Direct determination of Γ_t with `b_bar_4l`

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In collaboration with C. Herwig[†] *and B. Nachman*
based on [arXiv:1903.10519]

[†] my slides based on those of C. Herwig

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DIS 2019 TORINO

The top-quark width

- Though the top mass has been measured to sub-% precision, current direct width measurement sensitivity is ~50%

- The SM predicts a precise relation between the top-quark mass and width, and has been calculated at NNLO QCD

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

  - Precise measurements of the top width allow stringent tests of the SM

- Modifications from BSM physics remain possible:
  - Undetected decays: $t \to H^+ b$, FCNCs, SUSY, ...
  - Radiative corrections (g_{tWb}): SUSY, 2HDMs, $W - W'$ mixing

Previous measurements (I)

- Since Tevatron, there are two methods used to measure the top width

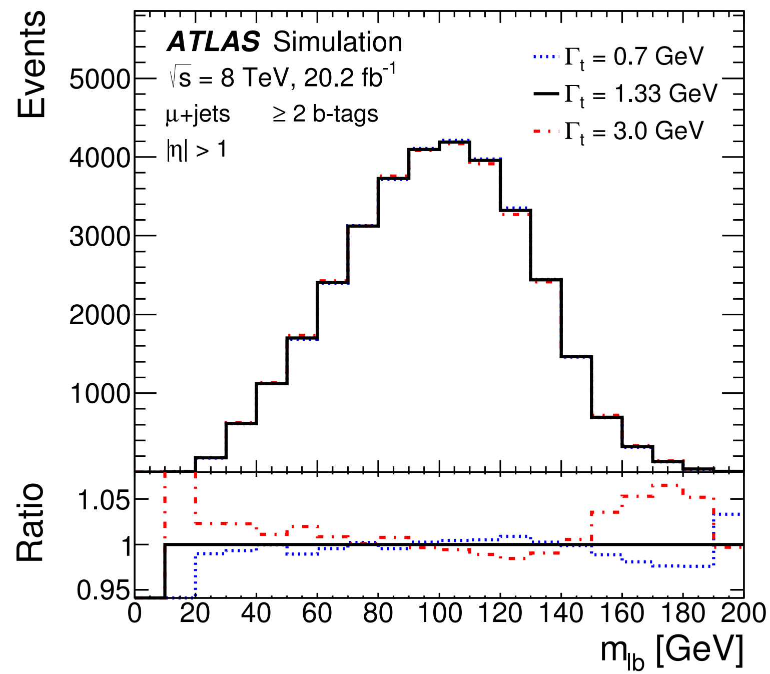
- Template fits to reconstructed mass spectra (lepton+jets) (direct measurement)
  - $\Gamma_t = 1.76 \pm 0.33(\text{stat.})^{+0.79}_{-0.68}(\text{syst.})$ GeV

- Combination of t-channel single-top XS and $(t \to Wb)/(t \to Wq)$ ratio (indirect measurement)

$$\Gamma_t = \frac{\sigma_{t\text{-ch.}}}{\mathcal{B}(t \to Wb)} \cdot \frac{\Gamma(t \to Wb)^{\text{theor.}}}{\sigma^{\text{theor.}}_{t\text{-ch.}}}$$

  - $\Gamma_t = 1.36 \pm 0.02(\text{stat.})^{+0.14}_{-0.11}(\text{syst.})$ GeV
  - But assumes $\mathcal{B}(t \to Wq) = 1$

[arXiv: 1709.04207]



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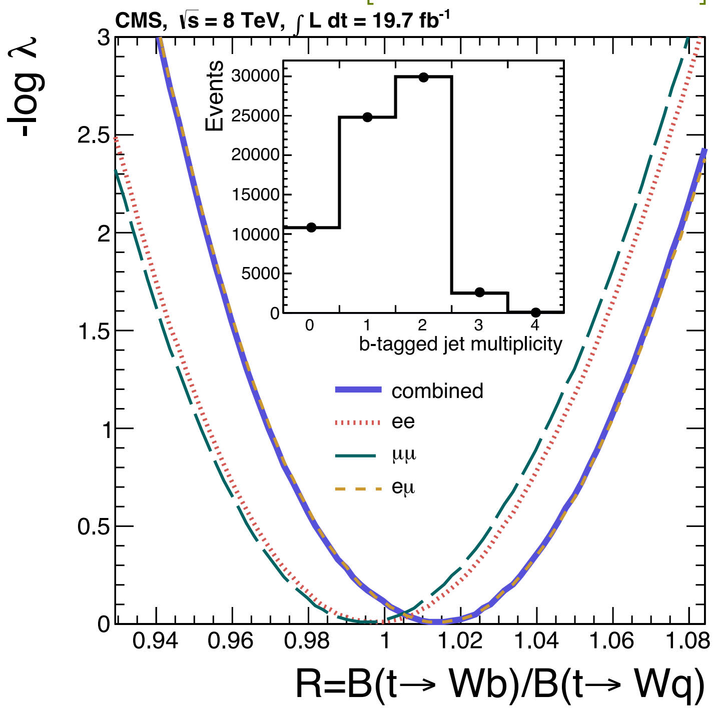
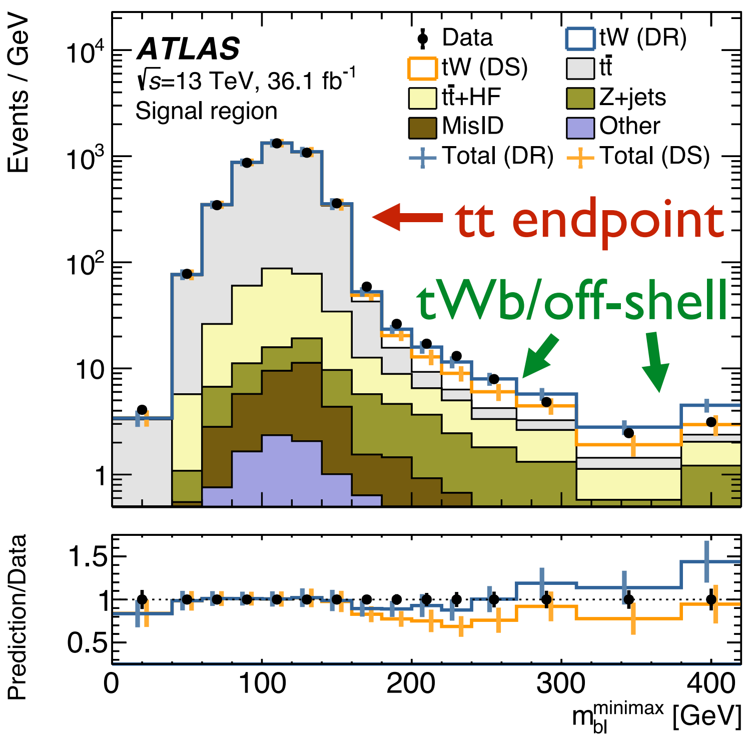
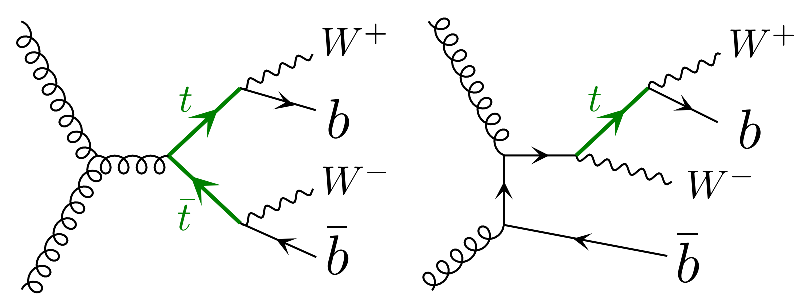


Our proposal

- Use the measurement of m_{bl}^{minimax} in the dilepton channel [TOPQ-2017-05] to extract Γ_t using off-shell events (direct measurement)



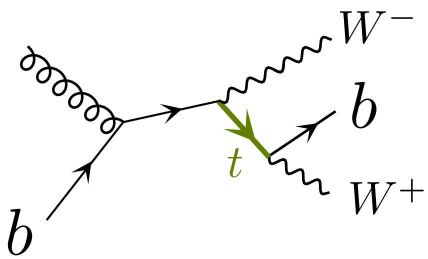
- $m_{bl}^{\text{minimax}} = \min\{\max(m_{b_1,\ell_1}, m_{b_2,\ell_2}),$ $\max(m_{b_1,\ell_2}, m_{b_2,\ell_1})\}$
- Kinematic endpoint at $\sqrt{m_t^2 - m_W^2}$ at LO
- Large m_{bl}^{minimax} dominated by off-shell $t\bar{t}$ and tW production



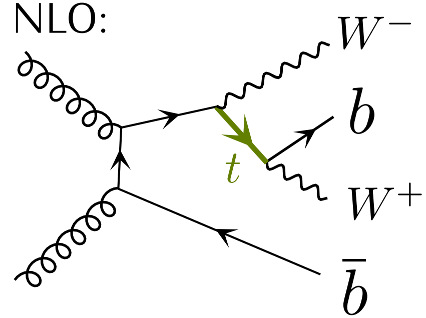
$t\bar{t}$ and tW interplay

- tW 5FNS (b in proton, $m_b = 0$)

LO:



NLO:



  - Requires a procedure to remove $t\bar{t}$ contribution

$$\mathcal{M} = \mathcal{M}^{tW} + \mathcal{M}^{t\bar{t}}$$

Diagram Removal: $\mathcal{R}^{\mathrm{DR}} = \dfrac{|\mathcal{M}^{tW}|^2}{2s}$

Diagram Subtraction: $\mathcal{R}^{\mathrm{DS}} = \dfrac{|\mathcal{M}^{tW} + \mathcal{M}^{t\bar{t}}|^2 - \mathcal{C}}{2s}$

Or others, see [arXiv: 1607.05862]

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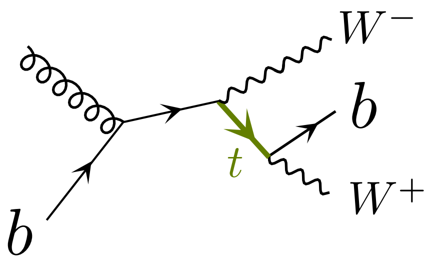

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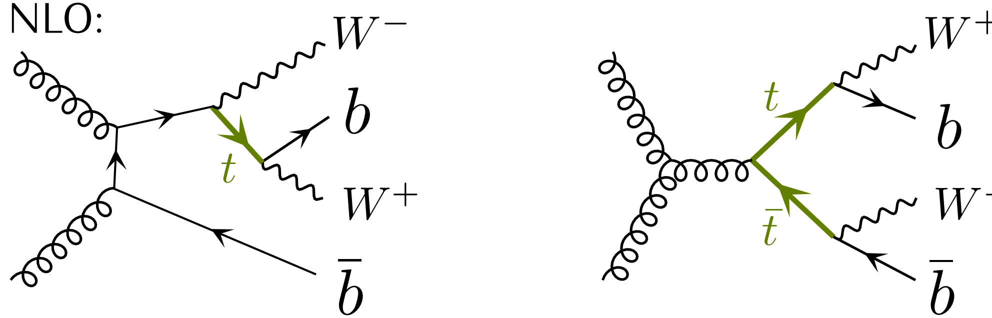

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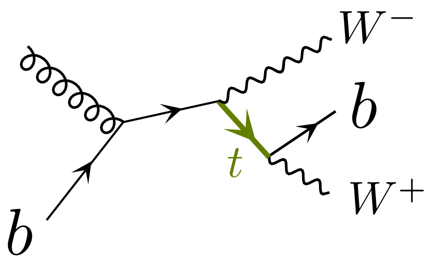

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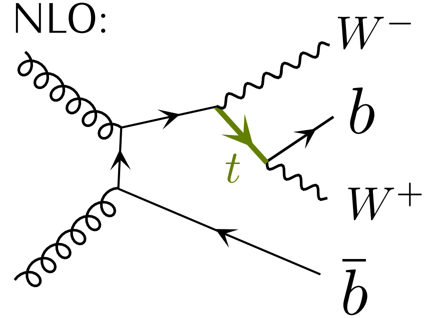

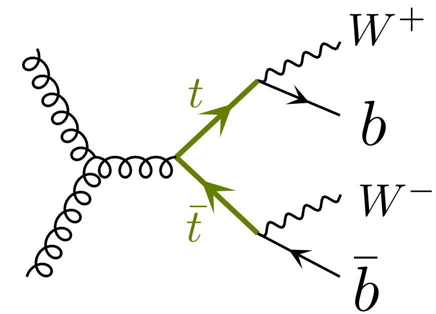

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- tW 5FNS (b in proton, $m_b = 0$)

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  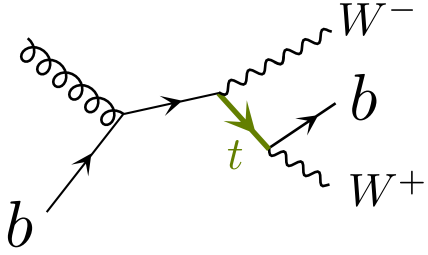

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  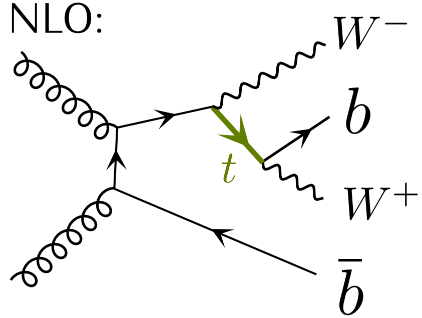

  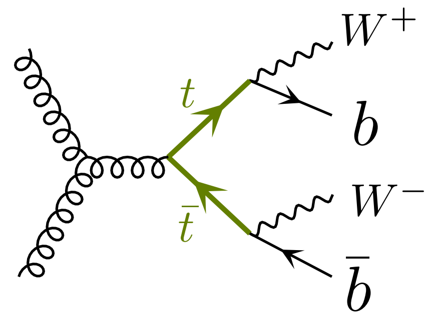

  - Requires a procedure to remove $t\bar{t}$ contribution

- tW 4FNS (no b in proton, $m_b > 0$)

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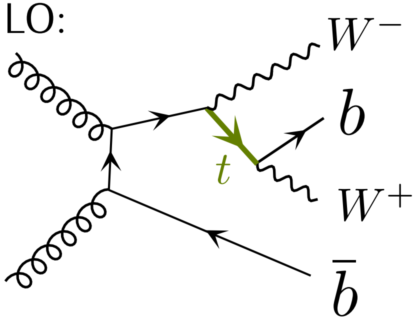
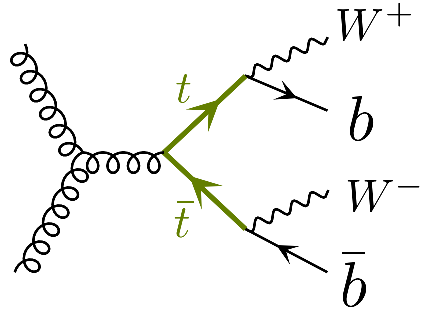
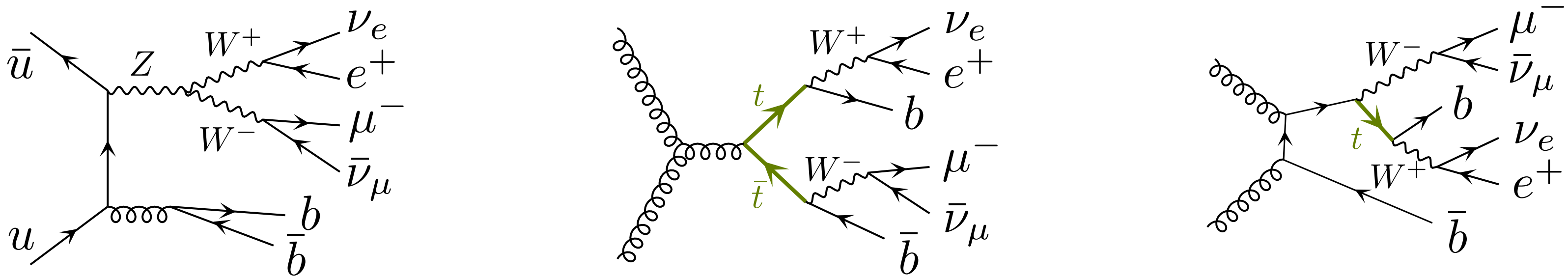
  

  - Unified treatment of $t\bar{t}$ and tW

$t\bar{t}$ & tW in POWHEG BOX RES: b_bbar_4l



- $pp \to \ell^+ \nu_\ell \, l^- \bar{\nu}_l \, b \, \bar{b}$ production at NLO
- Resonance-aware matching to parton showers [TJ, Nason, 2015]
- Exact spin correlations* and exact off-shell effects
- W hadronic decays work in progress
- Generator: `b_bbar_4l` [TJ, Lindert, Nason, Oleari, Pozzorini, 2016]

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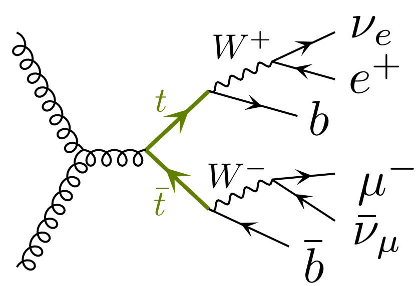

Multiple emissions
with ME (allrad)

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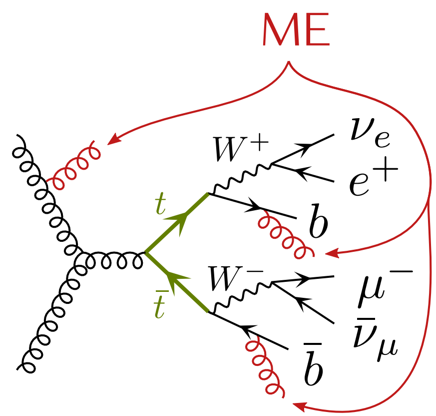

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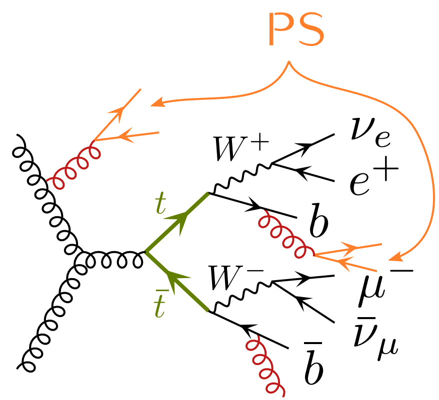

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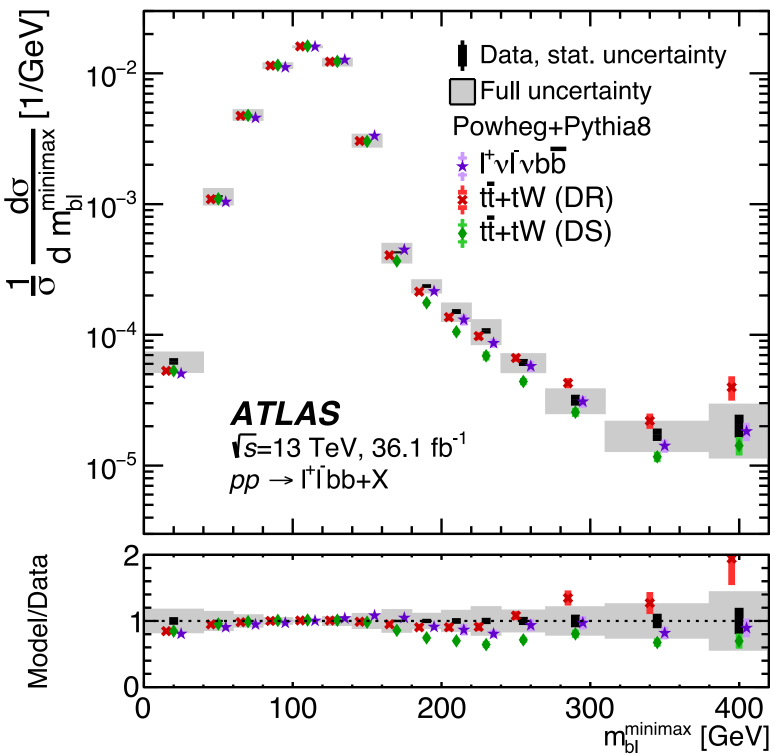
$t\bar{t}$ and tW interplay

- Probing the quantum interference between singly and doubly resonant top-quark production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector [TOPQ-2017-05]:



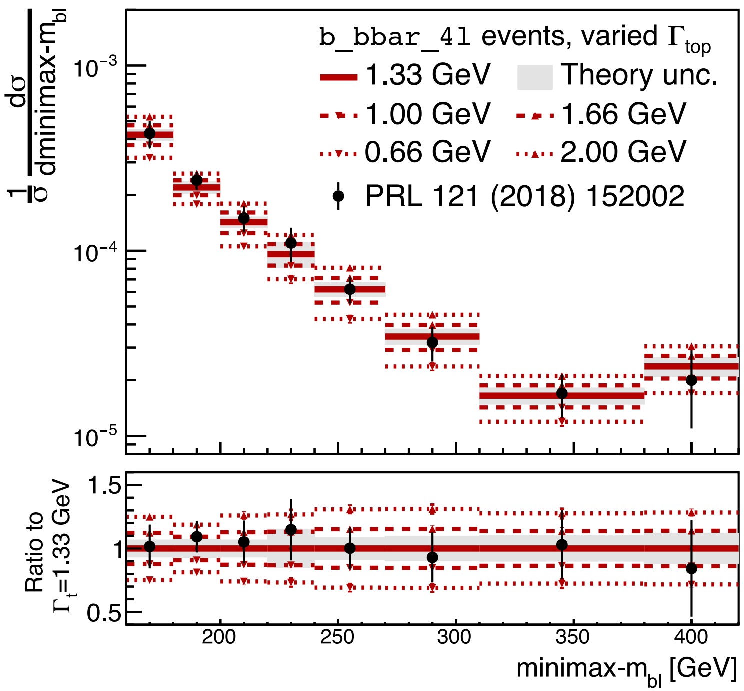
- b_bbar_41 prediction describes the data in the tail much better than predictions obtained using DR and DS prescriptions

Simulated samples

- Study width-dependence using the `b_bbar_4l` process implemented in `POWHEG BOX RES`
- This includes:
    - Consistent NLO+PS treatment of top resonances
    - Corrections to top propagators, and off-shell top-decay chains
    - Full NLO accuracy in production, decay, and their interference
    - Exact spin correlation at NLO
- Nominal sample uses $m_t = 172.5$ GeV and $\Gamma_t = 1.33$ GeV
    - Alternatives with $\Gamma_t = 0.66, 1.0, 1.66, 2.0$ GeV
    - Systematics: scale, PDF, α_S, and top mass variations
- Also generated a LO `MG5_aMC@NLO` sample for comparison

Extraction procedure (I)

- Calculate minimax-$m_{b\ell}$ using the dedicated TOPQ-2017-05 Rivet routine:
- Interpolate yields in each bin as a function of the width



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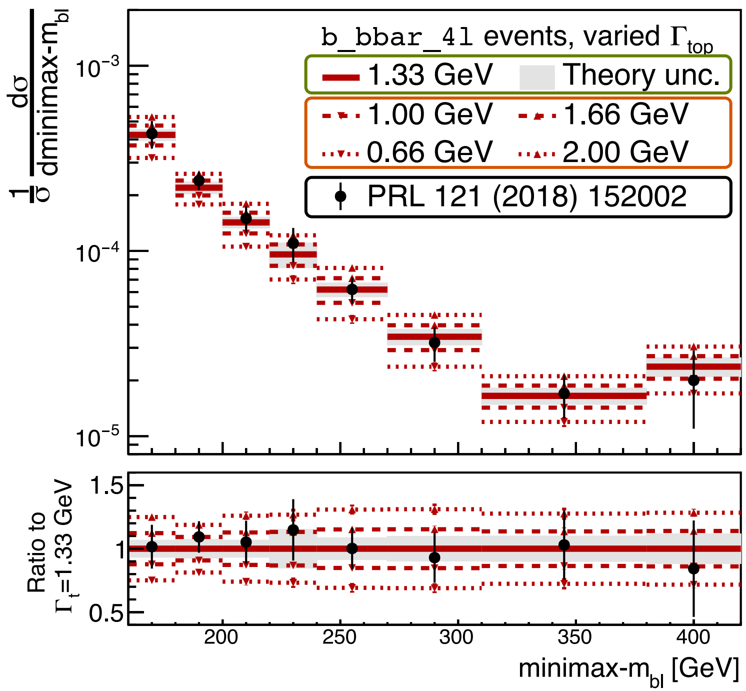

`b_bbar_4l` – nominal
(scale, PDF, α_S, m_t uncertainities)

`b_bbar_4l` – varied Γ_t

ATLAS data
TOPQ-2017-05

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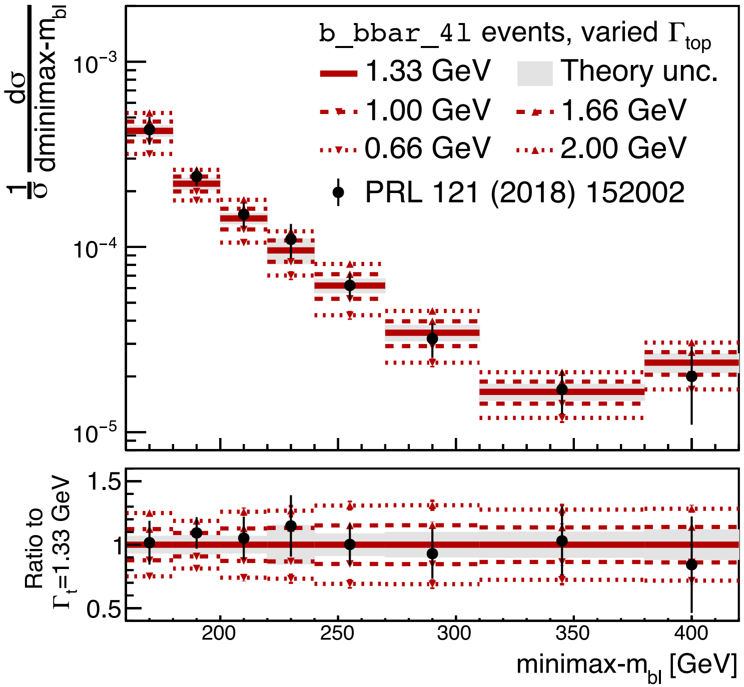


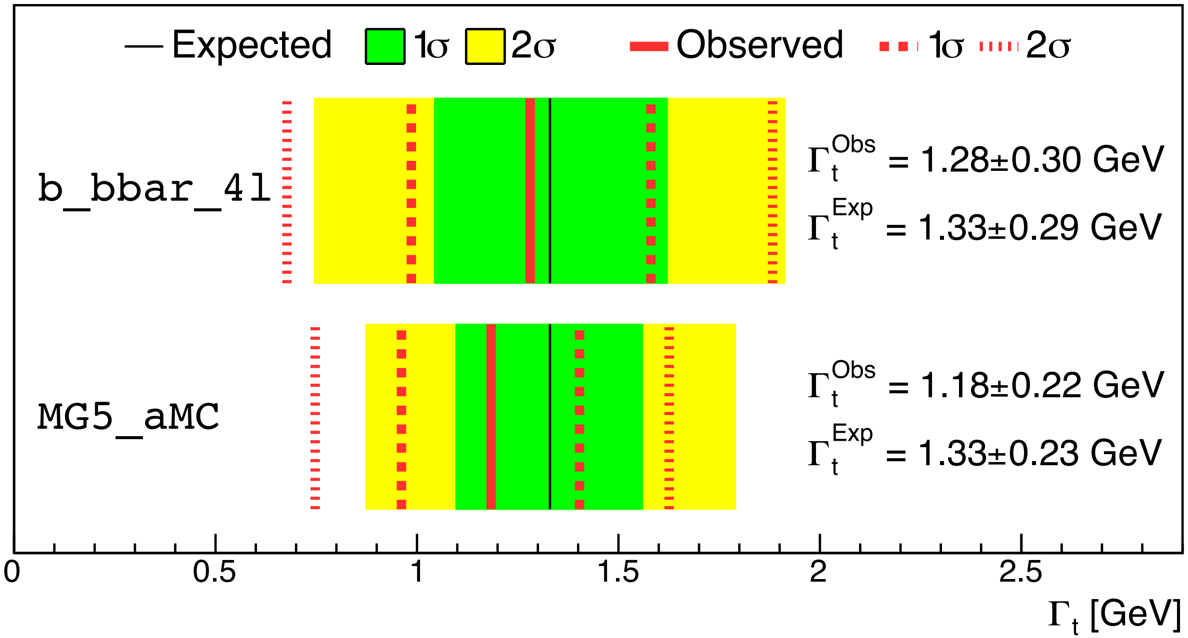
- Predictions in excellent agreement with the data
- Calculate a χ^2 using data + covariance matrix

$$\chi^2 = \sum_{i,j} (d_i - m_i) \cdot V_{ij}^{-1} \cdot (d_j - m_j)$$

- The best-fit width minimizes the χ^2
- Vary data (d_i) and model (m_i) to assess uncertainities

Results

- We find that $\Gamma_t = 1.28 \pm 0.30$ GeV using `b_bbar_4l` model
- Measurement uncertainty (0.27 GeV) dominates theory (0.14 GeV)
- The LO `MG5_aMC@NLO` model extracts $\Gamma_t = 1.18 \pm 0.22$ GeV
  - Predicts larger sensitivity to the width than the NLO model!



Compare to:

best direct result
1.76+0.86/-0.76 GeV
(ATLAS: [1709.04207])

best indirect result
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(CMS: [1404.2292])

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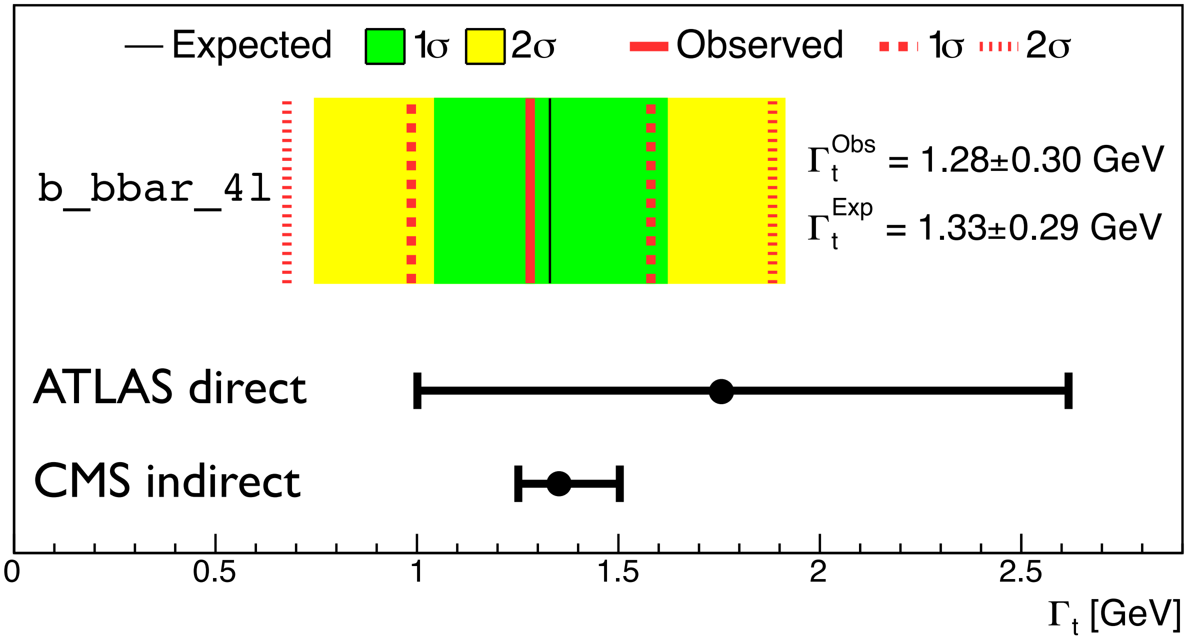

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Summary

- Direct measurements of the top-quark width are currently at the level of accuracy of 50%
- We present a new method that considers only off-shell events

- $W^+W^-b\bar{b}$ analysis strategy of TOPQ-2017-05 provides a clean extraction of the cross section in the off-shell regime
- The `b_bbar_4l` generator is the first even generator capable of describing the $t\bar{t}$ and tWb processes required for this analysis at NLO+PS accuracy
- The combination of the two yields $\Gamma_t = 1.28 \pm 0.30$ GeV

- This strategy should be pursued by LHC experiments to design new, more powerful analyses!

Backup slides

b_bbar_4l generator setup

- Nominal sample produced with m_t=172.5 GeV, Γ_H =1.33 GeV,
- Alternative widths simulated: 0.66, 1.0, 1.66, 2.0 GeV
- NNPDF3.0 NLO alpha$_S$ =0.118 set, with A14 tune
- Scale: geometric mean of (anti)top transverse mass, h_{damp}=m_t
- All different-family lepton flavor combs ("channel 7")
- Three hardest emissions kept ("allrad 1")
- Uncertainties
  - Top mass variations m_t=171.5, 173.5
  - alpha$_S$ variations: 0.115 (0.121) in PDF + Var3C in shower
  - Weights: 7-point scale variations, PDF eigenvectors
  - For statistically independent events, fit dependence per bin:

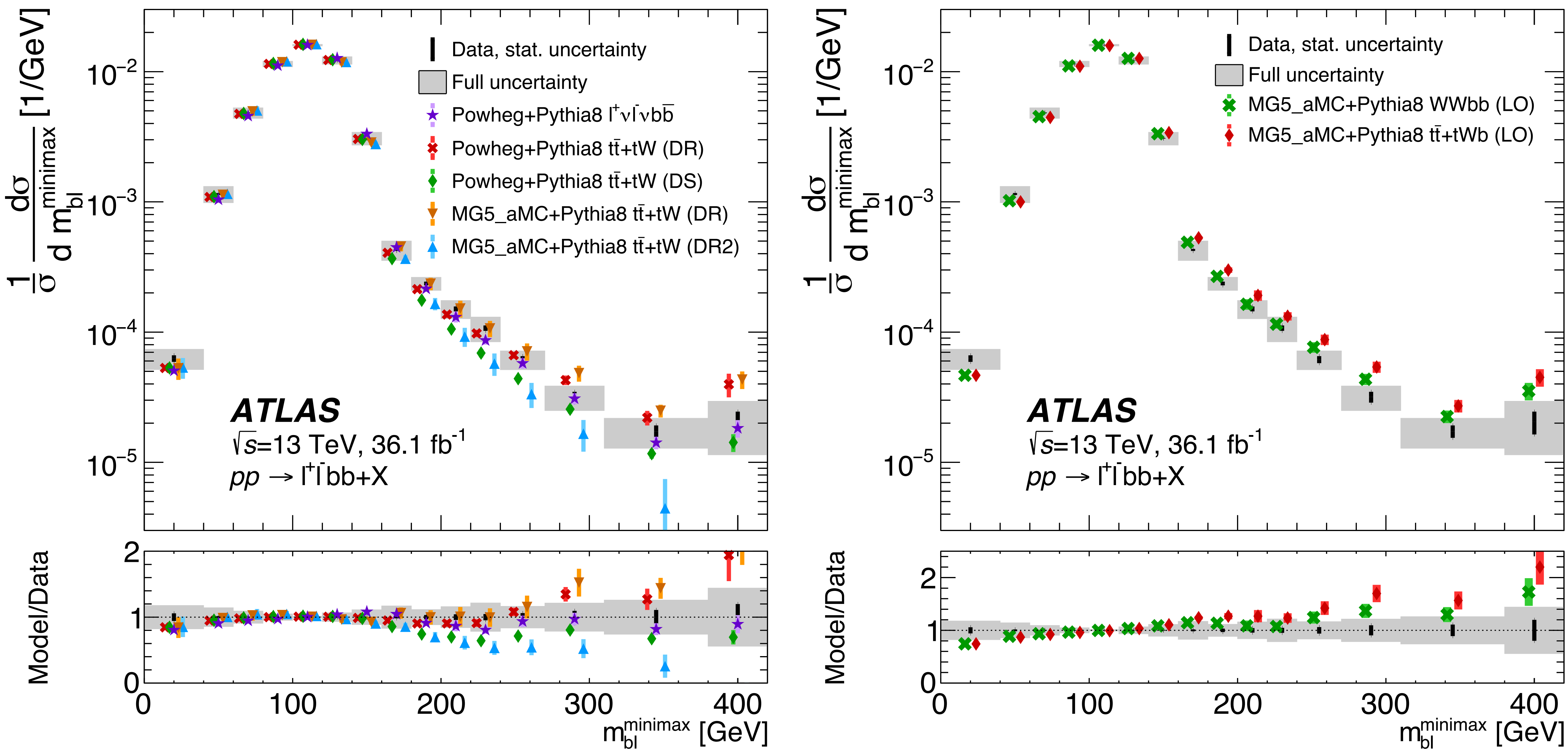
$$m_i(\alpha_s, m_t) = \hat{m}_i(\alpha_s^{\mathrm{SM}}, m_t^{\mathrm{SM}}) + \hat{a}_i(\alpha_s - \alpha_s^{\mathrm{SM}}) + \hat{b}_i(m_t - m_t^{\mathrm{SM}})$$

Uncertainty breakdown

Uncertainty [GeV]		`b_bbar_4l`	`MG5_aMC@NLO`
Experimental		+0.27/-0.26	$\pm$0.20
Theory	PDF	$\pm$0.06	$\pm$0.04
	Scale	$\pm$0.10	$\pm$0.06
	m_t	$\pm$0.03	$\pm$0.03
	α_s	$\pm$0.06	$\pm$0.04
	Combined	$\pm$0.14	$\pm$0.10
Simulation Stats.		$\pm$0.04	$\pm$0.04
Total		$\pm$0.30	$\pm$0.22

Uncertainties on the (observed) extracted widths, in GeV

Various generator comparisons



(1806.04667 / TOPQ-2017-05)

Goodness of fit

Model	Full Distribution		$m_{b\ell}^{\text{minimax}} > 160$ GeV	
	χ^2 / nDOF	p-value	χ^2 / nDOF	p-value
Powheg+Pythia8 $t\bar{t} + tW$ (DR)	10 / 14	0.71	8.5 / 8	0.40
Powheg+Pythia8 $t\bar{t} + tW$ (DS)	10 / 14	0.77	6.6 / 8	0.56
Powheg+Pythia8 $\ell^+\nu\ell^-\nu bb$	5.9 / 14	0.92	2.0 / 8	0.95
MG5_aMC+Pythia8 $t\bar{t} + tW$ (DR1)	26 / 14	0.14	13 / 8	0.17
MG5_aMC+Pythia8 $t\bar{t} + tW$ (DR2)	36 / 14	0.02	20 / 8	0.08
Powheg+Herwig++ $t\bar{t} + tW$ (DR)	26 / 14	0.07	7.3 / 8	0.48
MG5_aMC+Herwig++ $t\bar{t} + tW$ (DR)	30 / 14	0.04	11 / 8	0.23
Powheg+Pythia6 $t\bar{t} + tW$ (DR)	14 / 14	0.49	11 / 8	0.23
Powheg+Pythia6 $t\bar{t} + tW$ (DS)	14 / 14	0.49	10 / 8	0.32
MG5_aMC+Pythia8 (LO) $WWbb$	12 / 14	0.68	8.2 / 8	0.42
MG5_aMC+Pythia8 (LO) $WWbb$, no int.	28 / 14	0.05	22 / 8	0.005

(1806.04667 / TOPQ-2017-05)