Top-quark pole mass from pp-> l l nu nu b b j events

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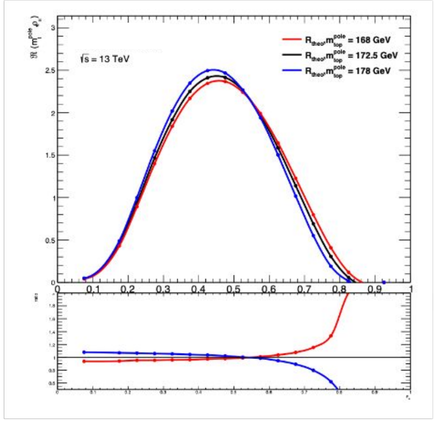
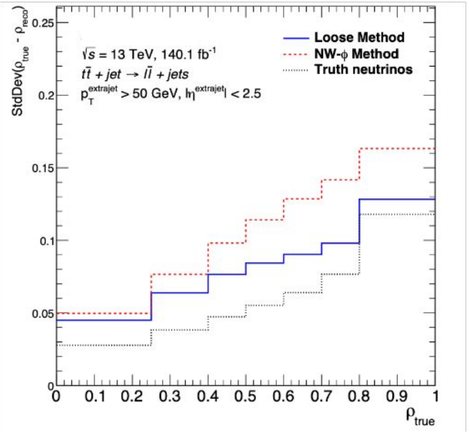
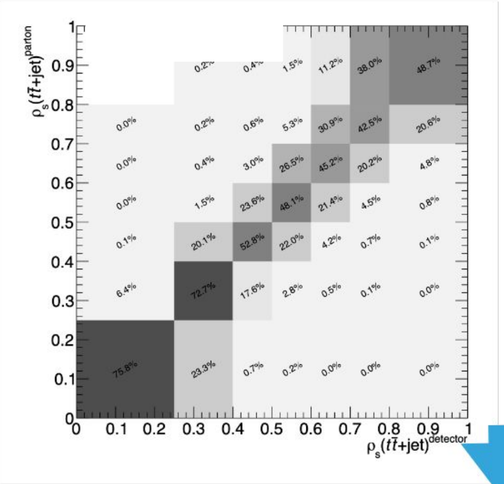
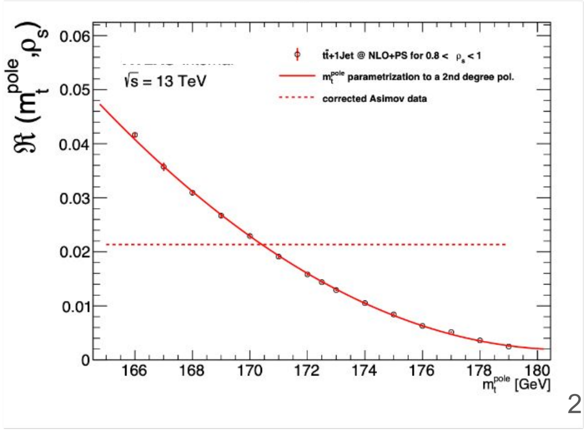
Top Mass Workshop
Desy, 29th January 2024

Introduction









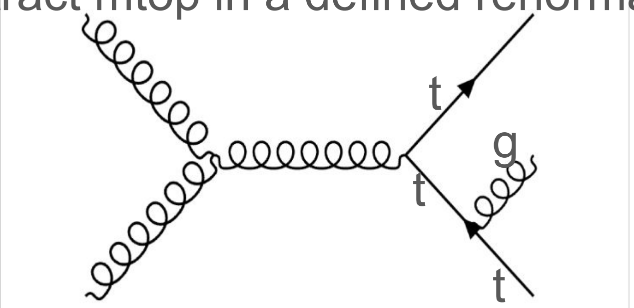
Normalised differential cross-section of tt+1jet events found to be powerful to measure mTop.

Usual steps to perform the measurement:

- **define observable** $\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \cdot \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}$, $\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$,
- **select events** and reconstruct “ttbar+1jet” system at detector level
- **unfold** (i.e. correct for some effects) to a defined theory/truth level
- get mass from a χ^2-**fit** to theory

Introduction - theory predictions available

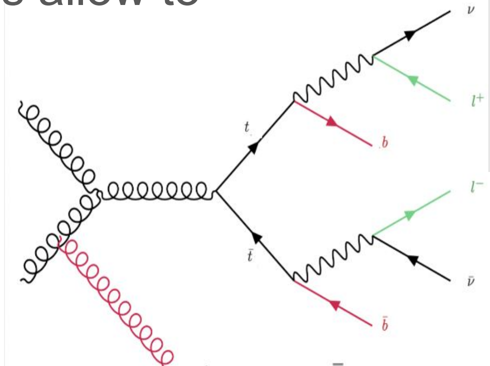
Comparison to fixed order (>)NLO QCD predictions allow to extract mtop in a defined renormalization scheme

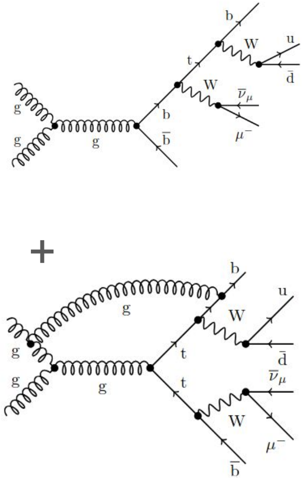


▸ **Fixed-Order NLO QCD** $t\bar{t} + 1$-jet

- provided by “ttbarj” in Powheg-Box-v2 [1110.5251]
- 2->3 process, top-quarks are “stable”
- scale choices and other parameters studied (for 13 TeV)in [2202.07975]

$$\frac{E_T}{2}: E_T = \sum_{i=1}^{3} \sqrt{p_{T,i}^2 + m_i^2}$$





▸ **FO NLO QCD** $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$

- provided by authors of [1509.09242]
- scale choices suggested

$$\text{Scale } \frac{H_T}{2}: \quad H_T = p_{T,e^+} + p_{T,\mu^-} + p_{T,b_1} + p_{T,b_2} + p_{T,j} + p_T^{\text{miss}}$$

- 2->7 process, diagrams with no tops, single-top, off-shell top-quarks included. Full off-shell effects also included.

Advantages/disadvantages

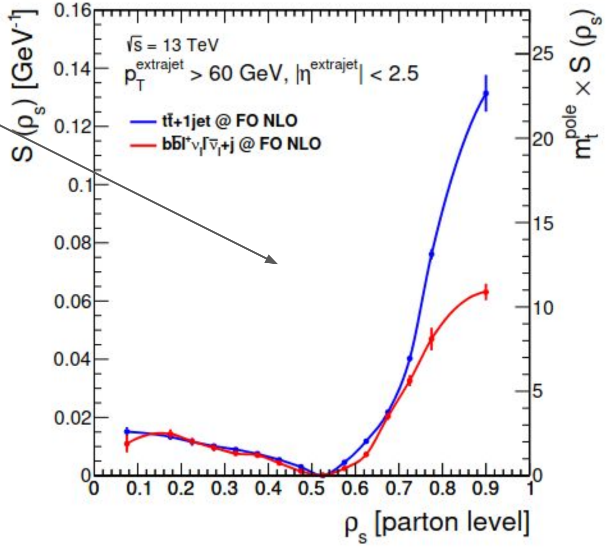
$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \cdot \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s},$$

Comparison of the 2->3 and 2->7 approaches:

- 3-objects system or 7-objects system used in the definition of ρ_s

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}},$$ m_0 fixed to 170 GeV

- sensitivity to top-quark mass is higher for 2->3 prediction
    - the same %unc at the observable level translates in a larger unc on extracted mass for the 2->7 compared to the 2->3
    - most sensitive region is for ϱ_s>0.7
- 2->7 in principle require "less" unfolding:
    - no need to correct for top-quark decay effects, the 2->7 level is closer to detector-level objects
    - in practice (so far) unfolding found to be similar:
        - strong cuts are applied at detector level which cannot be applied at truth level
    - unfolding is usually MonteCarlo-based
        - need a simulation to the detector level
        - need to match the definition of the theory levels by an adequate truth MC definition



Unfolding - definition of truth levels in MC

Truth level definition for 2->3 process

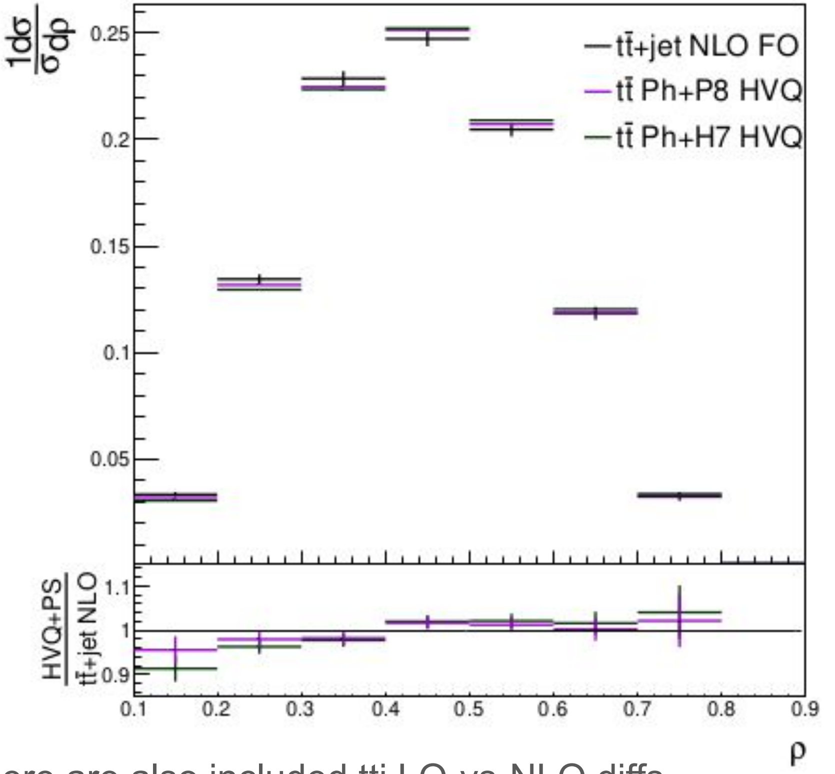
- **Last top quarks before decay after ISR/FSR (daughter not top quark)**
- Hardest additional jet in $|\eta| < 2.5$:
  - anti-k_T $R = 0.4$ on last particles **before hadronization after ISR/FSR**
    - **Pythia 8: status 62**
    - **Herwig 7: MC gen. chain** (daughter particle is hadron)
  - Top-quark decay products removed

Truth level definition for 2->7 process

- $t\bar{t} + tW$ **Ph+Py8 MC stack**:
  - **Parton jets**: Last particles before hadronization, as above
  - Clustering anti-k_T $R = 0.4$:
    - b-jets matched to b-quarks, $\Delta R < 0.4$
  - $\mathscr{R}$: Two b-jets, two leptons and neutrinos from W (no taus), one additional jet
    - Require $\Delta R > 0.4$ between all objects (same as theory calculation)
    - Same p_T cuts as the reco-distribution

Unfolding - definition of truth levels in MC

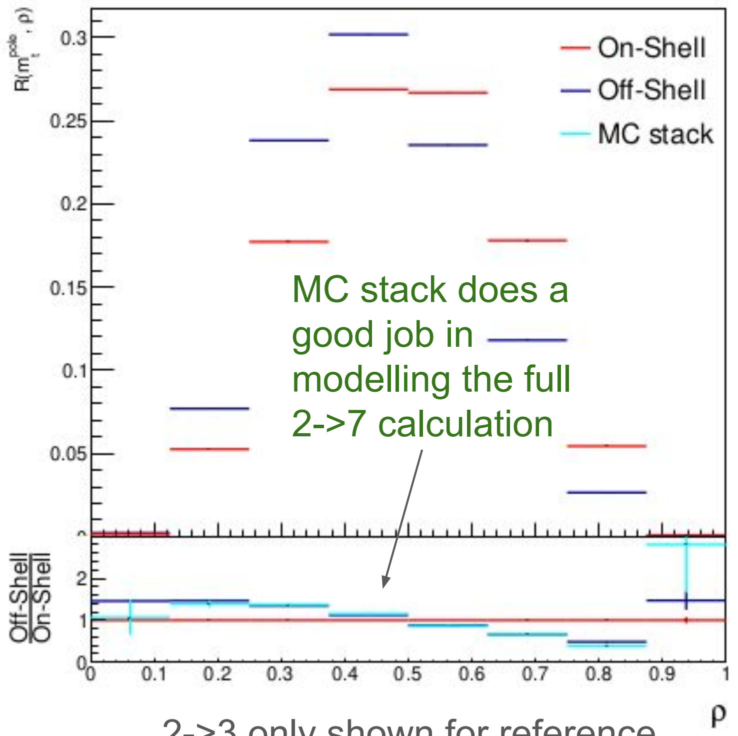
Truth level definition for 2->3 process



here are also included ttj LO-vs-NLO diffs.

Truth level definition for 2->7 process

- $t\bar{t} + tW$ **Ph+Py8 MC stack**:



2->3 only shown for reference

Unfolding - correction factors 1

Bkg-subtracted data (no tW subtracted for 2->7 case) is corrected with bin-by-bin factor for events not passing truth-level cuts, but reconstructed at detector level

$$f_i^{\mathrm{acc}} = \frac{\frac{\mathrm{d}\sigma_{t\bar{t}+1\text{-jet}}}{\mathrm{d}\rho_s}(\text{detector + parton phase space})_i^{\mathrm{MC,det}}}{\frac{\mathrm{d}\sigma_{t\bar{t}+1\text{-jet}}}{\mathrm{d}\rho_s}(\text{detector phase space})_i^{\mathrm{MC,det}}}.$$

- Larger correction for 2->7 truth level, as it has less inclusive cuts

Unfolding - correction factors 2

The IBU unfolding algorithm is given a response matrix to handle the bin migrations from detector to truth level.

Similar migrations for the two truth level definitions.

2->3 migration matrix

2->7 migration matrix

Unfolding - correction factors 3

The unfolded distribution is corrected with a bin-by-bin factor for events passing truth level cuts, but not surviving the detector-level selection

$$f_i^{\text{eff}} = \frac{\frac{\mathrm{d}\sigma_{t\bar{t}+1\text{-jet}}}{\mathrm{d}\rho_s}(\text{detector} + \text{parton phase space})_i^{\text{MC}}}{\frac{\mathrm{d}\sigma_{t\bar{t}+1\text{-jet}}}{\mathrm{d}\rho_s}(\text{parton phase space})_i^{\text{MC}}}.$$

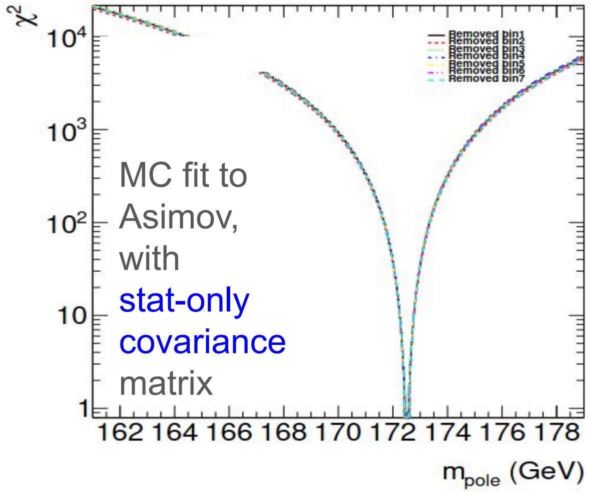
Smaller extrapolation needed for 2->7 truth level, as its fiducial phase space definition is closer to the detector level one (#objects,)

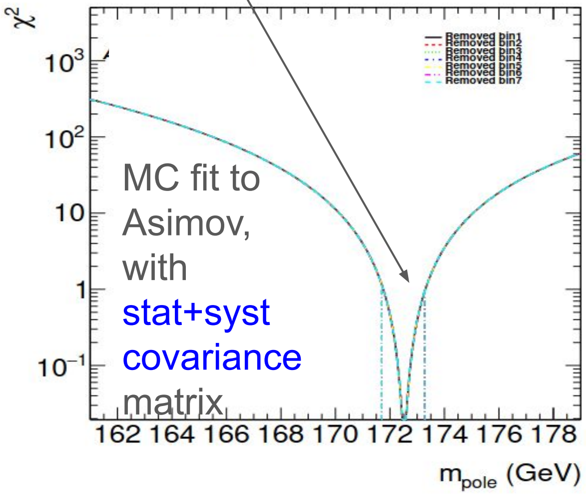
Fit - chi2 and bin removal

mTop value and uncertainty extracted minimizing

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

- one bin removed from sum (normalized distributions) -> removed first bin
- uncertainty obtained requiring looking where $\chi^2 = \chi^2_{min}+1$ (cross-checked with toys)

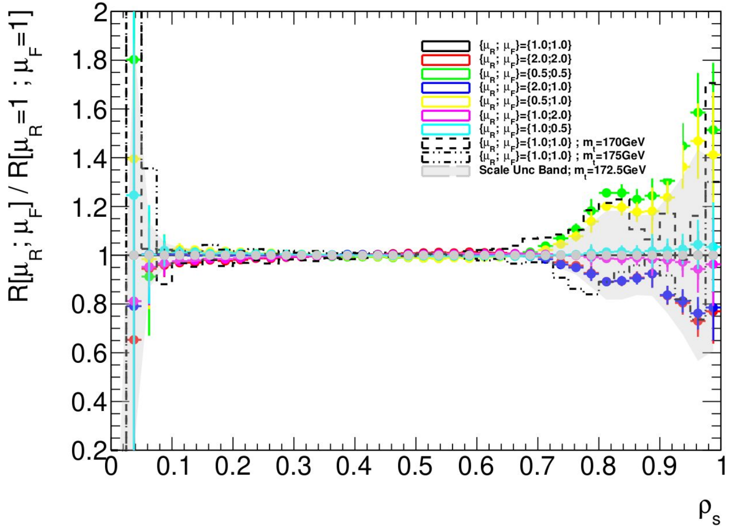




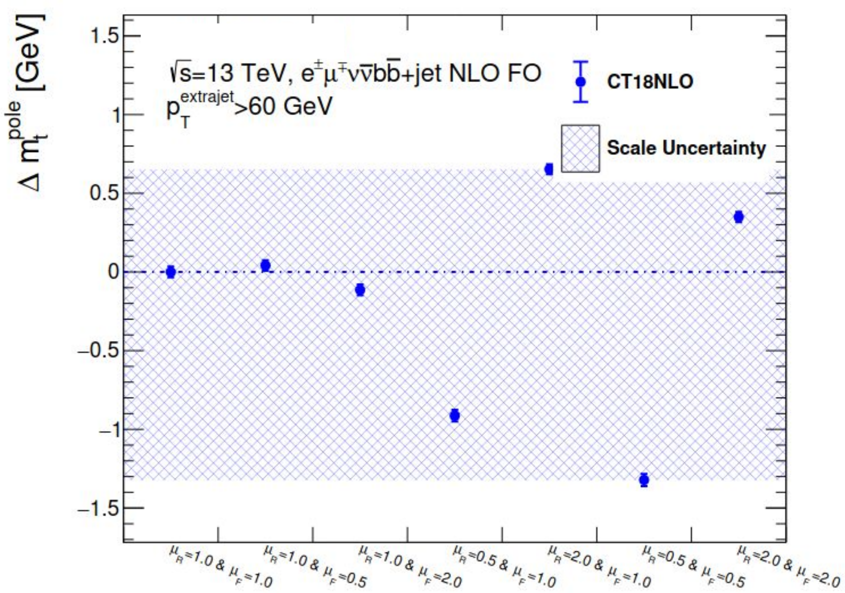
Theoretical uncertainty - scales

Theoretical uncertainties on mTop estimated by fitting nominal theoretical template to alternative theory prediction, through a chi2 fit

Scale variation impact on observable (wrt nominal)



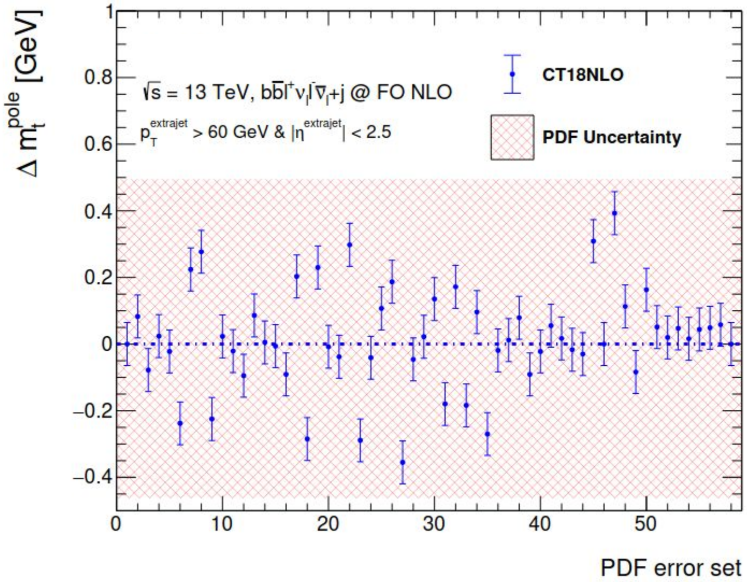
Scale variation impact on mTop



Large impact of scale variations for 2->7 prediction on mTop, in line with what was predicted by authors of calculation

Theoretical uncertainty - PDFs

Theoretical uncertainties on mTop estimated by fitting nominal theoretical template to alternative theory prediction, through a chi2 fit



PDF uncertainty affecting the theory calculation evaluated independently to the PDF uncertainty affecting the unfolding process

Preliminary result

Uncertainty Source	Δm_t^{pole} [GeV]
Theory Unc.	
Scale variations	+0.66 -1.34
PDF	+0.49 -0.46
Total	+1.86 -2.19

Blinded data mass values of 2->3 and 2->7 compared to check their compatibility:

$m_{(2\to7)} = m_{(2\to3)} + 1.19$ GeV

difference covered by scale uncertainties in the theory calculations (-1.34GeV for 2->7)

Frequently Asked Questions

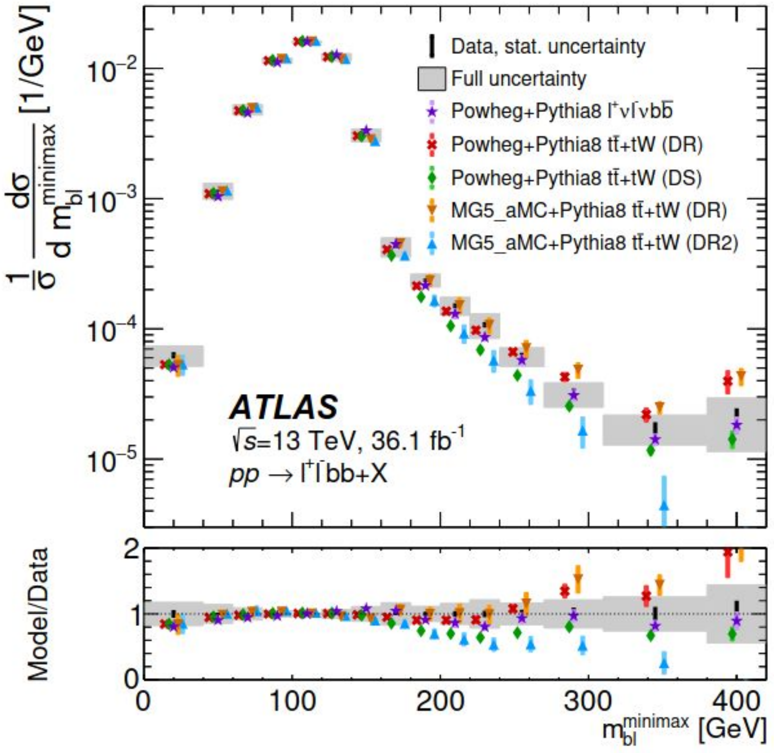
arxiv:1806.04667

cut on m(lb) variable

The mTop analysis cuts on m(lb) variable to avoid a phase space region which was found to be mismodelled in other analysis using the same final state and similar event selection.

Unfortunately such **cut also removes phase space where off-shell effects** are more important.

This is a limitation of the current analysis/status of MC modelling. Expect not to be an issue in the future



bb4l cross-check

The **cleanest approach** for the 2->7 analysis is to **use a matrix-element MC generator which simulates the 7-parton final state**, then matched to parton shower.

This is the case for the *“bb4l” Monte Carlo* simulation available in Powheg.

Cross-checked unfolding with bb4l or the MC-stack of ttbar(hvq)+tW.

$$m_{2\text{->}7}^{bb4l} = m_{2\text{->}7}^{tt+tW} - 100\ \text{MeV}$$

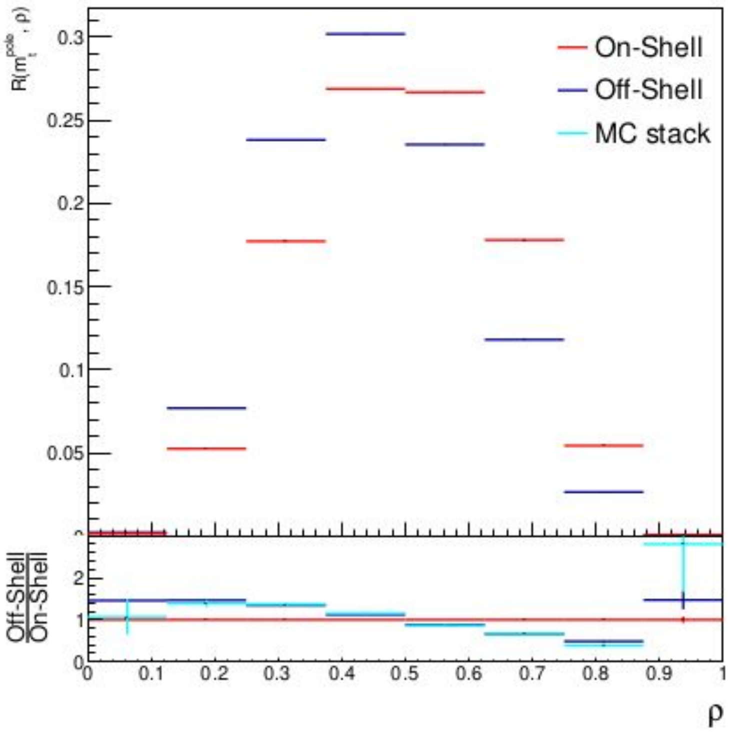
(result apply to ATLAS analysis under approval process, m(lb)<180 cut applied)

Additional Uncertainty for Parton-Level/FO Differences?

- **Question**: Do we need a systematic uncertainty to cover the difference between FO and Parton-Level distributions?

  What is the impact of multiple particle interactions (MPI) or underlying event (UE)?

  - not included in the fixed-order calculations but present in the MC simulations



Currently testing this, in the context of the ATLAS analysis. No quantitative answer yet.

Conclusions

Measurement of top-quark pole mass in pp-> l l nu nu b b j events nearly there:

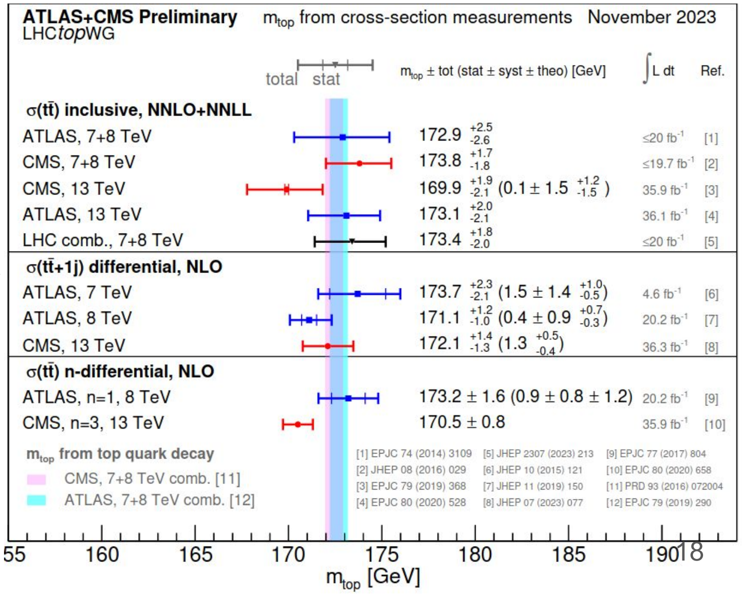
- first time using a 2->7 calculation which includes top-decay and full off-shell effects

Novelties in approach:

- new experimental systematics treatment (cov matrices) which should ease future combinations

Result has larger uncertainty than other measurements using 2->3 calculations:

- total uncertainty ~2 GeV
- theory scale uncertainty, as well as modelling and jets experimental uncertianties are dominant

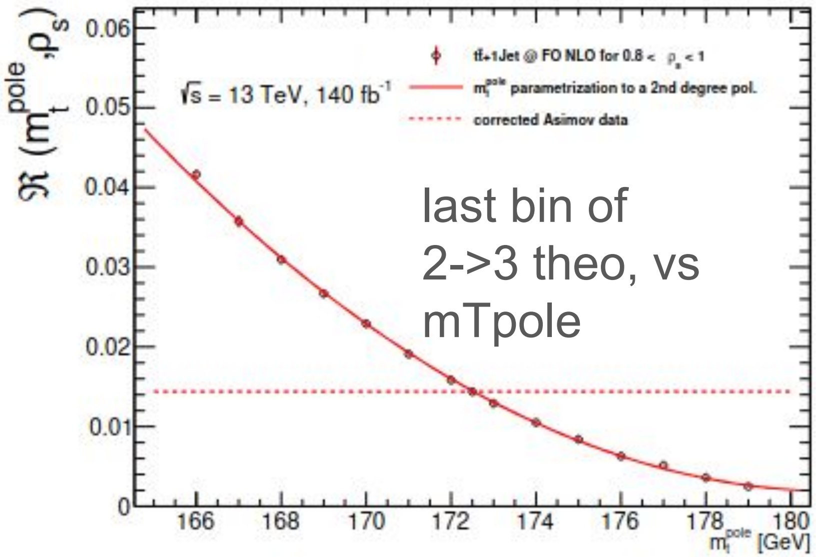


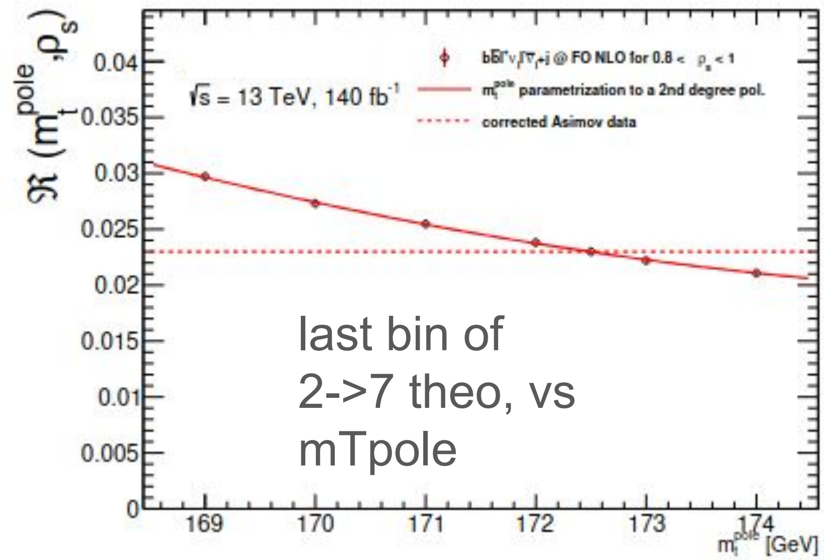
Back-up

Fit - Theoretical predictions parametrization

Theoretical prediction generated for various mass points and i**nterpolated with a 2nd order polynomial**:

- less points used for 2->7 theo, but still very good parametrisation.





Unfolding - covariance matrix and systematics

To estimate the effect of systematic effects on the extracted top-quark mass, the **historical approach** was to repeat the nominal analysis procedure (unfold+fit) on alternative detector/level distributions.

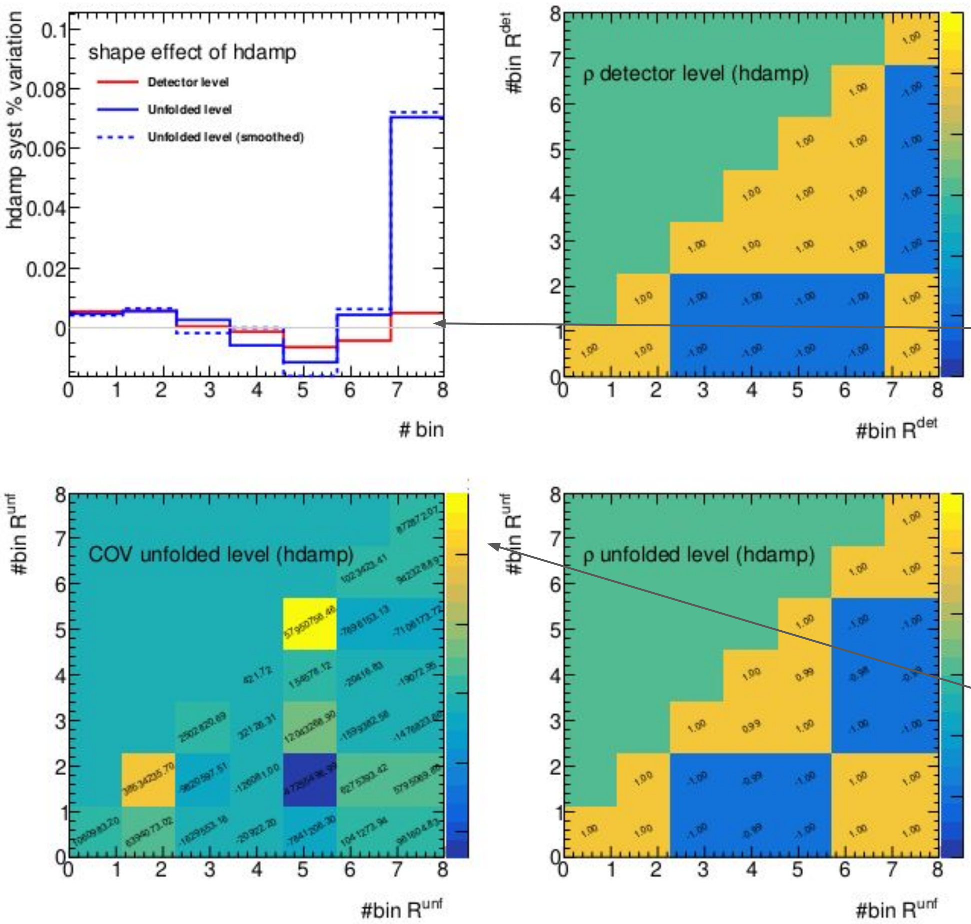
- the **covariance matrix used in the fit to data contains only statistical effects.**
- found to be still useful to evaluate tiny single-effects, but not used anymore

Now incorporated many systematics effects in a global covariance matrix, using the approach followed by boosted ttbar xsec analysis:

- unfold alternative det-level distributions with nominal (stat-only) unfolding
- for each systematic, define a cov matrix $\tilde{V}^{syst}_{i,j} = \delta_i \times \delta_j$ where δ_i syst shift in bin i
  - δ defined from post-unfolding unnormalised distributions and its sign is preserved
- define a total covariance matrix $\tilde{V}^{tot}_{ij} = \tilde{V}ij^{stat} + \sum_{syst} \tilde{V}^{syst}_{ij}$
- Normalise total covariance matrix with Cholensky decomposition and use it in the fit

Assumptions: all the systematic components are independent to each other and each individual systematic is fully correlated across all bins in the distribution

Unfolding - example of systematic covariance matrix



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

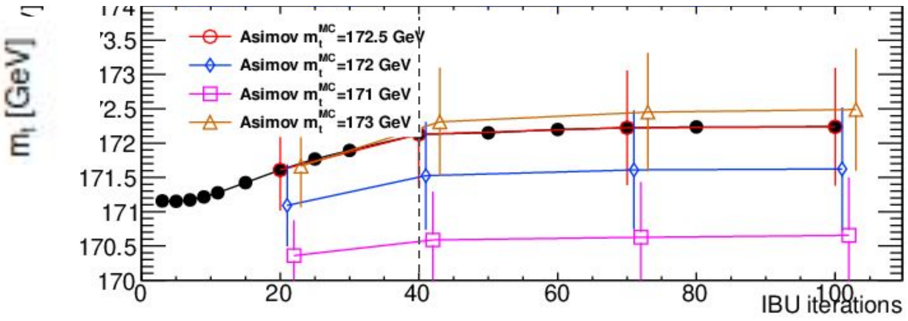
The systematic effect at detector level, is taken as fully correlated across bins, at detector level (+1 if positive shift)

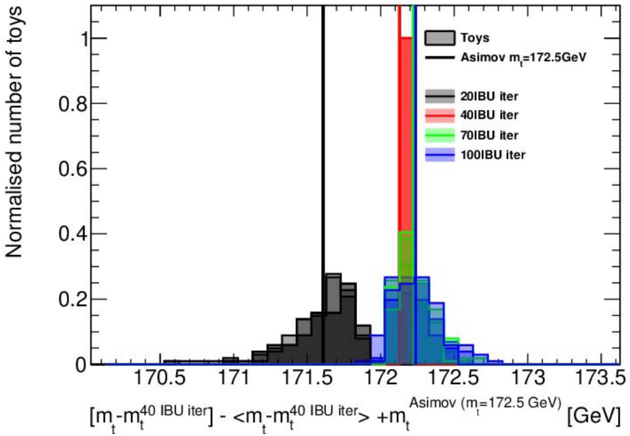
Using&unfolding toys, one can get the covariance at unfolded level.

Correlations at unfolded level can be inferred by looking at sign of unfolded-level syst shift

Unfolding validation - stability against #iterations for 2->3

The extracted top-quark mass and its uncertainty has been checked to be stable against the number of iterations chosen in the IBU algorithm





Spread of [#IBU -40IBU] amounts to 100-to-200 MeV

Histograms are centered on correspondent mTop(#IBU) value