Recent highlights of top-quark cross section and properties measurements with the ATLAS detector at the LHC

Lake Louise Winter Institute '23

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Introduction

Participants at the 2022 ATLAS Top Workshop in Valencia, Spain

- There are many recent results from the top group in ATLAS!
  - Since last years LLWI: 20 papers, 4 CONF notes, and 3 PUB notes
  - I cannot cover them all...
- For top+X, see talk by Knut right after me 🙂

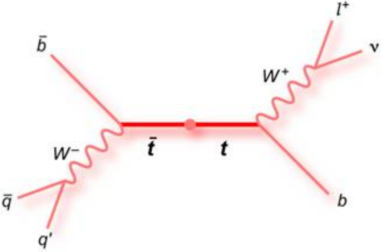
I have been tasked to cover **6** analyses in the next 12 minutes, so hang on tight for a whistle stop tour of top quark cross-sections and properties

Why do measurements of top quark processes?

The top quark is unique in the SM due to its large mass: $m_t = y_t v/\sqrt{2}$

- decays before hadronisation
  - $\rightarrow$ only quark that can be studied in isolation
  - $\hookrightarrow$ precision QCD test
- same order as V.E.V in SM
  - $\rightarrow$ $m_t \simeq 173$ GeV, $v = 246$ GeV
  - $\hookrightarrow$ Direct sensitivity to new physics

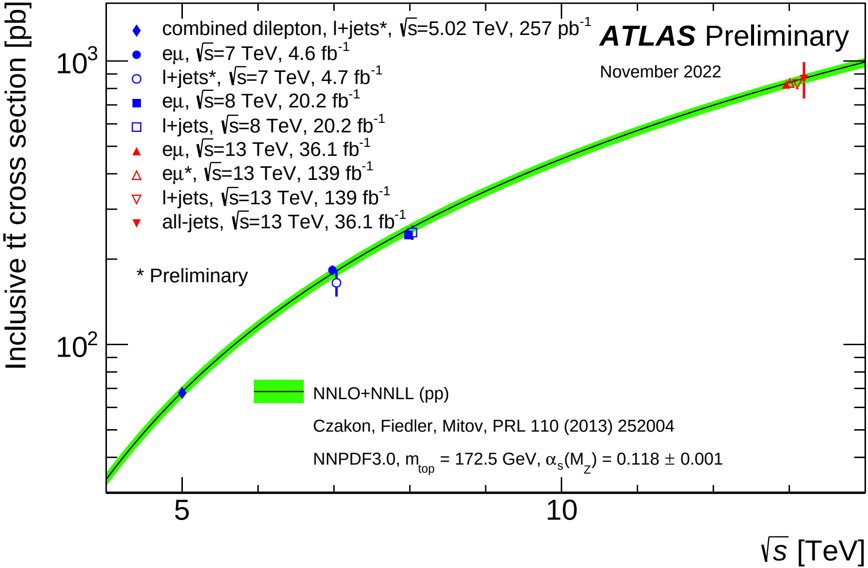
$$\Delta m_h^t \sim -\frac{m^2}{v^2}\frac{\Lambda}{4\pi^2}$$



- Also a major background to many interesting SM and exotic searches
  - Not always well described in current MC generators
  - $\rightarrow$ Precision measurements crucial input to MC tuning efforts!

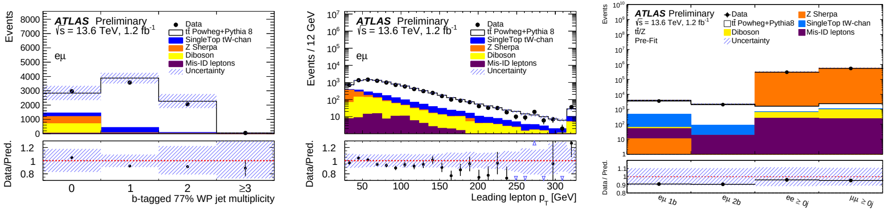
Top Cross-Section

Top Cross-Section



13.6TeV $t\bar{t}$ XSec CONF Note

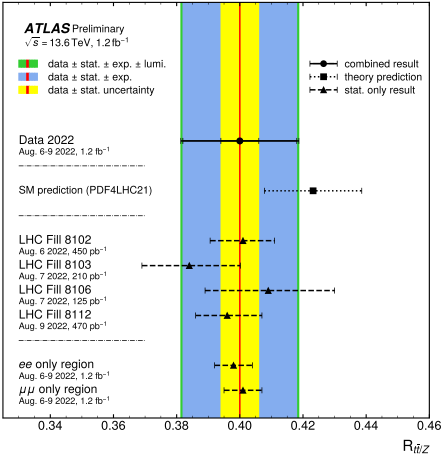
- Use 1.2fb^{-1} of 13.6 TeV data from 2022
- Serves as an extensive validation of the upgraded detector!
  - Conservative uncertainties are used to cover the preliminary nature of object calibrations, background predictions, luminosity measurement, etc
- Profile-likelihood fit method to extract cross-section and *b*-tagging efficiency simultaneously



- Standard Model Prediction: $\sigma_{t\bar{t}} = 924^{+32}_{-40}$ pb
- Fit result: $\sigma_{t\bar{t}} = 830 \pm 12(\mathrm{stat}) \pm 27(\mathrm{syst}) \pm 86(\mathrm{lumi})$ pb $= 830$pb$\pm 11\%$
  - $\epsilon_b = 0.553 \pm 0.007(\mathrm{stat}) \pm 0.005(\mathrm{syst}) \pm 0.001(\mathrm{lumi})$

$\rightarrow$ consistent within 1σ with SM

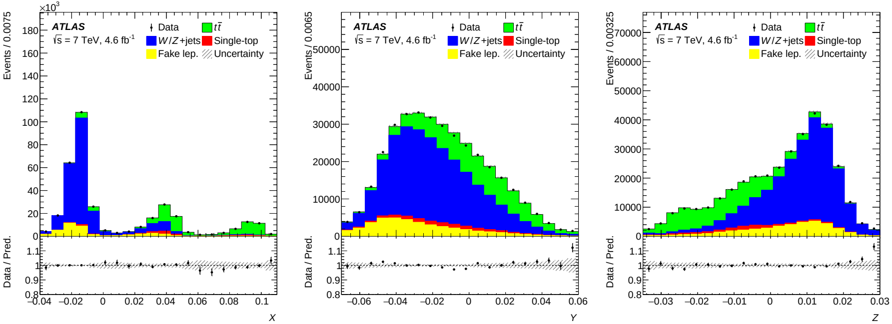
$t\bar{t}/ Z$ XSec Ratio @ 13.6 TeV CONF Note



- Some uncertainties - eg luminosity - can cancel when measuring **ratios** of cross-sections
  - Also sensitive to PDFs
- Utilise *ee* and $\mu\mu$ Z decays: orthogonal to $e\mu$ $t\bar{t}$ selection
- Consistency between fills, lepton channels
- Consistent with SM to 1σ, total uncertainty 4.7%

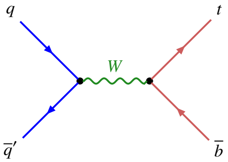
The same strategy was followed for an early Run II measurement as well as at 7 and 8 TeV

- Most precise ever measurement of top cross-section by using machine learning
- Select single lepton events and separate backgrounds with a 3-dimensional support vector machine based event classifier

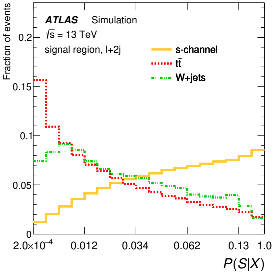


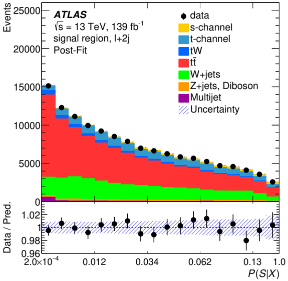
- Profile likelihood fit to 3D SVM output
- Result: $\sigma_{t\bar{t}} = 168.5 \pm 0.7(\mathrm{stat})^{+6.2}_{-5.9}(\mathrm{syst})^{+3.4}_{-3.2}(\mathrm{lumi})$ pb $= 168.5\mathrm{pm} \pm 4\%$
  - SM prediction: $\sigma_{t\bar{t}} = 177^{+10}_{-11}$ pb
- Limited by luminosity uncertainty, lepton ID/trigger, and signal modelling

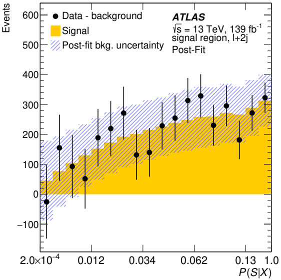
13 TeV s-chan Single Top XSec 2209.08990



- *s*-chan single top not yet observed at the LHC!
  - Discovered by CDF+D0 combination
  - ATLAS reached 3.2σ in Run1 (CMS 2.5σ)
  - Sig:Bkg ratio gets worse at 13TeV: $2.1\% \rightarrow 1.2\%$





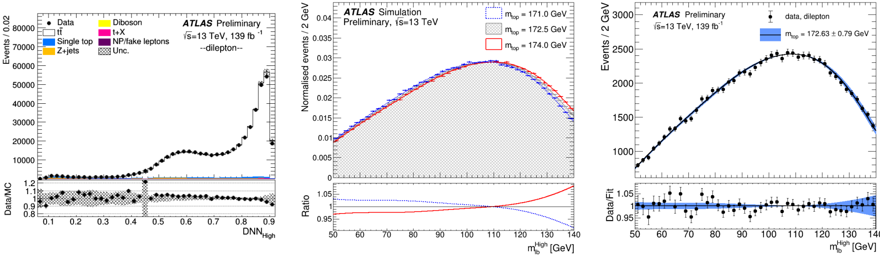


- Profile likelihood fit to Matrix Element Method probability
- Result: $\sigma_{s-\mathrm{chan}} = 8.2 \pm 0.6(\mathrm{stat})^{+3.4}_{-2.8}(\mathrm{syst})$ pb
  - SM: prediction: $\sigma_{SM} = 10.32\pm^{+0.40}_{-0.36}$ pb
  - Observed (expected): 3.3σ (3.9σ)
- Limited by signal & $t\bar{t}$ modelling, jet uncertainties

Top Properties

13 TeV Top Mass 2022-058

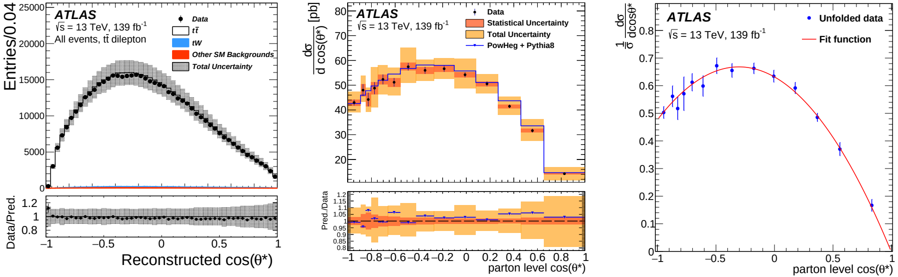
- Top quark mass a crucial SM parameter - stability of the universe depends on it!
- (Monte-Carlo) Mass extracted via template fit to $m_{\ell b}$
- lep-b-jet pairing with DNN using event kinematics as inputs



- Result: $172.63 \pm 0.20(\text{stat}) \pm 0.67(\text{syst}) \pm 0.37(\text{recoil})$ GeV
  - Limited by previously unaccounted for systematic uncertainty due to recoil effects of colored objects in top decays
  - Other significant uncertainties from $t\bar{t}$ modelling, jet reconstruction and color reconnection

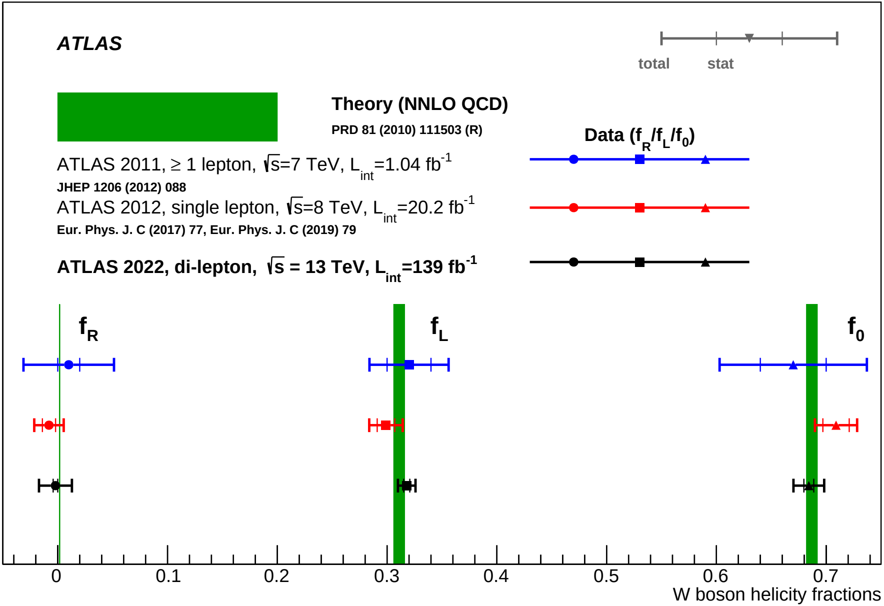
W polarisation 2209.14903

- Polarisation of W-boson from top decay comes from Wtb vertex structure
- Longitudinal, left-, and right-handed fractions extracted from polar angle in the W rest frame with χ^2 fit
- $t\bar{t}$ Reconstruction in dilepton channel with neutrino-weighting technique



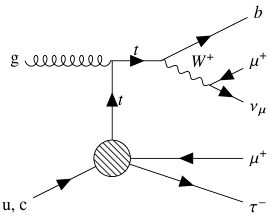
- Results:
  - $f_0 = 0.684 \pm 0.005(\mathrm{stat}) \pm 0.014(\mathrm{syst})$
  - $f_L = 0.318 \pm 0.003(\mathrm{stat}) \pm 0.008(\mathrm{syst})$
  - $f_R = -0.002 \pm 0.002(\mathrm{stat}) \pm 0.014(\mathrm{syst})$
- SM Prediction:
  - $f_0 = 0.687 \pm 0.005$
  - $f_L = 0.311 \pm 0.005$
  - $f_R = 0.0017 \pm 0.0001$
- Leading systematics from jet reconstruction and $t\bar{t}$ modelling

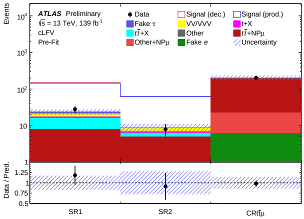
W polarisation 2209.14903



Search for Charged Lepton Flavor Violation 2023-001

- Charged lepton flavor is conserved in the SM; but recent (now superceded...) LHCb results made searches for violation of the symmetry very interesting
- Search for interactions like $\mu\tau qt$ diagrams involving top production/decay
  - eg some models with leptoquarks predict $BR(t \to \mu\tau q) \simeq 10^{-6}$
- Interpret in EFT and set limits on Wilson Coefficients
  - Sensitive to 2Q2L operators that are highly unconstrained to date





Operator	Lorentz Structure	
$\mathcal{O}_{lq}^{1(ijkl)}$	$(\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma_\mu q_l)$	Vector
$\mathcal{O}_{lq}^{3(ijkl)}$	$(\bar{l}_i\gamma^\mu\sigma^I l_j)(\bar{q}_k\gamma_\mu\sigma^I q_l)$	Vector
$\mathcal{O}_{eq}^{(ijkl)}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma_\mu q_l)$	Vector
$\mathcal{O}_{lu}^{(ijkl)}$	$(\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma_\mu u_l)$	Vector
$\mathcal{O}_{eu}^{(ijkl)}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma_\mu u_l)$	Vector
$^\ddagger\mathcal{O}_{lequ}^{1(ijkl)}$	$(\bar{l}_i e_j)\varepsilon(\bar{q}_k u_l)$	Scalar
$^\ddagger\mathcal{O}_{lequ}^{3(ijkl)}$	$(\bar{l}_i\sigma^{\mu\nu} e_j)\varepsilon(\bar{q}_k\sigma_{\mu\nu} u_l)$	Tensor

- Set overall limit of $BR(t \to \mu\tau q) < 11 \times 10^{-7}$
- Statistically limited, $t\bar{t}$ modelling and fake muons also significant

See further: measurement of BR(tau)/BR(mu) from 2020

Search for Charged Lepton Flavor Violation 2023-001

	95% CL upper limits on Wilson coefficients							c/Λ^2 [TeV^{-2}]
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
Previous (u) [22]	12	12	12	12	26	26	3.4	3.4
Expected (u)	0.47	0.44	0.43	0.46	0.49	0.49	0.11	0.11
Observed (u)	0.49	0.47	0.46	0.48	0.51	0.51	0.11	0.11
Previous (c) [22]	14	14	14	14	29	29	3.7	3.7
Expected (c)	1.6	1.6	1.5	1.6	1.8	1.8	0.35	0.35
Observed (c)	1.7	1.6	1.6	1.6	1.9	1.9	0.37	0.37

	95% CL upper limits on BR($t \to \mu\tau q$) ($\times$ 10^{-7})							
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
Expected (u)	4.6	4.2	4.0	4.5	2.5	2.5	5.8	5.8
Observed (u)	5.1	4.6	4.4	5.0	2.8	2.8	6.4	6.4
Expected (c)	54	51	51	52	35	35	61	61
Observed (c)	60	56	56	57	38	38	68	68

Conclusion

- Top quark measurements are a vibrant industry at the LHC
- Limitations are usually from Monte-Carlo modelling and jet reconstruction
- New techniques, such as deep learning, are pushing the boundary of sensitivity
- Most measurements so far are consistent with the Standard Model 😭

Backup

b-tag counting method for Run3 Xsec

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

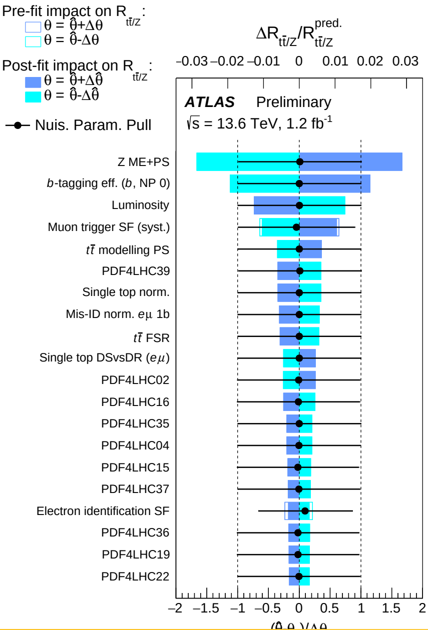
$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\mathrm{bkg}} \quad (2)$$

$$C_b = \epsilon_{bb}/\epsilon_b^2 = \frac{4N^{t\bar{t}}N_2^{t\bar{t}}}{\left(N_1^{t\bar{t}} + 2N_2^{t\bar{t}}\right)^2} \quad (3)$$

C_b is a correlation factor to correct for kinematic dependence of the two b's in each $t\bar{t}$ event, N_X is the number of events with X b-tags, and $\epsilon_{e\mu}$ is the efficiency for selecting $e\mu$ events.

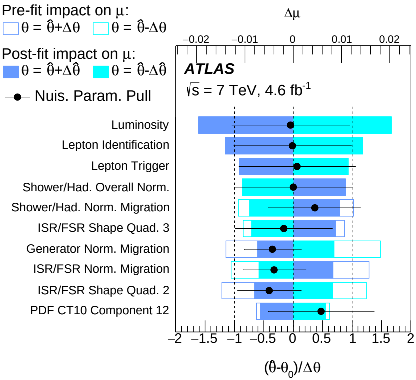
ϵ_b, the b-tagging efficiency, is then floated in the fit and measured simultaneously with $\sigma_{t\bar{t}}$.

Run3 XSec Uncertainties



	Category	Uncert. [%]		
		$\sigma_{t\bar{t}}$	$\sigma^{m_{\ell\ell}>40}_{Z\to\ell\ell}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ parton shower/hadronisation	0.6	0.2	0.7
	$t\bar{t}$ scale variations	0.5	0.1	0.5
Z	Z scale variations	0.2	2.9	2.9
Bkg.	Single top modelling	0.6	< 0.01	0.6
	Diboson modelling	0.1	< 0.01	0.5
	Mis-Id leptons	0.6	< 0.01	0.6
Lept.	Electron reconstruction	1.6	2.3	1.1
	Muon reconstruction	1.3	2.4	0.3
	Lepton trigger	0.2	1.3	1.1
Jets/tagging	Jet reconstruction	0.2	< 0.01	0.2
	Flavour tagging	1.9	< 0.01	1.9
	PDFs	0.5	1.4	1.3
	Luminosity	10.3	9.6	1.3
	Systematic Uncertainty	10.8	10.7	4.4
	Statistical Uncertainty	1.5	0.1	1.5
	Total Uncertainty	11	10.7	4.7

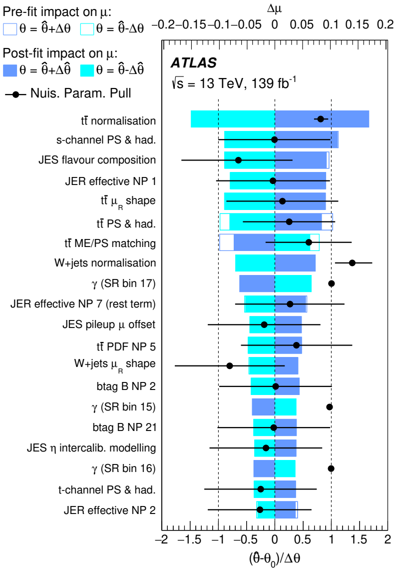
7TeV XSec Uncertainties & SVM Inputs



Number	Feature	Divided by
1	E_T^{miss} [GeV]	250
2	$\phi(E_T^{miss})$ [radians]	2π
3	Lepton E [GeV]	400
4	Lepton $p_{\|\|}$ [GeV]	400
5	Lepton p_z [GeV]	400
6	Mass(lepton+jets) [GeV]	750
7	Fox–Wolfram moment 1	1
8	Fox–Wolfram moment 2	1
9	Fox–Wolfram moment 3	1
10	Fox–Wolfram moment 4	1
11	Fox–Wolfram moment 5	1
12	Sum all jets E_T [GeV]	500
13	Sum all jets E [GeV]	750
14	Sum all jets $p_{\|\|}$ [GeV]	750
15	Sum all jets $p_\perp$ [GeV]	750
16	Sum all jets p_z [GeV]	750
17	H_T [GeV]	500
18	p-tensor eigenvalue 1	1
19	p-tensor eigenvalue 2	1
20	Number of jets	10
21	Number of b-tags	10

s-chan Uncertainties

Source	$\Delta\sigma/\sigma$ [%]
$t\bar{t}$ normalisation	$+24/-17$
$t\bar{t}$ shape modelling	$+18/-15$
PS & had.	$+12/-10$
ME/PS matching	$+10/-8$
h_{damp}	<1
s-channel modelling	$+18/-8$
PS & had.	$+18/-8$
ISR/FSR	$+3/-1$
Jet energy resolution	$+18/-12$
Jet energy scale	$+18/-13$
MC statistics	$+13/-11$
Flavour tagging	$+12/-10$
$W+$jets normalisation	$+11/-8$
PDFs	$+10/-9$
$t\bar{t}$	$+10/-9$
s-channel	±1
t-channel	±1
tW	±1
t-channel modelling	±6
PS & had.	±5
ISR/FSR	±4
$W+$jets $\mu_{\mathrm{r}}/\mu_{\mathrm{f}}$ shape	$+6/-5$
Normalisation of other processes	$+6/-5$
Pile-up	$+5/-3$
Luminosity	$+4/-3$
tW modelling	$+1/-2$
PS & had.	±1
$t\bar{t}$ overlap	±1
ISR/FSR	±1
Missing transverse momentum	±1
Multijet shape modelling	±1
Other detector sources	±1
Systematic uncertainties	$+42/-34$
Statistical uncertainty	±8



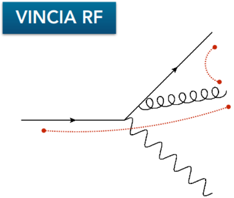
Top Mass Uncertainties

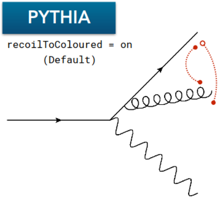
	m_{top} [GeV]
Result	172.63
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.35 ± 0.07
Parton shower and hadronisation	0.08 ± 0.05
Initial- and final-state QCD radiation	0.20 ± 0.02
Underlying event	0.06 ± 0.10
Colour reconnection	0.29 ± 0.07
Parton distribution function	0.02 ± 0.00
Single top modelling	0.03 ± 0.01
Background normalisation	0.01 ± 0.02
Jet energy scale	0.38 ± 0.02
b-jet energy scale	0.14 ± 0.02
Jet energy resolution	0.05 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.12 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.37 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.79 ± 0.06

Uncertainty	Δm_{top} [GeV]
Absolute in situ JES	0.23 ± 0.02
Relative in situ JES	0.12 ± 0.02
Flavour Composition	0.00 ± 0.02
Flavour Response	0.00 ± 0.02
Pile-up	0.26 ± 0.02
AFII non-closure	0.10 ± 0.02
Punch Through	0.00 ± 0.02
Total	0.38 ± 0.02

Recoil Scheme for Top Mass

- "Recently discovered" systematic effect in top MC
  - First gluon emission from top decay products straightforward
  - *Second* emission has am ambiguity on how the colored object should recoil





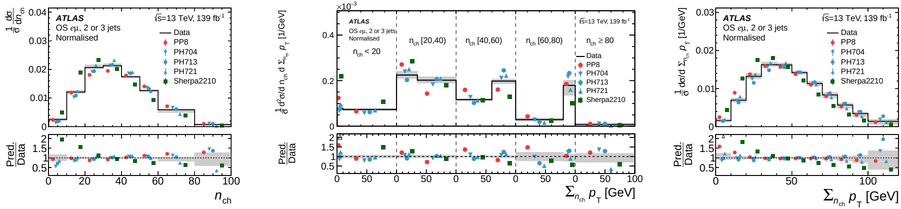
Credit: P. Skands

- Default is to the other colored object ie the *b*-quark
  - Results in too little out of cone radiation → narrower mass peak
- "Better" scheme recoils against the top quark itself
  - More out of cone radiation
  - But setup is untuned and therefore probably over-estimates the effect
  - → for now, take full difference as uncertainty
  - ↪ long term, switch to recoilToTop as default and tune this setup to data, or switch to more modern shower like VINCIA

Color Reconnection 2209.07874

- Monte-Carlo generators use the leading-color approximation
  - Dealing with overlapping phase space with MPI then requires poorly understood color reconnection models
  - This is now a leading uncertainty in measurements of top mass!

→ Unfold variables sensitive to these effects to aid in MC tuning



- Sherpa (no CR) has the worst agreement as expected
- Nominal Pythia does best, but not able to exclude any CR models
  - Dominant uncertainties from track and jet reconstruction
  - These distributions will be valuable components of future tuning efforts

W polarisation Uncertainties

Category	σ_{f_0}	σ_{f_L}	σ_{f_R}
Detector modelling			
Jet reconstruction	0.008	0.004	0.010
Flavour tagging	0.003	0.001	0.001
Electron reconstruction	0.003	0.002	0.002
Muon reconstruction	0.003	0.003	$< 10^{-3}$
E_T^{miss} (soft term)	$< 10^{-3}$	0.002	$< 10^{-3}$
Pile-up	0.002	0.002	$< 10^{-3}$
Luminosity	0.001	0.001	$< 10^{-3}$
Signal and background modelling			
$t\bar{t}$ production	0.011	0.005	0.010
PDF	0.002	0.001	$< 10^{-3}$
Single top production	$< 10^{-3}$	0.002	$< 10^{-3}$
Other background	0.002	0.001	$< 10^{-3}$
Total systematic uncertainty	0.014	0.008	0.014
Data statistical uncertainty	0.005	0.003	0.002
Total uncertainty	0.015	0.008	0.014