Top-quark mass measurement with $t\bar{t}$+1 jet events at 8 TeV in ATLAS

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(and the collaboration of P.Uwer and I. Irles)

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28th May 2019

Outline

This talk is based on a very recent ATLAS measurement (arXiv:1905.02302)

Introduction

- the top-quark at the LHC
- m_t relevance
- theo. unc on m_t measurements

See P. Nason talk here !

Intro to m_t measurement with $t\bar{t}+1$-jet - [EPJC 73(2013)5 2438, JHEP10(2015)121, EPJC77(2017) 11 794]

- the $\mathcal{R}$ observable and its properties
- 7 TeV results and 8 TeV improvements
- analysis strategy for 8 TeV

m_t measurement with $t\bar{t}+1$-jet in ATLAS at 8 TeV - [arXiv:1905.02302]

- Event selection & control plots
- Unfolding and results
- m_t extraction from NLO calculations

Use $t\bar{t}+$1-jet events for a high precision m_t measurement

$$\mathcal{R}\left(\rho_s, m_t\right) = \frac{1}{\sigma_{t\bar{t}+\text{1-jet}}} \times \frac{d\sigma_{t\bar{t}+\text{1-jet}}}{d\rho_s}, \text{ with } \rho_s = \frac{340\text{ GeV}}{\sqrt{s_{t\bar{t}+\text{1-jet}}}}$$

Needs

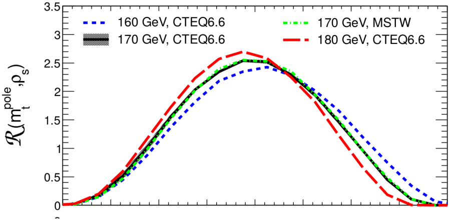
- Enough data
- Beyond LO
- Small theoretical corrections
- High sensitivity to m_t

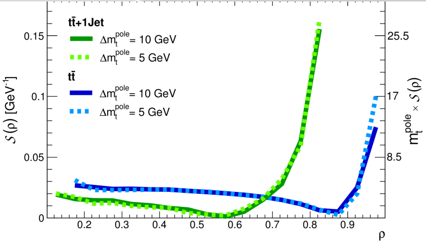
Why

- Low stat. unc.
- Fix renorm. scheme
- Small theoretical uncertainties
- Reduce exp. syst.

$\mathcal{R}$ properties

- $\sigma_{t\bar{t}+\text{1-jet}} \sim 25\%\ \sigma_{t\bar{t}}$
- NLO (m_t^{pole} and $m_t(\mu)$)
- NLO$\sim$10%LO, normalised
- 5x sensitivity of $\sigma_{t\bar{t}}^{incl}$

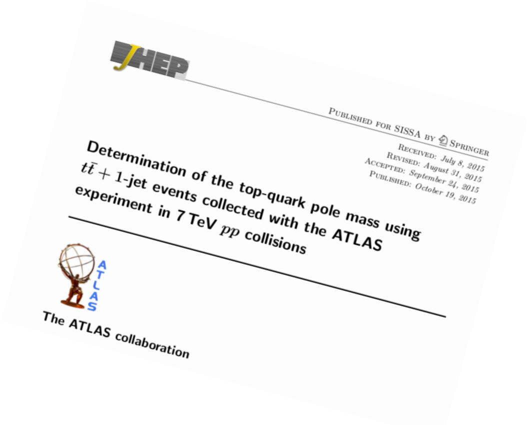




$t\bar{t} + 1$-jet analysis 7 TeV results

The $\mathcal{R}$ observable has been used to measure m_t^{pole} and $m_t(\mu = m_t)$ from data produced in 7 TeV pp collisions and collected by the ATLAS detector.

$$m_t^{\text{pole}} = 173.7 \pm 1.5 \text{ (stat.)} \pm 1.4 \text{ (syst.)}^{+0.9}_{-0.5} \text{ (theo.) GeV}$$


JHEP

Published for SISSA by Springer

Received: July 8, 2015
Revised: August 31, 2015
Accepted: September 24, 2015
Published: October 19, 2015

Determination of the top-quark pole mass using $t\bar{t} + 1$-jet events collected with the ATLAS experiment in 7 TeV pp collisions

The ATLAS collaboration

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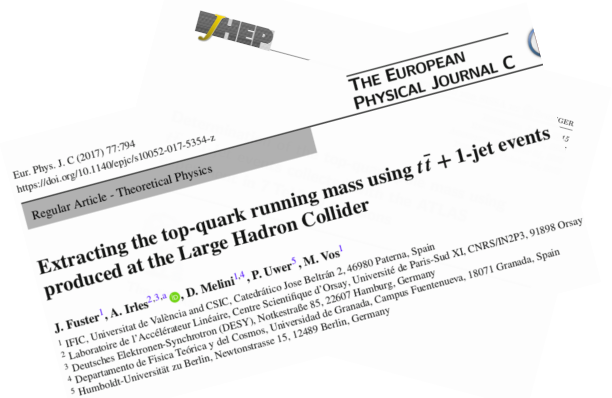
$$m_t(\mu = m_t) = 165.9 \pm 1.4\ (\text{stat.}) \pm 1.3\ (\text{syst.})^{+1.5}_{-0.6}\ (\text{theo.})\ \text{GeV}$$



Analysis improvements for 8 TeV

Increased statistics allow for a finer binning.
In particular higher resolution in the most sensitive region $0.7 < \rho_s < 1$.

improvements

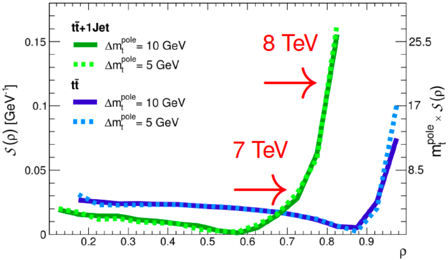
- increased statistics

  $\downarrow$

  reduced stat. unc.
- finer binning possible

  $\downarrow$

  increases sensitivity and reduce uncertainty



toy example

$$\frac{\Delta\mathcal{R}}{\mathcal{R}} = \mathcal{S} \times \Delta m$$

Assuming constant unc. on $\mathcal{R}$
if $\mathcal{S}$ [8TeV] $= 2 \times \mathcal{S}$ [7TeV]
then Δm [8TeV] $= \frac{1}{2} \times \Delta m$ [7TeV]

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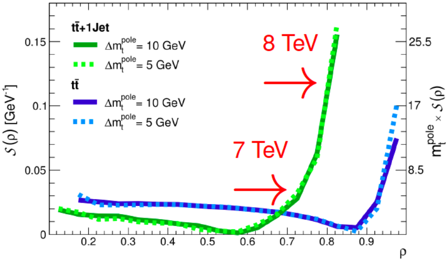

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increase $\mathcal{S}$ aiming for a 1 GeV total uncertainty on m_t^{pole}

(while keeping $\Delta\mathcal{R}$ under control!)

Analysis strategy

The top-quark mass is extracted from a comparison between measured data and theoretical predictions at NLO

Fixed order theo. calc. can be computed at

- *particle level* - particles before interaction with detector
- *parton level* - stable top-quarks

Data has to be corrected (unfolded) to the level where theo. predictions are defined.

Reporting results at both parton- and particle- level is useful to test effects of top-quark decay and hadronisation on m_t

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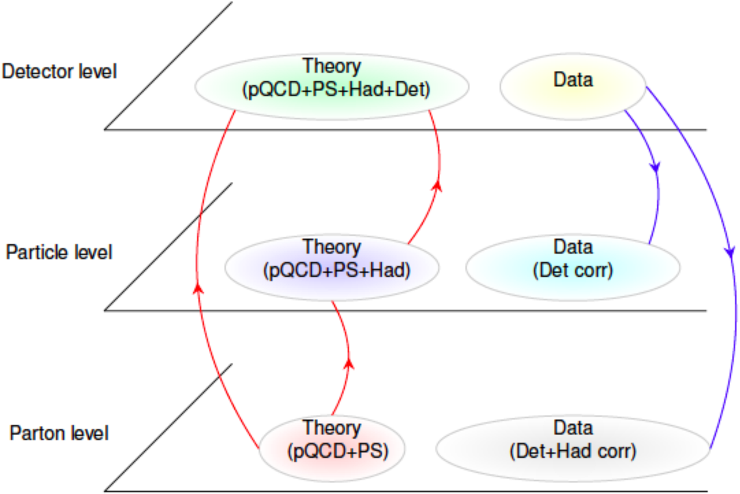
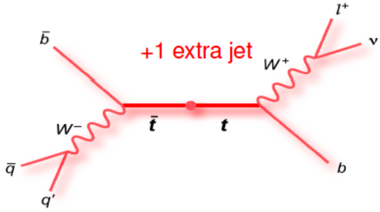


Event selection

Two sets of cuts are implemented to select a pure sample of $t\bar{t} + 1$-jet events.

Basic selection - semileptonic

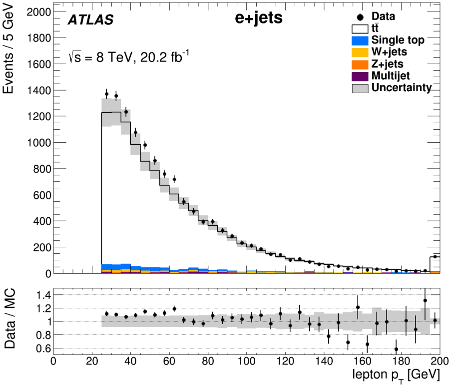
- one lepton trigger
- one good lepton (μ or e)
- ≥ 1 primary vertex with 5 tracks
- ≥ 5 good jets
- $== 2$ b-tagged jets
- $E_T^{miss} > 30$ GeV
- $m_T^W > 30$ GeV



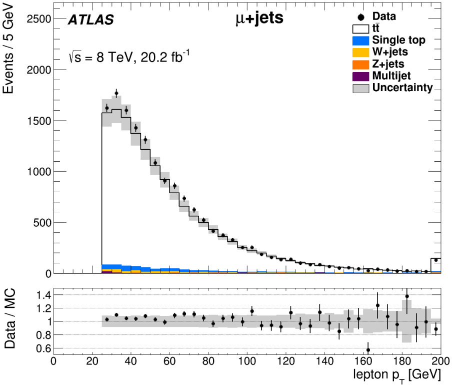
$t\bar{t} + 1$-jet system reconstruction

- W_{lep} sum of l and ν
  - ν assuming $m_W = m_W^{PDG}$
- W_{had} from light jets i and j
  - $0.9 < \frac{m_W^{PDG}}{m_{ij}} < 1.25$
  - $\min(p_T^i, p_T^j) \cdot \Delta R_{ij} < 90$ GeV
- Take b-jets plus $W_{lep/had}$
  - minimizing $\frac{|M_{t_{lep}} - M_{t_{had}}|}{M_{t_{lep}} + M_{t_{had}}}$
  - $M_{t_{lep}} / M_{t_{had}} > 0.9$
- Leading jet left taken as extrajet
  - $p_T^{jet} > 50$ GeV, $|\eta^{jet}| < 2.5$

Control plots - semileptonic selection only



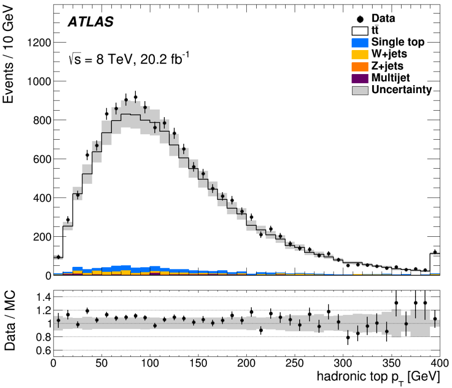
electron p_T

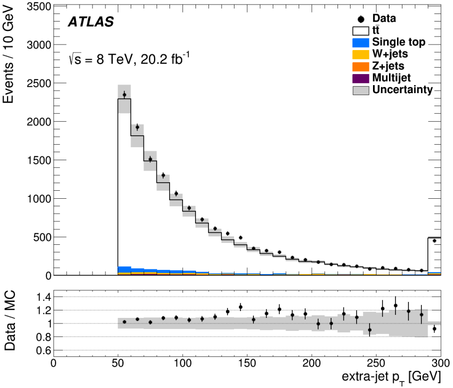


muon p_T

Overall good data-MC agreement

Control plots - full $t\bar{t}$ + 1-jet selection

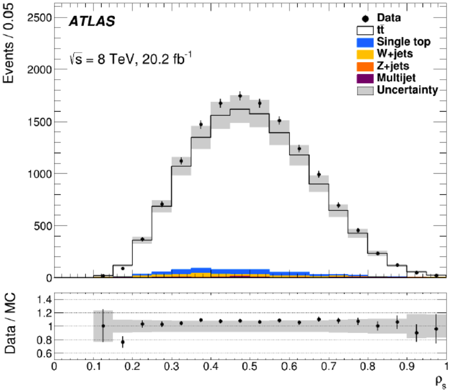




hadronic top p_T | extra-jet p_T

$t\bar{t}$ + 1-jet topology specific cuts do not introduce any bias

Detector level results



Channel	e+jets	μ+jets
$t\bar{t}$	5530 ± 470	7080 ± 600
Single top	191 ± 15	226 ± 18
W+jets	100 ± 33	121 ± 37
Z+jets	24 ± 8	13 ± 4
Multijet	21 ± 11	<11
Prediction	5870 ± 540	7440 ± 660
Data	6379	7824

- very small background contamination.
- ρ_s distribution still to be bkg-subtracted and normalised to get $\mathcal{R}$

Unfolding algorithm

Detector level distribution is corrected to parton and particle levels using Iterative Bayesian unfolding:

$$\mathcal{R}^{\text{corrected}} = f^{\text{acc.}} \cdot \left[\mathcal{M}^{-1} \otimes \mathcal{R}^{\text{detector}}\right] \cdot f^{\text{ph.sp}}$$

- $\mathcal{M}$ migration matrix from truth level to detector level
- $f^{\text{acc.}}$ bin-by-bin factor accounting for detector acceptance
- $f^{\text{ph.sp}}$ bin-by-bin correction accounting for phase space near threshold

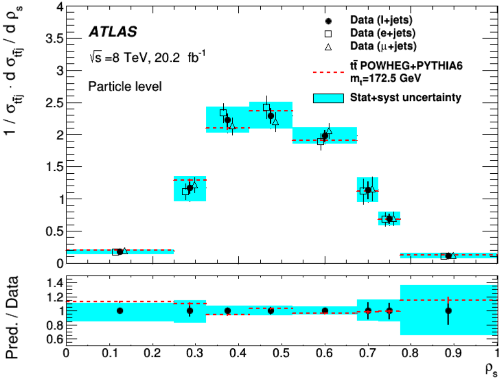
- Migration matrix and correction factors defined from $t\bar{t}$ Monte Carlo simulation
- effect of $f^{\text{ph.sp}}$ is
  - very small for parton level unfolding
  - null for particle level unfolding

  has a small dependence on m_t used in the MC.
  With or without $f^{\text{ph.sp}}$ the parton level result changes $\lesssim$ 300 MeV.

Globally, the unfolding procedure is found to be independent on the m_t parameter used to define the Monte Carlos simluation

Particle level results

In unfolding to particle level, only detector effects are corrected.



- Fiducial volume defined applying $t\bar{t}+1$-jet system recontruction algorithm
- $\mathcal{R}$ defined using the (pseudo) top-quarks reconstructed by the algorithm
- e+jets and μ+jets channels compatible
- Systematics evaluated repeating the unfolding on different detector-level distributions

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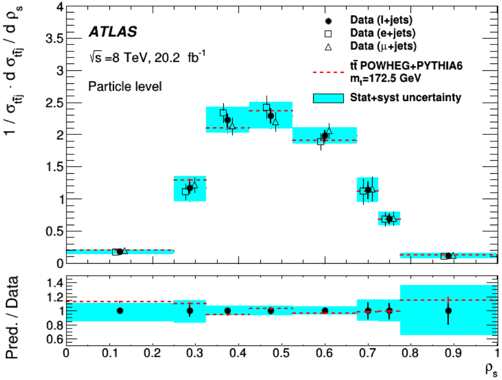

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Leading systs. from jet-energy-scale and $t\bar{t}$ modelling (as in other $t\bar{t}$ semilept. analysis)

No theo calc. in a well defined mass scheme to compare data with

↓

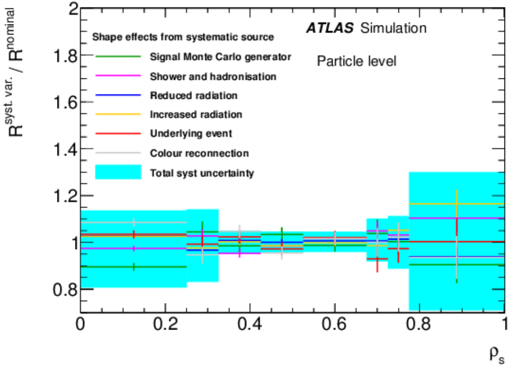
No m_t determination is attempted from $\mathcal{R}$ at particle level

Particle level results

All the elements to perform a future m_t determination from particle-level $\mathcal{R}$ are available

- bin values + unc. table
- covariance matrix
- $\mathcal{R}$ shape of main syst.

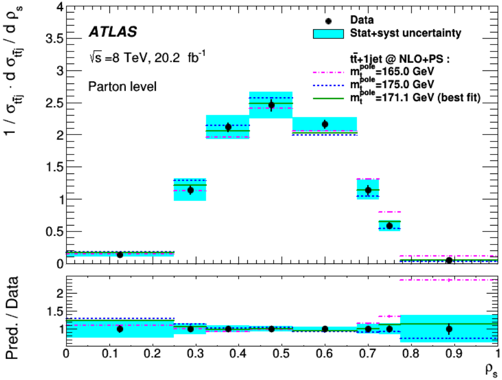
bin	$\mathcal{R}^{\text{particle}}$	stat.	syst.
$0.000 < \rho_s < 0.250$	0.179	±0.007	$^{+0.019}_{-0.027}$
$0.250 < \rho_s < 0.325$	1.169	±0.085	$^{+0.156}_{-0.188}$
$0.325 < \rho_s < 0.425$	2.226	±0.099	$^{+0.110}_{-0.107}$
$0.425 < \rho_s < 0.525$	2.296	±0.115	$^{+0.111}_{-0.106}$
$0.525 < \rho_s < 0.675$	1.982	±0.087	$^{+0.091}_{-0.081}$
$0.675 < \rho_s < 0.725$	1.138	±0.135	$^{+0.112}_{-0.090}$
$0.725 < \rho_s < 0.775$	0.690	±0.077	$^{+0.078}_{-0.078}$
$0.775 < \rho_s < 1.000$	0.113	±0.022	$^{+0.034}_{-0.033}$



ρ_s range	0.000 - 0.250	0.250 - 0.325	0.325 - 0.425	0.425 - 0.525	0.525 - 0.675	0.675 - 0.725	0.725 - 0.775	0.775 - 1.000
0.000 – 0.250	51.7	−26.9	−60.4	−89.0	−47.6	−44.2	−26.8	0.1
0.250 – 0.325	−26.9	1032.5	−117.6	133.6	−125.3	154.9	116.9	−23.3
0.325 – 0.425	−60.4	−117.6	2905.8	−583.8	201.1	154.2	200.6	−18.2
0.425 – 0.525	−89.0	133.6	−583.8	4147.3	−793.5	358.3	102.5	−88.0
0.525 – 0.675	−47.6	−125.3	201.1	−793.5	4371.9	−314.6	−234.6	176.4
0.675 – 0.725	−44.2	154.9	154.2	358.3	−314.6	1280.6	226.9	−239.1
0.725 – 0.775	−26.8	116.9	200.6	102.5	−234.6	226.9	463.2	−39.3
0.775 – 1.000	0.1	−23.3	−18.2	−88.0	176.4	−239.1	−39.3	603.9

Parton level results

Data corrected for detector, hadronisation, top-quark decay effects.



- $\mathcal{R}$ defined from on-shell top-quarks and a jet with $p_T^{\text{extrajet}} > 50$ GeV and $|\eta^{\text{extrajet}}| < 2.5$
- m_t determined by χ^2 minimisation
- Systematics on m_t evaluated repeating the mass extraction process on different detector-level distributions

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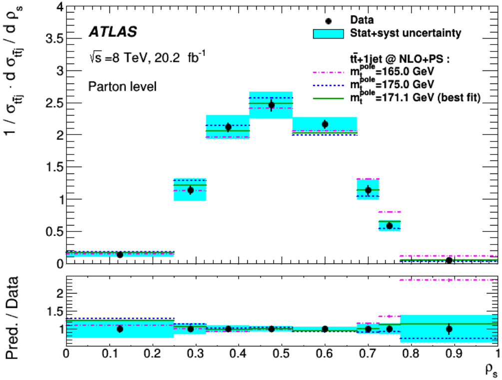

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Leading systs. from jet-energy-scale and $t\bar{t}$ modelling (as in other $t\bar{t}$ semilept. analysis)

Theo. calc. for $t\bar{t} + 1$-jet at parton level exist in pole-mass and $\overline{MS}$ schemes.

$\downarrow$

Same unfolded data can be used to determine m_t^{pole} and $m_t(\mu = m_t)$

Results for m_t

m_t^{pole} and $m_t(\mu = m_t)$ extracted minimising:

$$\chi^2 = \left[\mathcal{R}^{\text{ data}} \text{-} \mathcal{R}^{\text{ th.}}_{(m)}\right]_i C_{ij}^{-1} \left[\mathcal{R}^{\text{ data}} \text{-} \mathcal{R}^{\text{ th.}}_{(m)}\right]_j$$

Additional uncertainties are given to the m_t extraction from χ^2 minimisation

- parametrisation of $\mathcal{R}^{\text{ th.}}_{(m)}$
- fit non-closure & residual dependence

theoretical uncertainties associated to the $t\bar{t}$ + 1-jet theo calc. used:

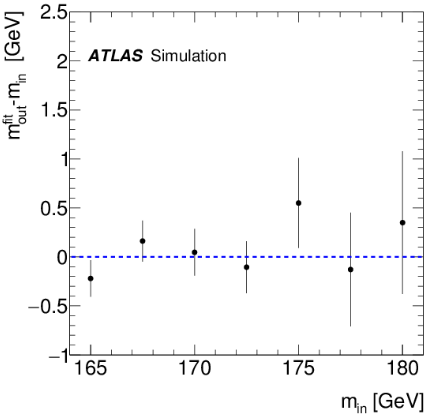
- missing higher orders (scales variations)
- PDFs, α_s variations

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)**

Crosschecks and validation

Various cross-checks performed:

- analysis independence on the value of m_t used in the MC
- unfolding tested with pulls (validate stat. unc.) and stress tests (unbiased on assumed input distribution)
- m_t^{pole} and $m_t(\mu = m_t)$ compatibility (known relation between two schemes)
- larger theo. unc. on $m_t(\mu = m_t)$ due to poorer description of the threshold region in the $\overline{MS}$ scheme. Pole-mass scheme has better convergence in threshold region.



The money result of the result of the analysis

$$m_t^{\text{pole}} = 171.1\ ^{+1.2}_{-1.1}\ \text{GeV}$$

Most precise measurement of m_t^{pole} from the 8 TeV dataset

Evaluation of off-shell effects on $\mathcal{R}$ at 13 TeV

many thanks to M. Worek for help and discussions

In the 8 TeV analysis, off-shell top-quarks and non resonant contributions were estimated to be covered by the theo.$\oplus$ MC modelling uncertainties

New $pp \to WbWbj$ NLO QCD available which includes all contrib. [JHEP 1803 (2018) 169]

Possible to compare NLO+PS approach to the Full pQCD calculation and evaluate the effects of the two calculations on m_t determination from $\mathcal{R}$.

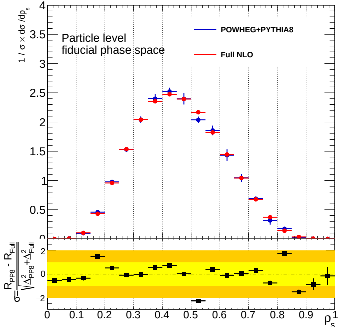
Setup of our NLO+PS the comparison

- dileptonic opposite-sign final state
- 13 TeV collisions energy
- POWHEG for $t\bar{t} + 1$-jet @NLO, matched to PYTHIA8 for showering and top-quark decay
- no hadronisation included in MC simulation
- fiducial volume defined as in Full calculation - (*off-shell* level from now on)

Off-shell effects in m_t from $t\bar{t}$ + 1-jet at 13 TeV

Can we reproduce $\mathcal{R}$ shape from Full NLO calculation with NLO (on-shell) + MC?

POWHEG+PYTHIA8 vs Full NLO QCD



- Comparison for m_t^{pole} =173.2 GeV
- Scales set to $\mu_R = \mu_F = m_t^{\text{pole}}$ (evaluation of unc. associated to the different predictions out of the scope of the study)
- MC is able to reproduce the Full NLO QCD calculation.
- Full $pp \to W^+W^-b\bar{b}j$ NLO QCD calculations can help to reduce MC modelling uncertainties

How m_t value is affected if using one theo. calc. or the other in its determination?

m_t determination at off-shell level

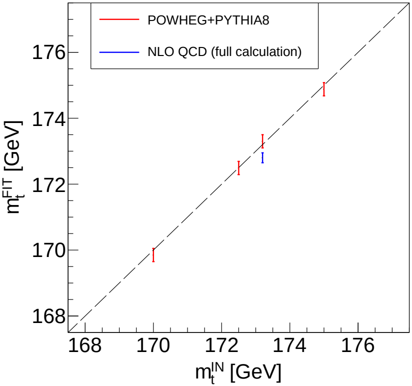
What do we have

- a $\mathcal{R}$ NLO at off-shell level, with m_t^{pole} =173.2 GeV [JHEP 1803 (2018) 169]
- various $\mathcal{R}$ NLO at parton level, with $m_t^{\text{pole}} = \{170, 172.5, 173.2, 175\}$ GeV
- one parton NLO (m_t^{pole} =173.2 GeV) + PYTHIA 8 for top-quark decay and showering.

Strategy

- get parton-to-offshell level correction
- fold parton level (on-shell) to off-shell level [bin-by-bin factor]
- get a parametrisation $\mathcal{R}$ (m_t^{pole}) at off-shell level
- perform a χ^2 minimisation to get a value of m_t^{pole} from each off-shell level $\mathcal{R}$.

m_t determination at off-shell level

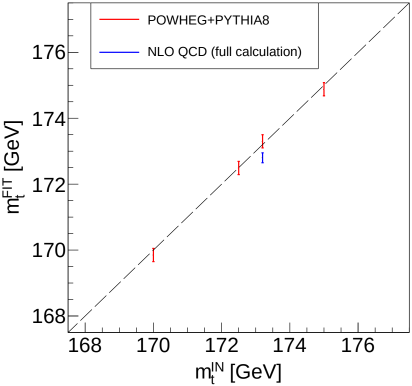


Linearity test shows m_t^{pole} from off-shell level compatible with m_t^{pole} from parton level

m_t^{pole} measurement at parton and off-shell level is equivalent

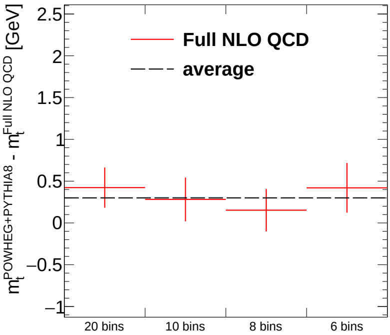
Error bars includes MC stat. $\oplus$ theo. par. unc.

m_t determination at off-shell level



Linearity test shows m_t^{pole} from off-shell level compatible with m_t^{pole} from parton level

Δm (on-shell vs off-shell) computed for different binning choices



m_t^{pole} measurement at parton and off-shell level is equivalent

On average, $\Delta m \sim 300$ MeV is covered so far by theo. unc. reported so far.

Error bars includes MC stat. $\oplus$ theo. par. unc.

Conclusions and outlook

Summary

- m_t is a fundamental parameter which has to be measured experimentally
- It become important to estimate theo. unc. on m_t with 100 MeV precision
- The $\mathcal{R}$ observable has good properties to extract m_t from a data-theo comparison
- ATLAS used $\mathcal{R}$ to obtain most precise m_t^{pole} measurement at 8 TeV

$$m_t^{\text{pole}} \text{ [ATLAS-ttj @8 TeV]} = 171.1\ ^{+1.2}_{-1.1} \text{ GeV}$$

- Results were given also for
  - different mass schemes (pole mass, running mass, . . .)
  - different levels (parton vs particle)

  which could help to improve our QCD understanding in m_t determinations.
- evaluated the impact of off-shell and non-resonant contributions in m_t determinations from $\mathcal{R}$
  - NLO+PS is good in reproducing Full pQCD calculation
  - Difference in m_t^{pole} determinations covered by current MC$\oplus$theo unc.

Back-up

Parton and particle level measurements

$\mathcal{R}$ unfolding to parton level

- assumptions on modelling of top-quark decay, hadronisation, detector response, ...
  (covered by MC modelling uncertainties - often the leading systematics!)
- off-shell and non resonant contributions not considered in ME+PS Monte Carlo
  (usually estimated to be small and covered by MC+theo uncertainties)
- NLO QCD calculations available $\rightarrow$ can perform m_t measurement

$\mathcal{R}$ unfolding to *particle level*

Particle level = {level made of stable particles before detector interaction. No top quark exist here, but only its decay products! $pp \rightarrow W^+W^-b\bar{b}j \rightarrow \ldots$ }

- data corrected for detector effects only in a fiducial volume
  (reduce systematics on observable and minimise assumptions on correction)
- NLO QCD calculations available [JHEP 1803 (2018) 169] for 13 TeV dileptonic final state
  (cannot measure m_t with available $\mathcal{R}$ measurements)
- can include off-shell and non resonant contributions in the calculation

Measuring m_t at both levels is an important check on our understanding of QCD

Particle level $t\bar{t} + 1$-jet system reconstruction

$p_T(\ell) > 25$ GeV	$p_T(j) > 25$ GeV	$\|\eta(\ell)\| < 2.5$ GeV	$\|\eta(j)\| < 2.5$ GeV	$\Delta R(\ell, j) > 0.4$
$p_T(\nu) > 30$ GeV		$m_T^W = \sqrt{2 \cdot p_T(\ell) \cdot p_T(\nu) \cdot [1 - \cos(\phi(\ell) - \phi(\nu))]} > 30$ GeV		

Build the leptonic W boson candidate (W_{lept}) summing the lepton and neutrino four momenta

Hadronic W boson candidates (W^{a}_{had}) are built from all the jet pairs $\{j_l, j_k\}$ which satisfies

$$0.9 < \frac{m_W^{\text{PDG}}}{\sqrt{(p_{j_l} + p_{j_k})^2}} < 1.25$$

$$\min\{p_T(j_l), p_T(j_k)\} \cdot \Delta R(j_l, j_k) < 90 \text{ GeV}$$

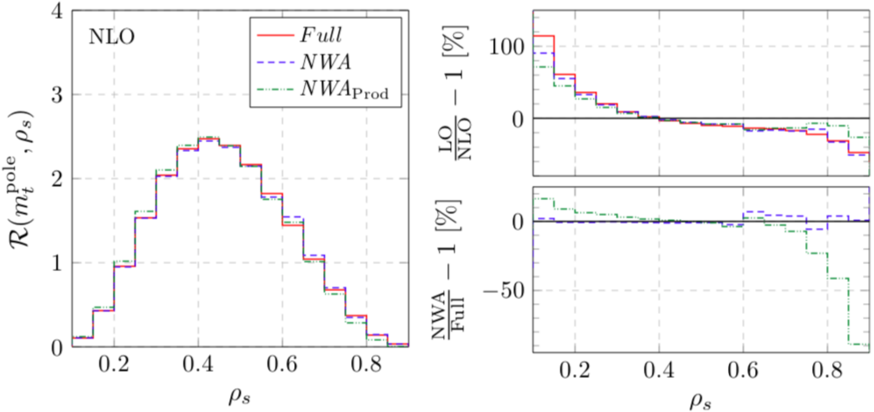
Construct hadronic and semileptonic top-quark candidates t^{l}_{had} and t^{k}_{had} from all the pairings of j_{b1} and j_{b2} with W_{lept} and all the W^{a}_{had}

Choose the combination $\{t_{\text{had}}, t_{\text{lep}}\}$ which minimises $\frac{|m(t^{k}_{\text{had}}) - m(t^{l}_{\text{lep}})|}{m(t^{k}_{\text{had}}) + m(t^{l}_{\text{lep}})}$ and require $\frac{m(t_{\text{lep}})}{m(t^{l}_{\text{had}})} > 0.9$

Between the jets not used in top-quarks reconstruction, take the leading p_T one and require $p_T^{\text{extrajet}} > 50$ GeV.

Off-shell level pQCD calculations

calculations reported in [JHEP 1803 (2018) 169]



- Full (all contributions included)
- NWA (no off-shell contributions included)
- NWAprod (no off-shell and no NLO in top decay)

Off-shell level fiducial volume

Off-shell level volume definition in [JHEP 1803 (2018) 169]

- l stands for lepton
- j stands for *every* jet
- $p_T^{\text{miss}} = (p_{\nu_e} + p_{\nu_\mu})_T$

$$p_T(\ell) > 30 \text{ GeV}\,, \qquad p_T(j) > 40 \text{ GeV}\,,$$
$$p_T^{miss} > 40 \text{ GeV}\,, \qquad \Delta R_{jj} > 0.5\,,$$
$$\Delta R_{\ell\ell} > 0.4\,, \qquad \Delta R_{\ell j} > 0.4\,,$$
$$|y_\ell| < 2.5\,, \qquad |y_j| < 2.5\,,$$

Off-shell level possible calculations

NAME	Initial State	Calculation			Final State
NLOprod	pp	$\xrightarrow{NLO}$	$t\bar{t}j$	$\xrightarrow{LO}$	$e\mu b\bar{b}\nu_e\nu_\mu j$
NLO	pp	$\xrightarrow{NLO}$	$t\bar{t}j$	$\xrightarrow{NLO}$	$e\mu b\bar{b}\nu_e\nu_\mu j$
Full	pp		$\xrightarrow{NLO}$		$e\mu b\bar{b}\nu_e\nu_\mu j$
PP8	pp	$\xrightarrow{POWHEG}$	$t\bar{t}j$	$\xrightarrow{PYTHIA}$	$e\mu b\bar{b}\nu_e\nu_\mu j$

On the theoretical uncertainty of m_t

Depending on the definition of the mass scheme used, the theoretical uncertainty associated to m_t can be difficult to evaluate.

example for *direct measurments*

Experiments report stat and syst uncert, but do not report pure theoretical unc.

In global EW fits, ± 0.5 GeV are added to the m_t^{MC} uncertainty to cover effects spoiling its identification with m_t^{pole}.

Wide ongoing discussion... some refs

G. Corcella arXiv: 1903.06574
M. Buttenschon etal. PRL117(2016)232001
S. Moch at al., arXiv 1405.4781
A. Juste et al., EPJC 74 (2014) 3119
P. Nason, arXiv:1712.02796
A. H. Hoang et al., arXiv:1412.3649

Pole mass and $\overline{MS}$ schemes allow to evaluate theoretical uncertainty from missing higher orders in the pQCD calculation

m_t^{pole} is well-defined up to the level of "renormalons" (non-perturbative corrections powers of α_s): (interpretation uncertainty $\lesssim 200 MeV$ much smaller than actual experimental uncertainties on m_t^{pole} and also covered by theo. unc. associated to missing higher orders and PDFs choice)

Uncertainty due to renormalons

Recent article from Nason et al. [1810.10931] claims renormalons effects are present when fiducial cuts are applied.
(non inclusive quantities, and they also affect the $\overline{MS}$ scheme)
Observables computed with or without renormalons contributions are corrected by few percent (tables 3-6 in Nason's article). In particular, the example of reconstructed top-quark mass is given.

What would the impact be on the $\mathcal{R}$ observable?

Suppose the reconstructed $m_{t\bar{t}+1\text{-jet}}$ is miscalculated due to renormalons effects.
From [1810.10931], the size of such uncertainties is of the $\sim$1 GeV order at NLO.
The ρ_s distribution would then be affected by $\lesssim 1\text{GeV}/(2m_t) \sim 0.5\%$
(smaller than JES for instance...)