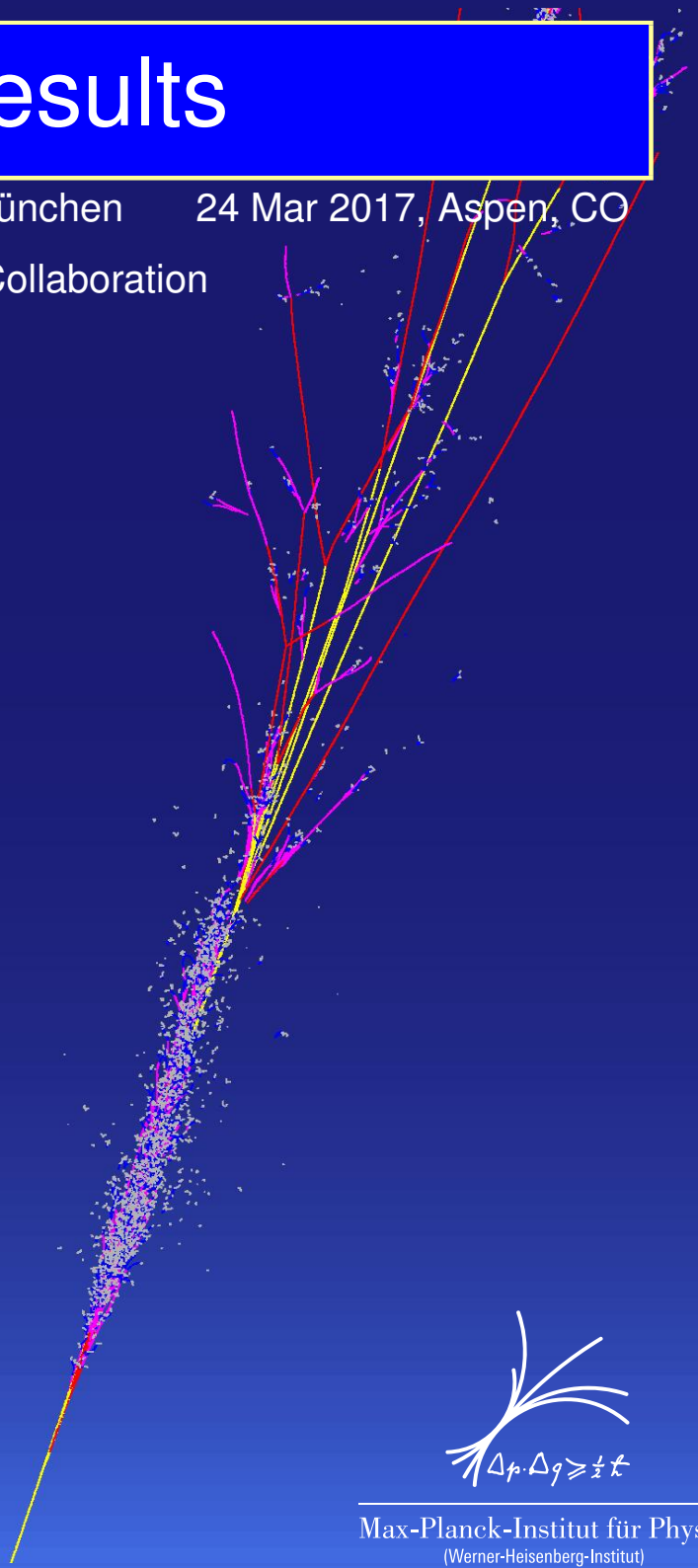
ATLAS top quark results

"From the LHC to Dark Matter and Beyond" Sven Menke, MPP München 24 Mar 2017, Aspen, CO

on behalf of the ATLAS Collaboration

- Introduction
  - Top quark
- Cross sections
  - Single top quark production
  - Pair production of top quarks
  - $t\bar{t}$ production in association with a W/Z boson
- Top quark properties
  - Spin correlations
  - W boson helicity
  - Wtb vertex structure
  - Top quark mass
- Conclusions

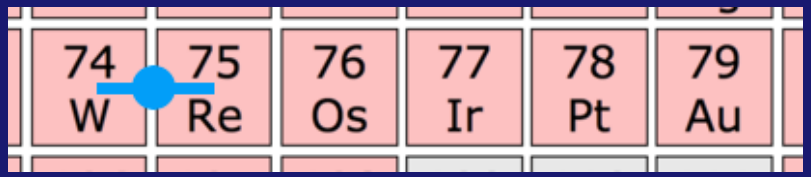


ATLAS EXPERIMENT

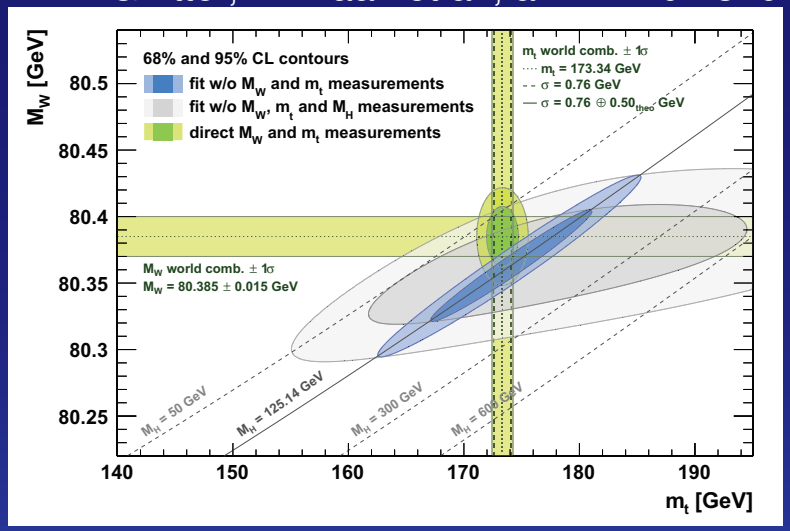
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Importance of the top quark mass

- The top quark is by far the heaviest known fermion
- And the heaviest known particle – outperforming the Higgs by $\sim 40\%$ and the E.W. gauge bosons by $\sim 100\%$
  - Compared to the periodic table of elements a single top quark is as heavy as a Rhenium atom – heavier than Tungsten and not far from Gold ...



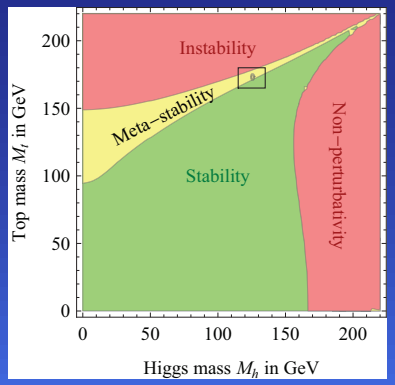
GFitter, M. Baak et al., arXiv:1407.3792

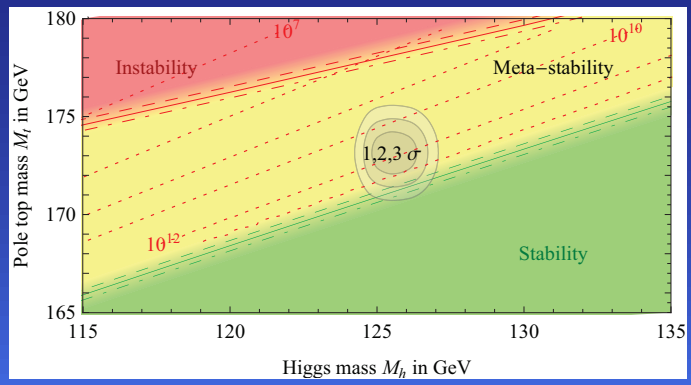


- m_{top} provides together with m_W and m_{Higgs} over-constraints to SM fits
- Direct measurements can be compared with indirect fit results to probe the validity of the SM

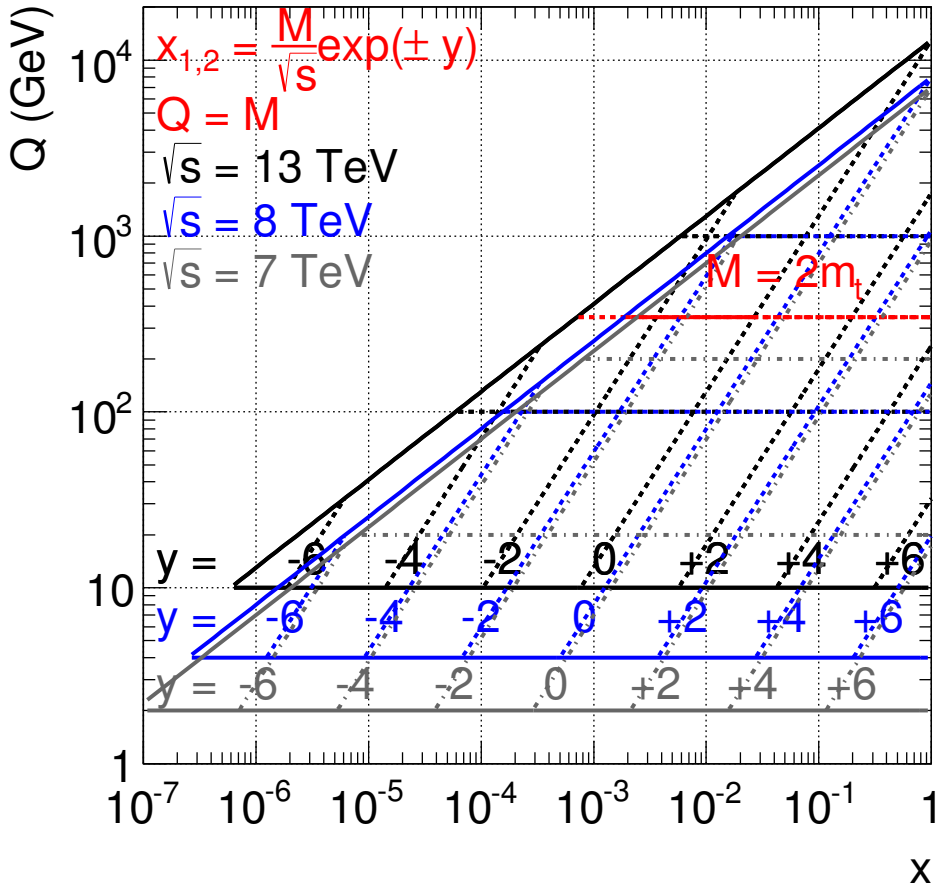
- m_{top} and m_{Higgs} determine the SM vacuum stability

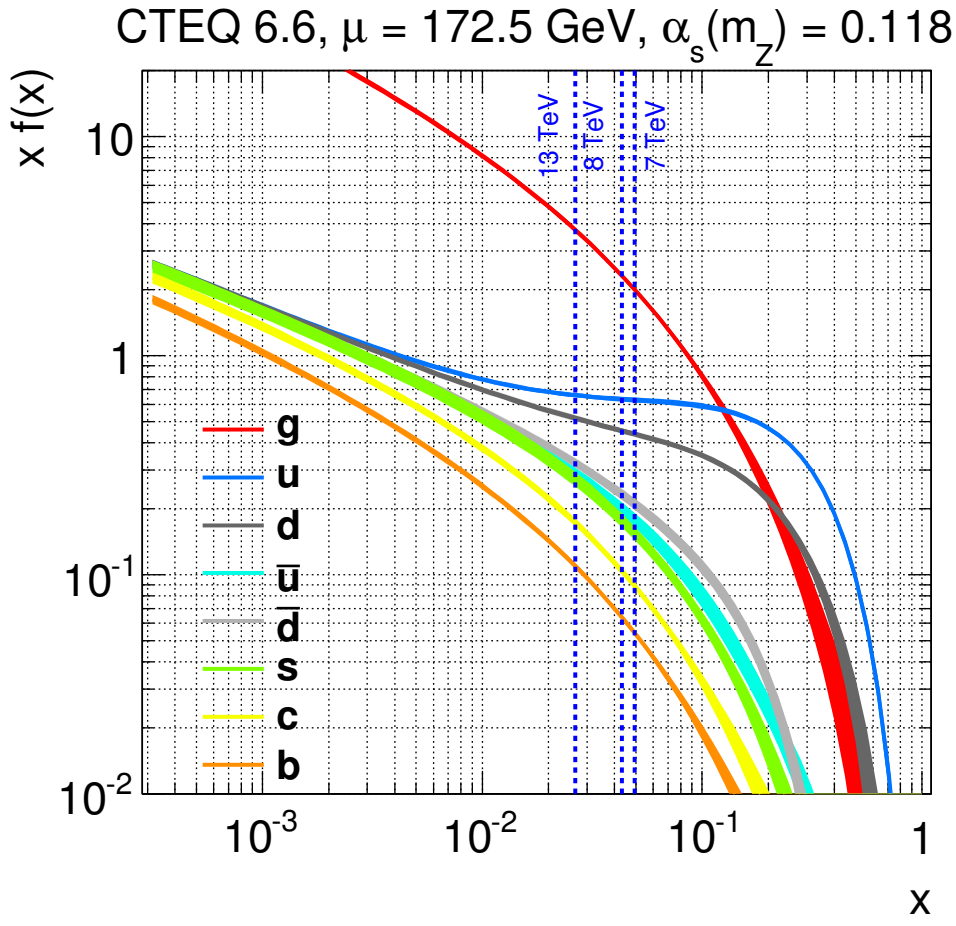
G. Degrassi et al., arXiv:1205.6497v2





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



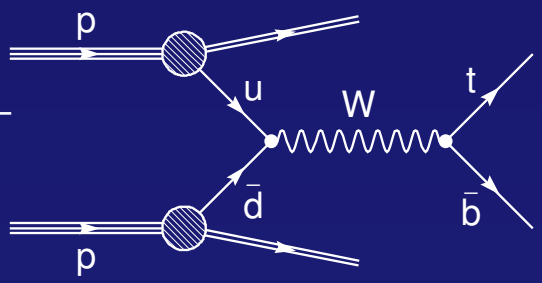


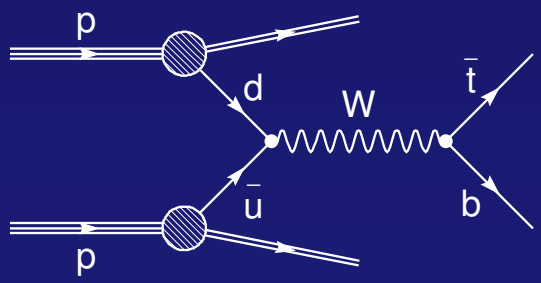
- Q vs. $x_{1,2}$ for the LHC at 7, 8, and 13 TeV (left)
- Red curve shows top-pair production as example
- QCD measurements constrain α_s and PDF's – here CTEQ 6.6 (right)

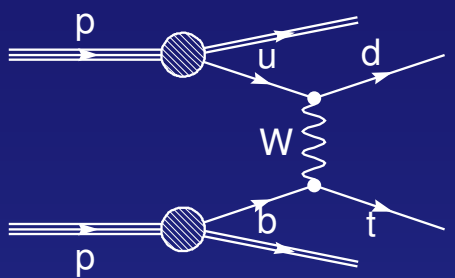
- Total cross section for single top production surprisingly large $\simeq 44(36)\,\%$ of $\sigma_{t\bar{t}}$ @8(13) TeV NLO single-top / NNLO+NNLL $t\bar{t}$ predictions
  - Calculations by TopLHCWG with `Top++`, arXiv:1112.5675 for $t\bar{t}$ and `Hathor v2.1`, arXiv:1007.1327, arXiv:1406.4403 for single-top

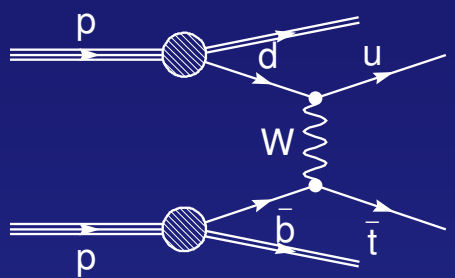
- *s*-channel

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







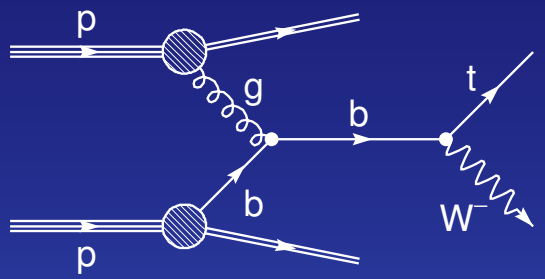


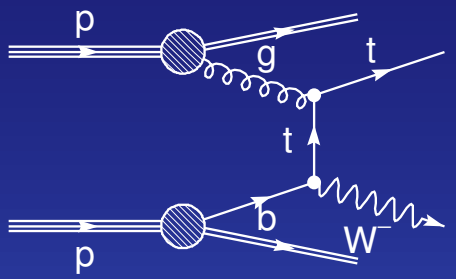
- *t*-channel

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

- Wt prod.

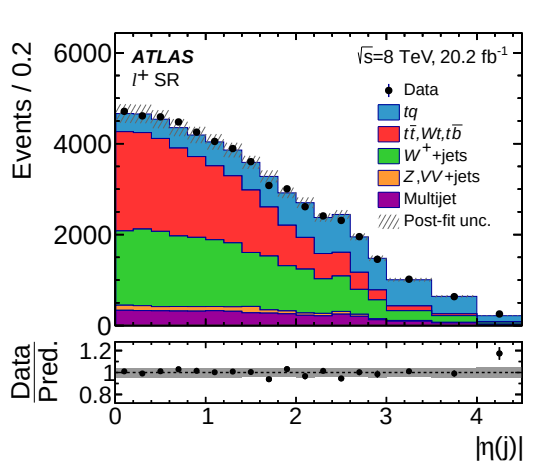
$\sqrt{s}$	$\sigma_{\mathrm{Wt}}/\sigma_{\mathrm{single\ t}}$
8 TeV	20 %
13 TeV	24 %



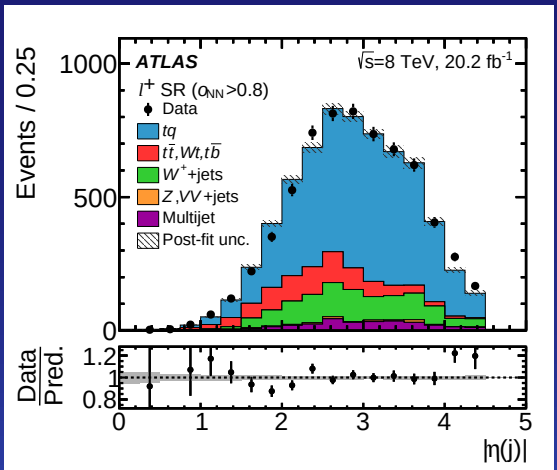


- $R_t = \sigma_{\mathrm{EWt}}(t)/\sigma_{\mathrm{EWt}}(\bar{t})$ sensitive to PDF
  - ratio of valence u to d quark density
- BSM physics would lead to deviations from SM expectations for total and differential cross-sections

arXiv:1702.02859



$|\eta(j)|$: Input to NN
+ other 6 kinematic observables



$|\eta(j)|$: After cut on NN

Analysis @8 TeV in the t-channel

- Require one central e or μ and two jets, exactly one b-tagged
- $E_{\perp}^{\text{miss}} > 30$ GeV and $m_{\perp}(\ell E_{\perp}^{\text{miss}}) > 50$ GeV
- Suppress fake leptons by higher $p_{\perp}$ cut on those back-to-back with a jet
- Validation regions for W+jets ($t\bar{t}$) with smaller (two) b-tag weight(s)

Remaining W+jets and $t\bar{t}$+single top background separated by a neural network (NN)

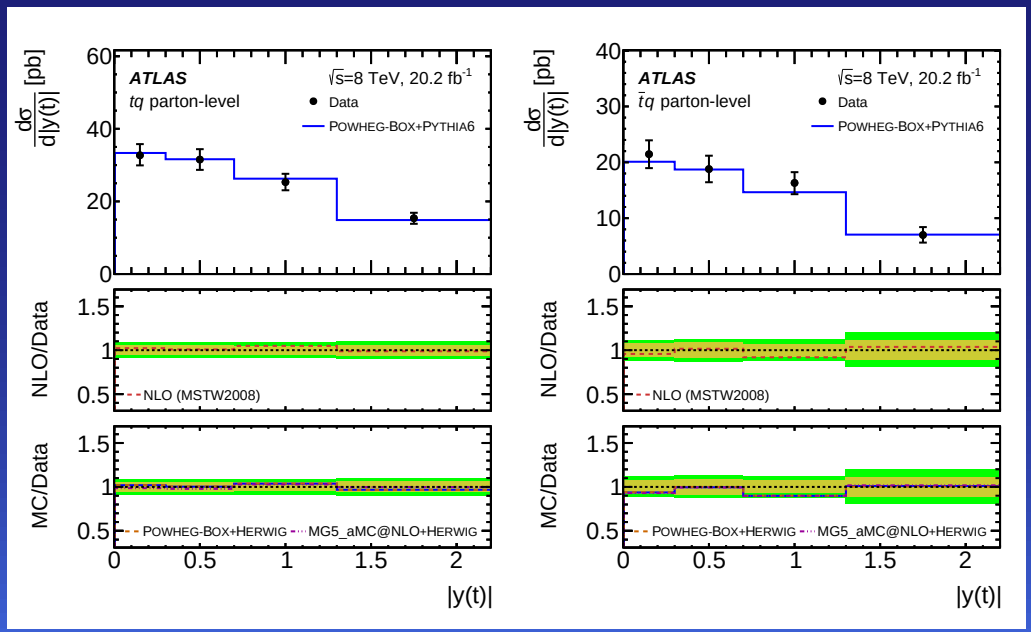
- Binned max-likelihood fit to NN output yields fiducial cross-sections
- Extrapolated to total phase space:

$$\sigma_{\text{EWt}}(t) = 56.7 \pm 0.9_{\text{stat}} \pm 2.7_{\text{exp}} \,^{+2.7}_{-1.7}{}_{\text{scale}} \ldots \text{pb}$$

$$\sigma_{\text{EWt}}(\bar{t}) = 32.9 \pm 0.8_{\text{stat}} \pm 2.3_{\text{exp}} \,^{+1.4}_{-0.8}{}_{\text{scale}} \ldots \text{pb}$$

- $R_t = \sigma_{\text{EWt}}(t)/\sigma_{\text{EWt}}(\bar{t}) = 1.72 \pm 0.05_{\text{stat}} \pm 0.07_{\text{exp}}$

arXiv:1702.02859

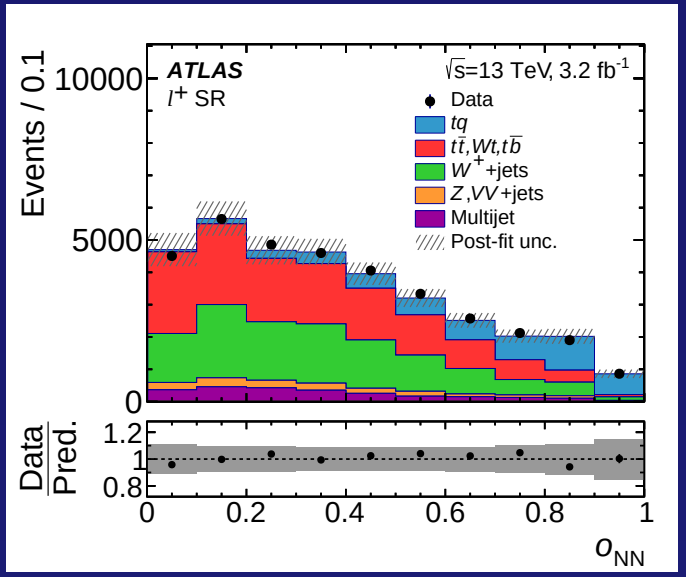


diff. x-sec in $|y(t)|$: for top and anti-top

► Unfolding in $p_{\perp}(t)$ and $|y(t)|$ after cut on NN output to extract differential cross-sections in good agreement with SM predictions

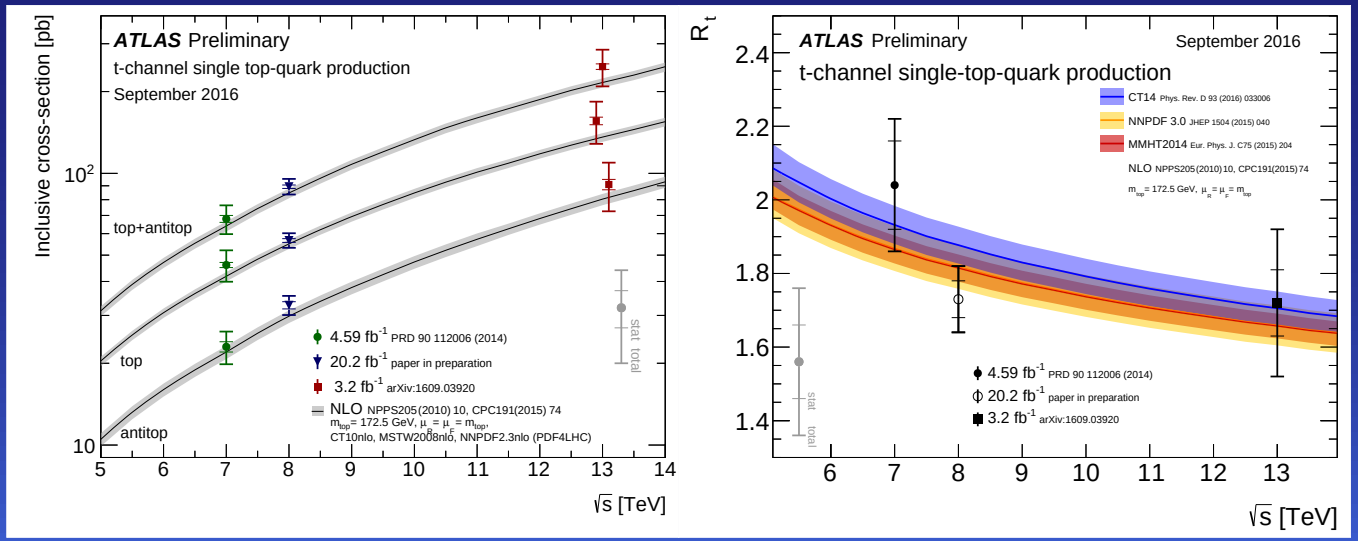
- Analysis @13 TeV in the t-channel
  - Very similar event selection as for 8 TeV analysis (prev. slide)
  - Validation regions for W+jets ($t\bar{t}$) with same selection but smaller (two) b-tag weight(s) and one additional jet for $t\bar{t}$
- Remaining W+jets and $t\bar{t}$+single top background separated by a neural network (NN) like for 8 TeV analysis
- Binned max-likelihood fit to NN output yields fiducial cross-sections

arXiv:1609.03920



NN output in ℓ^+ signal region

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP

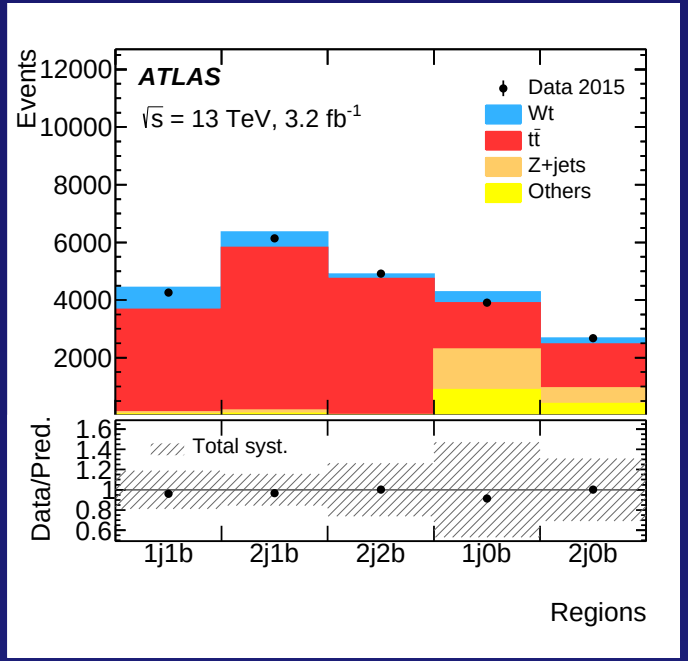


σ_{EWt} vs. $\sqrt{s}$ $\quad$ $R_t = \sigma_{EWt}(t)/\sigma_{EWt}(\bar{t})$ vs. $\sqrt{s}$

- Extrapolated to total phase space:
  $\sigma_{EWt}(t) = 156 \pm 5_{stat} \pm 27_{syst} \pm 3_{lumi}$ pb
  $\sigma_{EWt}(\bar{t}) = 91 \pm 4_{stat} \pm 18_{syst} \pm 2_{lumi}$ pb
- $R_t = \sigma_{EWt}(t)/\sigma_{EWt}(\bar{t}) = 1.72 \pm 0.09_{stat} \pm 0.18_{syst}$

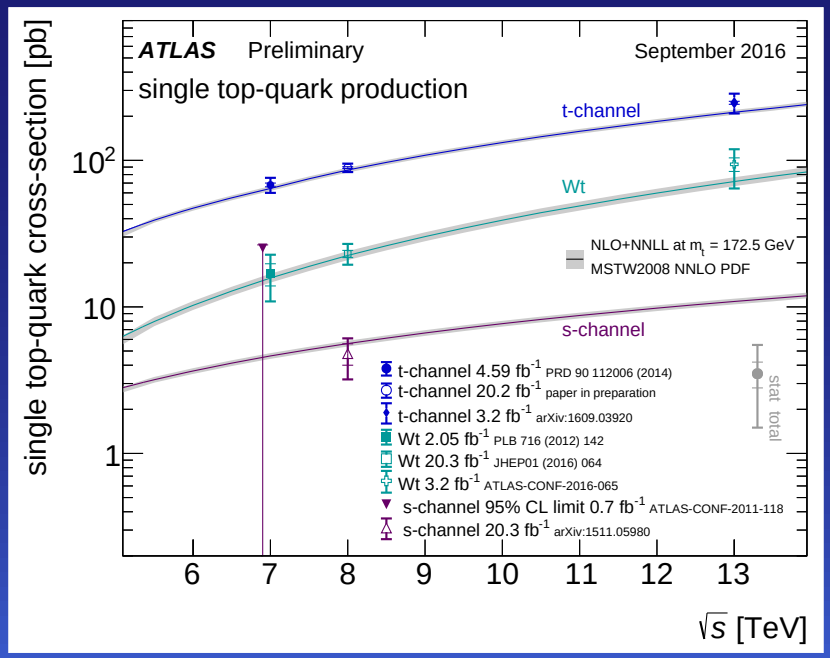
arXiv:1612.07231

- Analysis @13 TeV in the Wt-channel
  - Exactly two oppositely charged leptons and at least one jet
  - $m_{\ell\ell}$ and $E_{\perp}^{\text{miss}}$ cuts based on lepton flavours to veto Z+jets bkgd
  - Regions based on number of jets and b-tags to separate Wt (1j1b, 2j1b) from $t\bar{t}$ (2j2b) and Z+jets (1j0b, 2j0b)
  - Simultaneous BDT fit to Wt and $t\bar{t}$ regions



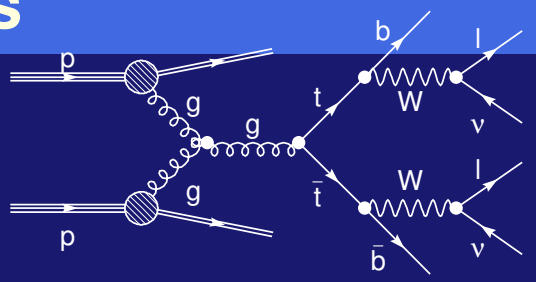
Event yield per region

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP



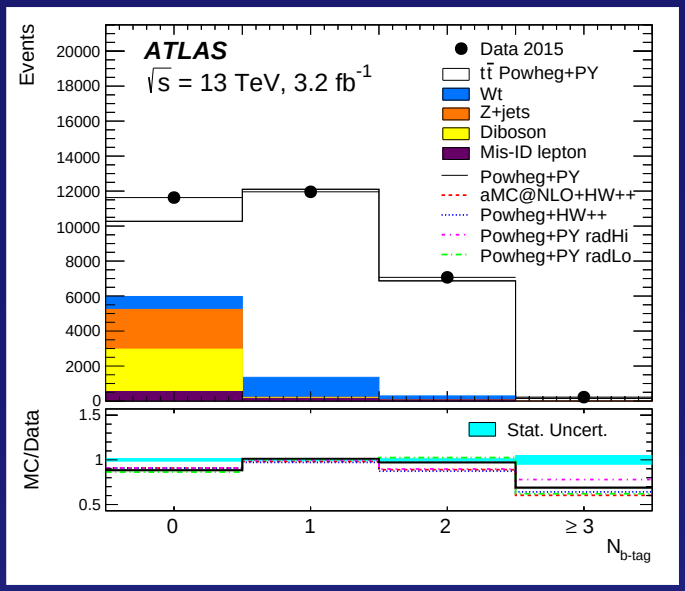
σ_{EWt}, σ_{Wt}, σ_{EWs} vs. $\sqrt{s}$

- BDT input: optimised set of kinematic variables of subset of selected objects
- Dominant systematic uncertainty from jet energy scale and resolution and NLO matrix element generator
- Likelihood fit of signal and background templates to binned BDT output:
  - $\sigma_{\text{Wt}} = 94 \pm 10_{\text{stat}} \,^{+28}_{-22\ \text{syst}} \pm 2_{\text{lumi}}$ pb
- Good agreement to SM prediction
- Comparison of all single top-quark cross sections (left)



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

arXiv:1606.02699



Number of b-tagged jets

- Event selection @13 TeV
  - Exactly two isolated oppositely charged leptons central (one electron and one muon) with $p_\perp > 25$ GeV
  - Corresponding same-charge sample used to estimate background
  - Jets: Central AntiKt jets with $R = 0.4$, $p_\perp > 25$ GeV
  - Keep events with exactly 1 or 2 b-tagged jets

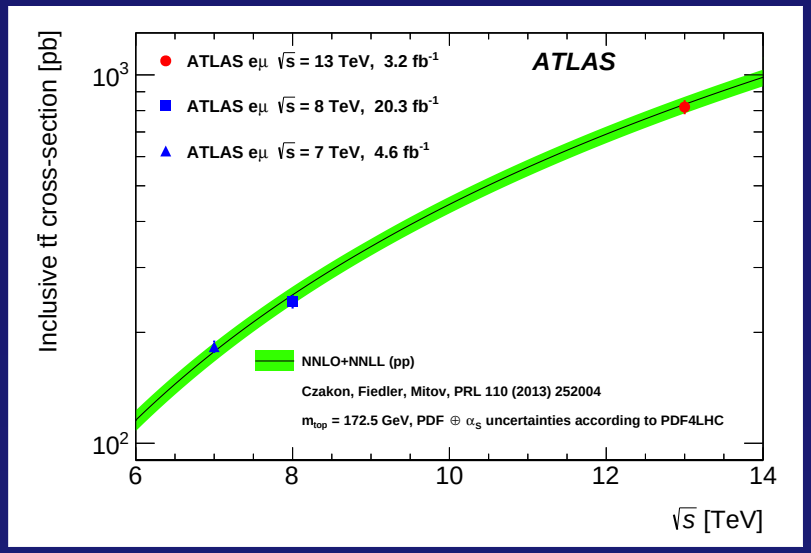
- Biggest systematic uncertainty from modelling preselection efficiency
  - Preselection efficiency: $\epsilon_{e\mu} = A_{e\mu} \times G_{e\mu}$ is product of acceptance: $A_{e\mu}(1.38\%) = \mathrm{BR}_{WW\to e\mu\,(\text{incl. tau decays})}(2.7\%) \times \epsilon_{p_\perp>25\,\mathrm{GeV}\wedge|\eta|<2.5}(51.1\%)$ and reconstruction efficiency: $G_{e\mu} \simeq 60.1\%$
  - In particular $t\bar{t}$-hadronisation contributes with $2.8\%(1.9\%)$ to total (fiducial) cross section systematic uncertainty followed by $t\bar{t}$ NLO modelling with $0.8\%(0.6\%)$

$$\sigma^{\mathrm{fid}}_{t\bar{t}} = 11.32 \pm 0.10_{\mathrm{stat}} \pm 0.29_{\mathrm{syst}} \pm 0.26_{\mathrm{lumi}} \pm 0.17_{\mathrm{beam}}\ \mathrm{pb}$$

$$\sigma_{t\bar{t}} = 818 \pm 8_{\mathrm{stat}} \pm 27_{\mathrm{syst}} \pm 19_{\mathrm{lumi}} \pm 12_{\mathrm{beam}}\ \mathrm{pb}$$

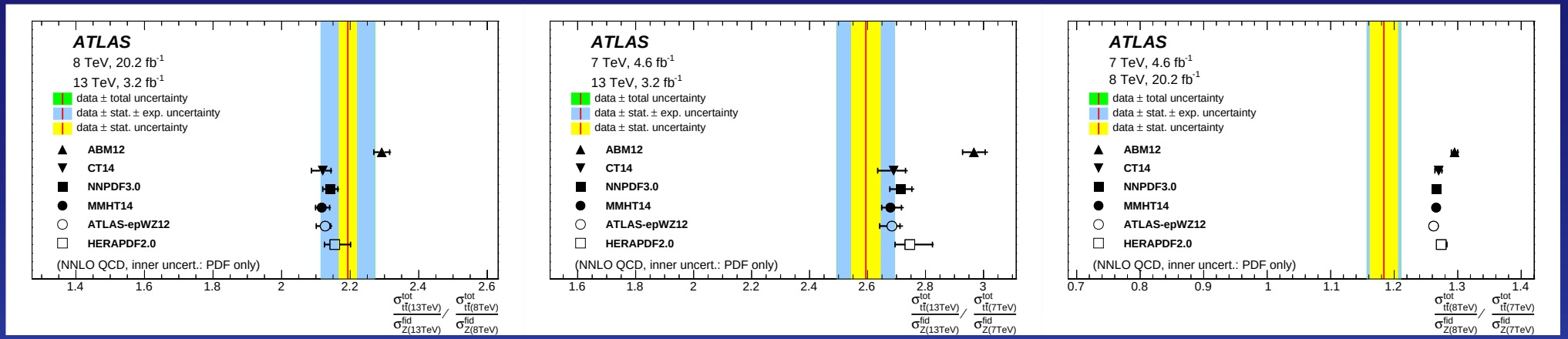
arXiv:1606.02699

- Compare to measurements @7&8 TeV
  - $e\mu$-channel: arXiv:1406.5375
    $\sigma_{t\bar{t}}(7\,\text{TeV}) = 182.9 \pm 3.1_{\text{stat}} \pm 4.2_{\text{syst}} \pm 3.6_{\text{lumi}} \pm 3.3_{\text{beam}}$ pb
    $\sigma_{t\bar{t}}(8\,\text{TeV}) = 242.9 \pm 1.7_{\text{stat}} \pm 5.5_{\text{syst}} \pm 5.1_{\text{lumi}} \pm 4.2_{\text{beam}}$ pb
  - τ+jets channel: arXiv:1702.08839
    $\sigma_{t\bar{t}}(8\,\text{TeV}) = 239 \pm 4_{\text{stat}} \pm 28_{\text{syst}} \pm 5_{\text{lumi}}$ pb
- Normalisation to precisely measured Drell-Yan production of Z-bosons



Double ratios of $\sigma_{t\bar{t}}/\sigma_Z$ at different $\sqrt{s}$

arXiv:1612.03636



13 TeV/8 TeV | 13 TeV/7 TeV | 8 TeV/7 TeV

- Removes luminosity uncertainties
- Enhances PDF sensitivity

- 8 TeV/7 TeV deviates on 3σ-level from closest prediction
- No easy explanation from PDF since ratios look o.k. when comparing to 13 TeV
- ATLAS-epWZ12 and HERAPDF2.0 best

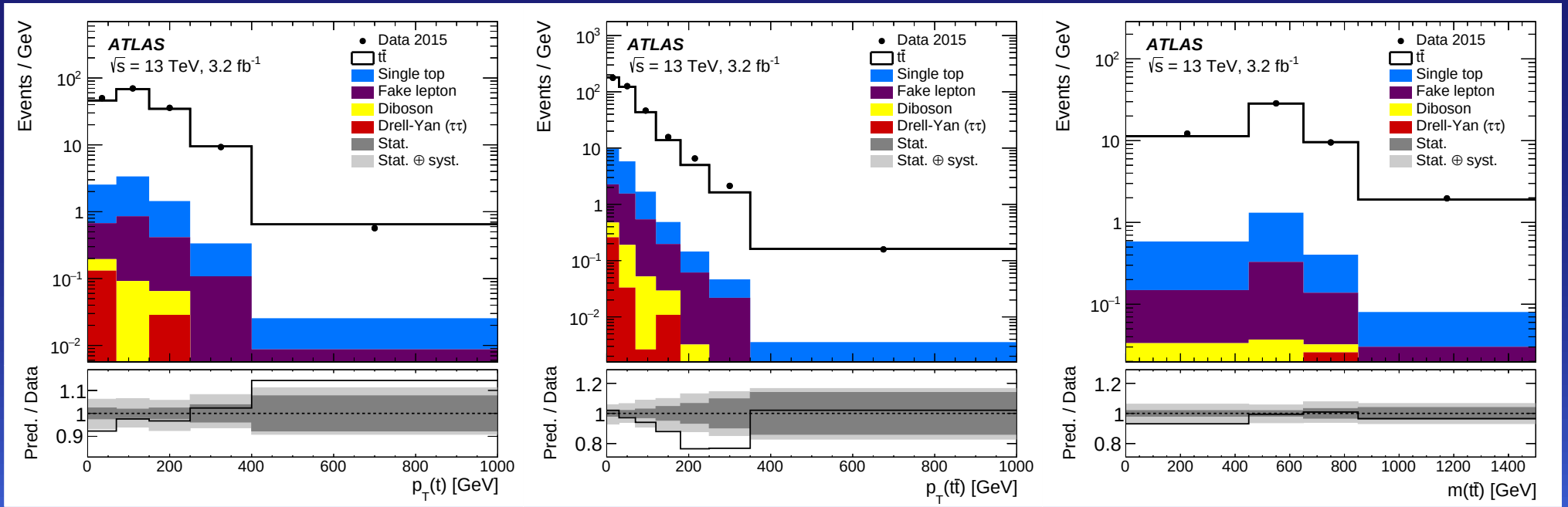
- Differential cross sections measured in 5 observables @13 TeV:
  - $p_\perp(\mathrm{t})$, $m(\mathrm{t\bar{t}})$: Sensitive to higher order QCD corrections
  - $|y(\mathrm{t})|$, $|y(\mathrm{t\bar{t}})|$: Sensitive to PDF
  - $p_\perp(\mathrm{t\bar{t}})$: Sensitive to gluon radiation

$$\frac{\mathrm{d}\sigma_{\mathrm{t\bar{t}}}}{\mathrm{d}X_i} = \frac{\sum_j R_{ij}^{-1} \cdot \epsilon_i^{\mathrm{fid}} \cdot \left(N_j^{\mathrm{obs}} - N_j^{\mathrm{bkg}}\right)}{\mathcal{L} \cdot \mathcal{B} \cdot \Delta X_i \cdot \epsilon_i}$$

- Neutrino weighting technique and unfolding to particle level in the $\mathrm{e}\mu$ channel

Kinematic distributions after $\mathrm{t\bar{t}}$-reconstruction, before unfolding

arXiv:1612.05220

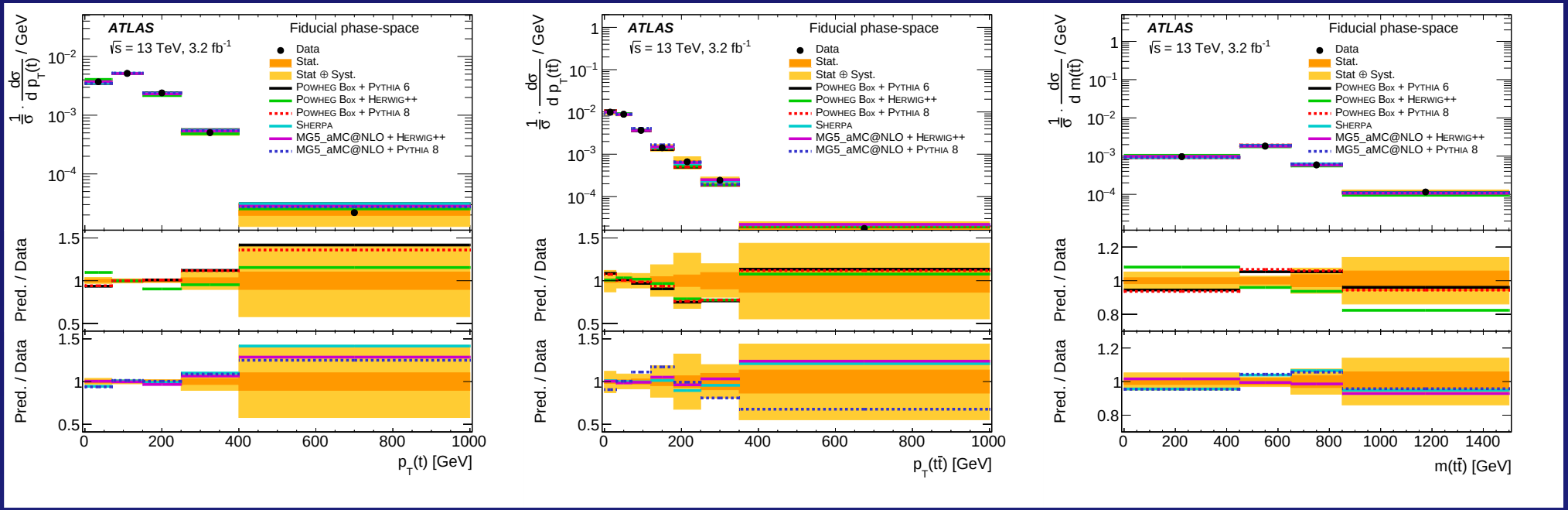


$p_\perp(\mathrm{t})$ $p_\perp(\mathrm{t\bar{t}})$ $m(\mathrm{t\bar{t}})$

Differential cross sections ► Pair production of top quarks

Differential cross section shapes after unfolding

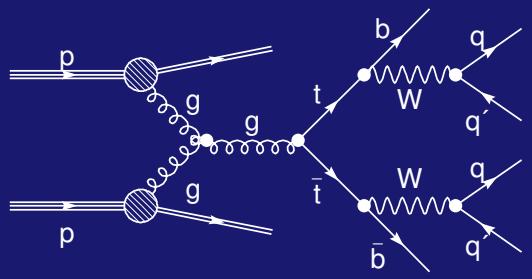
arXiv:1612.05220



$p_\perp(\mathrm{t})$ $p_\perp(\mathrm{t\bar{t}})$ $m(\mathrm{t\bar{t}})$

- Systematic uncertainties largest for high $|y|$ and large $p_\perp$
  - Dominated by parton shower model
- Normalisation reduces systematic uncertainties
  - By factors $\sim 5 - 8$ in best bins
- Comparison to NLO predictions
  - `PowhegBox + Pythia6/Herwig++/Pythia8`
  - `Sherpa`
  - `MadGraph5_aMC@NLO + Herwig++/Pythia8`
- Agree within uncertainties except:
  - `PowhegBox + Herwig++` shows large deviations in $p_\perp(\mathrm{t})$ and $m(\mathrm{t\bar{t}})$

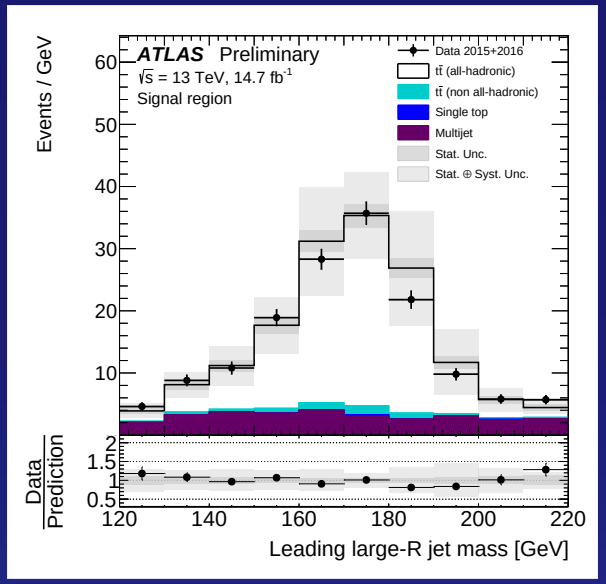
Differential cross sections ► Pair production of top quarks



- The full-hadronic channel provides a fully reconstructed final state of $t\bar{t}$ events but suffers from large QCD multijet background

- Differential cross section in the full hadronic channel with highly boosted top-quarks @13 TeV
  - Large AntiKt jets with $R = 1.0$
  - Boosted tops: $p_\perp > 500(350)$ GeV
  - Both jets b-tagged
  - Substructure to further reduce QCD multijet background

ATLAS-CONF-2016-100



Leading large-R jet mass

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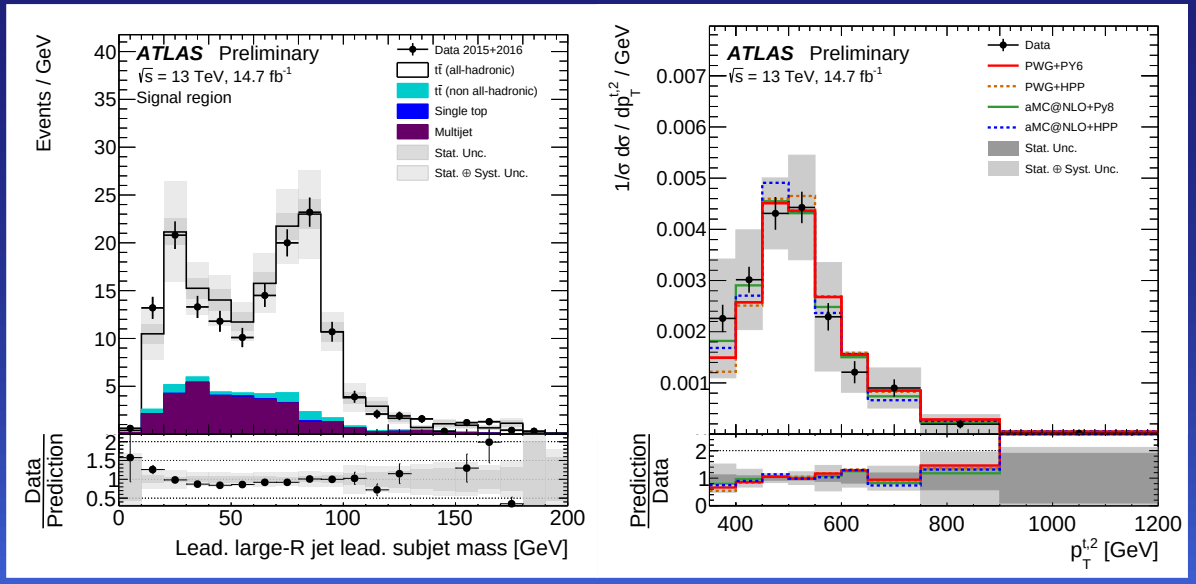
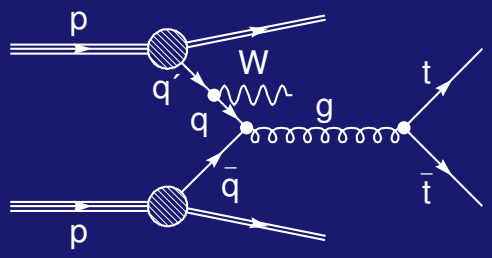
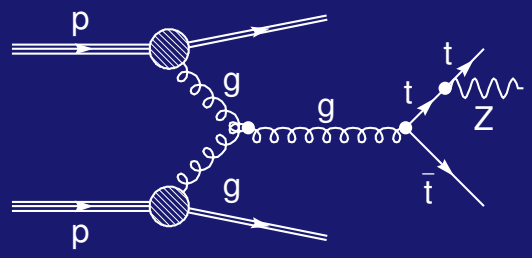


Leading subjet mass Diff. x-sec shape in $p_\perp$ (t)

- Trimming/top-tagging with $\epsilon_t = 50\%$
- QCD rejection factor $10 - 17$
- Unfolding procedure similar to $e\mu$ analysis
- Systematic uncertainties dominated by large R-jet energy scale, $t\bar{t}$-modelling and b-tagging
- Good agreement to NLO predictions

Cross sections ► $t\bar{t}$ production in association with a W/Z boson





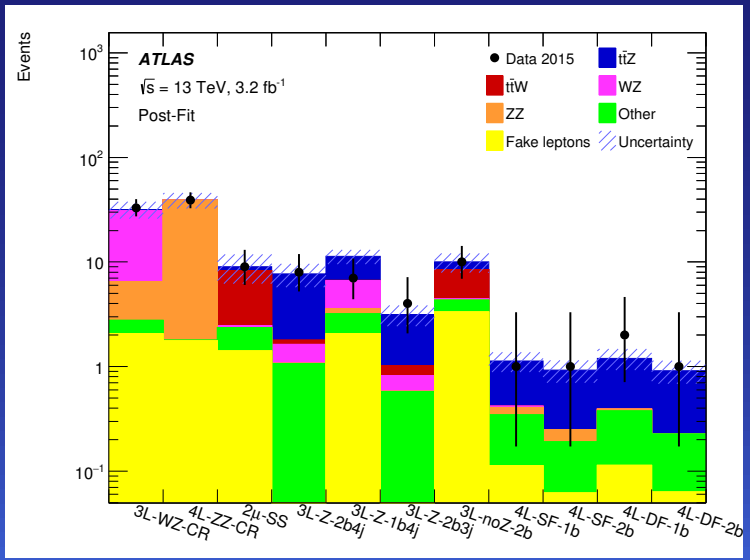
- $\sigma_{t\bar{t}V}$ sensitive to BSM and $\sigma_{t\bar{t}Z}$ to neutral current coupling

	$t\bar{t}$ decay	V decay	Channel
$t\bar{t}W$	$\mu^{\pm}\nu b\ q'\bar{q}b$	$\mu^{\pm}\nu$	SS 2μ
	$\ell^{\pm}\nu b\ \ell^{\mp}\nu b$	$\ell^{\pm}\nu$	Tri-ℓ
$t\bar{t}Z$	$\ell^{\pm}\nu b\ q'\bar{q}b$	$\ell^{+}\ell^{-}$	Tri-ℓ
	$\ell^{\pm}\nu b\ \ell^{\mp}\nu b$	$\ell^{+}\ell^{-}$	Tetra-ℓ

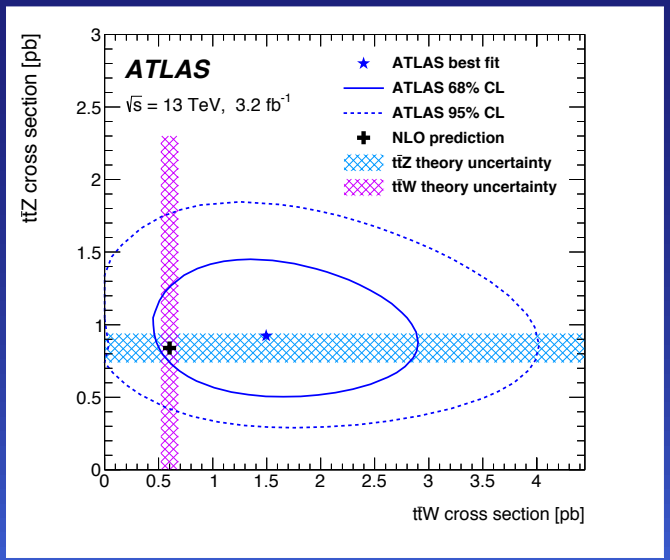
- 9 Signal and 2 control regions are defined based on number, charge and flavour of leptons, number of jets and b-tags
- Simultaneous fit for $\sigma_{t\bar{t}W}$ and $\sigma_{t\bar{t}Z}$ to all 11 regions
- Systematic uncertainty dominated by fake leptons and charge misID ($\sigma_{t\bar{t}W}$) and electron identification efficiency ($\sigma_{t\bar{t}Z}$)
- Measurements are statistically limited

arXiv:1609.01599

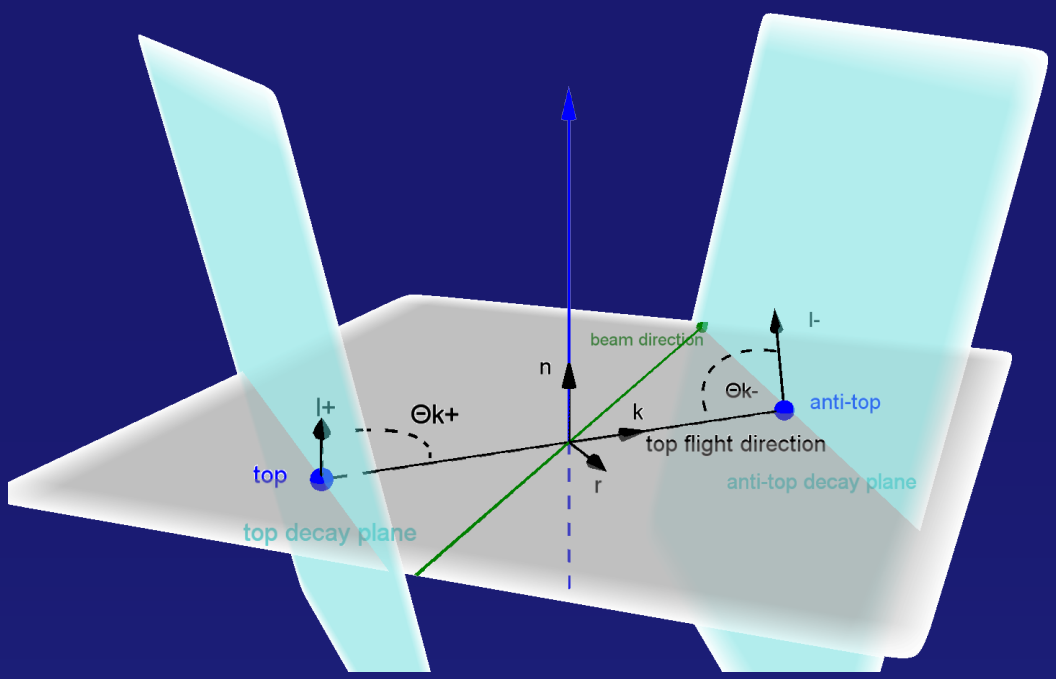
- @13 TeV
- $\sigma_{t\bar{t}W} = 1.5 \pm 0.8$ pb
  - $\mu = 2.2\sigma$ over bkgd
- $\sigma_{t\bar{t}Z} = 0.9 \pm 0.3$ pb
  - $\mu = 3.9\sigma$ over bkgd
- Consistent with NLO predictions



Yields in control and signal regions



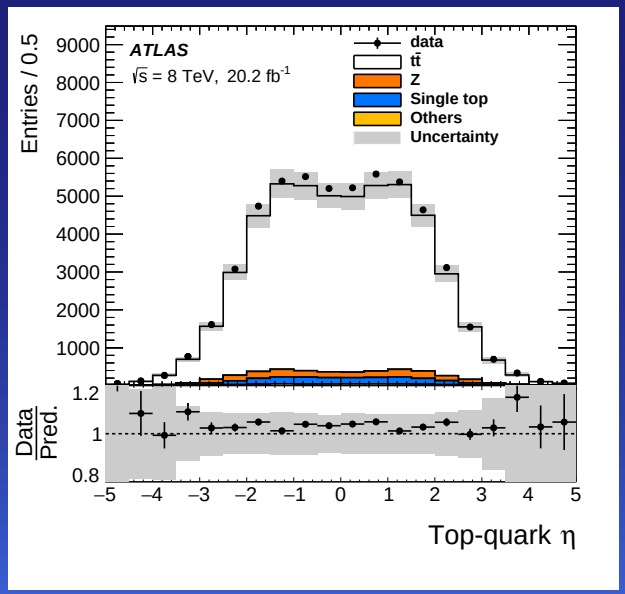
$\sigma_{t\bar{t}Z}$ vs. $\sigma_{t\bar{t}W}$



- $t\bar{t}$ produced unpolarized
- Decay products retain top-quark spin information
- Production plane in $t\bar{t}$-rest-frame defines quantisation axes:
  - k: Flight direction of top-quarks (helicity)
  - n: Perpendicular to k and beam (transverse)
  - r: Perpendicular to k and n
- Use charged leptons in di-lepton channel in parent top-quark rest-frame

arXiv:1612.07004

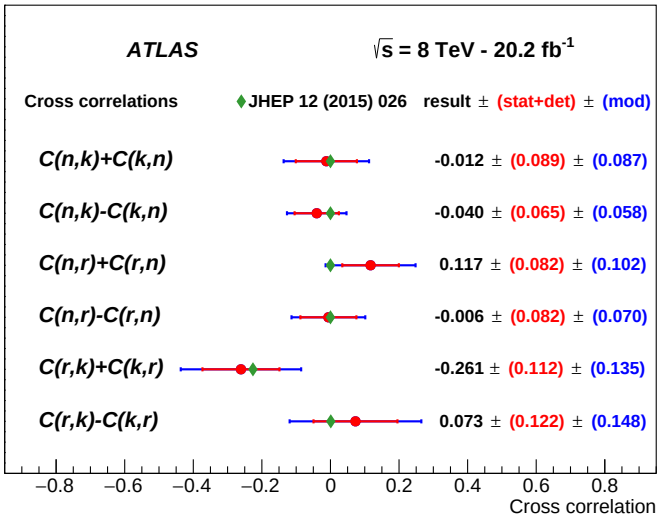
- Analysis @8 TeV
  - $\theta^a_\pm$: angle of $\ell^\pm$ momentum w.r.t. axis a
    - 3 per top-quark
  - $B^a_\pm = 3\langle\cos\theta^a_\pm\rangle$: polarisations
    - 3 per top-quark
  - $C(a,b) = -9\langle\cos\theta^a_+\cos\theta^b_-\rangle$: spin- and cross-correlations
    - 3 for $C(a,a)$ and 6 for $C(a,b) \pm C(b,a)$
  - Neutrino weighting with jet smearing to reconstruct $t\bar{t}$
  - Bayesian unfolding to either parton- or stable-particle-level to remove effects due to detector resolution and selection cuts

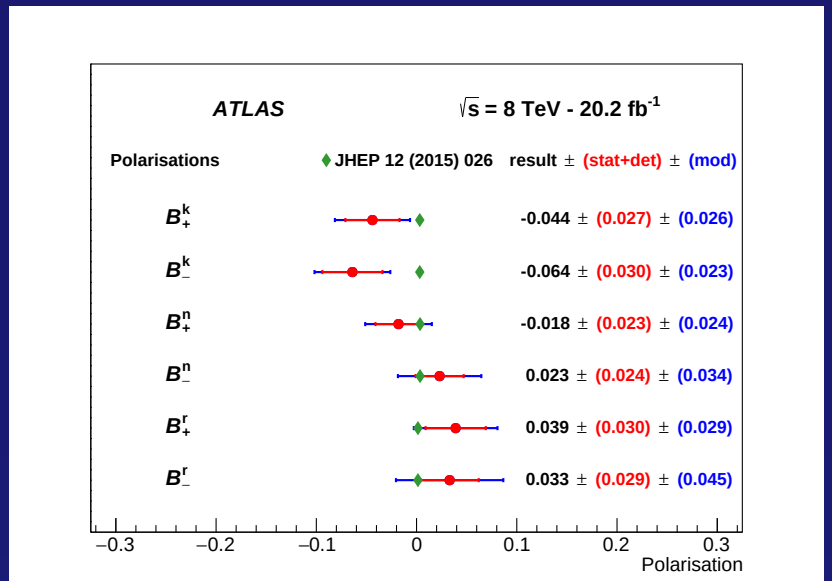


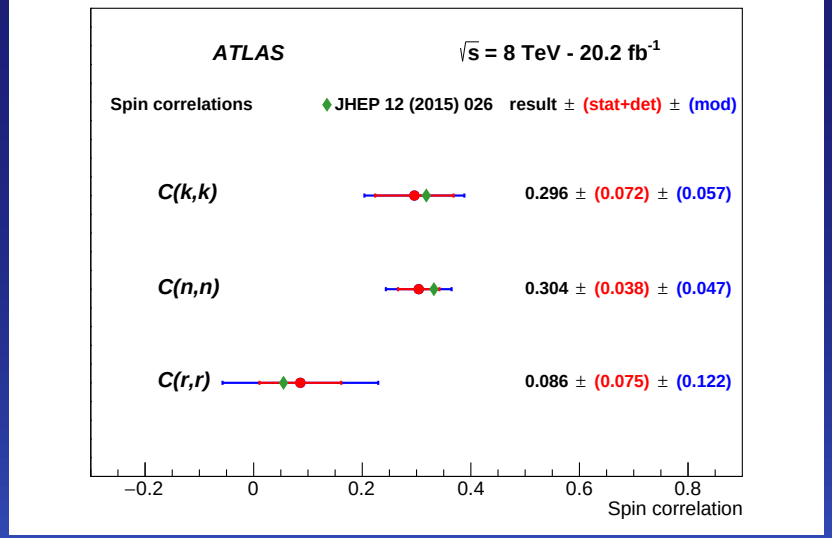
Top-quark η after neutrino weighting

- Systematic uncertainties
  - Dominated by $t\bar{t}$-modelling
  - Dependency on m_{top} not included in total error
    - Separate error given for $\Delta m_{top}^{ATLAS} = 0.70\,GeV$
    - For measurements w.r.t. helicity axis similar in magnitude as modelling; For other axes much smaller
- Statistics and detector response uncertainties together match modelling uncertainty
- Polarisations and spin correlations after parton-level unfolding compared to SM predictions

arXiv:1612.07004

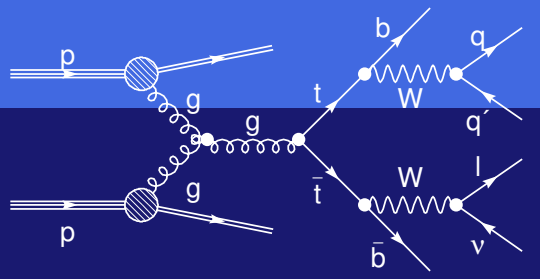






- Good agreement with SM (♦) expectations
- $C(n, n)$ differs from 0 by 5.1σ

Top quark properties ► W boson helicity

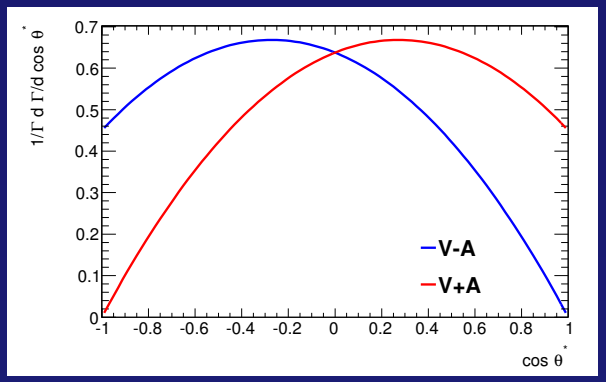


- In the SM the t-decay is almost always $t \to W^+ b$ via a $V - A$ current interaction
  - Deviations from expected $V - A$ behaviour indicate new physics
  - In general for any combination of V and A:

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

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

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



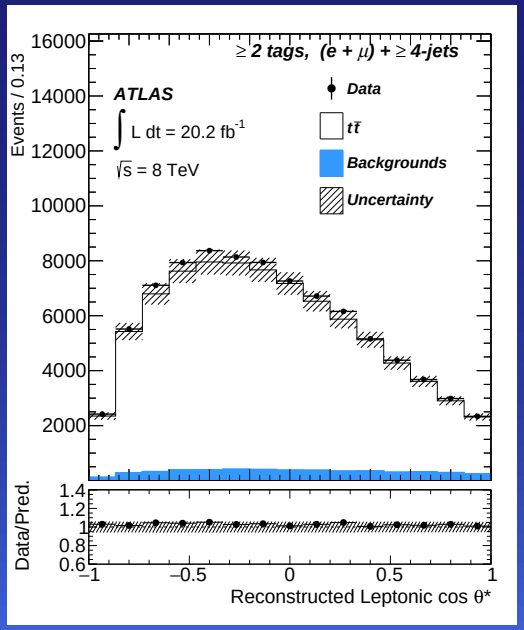
- Measure θ^* in lepton+jets channel @8 TeV with 1 or 2 b-tagged jets

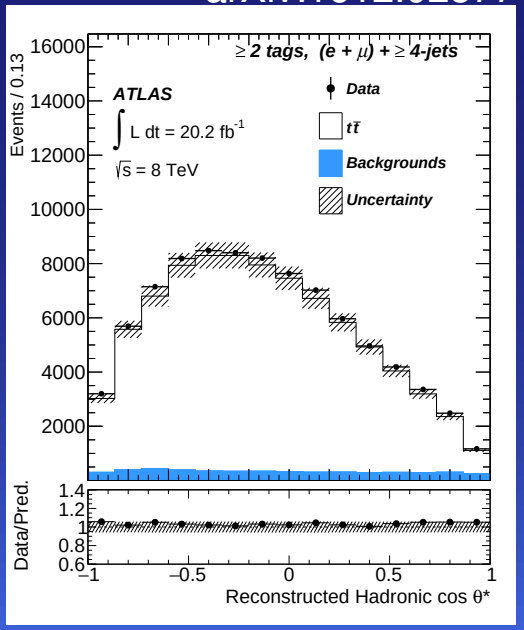
arXiv:1612.02577

  - Best permutation for partons to jets (KLFitter)
  - θ^* from charged lepton or light jet direction
  - Fit to signal templates for each polarization and background templates
  - Results for leptonic W:

$$F_0 = 0.709 \pm 0.012_{\text{stat+bkg norm}} \pm 0.015_{\text{syst}}$$
$$F_L = 0.299 \pm 0.008_{\text{stat+bkg norm}} \pm 0.013_{\text{syst}}$$
$$F_R = -0.008 \pm 0.006_{\text{stat+bkg norm}} \pm 0.012_{\text{syst}}$$

  - Hadronic results compatible but with much larger uncertainties
    - uses b-tagging to discriminate u/c from d/s





Reco $\cos\theta^*$: leptonic hadronic

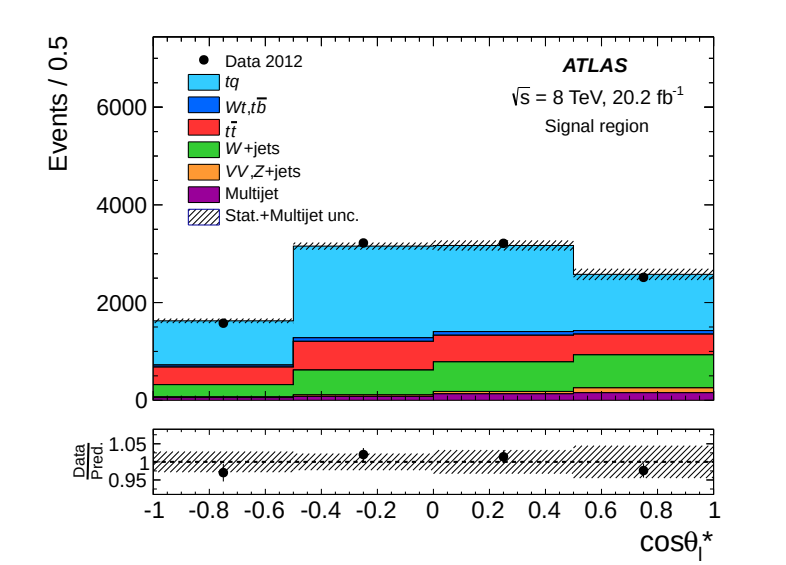
- In t-channel single top-quarks are polarised to large degree ($O(\pm 90\%)$) in direction of spectator quark
  - Double-differential decay width in the W-boson rest frame:

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta^*\,\mathrm{d}\phi^*} = \frac{3}{8\pi}\left\{\frac{2}{3} + \frac{1}{2\sqrt{6}}\langle T_0\rangle(3\cos^2\theta^* - 1) + \langle S_3\rangle\cos\theta^* + \left(\langle S_1\rangle\cos\phi^* + \langle S_2\rangle\sin\phi^*\right)\sin\theta^* - \left(\langle A_1\rangle\cos\phi^* + \langle A_2\rangle\sin\phi^*\right)\sin 2\theta^*\right\}$$

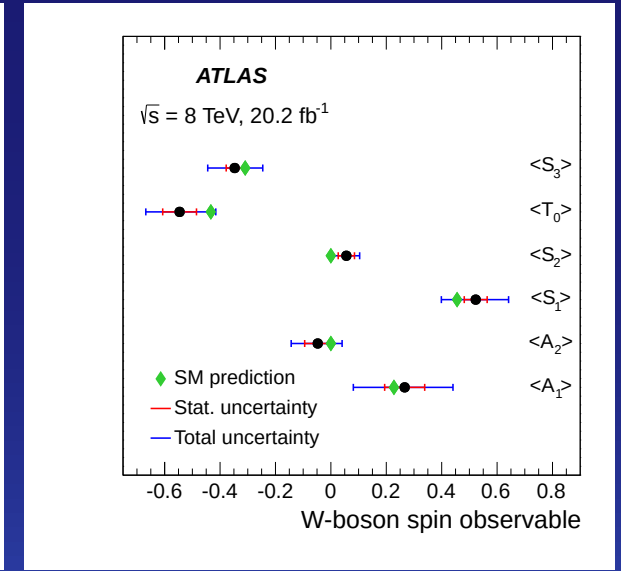
  - θ^* (ϕ^*) is the polar (azimuthal) angle in the W rest frame between the $\mathrm{W}^{+(-)}$ momentum direction and the $\ell^{+(-)}$

arXiv:1702.08309

- Event selection like in cross-section analysis (slide 5)
  - Central e or μ, two jets, exactly one b-tagged, $E_\perp^{\mathrm{miss}} > 30$ GeV and $m_\perp(\ell E_\perp^{\mathrm{miss}}) > 50$ GeV
  - Neutrino p_z from W mass constraint
  - Unfolding to parton-level



Reco cos θ^* in signal region

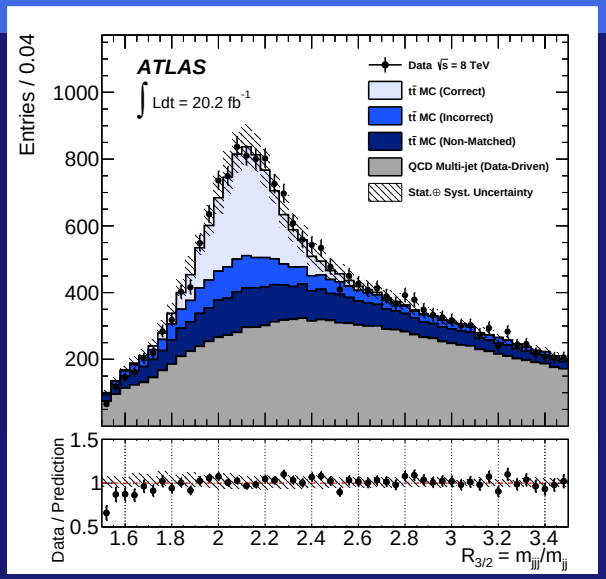


Derived W-boson spin observables

- Largest systematic uncertainties from modelling of t-channel and $\mathrm{t\bar{t}}$ processes and jet energy scale

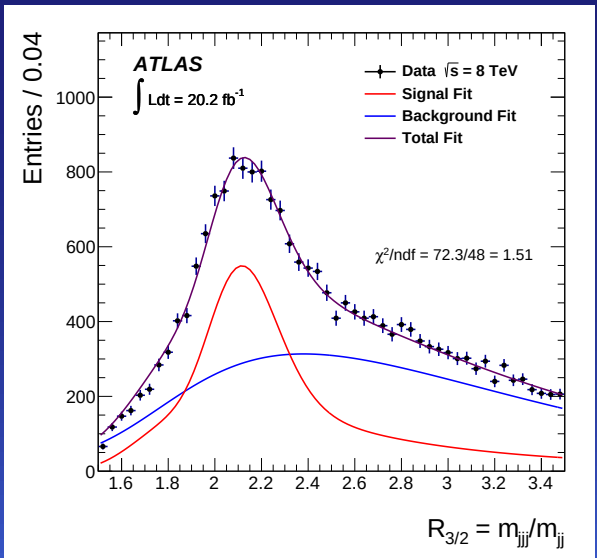
arXiv:1702.07546

- Direct measurements in di-lepton, lepton+jets and all-jets channel from kinematic reconstruction of top-quarks
  - Calibrated with MC mass (the parameter put into a MC generator program)
- Most recent: All-jets result @8 TeV
- Most precise: Di-lepton result @8 TeV
- Indirect measurements from cross-sections
  - The pole mass (the parameter that enters the top propagator)



$R_{3/2}$ prior to template fit

arXiv:1702.07546

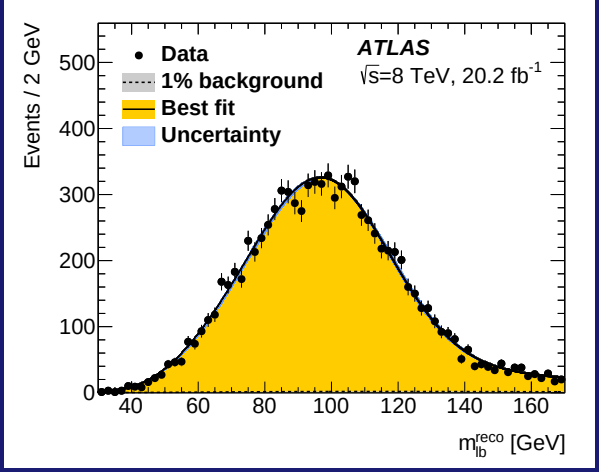


$R_{3/2}$ with template fit

- All-jets analysis with ≥ 6 central jets, five with $p_\perp > 60$ GeV, 2 of them b-tagged
- Topological cuts (large distance of b-tagged jets; small distance of W,b pairs from best kinematic solution) and $E_\perp^{\text{miss}} < 60$ GeV reduce bkgd.
- Data-driven method in regions defined by number of b-tags and proximity of W,b pairs to determine bkgd.
- Template fit to $R_{3/2} = m_{jjj}/m_{jj}$ with m_{top} and bkgd. fraction as free parameters
  - $m_{\text{top}} = 173.72 \pm 0.55_{\text{stat}} \pm 1.01_{\text{syst}}$ GeV
- Largest systematic uncertainty from hadronisation modelling and jet energy scale

Top quark properties ► Mass

arXiv:1606.02179

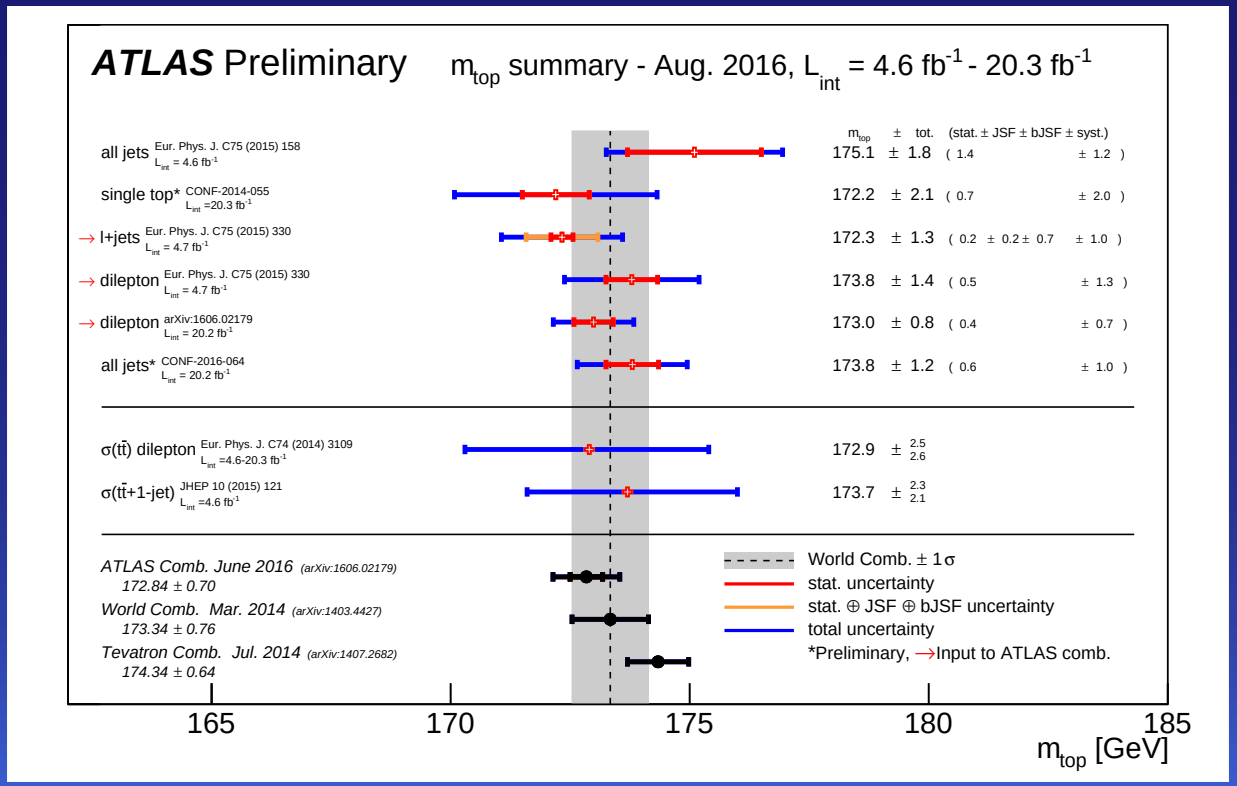


$m_{\ell b}^{\text{reco}}$ with template fit

- Dilepton analysis with exactly 2 oppositely charged central leptons @8 TeV
- For ee and $\mu\mu$ require $E_{\perp}^{\text{miss}} > 60$ GeV, Z-veto and $m_{\ell\ell} > 15$ GeV
- For eμ require scalar sum of $p_{\perp}$ of leptons and jets > 130 GeV
- At least 2 jets, one of them b-tagged
- Optimisation with $p_{\perp,\ell b} > 120$ GeV
- Template fit to $m_{\ell b}^{\text{reco}}$ with m_{top} as free parameter
  - $m_{\text{top}} = 172.99 \pm 0.41_{\text{stat}} \pm 0.74_{\text{syst}}$ GeV
- Largest systematics from jet energy scale, hadronisation, ISR and FSR

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP

- Combination of di-lepton results @7 & 8 TeV and lepton+jets result @7 TeV
- Careful evaluation of correlations taken into account
- $m_{\text{top}} = 172.84 \pm 0.34_{\text{stat}} \pm 0.61_{\text{syst}}$ GeV



Summary of ATLAS m_{top} results @7&8 TeV

Conclusions

- Top-quark physics are studied with high precision at LHC
- Single top-quark production cross-sections
  - $\sqrt{s}$ dependency and ratios of cross-sections to constrain PDFs
  - Different channels (s, t, Wt) with sensitivity to different BSM effects
  - So far good agreement with SM predictions
- Top-quark-pair production cross-sections
  - Fiducial, total and differential cross-sections measured at different $\sqrt{s}$
  - Some tension comparing 8 TeV to 7 TeV x-sec. ratio
  - But not in comparisons to 13 TeV
    - also good agreement with SM predictions
- Top-quark properties
  - Polarisation, spin- and cross-correlations measured at 8 TeV in $t\bar{t}$ events
  - 10 of the 15 spin observables measured for the first time
  - W helicity measured for both leptonic and hadronic decays
  - W-boson spin observables from single top-quark t-channel
  - Top-quark mass measured to very high precision with careful combination of different channels under consideration of correlations
- Expect more precision top-quark results @13 TeV