NLO+PS off-shell effects in precise determinations of the mass and width of the top-quark at the LHC

Eps-Hep 2023

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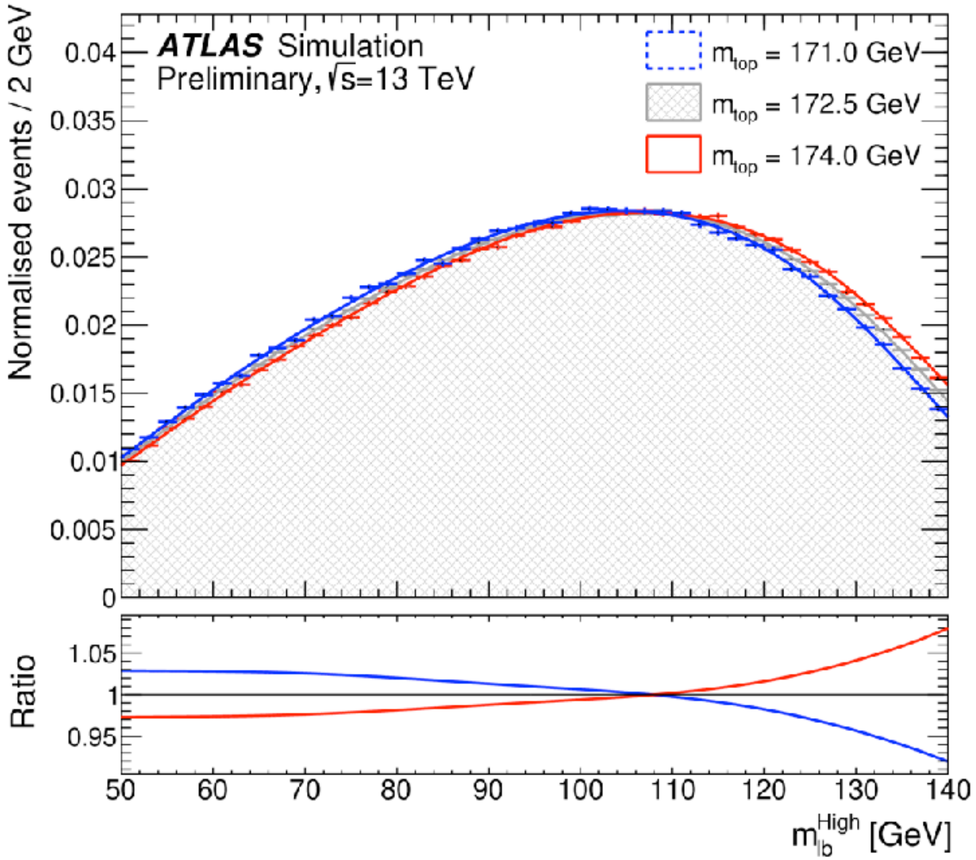
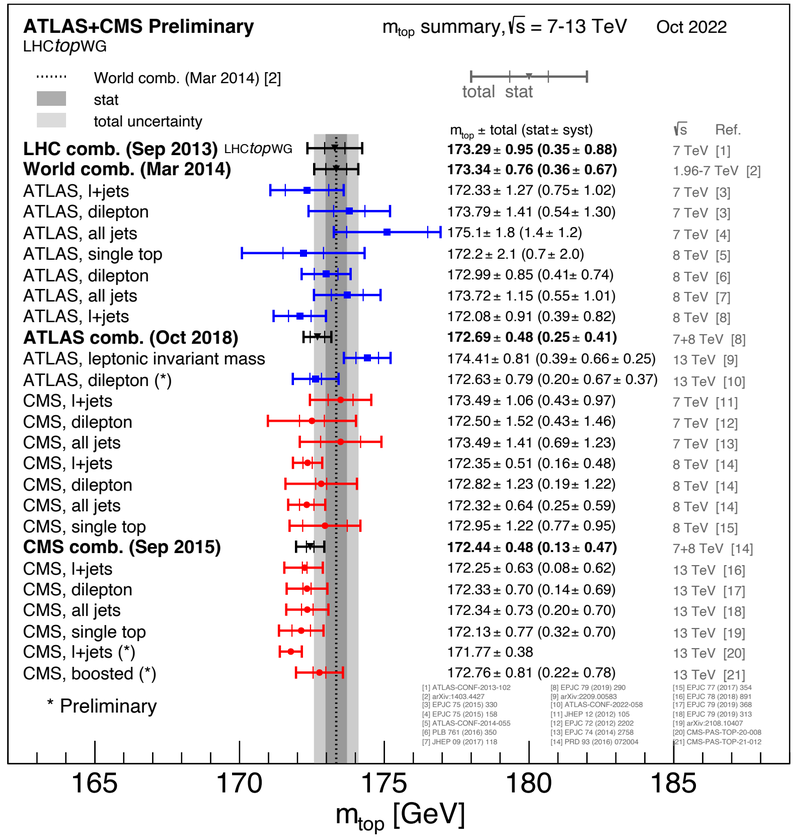
S. Kluth, L. Scyboz

Top quark mass at hadron colliders

- Most accurate top quark mass determinations through ***direct measurements***, from the reconstruction of the top decay products (lepton, jets, b-jets)
- Fits to data using templates obtained from exclusive Monte Carlo predictions





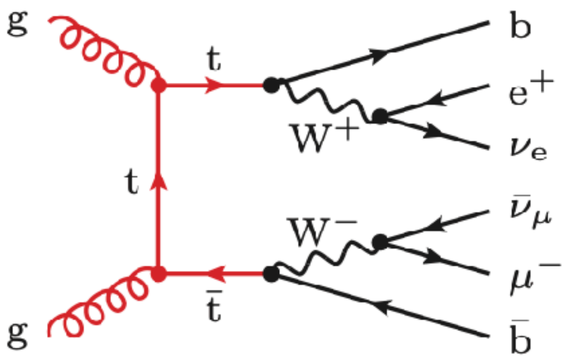
ATLAS-CONF-2022-058

TOPLHCWG

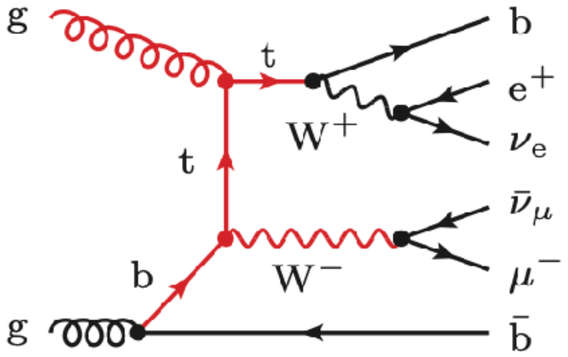
The Powheg bb4l event generator

- All recent direct measurements of m_{top} use ***NLO+PS Monte Carlo*** samples
  - NLO in production, LO spin correlations and NLO decay through shower ME corrections

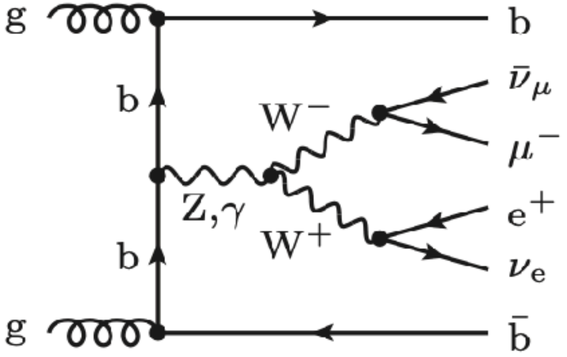
S. Frixione, P. Nason, G. Ridolfi JHEP 0709 (2007) 126



double-resonant



single-resonant



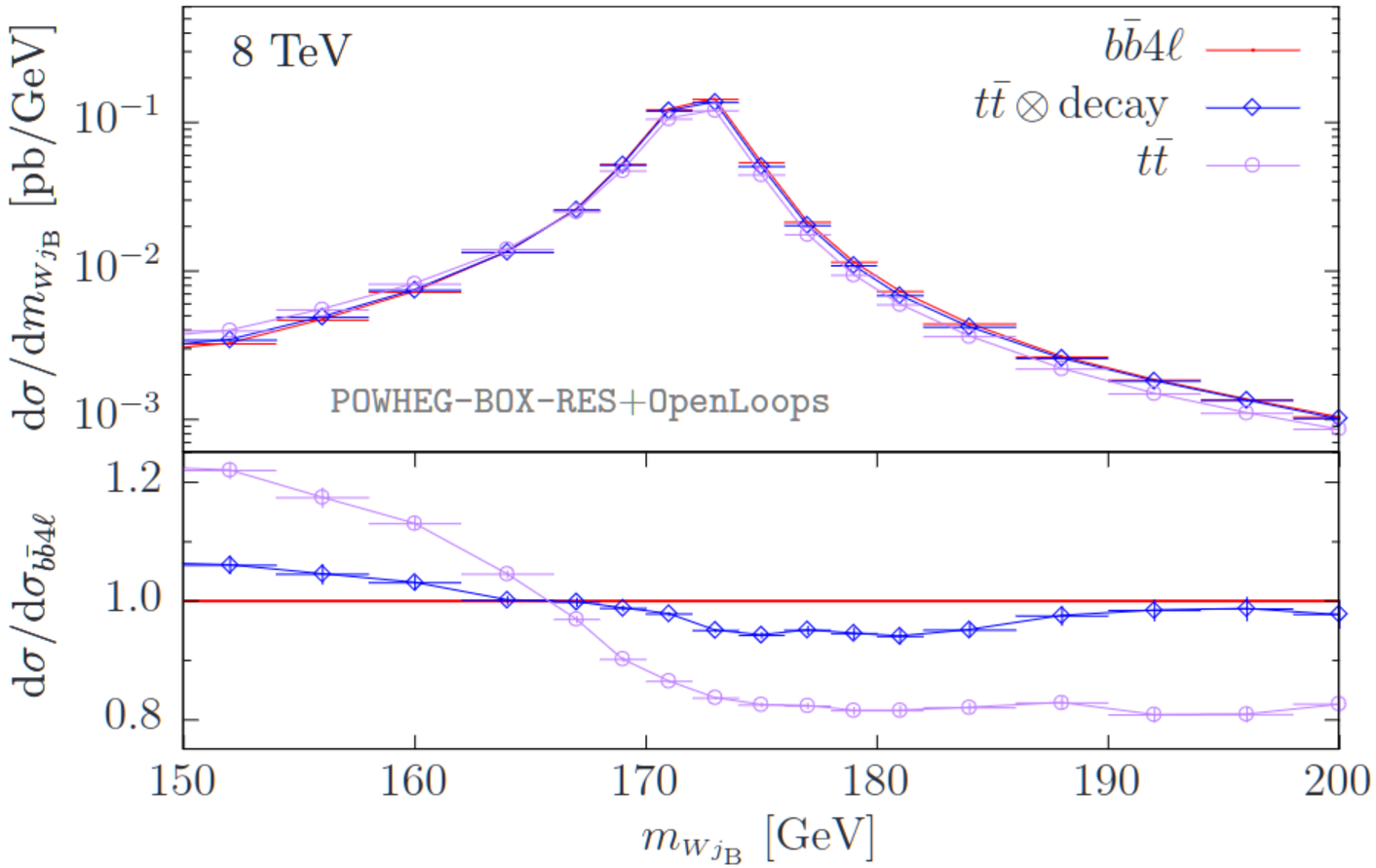
non-resonant

- State of the art since a few years the bb4l code in Powheg-Box-RES
  - NLO computation of the full 6-fermion process
  - non-resonant, off-shell , interference & spin-correlation effects at exact NLO QCD
  - Unified treatment of ttbar and Wt single-top

T. Jezo, P. Nason, JHEP 12 (2015) 065
T. Jezo et al, Eur.Phys.J.C 76 (2016) 12, 691
T. Jezo, J.M. Lindert, S. Pozzorini, [2307.15653] [hep-ph]

Off-shell effects in top production

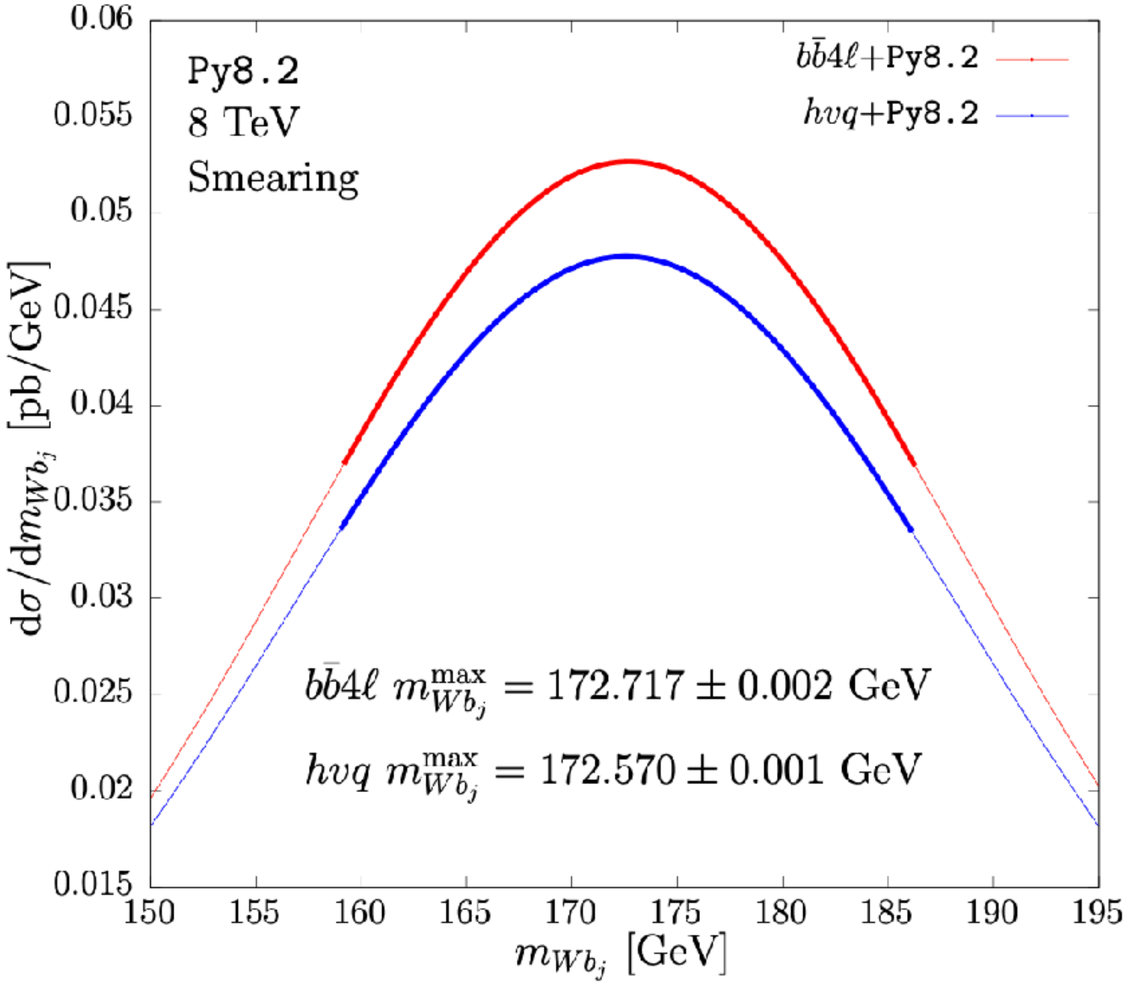
- Compare bb4l with hvq including NLO decays of the tops in the NWA
- Distortions in the m_{Wb} lineshape at particle level
- Do they impact direct determinations of m_{top}?



T. Jezo, J.M. Lindert, S. Pozzorini, [2307.15653] [hep-ph]

Off-shell effects in top production

- Particle-level study including smearing to emulate detector effects
- Finds effects of the order of O(200 MeV) on the peak position of the reconstructed top mass
- Some dependence on the specific observable and parton shower code
- Can we learn anything using existing measurements?



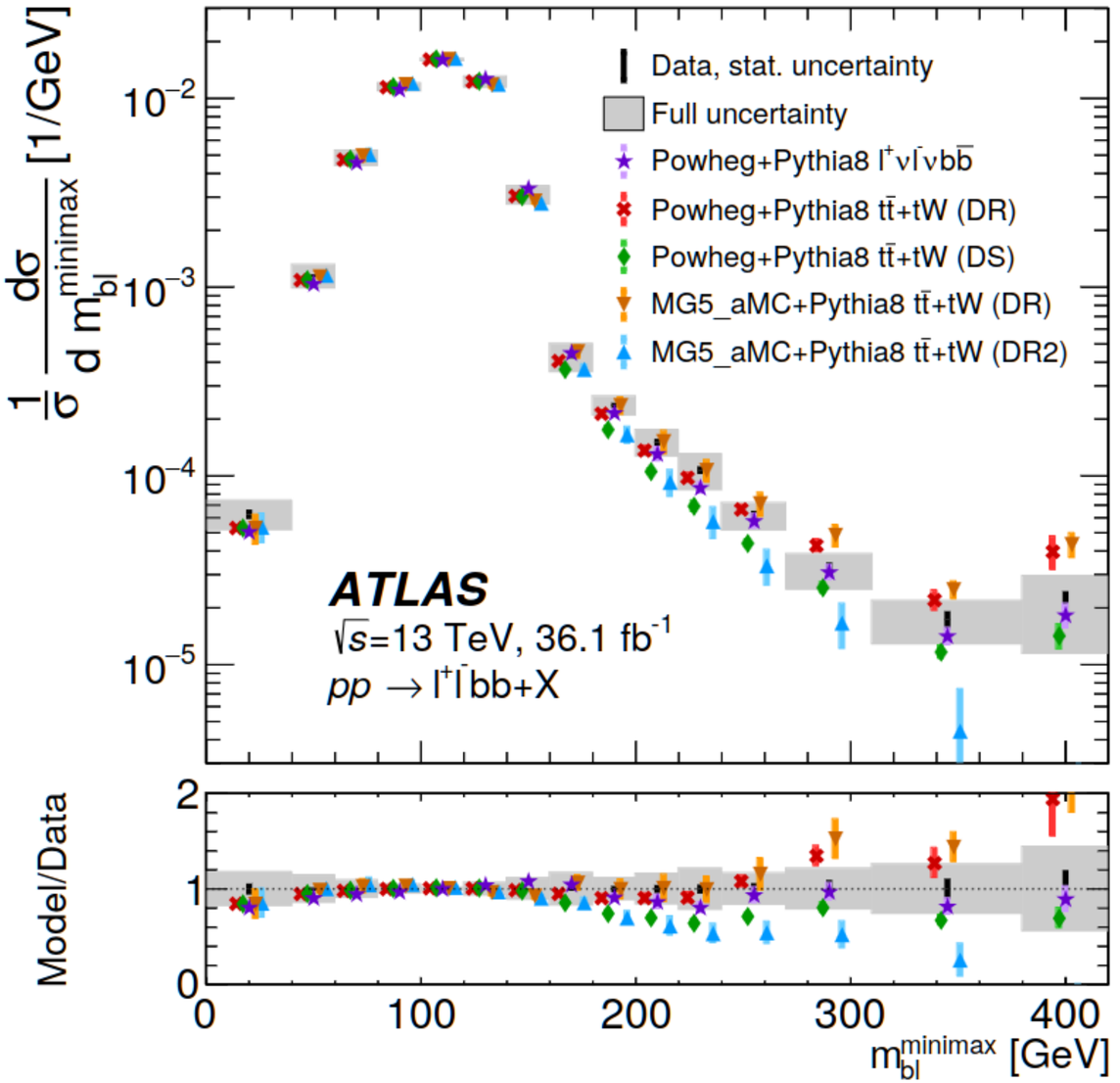
S. Ferrario Ravasio, T. Jezo, P. Nason, C.Oleari Eur.Phys.J.C 78 (2018) 6

ATLAS measurement of $m_{lb}^{minimax}$

- ATLAS $\sqrt{s}$ = 13TeV measurement
  - 36.1 fb^{-1} of Run-II data
  - Dileptonic channel (ee, eμ, μμ)
  - Combine one lepton and one b-jet using $m_{lb}^{minimax}$ variable

$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

- Kinematic endpoint at $\sqrt{m_{\text{top}}^2 - m_W^2}$ sensitive to the top quark mass
- Above endpoint sensitive to tt/Wt interference and top-quark width effects



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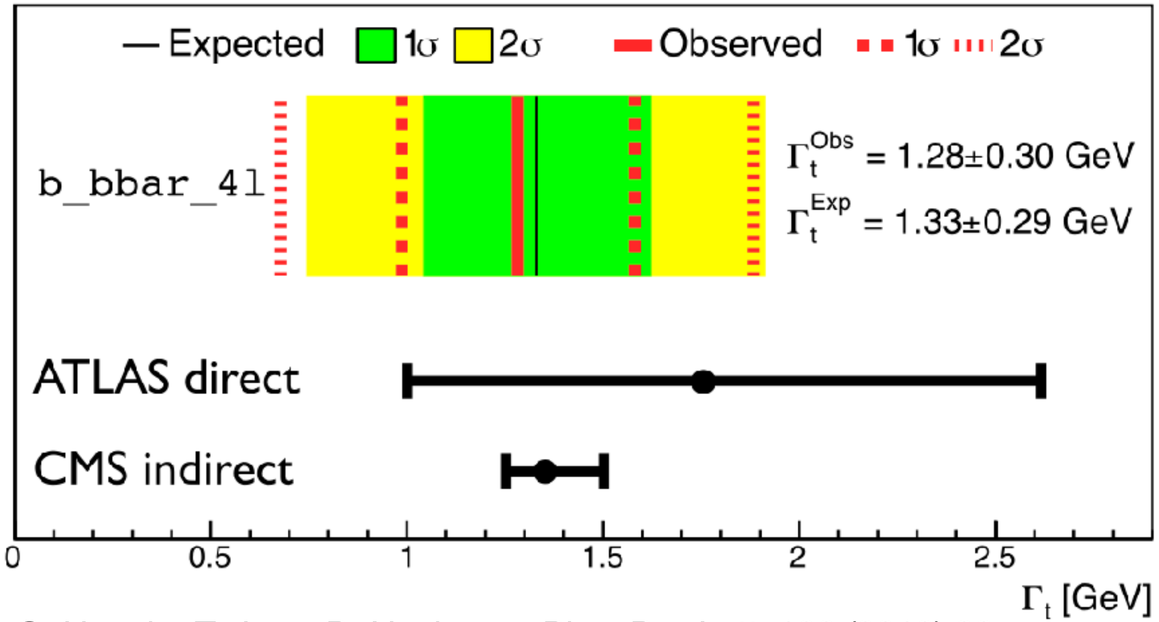


$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

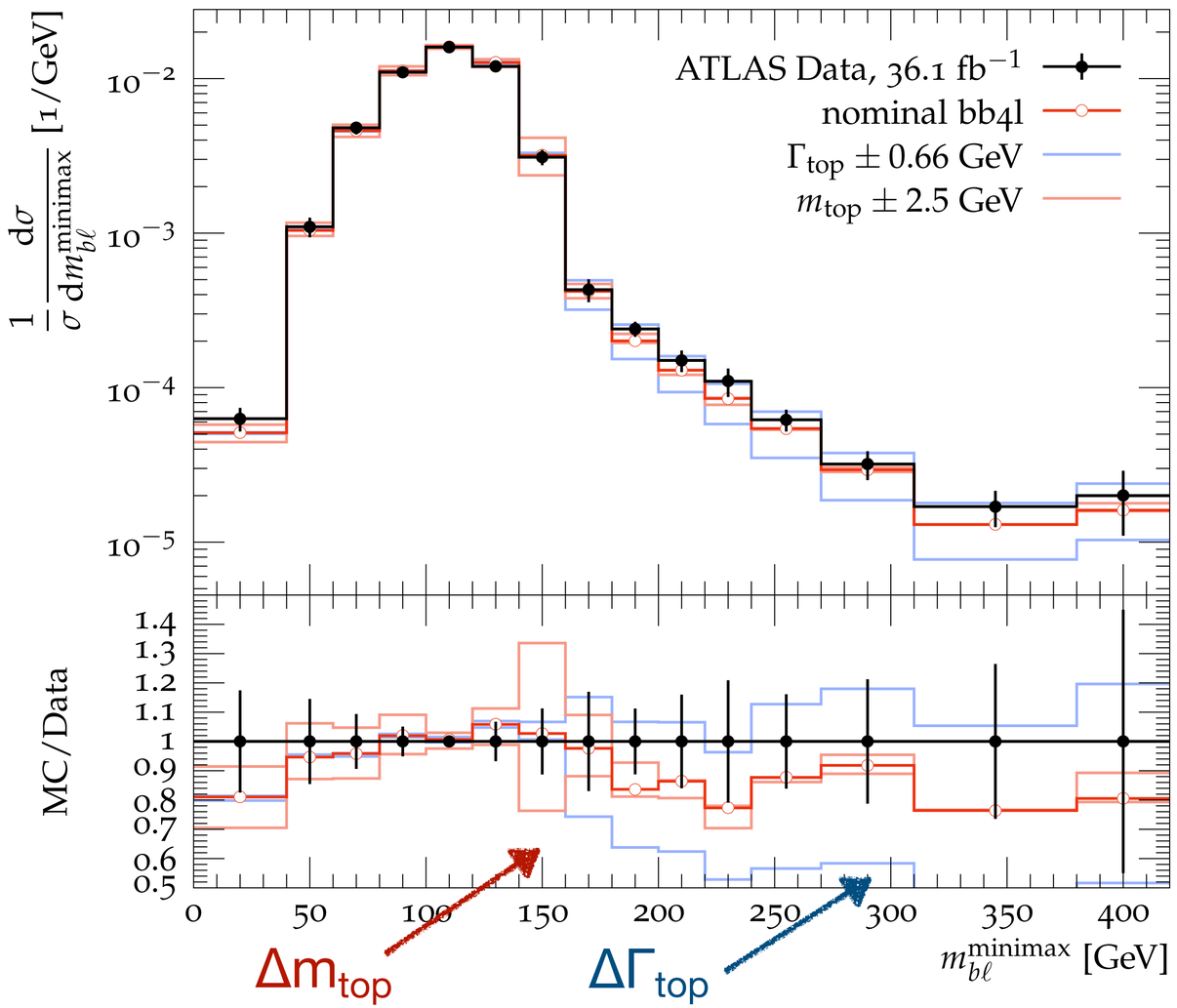
C. Herwig, T. Jezo, B. Nachman, Phys.Rev.Lett. 122 (2019) 23

- Kinematic endpoint at $\sqrt{m_{\text{top}}^2 - m_W^2}$ sensitive to the top quark mass
- Above endpoint sensitive to tt/Wt interference and top-quark width effects

- ATLAS measurement used for a competitive direct extraction of Γ_{top}
- Can we use it to also learn something on m_{top}?

bb4l predictions

- $2 \cdot 10^7$ bb4l LHE events generated
  - $m_{top} = 172.5$ GeV, $\Gamma_{top} = 1.33$ GeV
  - $h_{damp} = m_{top}$
  - NNPDF31_nnlo_hessian PDF
  - Same-flavor lepton decays included by relabeling LHE events (see ***L. Jeppe poster***)
- Interfaced to Pythia8.307 using dedicated bb4l UserHook
- Templates generated for
  - $m_{top} = 170.0, 171.5, 173.5, 175.0$ GeV
  - $\Gamma_{top} = 0.66, 1.00, 1.66, 2.00$ GeV



The "linear template fit"

- Goodness of fit for binned distributions with gaussian uncertainties

$$\chi^2(\alpha) = (d - \lambda(\alpha))^T V^{-1} (d - \lambda(\alpha))$$

λ: theory-prediction
α parameter(s) of interest, (top mass and/or width)
d the measurement,
V covariance matrix ($W=V^{-1}$)

The Linear Template Fit

D. Britzger, Eur.Phys.J.C 82 (2022) 8, 731

- The parameter dependence $\lambda(\alpha)$ approximated linearly from 'templates'
  → Valid approximation when templates are close to the best estimator
- The fit result ('best estimator') is directly obtained in ***closed analytic form***:

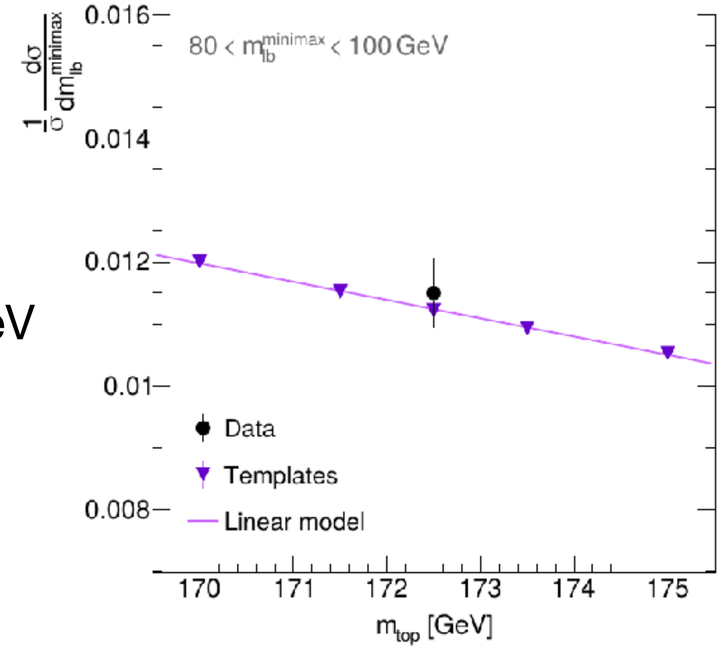
$$\hat{\alpha} = [(Y\tilde{M})^T W Y \tilde{M}]^{-1} [(Y\tilde{M})^T W (d - Y\overline{m})]$$

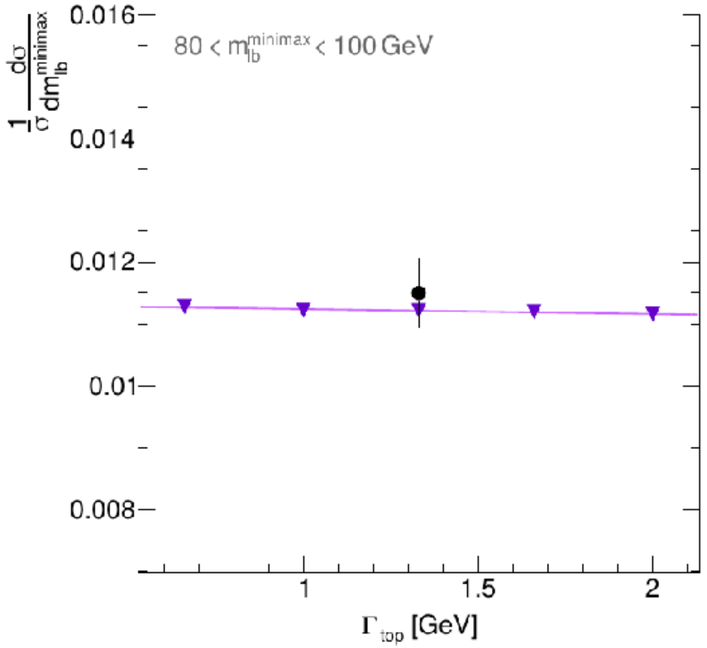
Y: matrix of the templates

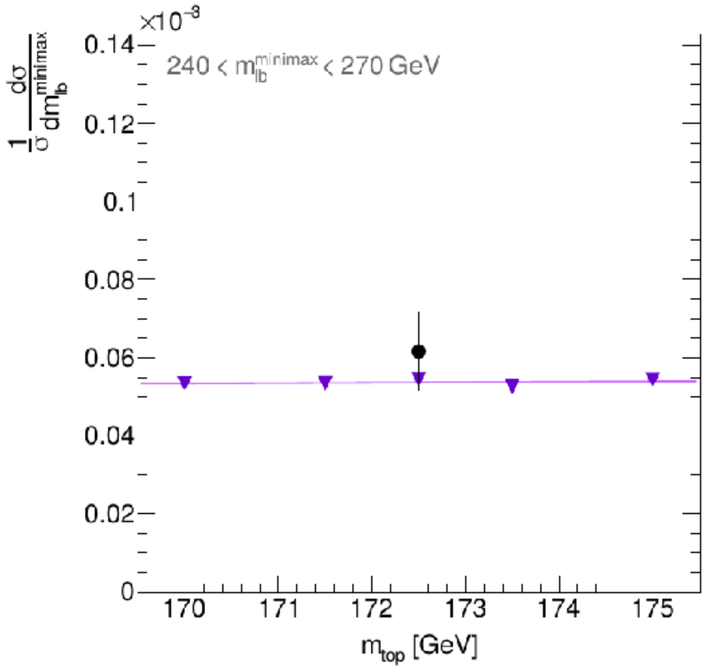
M, m: quantities computed from the reference values of the templates

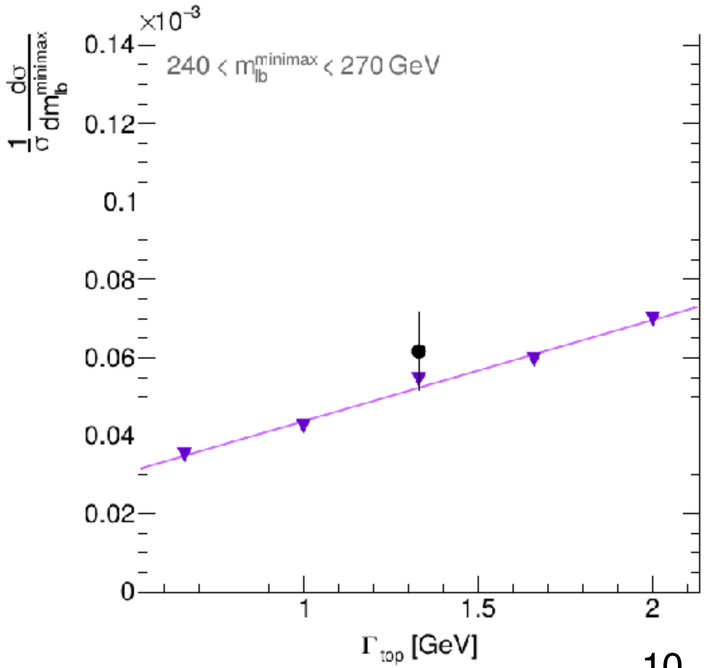
Sensitivity

- Templates generated for
  - m_{top} {170, 171.5, 172.5, 173.5, 175} GeV
  - Γ_{top} {0.66, 1.0, 1.33, 1.66, 2.0 } GeV
- Good linearity observed in all bins
  - No difference between linear and quadratic interpolation
- Low m_{lb} mostly sensitive to m_{top}
- High m_{lb} mostly sensitive to Γ_{top}

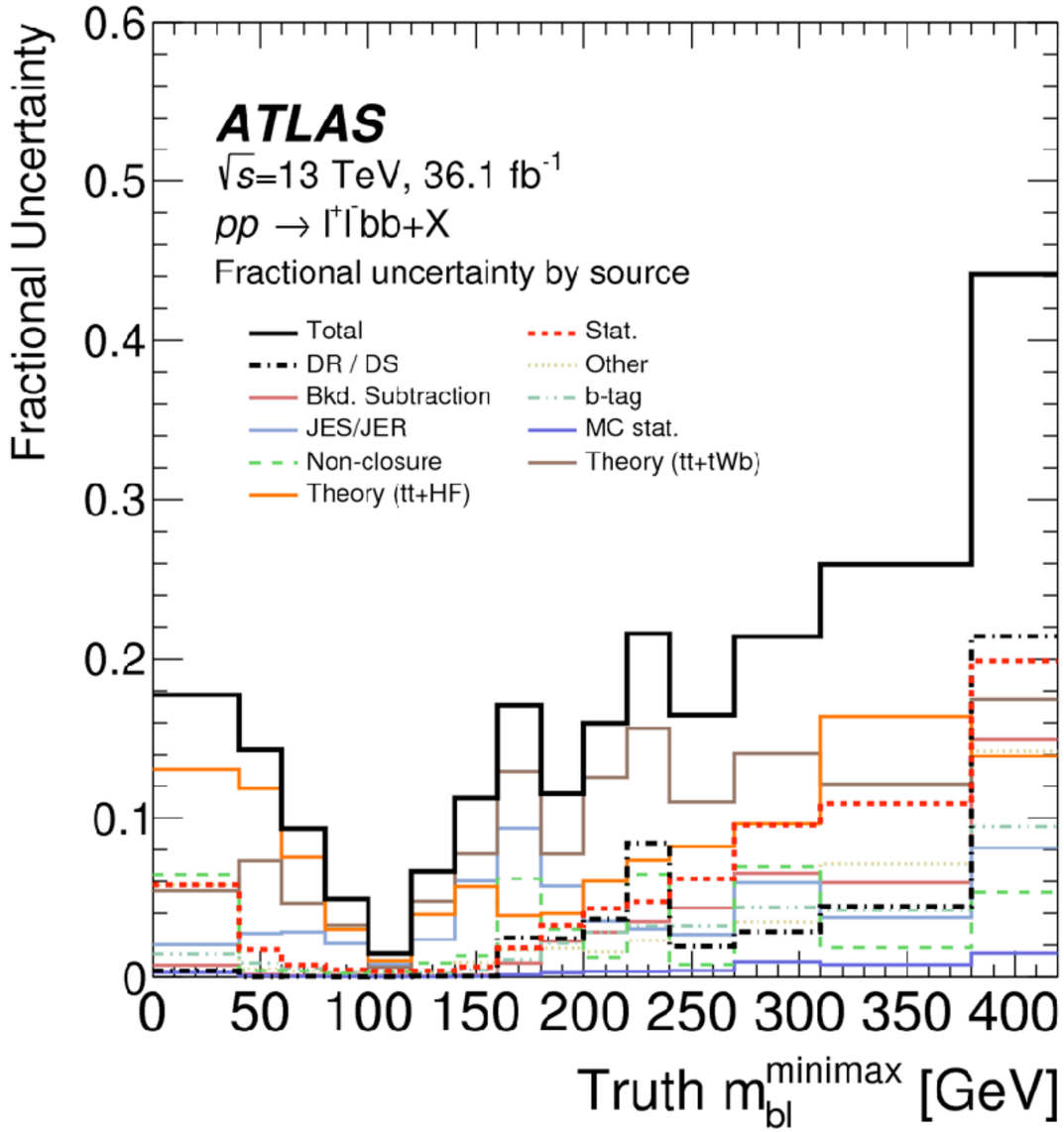








Systematic uncertainties

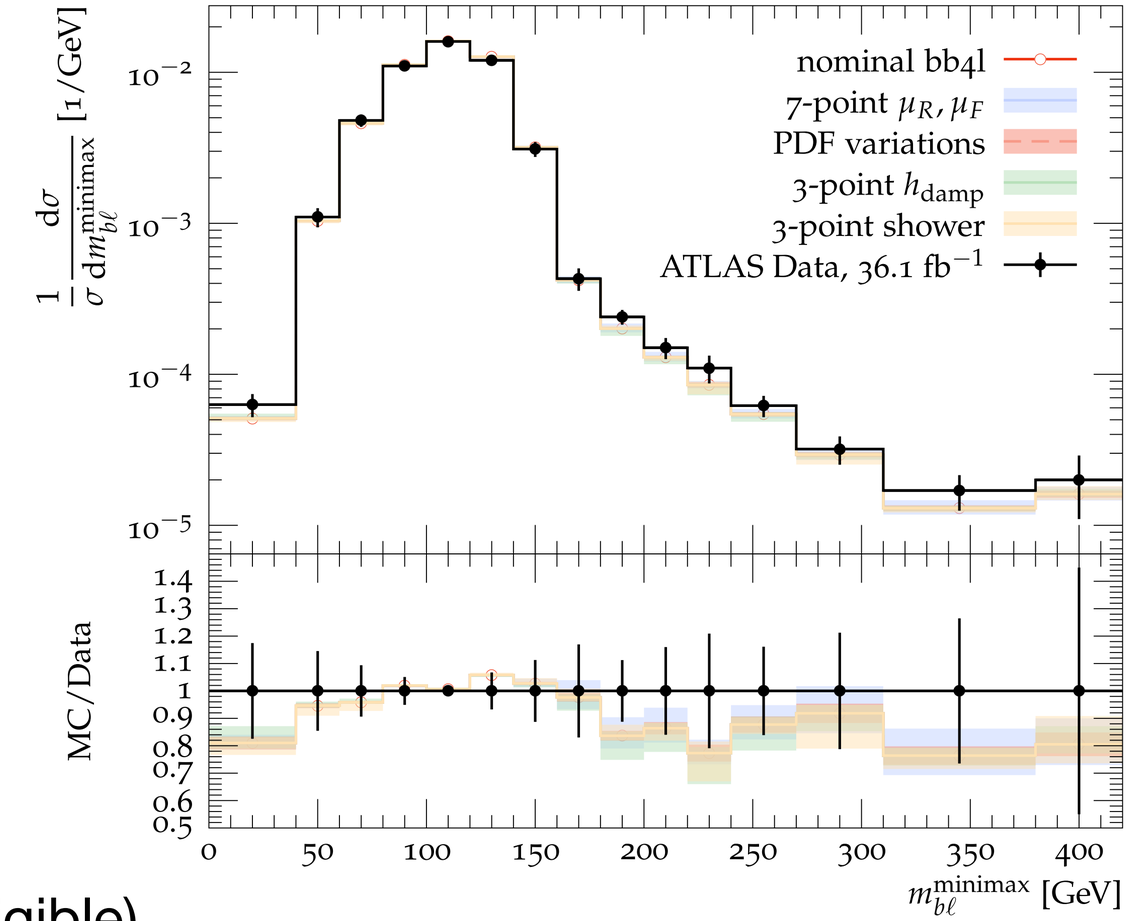


- Experimental uncertainties all encoded in data covariance matrix
- Dominated by uncertainties in the **theoretical modeling of tt+Wt** and in the description of additional b-tagged jets
- Could be significantly reduced in the future by directly using bb4l predictions in the measurement

Systematic uncertainties

- For the interpretation, need to consider theoretical uncertainties on bb4l prediction:

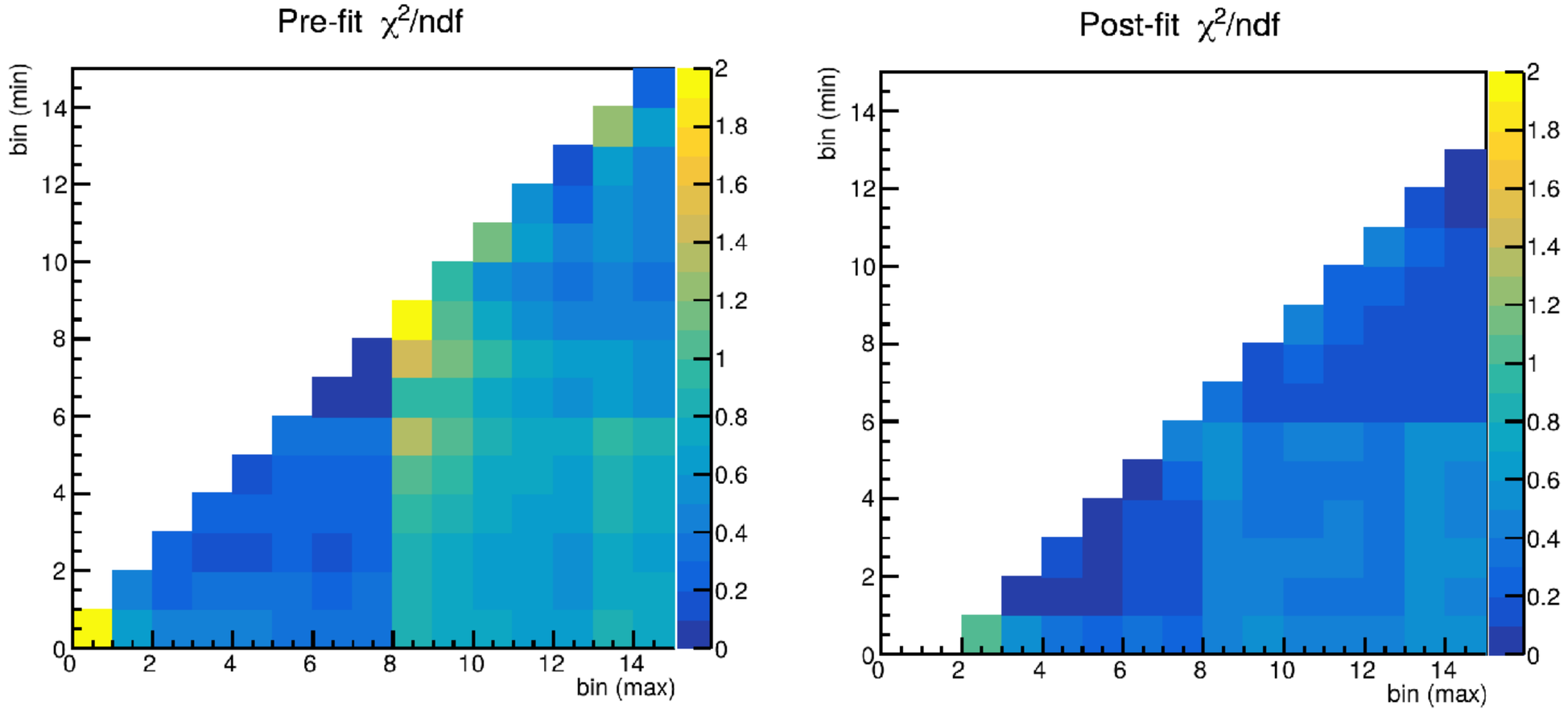
  - ***7-point scale variations*** and ***NNPDF31 eigenvector variations*** obtained through bb4l reweighting
  - ***3-point hdamp variations*** (0.5, 2.0 m_{top})
  - ***3-point shower scales and non-singular terms variations*** in the splitting kernels through Pythia8 reweighting



- NB: Work ongoing to evaluate uncertainties on the matching to Pythia (negligible) and possible bias due to wrong shower recoils (few ~100 MeV on m_{top})

GoF dependence on the fit range

- χ^2/ndf for different m_{bl} fit ranges before and after the fit



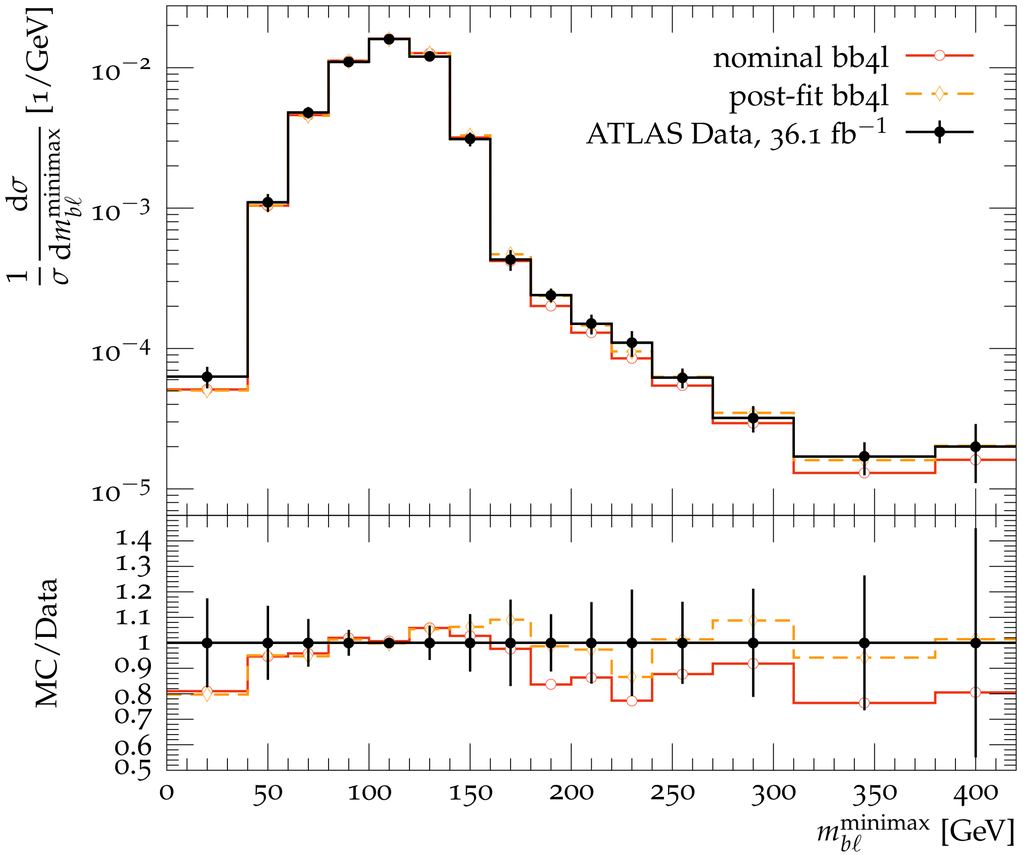
- Very good agreement of the post-fit predictions with data in the entire m_{bl} range

Simultaneous determination of mass and width

- Fit performed between 40 < m_{lb} < 380 GeV

Results

$$m_t = 172.67 \pm 0.46_{(\mathrm{exp})} \pm 0.57_{(\mathrm{th})}\ \mathrm{GeV}$$
$$\Gamma_t = 1.70 \pm 0.21_{(\mathrm{exp})} \pm 0.27_{(\mathrm{th})}\ \mathrm{GeV}$$



- Excellent agreement of data and bb4l post-fit
- Weak correlation (-30%) between m_{top} and Γ_{top}
- Extracted width consistent with previous determination
- Theoretical uncertainty dominated by h_{damp} and shower variations

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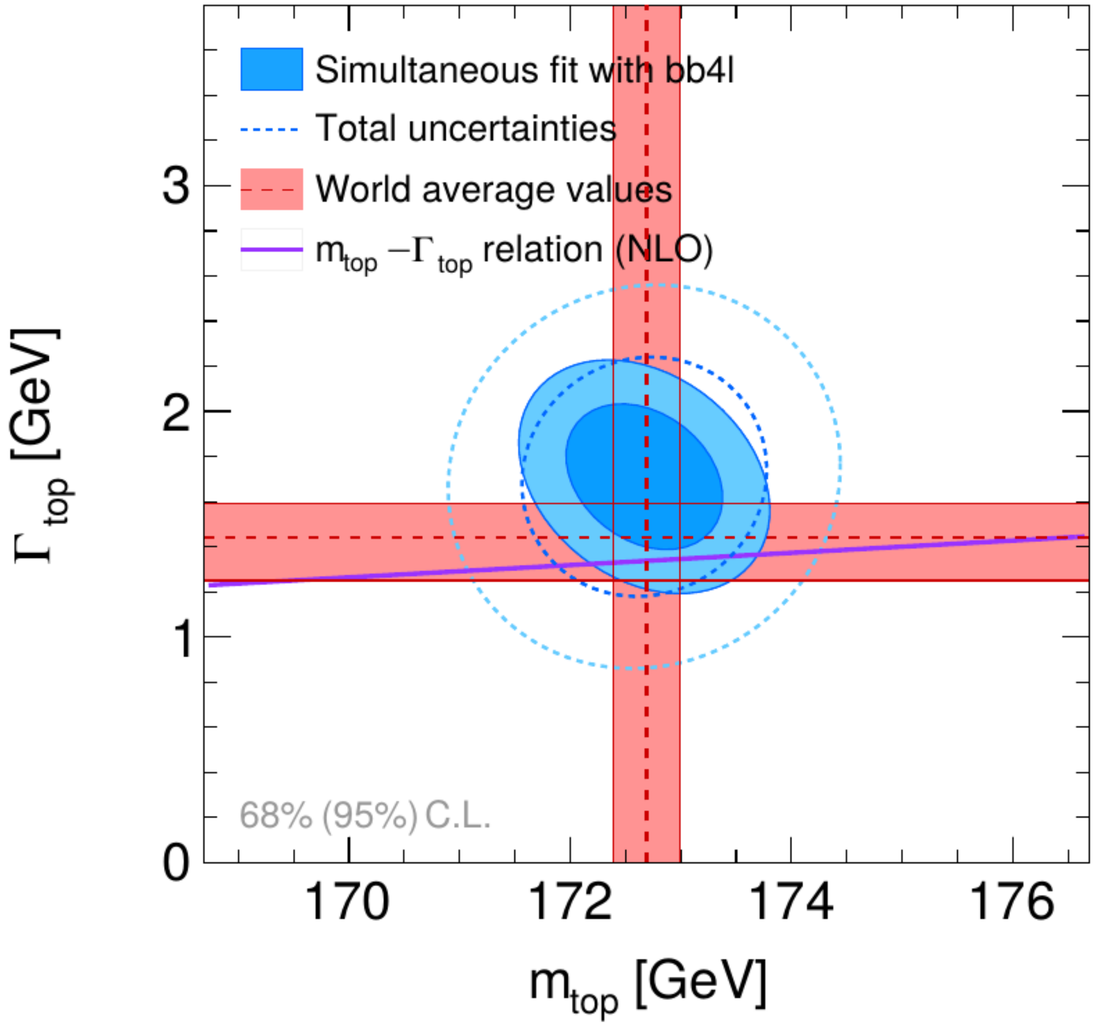


Top quark mass determination

- m_{top} determination including the top-mass dependence in Γ_{top}

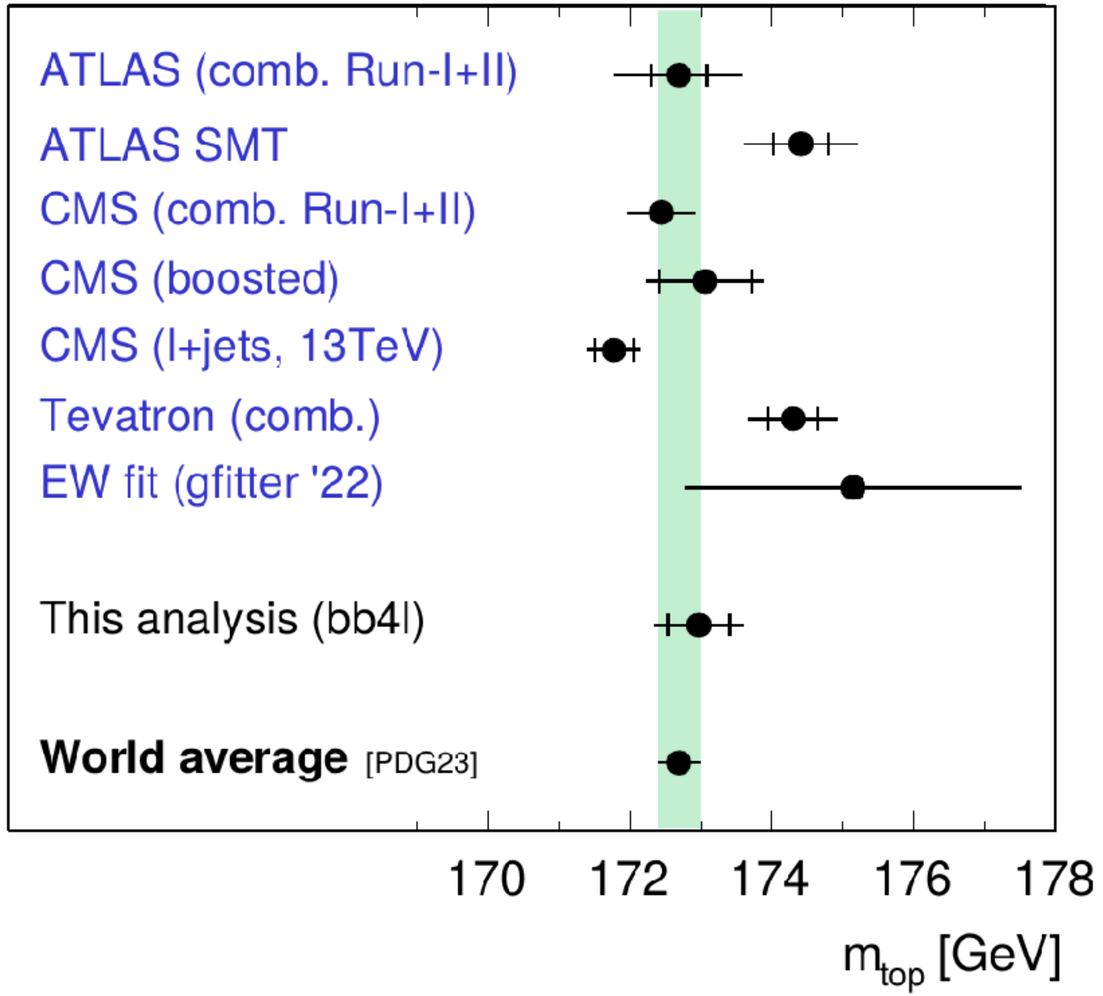
LO Γ_{top} relation

$$\Gamma_t^{(0)} = G_F \frac{m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{m_W}{m_t}\right)^2 \left(1 + 2\frac{m_W}{m_t}\right)$$

Result

$$m_t = 172.97 \pm 0.43_{(\mathrm{exp})} \pm 0.46_{(\mathrm{th})}\ \mathrm{GeV}$$

- Moderate reduction of exp. uncertainties (limited precision of data at large m_{lb})
- Reduced theoretical uncertainties
- Competitive with dedicated measurements



Summary

- Simultaneous determination of m_{top} and Γ_{top} from a single measurement
  - ***First m_{top} with full NLO treatment of non-resonant and interference effects*** exploiting the bb4l Monte Carlo event generator
  - Using ***ATLAS measurement of $m_{lb}^{minimax}$*** at $\sqrt{s}$=13 TeV
  - Multivariate Linear Template Fit to study sensitivity to m_{top} and Γ_{top}

- Already ***competitive uncertainties to dedicated measurements***
- Results consistent with world average and previous determinations
- Top-quark mass effects in Γ_{top} provides small additional sensitivity to m_{top} with dominant model uncertainties found to be reduced

- Promising avenue for future LHC measurements

Backup