Measurements of the top-quark mass using the ATLAS detector at the LHC

Davide Melini, on behalf of ATLAS

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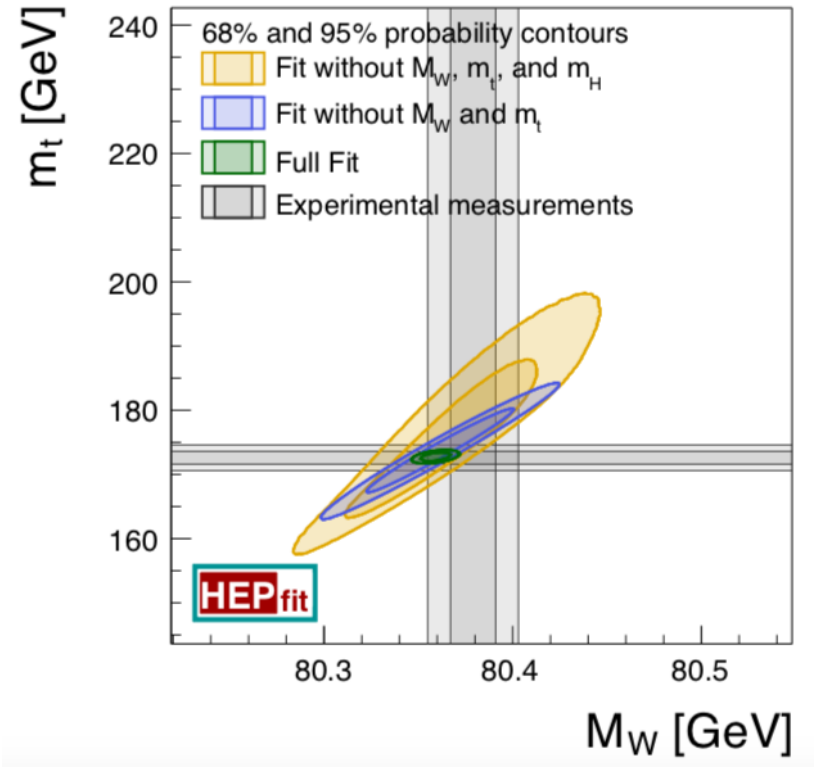
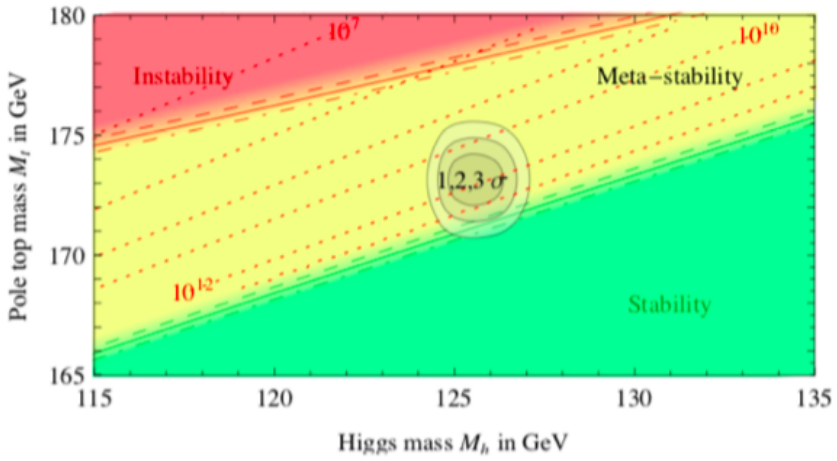
Introduction

- The top-quark mass (m_t) is a fundamental Standard Model (SM) parameter
- Accurate & precise measurement of m_t important (i.e. SM-consistency fits)
- top-quark is the heaviest SM particle $\rightarrow m_t$ affects many new physics models

arXiv: 2112.07274
... or the updated version arXiv: 2204.04204



JHEP 08 (2012) 098



When experimental uncertainties on m_t becomes of sub-GeV size, arguments on the theoretical interpretation of the m_t parameter becomes relevant.

Direct vs indirect m_t measurements

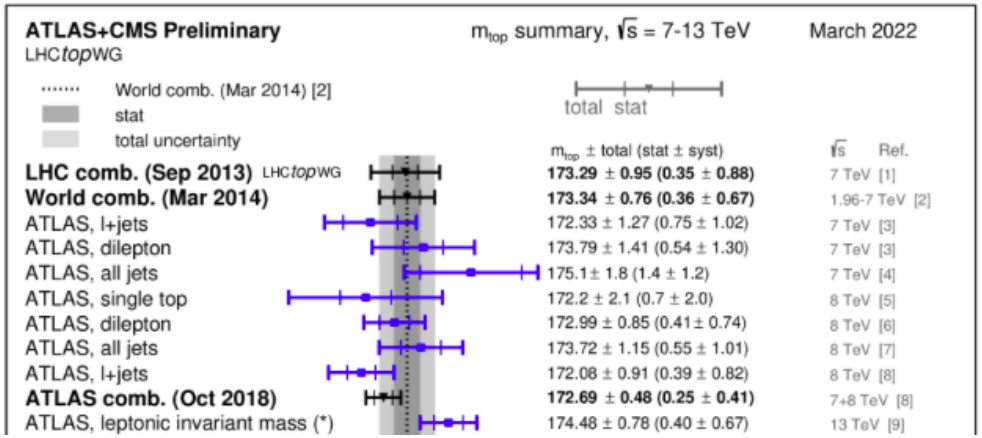
ATLAS measured the top-quark mass in various ways. Two main categories:

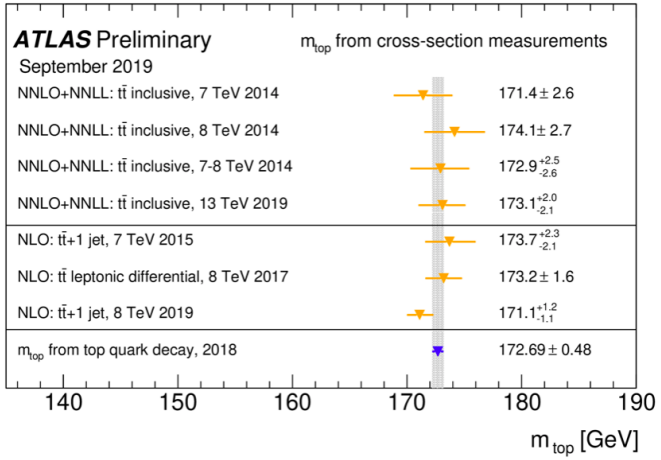
Direct measurements

- kinematic reconstruction of variables related to the top-quark momentum
- typically have a high experimental precision
- m_t extracted at detector level: difficult to define theoretically and interpretation linked to Monte Carlo (MC) implementation. Usually $\sim$ 0.5 GeV *interpretation unc* taken.

Indirect measurements

- measure observable(s) which have a strong dependence on m_t
- with data unfolding, infer m_t in a theoretically well defined phase space
- compare to fixed-order predictions for a better control over the theo. unc. on m_t





Will present ATLAS latest direct and indirect measurements, and a study which aims at interfacing the two measurement types

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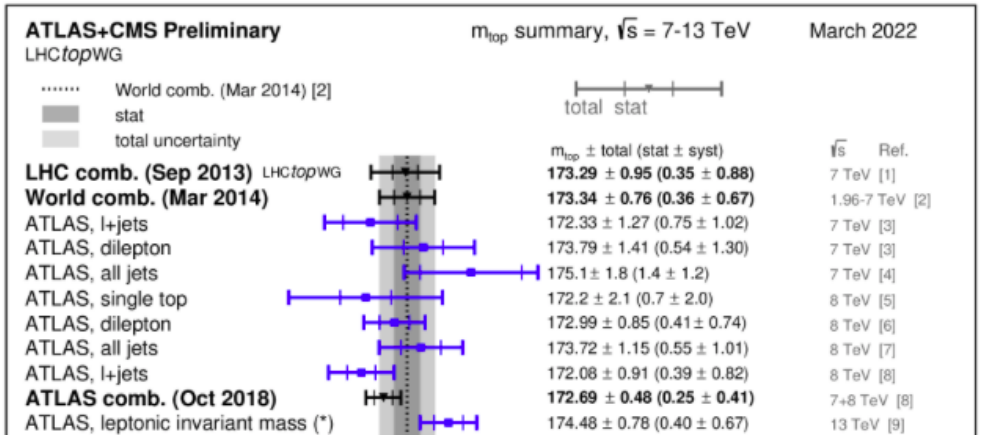

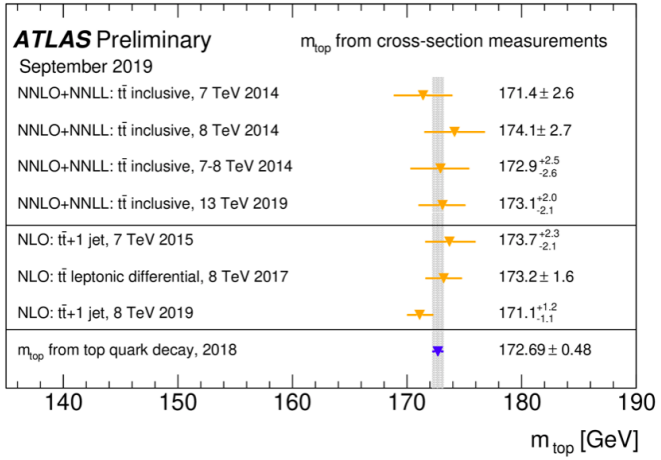

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Direct measurements

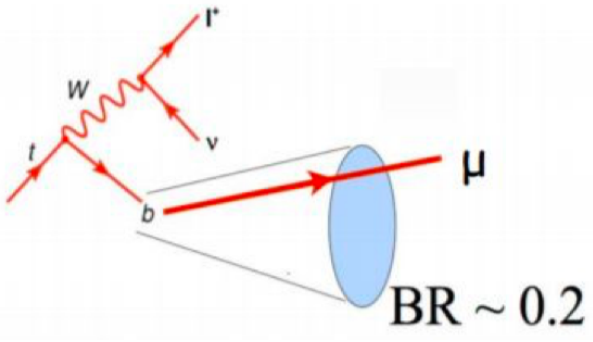
Most recent ATLAS combination from Oct. 2018 (Eur. Phys. J. C 79 (2019) 290)

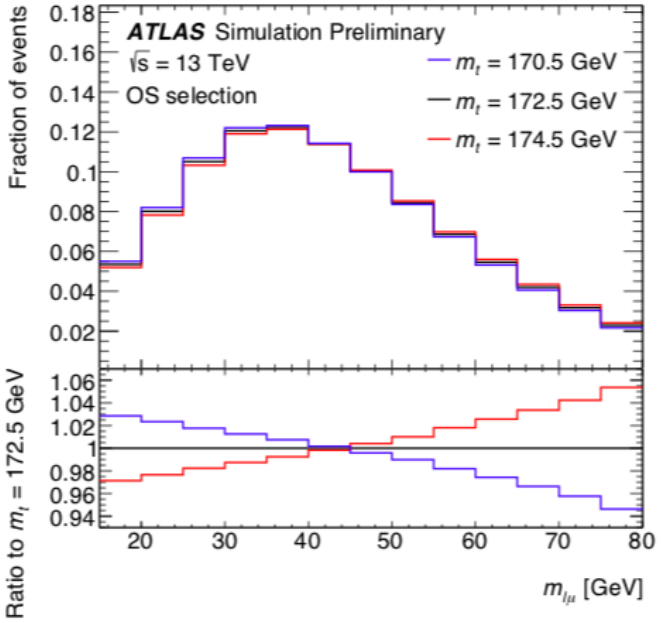
- Combine measurement from 8TeV dataset $\rightarrow m_t = 172.69 \pm 0.48$GeV

Measurements dominated by different systematic uncertainties or with anti-correlated systematics can help improve the combination

Most recent ATLAS measurement is ATLAS-CONF-2019-046:

- First m_t ATLAS measurement at 13TeV
- uses a leptonic observable $m_{\text{lep},\mu}$ from semi-leptonic top-quark decay:
  - lepton from W boson decay, (soft) μ from B-hadron decay
- dominant syst uncertainties expected to be largely uncorrelated to the usual ones





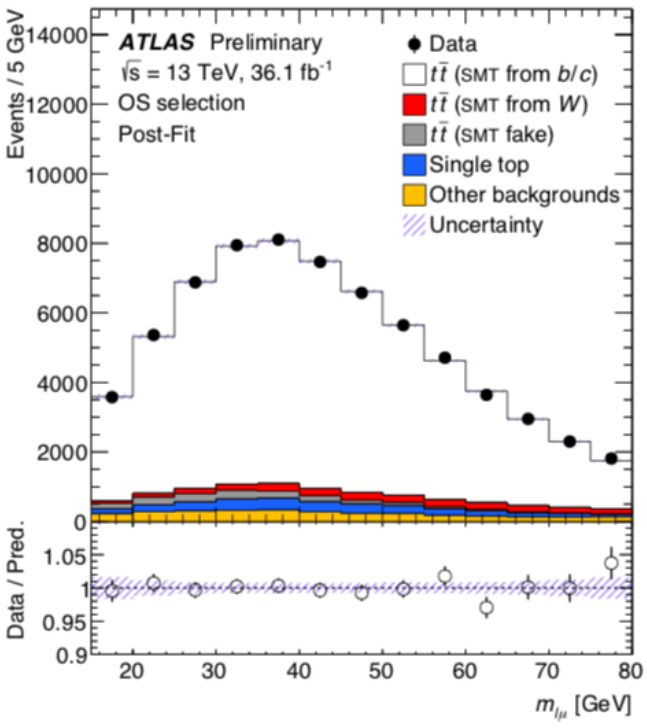
m_t from μ+jets with Soft Muon Tagger

Dedicated tagger (SMT) developed to select (soft) μ + jets events:

- reduce bkg from π and K in-flight decays
- calibrated using J/ψ events (tag eff.) and $W + j$ events (tag mis-ID)

- used 36 fb^{-1} of data, syst unc dominates
- leading syst uncertainties from:
  - unc on branching ratios to soft μ
  - $t\bar{t}$ b-fragmentation function modelling
  - pile-up reweighting and SMT-fake normalisation
- from profile likelihood fit

$$m_t = 174.48 \pm 0.40(\text{stat}) \pm 0.67(\text{syst})\text{GeV}$$



most precise m_t single-measurement among the ATLAS ones

Indirect measurements - m_t from $t\bar{t}$+1 jet

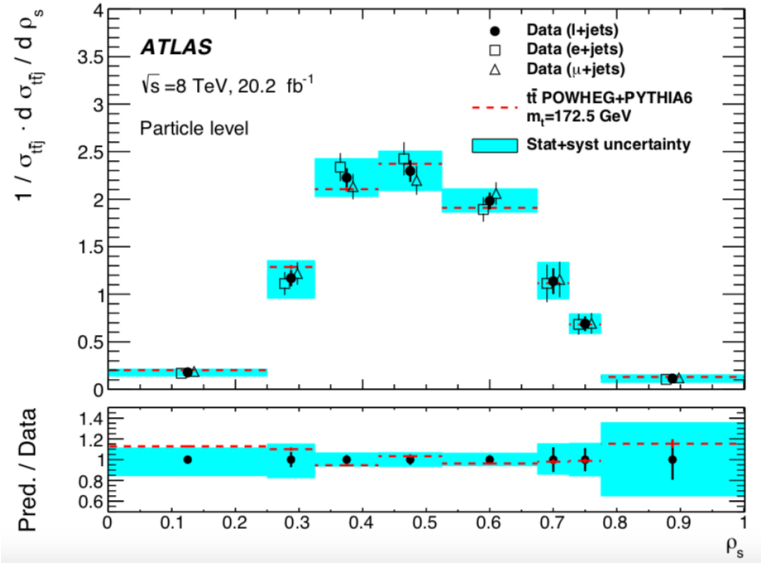
ATLAS most precise indirect m_t measurement is from $t\bar{t}$+1 jet cross-section
Latest result JHEP 11 (2019) 150 uses 8 TeV data, 13 TeV analyses ongoing.

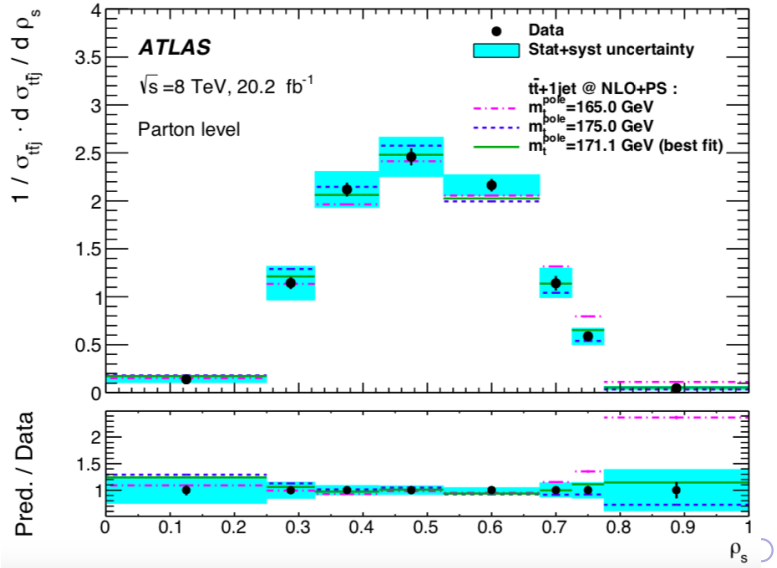
Observable choice is $t\bar{t}$+ 1 jet normalised differential cross-section vs $1/m(t\bar{t}+1jet)$

- higher sensitivity to m_t than inclusive cross section
- extra-jet enhances sensitivity to m_t, but keeps statistics high
- syst unc reduced in normalisation
- fixed-order calculations available

Experimental strategy:

- select semi-leptonic $t\bar{t}$ events and allow for extra jet (p_T^{jet}>50 GeV)
- iterative Bayesian unfolding to correct to:
  - the level of semi-stable particles (particle level)
  - the level of stable top-quarks (parton level)





m_t from $t\bar{t}$+1jet at parton level

Parton level-corrected distribution used in top-quark mass extraction:

- fit minimizes χ^2 of measured vs predicted (unfolding correlations included)
- Comparison to calculations in *pole* and $\overline{MS}$ renormalisation schemes
  - Extract m_t^{pole} and $m_t(m_t)$ (different values, but connected by known relation)
  - Allow for an accurate evaluation of theoretical uncertainties

$$m_t^{\text{pole}} = 171.1 \pm 0.4\ (\text{stat}) \pm 0.9\ (\text{syst})\ ^{+0.7}_{-0.3}\ (\text{theo})\ \text{GeV}$$

$$m_t(m_t) = 162.9 \pm 0.5(\text{stat}) \pm 1.0(\text{syst})\ ^{+2.1}_{-1.2}\ (\text{theo})\ \text{GeV}$$

Values are compatible, given a know $m_t(m_t)$-to-m_t^{pole} relation

Leading uncertainties

Experimental:

- $t\bar{t}$ modelling
- jet energy scale
- statistics

Theoretical

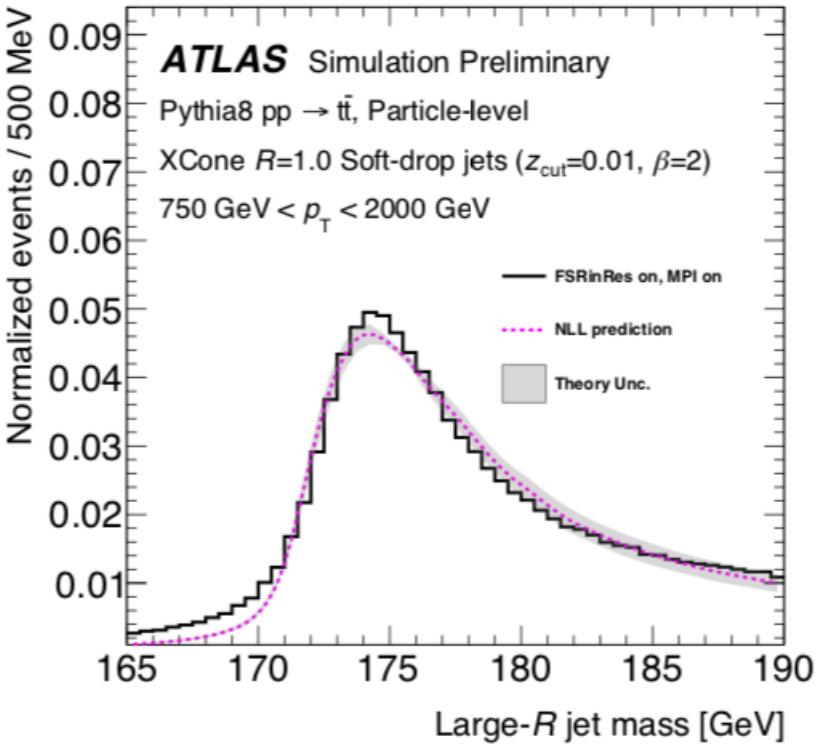
- renormalisation/factorisation scale variations

Particle level-distribution not used in m_t extraction. Can potentially be useful if theoretical calculation at the same level becomes available.

m_t^{MSR} from large-R jet mass

A recent ATLAS MC-based study ATL-PHYS-PUB-2021-034 aims at relating m_t as implemented in MC (m_t^{PP}), to a theoretically well-defined field theory parameter. Possible thanks to NLL calculation (PhysRevD.100.074021) for mass distribution of top-quarks hadronically decaying into large-radius jets.

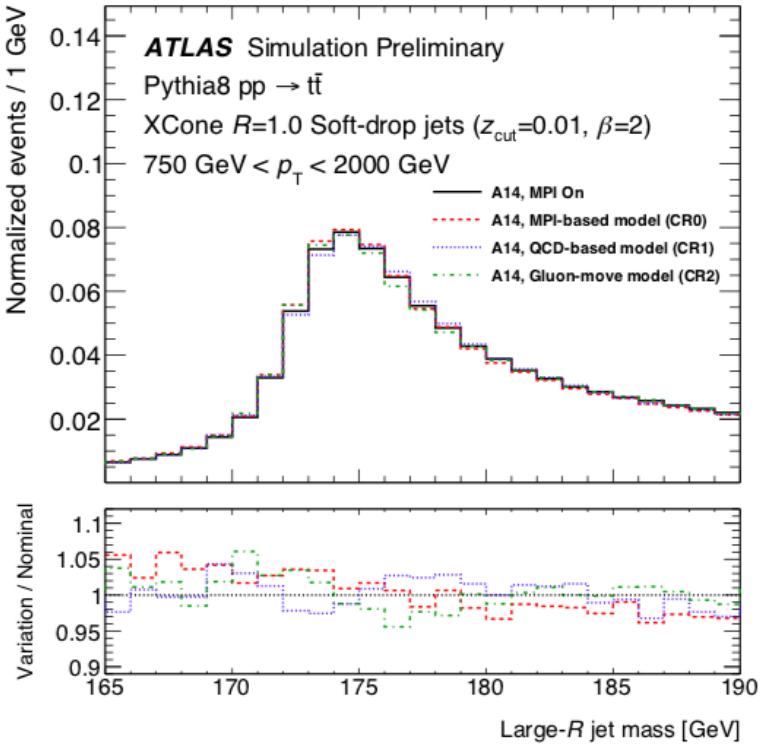
- theory prediction details
  - particle level , very high $p_T^{\mathrm{jet}} \in [0.75, 2]$TeV
  - XCone jet algorithm, soft-drop grooming
  - m_t in MSR renormalization scheme: $m_t^{\mathrm{MSR}}(R)$
  - three pars ($m_t^{\mathrm{MSR}}, \Omega, x$) affect the jet mass shape
- compare to Powheg+Pythia (PP) MC simulation with template fit
  - MultipleParticleInteraction off



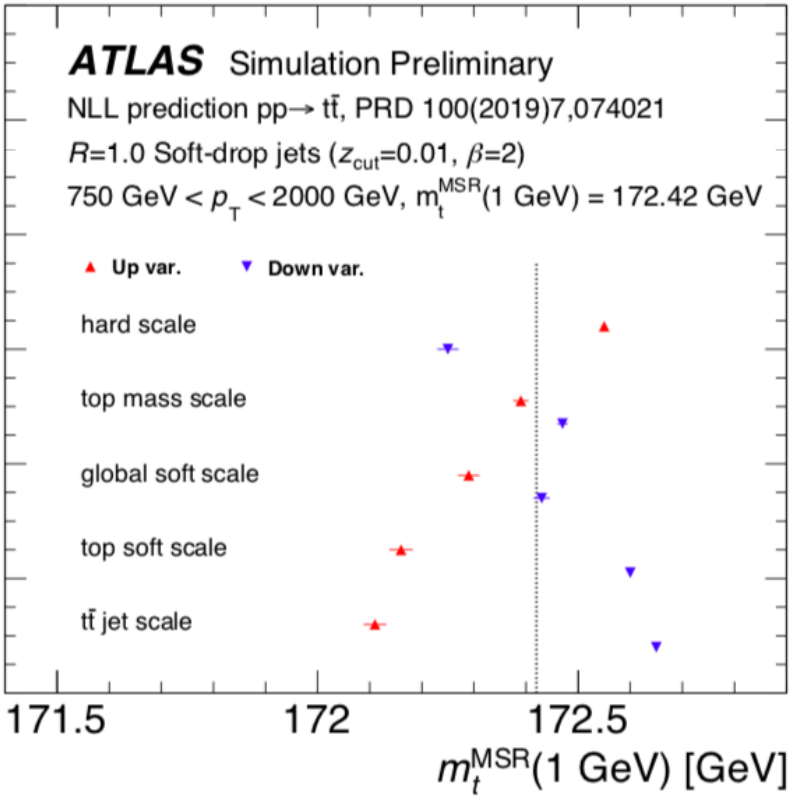
Challenging phase space to perform a measurement of the observable, but effort is ongoing.

m_t^{MSR} from large-R jet mass

Detailed study of Underlying Event (UE) and Color Reconnection (CR)impact



Theo unc varied by varying dynamic scales. Additional unc on fit procedure

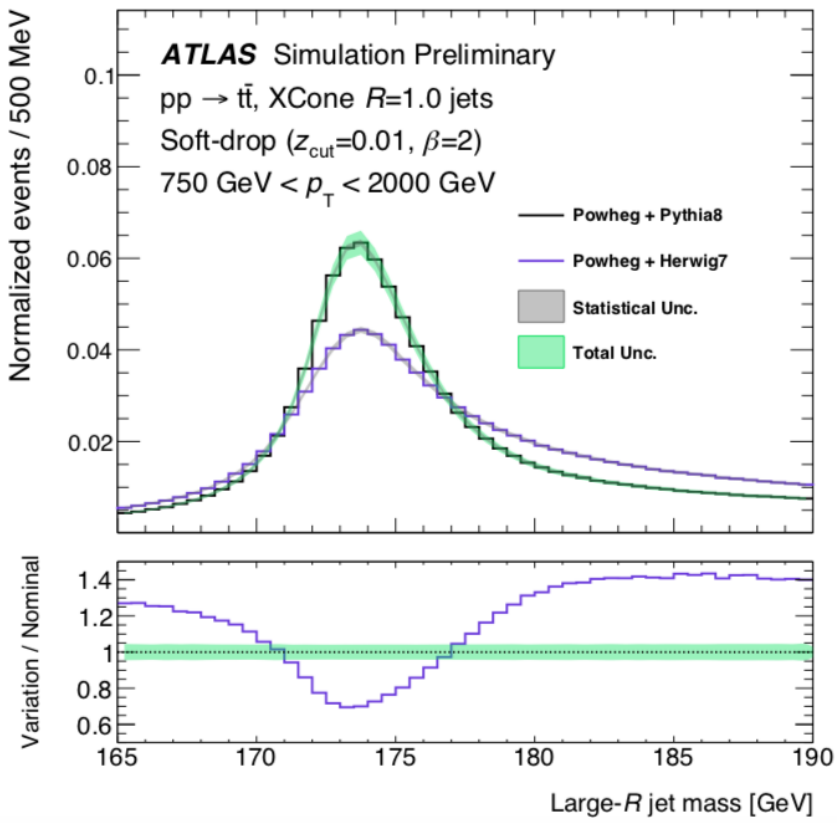


$$m_t^{\mathrm{MSR}}(1\,GeV) = m_t^{\mathrm{PP}} - 80^{+350}_{-400}\,\mathrm{MeV}$$

and using the m_t^{MSR}-to-m_t^{pole} relation: $m_t^{\mathrm{pole}} = m_t^{\mathrm{PP}} - 350^{+300}_{-360}\,\mathrm{MeV}$

observable-dependent result, but quite stable for other large-R jet definitions!

m_t^{MSR} from large-R jet mass - Pythia vs Herwig



Interesting Herwig vs Pythia comparison
Very different mass spectra, but very close m_t^{MSR} from fit.
Differences absorbed by Ω and x_2 parameters.

Ω accounts for the QCD-leading hadronization effects
x_2 accounts for hadronic corrections poorly correlated to m_t

Powheg+Pythia result:

$$m_t^{MSR}(R = 1\ \mathrm{GeV}) = 172.42 \pm 0.10\ \mathrm{GeV},\ \ \Omega_{1q}^{\infty} = 1.49 \pm 0.03\ \mathrm{GeV},\ \ x_2 = 0.52 \pm 0.09,$$

Powheg+Herwig result

$$m_t^{MSR}(1\ \mathrm{GeV}) = 172.27 \pm 0.09\ \mathrm{GeV},\ \ \Omega_{1q}^{\infty} = 1.9 \pm 0.07\ \mathrm{GeV},\ \ x_2 = 0.98 \pm 0.12,$$

Conclusions

The top-quark is a fundamental particle of the SM and its mass is of great relevance both for SM and NP scenarios.

ATLAS measured m_t with *direct* and *indirect* methods:

- latest ATLAS combination (from 2018, 7-8 TeV dataset) resulted in

$$m_t = 172.69 \pm 0.48\text{GeV } (\pm 0.3\%)$$

- most precise direct-method single-measurement result uses soft-μ tagger and $m_{l\mu}$ observable in semileptonic $t\bar{t}$ events at 13 TeV:

$$m_t = 174.48 \pm 0.78\text{GeV } (\pm 0.5\%)$$

- most precise indirect method uses differential normalised cross section of $t\bar{t}$+1jet events, with semi-leptonic $t\bar{t}$ decay, at 8TeV:

$$m_t^{\text{pole}} = 171.1^{+1.2}_{-1.1}\text{GeV } (\pm 0.8\%)$$

$$m_t(m_t) = 162.9^{+2.3}_{-1.6}\text{GeV } (^{+1.5\%}_{-1\%})$$

ATLAS performed a MC-based study using the mass spectrum of high-p_T top-quarks decaying hadronically to a large-radius jet, finding:

$$m_t^{\text{PP}} = m_t^{\text{MSR}}(1GeV) + 80^{+350}_{-400}\text{MeV} = m_t^{\text{pole}} + 350^{+300}_{-360}\text{MeV}$$

13TeV analyses are ongoing: stay tuned for new updated results!

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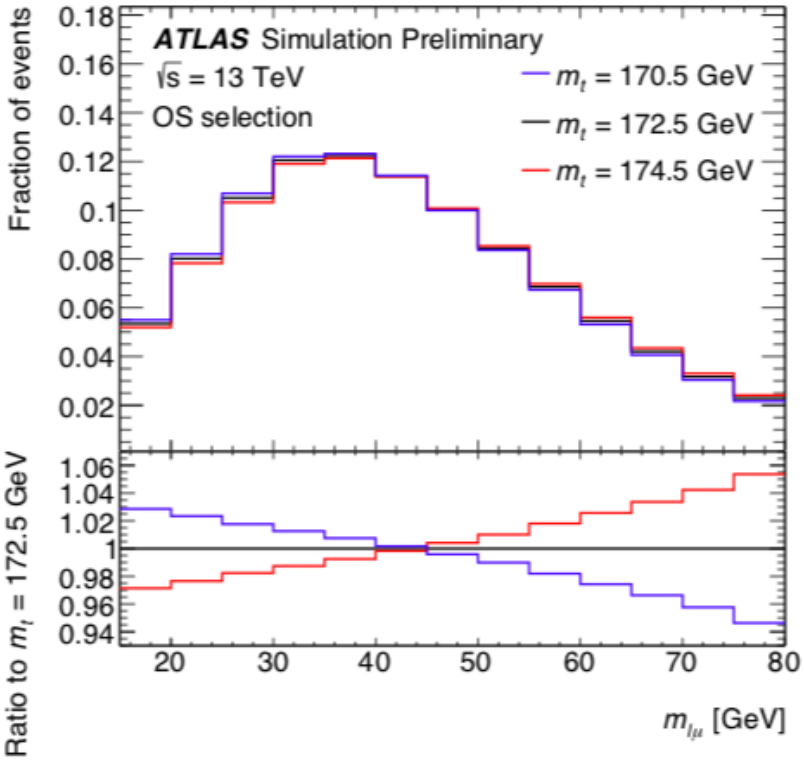
Back-up

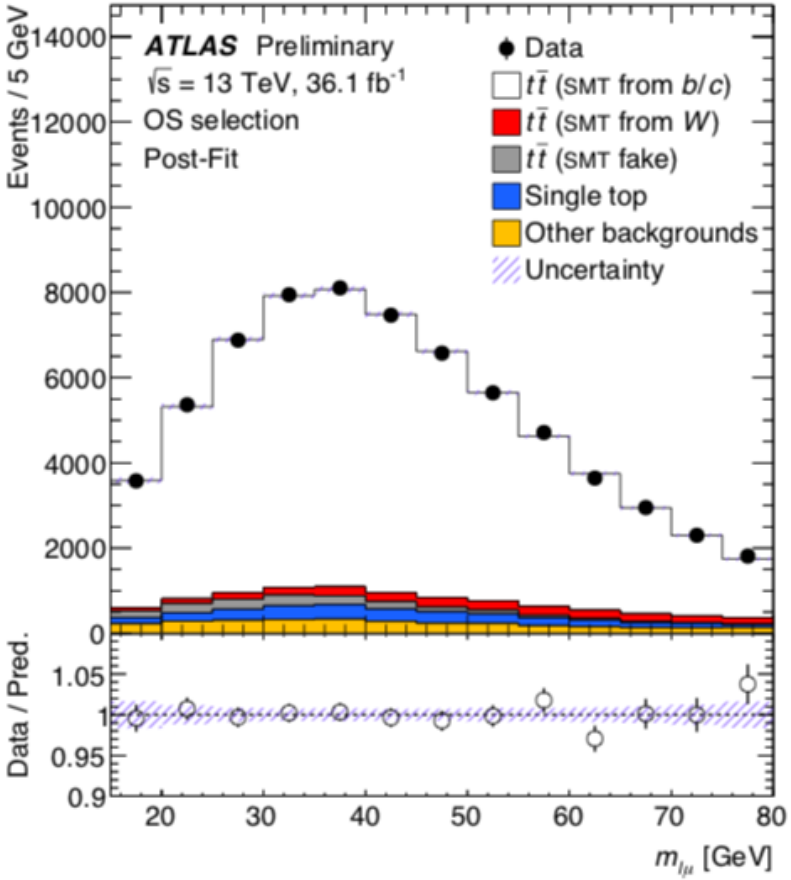
These slides are dedicated to my colleague and CERN-officemate Esteban.

Unfortunately, he passed away on 2nd July 2022 .

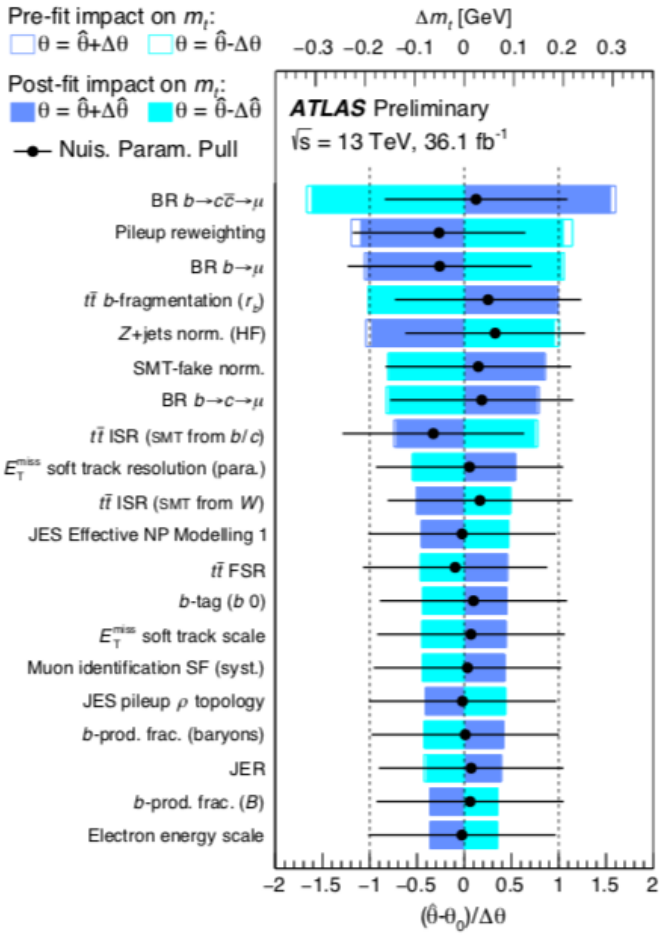
Esteban was working, among other things, on the 13 TeV $t\bar{t}$+1jet m_t measurement.

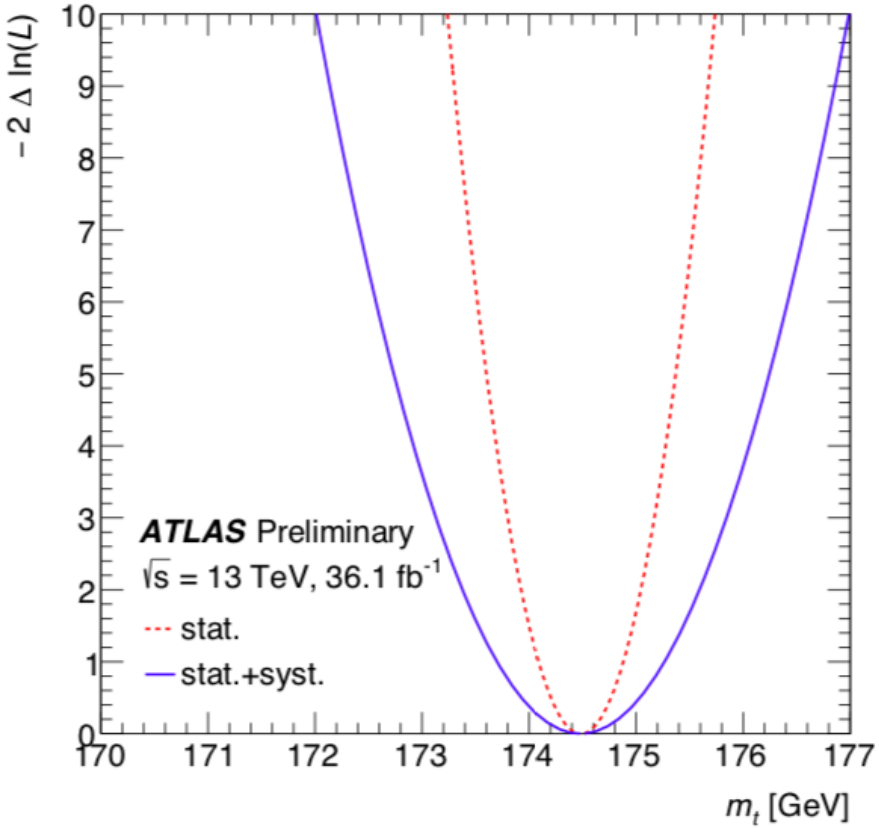
m_t with SMT: data/MC and sensitivity





m_t with SMT: NP breakdown



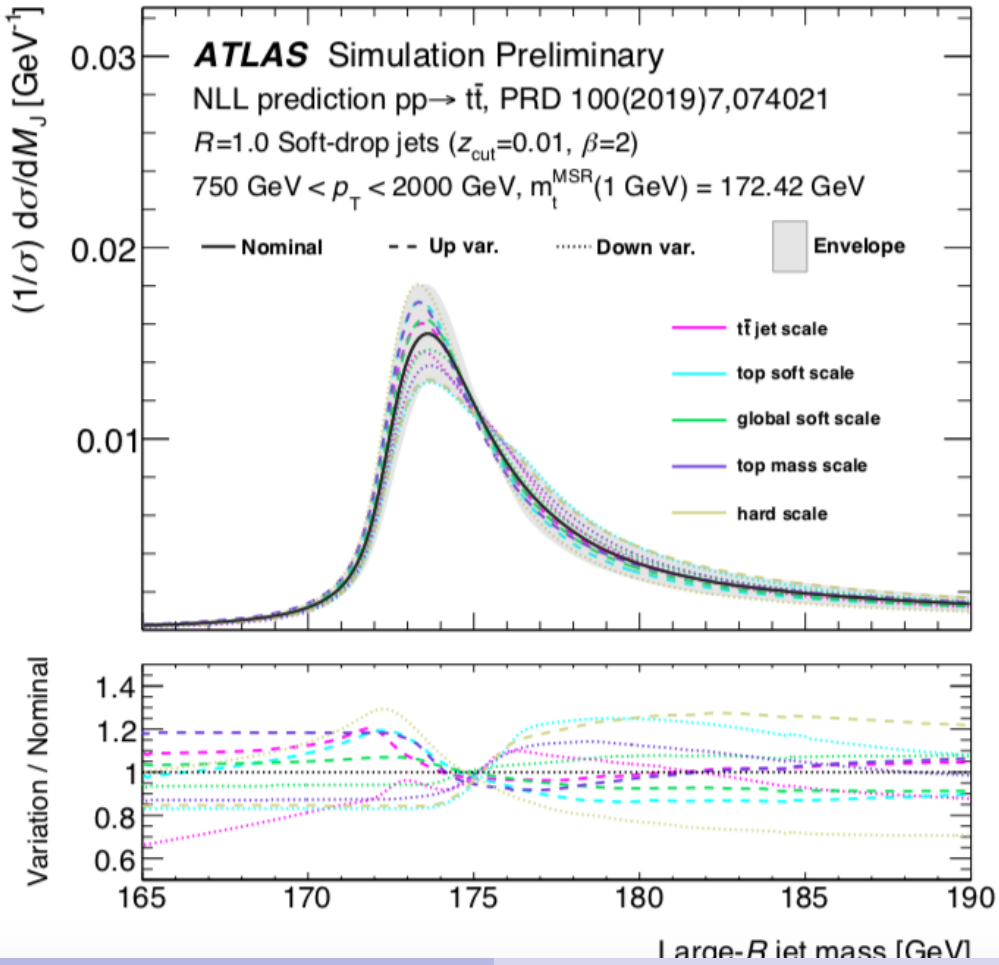


$t\bar{t}$+1 jet systematics breakdown

Mass scheme	m_t^{pole} [GeV]	$m_t(m_t)$ [GeV]
Value	**171.1**	**162.9**
Statistical uncertainty	**0.4**	**0.5**
Simulation uncertainties		
Shower and hadronisation	0.4	0.3
Colour reconnection	0.4	0.4
Underlying event	0.3	0.2
Signal Monte Carlo generator	0.2	0.2
Proton PDF	0.2	0.2
Initial- and final-state radiation	0.2	0.2
Monte Carlo statistics	0.2	0.2
Background	<0.1	<0.1
Detector response uncertainties		
Jet energy scale (including b-jets)	0.4	0.4
Jet energy resolution	0.2	0.2
Missing transverse momentum	0.1	0.1
b-tagging efficiency and mistag	0.1	0.1
Jet reconstruction efficiency	<0.1	<0.1
Lepton	<0.1	<0.1
Method uncertainties		
Unfolding modelling	0.2	0.2
Fit parameterisation	0.2	0.2
Total experimental systematic	**0.9**	**1.0**
Scale variations	(+0.6, −0.2)	(+2.1, −1.2)
Theory PDF$\oplus\alpha_s$	0.2	0.4
Total theory uncertainty	**(+0.7, −0.3)**	**(+2.1, −1.2)**
Total uncertainty	**(+1.2, −1.1)**	**(+2.3, −1.6)**

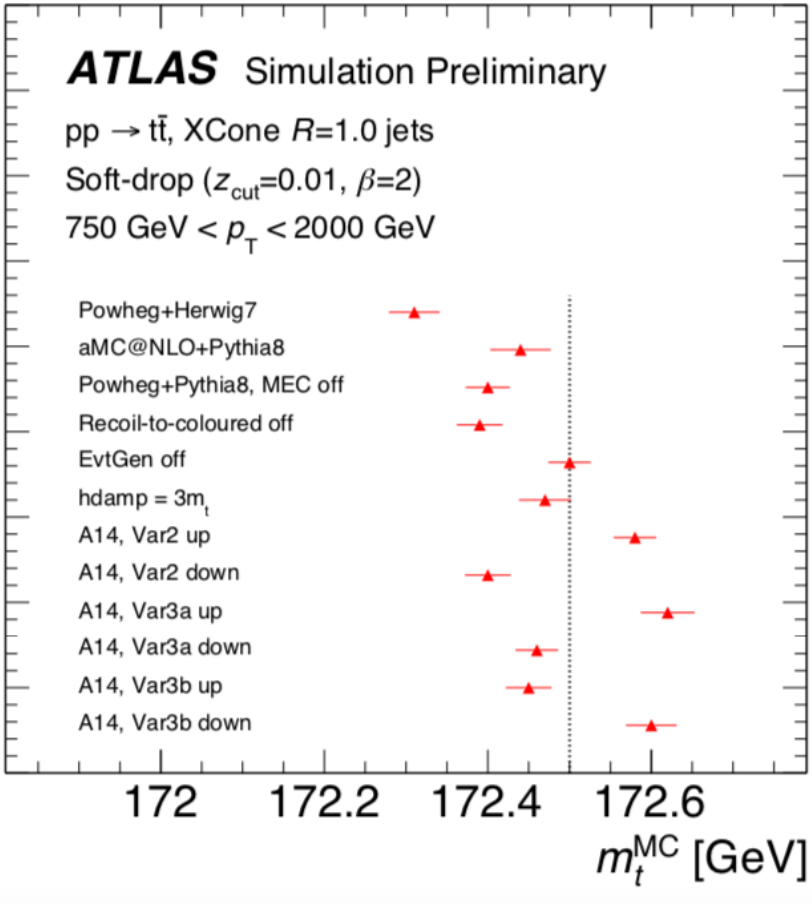
NLL large-R jet mass shape calculation

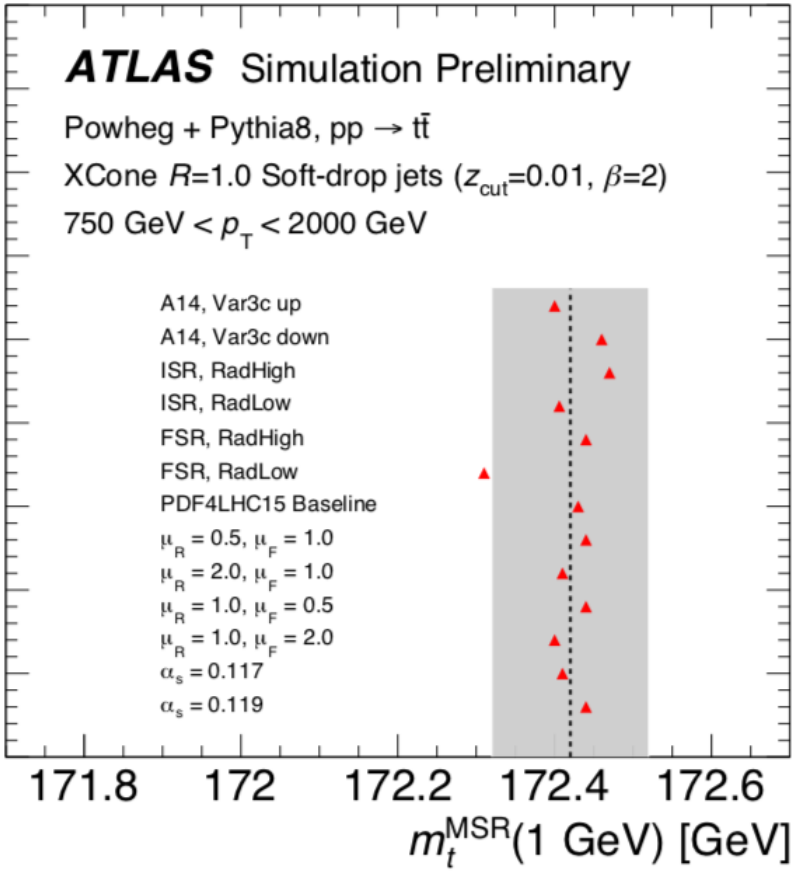
Hadronization effects at leading power are proportional to an $O(\Lambda_{QCD})$ nonperturbative parameter, Ω, that is independent of any kinematic and grooming parameters, as well as top decay product phase space.
On the other hand, the dependence of the hadronisation correction on these variables factorizes into perturbatively-calculable coefficients: x_2 accounts for hadronic corrections that are less correlated with m_t



NLL large-R jet mass MC predictions

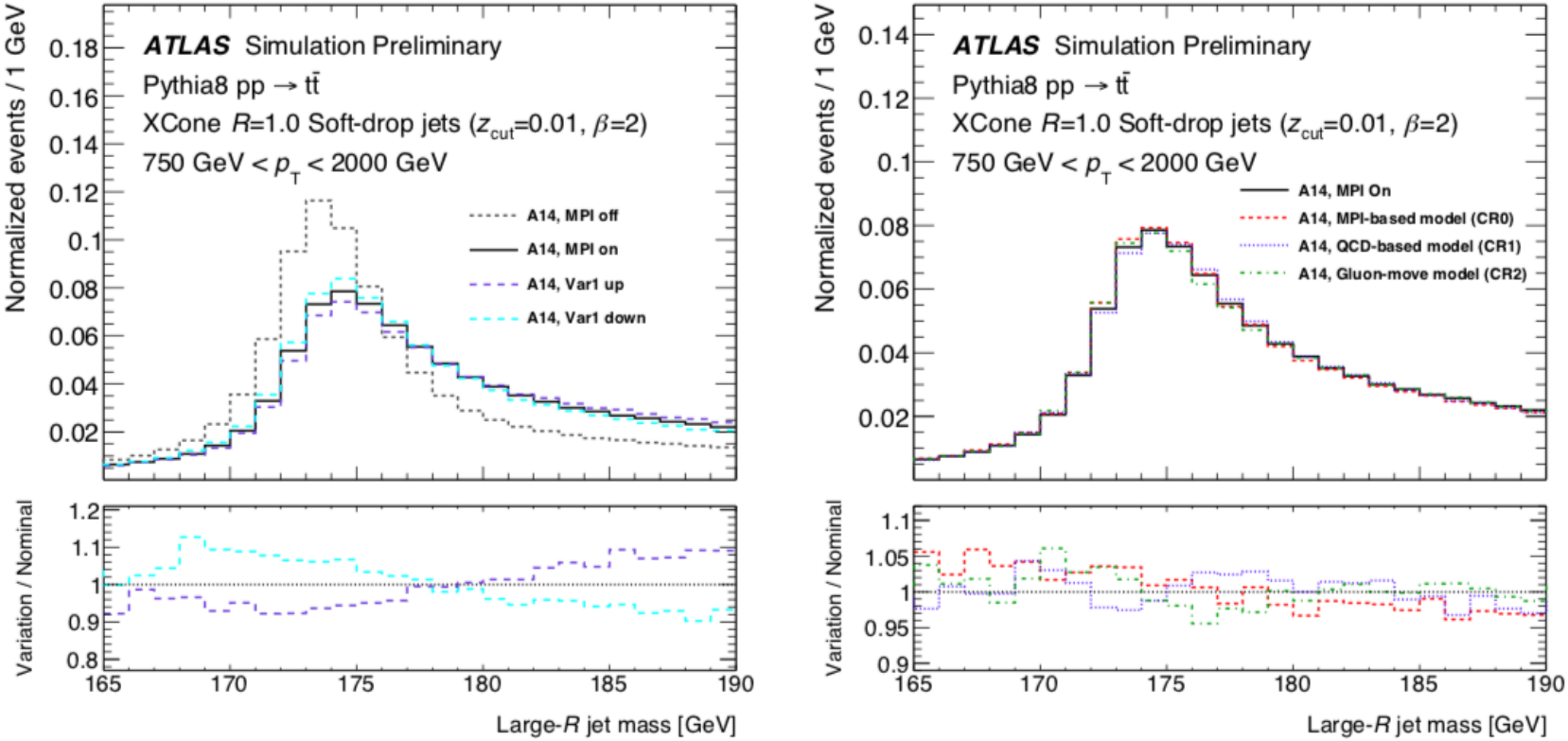
Potential impact of $t\bar{t}$modelling uncertainties on an analysis measuring $m_t$with high p_T top-quarks decaying to a large-radius jet.
On the left the impact of different MC simulations are compared, on the right the impact due to changes in Pythia internal parameters





NLL large-R jet mass MC predictions

The impact of UE and CR modelling on the large-R jet mass distribution. Differences are used to estimate the uncertainty on the m_t^{MSR}-to-m_t^{PP} relation.



Other $t\bar{t}$ modelling effect (change of parton shower or matrix element generators, for instance) are not considered to be part of that uncertainty. In principle each MC can have its own m_t^{MSR}-to-m_t^{PP} calibration.