Top-quark pole mass from tt+j events ATLAS overview

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Top Mass Workshop
Desy, 30th January 2025

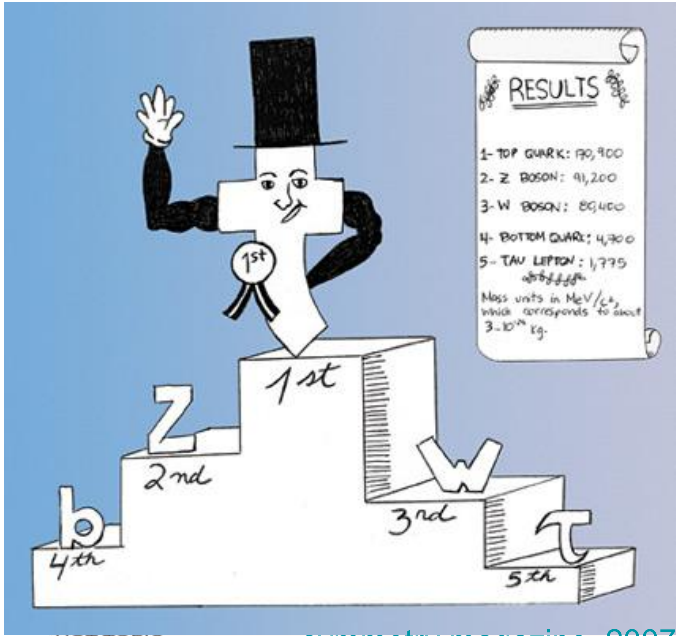
Introduction

Two mtop from ttj analyses in ATLAS :

- **dileptonic** channel
  - more advanced and close to ATLAS circulation
- **semileptonic** channel
  - slightly behind

Analysis team:

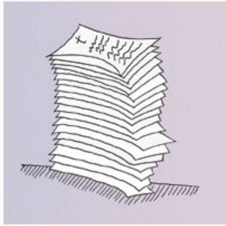
- Luis Monsonis Romero (Valencia, PhD on dilep ttj mtop)
- Alberto Prades Ibanez (Rome, PhD on semilep ttj mtop)
- Andrej Saibel (Valencia-just left)
- Davide Melini (Valencia)
- Marcel Vos (Valencia)
- Juan Fuster Verdu (Valencia)



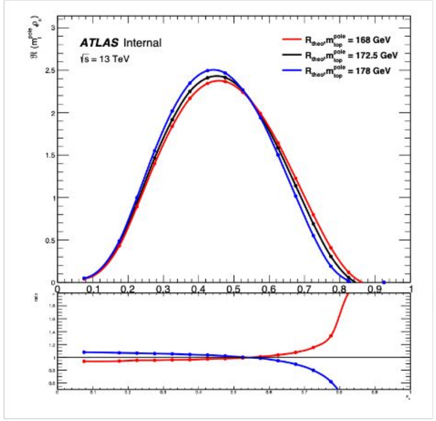
symmetry magazine, 2007

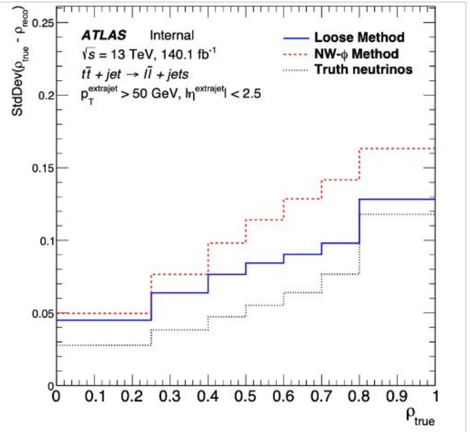
HOT TOPIC

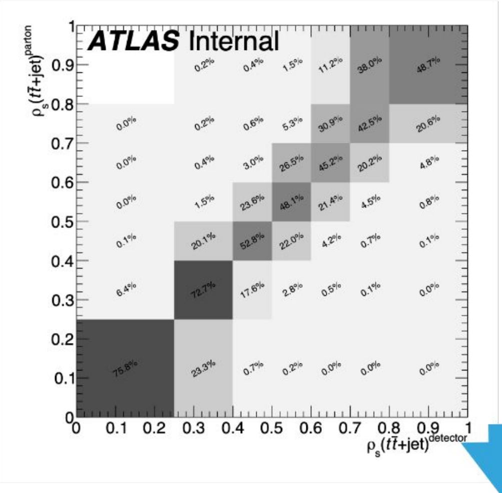
Since 1977, when the search for it began, the top quark has been the subject of more than 8000 scientific papers. The particle physics community still publishes about 300 papers a year related to the top–an indication of continued interest in the particle. More than 250 graduate students have received PhDs for related research.



Introduction - analysis in one slide



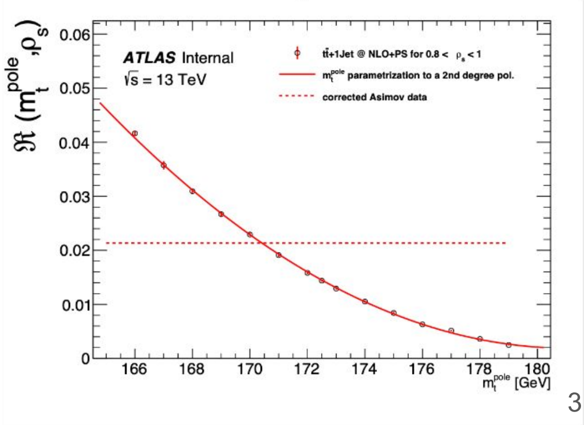




Use normalised observable R∝1/m(ttbar+1jet) to get mTop

Steps:

- select events and reconstruct ttbar+1jet system
- unfold to a defined theory/truth level
- get top-quark pole mass from a χ^2-fit to fixed-order NLO QCD prediction



Analysis - event selection dileptonic

Select di-leptonic ttbar events produced in association with at least an additional jet.

Two steps: standard di-leptonic ttbar cuts + dedicated tt+1jet system reconstruction.

Pre-selection kinematic cuts:

- single-lep trigger, two opposite sign leptons
- >=3jets (2 b-tagged)
- m(ll)>15GeV
- m(lb)<200GeV
- avoid angular overlap of selected objects

Table 4: Event yields after the basic selection are shown.

$\int \mathcal{L}$ = 140.1 fb^{-1}	$e^{\pm}\mu^{\mp}$
$t\bar{t}$	204327.0
Single Top	5813.3
Diboson	169.6
Z + jets	161.2
$t\bar{t}$ V+$t\bar{t}$ H	894.5
fake lepton	1495.7
Total MC	212861.0
Data	208043.0
MC/Data	1.023

Analysis - event selection semileptonic

Select semi-leptonic ttbar events produced in association with at least an additional jet.

Two steps: standard semi-leptonic ttbar cuts + dedicated tt+1jet system reconstruction.

Pre-selection kinematic cuts:

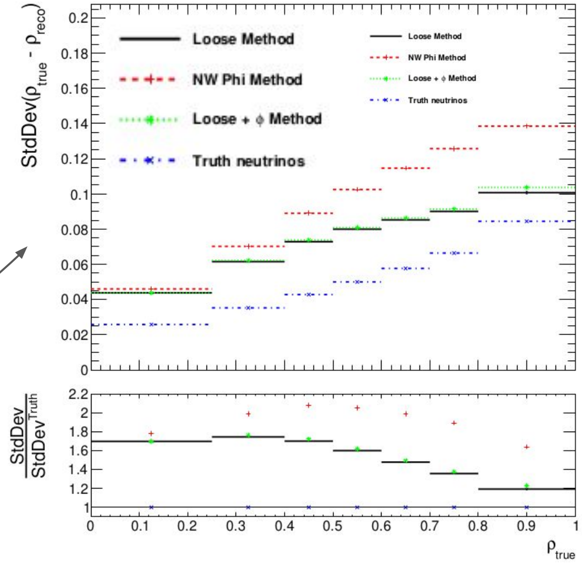
Event Preselection

Leptons	N_ℓ $(\ell = e^\pm/\mu^\pm) = 1$	$p_T^\ell > 25$ GeV	(2015)
		$p_T^\ell > 27$ GeV	(2016, 2017, 2018)
Jets	$N_{\text{jet}} \geq 4$	$p_T^{\text{jet}} > 25$ GeV	
	$N_{b\text{-jet}} \geq 1$		(70% eff. WP DL1r b-tagger)
Missing Transverse Energy	$E_T^{\text{miss}} > 30$ GeV	$m_T^W > 30$ GeV	(Same for e and μ channels)

	Preselection e+jets	Preselection μ+jets
$t\bar{t}$	2947425 (84.7%)	3036326 (84.8%)
Single Top	175610 (5.1%)	178783 (5.0%)
W+jets	233554 (6.7%)	273988 (7.6%)
Z+jets	54928 (1.6%)	41271 (1.2%)
Diboson+$t\bar{t}X$	22565 (0.6%)	23229.9 (0.6%)
Fake leptons	45540.2 (1.3%)	29079.3 (0.8%)
Total pred.	3479622.2	3582677.2
Data	3437242	3501047
Data/Prediction	0.99	0.98

Analysis - ttbar+1jet event selection dilep

Dedicated ttbar+1jet selection cuts:



- use a combination of “Loose” and “ϕ-weighting” neutrino reconstruction method -> 98% reco eff.
  - “Loose”: ttbar system is reconstructed as a whole (no separate reconstruction of each of the top). Efficiency at ~74%, down to 55-60% for ϱ_s>0.7 .
  - “ϕ-weighting” used to recover events rejected by “Loose”
  - good resolution of the observable
- extrajet selected after ttbar reconstruction, with pT>50GeV for 2->3 analysis
  - match cuts used in theoretical predictions

Analysis - ttbar+1jet dilep event selection

Selection efficiency vs pileupMu, in the ϱ_s>0.7 region

"Loose" only

MC ttbar

$\tilde{\mu}$ region	Percentage of events [%]
$20 > \tilde{\mu} > 0$	5.04
$30 > \tilde{\mu} > 20$	4.92
$40 > \tilde{\mu} > 30$	4.81
$50 > \tilde{\mu} > 40$	4.65
$90 > \tilde{\mu} > 50$	4.53

10% drop

Data

$\tilde{\mu}$ region	Percentage of events [%]
$20 > \tilde{\mu} > 0$	4.94
$30 > \tilde{\mu} > 20$	5.03
$40 > \tilde{\mu} > 30$	5.02
$50 > \tilde{\mu} > 40$	4.96
$90 > \tilde{\mu} > 50$	4.84

~ no drop

"Loose" + "Phi"

MC ttbar

$\tilde{\mu}$ region	Percentage of events [%]
$20 > \tilde{\mu} > 0$	7.68
$30 > \tilde{\mu} > 20$	7.58
$40 > \tilde{\mu} > 30$	7.37
$50 > \tilde{\mu} > 40$	7.08
$90 > \tilde{\mu} > 50$	6.92

10% drop

Data

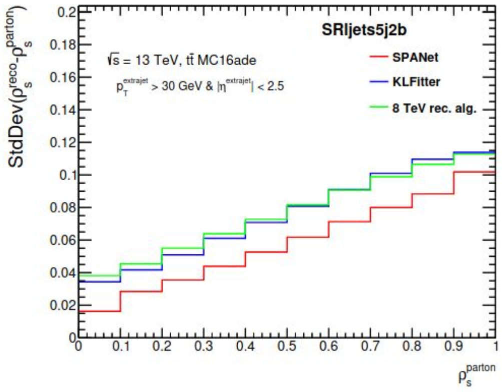
$\tilde{\mu}$ region	Percentage of events [%]
$20 > \tilde{\mu} > 0$	7.62
$30 > \tilde{\mu} > 20$	7.71
$40 > \tilde{\mu} > 30$	7.59
$50 > \tilde{\mu} > 40$	7.24
$90 > \tilde{\mu} > 50$	6.96

10% drop

The data/MC behaviour with the "Loose+Phi" reconstruction is in better agreement.
The events recovered by the "Phi" method ~double the stat in most sensitive bins

Analysis - ttbar+1jet event selection <u>semilep</u>

Dedicated ttbar/ttbar+1jet selection cuts:



- use SpaNet to reconstruct ttbar events
  - best possible reconstruction resolution of ttbar system
  - give probabilities of something being a top,jet,W,..
- defined multiple regions (ttbar, ttbar+1jet, not-so-likely-ttbar, …) to be used as signal/control regions in a profile likelihood fit

Final Event Selection

Signal Regions (ρ_s)	$N_{jet} \geq 5$		t^{had} detec. prob. > 0.5
	$N_{b\text{-}jet} = 1,\ 2$		t^{lep} detec. prob. > 0.5
	$p_T^{extrajet} > 30$ GeV	$\lvert\eta^{extrajet}\rvert < 2.5$	extrajet detec. prob. > -1
Control Regions (M_{lb})	$N_{jet} = 4$		t^{lep} detec. prob. > 0.5
	$N_{b\text{-}jet} = 1,\ 2$		t^{lep} assign. prob. > -0.5
	20 GeV $< M_{lb} <$ 160 GeV		
Control Region (m_W^{had})	$N_{jet} = 4$		t^{had} detec. prob. > 0.5
	$N_{b\text{-}jet} = 2$		t^{lep} detec. prob. < 0.5
			OR
	50 GeV $< m_{W^{had}} <$ 110 GeV		t^{lep} assign. prob. < -0.5

Analysis - ttbar+1jet event selection semilep

Dedicated ttbar/ttbar+1jet selection cuts:

Region	leptons	n_{jets}	$n_{b-\text{tagged}}$	Variable	Motivation
SRljets5j2b	$e^{\pm}$ or $\mu^{\pm}$	≥ 5	2	ρ_s	Unfold to parton level
SRljets5j1b	$e^{\pm}$ or $\mu^{\pm}$	≥ 5	1	ρ_s	Unfold to parton level
CRljets4j2b	$e^{\pm}$ or $\mu^{\pm}$	4	2	M_{lb}	Sensitive m_t^{MC}
CRljets4j1b	$e^{\pm}$ or $\mu^{\pm}$	4	1	M_{lb}	Sensitive m_t^{MC}
CRljets4j2b inv.	$e^{\pm}$ or $\mu^{\pm}$	4	2	m_W^{had}	Sensitive to jet syst. unc.

Unfolding - dileptonic

Data is corrected to truth level with IterativeBayesianUnfolding (**IBU**) algorithm

$$\frac{\mathrm{d}\sigma_{t\bar{t}+1\text{-jet}}}{\mathrm{d}\rho_s}(\rho_s)^{\text{parton}}_{\text{data}} = \mathcal{M}^{unf} \otimes [\frac{\mathrm{d}\sigma_{t\bar{t}+1\text{-jet}}}{\mathrm{d}\rho_s}(\rho_s)^{\text{det}}_{\text{data}} \cdot f^{\text{acc}}] \cdot f^{\text{eff}^{-1}},$$

Unfolding consists in various steps:

- subtract background from data
- define unfolding from **one** MC simulation (algorithm parameters and correction factors)
- perform unfolding on un-normalised distributions with stat-only uncertainties
- get stat-only covariance matrix for no-normalised spectrum (done by IBU via toys)
- systematic effects are added via a systematic covariance matrix
    - built from unfolded systematic-shifted MC simulations, keeping unfolding correction fixed.

Normalization of distributions & covariance matrix happens on a second stage:

- the unfolded un-normalised distributions are normalised
- the cov mat is normalised with Cholesky decomposition and toys
    - N.B: syst effects are added to the cov mat before normalization

Unfolding validation - Linearity tests and #IBUiterations

The bias due to the assumed MC truth distribution in the unfolding is best described by the out-vs-in top MCmass (linearity tests) , where unfolded MC is fit to a MC-template

“Iterative” unfolding:

progressively move away from bias due to choice of MC in unfolding

increasing number of unfolding iterations reduce bias on MCmass

In the end small bias (~100MeV) on input MC mass choice observed. Added unc

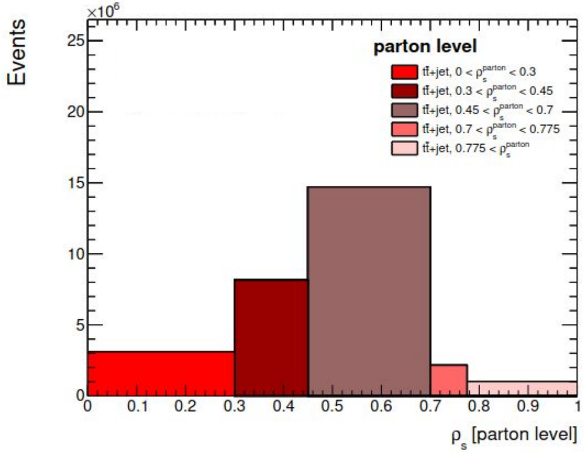
Unfolding - semileptonic

Data is unfolded to truth level with ProfileLikelihoodUnfolding (**PLU**) algorithm

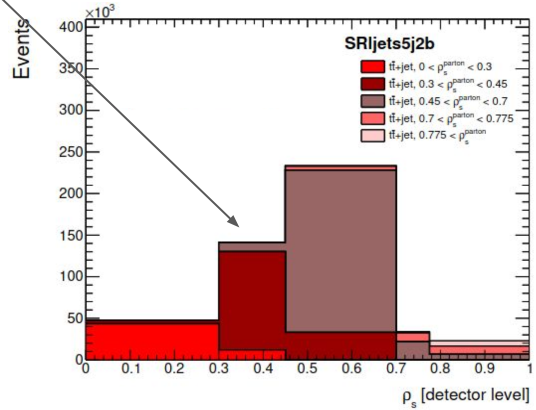
$$\underbrace{\nu_i(\vec{\mu}_{t\bar{t}+\text{jet}}, \mu_{t\bar{t}+0\text{jet}}, m_t^{\text{MC}}, \vec{w}, \vec{\theta})}_{\text{Data}} = \sum_{k=1}^{n_{\text{bins}}} \underbrace{S_i^k(\mu^k_{t\bar{t}+\text{jet}}, m_t^{\text{MC}}, \vec{\theta})}_{\text{tt+1jet}} + \underbrace{B_i^{t\bar{t}+0\text{jet}}(\mu_{t\bar{t}+0\text{jet}}, m_t^{\text{MC}}, \vec{\theta})}_{\text{tt+0jet}} + \underbrace{\sum_j B_i^j(w_j, m_t^{\text{MC}}, \vec{\theta})}_{\text{other bkgs}}.$$

Unfolding consists in various steps, mostly the same steps as dileptonic. But:

- normalization of ttj out of the box (1bin defined in terms of others, Nbins-1 POI)

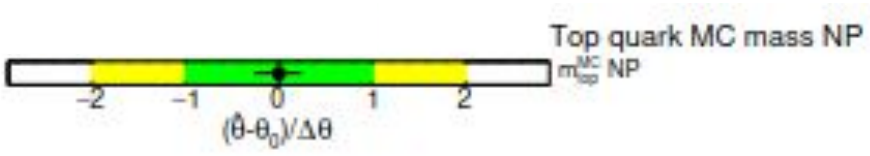


tt+1jet truth bins mixing due to folding



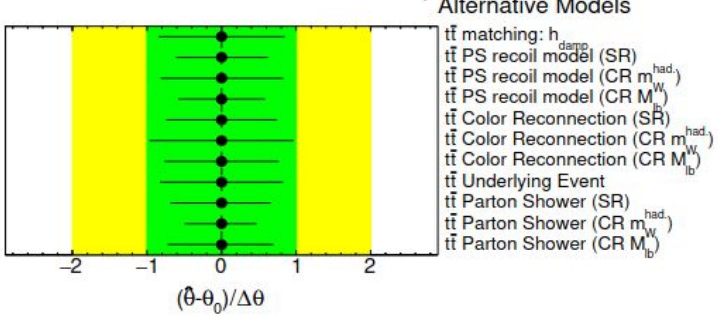
Unfolding validation - Linearity tests and PLU “mMC” param

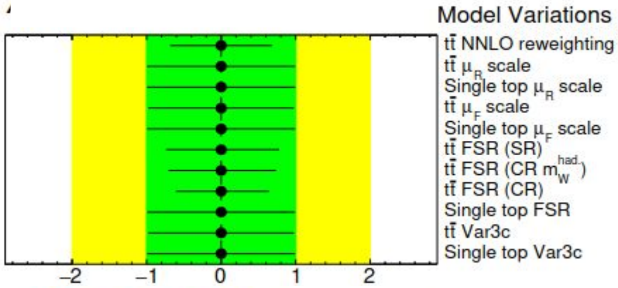
In the PLU fit, added a free parameter for mMC.
This helps linearity test, but it can be constrained and is correlations to POI have to be taken into account in final fit. This gives a mMC measurement.

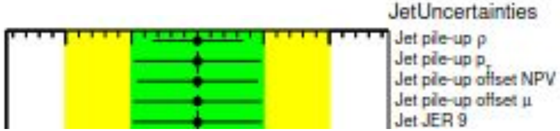


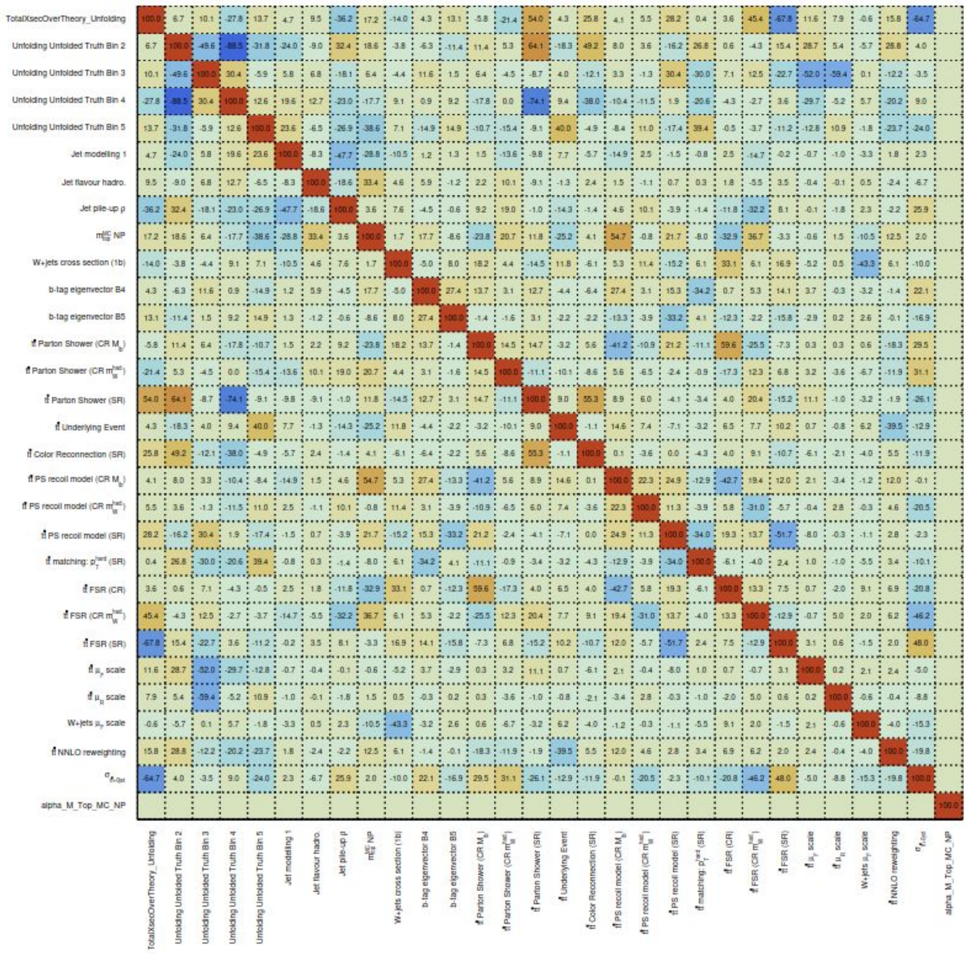
Small bias (~50MeV) on input mass observed, strong constraint in mMC parameter

PLU unfolding results









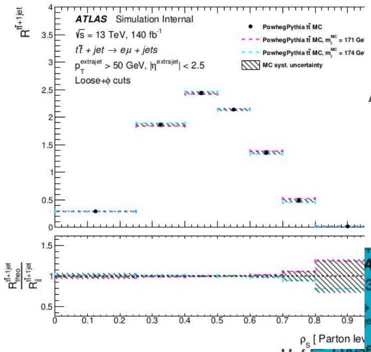
MC modelling systematic NP pulls de-correlated across SR/CR regions to minimize constraints

correlation matrix among the NPs

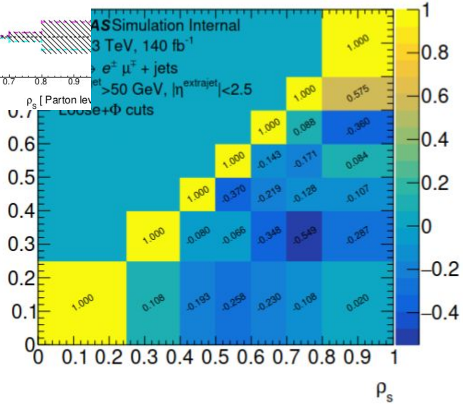
Fit - chi2 and bin removal

mTop value and uncertainty extracted minimizing

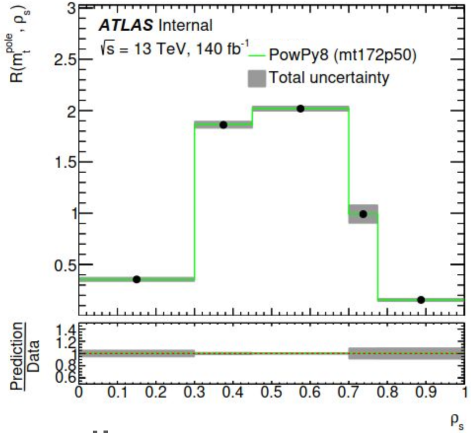
$$\chi^2 = \sum_{i,j} \left[\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{data}} - \mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{theo@NLO}}(m_t^{\text{pole}}) \right]_i \left[V^{-1}\right]_{ij} \left[\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{data}} - \mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{theo@NLO}}(m_t^{\text{pole}}) \right]_j$$



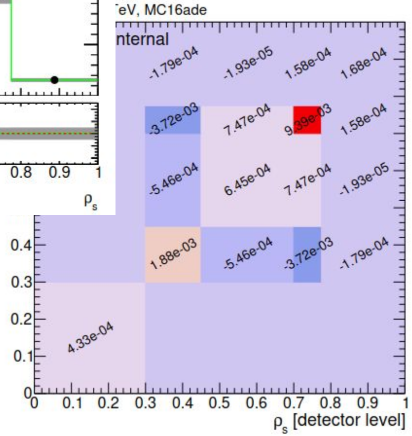
Asimov unfolded
+ correlation mat



dilep experimental unc
~1.3 GeV

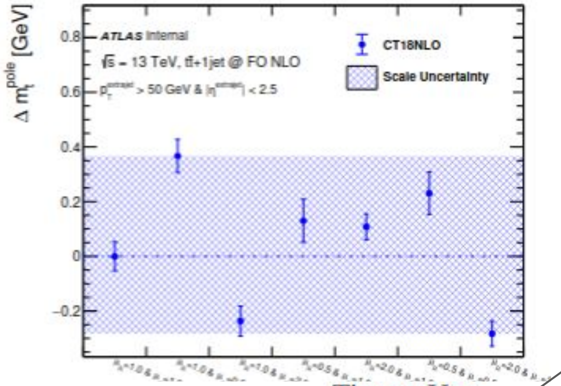


Asimov unfolded
+ inverted cov mat

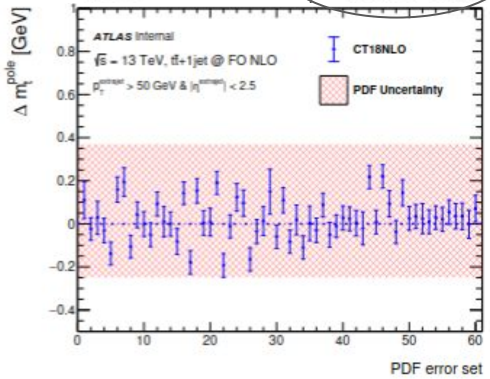


semilep experimental unc
~1.1 GeV

Theory uncertainties - scale and PDF

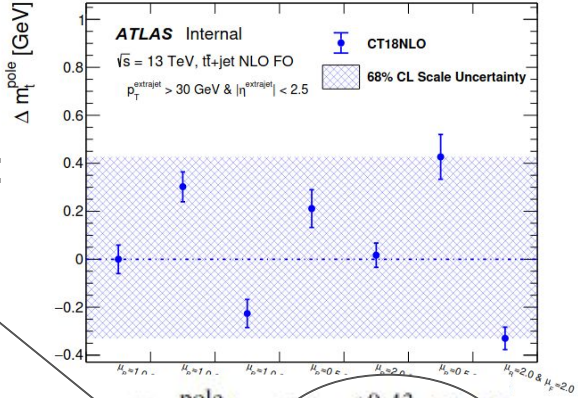


	Theory Unc.
Scale variations	+0.37 -0.28
PDF	+0.38 -0.24



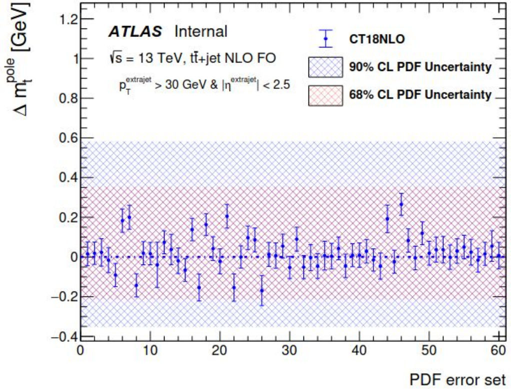
Same theoretical uncertainties:

- binning different in the two analyses
  - but most sensitive bin was ~same [0.8;1]
- different extrajet pT cut applied in the two analyses (50-vs-30)



$$\Delta m_t^{\text{pole}}(\text{scale}) = ^{+0.43}_{-0.31}\ \text{GeV}$$

$$\Delta m_t^{\text{pole}}(\text{PDF} + \alpha_S) = ^{+0.34}_{-0.21}\ \text{GeV}$$



Threshold effects in tt+1jet

What we do to estimate Coulomb correction exists for tt+1jet calculation:

- enhancement of ttbar xsec up to 20% in 340<Mttbar/Gev<355 region
- presence of extrajet dilute the effect

Impact on measurement evaluated by enhancing ttbar threshold region contribution by 10 & 20%.

Impact on mTop extraction <~200MeV.

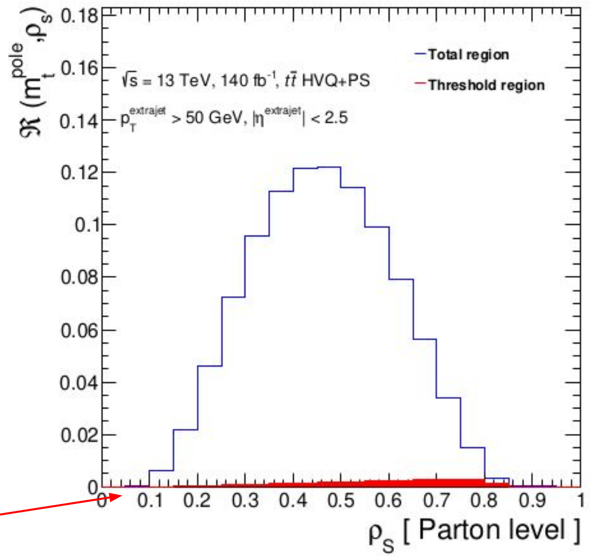


Figure 28: The normalized differential cross section $\mathcal{R}(m_t^{pole}, \rho_s)$ from the nominal MC sample at the parton level. All events passing the $p_T^{extrajet} > 50$ GeV selection are shown in blue while the contribution of events with parton-level top quark pair invariant mass satisfying 340 GeV $< M_{t\bar{t}} <$ 355 GeV is shown in red.

No dedicated uncertainty assigned, as no consensus on the theory side on Coulomb corrections in tt+1jet

- when theory will be available, re-fit of data possible with HEPdata info
- impact of Coulomb is so far covered by theoretical uncertainties (even if those account for different effects)

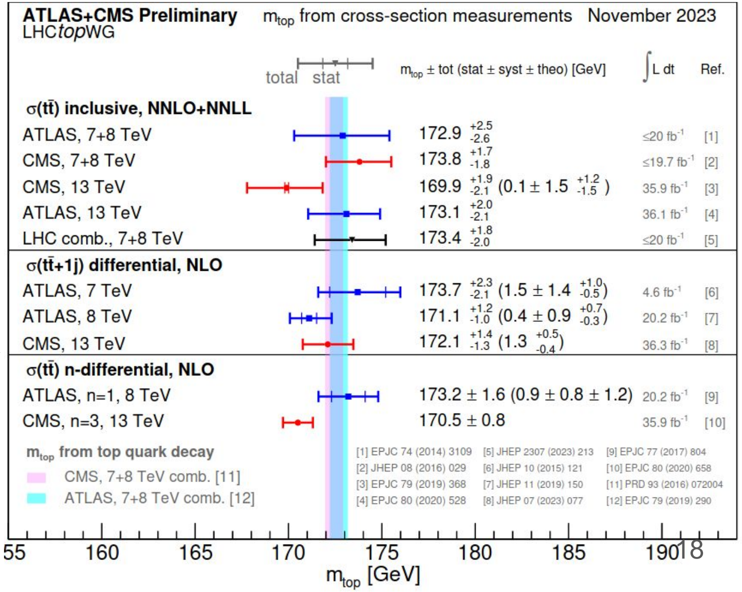
Conclusions

Measurements of top-quark pole mass in tt+1jet topologies undergoing in ATLAS:

- di-leptonic final state, with iterative unfolding
- semi-leptonic final state, with profile likelihood unfolding

News :

- new experimental systematics treatment (cov matrices) in dileptonic analysis
  - should ease future combinations
  - re-interpreted 8TeV result with this approach, new cov mats available for potential combinations
- new (for ATLAS) approach in the semi-leptonic analysis
  - same format as CMS
  - for straightforward (?!) combination



Expect total uncertainties around 1-1.4 GeV

- competitive with other pole mass analyses

Back-up

Background contribution in each bin

- Most important background contributions? What is the contribution of single-top processes?
- the most important background is **tW** total event yield **1.7% (2->3).**
  - Table shows tW contribution in each bin of Rho
  - **s- and t-channel** single-top production taken into account in the **fake-lepton and non-prompt** contribution
    - Total less than 0.05% total event yield
  - **WW** contributes with **less than 0.05%** to the total event yield in the final selection. Therefore not part of MC signal definition in 2->7.

Table 11: The percentage of single top events in each bin of ρ_s

ρ_s region	Percentage of single top events [%]
$0.25 > \rho_s > 0.00$	1.52
$0.40 > \rho_s > 0.25$	1.80
$0.50 > \rho_s > 0.40$	1.96
$0.60 > \rho_s > 0.50$	1.76
$0.70 > \rho_s > 0.60$	1.52
$0.80 > \rho_s > 0.70$	1.36
$1.00 > \rho_s > 0.80$	1.43

- **2->7 largest backgrounds**:
  - Fake leptons:
    - 0.7% of total event yield
  - ttV+ttH:
    - 0.6% of total event yield

Neutrino momenta reconstruction method

A combination of "Loose" and "ϕ-weighting" neutrino reconstruction method is used -> 98% reco eff.

- "Loose": the ttbar system is reconstructed as a whole (no separate reconstruction of each of the top), requiring pT($\nu\nu$)=E_T^{miss}, pL($\nu\nu$)=pL(ll) . Reject un-physical solutions with $m(W^+W^-) < 2m_W$ and $m(\nu\nu) < 0$. Efficiency at ~74%, down to 55-60% for ϱ_s>0.7 .

- "ϕ-weighting" used for rejected solutions of "Loose": throw random values to neutrino azimuthal angle and reconstruct neutrino 4-momenta and top-quarks with all possible objects pairings. Take the solution which minimize difference in reco top-quark masses.

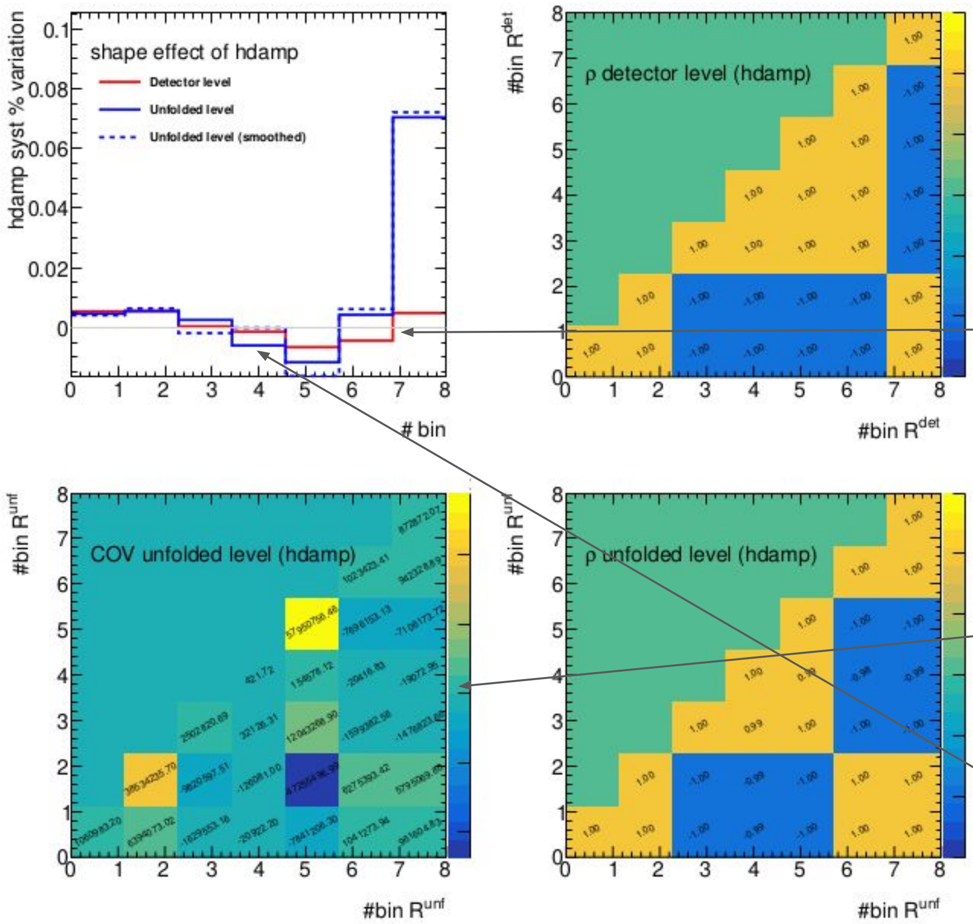
parton ρ_s region	Percentage of events [%]
$0.25 > \rho_s > 0.00$	98.64
$0.40 > \rho_s > 0.25$	98.59
$0.50 > \rho_s > 0.40$	98.31
$0.60 > \rho_s > 0.50$	97.96
$0.70 > \rho_s > 0.60$	97.62
$0.80 > \rho_s > 0.70$	97.17
$1.00 > \rho_s > 0.80$	96.68
$1.00 > \rho_s > 0.00$	98.22

The year dependence

The loose+phi reconstruction:

- reduces the impact of lowpT jets in the high ρ_s/low m_{ttj} region by diluting those with other higher jet pT events
  - the high rho_s region must be populated with other lowpT objects -> lowpT leptons!
  - recover events discarded by loose reco method with the phi reco method
    - mostly lowpT leptons contributing to high ρ_s
    - resolution of observable ~unchanged
    - get back 25% of events, getting to 98% reconstruction efficiency

Unfolding - example of systematic covariance matrix



A visual example, for the hdamp MC modelling systematics in the 2->3 measurement

The systematic effect at detector level, is taken as fully correlated across bins (+1 if positive shift)

Generating&unfolding toys, one can get the covariance due to syst effect at unfolded level. Correlations at unfolded level can be inferred by looking at sign of unfolded-level syst shift