\ -0.7 \end{matrix}_{\text{syst}} \text{ GeV (charge combined), } \Delta(m_t, m_{\bar{t}}) = m_t - m_{\bar{t}} = 0.83 \begin{matrix} +0.77 \\ -1.01 \end{matrix}_{\text{tot}} \text{ GeV}$$

▶ Indirect mass measurements

▶ Opposite approach than for Template/Ideogram methods

- Instead of fitting to MC distributions “folded” with the detector response unfold the data to hadron-/parton-level
- Compare to QCD predictions with $m_{\text{top}}^{\text{pole}}$ as parameter
- Pro: More control over mass scheme
- Caveat: Larger uncertainties on both theory and experiment

▶ Example: Cross section as function of $m_{\text{top}}^{\text{pole}}$ in LO, NLO and NNLO

- Large dependency on order: $\sigma_{\text{NNLO}}/\sigma_{\text{NLO}} \simeq 10\%$
- Relative uncertainty stable: $\Delta\sigma_{\text{t}\bar{\text{t}}}/\sigma_{\text{t}\bar{\text{t}}} \simeq 5\% \rightarrow \Delta m_{\text{top}}/m_{\text{top}} \simeq 1\%$

▶ Experimental challenges:

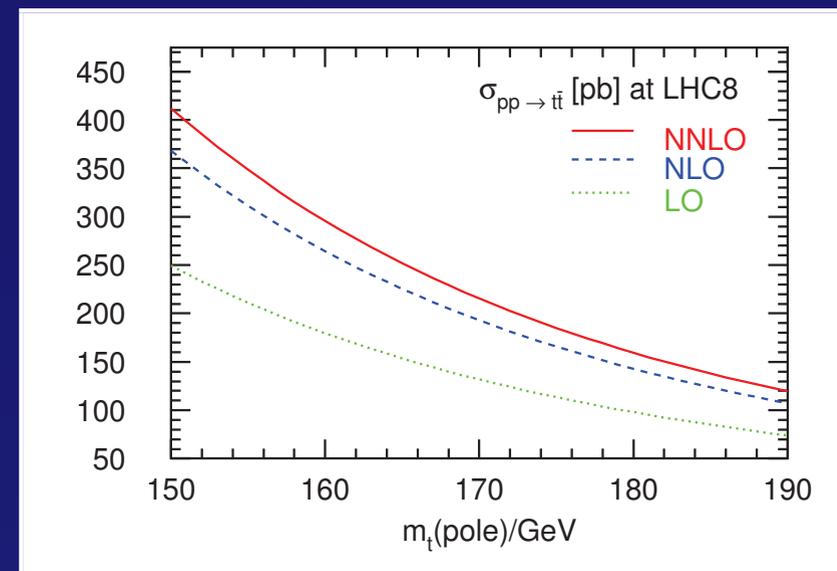
- Unfolding is more difficult than folding
 - ▶ and potentially could re-introduce a dependency on m_{top} used in the MC
- Cross sections need absolute normalisation

▶ New observables help

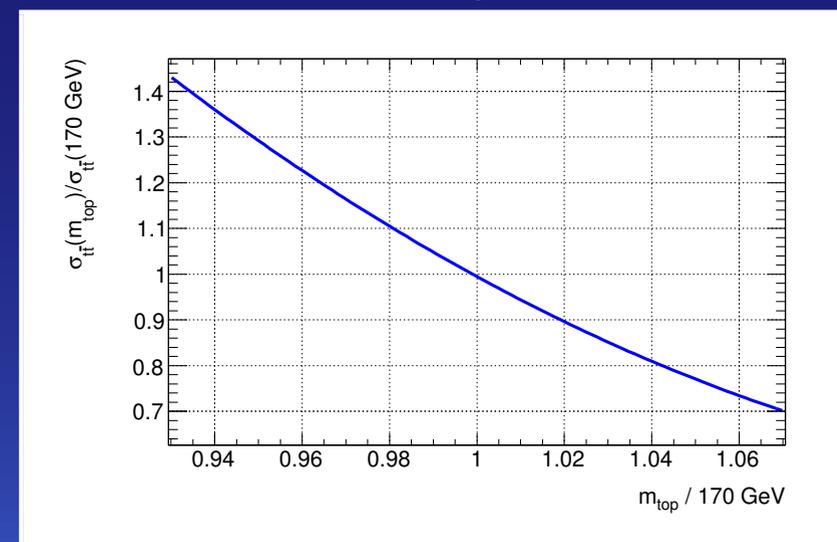
- Use shapes of differential cross-sections instead of total cross sections

- For example $\mathcal{R}(m_{\text{top}}^{\text{pole}}, \rho_S) = \frac{1}{\sigma_{\text{t}\bar{\text{t}}+1\text{jet}}} \frac{d\sigma_{\text{t}\bar{\text{t}}+1\text{jet}}}{d\rho_S}(m_{\text{top}}^{\text{pole}}, \rho_S)$,

with $\rho_S = \frac{2m_0}{\sqrt{s_{\text{t}\bar{\text{t}}j}}}$ (S. Alioli et al., Eur.Phys.J. C73 (2013) 2438)

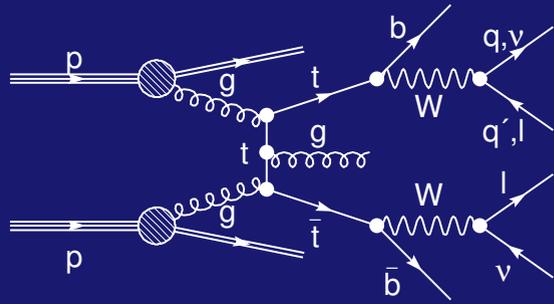


LO shape – NNLO identical



Indirect mass measurements ▶ $t\bar{t} + 1\text{jet}$

▶ $m_{\text{top}}^{\text{pole}}$ from differential cross section observable in $t\bar{t} + 1\text{jet}$ in the lepton+jets channel @ 8 TeV by ATLAS



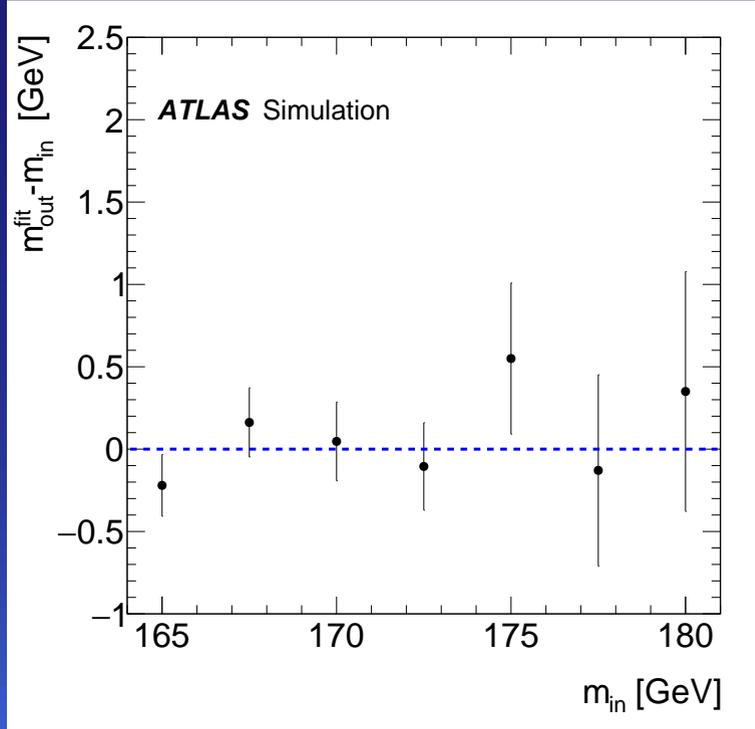
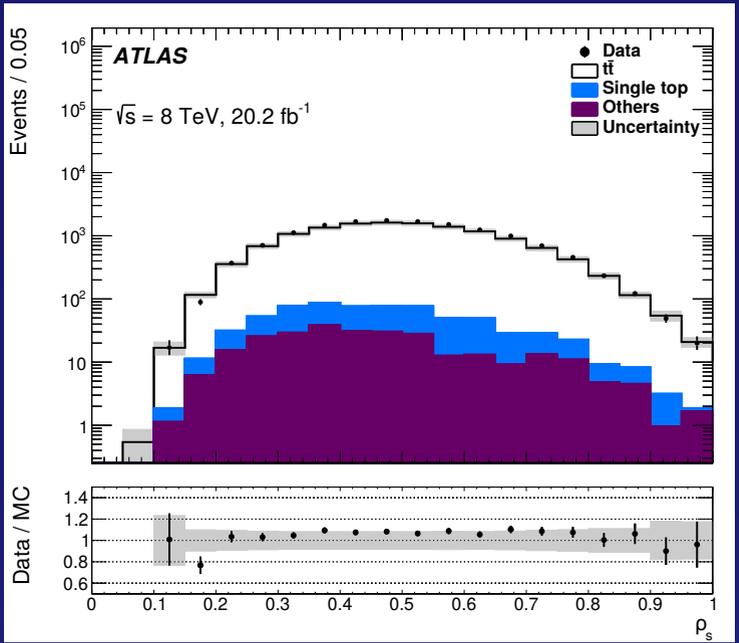
JHEP11(2019)150

▶ Event selection

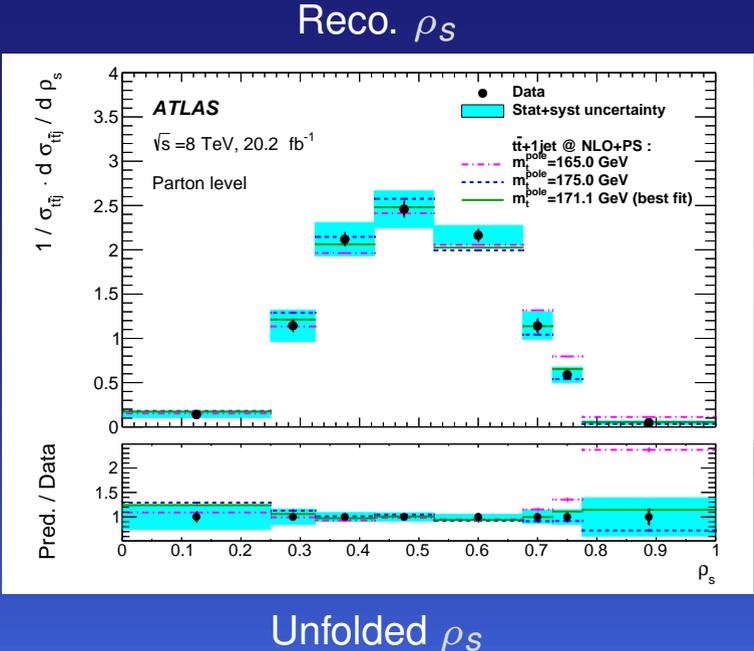
- exactly one central, isolated, e or μ , at least 5 central jets, exactly 2 of them b-tagged, $E_{\perp}^{\text{miss}} > 30 \text{ GeV}$, $m_{\perp}(W_{\ell}) > 30 \text{ GeV}$
- Leading unused jet must satisfy $p_{\perp} > 50 \text{ GeV}$ and is combined with $t\bar{t}$ -system to reconstruct ρ_S

▶ Unfolding of distribution in ρ_S to parton-level

- Compare to calculations in NLO with parton showering
- $m_{\text{top}}^{\text{pole}}$ extracted from χ^2 -fit to theory in unfolded $\rho_S \in [0, 1]$
- Most sensitive regions are the low and high ρ_S -bins
- Validation with MC samples with different top-quark masses



$\Delta(m_t^{\text{out}}, m_t^{\text{in}})$ vs. m_t^{in}



$$m_{\text{top}}^{\text{pole}} = 171.1 \pm 0.4_{\text{stat}} \pm 0.9_{\text{syst}} \begin{matrix} +0.7 \\ -0.3_{\text{theo}} \end{matrix}$$

Properties and decays ▶ Top quark mass

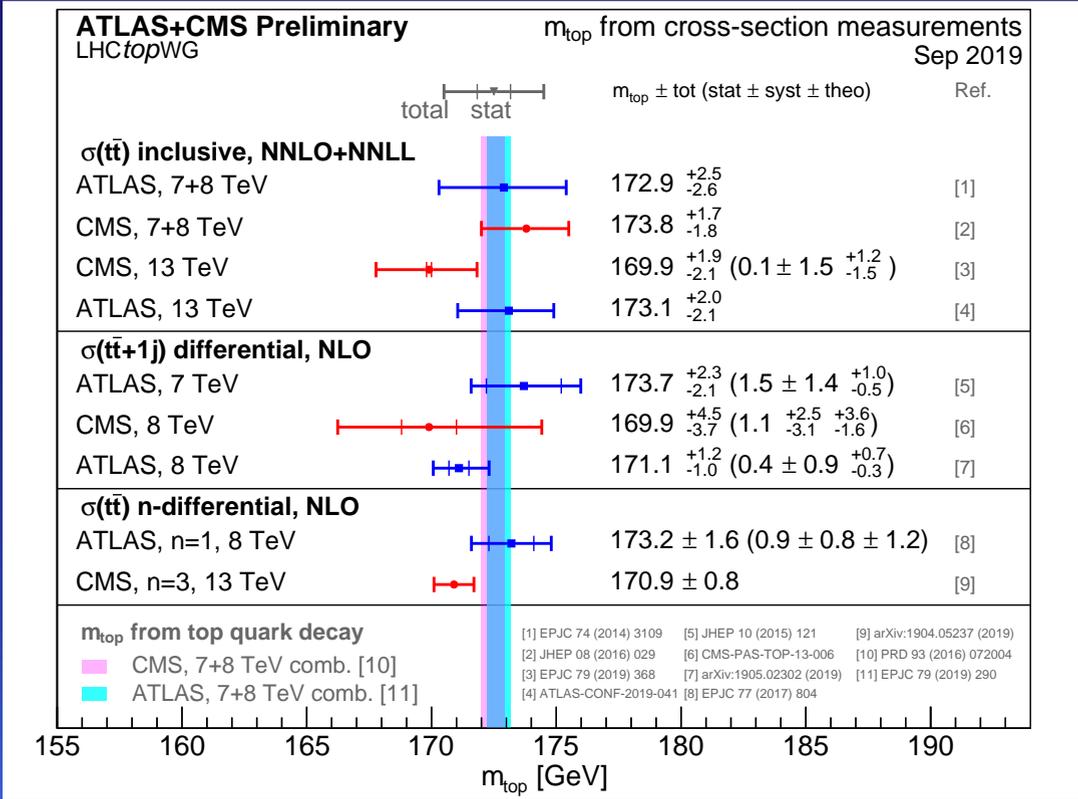
▶ Direct mass measurements

- most precise from Run-1 combinations
- ATLAS: $m_t = 172.69 \pm 0.48_{\text{tot}}$ GeV
- CMS: $m_t = 172.44 \pm 0.48_{\text{tot}}$ GeV

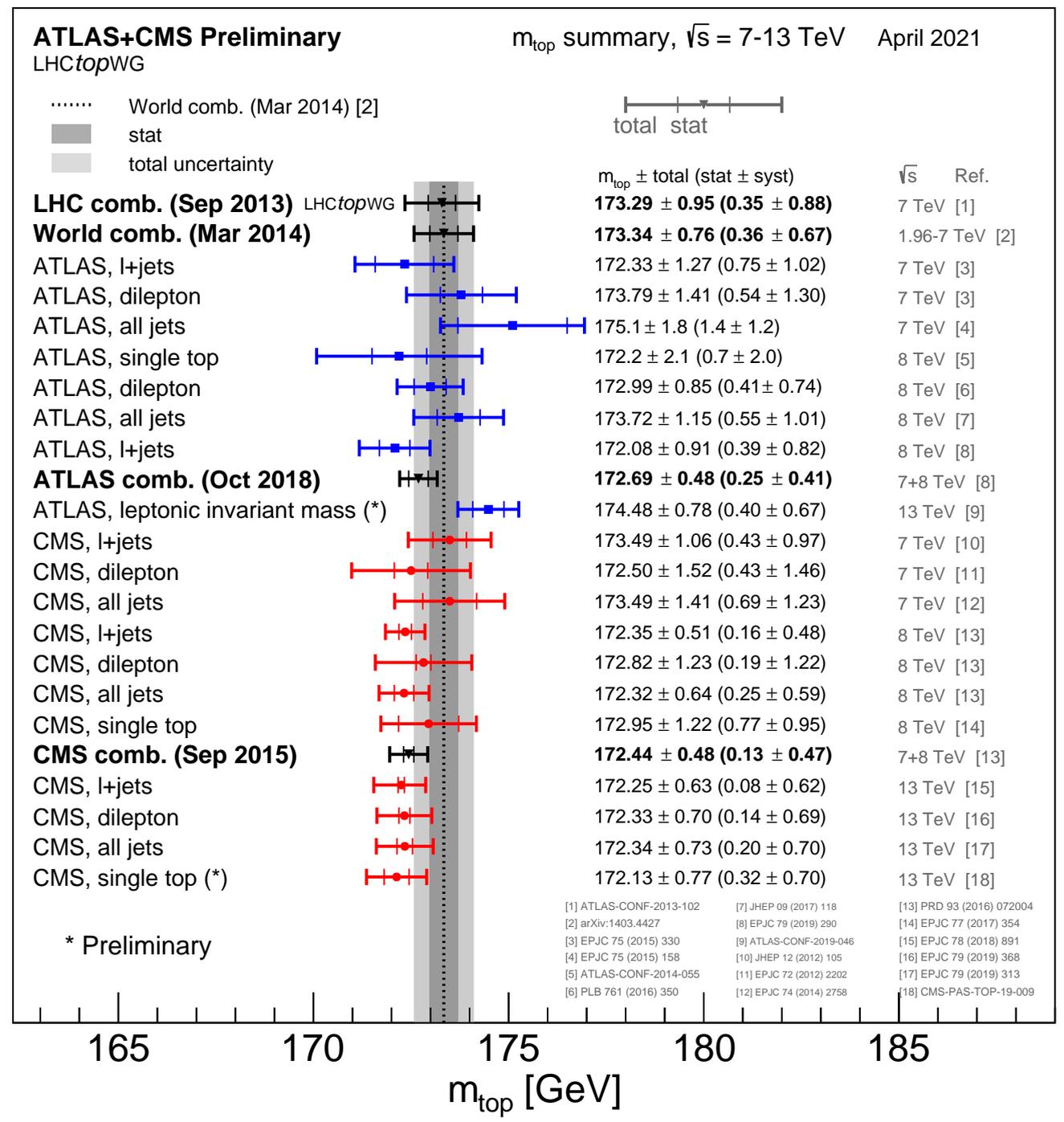
▶ Indirect mass measurements

- most precise from CMS differential cross-section @ Run-2
- CMS: $m_t = 170.9 \pm 0.8_{\text{tot}}$ GeV
 - ▶ but neglected Coulomb- and soft-gluon-resummations near $t\bar{t}$ -threshold could shift this by up to +1 GeV
- close in precision is $t\bar{t} + \text{jets}$ @ 8 TeV from ATLAS
- ATLAS: $m_t = 171.1^{+1.2}_{-1.0}$ GeV

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCtopWGSummaryPlots>



Indirect mass measurements: Sep 2019



Direct mass measurements: Apr 2021

Conclusions

▶ Top quark production at the LHC

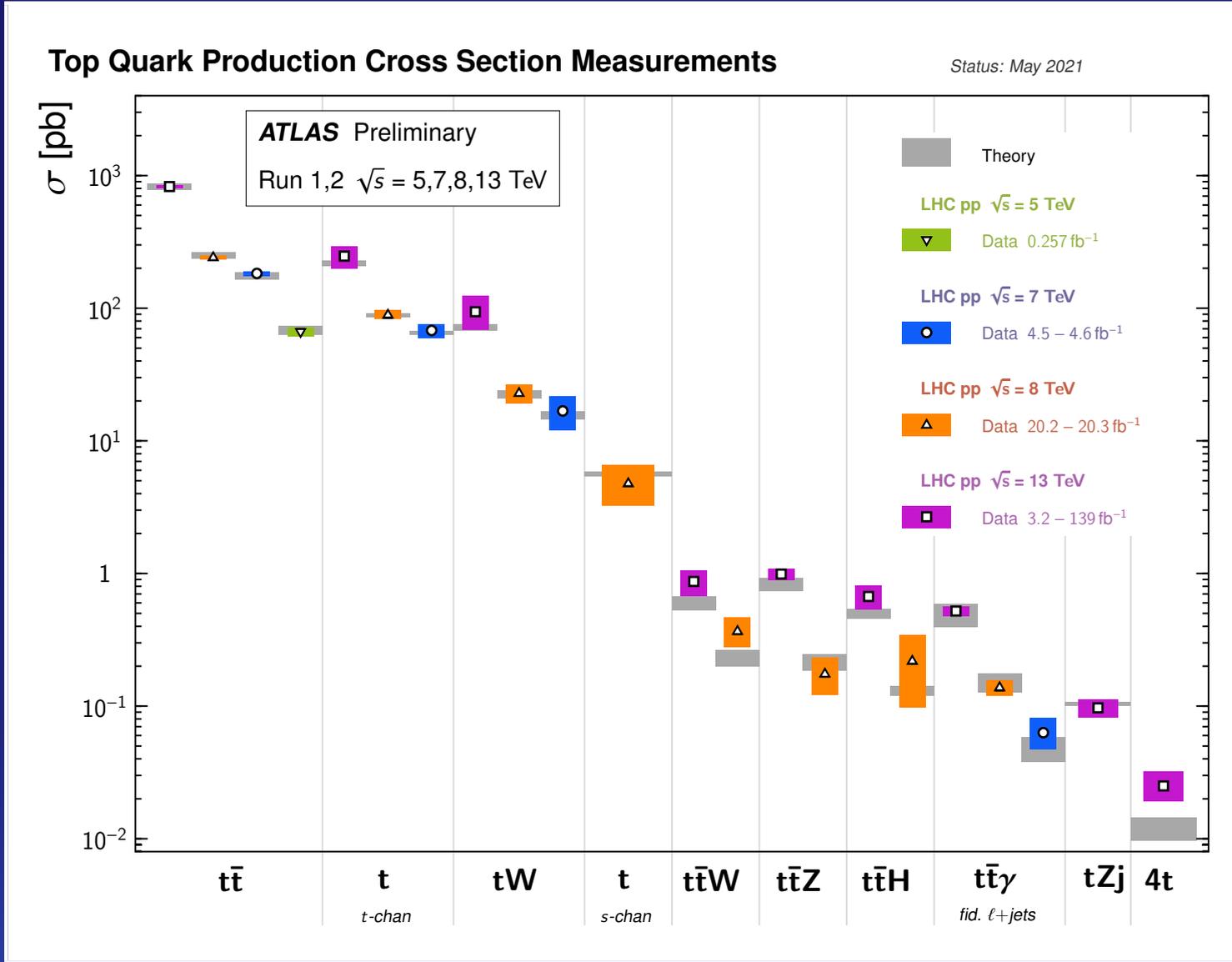
- measured with high precision by CMS and ATLAS at 5, 7, 8 and 13 TeV and in forward phase-space by LHCb
- $t\bar{t}$ production most dominant
- 5 single-top production channels measured
- recently $t\bar{t}t\bar{t}$ production cross-section measured by ATLAS (ATLAS-CONF-2021-013):
 - ▶ $\sigma_{4t}(13 \text{ TeV}) = 24^{+7}_{-6} \text{ fb}$
- (multi-)differential cross-section comparisons to NLO and NNLO calculations

▶ Top quark decays at the LHC

- rich laboratory to explore
 - ▶ Wtb-vertex structure
 - ▶ spin-correlations and \mathcal{CP} -violation
 - ▶ b-fragmentation
 - ▶ lepton universality
 - ▶ top-quark polarisation

▶ Measurements of the top-quark mass

- with direct and indirect methods
- direct measurements reached $O(0.5 \text{ GeV})$ precision
- indirect measurements reached $O(0.8 \text{ GeV})$
- so far no tension between the results



▶ More top-quark production and properties presentations at LHCP2021:

- Monday: Top physics: Top production
- Thursday: Top physics: Top mass and properties